NATIONAL ACADEMIES *Sciences Engineering Medicine*

TRB TRANSPORTATION RESEARCH BOARD

TRB Webinar: Addressing Moisture Damage in Asphalt Concrete

October 16, 2024

1:00 – 2:30 PM

PDH Certification Information

1.5 Professional Development Hours (PDH) – see follow-up email

You must attend the entire webinar.

Questions? Contact Andie Pitchford at TRBwebinar@nas.edu

The Transportation Research Board has met the standards and requirements of the Registered Continuing Education Program. Credit earned on completion of this program will be reported to RCEP at RCEP.net. A certificate of completion will be issued to each participant. As such, it does not include content that may be deemed or construed to be an approval or endorsement by the RCEP.

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AICP Credit Information

1.5 American Institute of Certified Planners Certification Maintenance Credits

You must attend the entire webinar

Log into the American Planning Association website to claim your credits

Contact AICP, not TRB, with questions

Purpose Statement

This webinar will examine the current state of the knowledge and critical knowledge gaps with respect to asphalt pavement moisture damage. Presenters will cover basic mechanisms related to moisture damage, examine experimental methods, and present current models for evaluating moisture damage impacts.

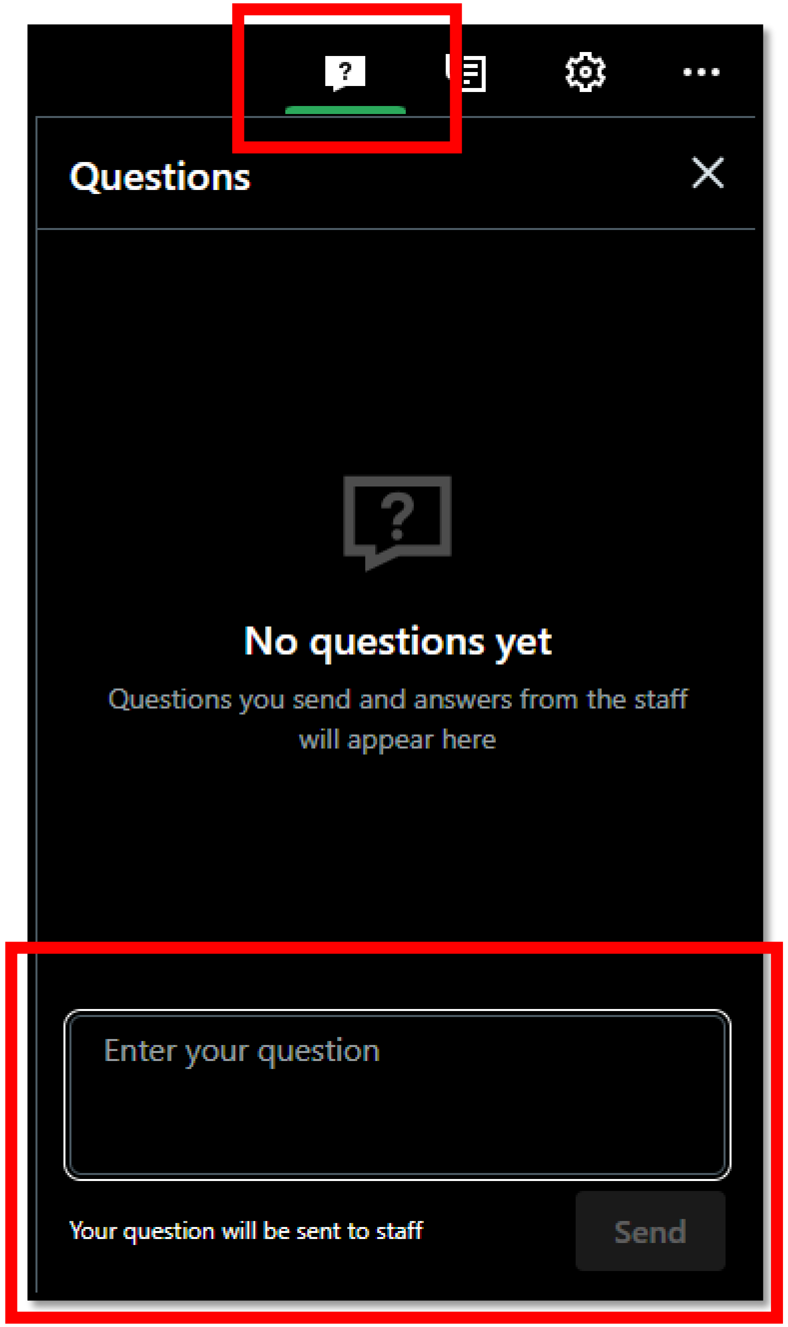
Learning Objectives

At the end of this webinar, you will be able to:

- Describe the essential mechanisms that induce and promote moisture damage in asphalt concrete mixtures
- Identify challenges and capabilities in current experimental methods and models that are used for measuring and predicting moisture damage
- Establish the need for experimental methods and models that can assess the impact of extreme moisture events on pavements

Questions and Answers

- Please type your questions into your webinar control panel
- We will read your questions out loud, and answer as many as time allows



Today's presenters

Silvia Caro
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Hamad Bin Khalifa University

Gordon Airey
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Jaime Hernandez
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Addressing Moisture Damage in Asphalt Concrete

TRB Webinar

October 16, 2024

Speakers

Silvia Caro, *Universidad de los Andes*

Gordon Airey, *University of Nottingham*

Eyad Masad, *Hamad Bin Khalifa University*

MARQUETTE UNIVERSITY

BE THE DIFFERENCE.

Addressing Moisture Damage in Asphalt Concrete

- Moisture damage is a common distress that requires costly and time-consuming repairs:
  - 39 states require testing for moisture susceptibility[1]
  - Lead to $54 billion in annual extra vehicle operating cost[2]
- Climate change: heavy precipitation events are expected to increase in frequency and magnitude[3]

Moisture Damage

https://pavementinteractive.org/reference-desk/testing/asphalt-tests/moisture-susceptibility/

1. NCHRP Synthesis 595
2. Copelan 2005, as cited in Caro et al., 2008
3. https://science2017.globalchange.gov/chapter/7/

Addressing Moisture Damage in Asphalt Concrete

- *Mechanisms of moisture damage* – Silvia Caro
- *Moisture damage experimental methods* – Gordon Airey
- *Moisture damage modeling: review and future directions* – Eyad Masad

Mechanisms of moisture damage

Silvia Caro, PhD

Departament of Civil and Environmental Engineering

Universidad de los Andes (Bogotá)

Universidad de los Andes Colombia

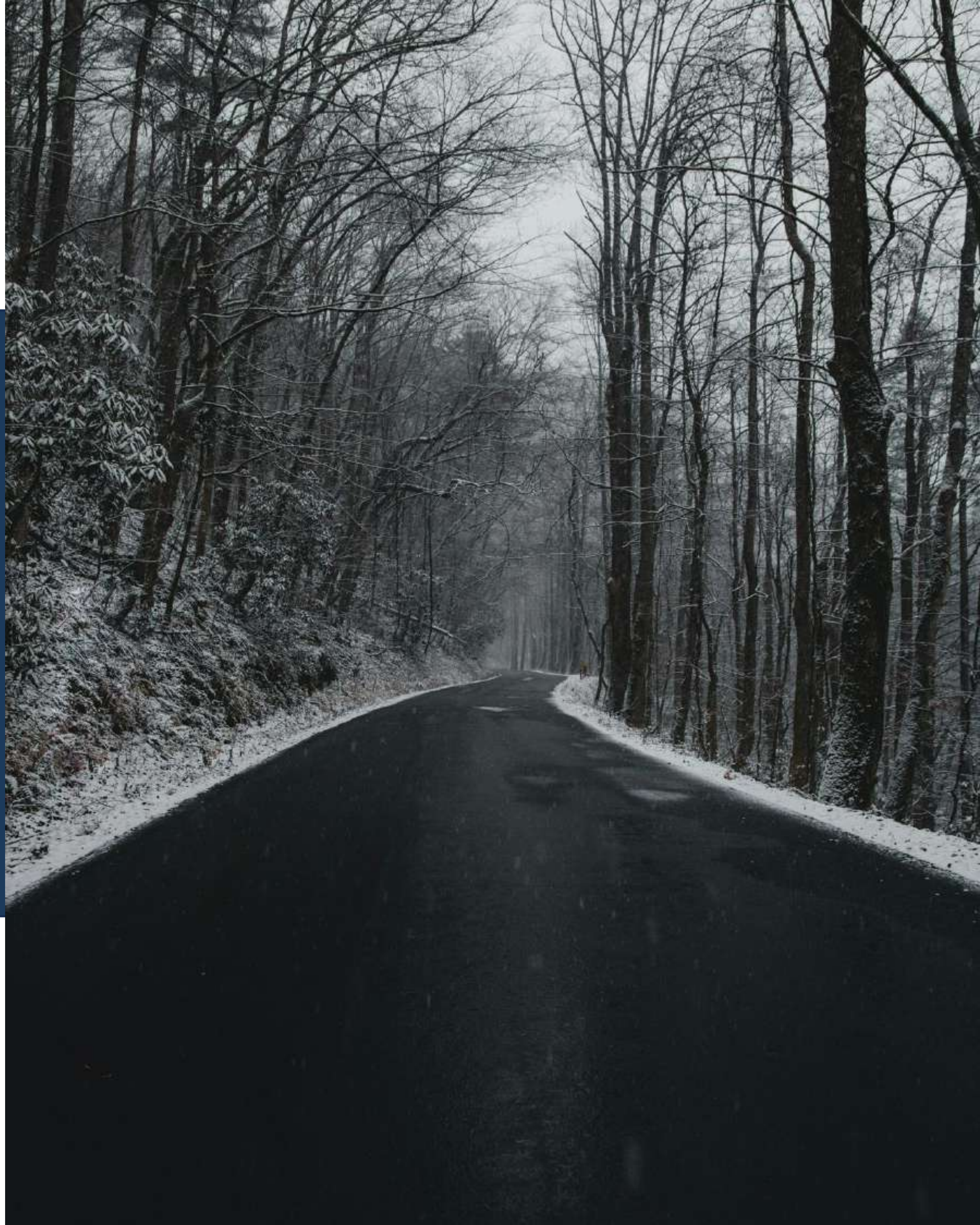
TRB WEBINAR

Addressing Moistue Damage in Asphalt Concrete

TRB

October 16th 2024

Definition



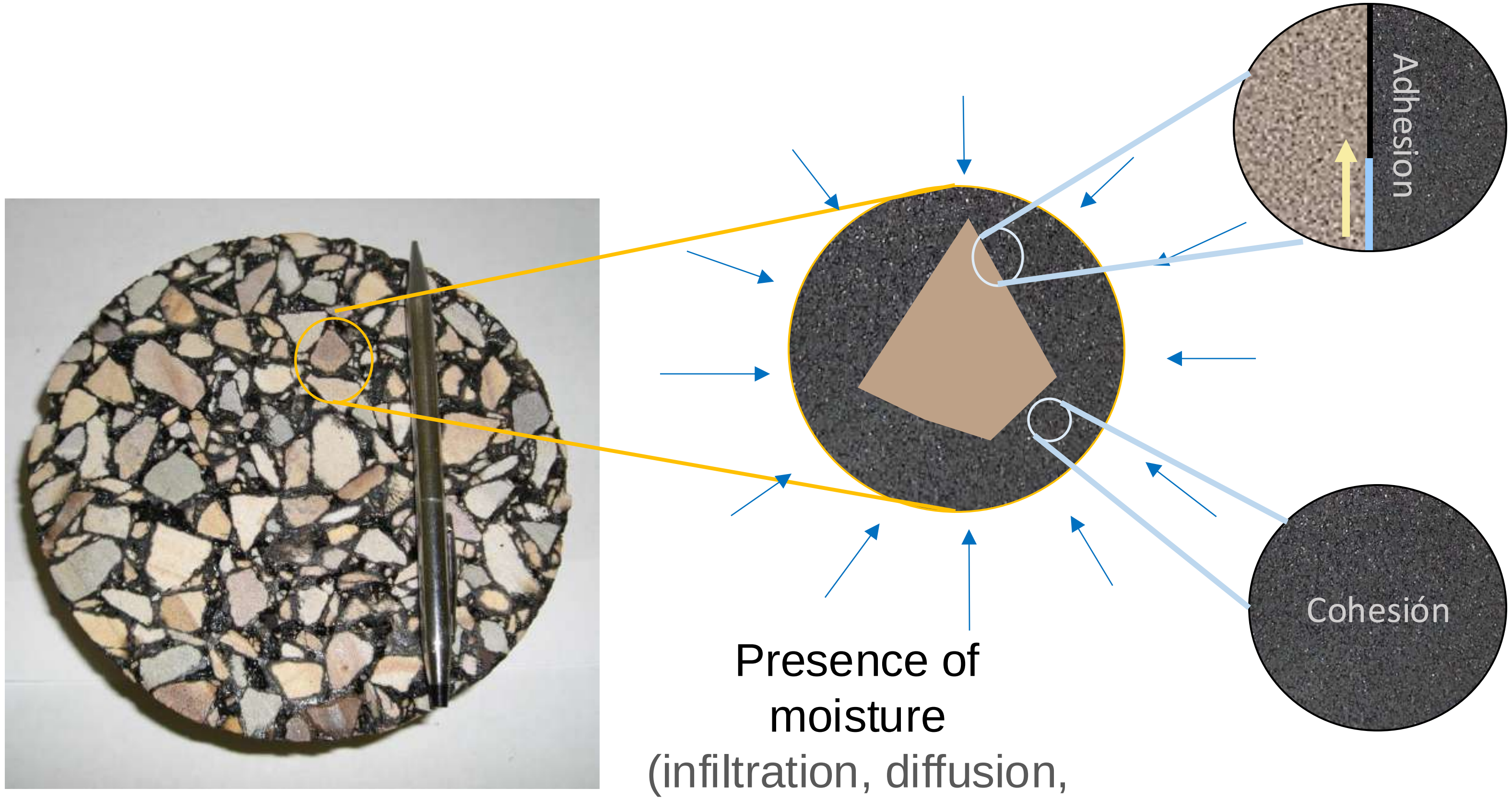
Moisture damage in asphalt mixtures

Definition

'progressive degradation of the functionality of an asphalt mixture in a pavement due to the loss of adhesion between the asphalt cement and the surface of the aggregate and/or to the loss of cohesion in the asphalt cement, mainly due to the action of water'

Kiggundu and Roberts (1988)

Moisture damage in asphalt mixtures

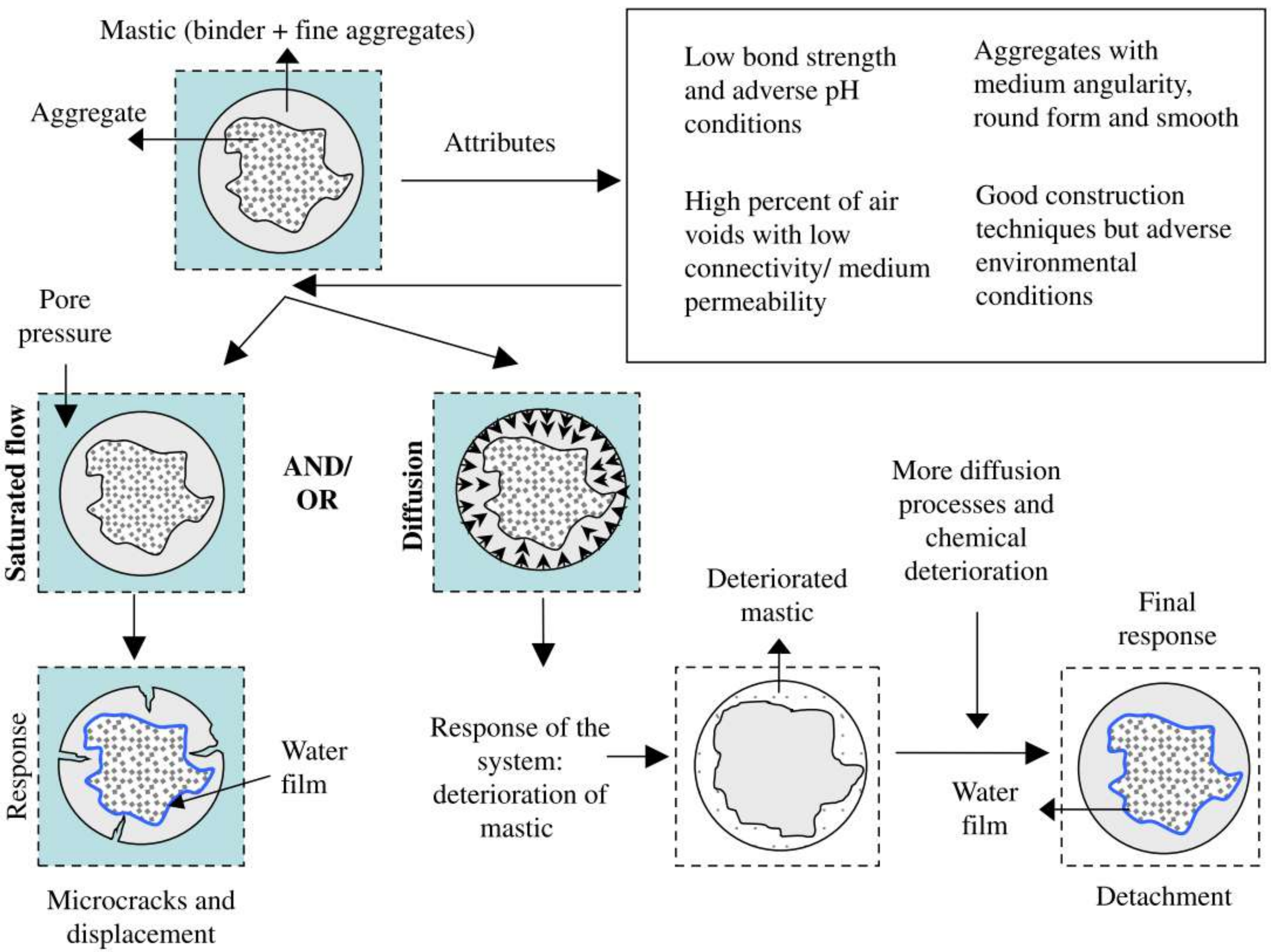


Presence of moisture
(infiltration, diffusion, capillary rise)

Adhesion loss between the asphalt binder and the aggregates (*stripping*)

Changes in the properties of the asphalt binder (rheological|chemical| thermodynamic|mechanical)

Moisture damage in asphalt mixtures

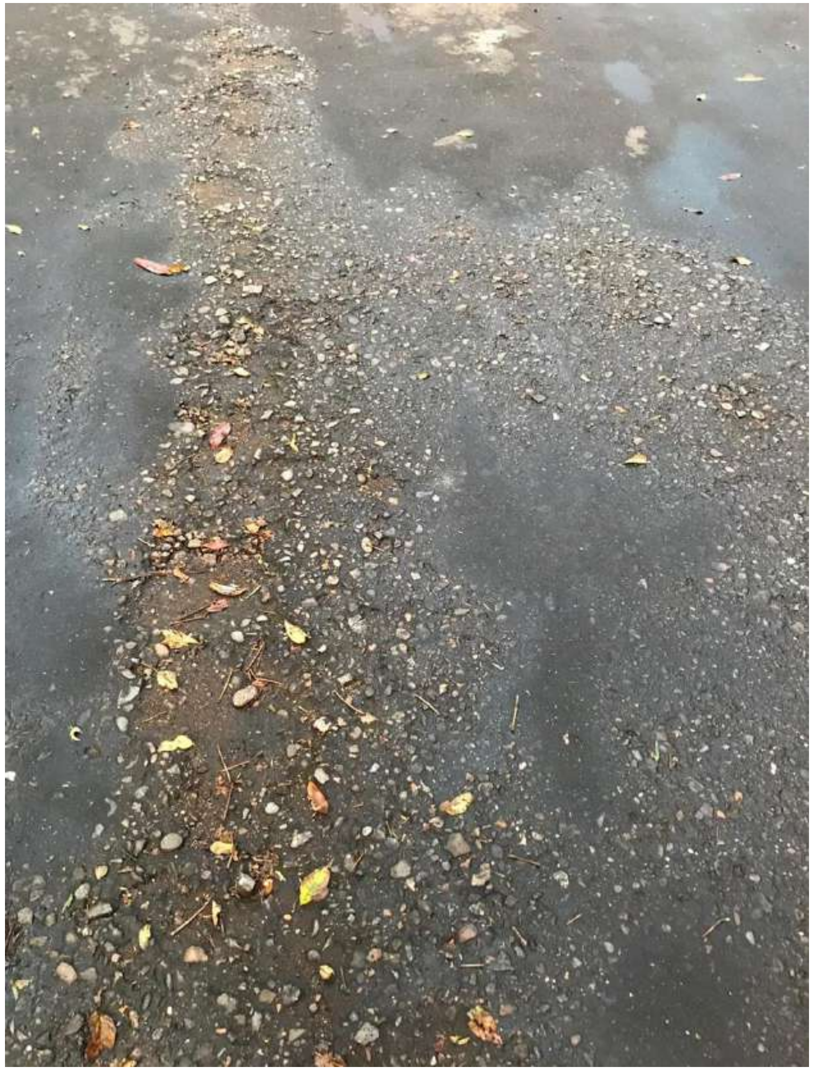


Caro et al. (2009)

Moisture damage in asphalt mixtures



Moisture damage in asphalt mixtures



Moisture damage in asphalt mixtures

Moisture damage in asphalt mixtures



Moisture damage in asphalt mixtures



Evolution of moisture damage prevention and control

Moisture damage in asphalt mixtures

https://digitalcommons.lsu.edu/cgi/viewcontent.cgi?article=1002&context=transet_pubs

Acelerates other distresses

↓

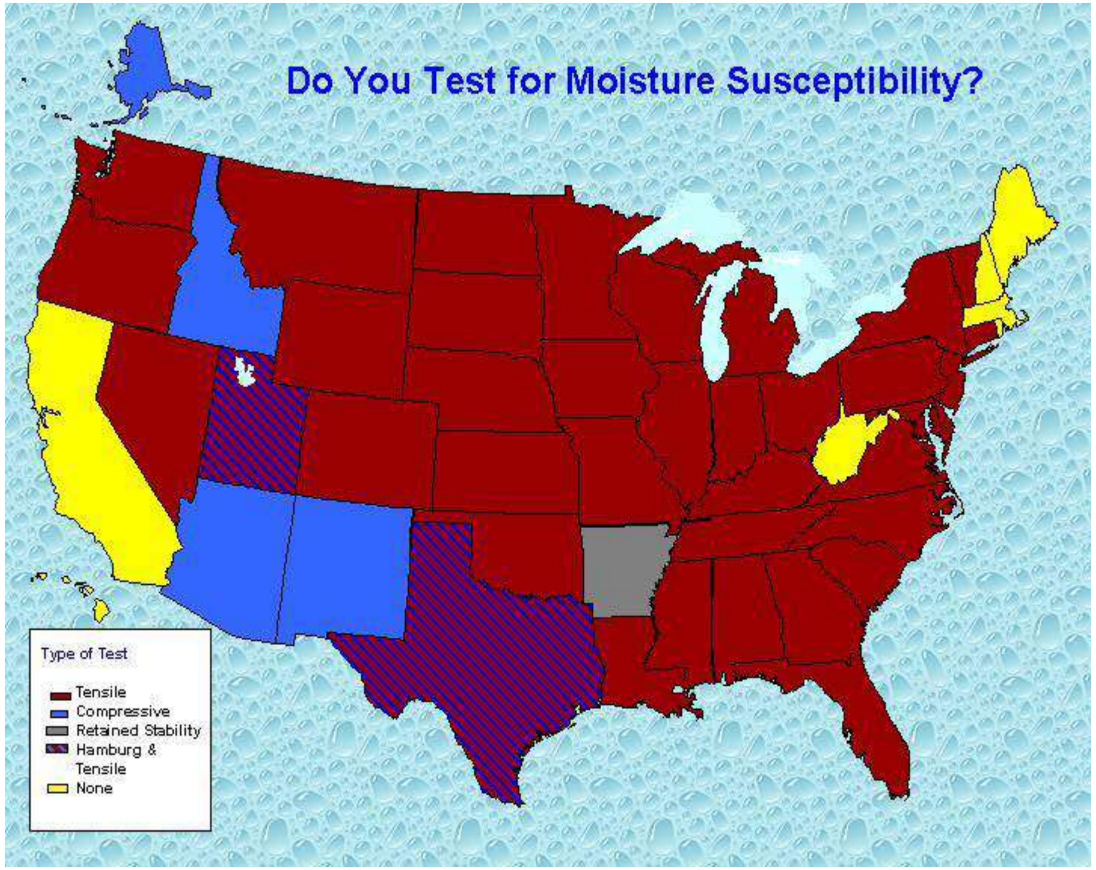
Low durability:
high maintenance costs

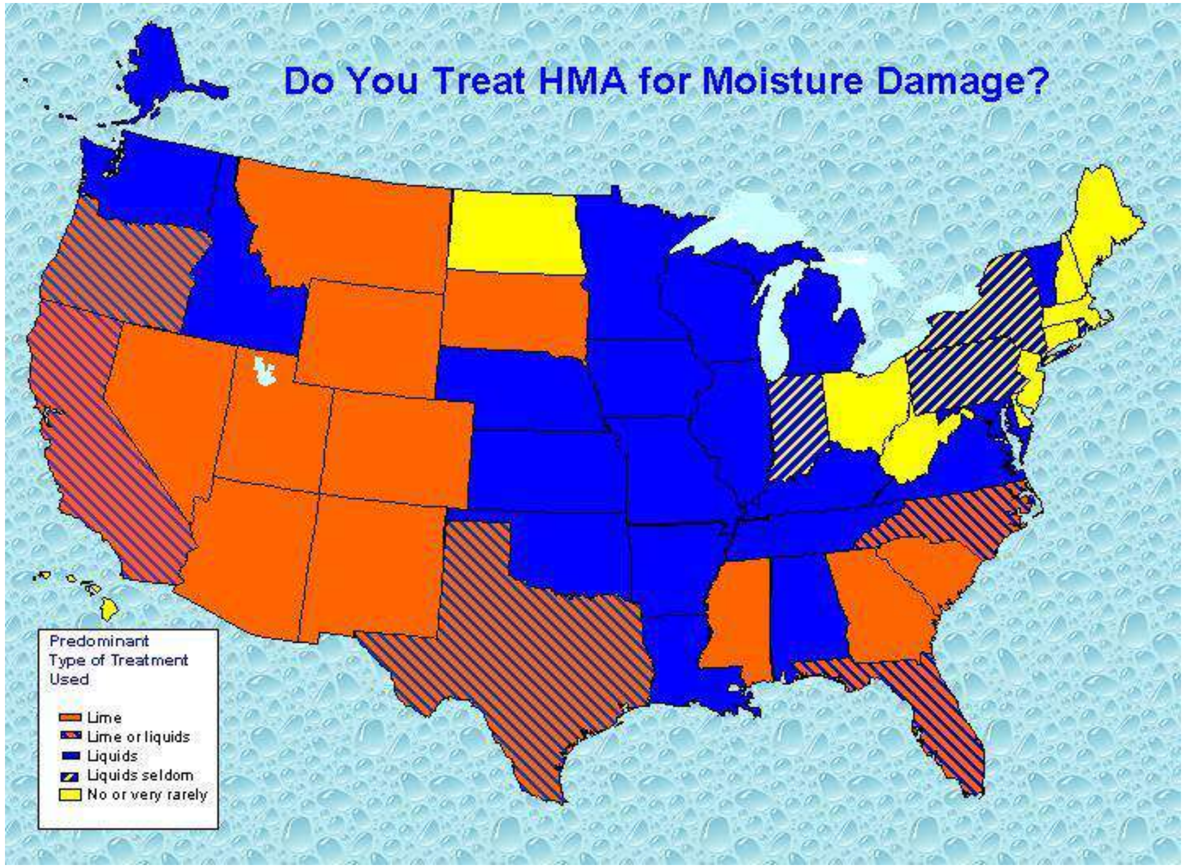
↓

Actions:
proper selection of materials [aggregates, asphalt, use of antistripping] and evaluation of their moisture damage susceptibility

How have moisture damage prevention and control evolved?

Survey in 2003 about moisture damage (Hicks et al., 2003)





* by Colorado DOT, 55 States (cited in Hicks et al, 2003)

How have moisture damage prevention and control evolved?

Survey to 50 States in the U.S. (NCHRP Synthesis 595) - 2022

States where moisture damage is considered a major issue affecting the durability of flexible pavements

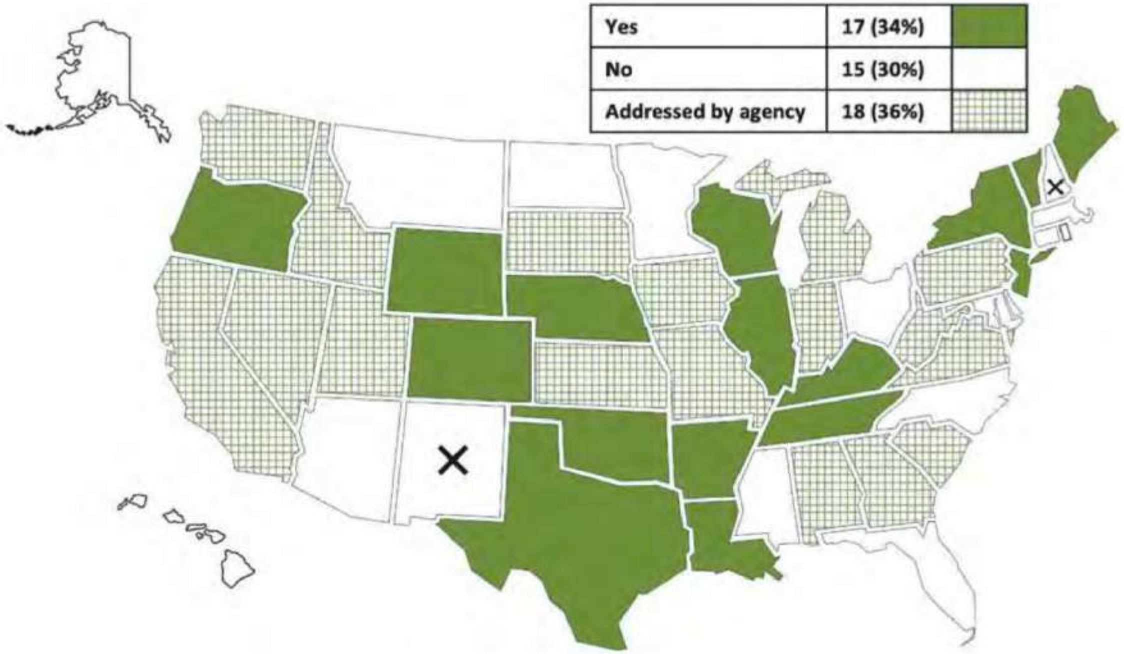


Figure 8. States where moisture damage is considered a major issue affecting the durability of flexible pavements (Q1, 50 respondents).

State DOTs that require testing asphalt mixtures or components for moisture susceptibility during the design stage

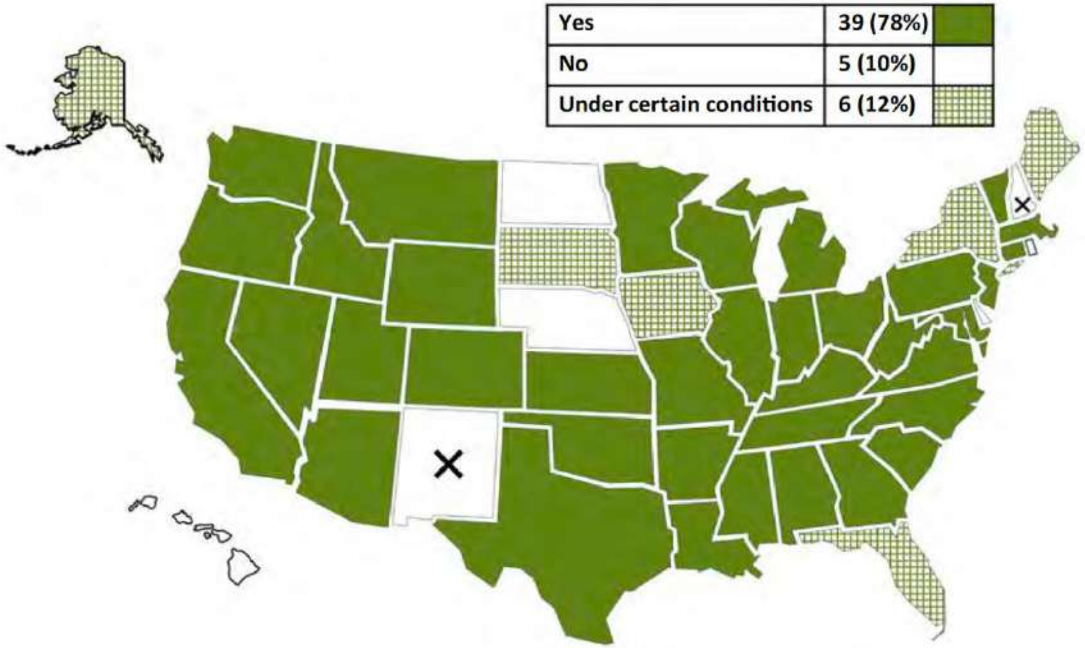


Figure 9. State DOTs that require testing of asphalt mixtures or component materials for moisture susceptibility during the mix design stage (Q2, 50 respondents).

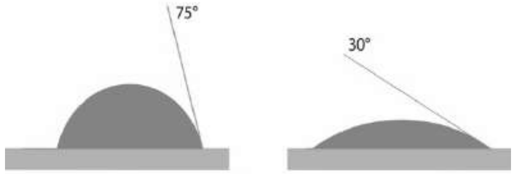
What knowledge have we gained about moisture damage?

Adhesion between asphalt and aggregates

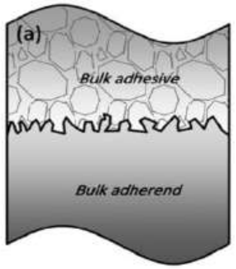
Adhesion Asphalt-aggregate

1 Chemistry

2 Physics and thermodynamics



3 Mechanics (rugosity)



(Park, 2010)

Aggregate chemistry is fundamental in the quality and durability of adhesion

Curtis (1992)
Curtis et al. (1993)
Grenfell et al. (2013)
Zhang et al. (2015)
Cala et al. (2020)
Cala et al. (2021)

Silicious rocks (rocks with high contents of SiO_2) are **more susceptible** to adhesive degradation due to moisture)

Adhesion between asphalt and aggregates

Siliceous rocks (silica or silicon dioxide [SiO_2] is the main component)

Mafic

Felsic

- High quantities of **Magnesium (Mg)** and **Iron (Fe)**

- High quantities of Quartz **(Qz)** and **Feldspar**

Ingenous

Metamorphic

Sedimentary

Cala et al. (2020); Cala and Caro (2021)

Adhesion between asphalt and aggregates

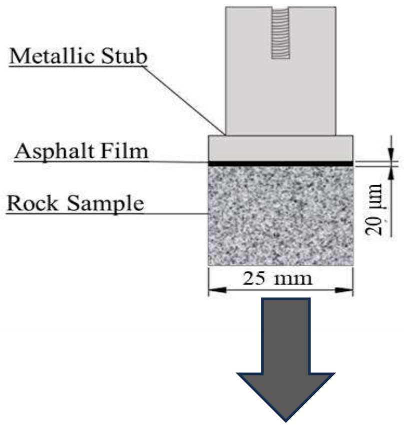
Siliceous rocks (silica or silicon dioxide [SiO_2] is the main component)

Mafic ⟷ Felsic

- High quantities of **Magnesium (Mg)** and **Iron (Fe)**

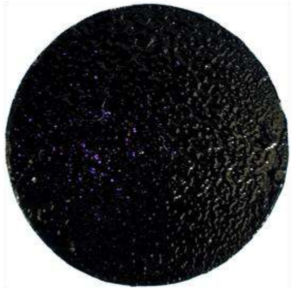
- High quantities of Quartz **(Qz)** and **Feldspar**

Pull-off test



Force

Serpentinite



Dry condition

After 7 days in water

Highly resistant to moisture damage

Quartzite

Dry condition

After 7 days in water

Highly susceptible to moisture damage

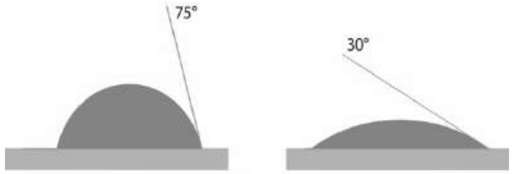
Cala et al. (2020); Cala and Caro (2021)

Adhesion between asphalt and aggregates

Adhesion
Asphalt-aggregate

1 Chemistry

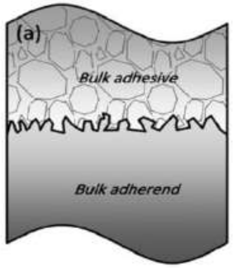
2 Physics and thermodynamics



Surface free energy

Energy required to create a new unit of area in vacuum conditions

3 Mechanics (rugosity)



(Park, 2010)

Fundamental material property

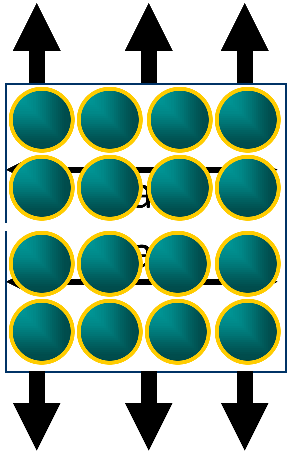
Adhesion between asphalt and aggregates

Surface free energy of asphalt binder and aggregates and corresponding equations

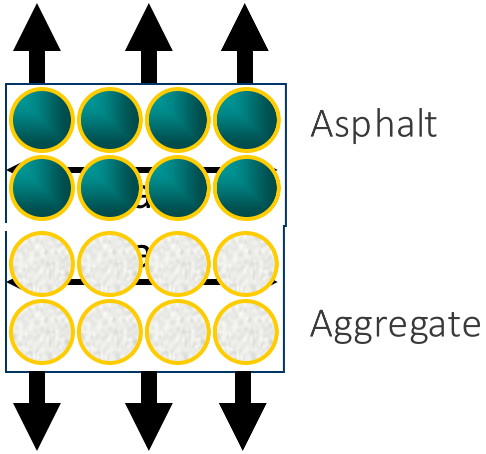
$$\Gamma = \Gamma^{LW} + 2\sqrt{\Gamma^{+}\Gamma^{-}} = \Gamma^{LW} + \Gamma^{AB}$$

Γ = total surface free energy
Γ^{LW} = non-polar component (Lifshitz-Van der Waals)
Γ^{+} = acidic monopolar component
Γ^{-} = basic monopolar component

Work of cohesion



Work of adhesion



Work of adhesion with the presence of moisture

Theoretical framework to assess moisture damage potential of aggregate-asphalt combinations

Bashin., Little, Lytton et al. (2006)

Use of anti-strip agents

Survey to 50 States in the U.S. (NCHRP Synthesis 595) - 2022

Agencies requiring the use of any anti-strip additives, such as lime of liquid anti-strips

Yes, for all mixtures	18 (36%)	
Yes, for certain mixtures or materials (aggregate)	10 (20%)	
Yes, based on results of testing	17 (34%)	
No	5 (10%)	

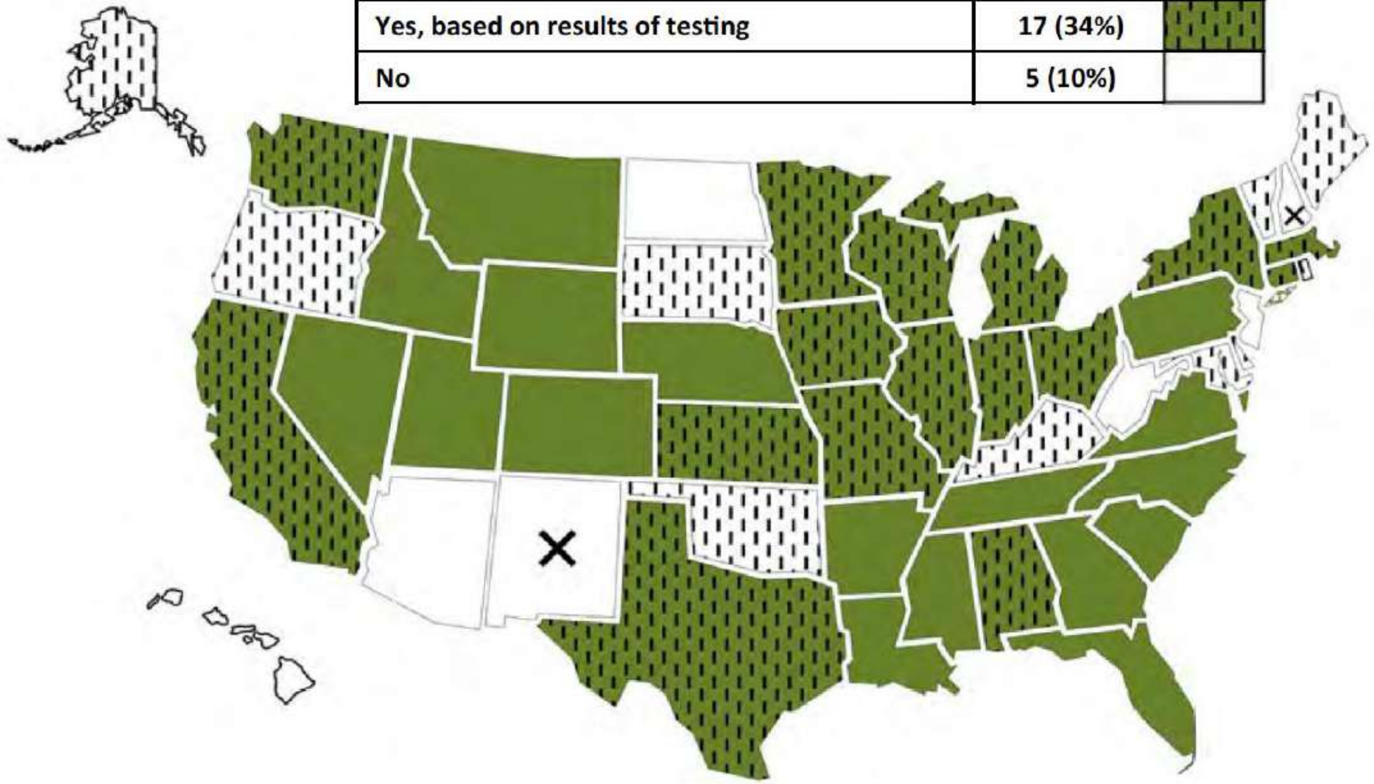


Figure 16. Agencies requiring the use of any anti-stripping additives, such as lime or liquid anti-strips (Q4, 50 respondents).

Use of anti-strip agents

Survey to 50 States in the U.S. (NCHRP Synthesis 595) - 2022

State DOTs using hydrated lime and/or liquid anti-strip additives

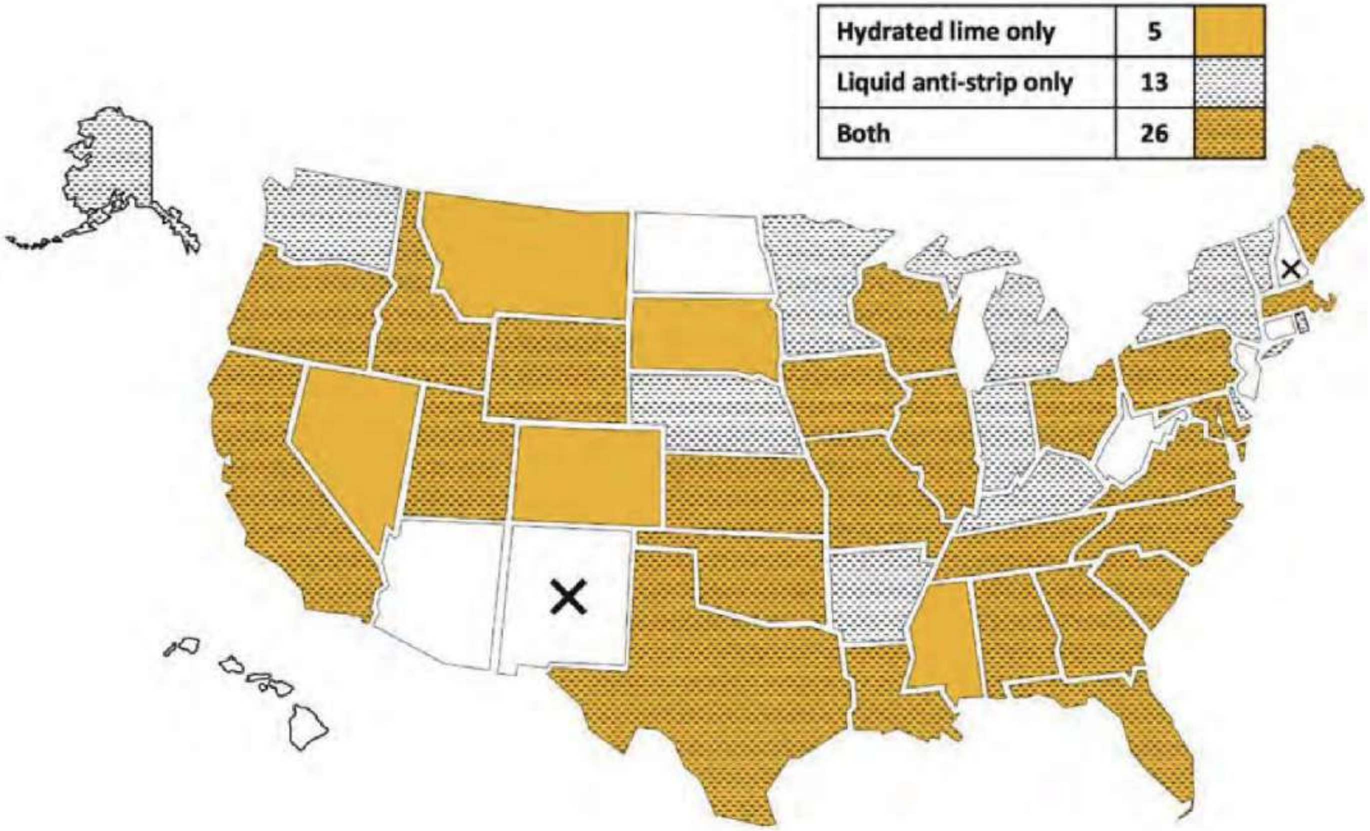


Figure 17. State DOTs using hydrated lime and/or liquid anti-stripping additives (Q4a).

Research interest on moisture damage

Survey to 50 States in the U.S. (NCHRP Synthesis 595) - 2022

Agencies that **have conducted** or **sponsored research** related to moisture damage

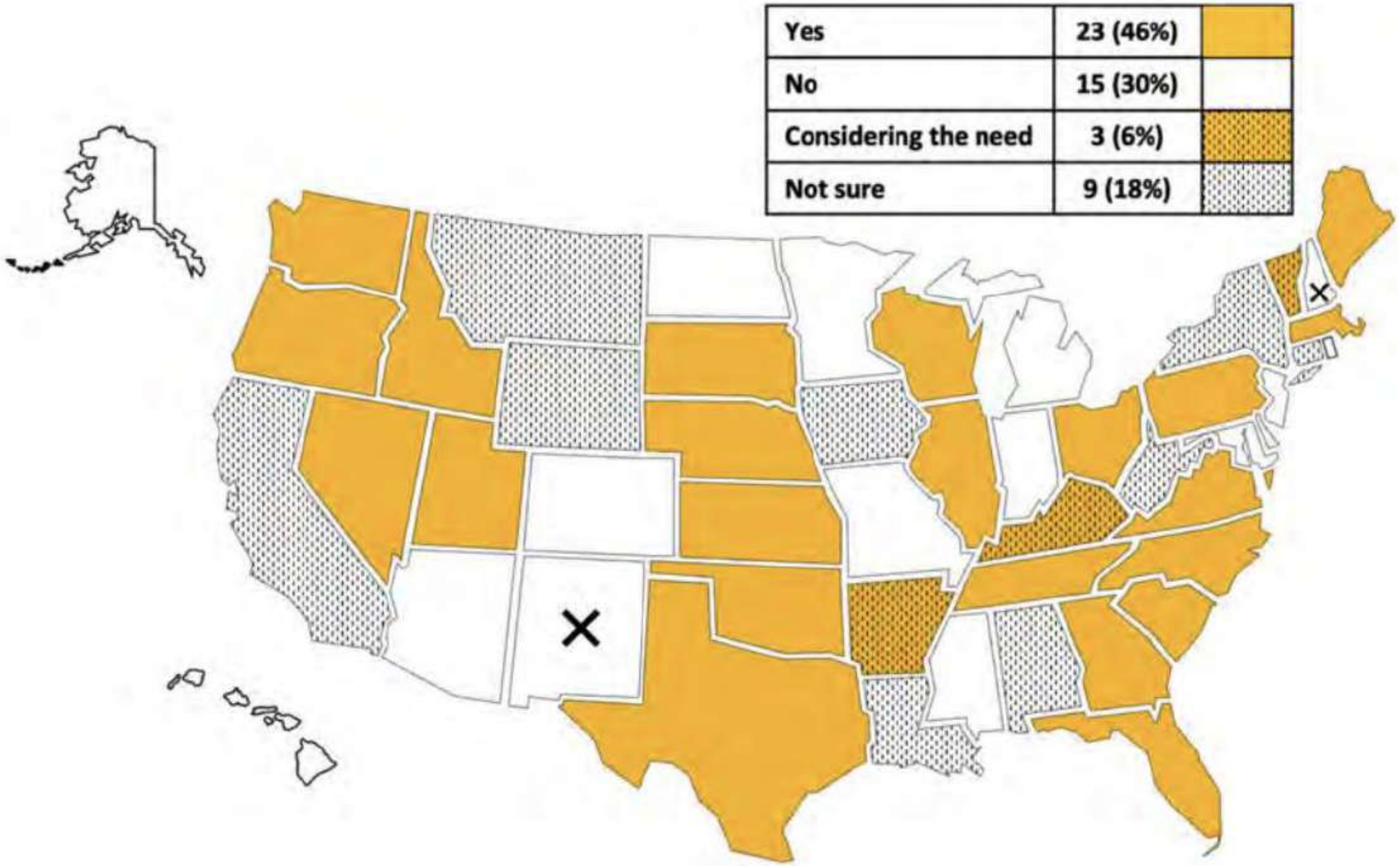
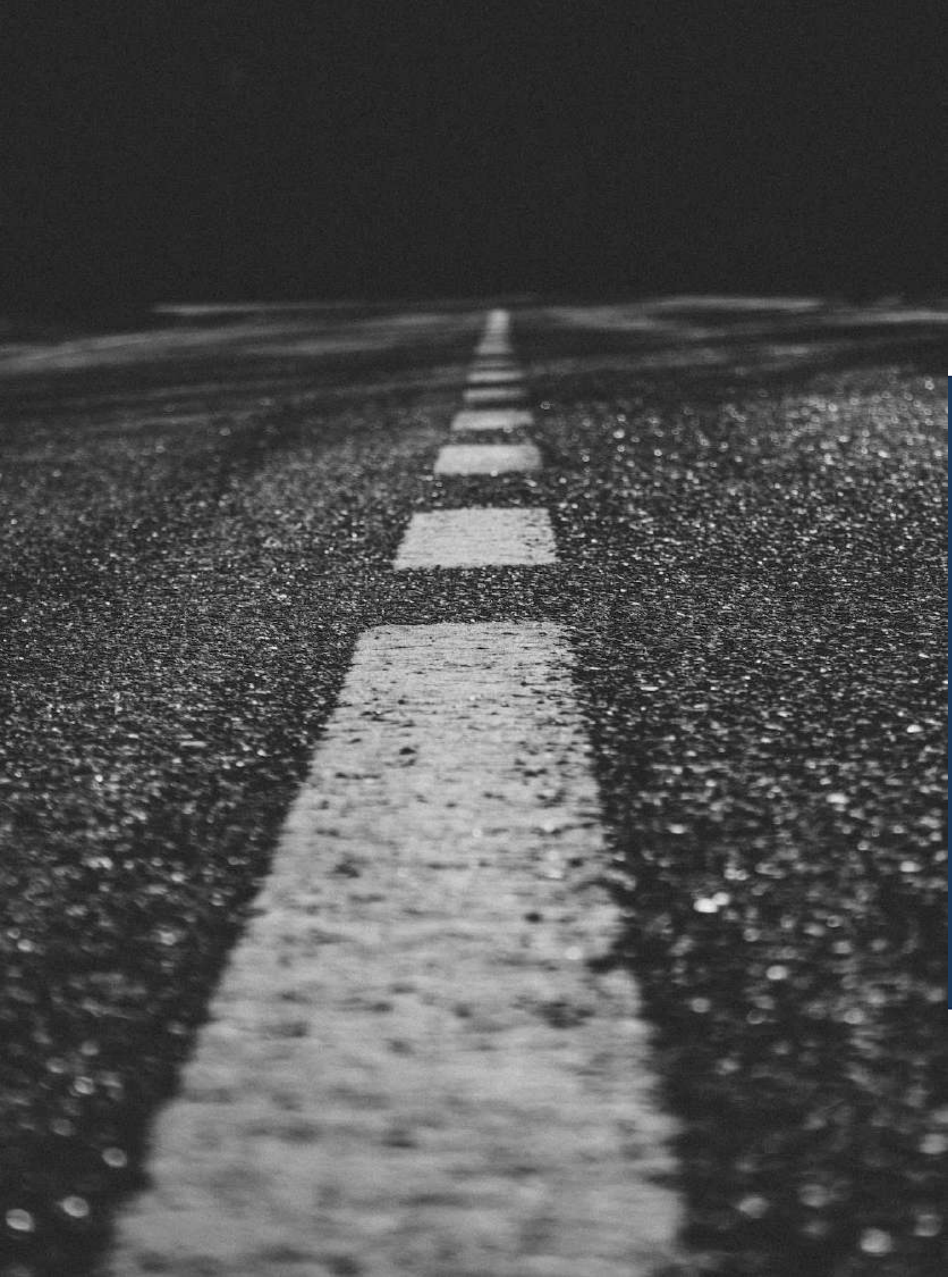


Figure 26. Number of states that conducted or sponsored research related to moisture susceptibility (Q8, 50 respondents).

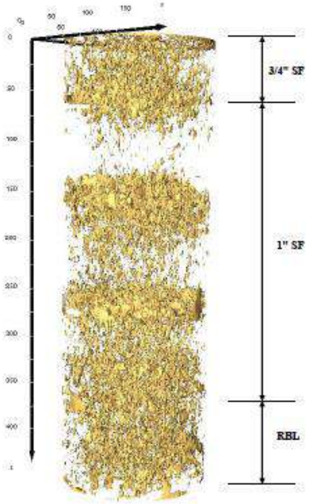


Five challenges when characterizing and controlling moisture damage

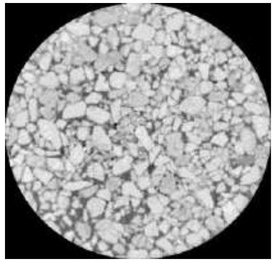
- Water can:
  - be present in different states (liquid, solid, vapor)
  - access the internal structure of the mixture through different transport modes (inflitration, diffusion, capillary rise)

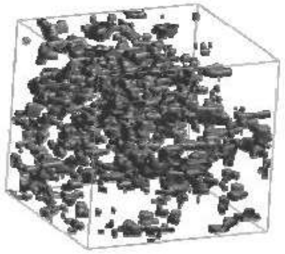
- The velocity of moisture reaching the mixture depends on the materials and on the microstructure of the mixture:

(Kassem 2008)



Air void distribution

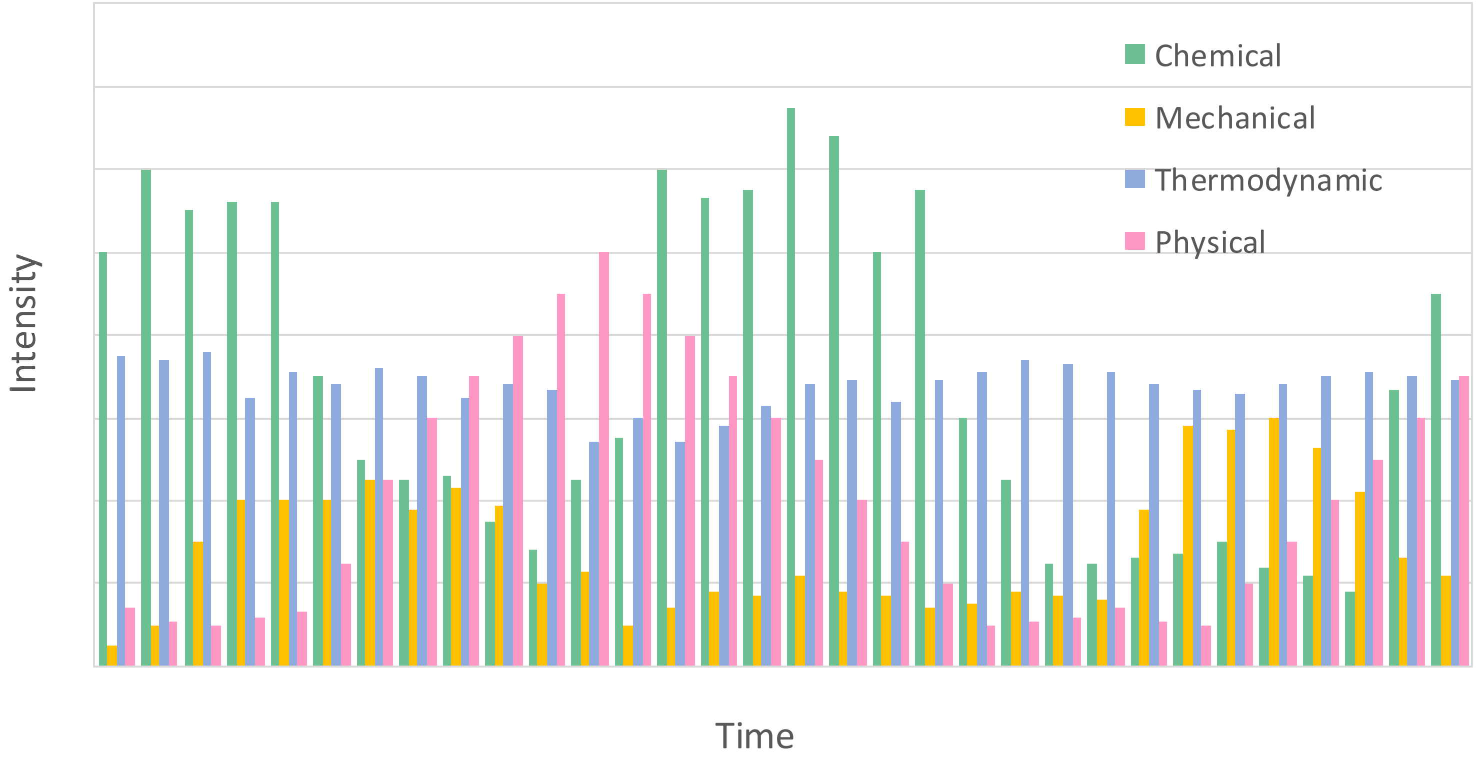




Air void distribution

(Castelblanco et al., 2006)

- It involves multiple processes (physical, chemical, thermodynamic, mechanical) ocurring simultaneously and at different magnitudes and rates:



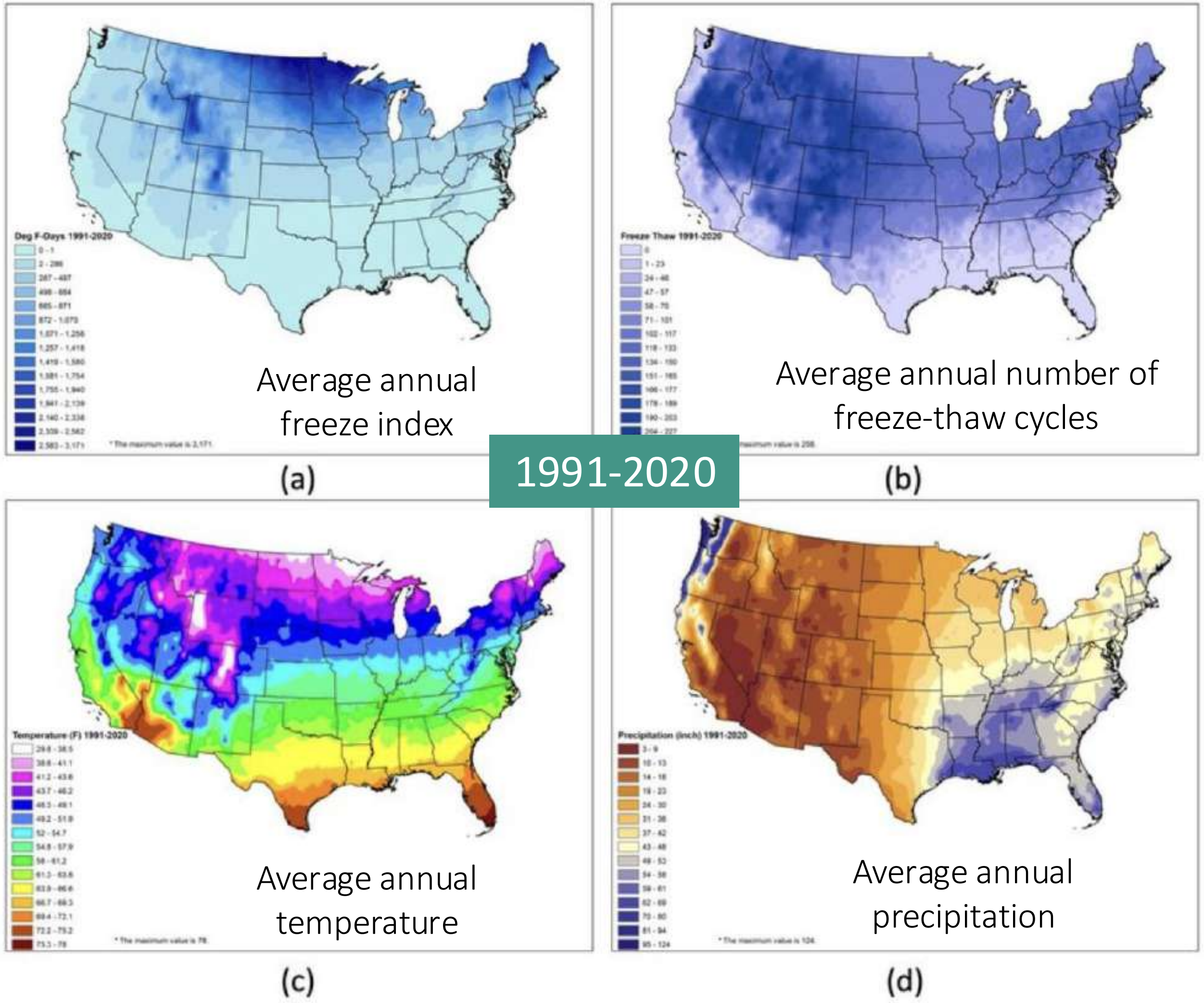
2 Complexity

- Degradation processes are driven by different processes (physical, chemical, thermodynamic, mechanical) :

• Detachment / debonding	→	• Chemical, thermodynamic
• Displacement	→	• Mechanical
• Dispersion	→	• Chemical, thermodynamic
• Film rupture	→	• Mechanical, thermodynamic
• Desorption	→	• Mechanical (after other processes)
• Spontaneous emulsification	→	• Chemical

3 Project specific

- Weather conditions are project-specific, as they depend on the geographical position



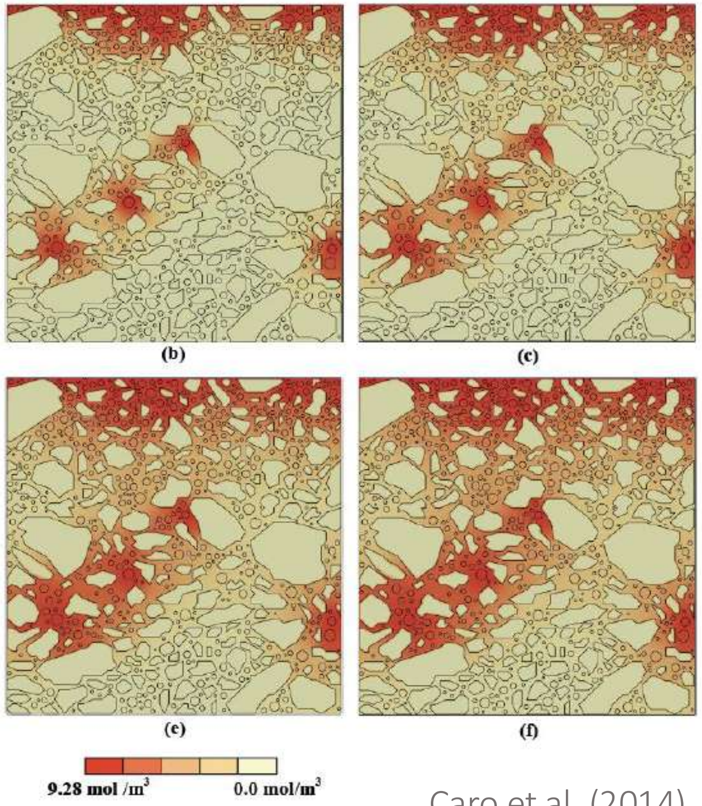
+ Climate change

https://www.researchgate.net/figure/a-average-annual-freeze-index-1991-2020-b-average-annual-number-of-freeze-thaw_fig3_358899176

Coupling with other climatic conditions

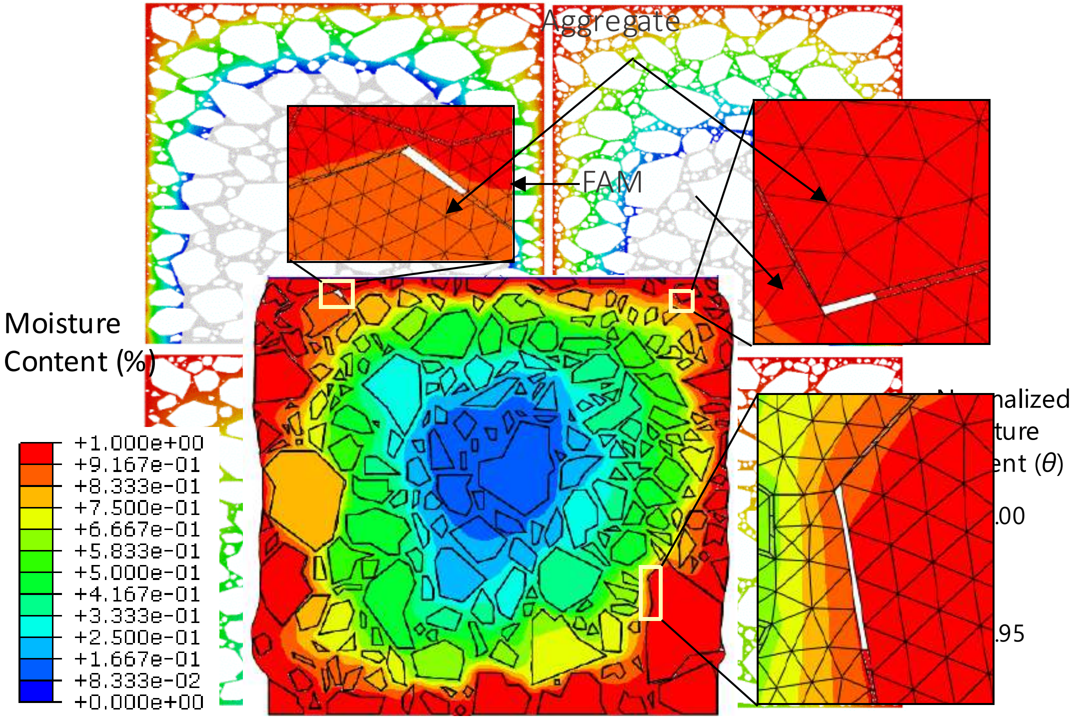
- Moisture damage occurs simultaneously with aging-oxidation. We do not know enough about these coupling phenomena:

Oxygen diffusion



Caro et al. (2014)

Moisture diffusion and adhesion failure



Castillo et al. (2014)

Caro et al. (2011)

5 Laboratory characterization

- Having a **‘universal’ test** to measure **moisture damage susceptibility** is <u>very</u> difficult, mainly because the results of the test depend on a moisture conditioning process that **cannot predict weather conditions in every project**.

Moisture conditioning process

Pass

Fail

Hamburg wheel tracking test (HWT)

TSR: tensile strength ratio (σ_t)wet/ (σ_t)dry

- It is difficult to have a test able to capture the climatic conditions in the field of any project:

Colombia

University of Nottingham
Nottingham Transportation Engineering Centre

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

Transportation Research Board (TRB) Webinar:

Addressing Moisture Damage in Asphalt Concrete

Moisture Damage Experimental Methods

Professor Gordon Airey
Nottingham Transportation Engineering Centre (NTEC)
University of Nottingham
16th October 2024

Outline

- MD experimental methods and approaches
  - Coated aggregate (stripping) tests
    - Rolling bottle, boiling water, etc
  - Adhesion assessment (intrinsic and mechanical)
    - Surface free energy and thermodynamics
    - Peel and BBS tests
  - Asphalt mixture bulk properties
    - MD conditioning regimes
- Gaps and future direction

Identify challenges and capabilities in current experimental methods and models that are used for measuring and predicting moisture damage.

Moisture damage experimental methods state of the knowledge/art and gaps/future directions

Test Methods

- Water present at aggregate-binder interface – studied since 1930s
- Test method development – 1980 to 1995
- Two categories
  - Tests conducted on loose coated aggregate
    - Stripping type (empirical) methods
    - Thermodynamic, surface free energy (SFE) and mechanical approaches
  - Tests performed on compacted mixtures (conditioning & damage ratios)
- State of the Art papers/documents:
  - Airey, G.D. and Choi, Y-K. (2002) ‘State of the art report on moisture sensitivity test methods for bituminous pavement materials’, *International Journal of Road Materials and Pavement Design*, 3 (4), 355–372.
  - Solaimanian, M., Harvey, J., Tahmoressi, M. and Tandon, V. (2003) ‘Test methods to predict moisture sensitivity of hot mix asphalt pavements’, *Moisture Sensitivity of Asphalt Pavements: A National Seminar*, San Diego, California, Transportation Research Board.

Stripping – Loose Aggregate

Test method	Water volume	Duration	Aggregate size	Sample size	Extra features
Static immersion test – AASHTO T182, ASTM D1664	400 ml distilled water	16 to 18 hours	Single size	100 g	-
Total water immersion test 'twit' [WHI 90]	Distilled water	48 hours	14 mm aggregate	-	25°C
Rolling bottle method – EN 12697-11	250 ml deionised water	75 minutes	6.3 mm to 8 mm with 0.1 mm binder film	200 particles	Glass rod, flask rotated @ 40 rpm
Boiling water test [KEN 83] – ASTM D3625	500 ml distilled water	1 to 10 minutes	Single size or graded	200 to 300 g	Boiling water
Ancona stripping test (AST) [BOC 93]	200 ml distilled water	45 minutes	6 mm to 10 mm with 3 g of bitumen	60 g	Boiling water
Boiling water stripping test [CHO 93]	600 ml demineralised water	10 minutes	10 mm to 14 mm with 1.8% binder	200 g	Boiling water, Chemical attack
Ultrasound method [VUO 99]	Water	-	Test piece – 20 mm x 80 mm	2 g bitumen – 0.12 film	Ultrasound
Net adsorption test [CUR 93] - SHRP Designation M-001	2 ml of water	6 hours 8 hours	Minus 4.75 mm	50 g	140 ml – bitumen-toluene sol
Modified net adsorption test [WAL 96]	2 ml of water	6 hours 8 hours	Graded minus 4.75 mm	50 g	140 ml – bitumen-toluene sol

Coated Aggregate (Adhesion) Tests

Static Immersion Test (AASHTO T182, ASTM D1664)

Before & after coating

- Single size aggregate
- 100g aggregate
- 5.5g bitumen
- Distilled water
- 16 to 18 hrs

Rolling Bottle Test (EN 12697-11)

- 6.3mm to 8mm aggregate
- 170g aggregate
- 5.7g bitumen
- Distilled water
- 6 to 72 hrs

Rolling bottle apparatus

Boiling Water Test (ASTM D3625)

Burner & beaker

- 6.3mm to 8mm aggregate
- 300g aggregate
- 15g bitumen
- Distilled water
- Boiling water
- 10 mins

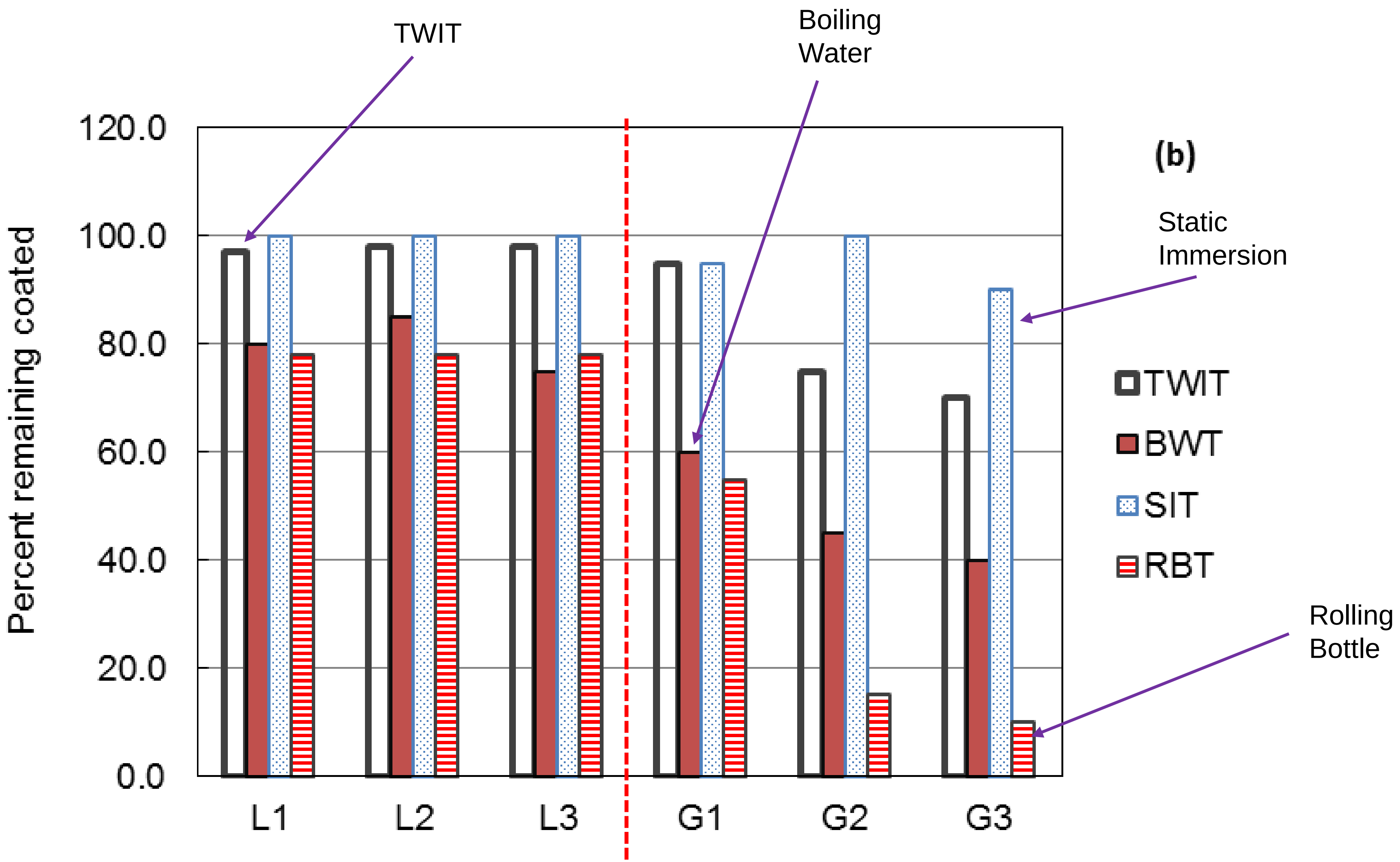
Total Water Immersion Test (TWIT)

- 6.3mm to 8mm aggregate
- 300g aggregate
- 15g bitumen
- Distilled water
- 40ºCwater bath
- 3 hrs

Water bath & beakers

Liu et al. 2014. *Int J Pavement Eng.*

Stripping Results



SFE adhesion calculations

Adhesive bond energy (**dry**)

High values

$$\Delta G_{BA}^{a} = 2\sqrt{\gamma_B^{LW}\gamma_A^{LW}} + 2\sqrt{\gamma_B^{+}\gamma_A^{-}} + 2\sqrt{\gamma_B^{-}\gamma_A^{+}}$$

Adhesive bond energy (**wet**)

Low values

$$\Delta G_{BWA}^{a} = 2\gamma_W^{LW} + 2\sqrt{\gamma_B^{LW}\gamma_A^{LW}} - 2\sqrt{\gamma_B^{LW}\gamma_W^{LW}} - 2\sqrt{\gamma_A^{LW}\gamma_W^{LW}} + 4\sqrt{\gamma_W^{+}\gamma_W^{-}} - 2\sqrt{\gamma_W^{+}}\left(\sqrt{\gamma_B^{-}} + \sqrt{\gamma_A^{-}}\right) - 2\sqrt{\gamma_W^{-}}\left(\sqrt{\gamma_B^{+}} + \sqrt{\gamma_A^{+}}\right) + 2\sqrt{\gamma_B^{+}\gamma_A^{-}} + 2\sqrt{\gamma_B^{-}\gamma_A^{+}}$$

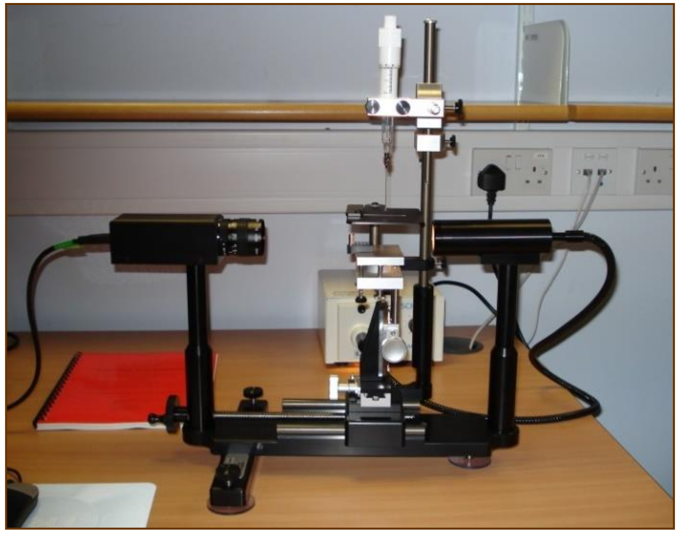
Bond energy ratio

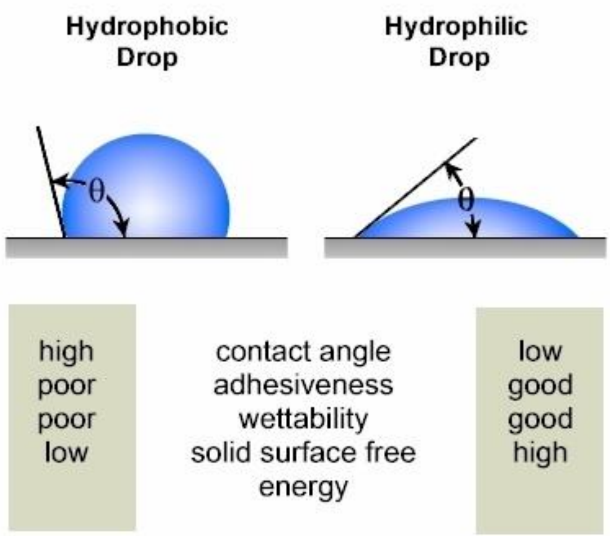
$$R^{Total} = \left|\frac{\Delta G_{BA}^{a}}{\Delta G_{BWA}^{a}}\right|$$

Moisture damage ratios (indices)

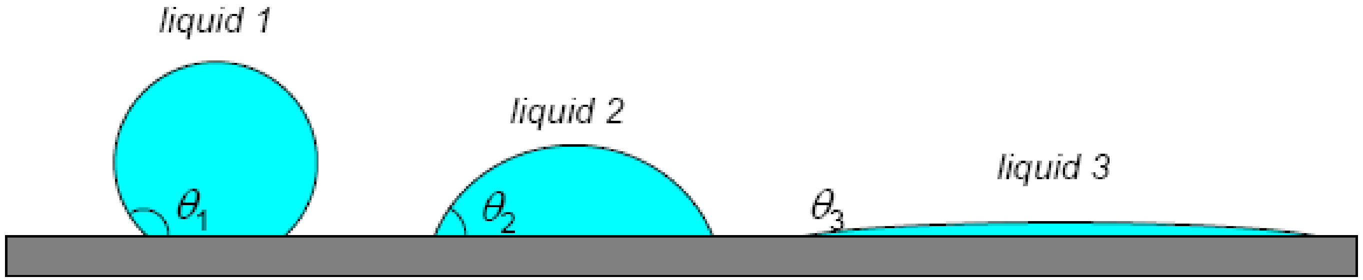
$$ER_1 = \left|\frac{W_{12}}{W_{132}}\right| \qquad ER_2 = \left|\frac{W_{12} - W_{11}}{W_{132}}\right| \qquad ER_3 = \left|\frac{W_{12}}{W_{132}}\right| * SSA \qquad ER_4 = \left|\frac{W_{12} - W_{11}}{W_{132}}\right| * SSA$$

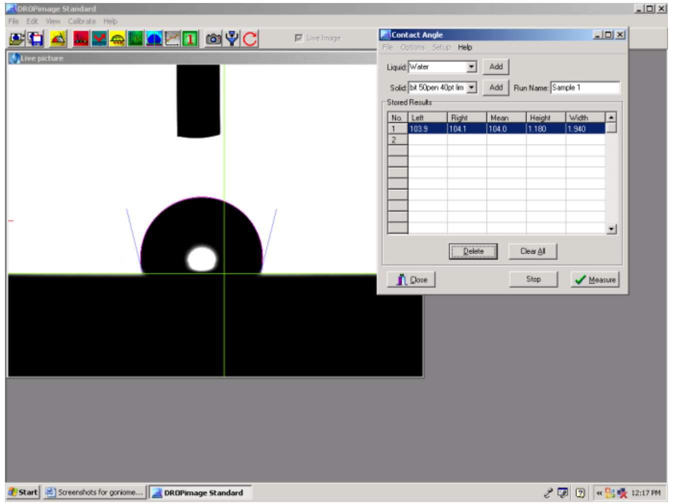
Contact angle - Goniometer



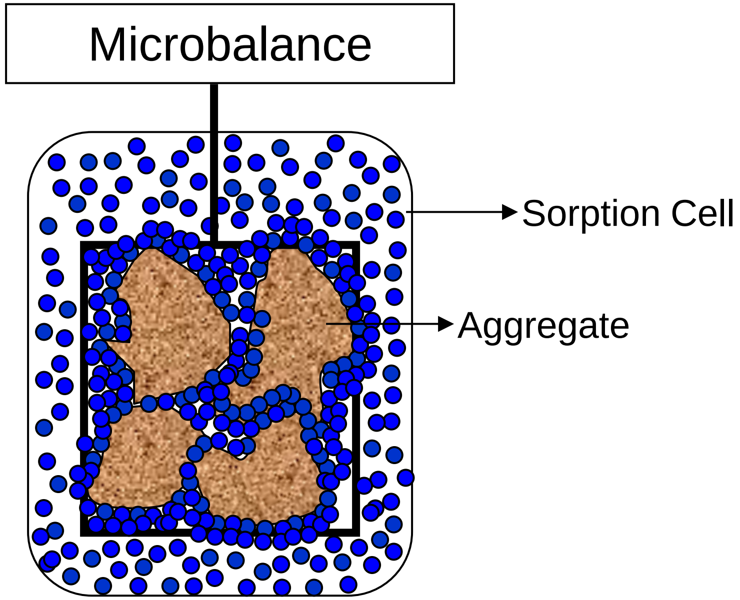


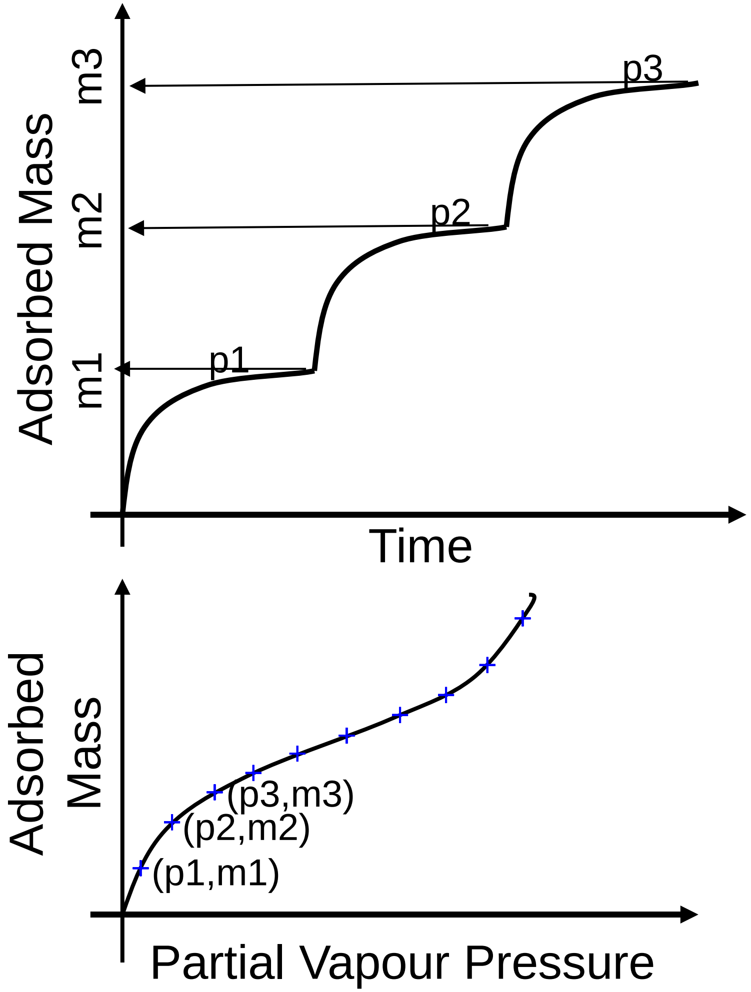
Goniometer - Bitumen





Dynamic Vapour Sorption (DVS)

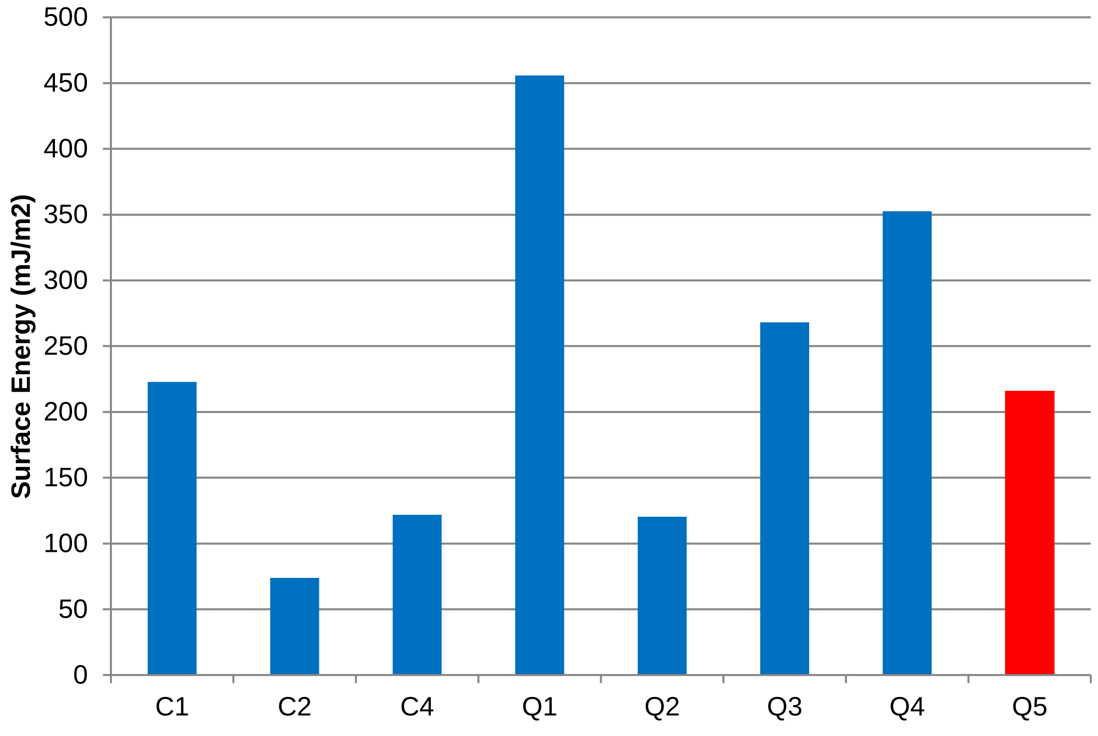




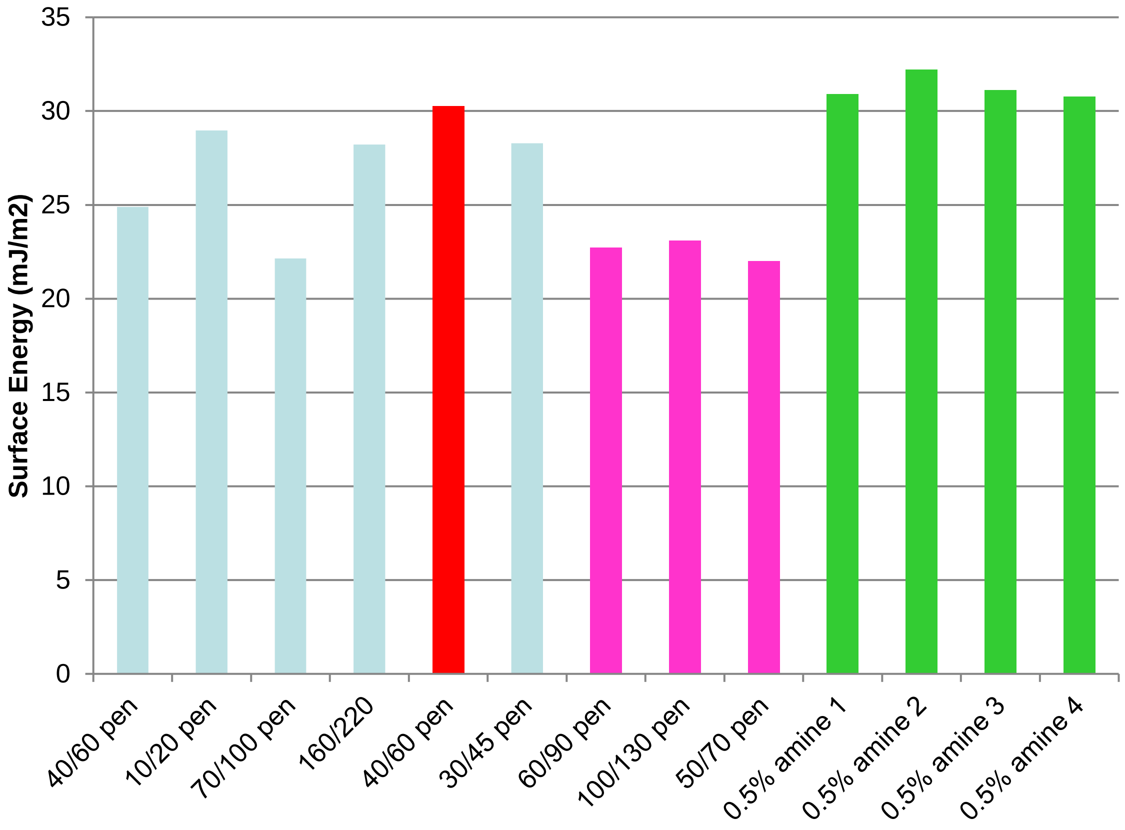
- Absorption Isotherm
- SFE & SSA

SFE of aggregates & binders

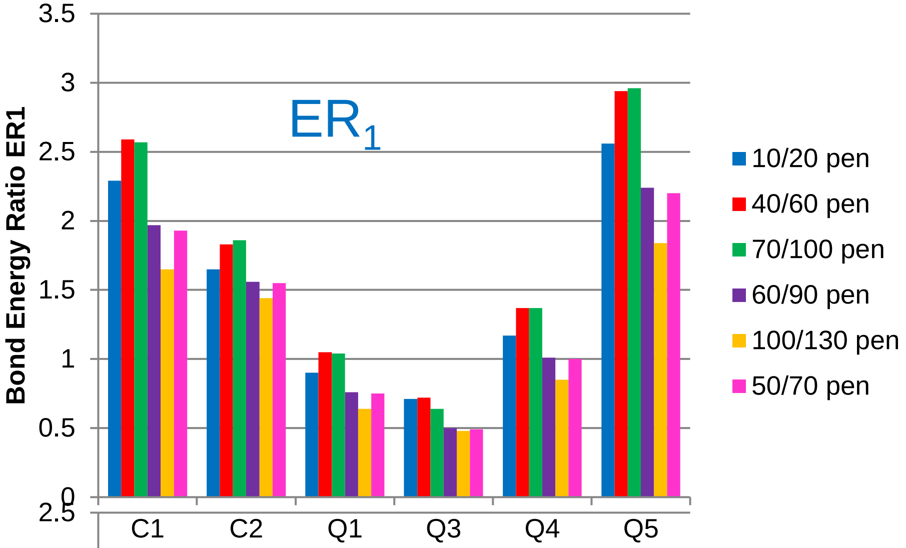
Aggregates

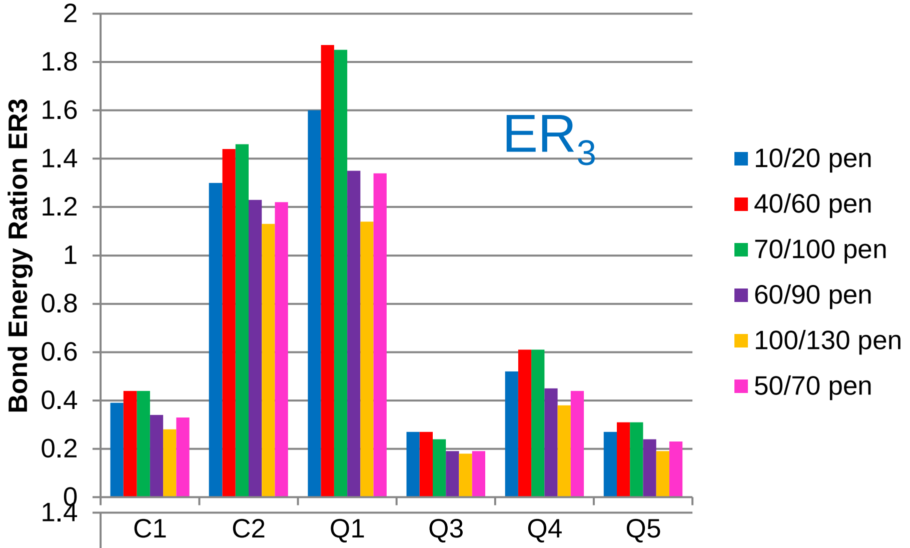


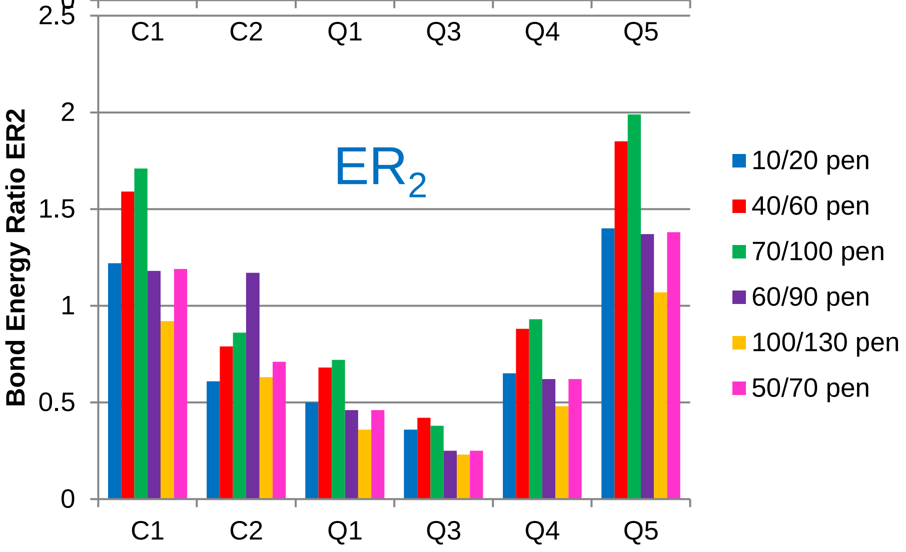
Asphalt Binders

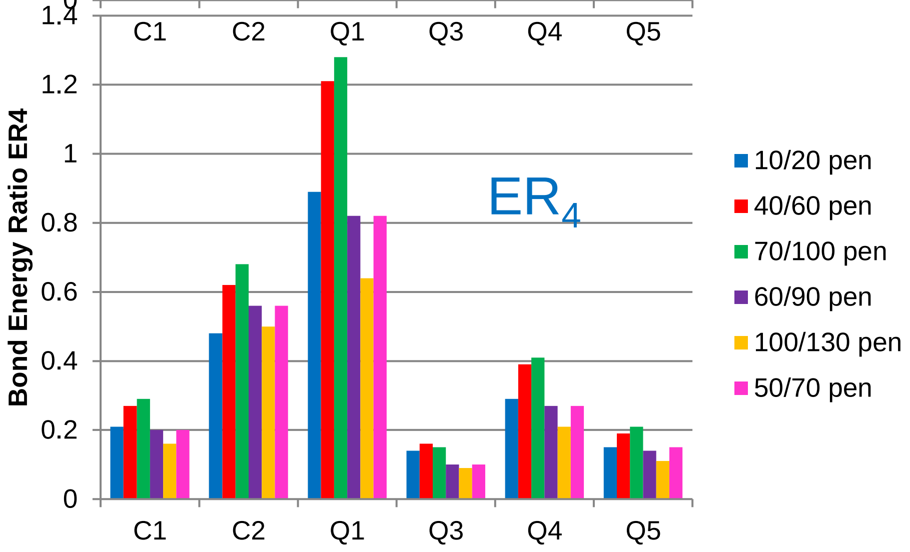


Adhesive bond energy ratios



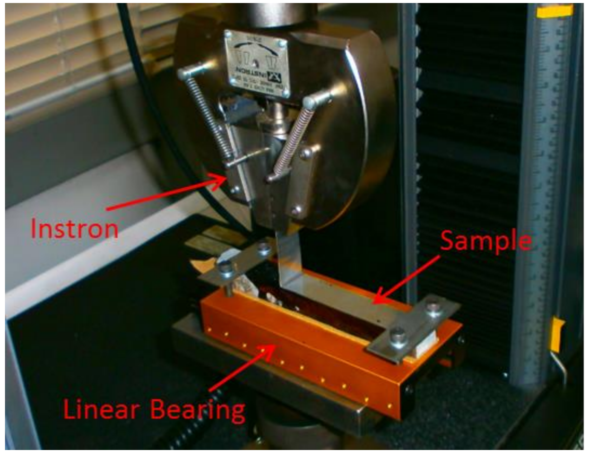


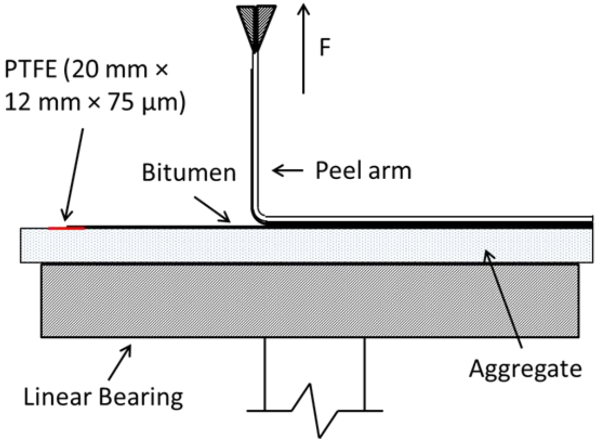




Aggregate-bitumen adhesion

Peel (adhesion) Test (ASTM D6862)

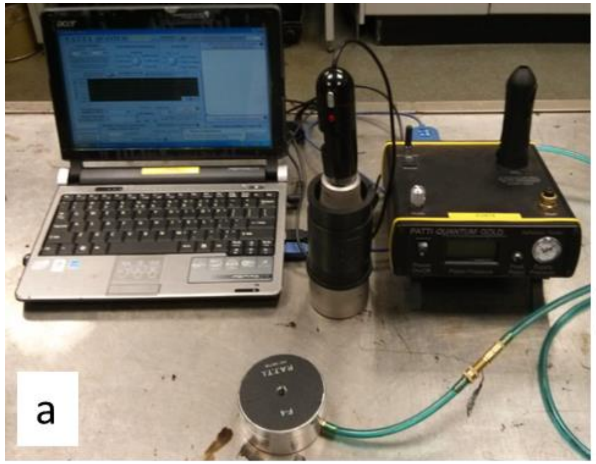


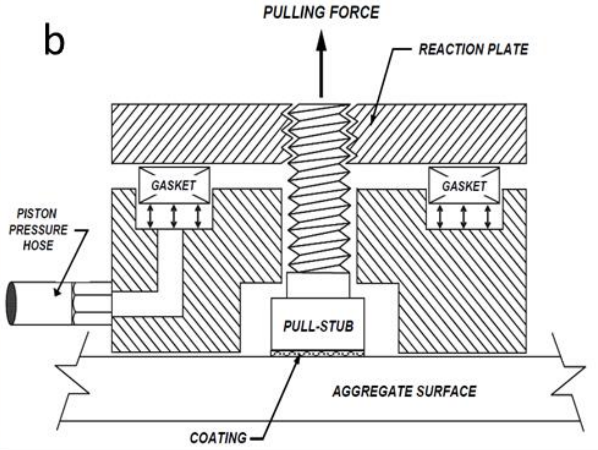


- Substrate – 100 x 20 x 10 mm
- Bitumen thickness – 0.25 mm
- 90^{o} peel angle
- Peel speed – 10 mm/min

Test configuration and geometry

Pneumatic Adhesion Tensile Test Instrument (PATTI) – Bitumen Bond Strength (BBS) Test



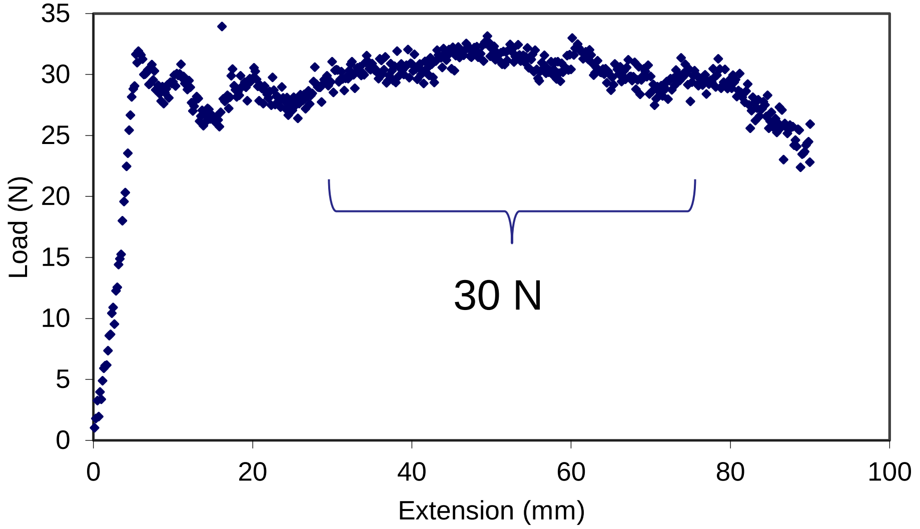


- Substrate – 100 x 100 x 20 mm
- Bitumen thickness – 0.80 mm
- Constant pulling pressure

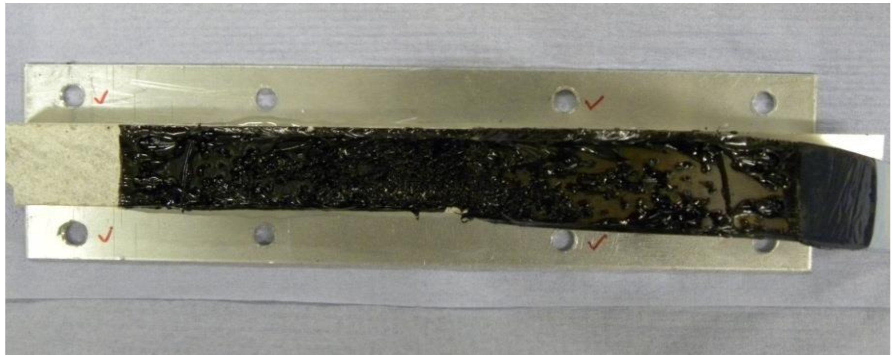
Test setup & cross-section view of piston attached to pull stub

Dry versus wet (7 days) specimen

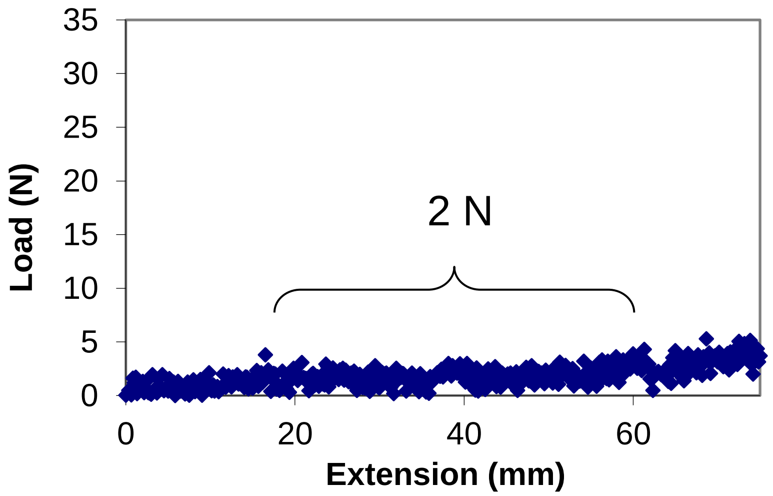
DRY



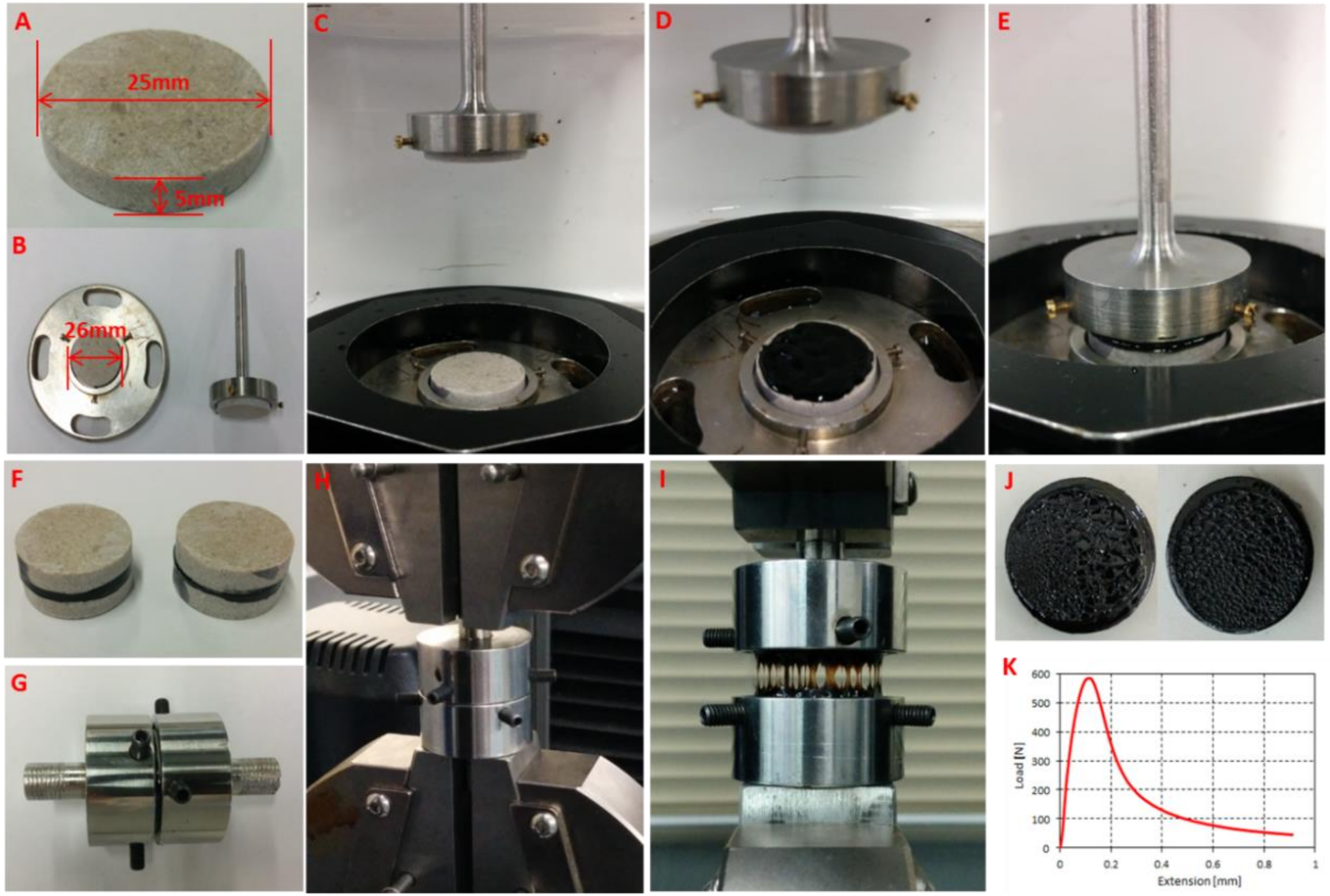
Peel arm thickness h = 0.2 mm



WET



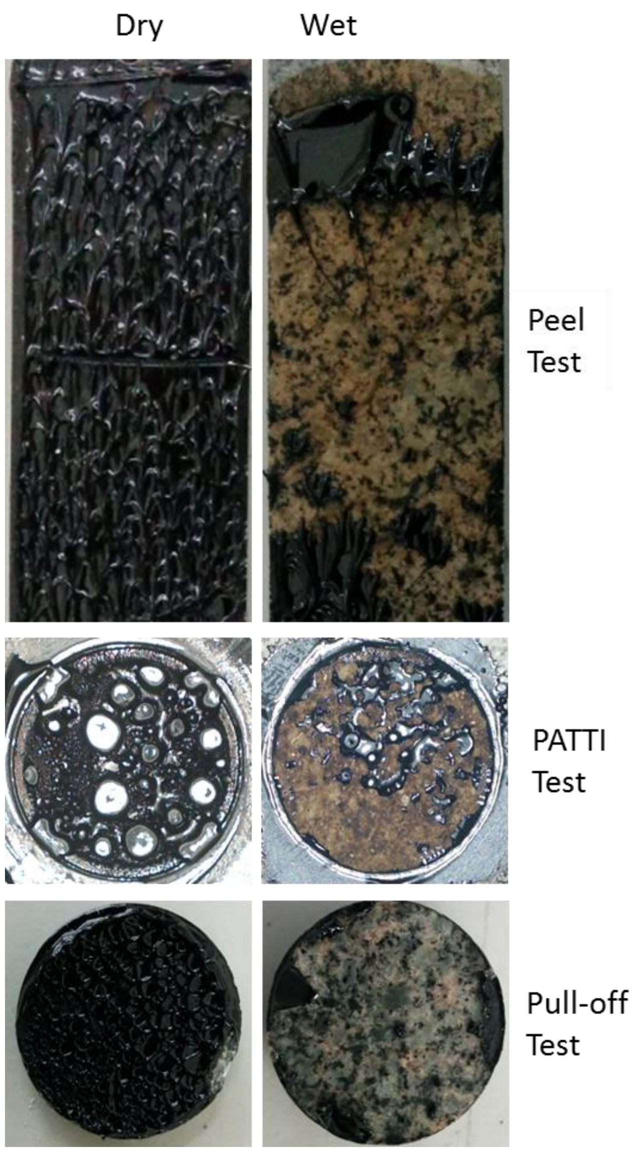
Aggregate-bitumen adhesion



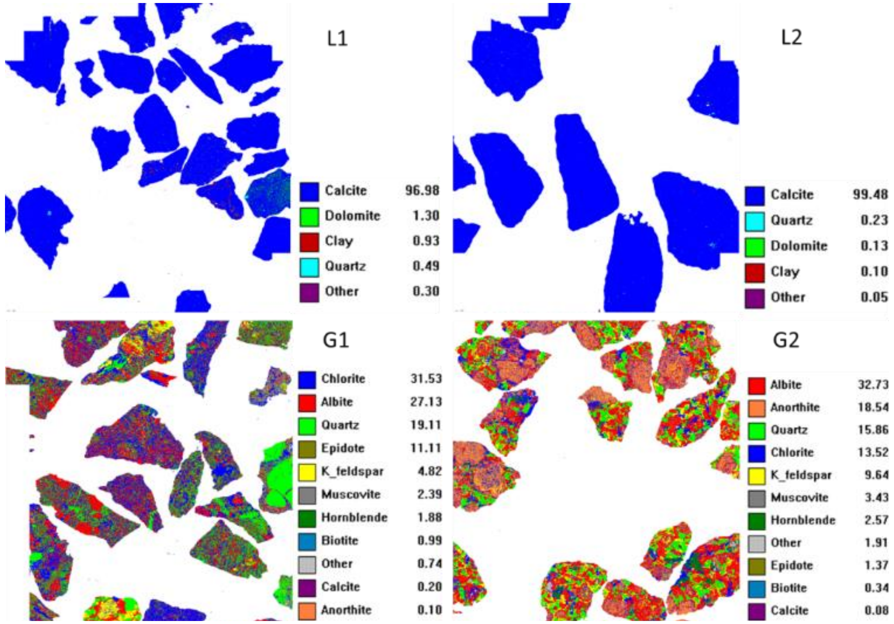
- Substrate – aggregate discs – 25 mm diameter x 5 mm
- Bitumen thickness – 0.02 mm
- Extension speed – 10 mm/min

Sample preparation and test procedure

Adhesion Test Comparison

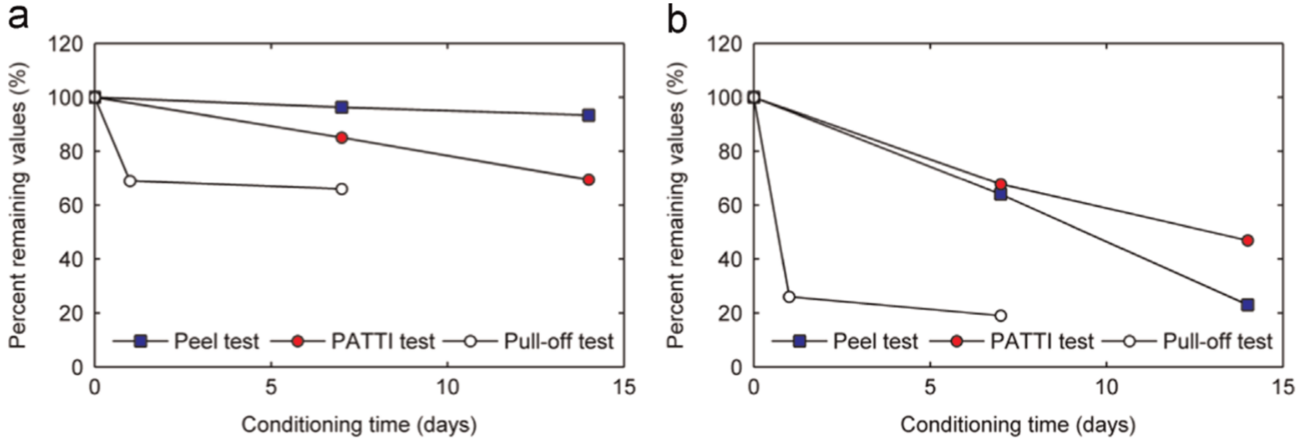


MLA Aggregate Minerology



Zhang et al., *IJAA*, Vol 62, 2015

Retained adhesion



Asphalt mixture tests

Test method	Thermal cycling	Performance tests
Freeze-thaw pedestal test (FTPT) [KEN 82]	23°C for 3 days followed by -12°C for 15 hours, 23°C for 45 minutes & 49°C for 9 hours	Cracking of specimen over a fulcrum
Immersion compression test – AASHTO T165, ASTM D1075	49°C for 4 days or 60°C for 24 hours, 23°C for 4 hours	Compressive strength
Marshall stability test – AASHTO T245	[illegible]	Marshall stability
Duriez test – NFP 98-251-1	18°C for 7 days	Unconfined compression @ 18°C and 1 mm/s
Lottman procedure [LOT 82]	Distilled water @ partial vacuum of 600 mm Hg for 30 minutes, atmospheric pressure for 30 minutes, -18°C to -12°C for 15 hours, 60°C for 24 hours	Indirect tensile strength and stiffness
Tunnicliff and Root procedure [TUN 82]	Distilled water @ partial vacuum of 508 mm Hg until 55% to 80% saturation [illegible]	Indirect stiffness
Modified Lottman procedure – AASHTO [illegible]	[illegible] -18°C to -12°C for 15 hours, 60°C for 24 hours	Indirect tensile strength and stiffness
Bitutest protocol [SCH 95]	Partial vacuum of 510 mm Hg @ 20°C for 30 minutes, saturation at 60°C for 6 hours, 5°C for 16 hours	NAT ITSM testing @ 20°C
Immersion wheel tracking test [MAT 62]	[illegible]	Wheel tracking @ 25 cycles/min
Hamburg wheel tracking device	[illegible]	Wheel tracking @ 50 passes/min
Environmental conditioning system (ECS) [TER 94]	Water @ partial vacuum of 254 mm Hg or 508 mm Hg for 30 minutes, 3 hot cycles @ 60°C for 6 hours, one freeze @ -18°C for 6 hours	Resilient modulus (stiffness) & permeability @ 25°C

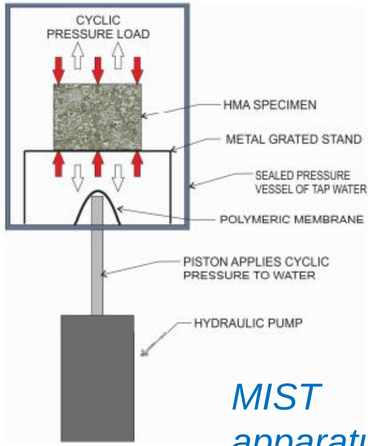
Various Performance Tests

Standard Performance Tests

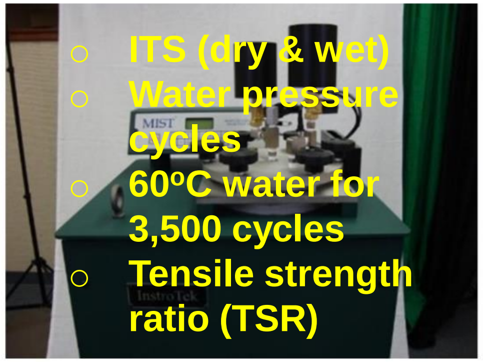
Wheel Tracking Tests

Comparative Evaluation

Moisture Induced Stress Tester (MIST) (ASTM D7870)

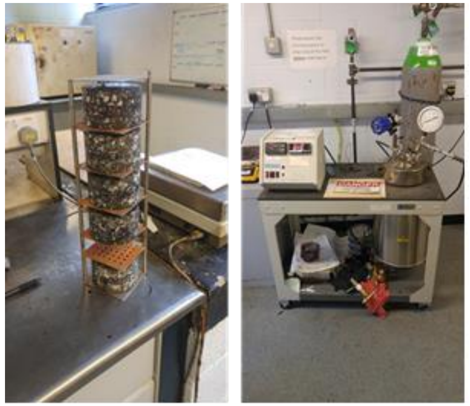


MIST apparatus



A. Zofka et al. 2013. *9th Conference Environmental Engineering*

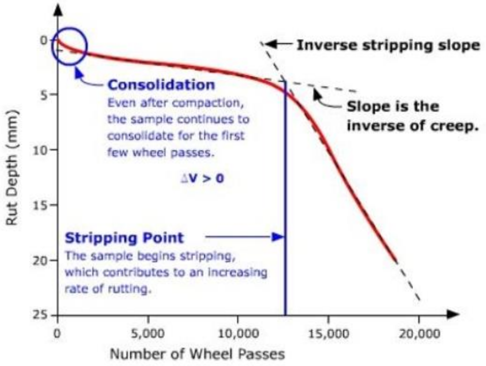
SATS Test (SHW Cl 943)



SATS specimen rack and pressure chamber

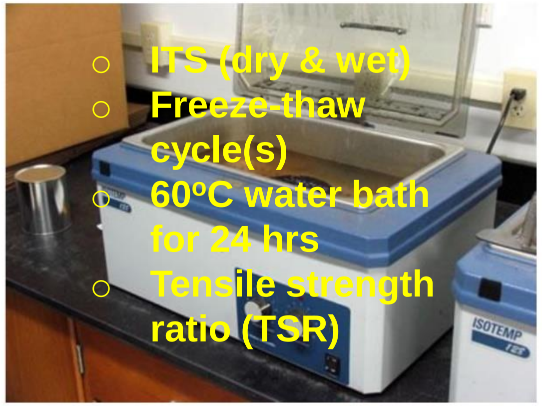
Hamburg Wheel Tracker (AASHTO T324)

Wheel tracker



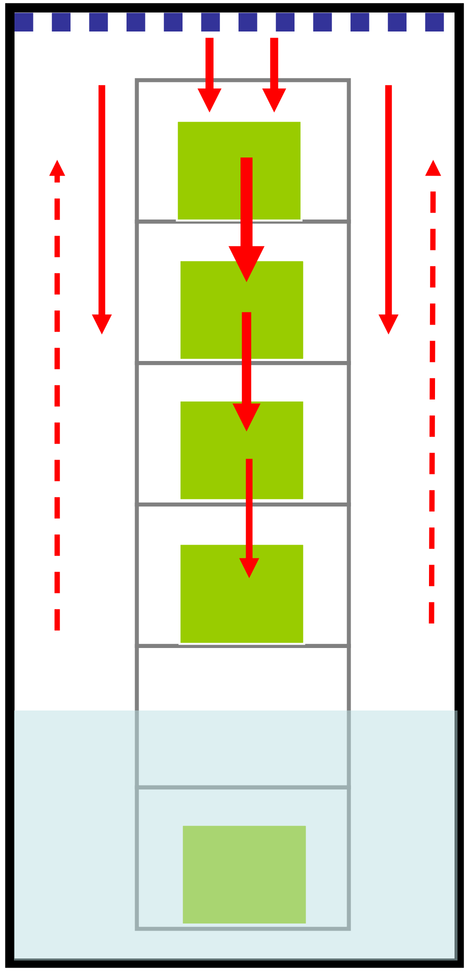
Analysis

Modified Lottman (AASHTO T283, ASTM D4867)



Water bath & conditioning

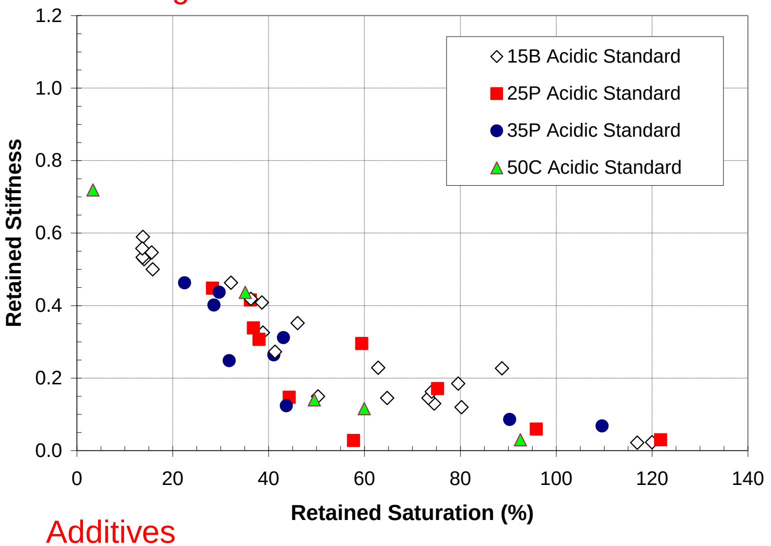
Saturation Ageing Tensile Stiffness (SATS) test



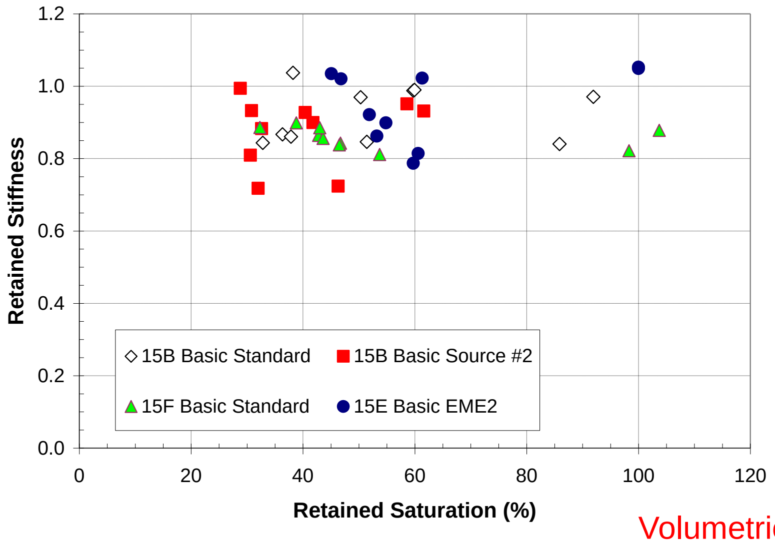
Initial Saturation Level	Final Saturation Level
55%	66%
55%	49%
55%	26%
55%	6%
55%	80%

SATS – Influence of materials & volumetrics

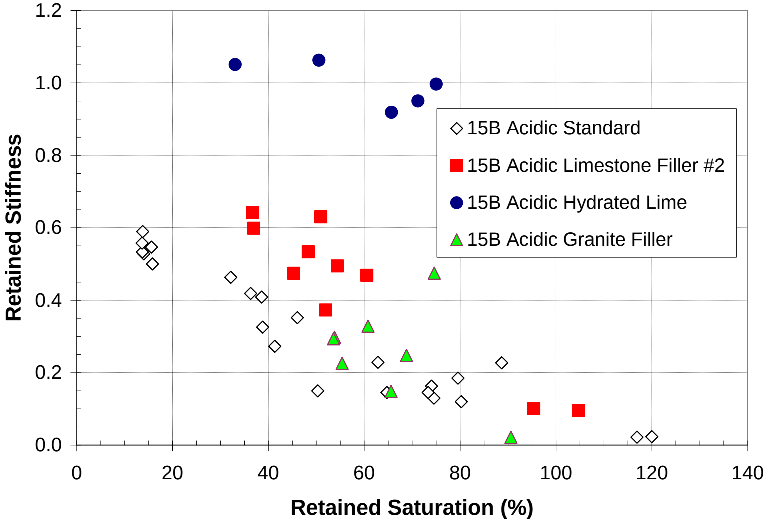
Bitumen grades



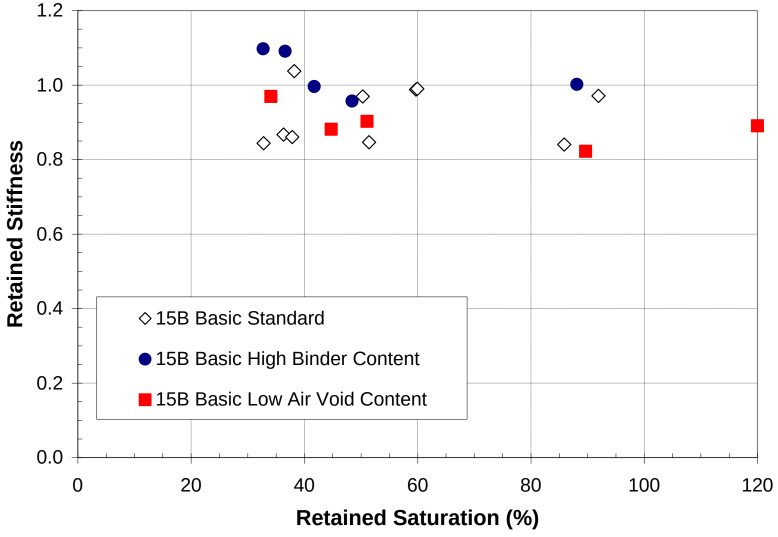
Bitumen sources



Additives

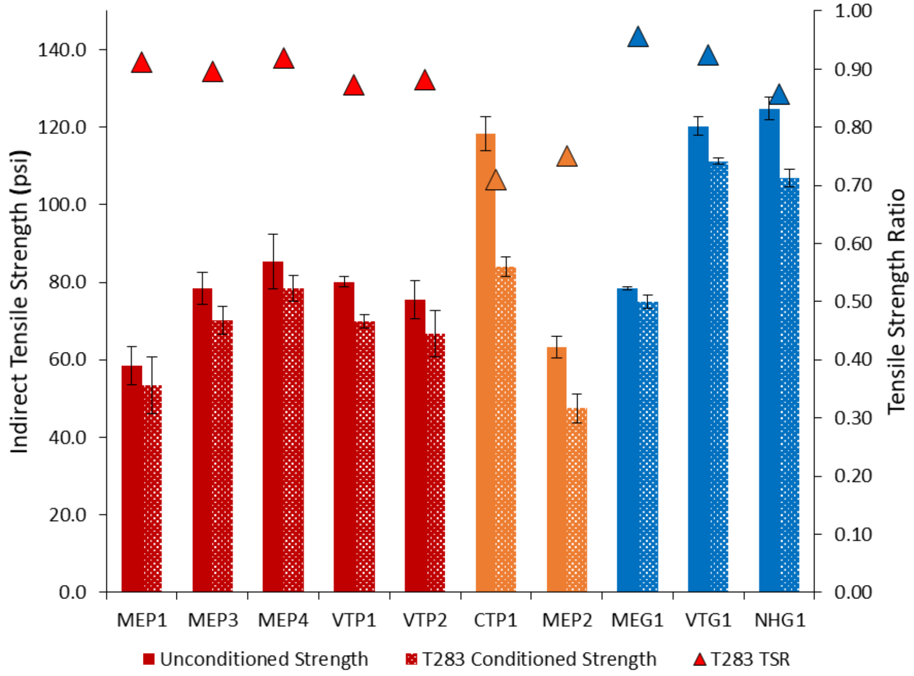


Volumetrics



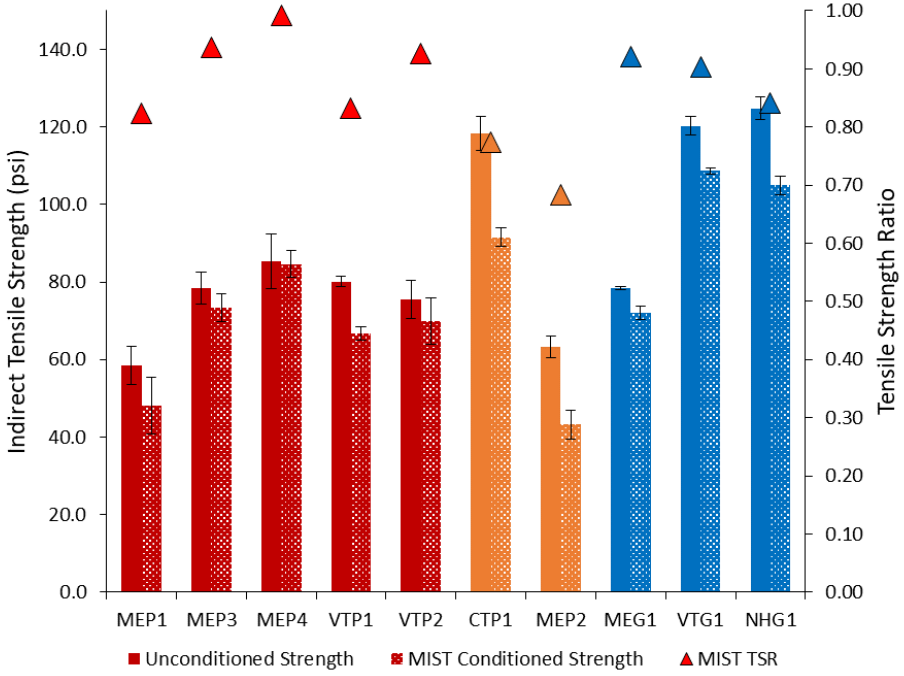
Comparative Evaluation

Modified Lottman (AASHTO T283, ASTM D4867)



- ITS (dry & wet)
- Freeze-thaw cycle(s)
- 60°C water bath for 24 hrs
- Tensile strength ratio (TSR)

Moisture Induced Stress Tester (MIST) (ASTM D7870)

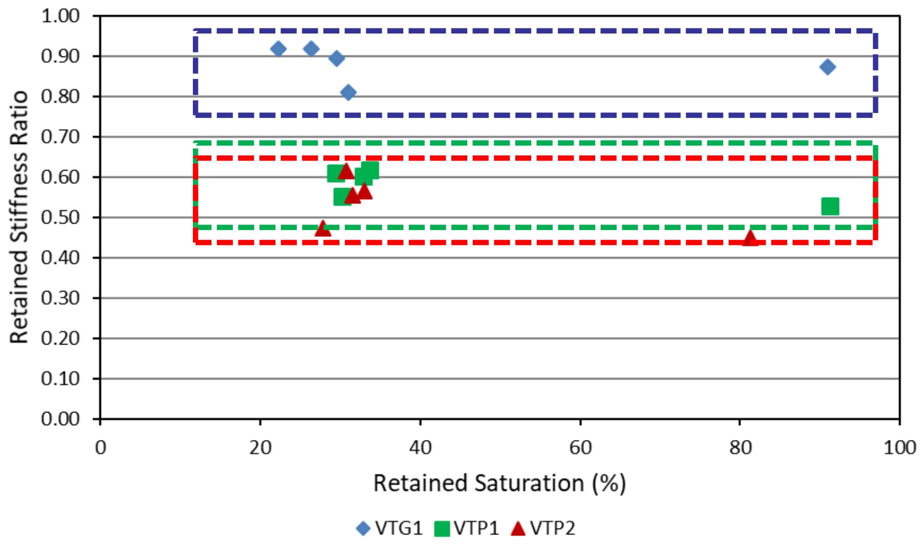


- ITS (dry & wet)
- Water pressure cycles
- 60°C water for 3,500 cycles
- Tensile strength ratio (TSR)

DeCarlo et al. 2019. *Journal of Testing and Evaluation*

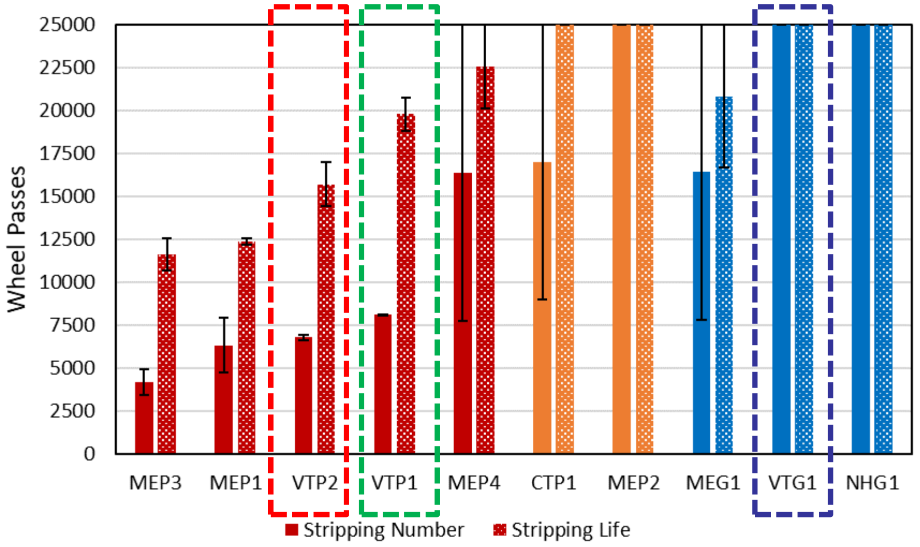
Comparative Evaluation

SATS Test (SHW Cl 943)



- ITSM (stiffness) (dry & wet) – retained stiffness ratio
- Retained saturation (moisture level)
- 85ºC, 0.5 MPa for 24 hrs
- Tensile strength ratio (TSR)

Hamburg Wheel Tracker (AASHTO T324)



- 25,000 wheel passes
- Stripping inflection point (SIP)
- Failure – 12.5 mm rut
- Stripping number & life
- 45ºC water

DeCarlo et al. 2019. *Journal of Testing and Evaluation*

Gaps & future directions

- Moisture damage is an extremely complex mechanism ☹
- Considerable work to understand mechanisms and produce experimental methods to simulate process ☺
- Climate change and increasing extreme weather conditions adds a new dimension to this problem ☹
- Issues (gaps) in accurately simulating MD and predicting performance ☹
- Linked up approaches (experimental testing with multi-scale and multi-physics modelling and possibly machine learning) can provide solutions ☺

جامعة حمد بن خليفة
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عضو في مؤسسة قطر
Member of Qatar Foundation

Modeling of Moisture Damage: Review and Future Directions

TRB Webinar: Addressing Moisture Damage in Asphalt Concrete
October 16, 2024

Eyad Masad, Dist. M. ASCE, F. AAAS
Professor
College of Science and Engineering
Hamad Bin Khalifa University

Outline

- Water Transport Mechanisms
- Moisture Damage Mechanism
- Computational Modeling of Moisture Damage (various mechanisms)
- Analytical Analysis of Moisture Damage
- Analytical and Computational Models of Permeability
- Findings and Future Directions

Transport Mechanisms

Advection Flow

Water movement through interconnected voids

Driven by pressure differences or hydraulic gradients,

Water flows from regions of higher pressure to lower pressure.

Darcy’s law.

Diffusion of Liquid or Vapor

Movement of water molecules (liquid or vapor) through material or pores.

Driven by liquid concentration gradient or relative humidity gradient.

Water liquid or water vapor moves from high concentration to low concentration.

Fick’s law.

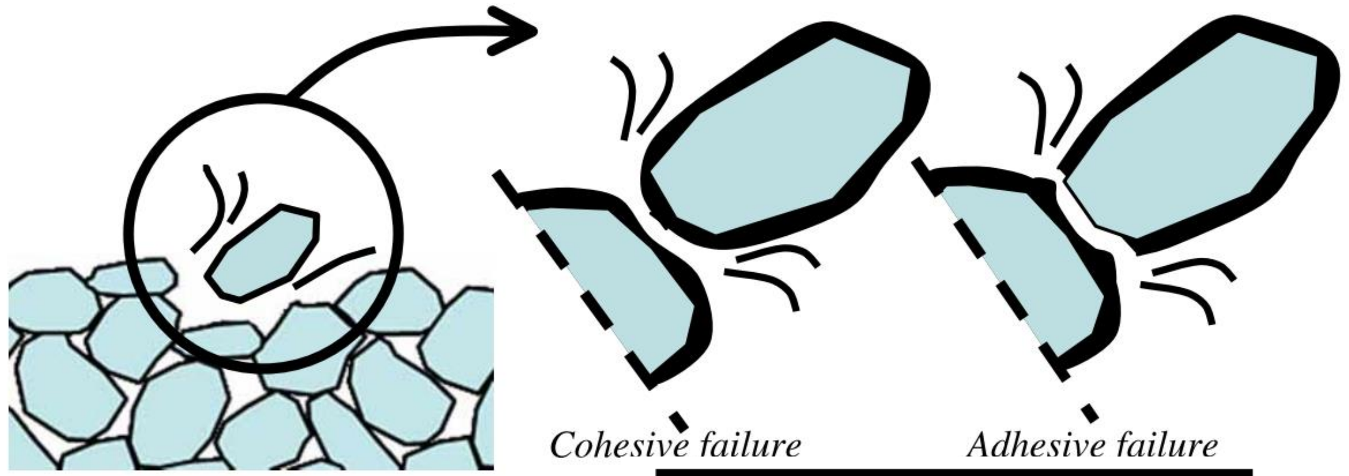
Water Capillary Rise

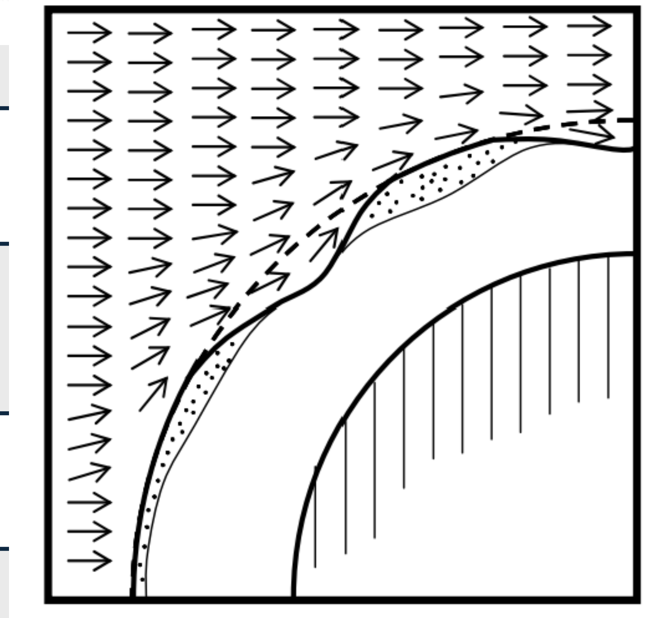
Upward movement of liquid water through pores

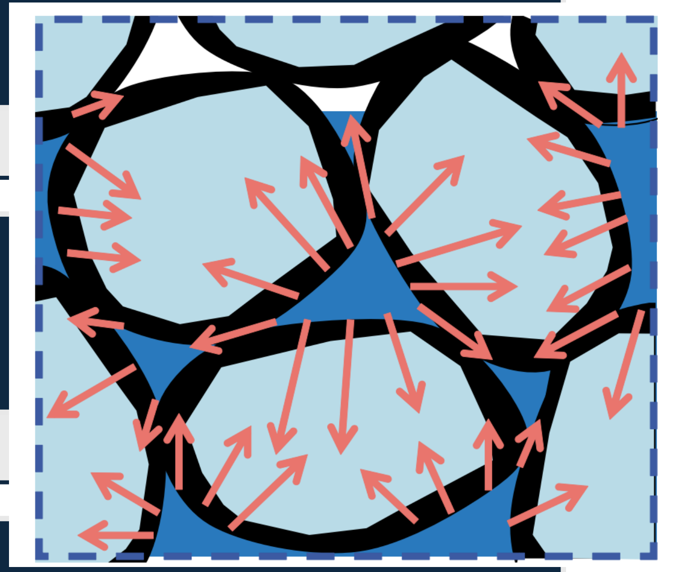
- Driven by the interaction between water's surface tension (cohesive forces)) and with the solid surface (adhesive forces)
- Water moves against gravity
- The Young–Laplace equation and Jurin’s law.

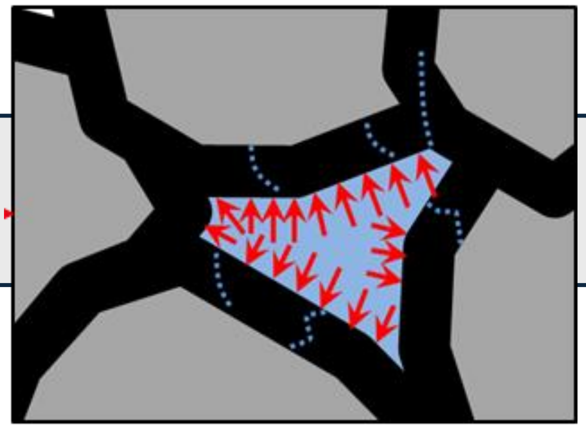
Damage Mechanisms

- Weakening of mastic cohesion
- Weakening of mastic-aggregate adhesion
- Washing away of mastic
- Pumping action-mechanical stresses
- Freezing -mechanical Stresses



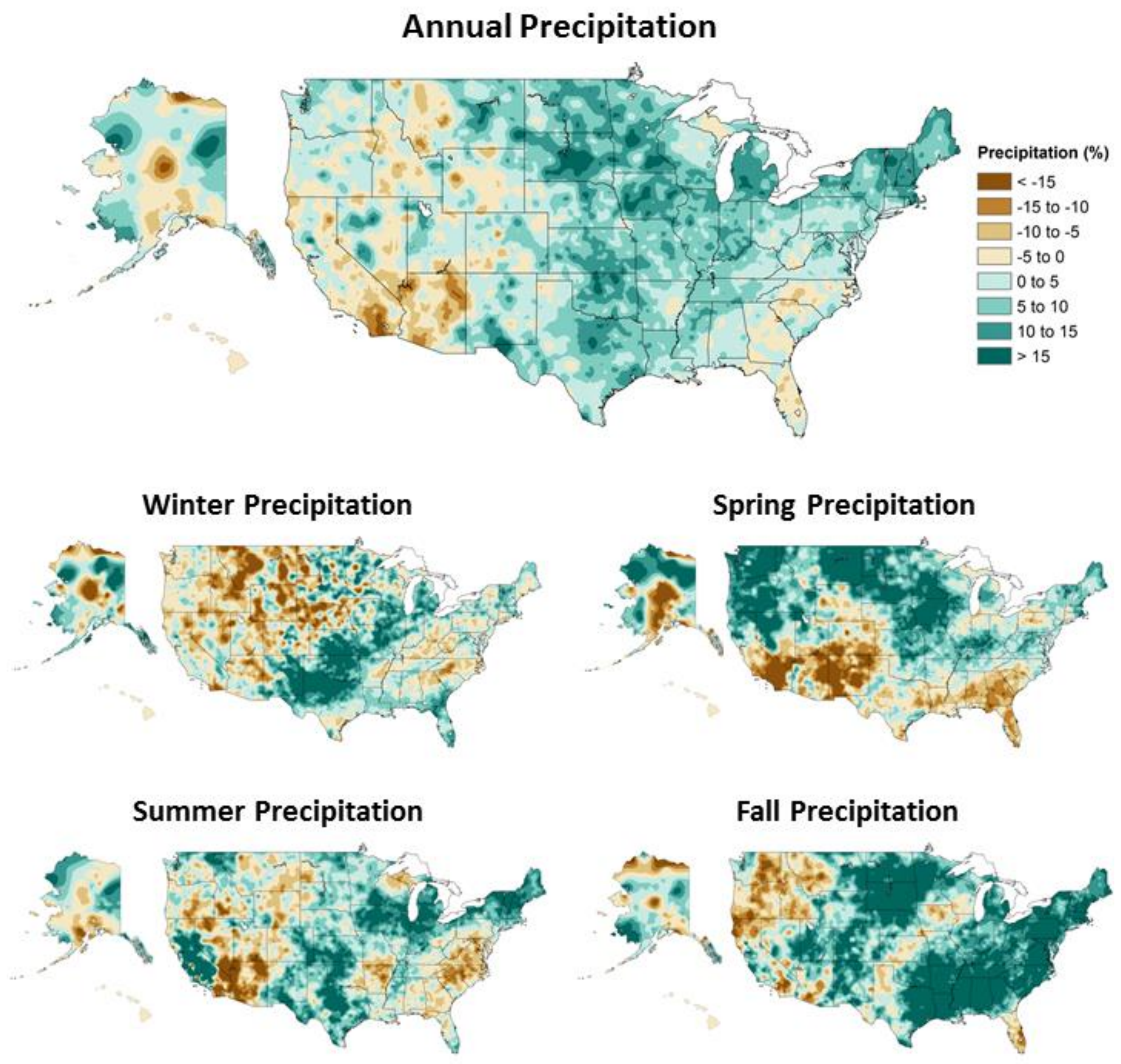






Caro et al. (2008)
Kringos et al.(2008a)
Varveri et al. (2014)

Climate Change - Annual Precipitation



Annual and seasonal changes in precipitation over the United States. Changes are the average for present-day (1986–2015) minus the average for the first half of the last century (1901–1960) for the contiguous United States, 1925–1960 for Alaska and Hawai'i) divided by the average for the first half of the century.

Sources:
https://pavementinteractive.org/climate-change-impacts-on-pavements-and-resilience/
https://science2017.globalchange.gov/

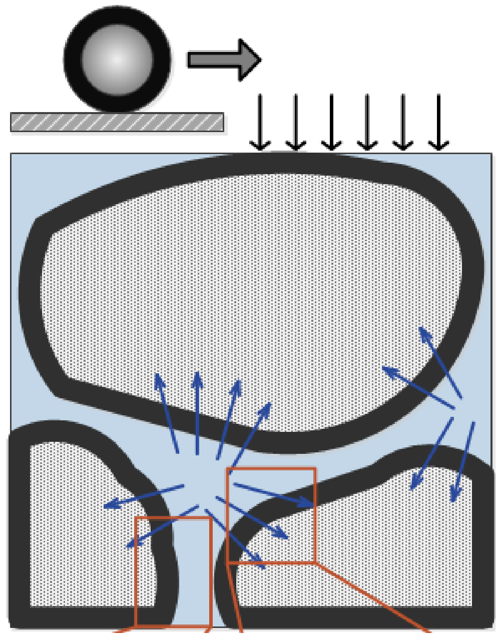
Climate change Impact	Affected Components and Strategies
More Extreme Rainfall Events **Higher Average Annual Precipitati on**	▪ Increased need for surface drainage ▪ More frequent use of elevated pavement section ▪ Better understanding of how submergence affects pavement layer structural capacity ▪ Reduction in pavement structural capacity due to increased levels of saturation —Reduce moisture susceptibility of unbound base/subgrade materials through stabilization —Ensure resistance to moisture susceptibility of asphalt mixes

Sources:
NCHRP Report 750: Strategic Issues Facing Transportation, Volume 2: Climate Change, Extreme Weather Events, and the Highway System:
Practitioner's Guide and Research Report Tech Brief: Climate Change Adaptation for Pavements, FHWA-HIF-15-015 August 2015

Computational Modeling of Moisture Damage

Moisture Damage Models (PANDA) – Advection and Diffusion

Pore Water Pressure



Constitutive equation (Stress-strain)

$$\boldsymbol{\sigma} = \boldsymbol{\sigma}^T - f(p)\mathbf{I}$$

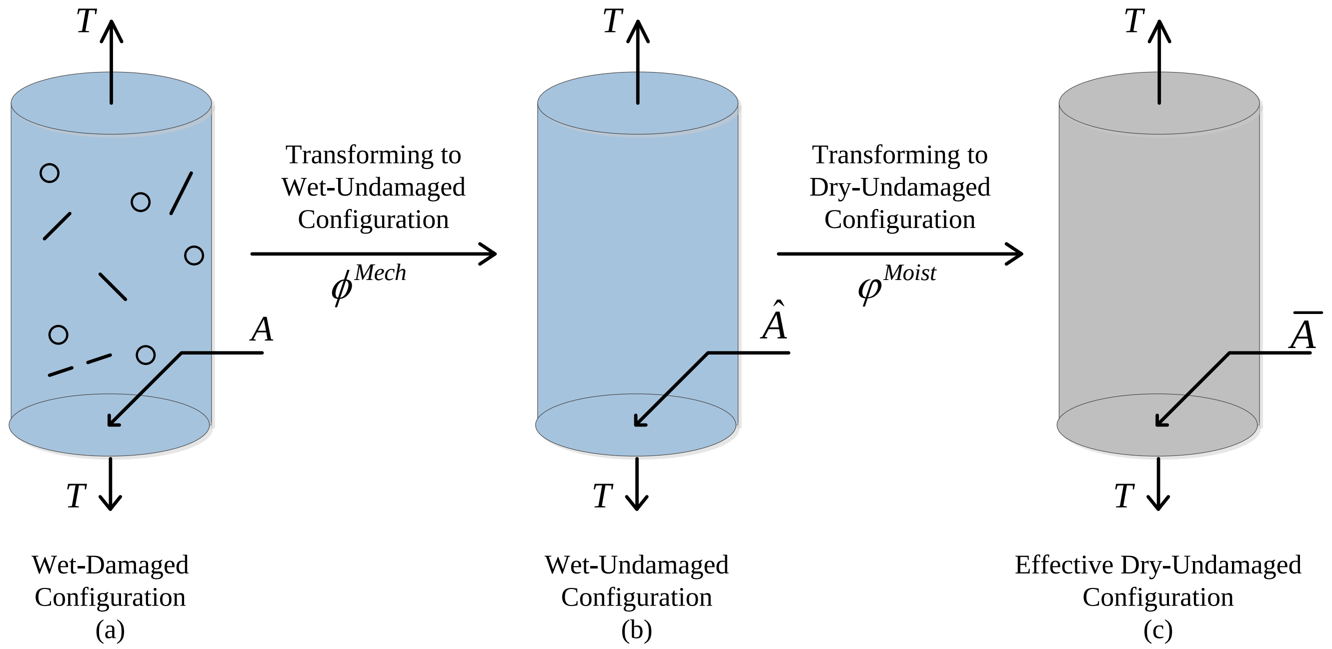
Effective stress tensor

Total stress tensor

Shakiba et al. (2014)

Shakiba et al. (2016)

Moisture diffusion



Evolution function $\dot{\varphi}\left(x, \theta(t)\right) = k\theta(x,t)\left(1-\varphi^{total}\right)^q$

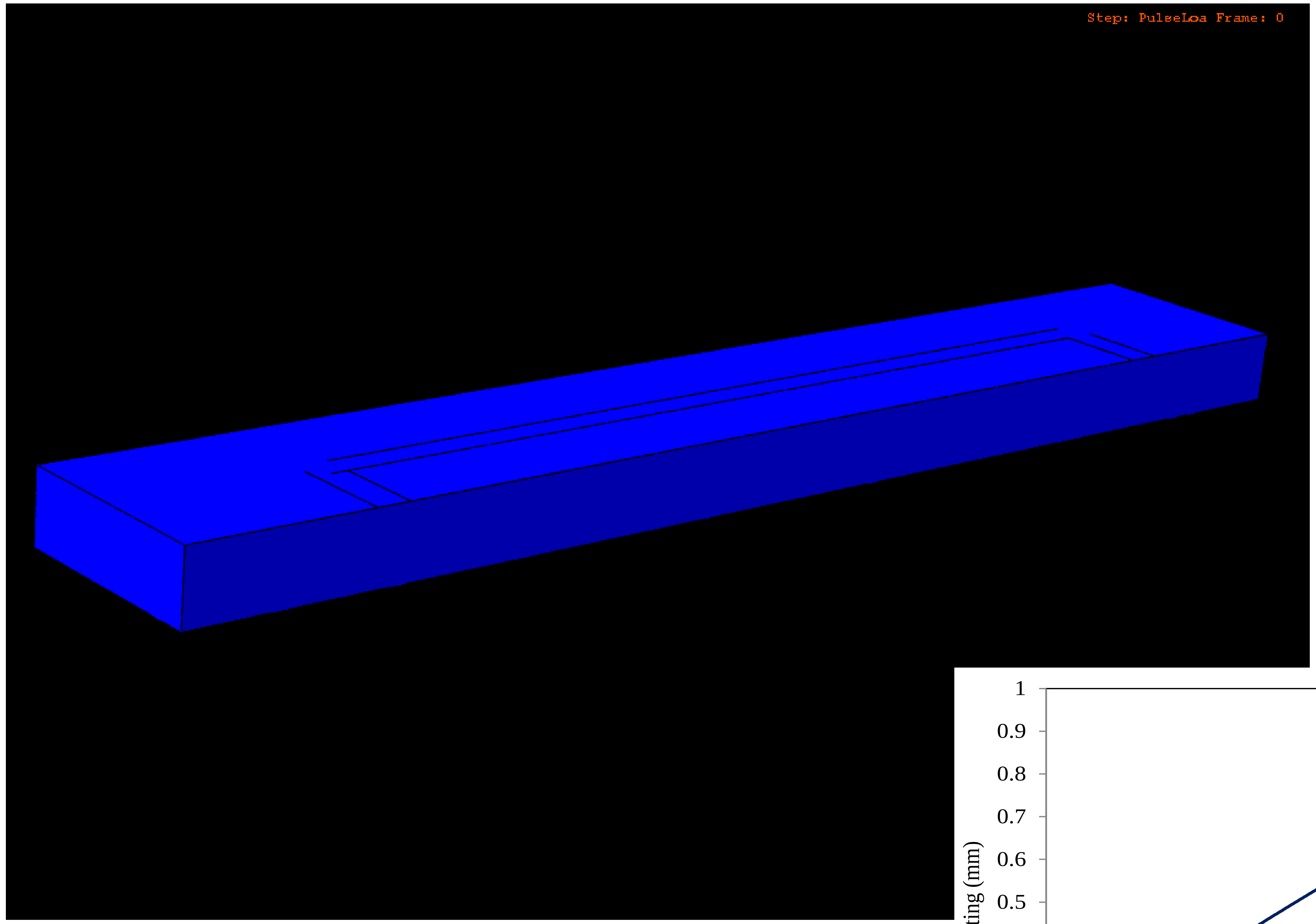
Moisture content

Coupling between moisture and mechanical damage

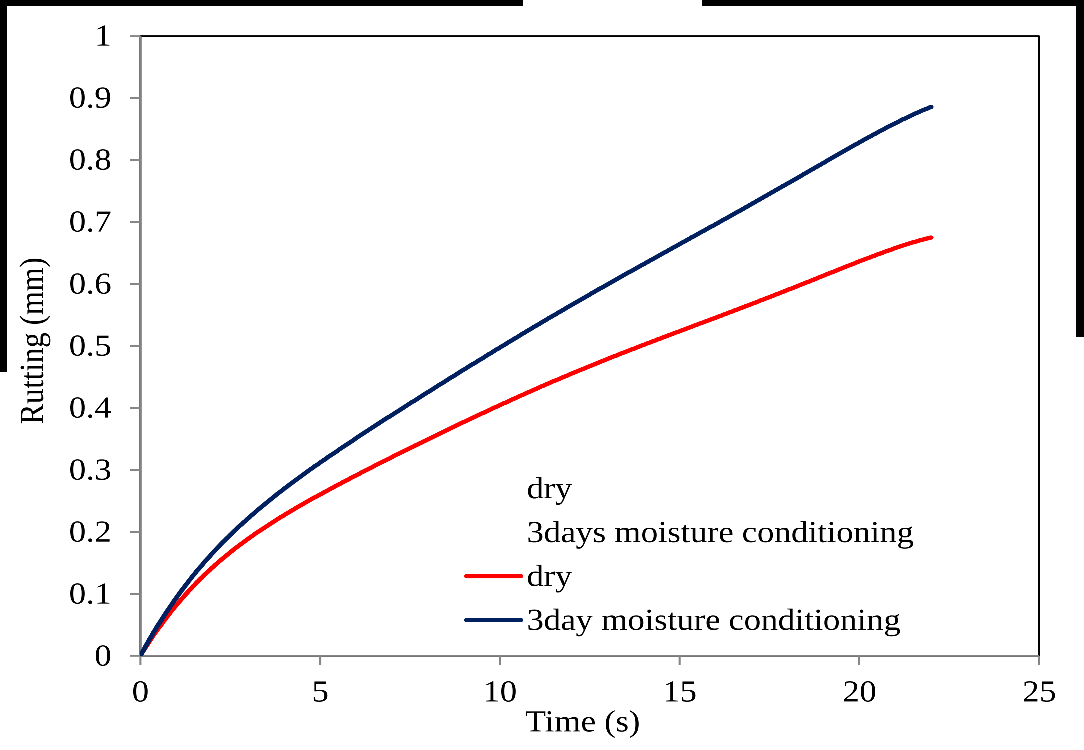
$$\left(1-\phi_{eff}\right) = \left(1-\phi^{Mech}\right)\left(1-\varphi^{Mois}\right)$$

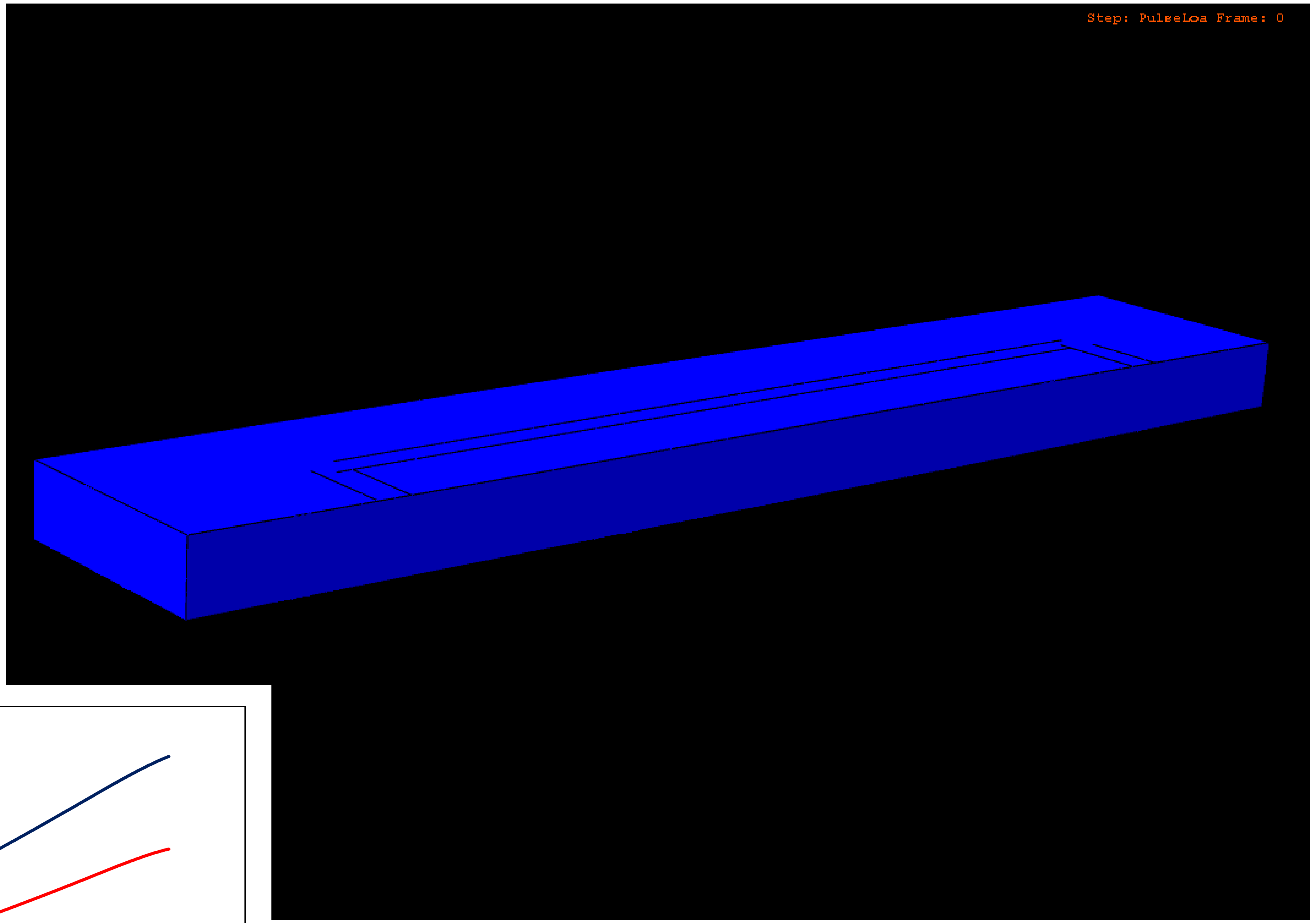
$$\bar{\sigma}_{ij} = \frac{\sigma_{ij}}{1-\phi_{eff}}$$

Effect of Moisture Diffusion on Viscoplastic Deformation



Dry State



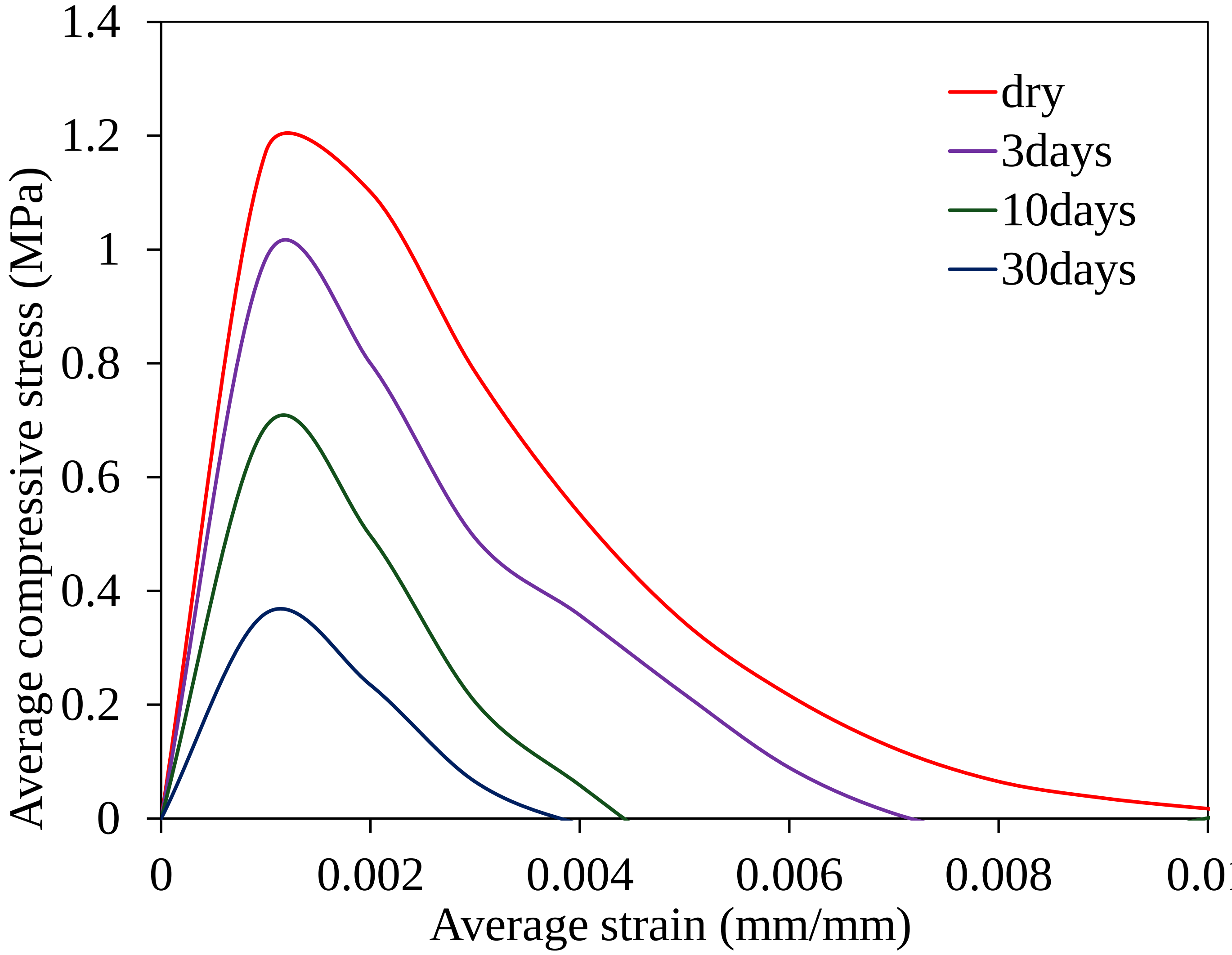


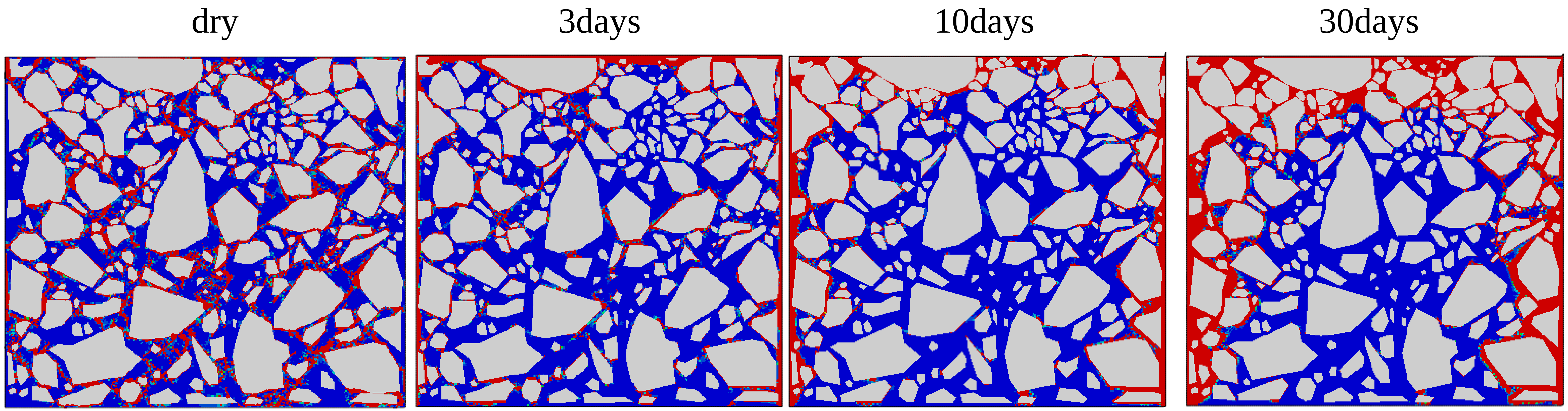
3 days of moisture conditioning

Effect of Moisture Diffusion on Micromechanical Damage – 2D Simulations

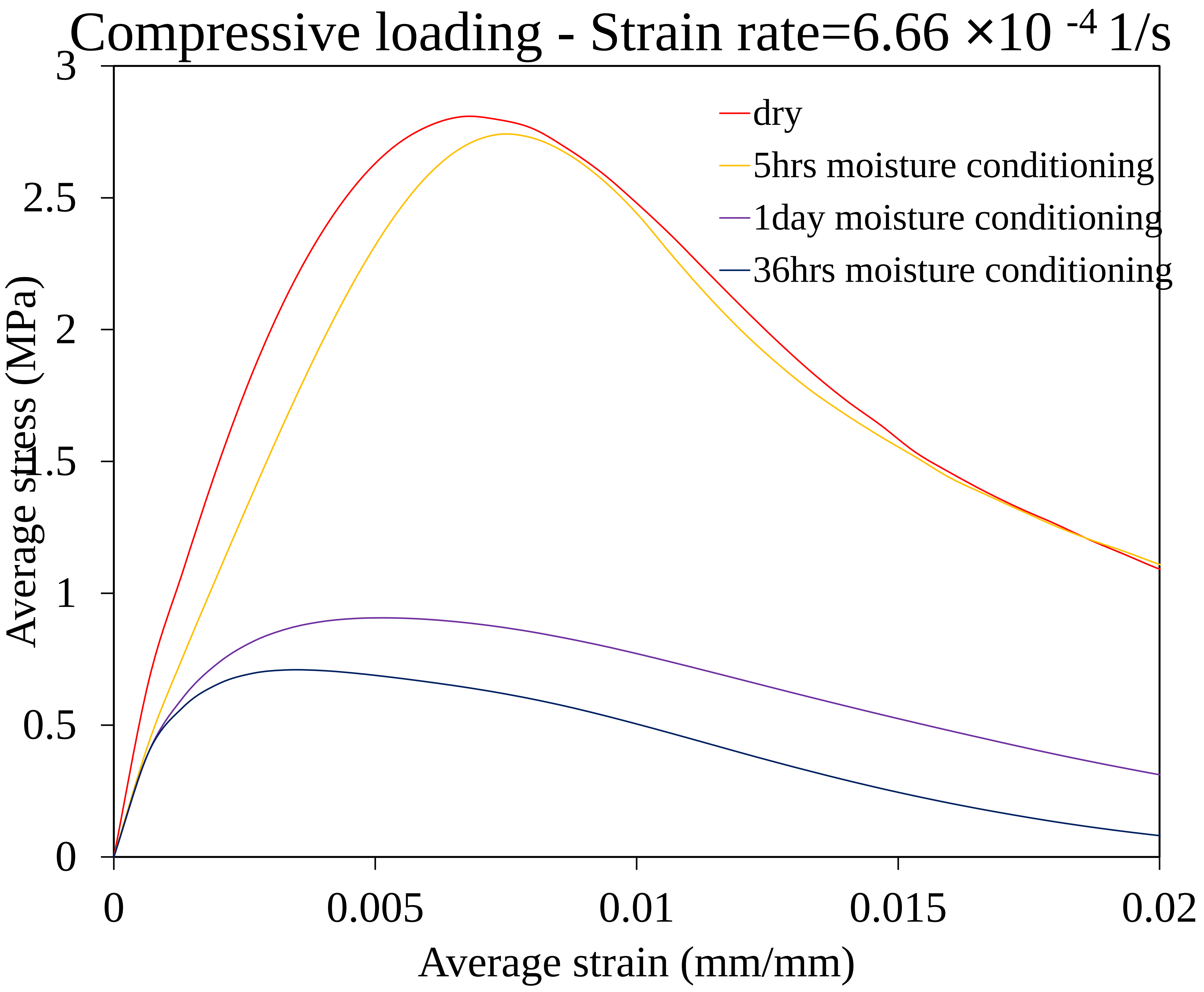
Compressive loading

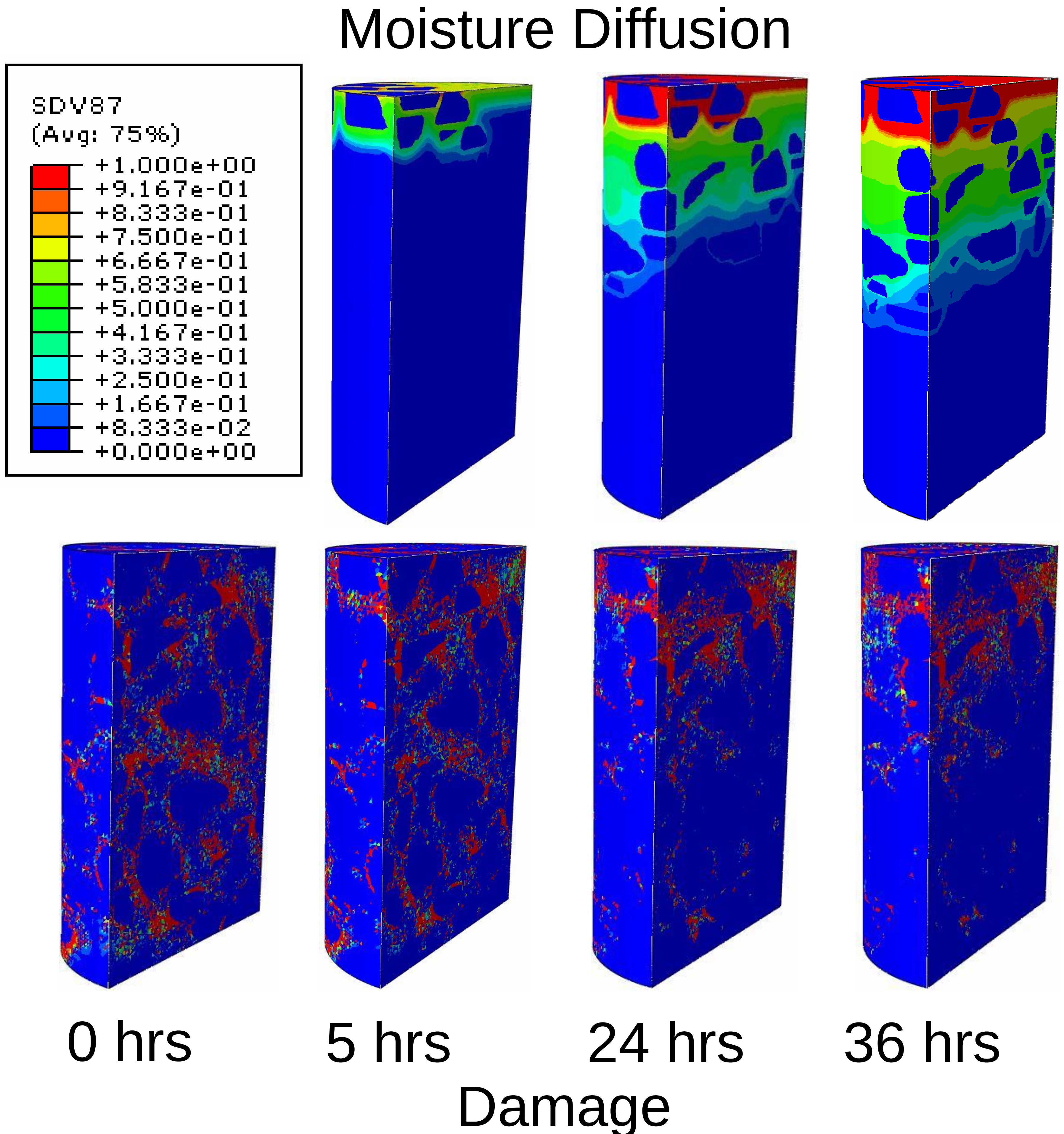
Temperature=20°C





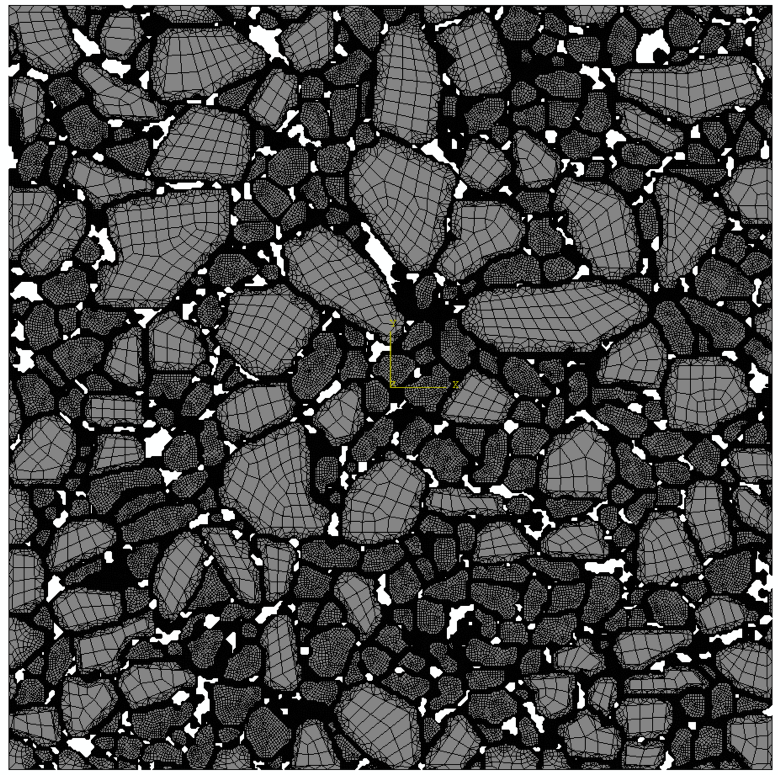
Effect of Moisture Diffusion on Micromechanical Damage – 3D Simulations

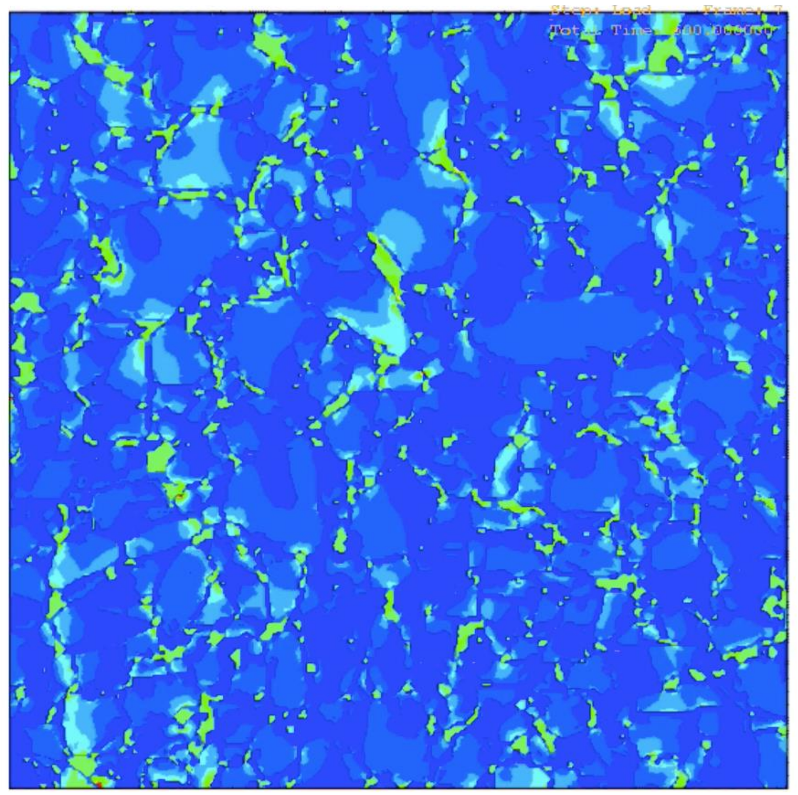




Effect of Pore Pressure on Micromechanical Damage – 2D Simulations

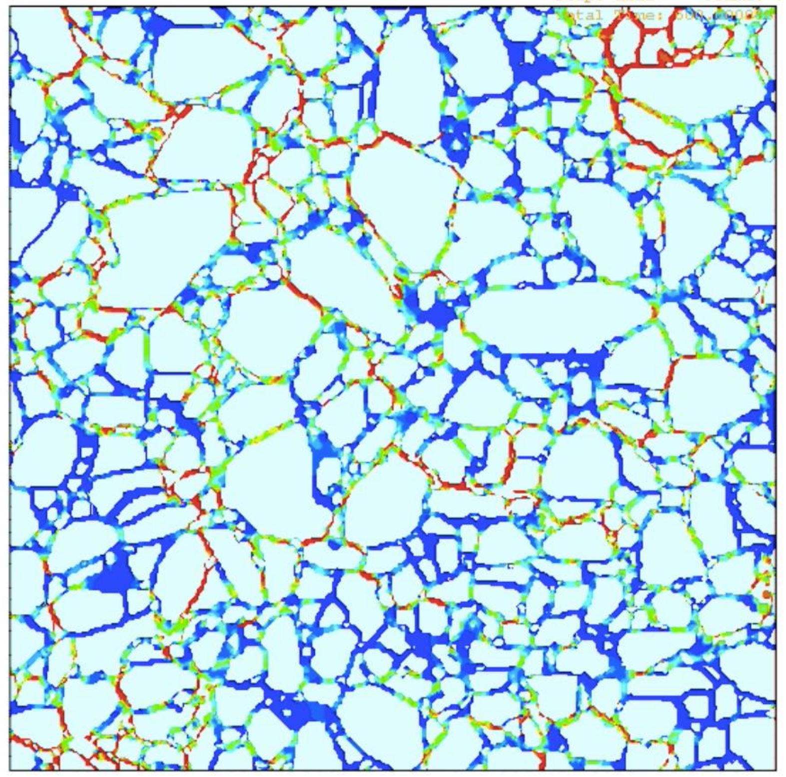
X-ray CT image of asphalt concrete including aggregates, mastic, and air voids

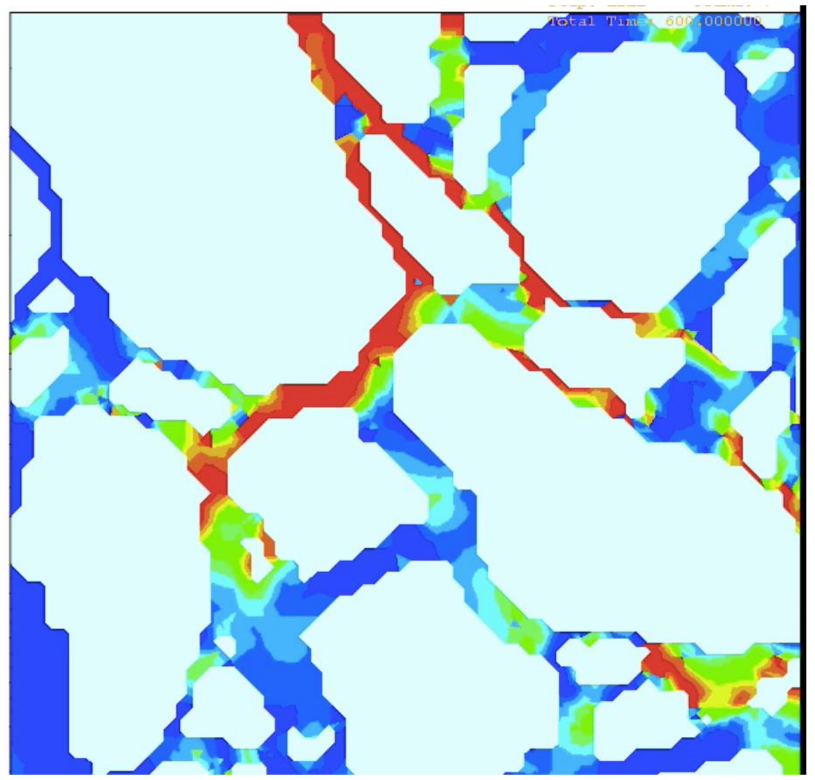




Devatoric stress distribution considering saturated air voids and the effect of pore water pressure

Damage distribution considering the effect of pore water pressure

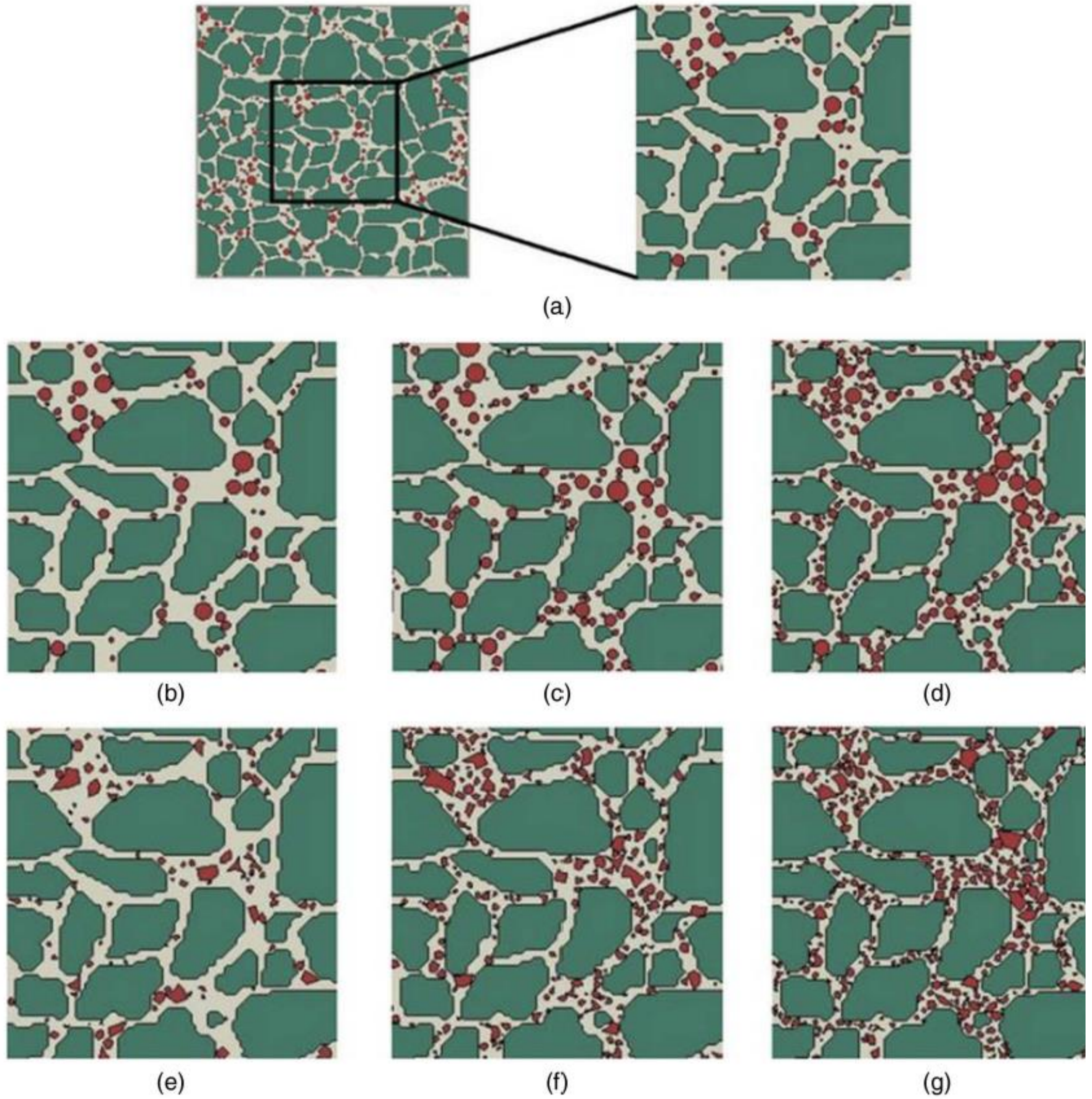




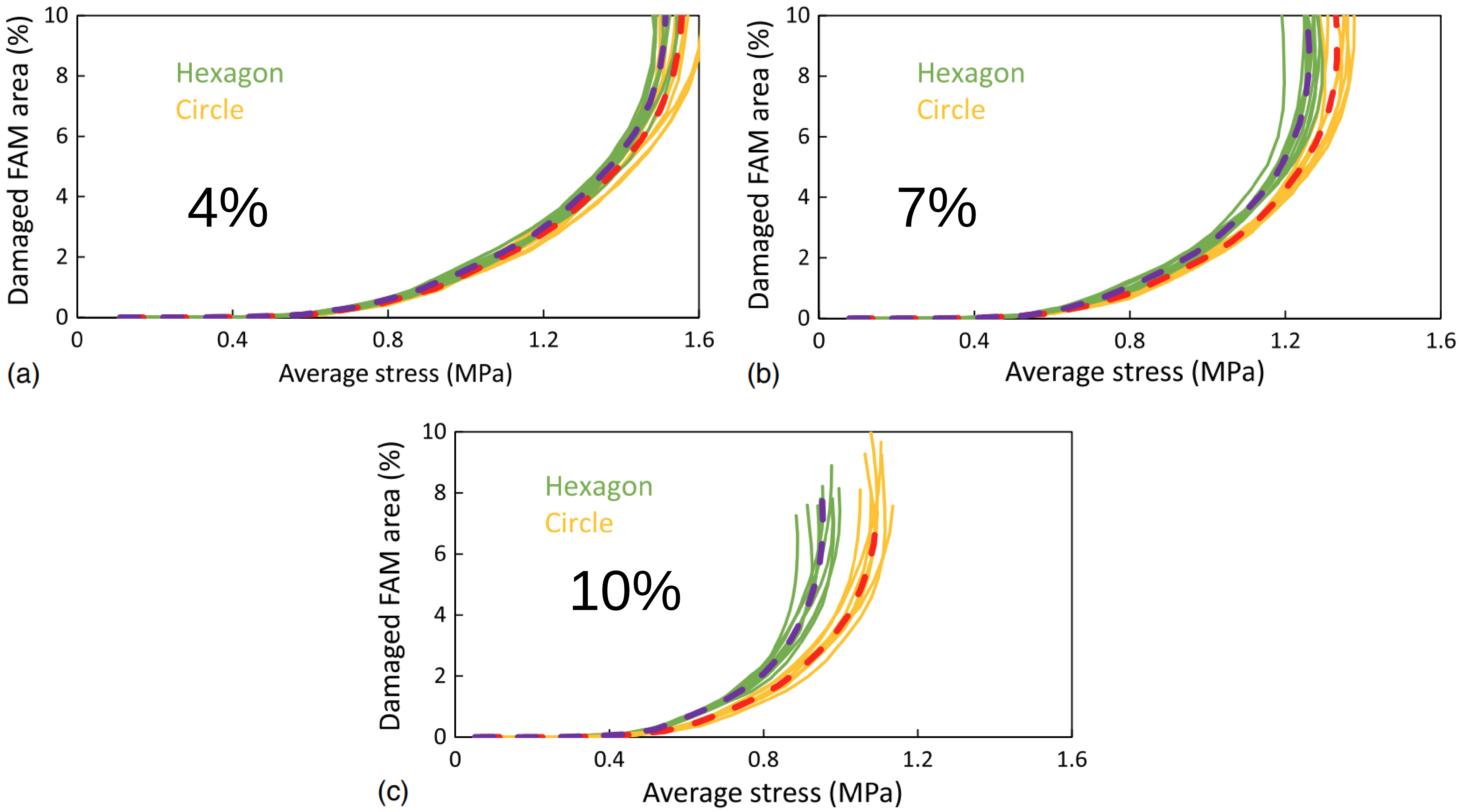
Damage distribution, zooming on the top right corner

Shakiba, Darabi and Little. (2017).

Effect of Voids Distribution on Micromechanical Damage (Diffusion and Pore Pressure)



Different Voids Distributions



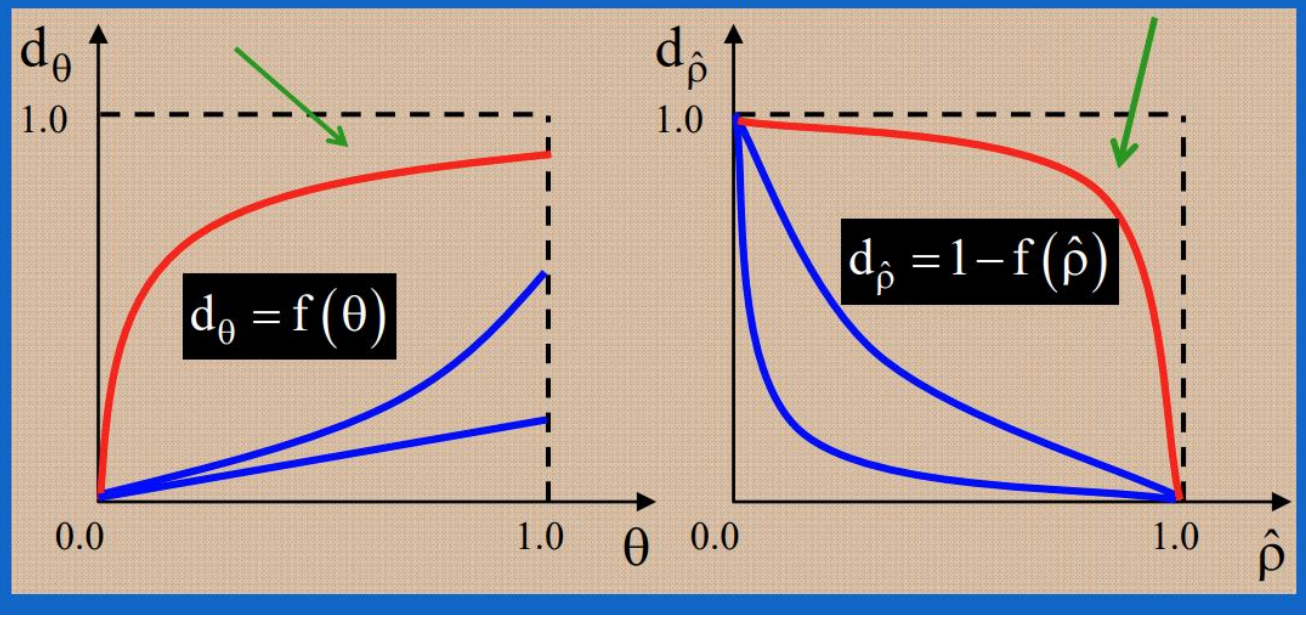
Najmeddine and Shakiba (2021)

Moisture Damage Models (CAPA3D) – Advection and Diffusion

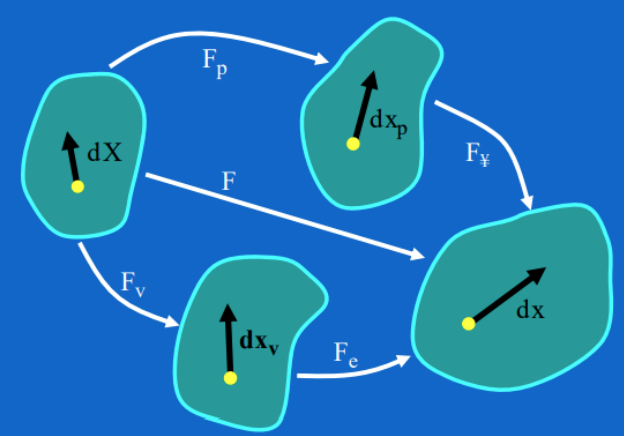
$$\Psi_m = (1-d_m)\left[\Psi_v(\mathbf{F}_e) + \Psi_p(\mathbf{F}_\infty, \xi)\right]$$

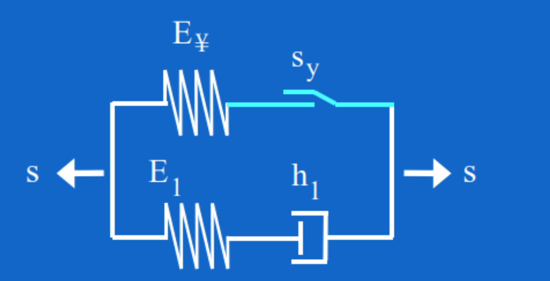
$$d_m = (1-d_\theta)(1-d_{\hat{\rho}})$$

diffusion damage function | **advection damage function**



Dry material Helmholtz free energy function



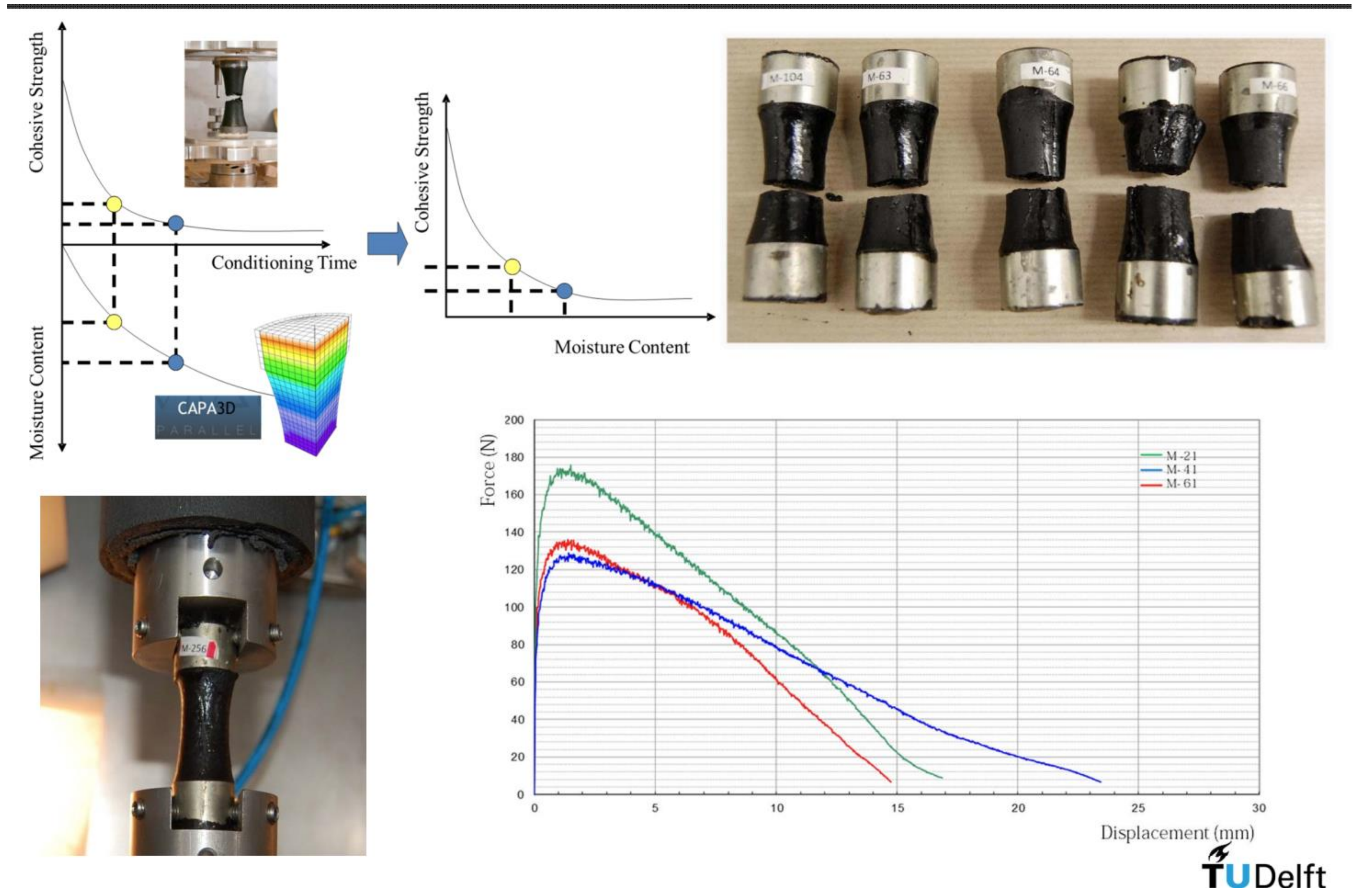


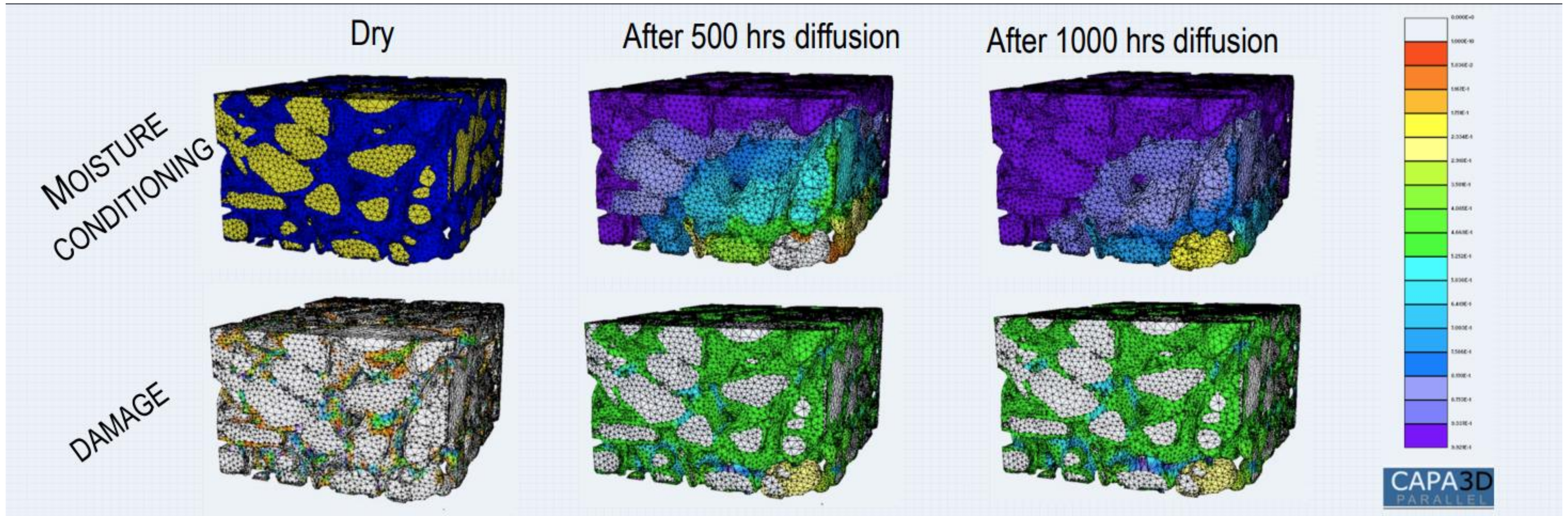
$$\Psi = \Psi_v(\mathbf{C}_e) + \Psi_p(\mathbf{C}_\infty, \xi)$$

Saturated material Helmholtz free energy function

$$\Psi_m = (1-d_m)\,\Psi$$

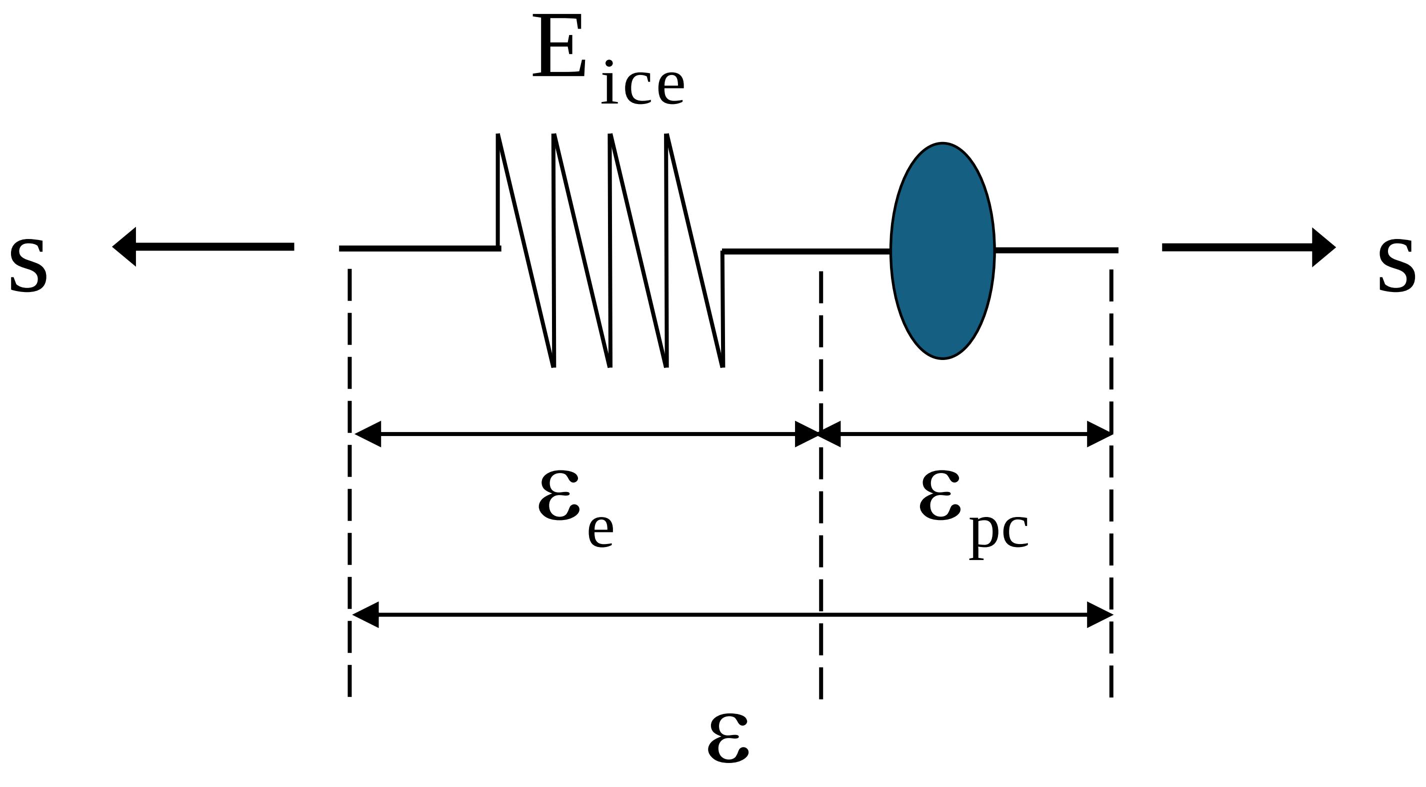
$$= (1-d_m)\left[\Psi_v(\mathbf{C}_e) + \Psi_p(\mathbf{C}_\infty, \xi)\right]$$



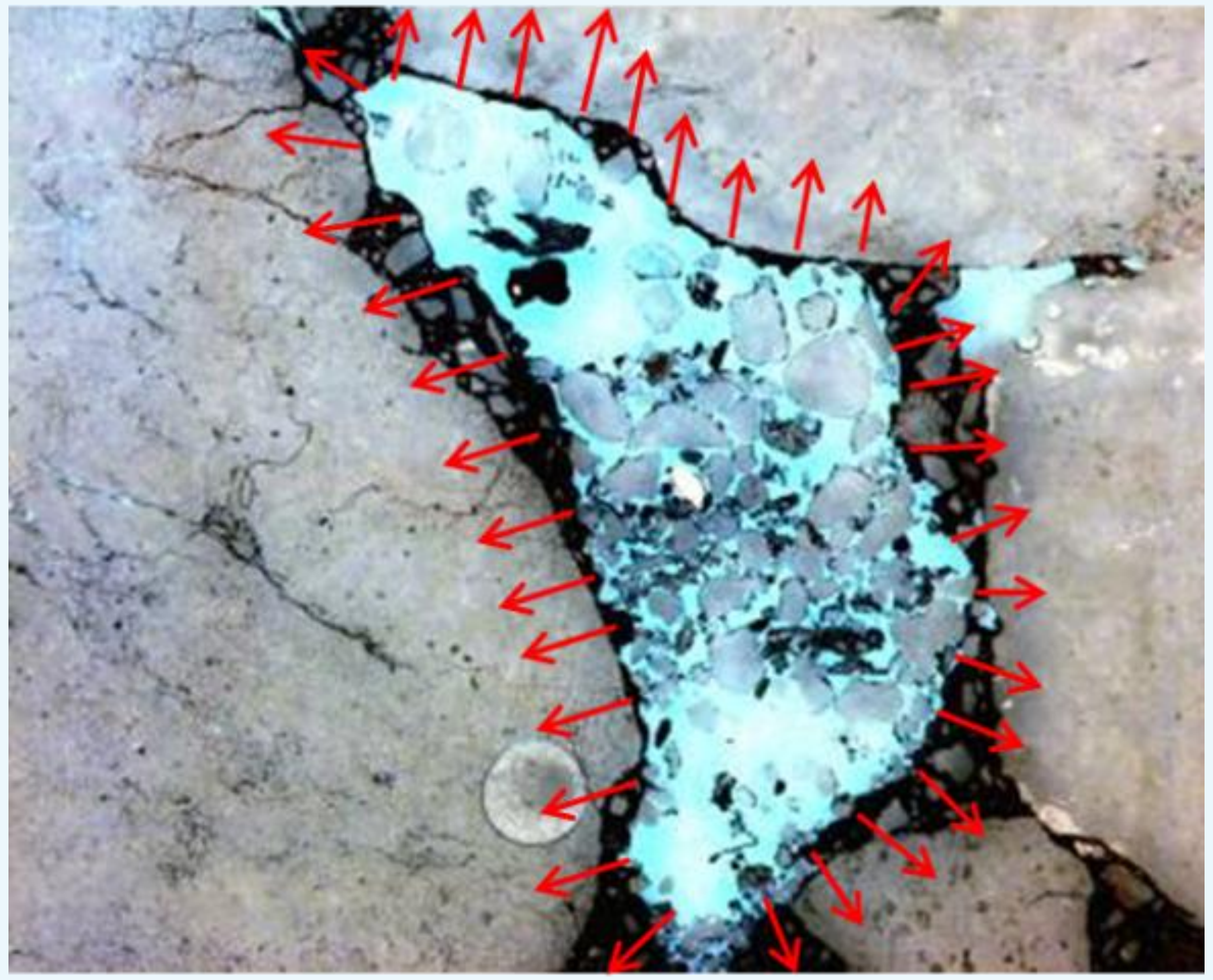


Scapras (2013) ;Kringos et al. (2013); Ververi et al. (2016)

Frost Damage Models (CAPA3D)



$$\varepsilon_{\substack{\text{phase}\\\text{change}}} = \varepsilon_{pc} = \kappa\,\xi_f$$

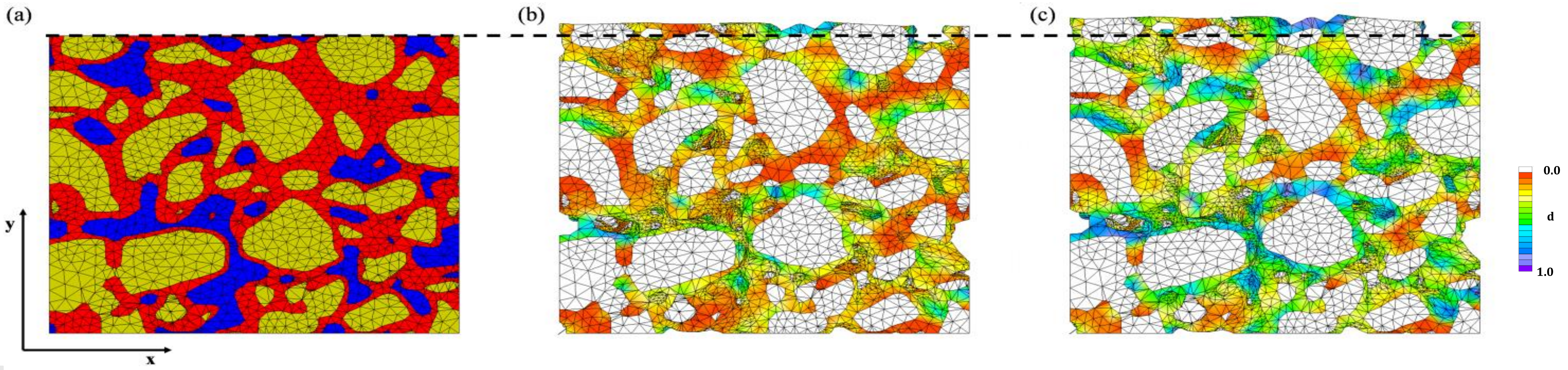


$$\Psi = \Psi_e(\mathbf{C}_e) + \Psi_f(\xi_f)$$

Helmholtz free energy

Clausius-Planck inequality

$$\sigma \cdot \dot{\varepsilon} - \dot{\Psi} \geq 0$$

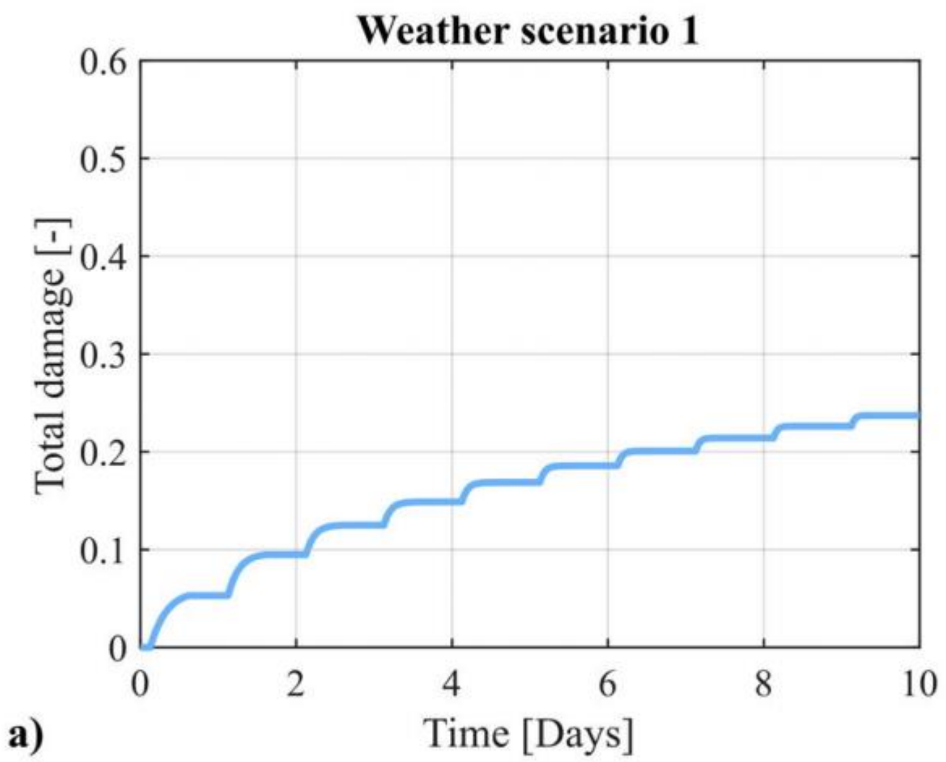


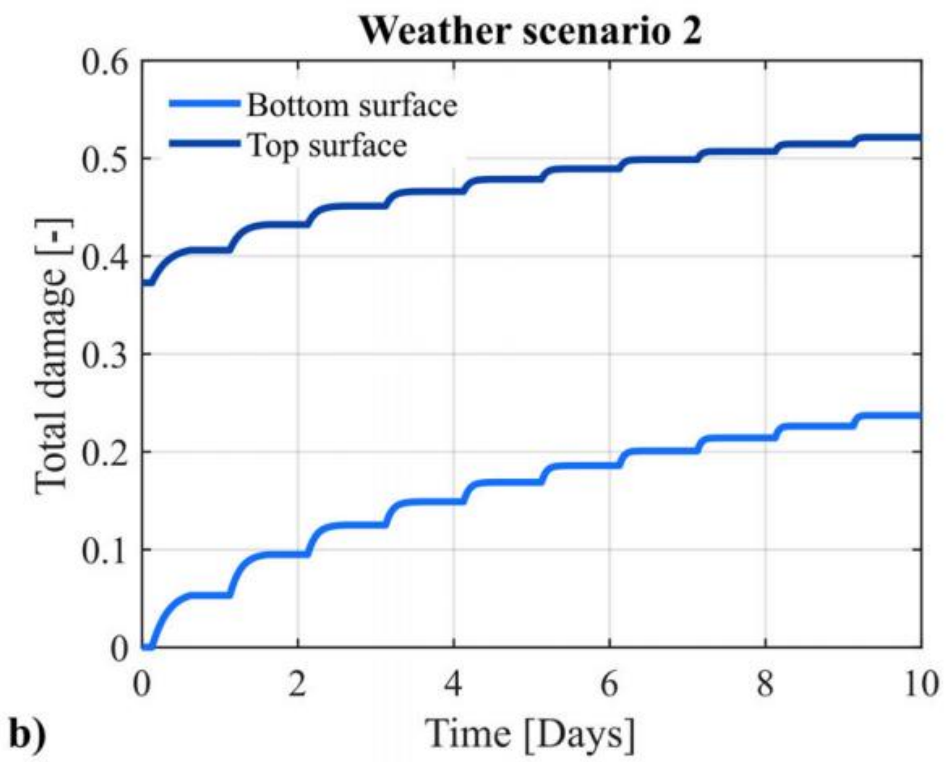
Varveri et al. (2014)

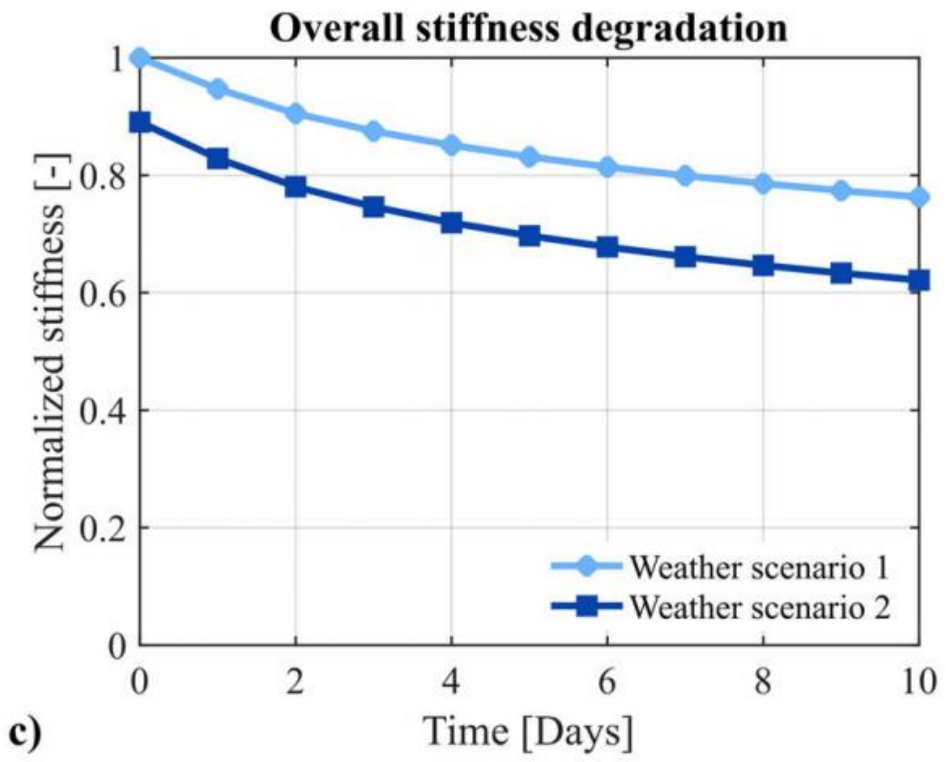
Damage due to Moisture Diffusion and Frost, and Mechanical Loading

$$(1 - d^{G}) = (1 - d^{G,\theta})(1 - d^{G,E})(1 - d^{G,FTC})$$

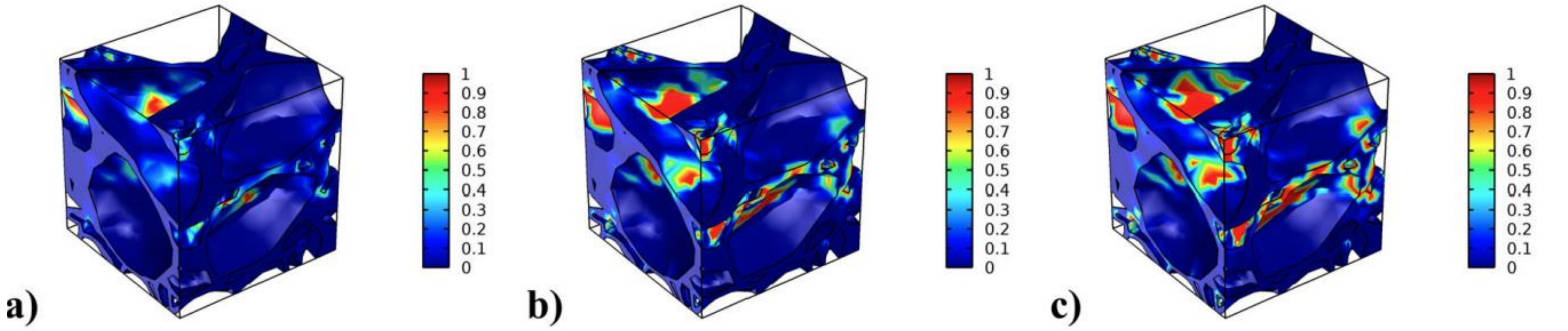
Moisture Damage | Mechanical Loading Damage | Feeze-thaw Damage



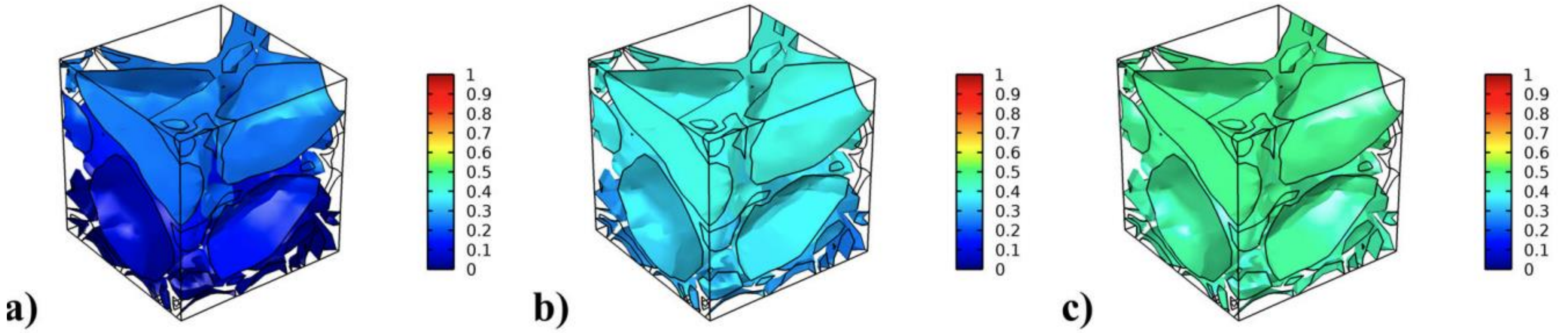




Weather 1: only freeze-thaw cycles
Weather 2: freeze-thaw cycles and moisture exposure



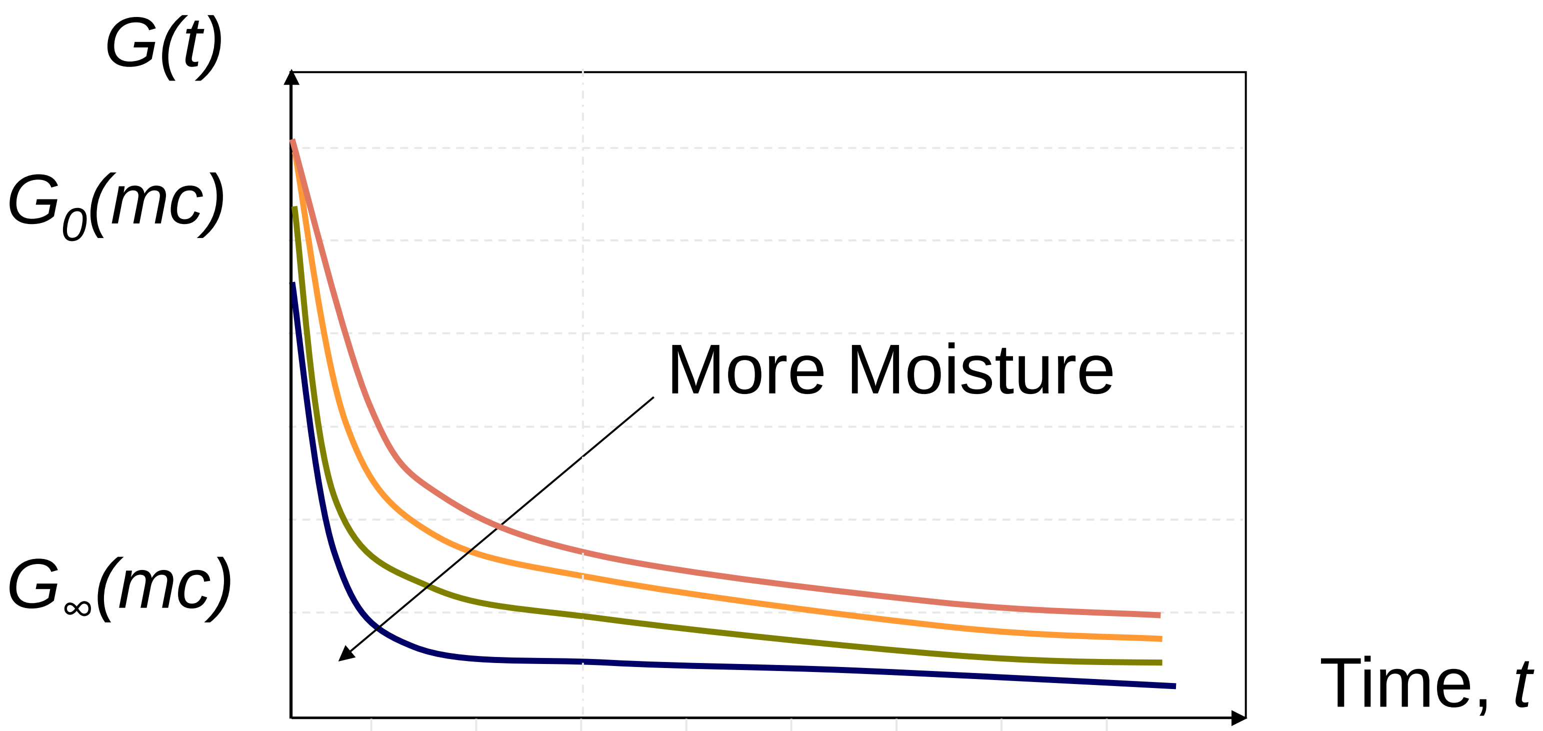
Cohesive Damage due to freeze-thaw
(a) 2 Cycles, (b) 6 Cycles, and (c) 10 Cycles

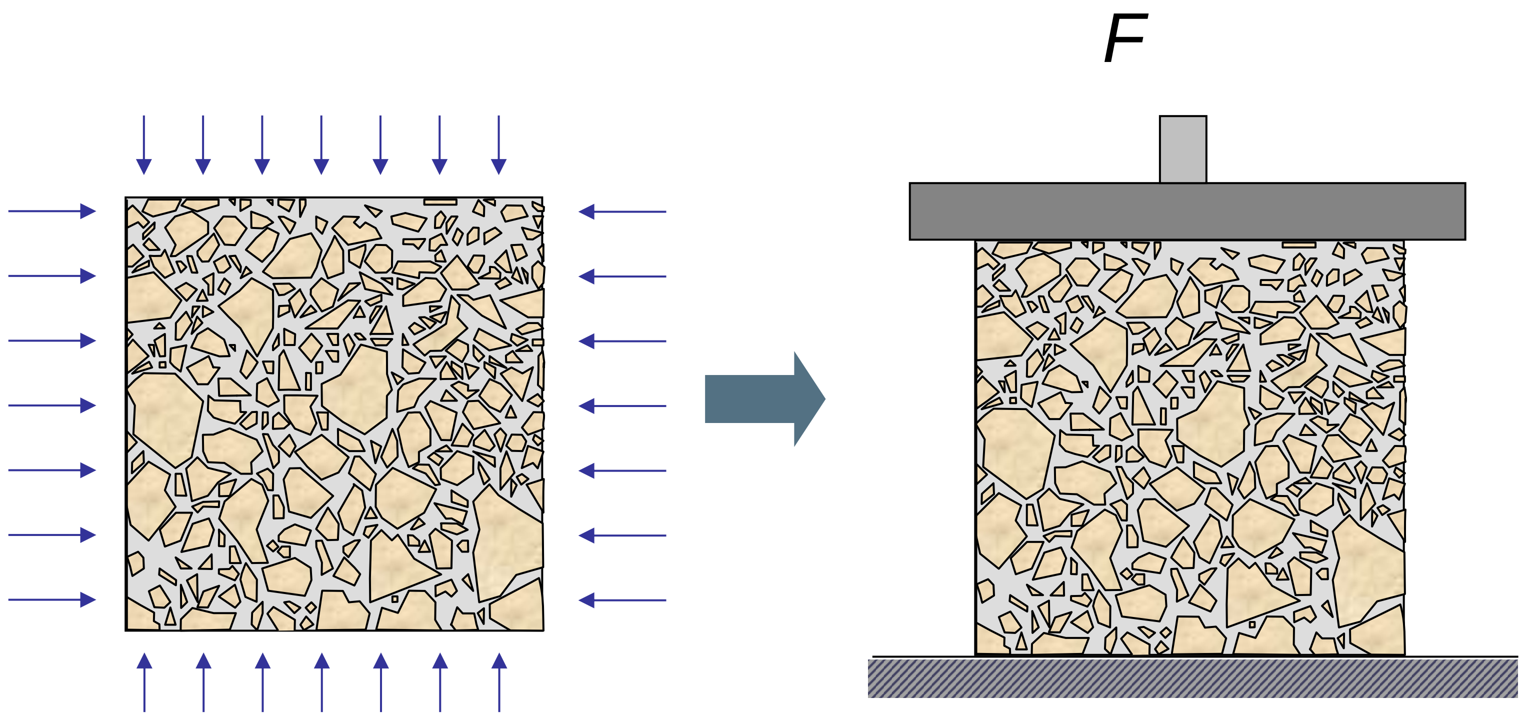


Adhesive Damage due to moisture diffusion
(a) 10 days, (b) 50 days, and (c) 150 days

Lövqvist, et al. (2022)

Micromechanical Modeling of Cohesive and Adhesive Damage



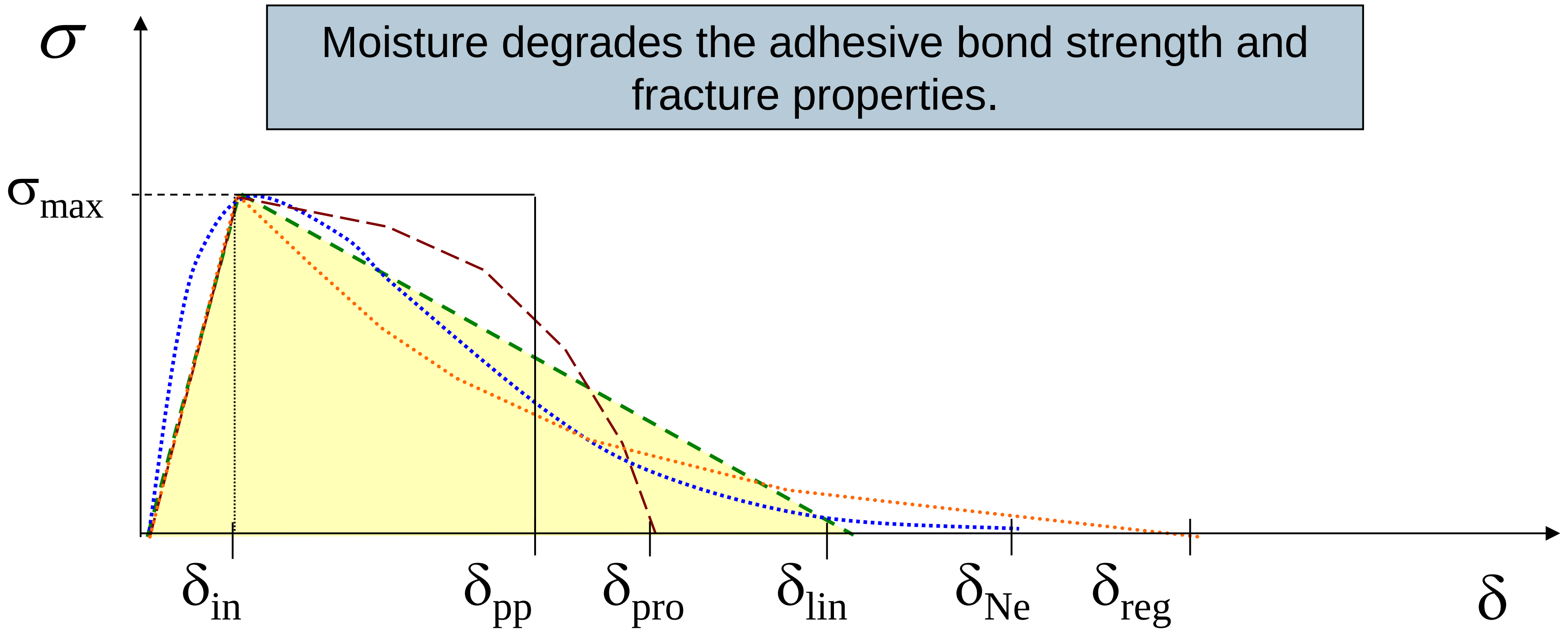


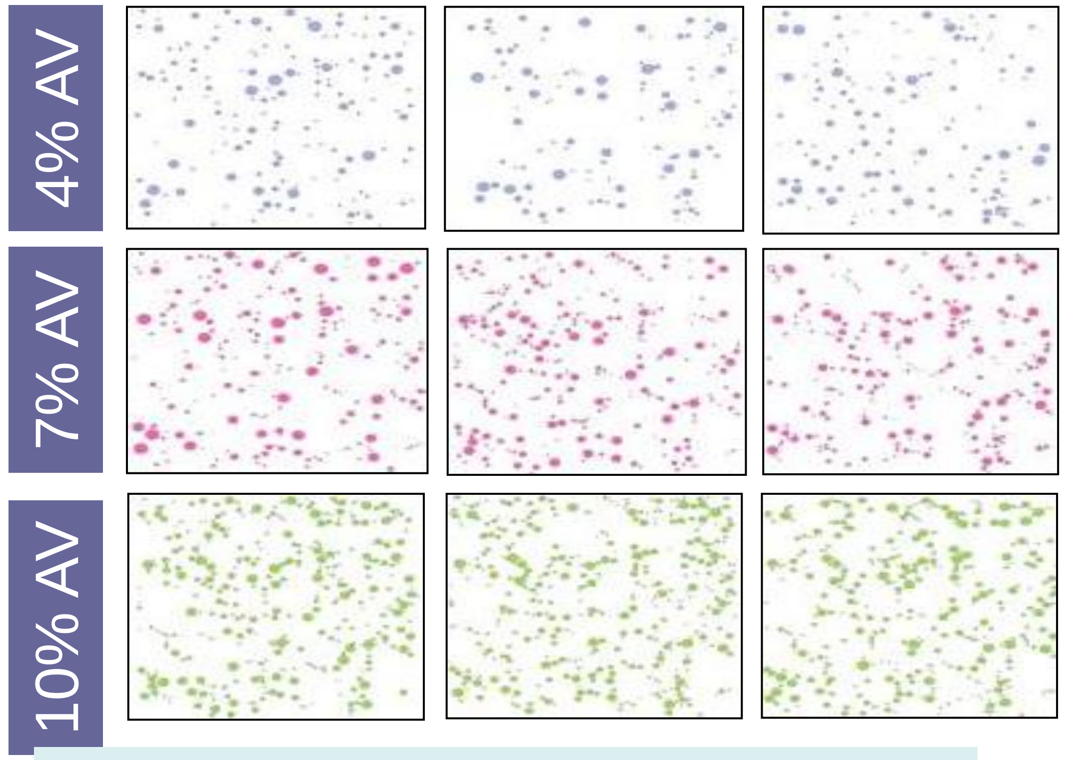
10 days moisture conditioning

Fracture test

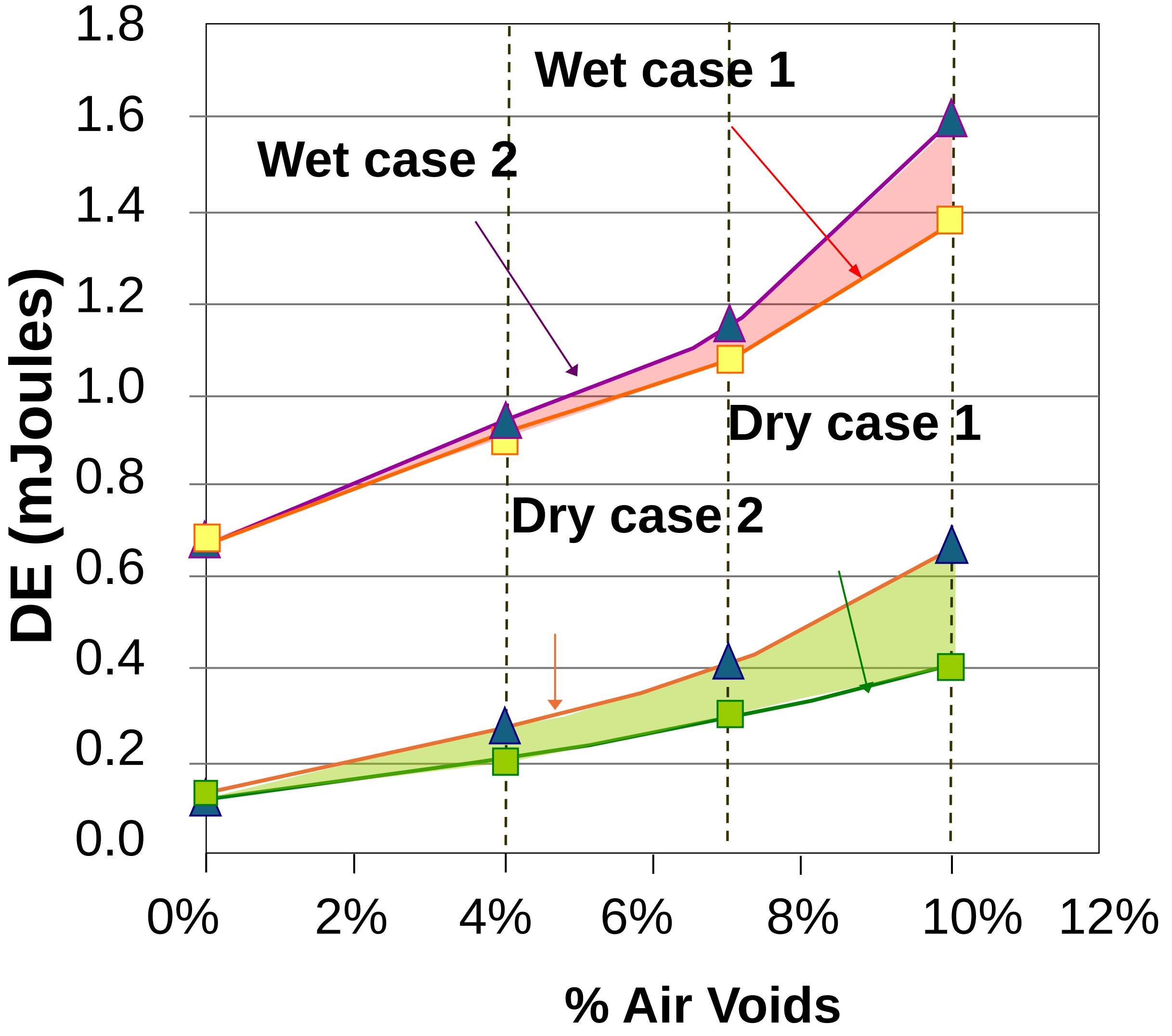
Moisture degrades the linear viscoelastic material properties of the bulk matrix

Moisture degrades the adhesive bond strength and fracture properties.

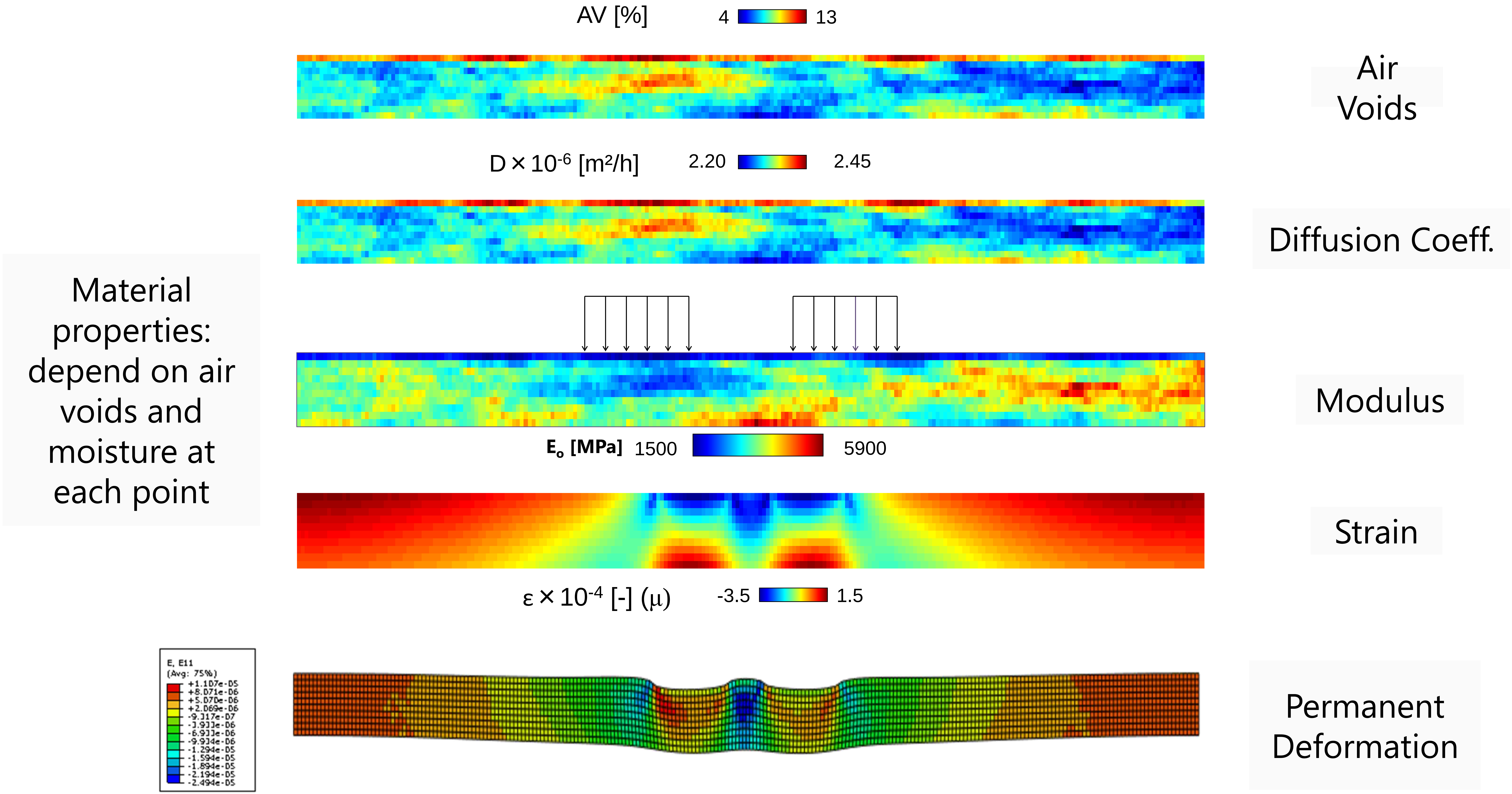




10 replicates at each level of %AV



Castillo, et al. (2017)


AV [%]
4
13
Air Voids
D × 10-6 [m²/h]
2.20
2.45
Diffusion Coeff.
Material properties: depend on air voids and moisture at each point
Modulus
Eo [MPa]
1500
5900
Strain
ε × 10-4 [-] (μ)
-3.5
1.5
E, E11
(Avg: 75%)
+1.107e-05
+8.071e-06
+5.070e-06
+2.069e-06
-9.317e-07
-3.933e-06
-6.933e-06
-9.934e-06
-1.294e-05
-1.594e-05
-1.894e-05
-2.194e-05
-2.494e-05
Permanent Deformation

Analytical Analysis of Moisture Damage

Relationship Between Crack Size and Dissipated Pseudo Strain Energy (WR)

$$\frac{d\bar{r}}{dN} = A[J_R]^n$$

$$J_R = \frac{\dfrac{\partial W_R}{\partial N}}{\dfrac{\partial (c.s.a)}{\partial N}}$$

$$\frac{\partial (c.s.a)}{\partial N} = 4\pi m \bar{r} \frac{\partial \bar{r}}{\partial N}$$

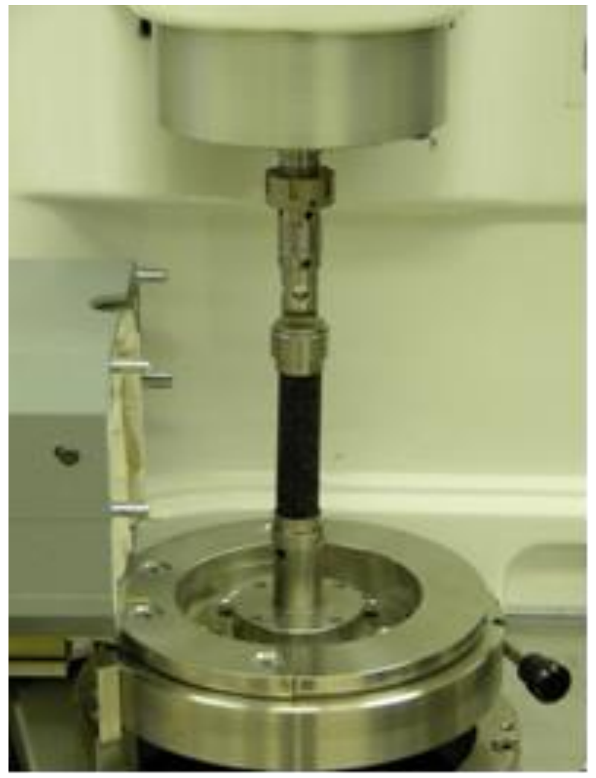
$$\bar{r}(N) = \left(\frac{2n+1}{n+1}\right)^{\frac{n+1}{2n+1}} \left(\frac{A}{(4\pi m)^n}\right)^{\frac{1}{2n+1}} \left(\int_{N=0}^{N_f} \left(\frac{\partial W_R}{\partial N}\right)^{\frac{n}{n+1}} dN\right)^{\frac{n+1}{2n+1}}$$

J_R = *Pseudo J - Integral representing the amount of dissipated pseudo strain energy per unit area of crack surface area.*

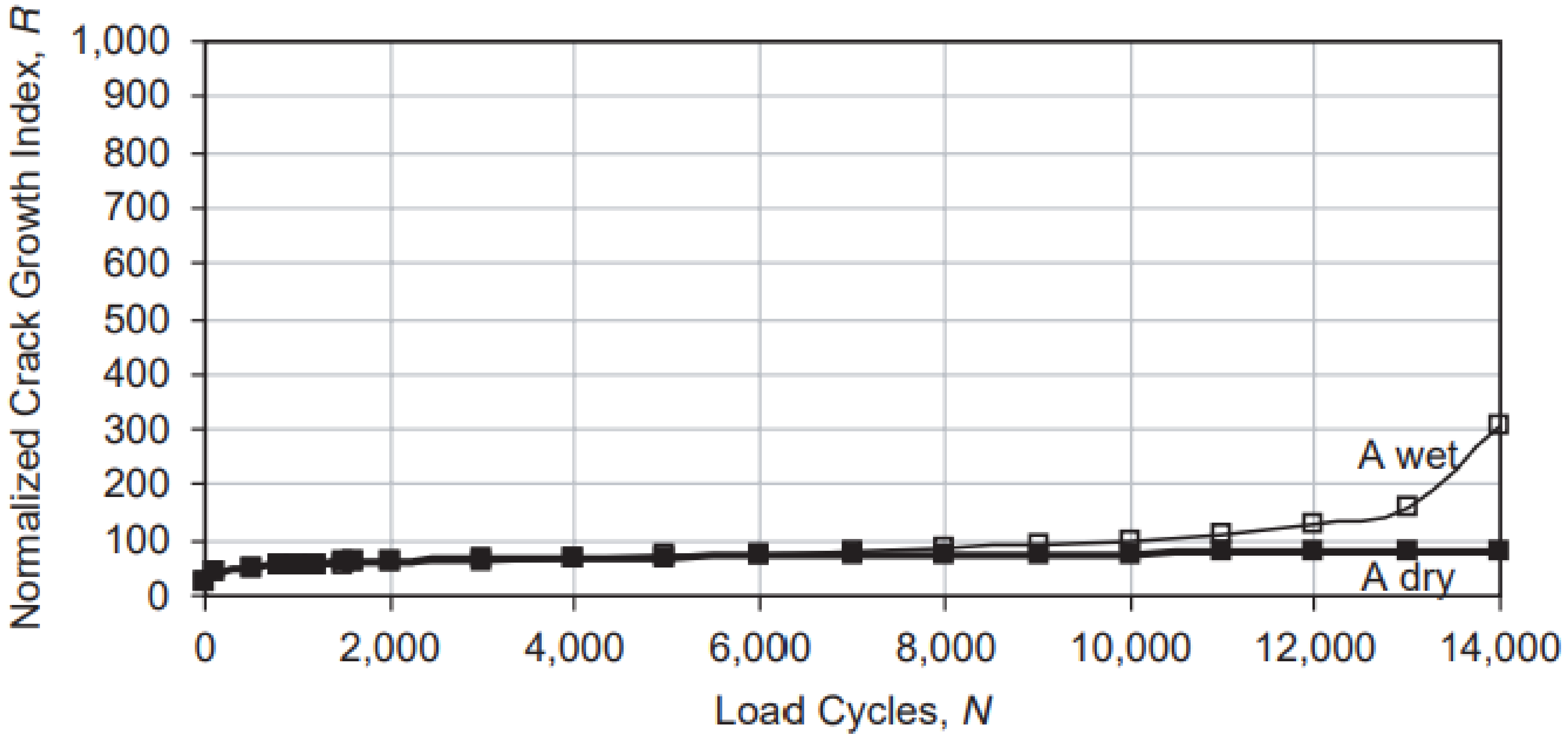
$c.s.a$ = *Crack surface area.*

$\bar{r}$ = *Crack radius.*

m = *Number of cracks*

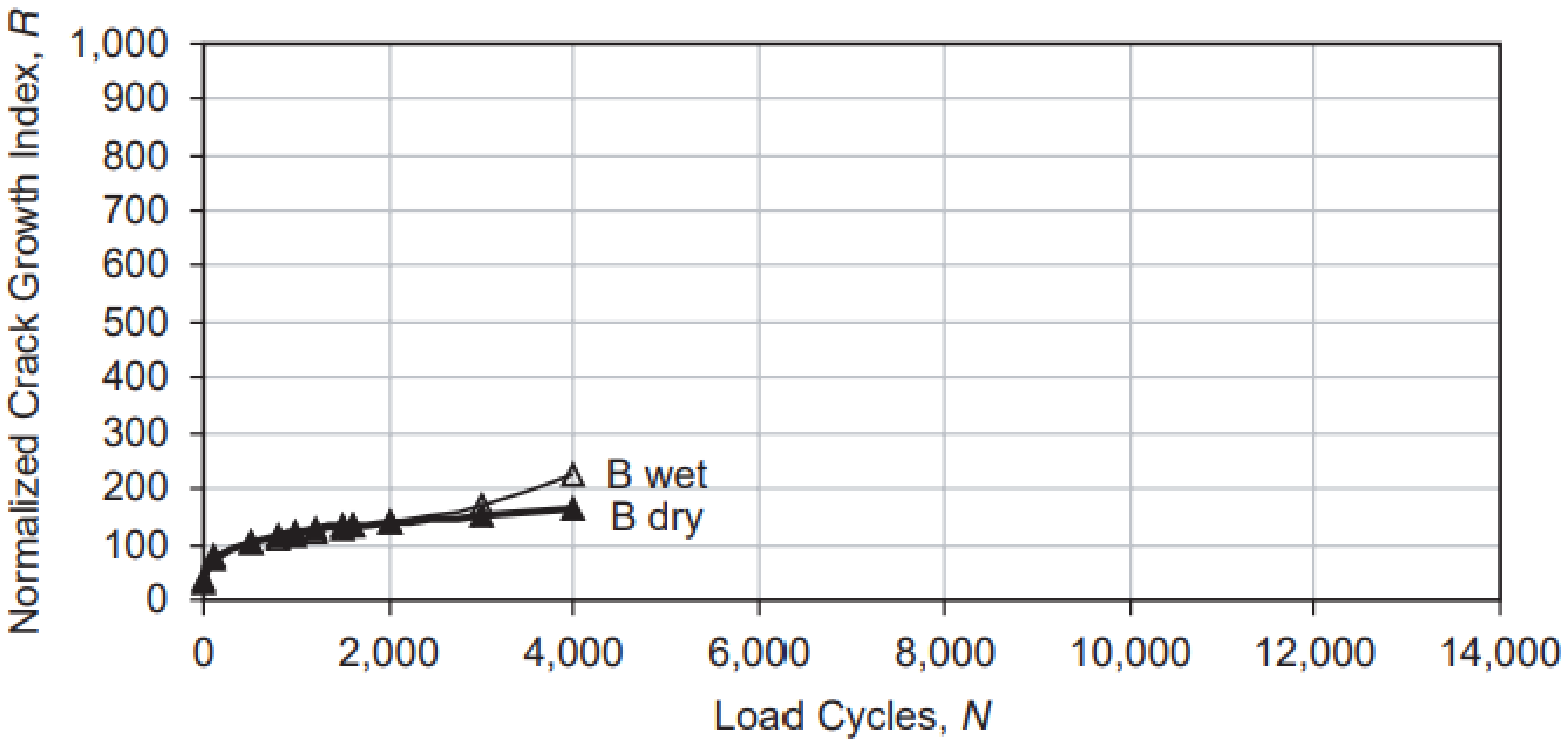


Arambula et al. (2007).

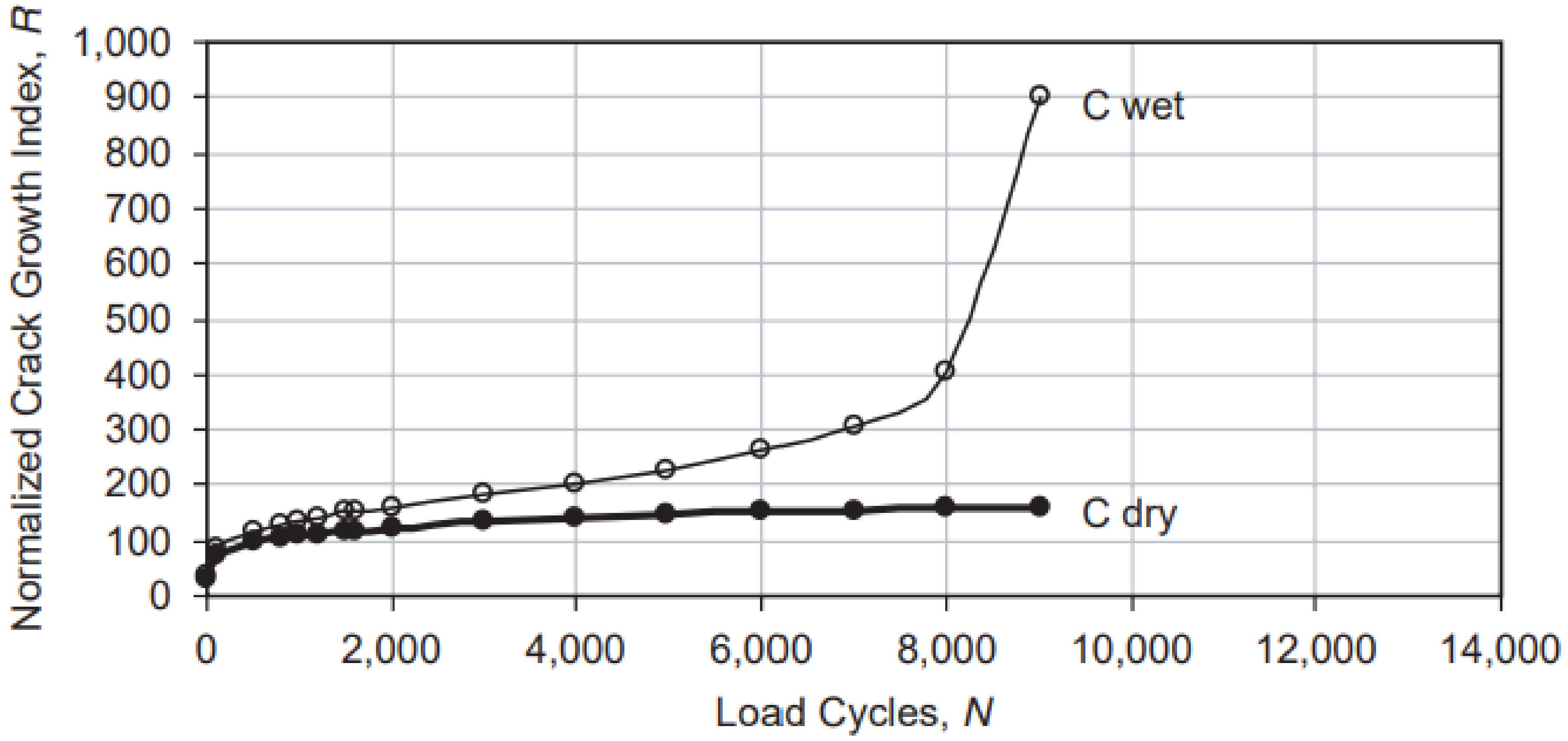


(a)

Mixture	Field Moisture Performance	Aggregate	Adhesive Dry ΔG_{12}^{a} (erg/cm^2)	Adhesive Wet ΔG_{123}^{a} (erg/cm^2)
A	Good	Gravel	93.36	−75.20
		TXI limestone	118.87	−151.14
B	Fair to poor	Limestone	87.49	−115.58
		Gravel	94.56	−160.22
C	Poor	Limestone	81.27	−119.82
		Gravel	90.92	−161.87



(b)



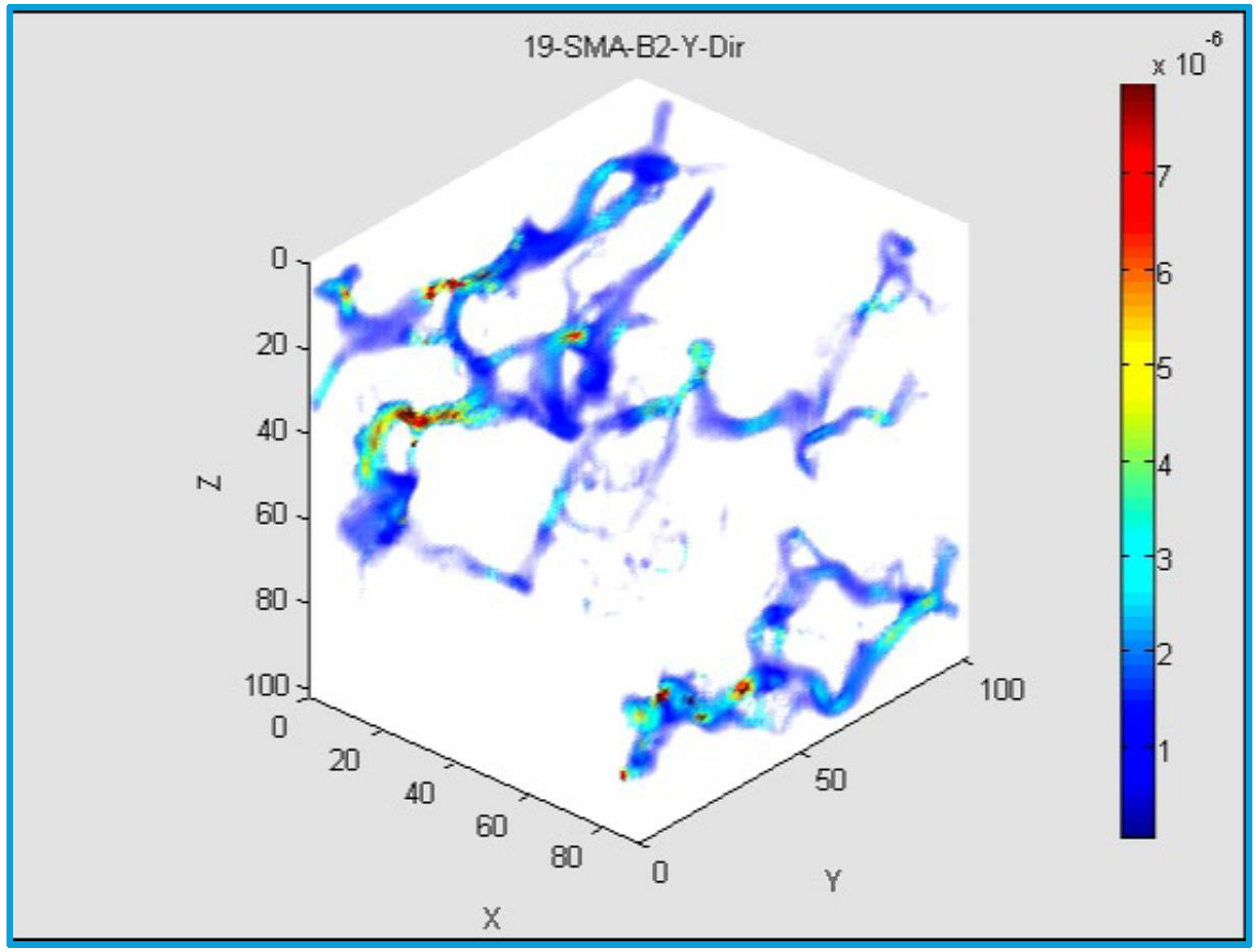
(c)

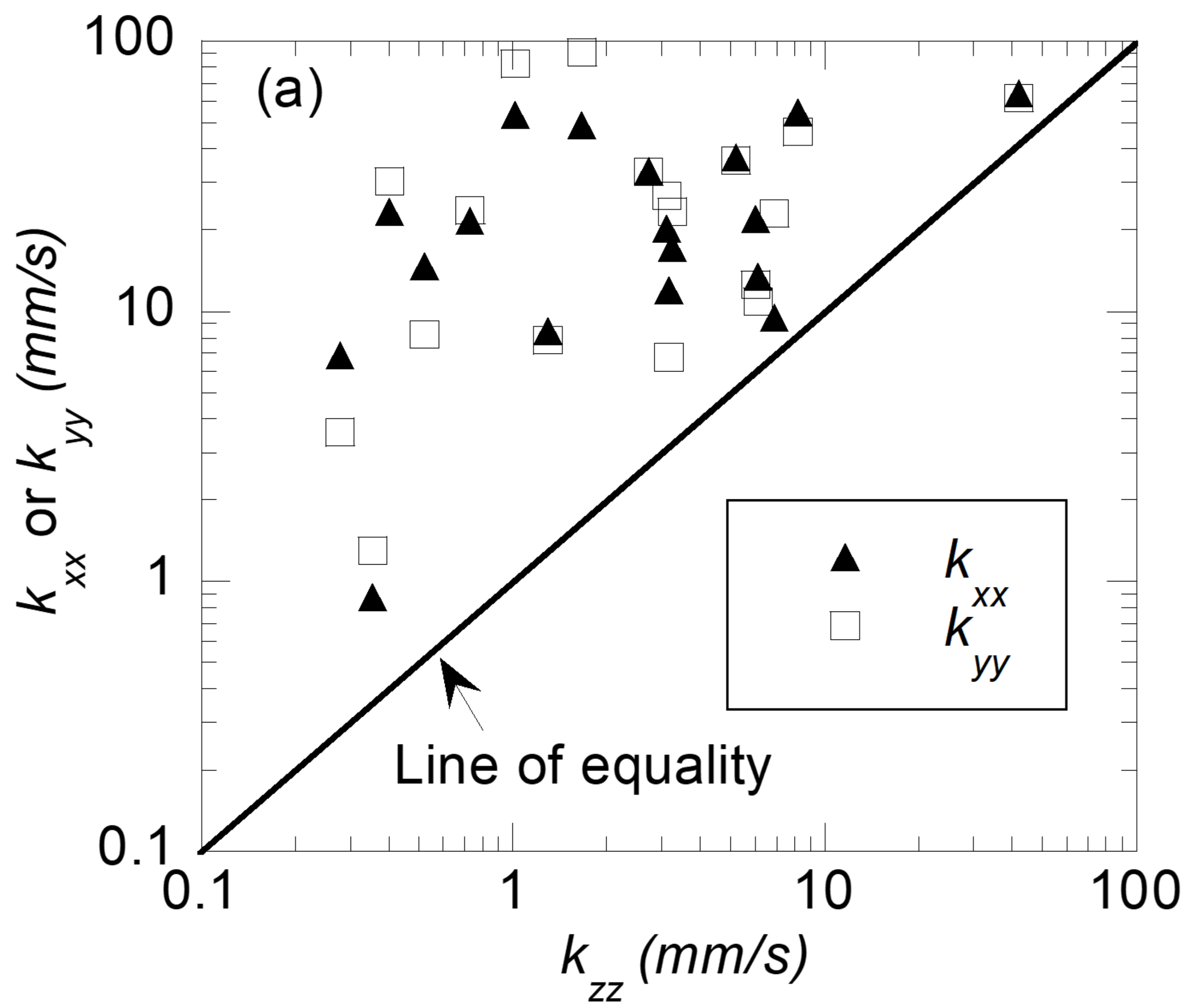
Arambula et al. (2007).

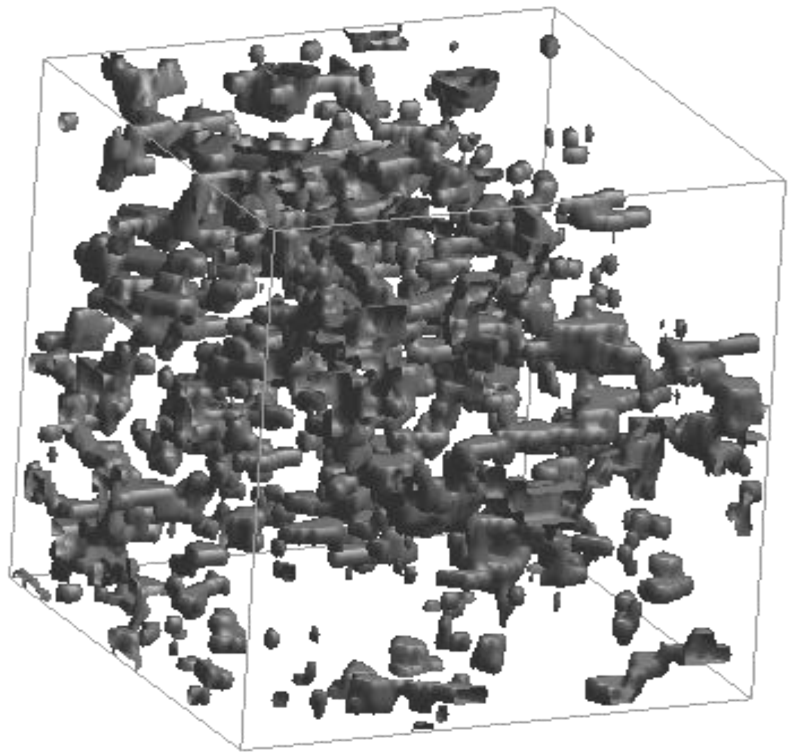
Numerical and Analytical Modeling of Permeability

Numerical Modeling of Permeability

$$\begin{bmatrix} \bar{u} \\ \bar{v} \\ \bar{w} \end{bmatrix} = -\frac{1}{\mu} \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \begin{bmatrix} \partial P / \partial x \\ \partial P / \partial y \\ \partial P / \partial z \end{bmatrix}$$







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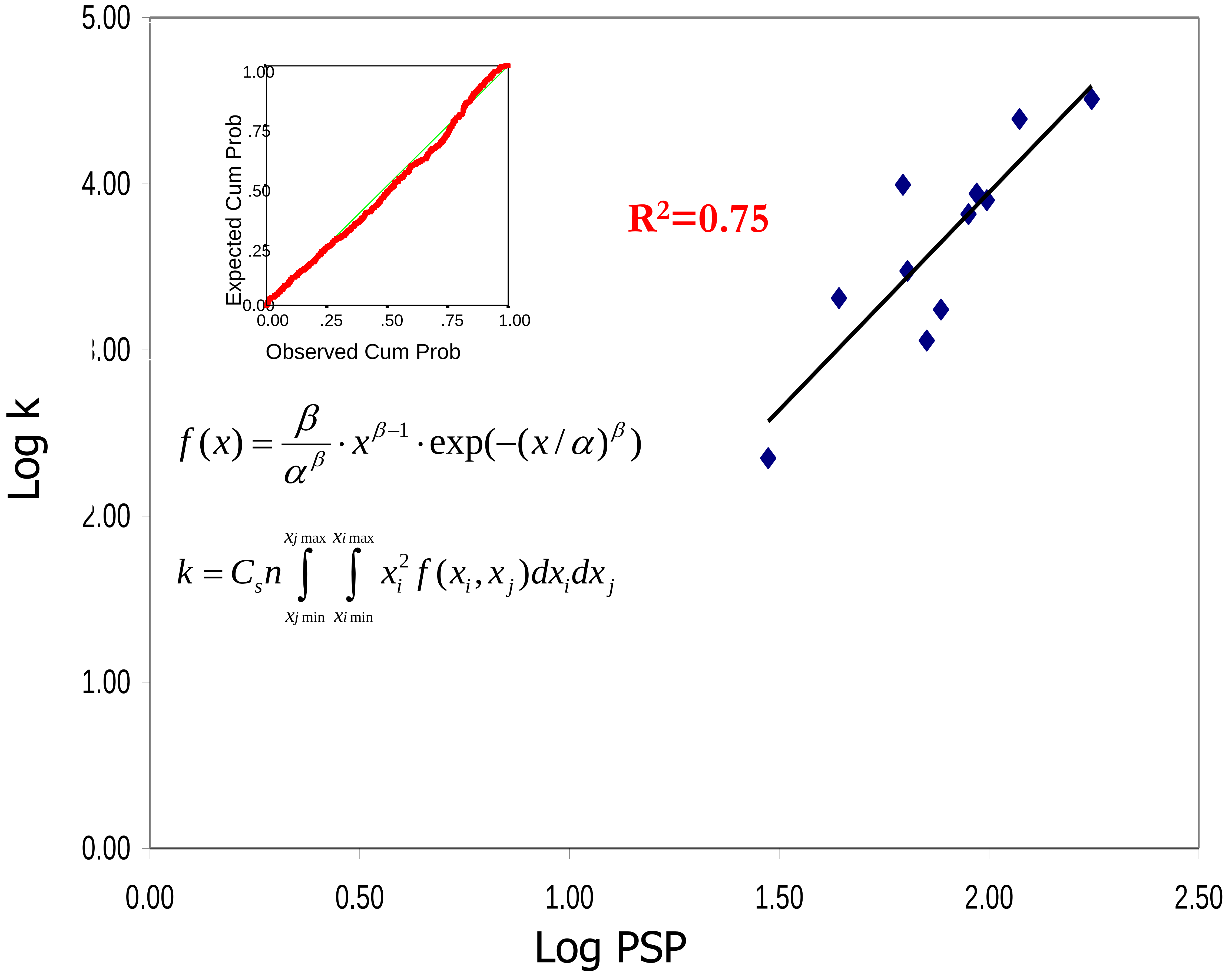
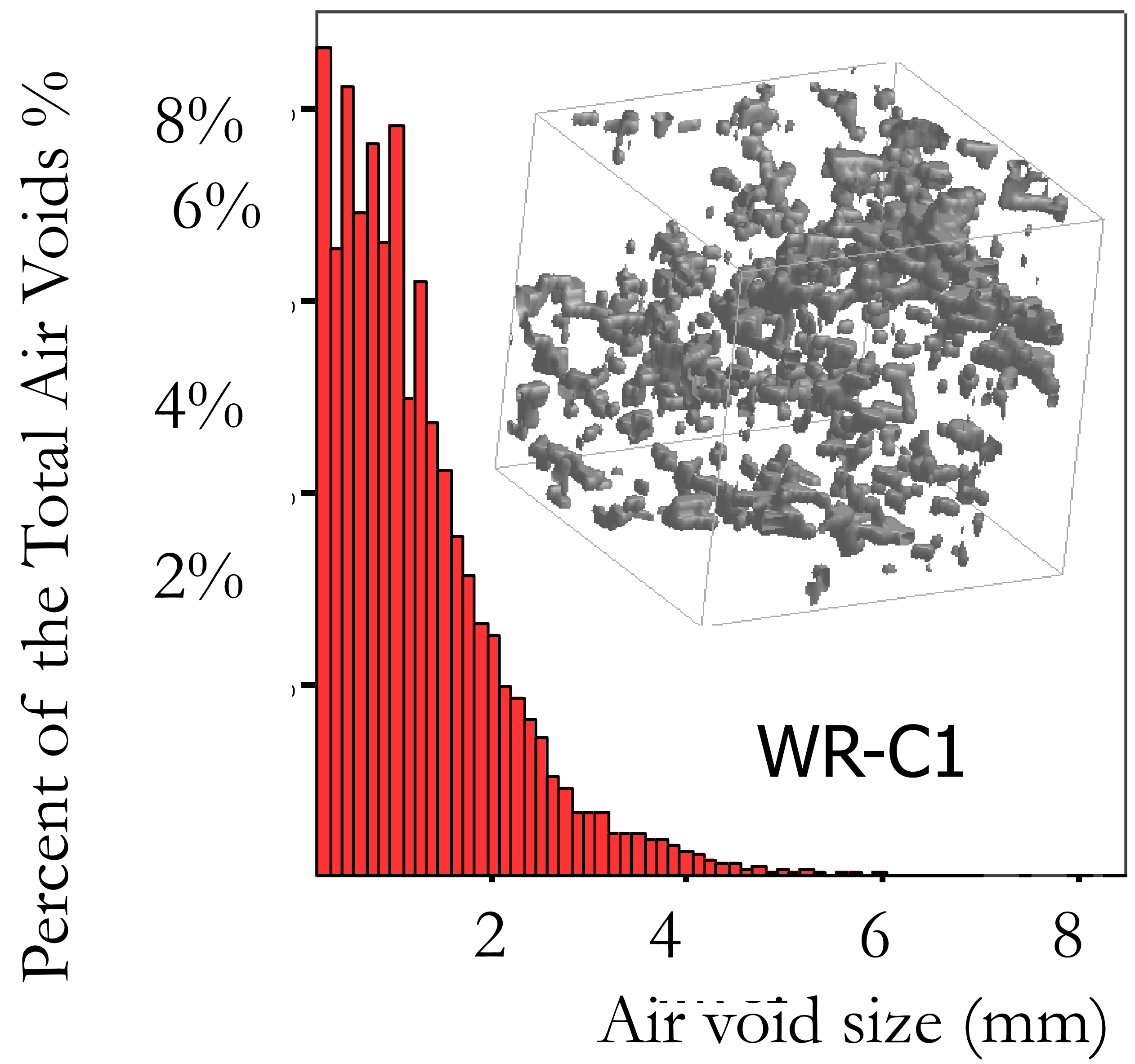
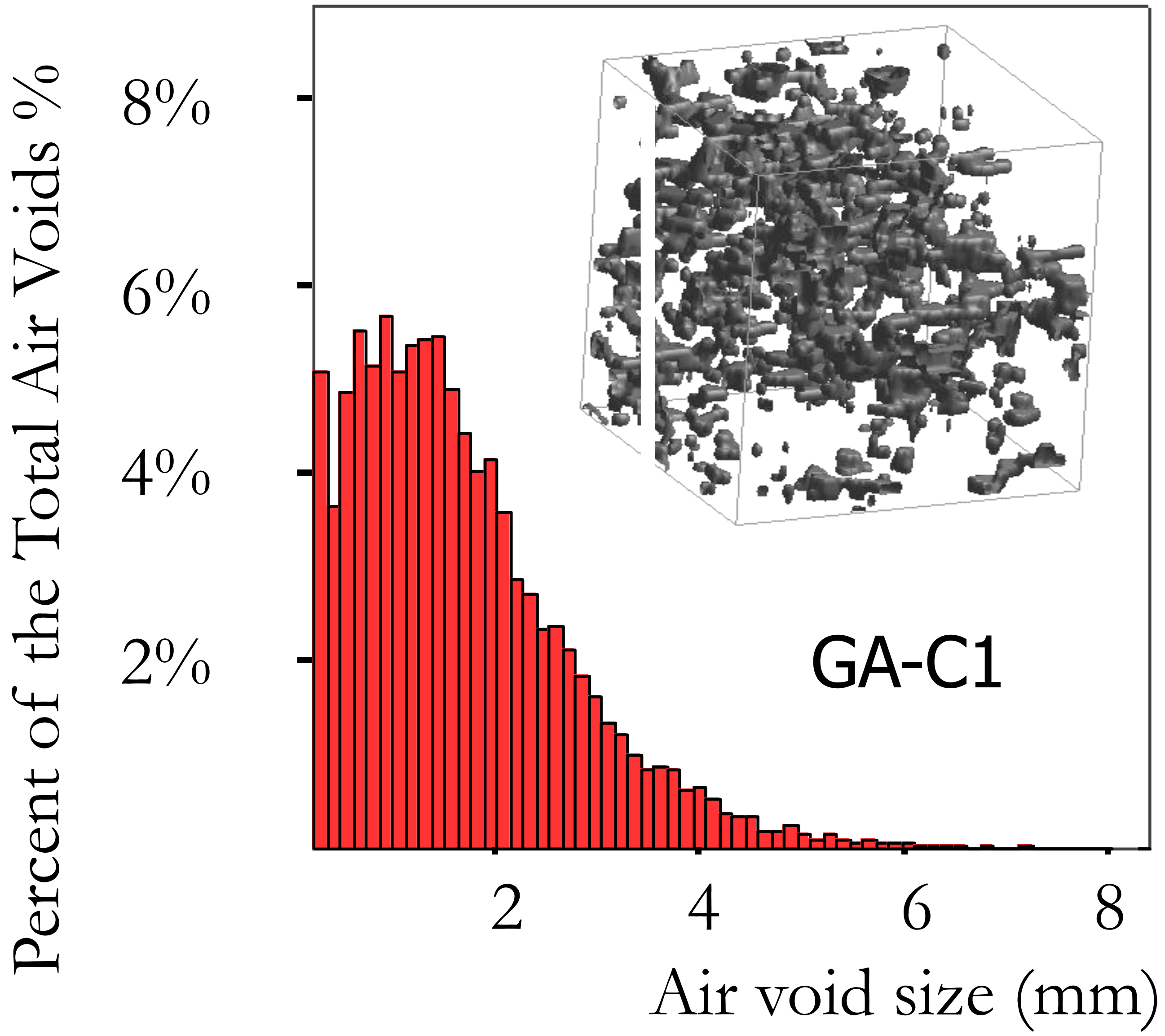
Probabilistic Analytical Modeling of Permeability



$$f(x) = \frac{\beta}{\alpha^{\beta}} \cdot x^{\beta-1} \cdot \exp(-(x/\alpha)^{\beta})$$

$$k = C_s n \int_{Xj\,\min}^{Xj\,\max} \int_{Xi\,\min}^{Xi\,\max} x_i^2 f(x_i, x_j) dx_i dx_j$$

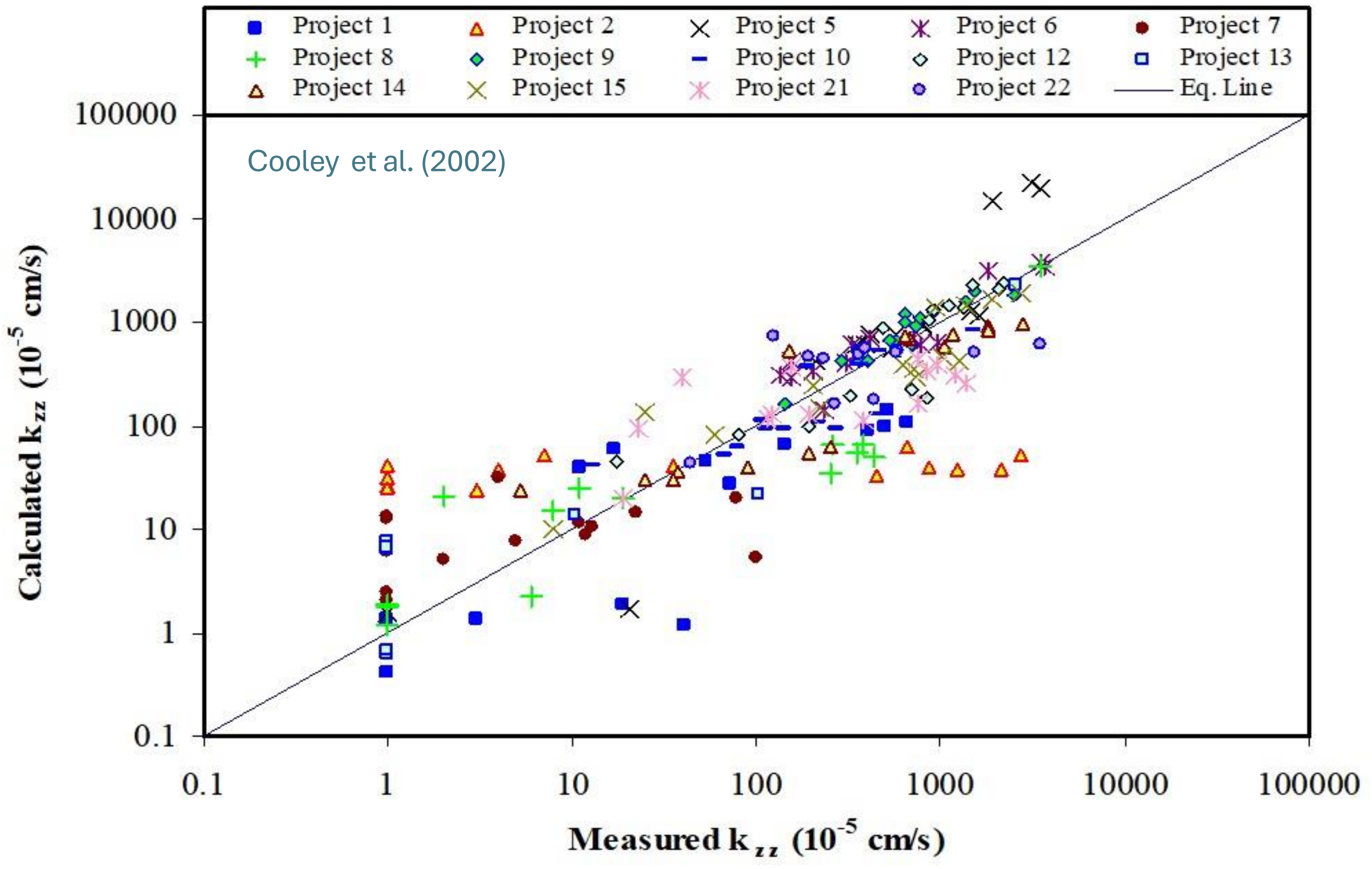


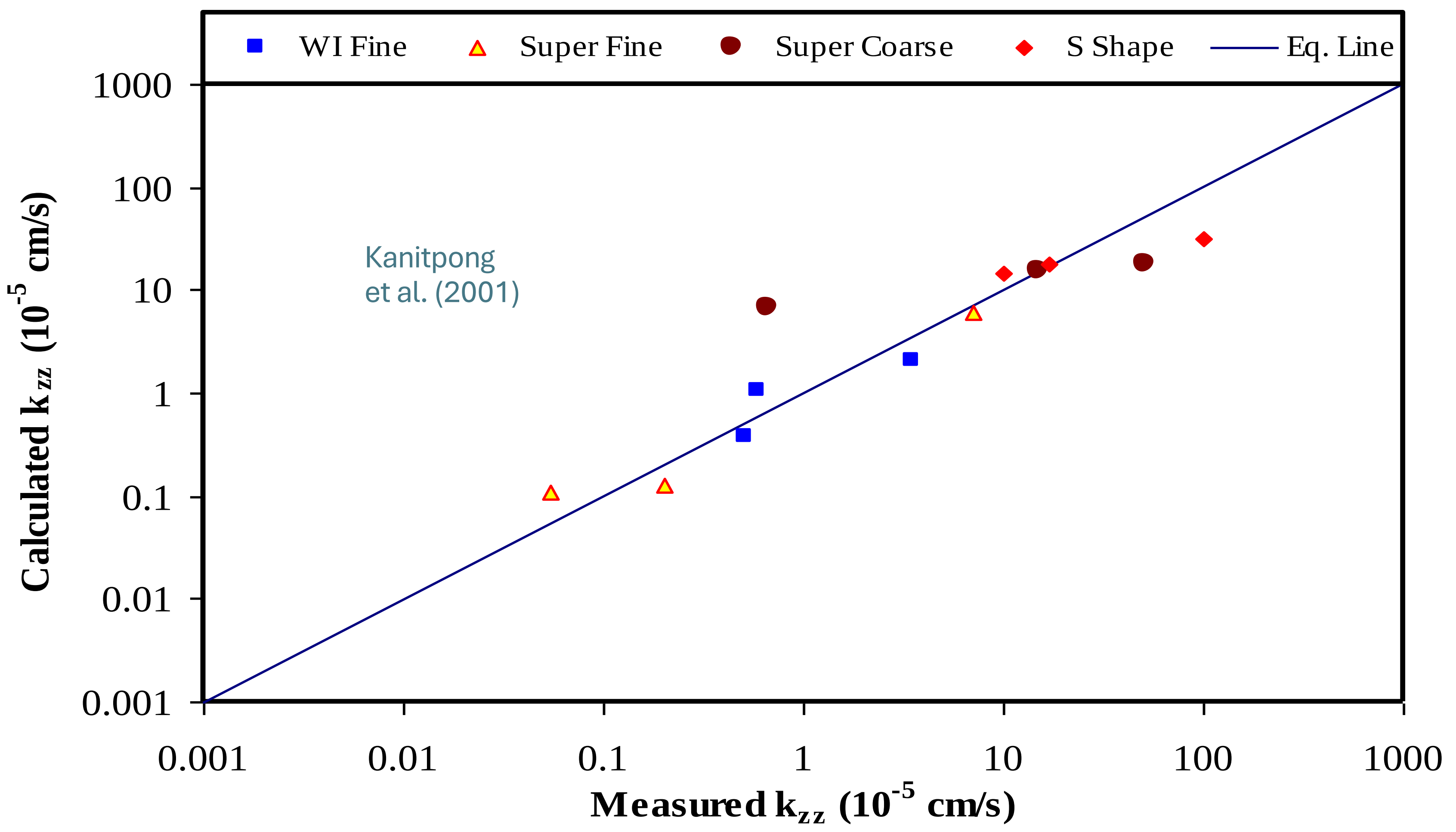


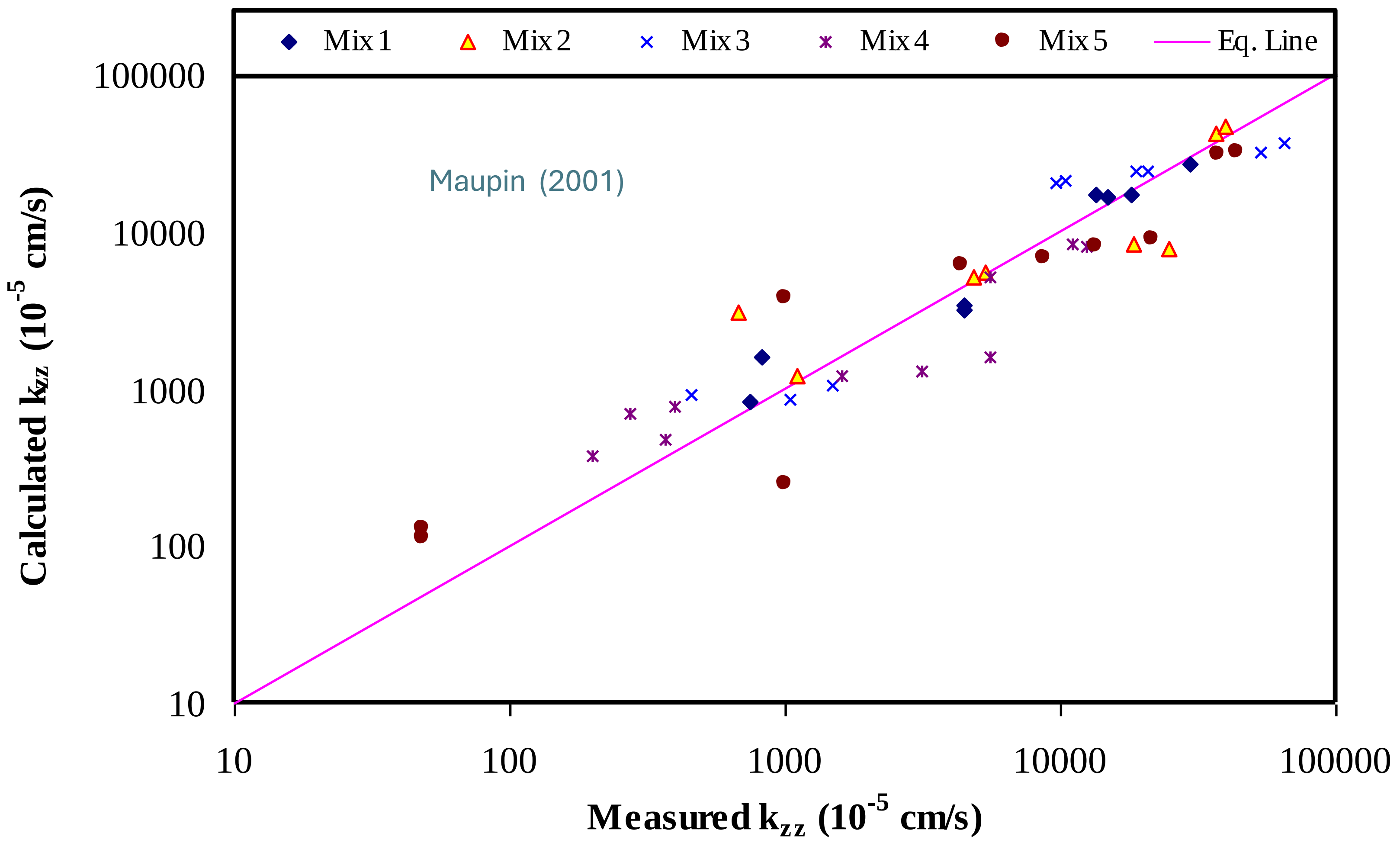
Masad et al. (2006)

Analytical Modeling of Permeability

$$K = \bar{C}\frac{n^3}{(1-n)^2}D^2_{Effective}$$



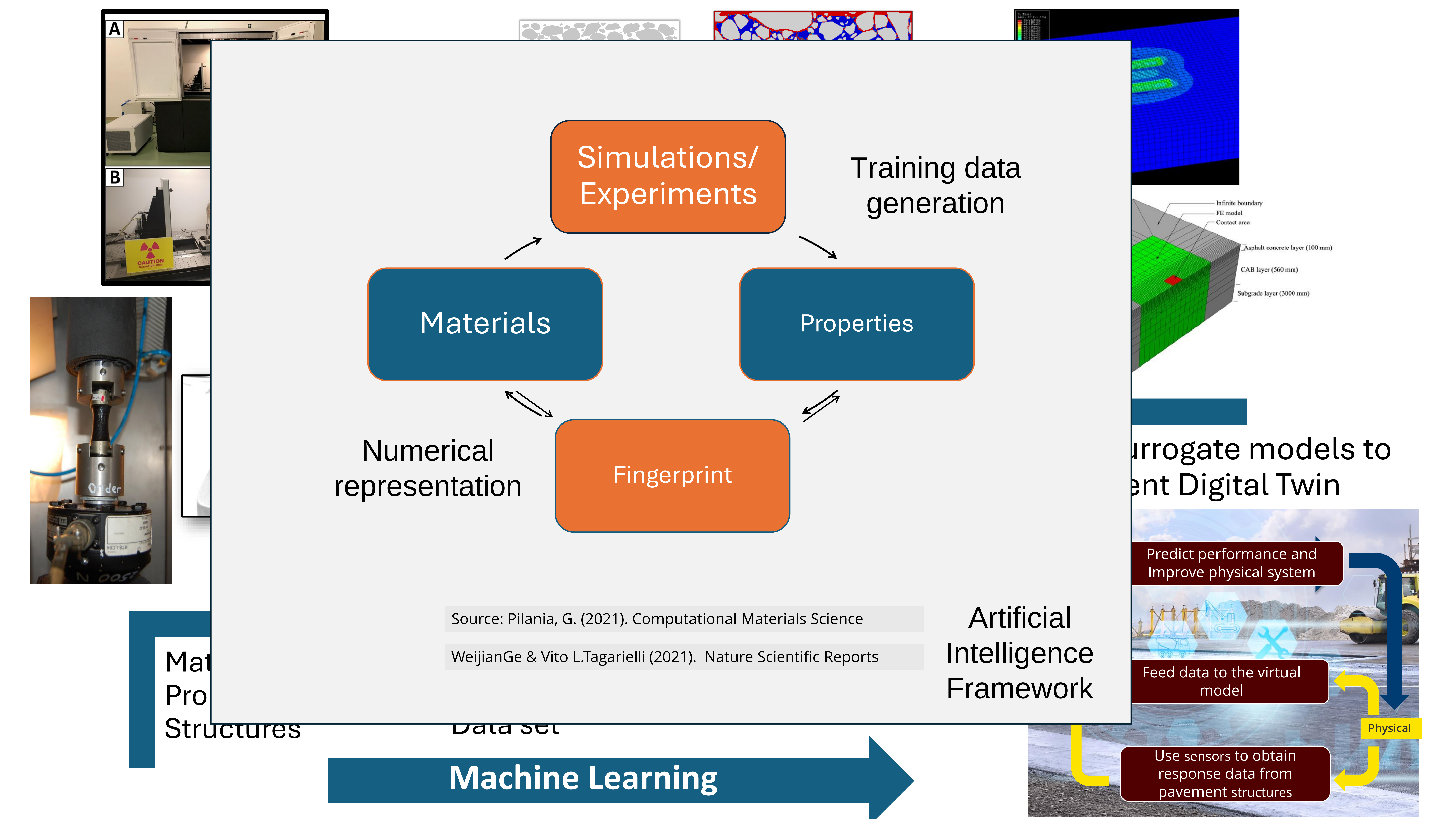




Masad et al. (2006)

Findings and Future Directions

- Computational models provided insights regarding the effect of mixture designs and material properties on moisture damage.
- However, they have fallen short of predicting performance primarily because of multi-scale and multi-physics of moisture damage.
- **AI can be utilized to predict permeability** and **moisture damage** using mixture design and material properties.
- The above can be achieved by high throughput tests of fundamental material properties and testing moisture damage under relevant mechanisms (diffusion, pore pressure).
- **Develop digital twinning of asphalt pavements** that account for various phenomena (loads, aging, and moisture).


A
B
CAUTION
Simulations/
Experiments
Training data
generation
Infinite boundary
FE model
Contact area
Asphalt concrete layer (100 mm)
CAB layer (560 mm)
Subgrade layer (3000 mm)
Materials
Properties
Fingerprint
Numerical
representation
urrogate models to
ent Digital Twin
Predict performance and
Improve physical system
Source: Pilania, G. (2021). Computational Materials Science
WeijianGe & Vito L.Tagarielli (2021). Nature Scientific Reports
Artificial
Intelligence
Framework
Feed data to the virtual
model
Mat
Pro
Structures
Data set
Physical
Use sensors to obtain
response data from
pavement structures
Machine Learning

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شكرًا
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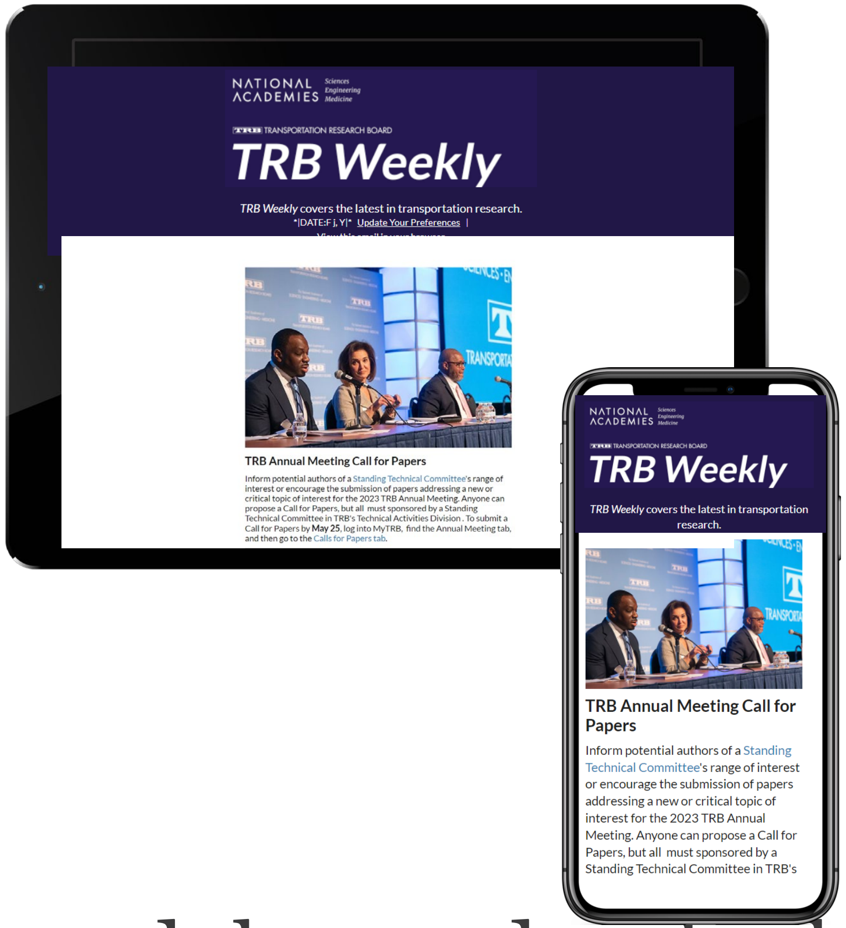

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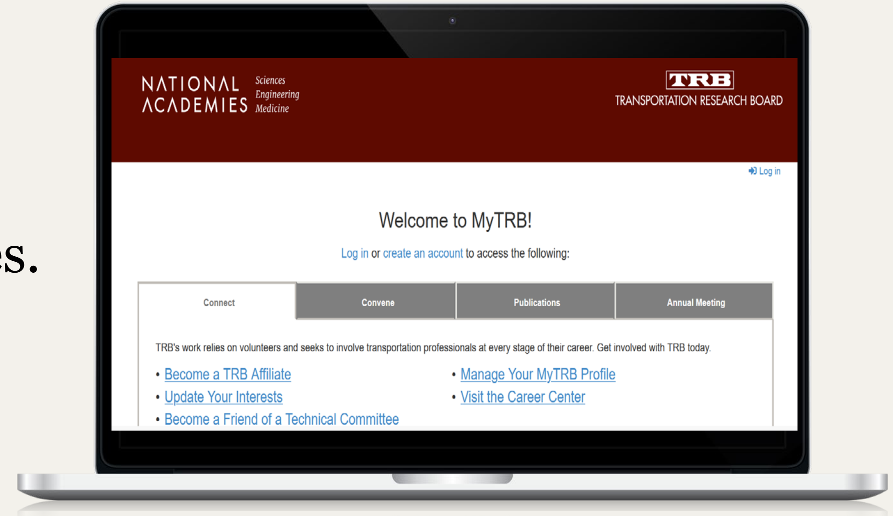

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