National Slag Association 2024 Annual Meeting

Advancing Sustainable Transportation Infrastructure: The Role of Slag in Enhancing Soil and Asphalt Mixture's Performance

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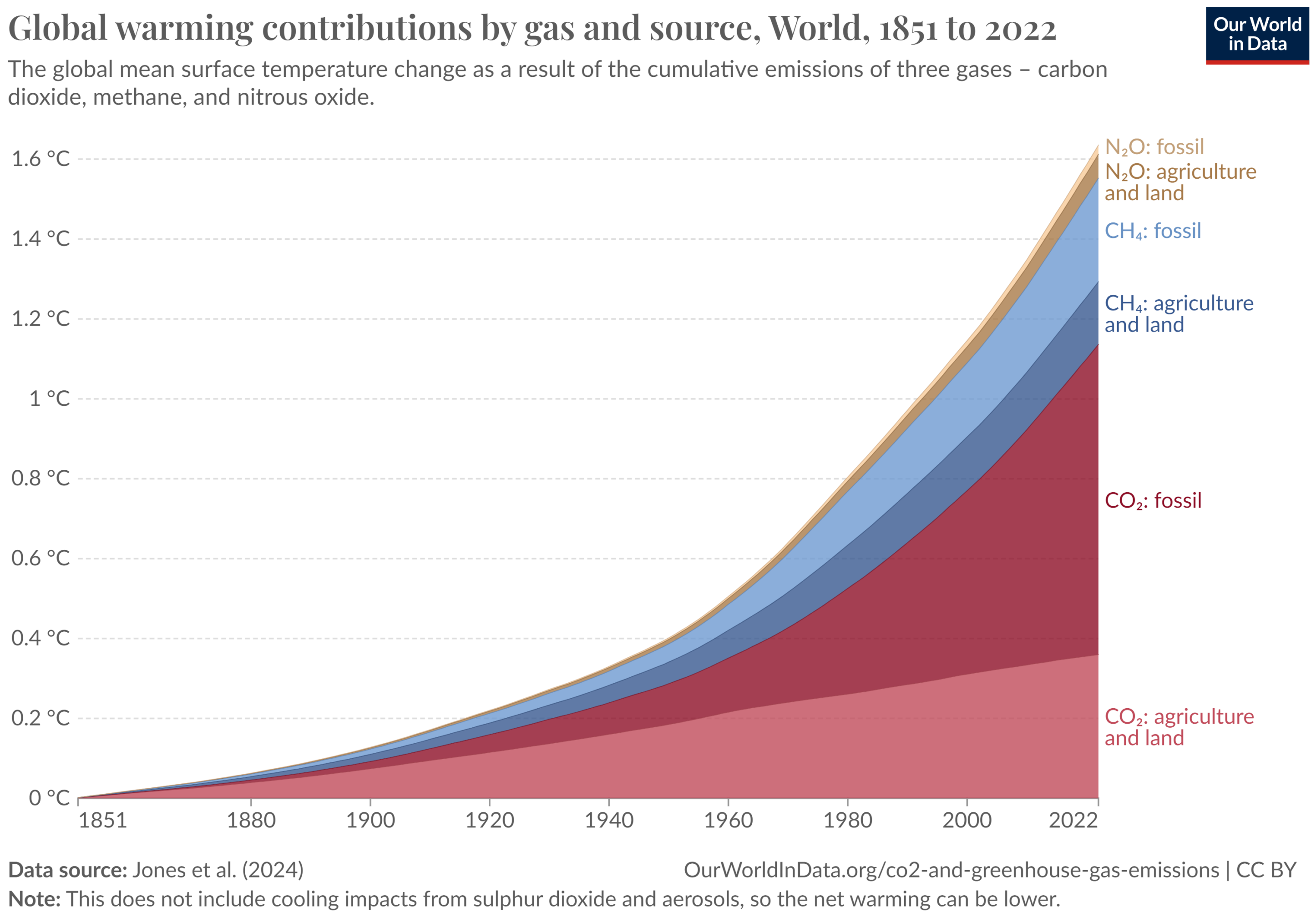
TRANSPORTATION AND CLIMATE CHANGE

01 | Introduction and Research Motivations

The emissions of **greenhouse gases** (GHG) resulting from human activities continue to **increase**.



A collage of typical climate and weather-related events: floods, heatwaves, drought, hurricanes, wildfires and loss of glacial ice. (Image credit: NOAA)

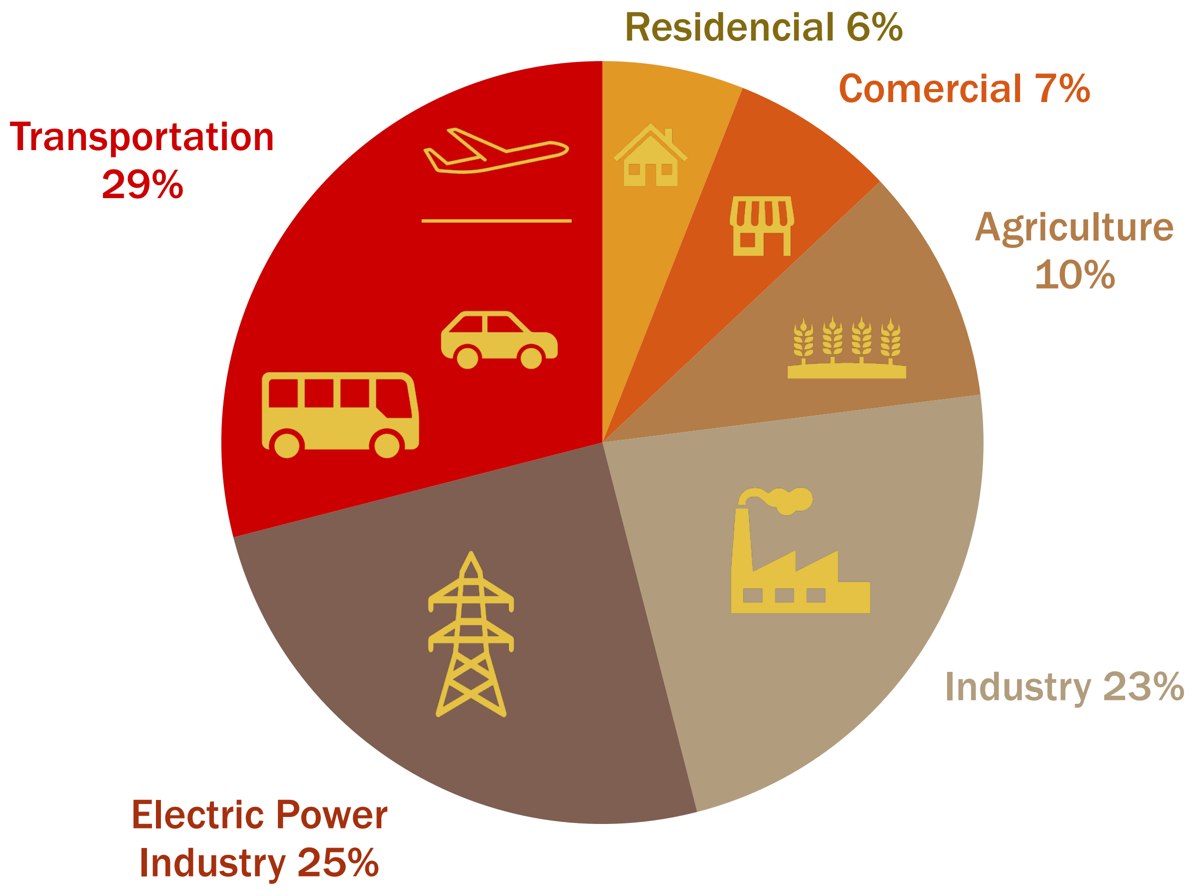
Climate change threatens the planet's **well-being** and **health**.

Climate change **impacts** are seen throughout every aspect of the world we live in.

The projections of a climate change-impacted future **are not inevitable**.

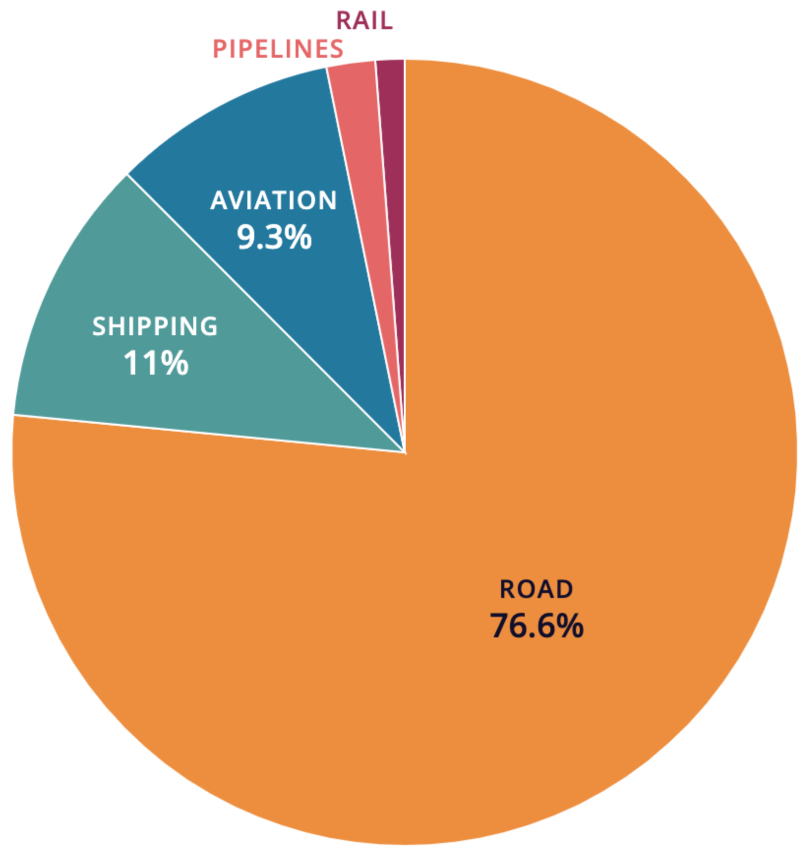
01 | Introduction and Research Motivations

The **transportation sector** is responsible for **29%** of U.S. GHE



U.S. Transportation
Greenhouse Gas (GHG) Emissions by Sector. 2023 (EPA)

Road transportation is the leading source of CO_2 emissions in all transportation sectors.



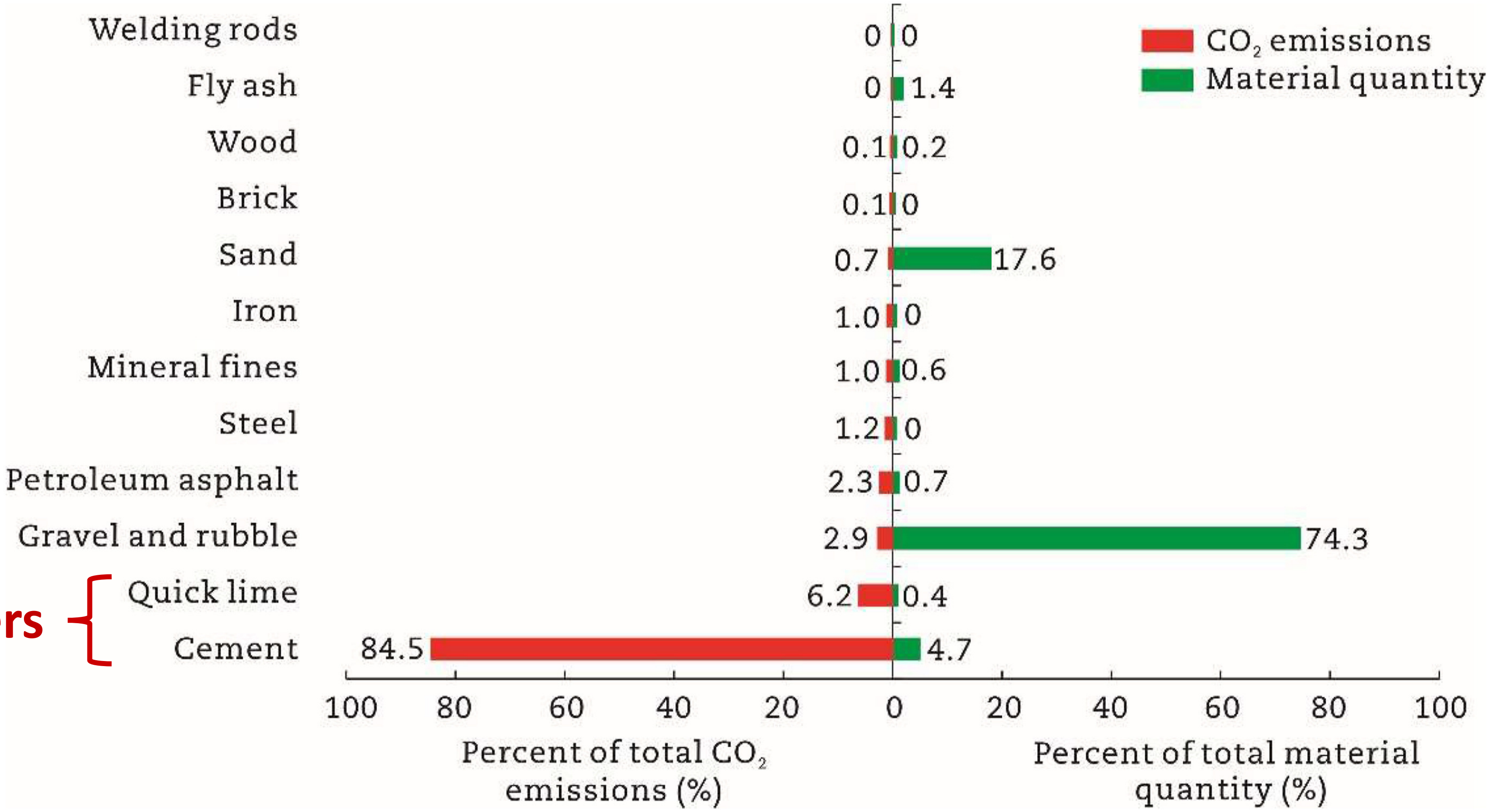
Source: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

01 | Introduction and Research Motivations

Emissions from the **road infrastructure** including *material production and transportation, road construction, and maintenance* make up **5%–25%** of **total CO_2 emissions** from transport (*Liu et al.. 2022*).

Natural Aggregates

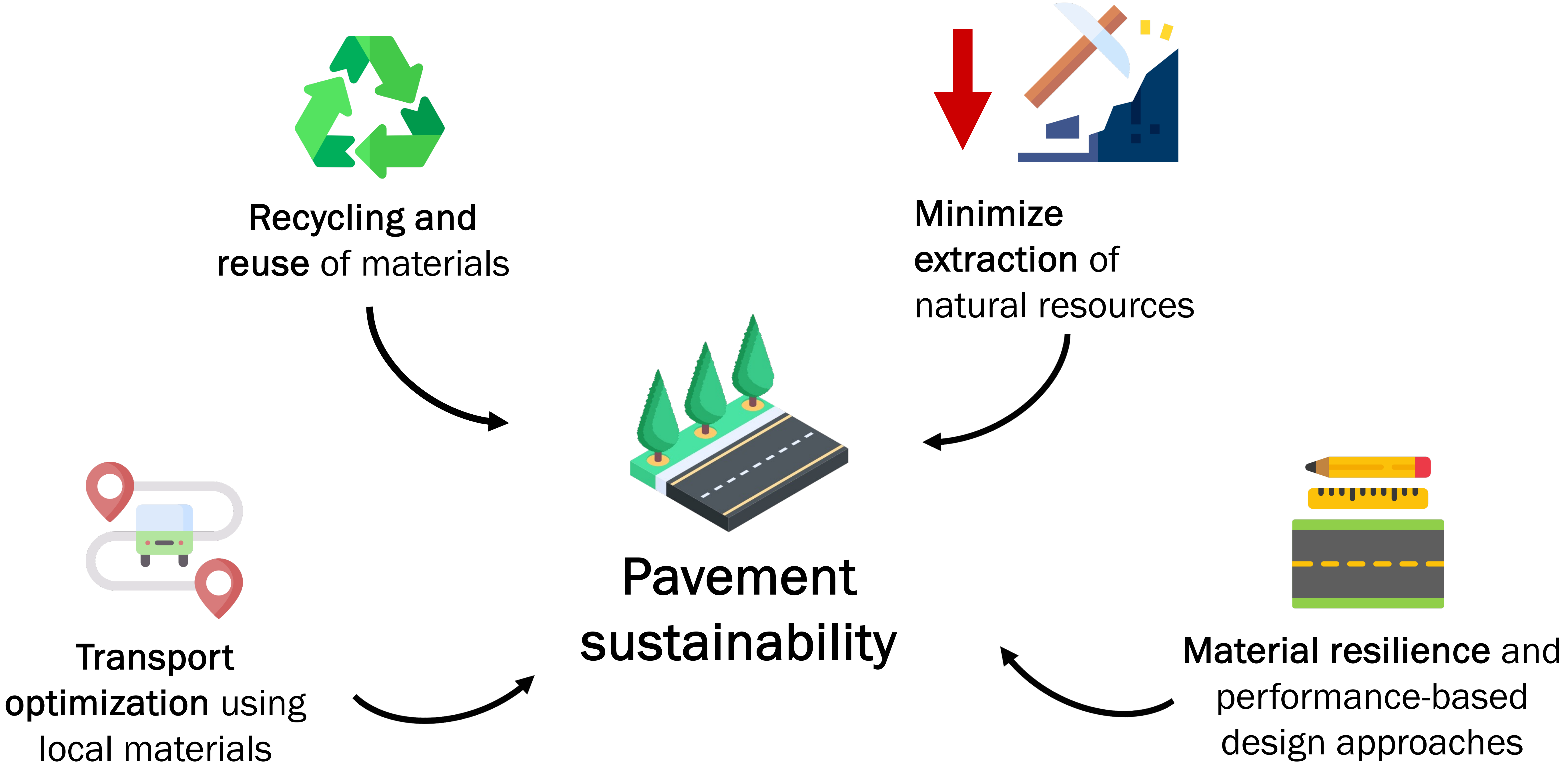
Common Soil Stabilizers



Proportional distribution of materials for the road (Source: Liu et al., 2022).

What are the alternatives to minimize the impacts of roadway material production?

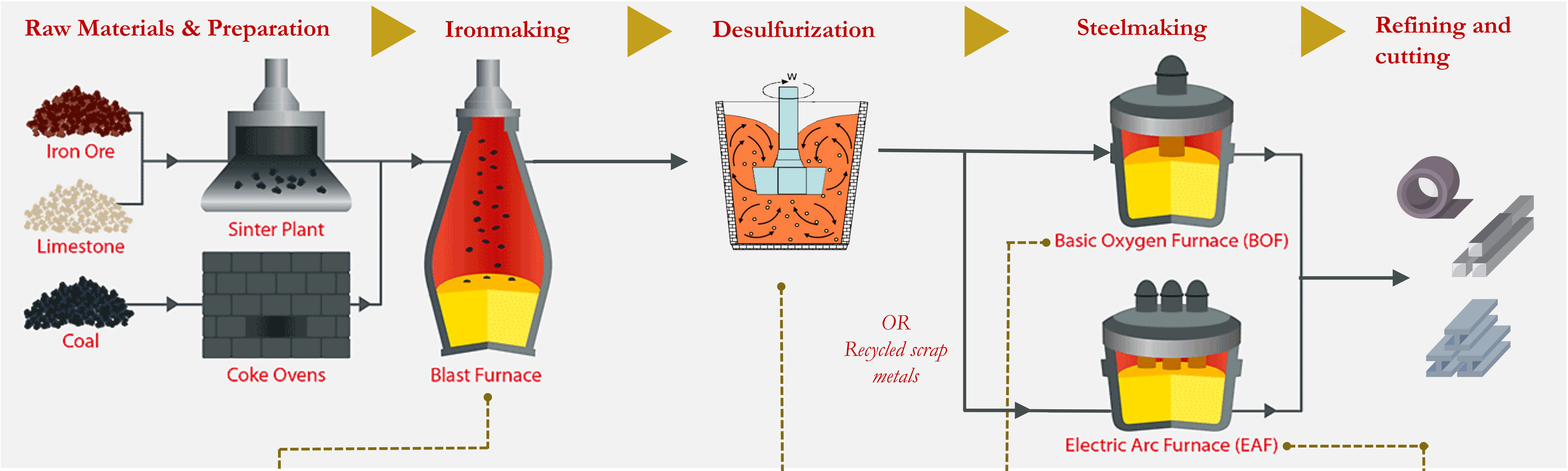
01 | Introduction and Research Motivations



The use of slag for soil stabilization has a great potential to contribute to pavement sustainability

01 | Introduction and Research Motivations

Steel Products



Slag Products

BF Slag	KR Slag	BOF Slag	EAF Slag
200-300kg/ton molten iron	120kg/ton steel	110-160kg/ton steel	40-70kg/ton steel

Common characteristics:

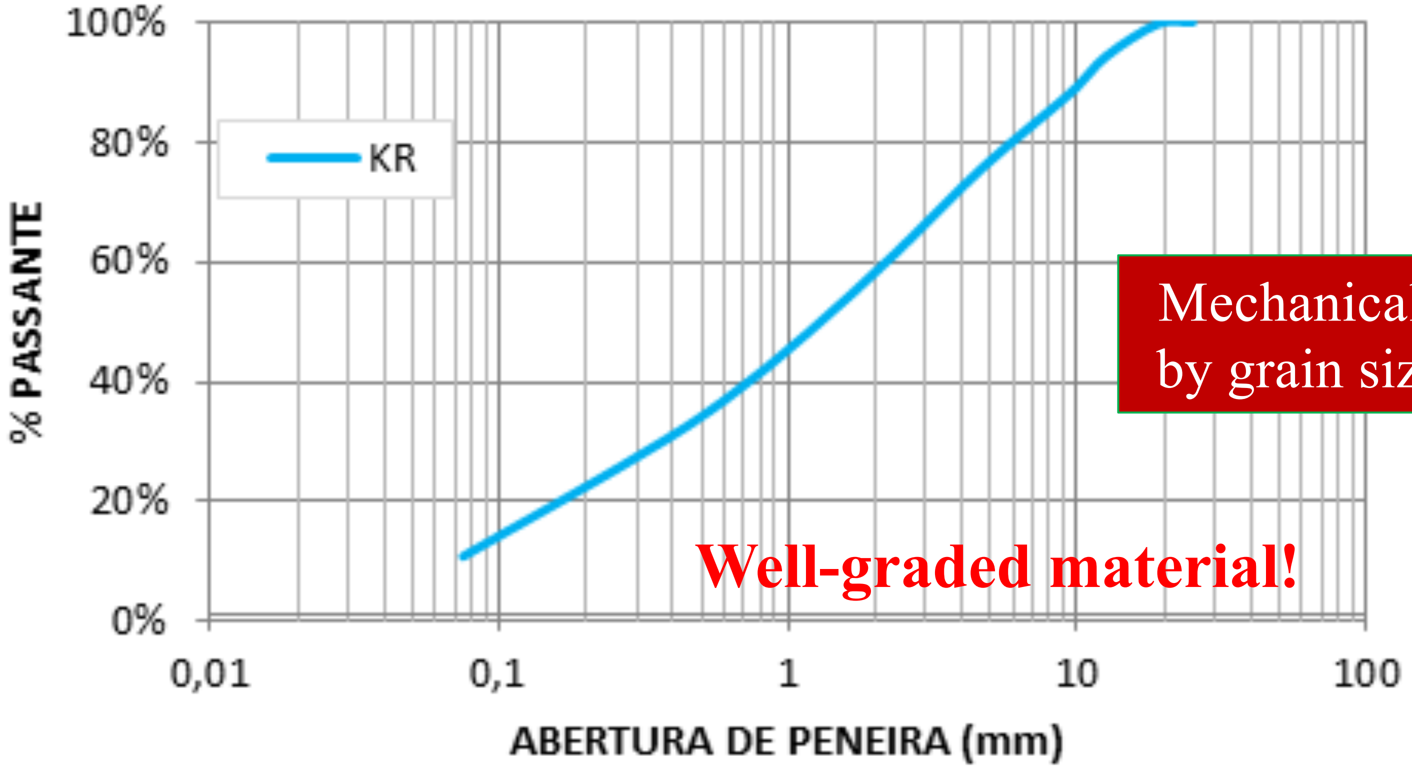
- Solidity
- Abrasion resistance
- High angle of friction
- High strength

Different chemical and thermodynamical properties!

2

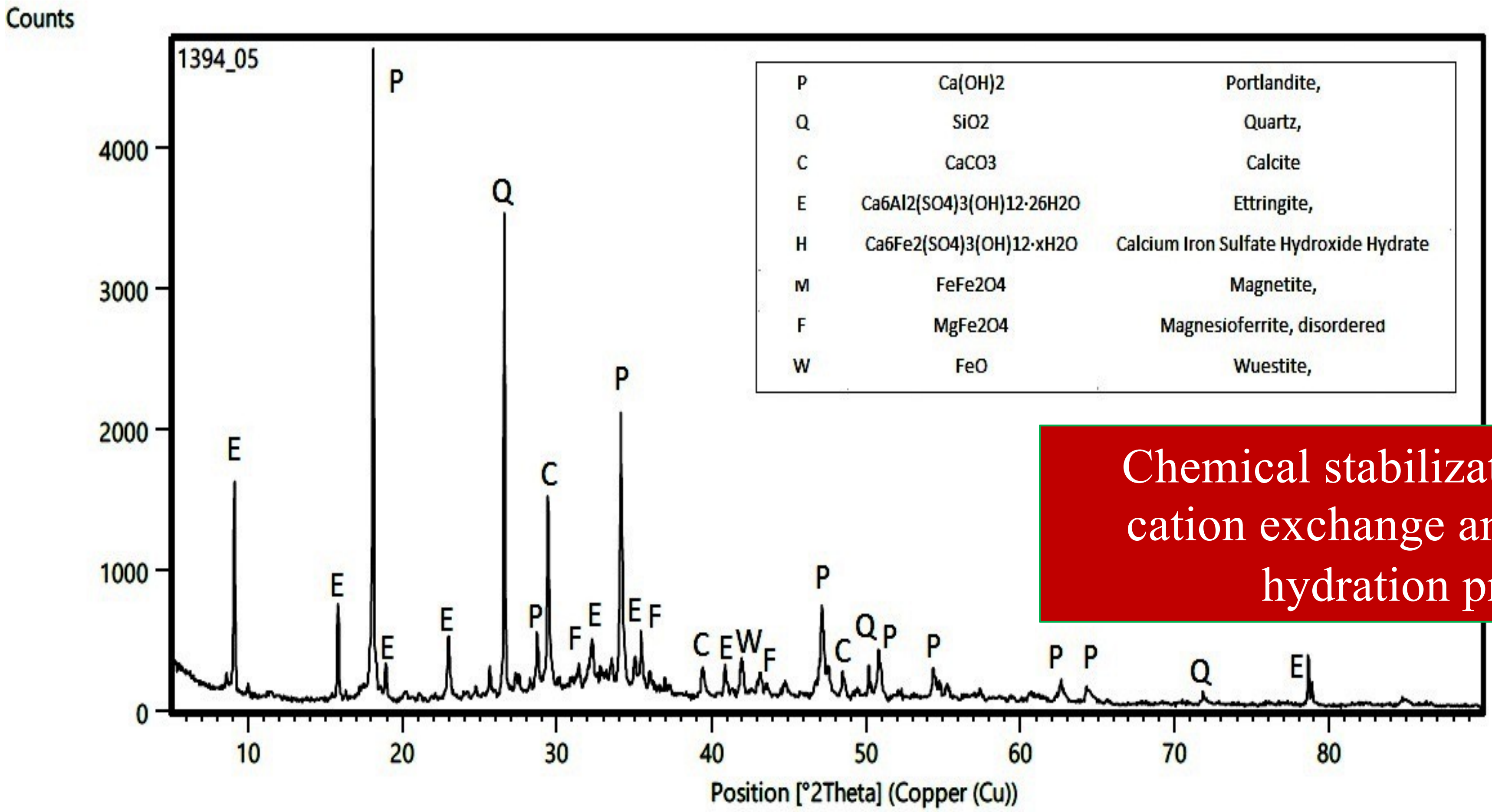
CLAY SOIL STABILIZATION USING KR SLAG

02 | Kr Slag Physical. Chemical and Mineralogical Characteristics



Mechanical stabilization by grain size correction?

Oxide	Content (%)
Na_2O	0.12
MgO	2.70
Al_2O_3	5.10
SiO_2	14.60
P_2O_5	0.51
SO_3	3.80
K_2O	< 0.10
CaO	44.80
TiO_2	0.33
MnO	1.70
Fe_2O_3	26.00
SrO	0.11



Chemical stabilization induced by cation exchange and formation of hydration products?

02 | Soil stabilization with Kr slag

- **KR slag** has chemical and mechanical characteristics that might be suitable for soil stabilization.
- **Sustainable material: Minimize** natural aggregate extraction and/or **emission of CO_2** if used in place of **Lime or Portland Cement!**
- **Economic reasons:** typical chemical stabilization solutions are expensive ($ of commercial binding agents);
- There is **no significant volumetric expansion** in KR.

Laboratory Investigation

- Engineering Properties
- Soil-KR mixes (15-25% KR)
- CBR, CBR Swelling, UCS, RM

Field Performance Assessment

- Trial Sections Design
- APT - HVS simulator
- Cracking, Rut depth, Surface friction

Pires et al. (2019). J. of Mat. in Civil Eng.

02 | Soil stabilization with Kr slag: Trial Sections

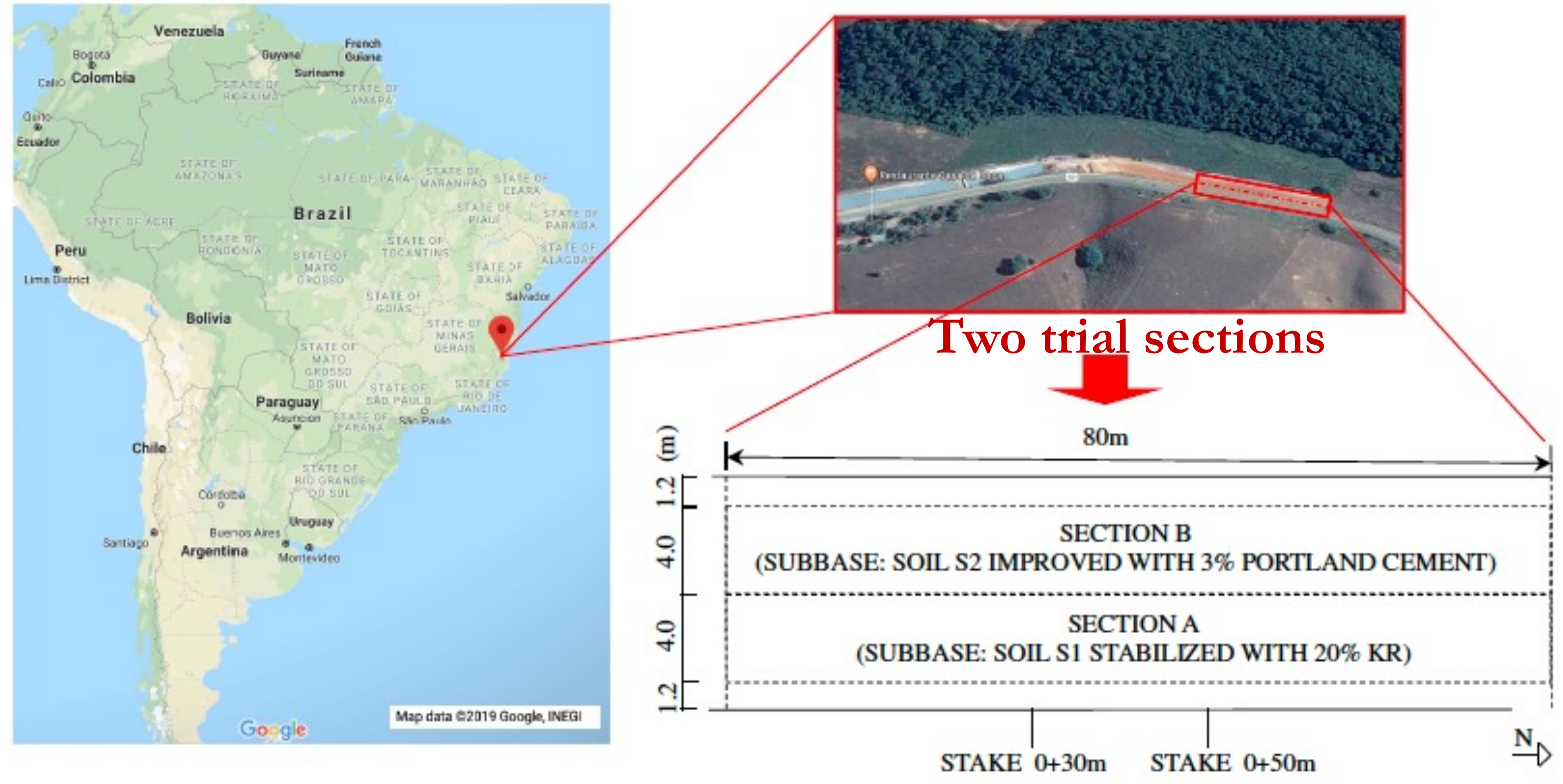


Fig. 4. Location of the pavement experimental sections. (Map data © 2019 Google, INEGI.)

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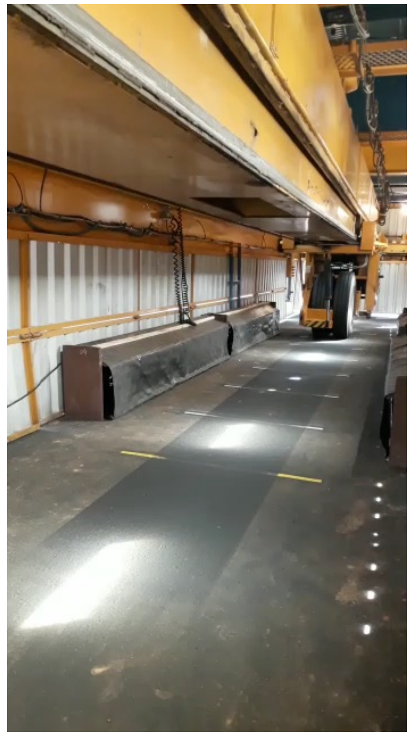
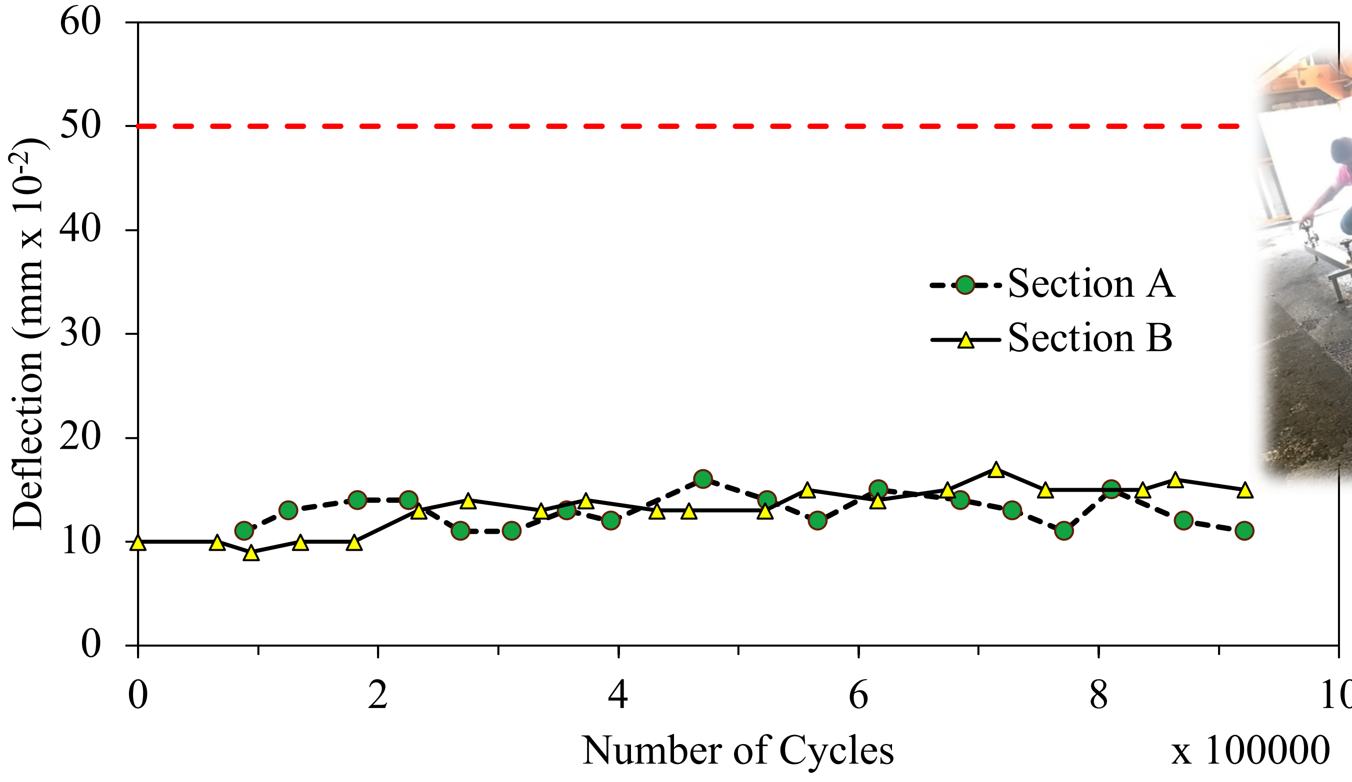




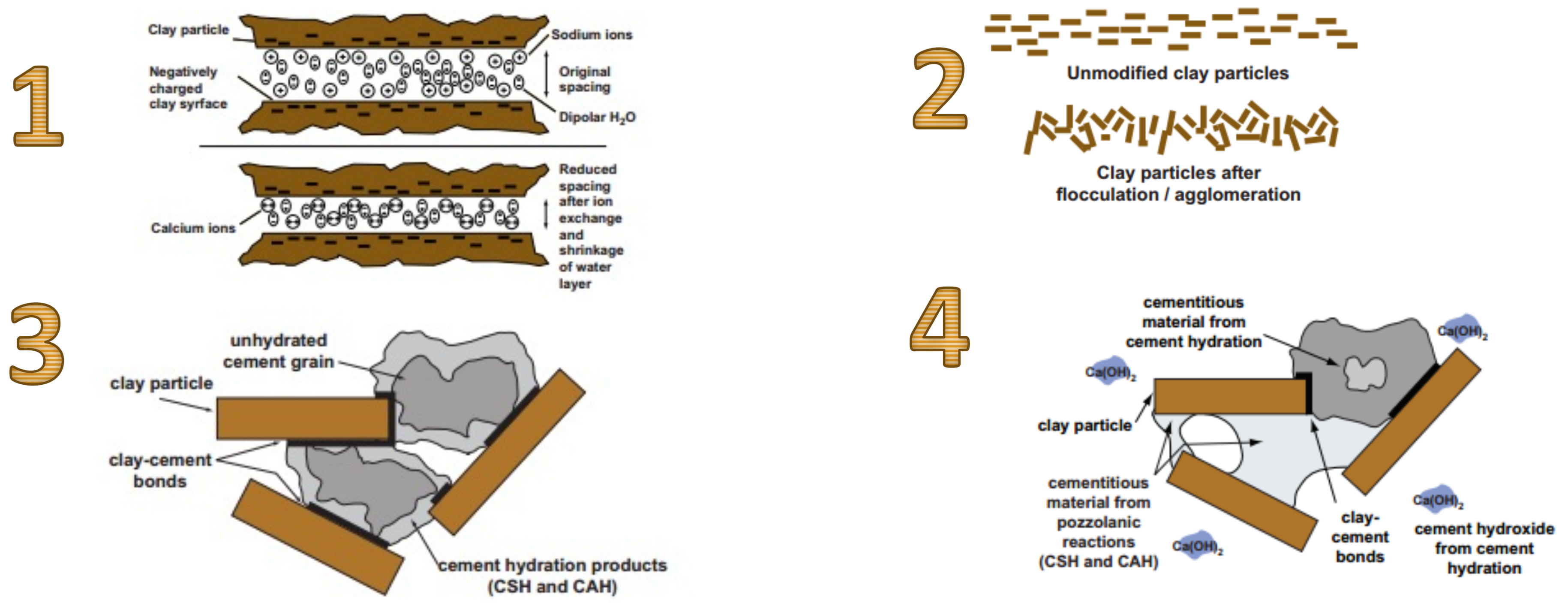
Pires et al. (2019). J. of Mat. in Civil Eng.

02 | Soil stabilization with Kr slag: Plasticity Indices

Soil	Mixture	Unit mass (g/cm3)	Liquid Limit (%)	Plastic Limit (%)	Plasticity index (%)
S1 (A-7-6)	S1	2.65	49.0%	24.8%	24.2%
	S1KR15%	2.73	43.3%	29.5%	13.8%
	S1KR20%	2.74	42.1%	29.8%	12.3%
	S1KR25%	2.76	43.0%	31.7%	11.3%
S2 (A-2-6)	S2	2.65	26.0%	15.1%	11.0%
	S2KR15%	2.73	30.4%	21.4%	9.0%
	S2KR20%	2.75	30.5%	23.4%	7.1%
	S2KR25%	2.73	32.4%	22.8%	9.6%

KR slag mechanisms?

Cement-modified Soil Mechanisms =>



Source: Guide to Cement-Modified Soil (CMS), PCA

Pires et al. (2019). J. of Mat. in Civil Eng.

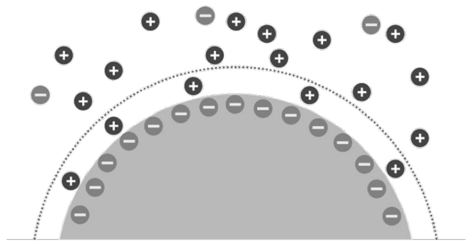
02 | Soil stabilization with Kr slag: Main Stabilization Mechanisms?

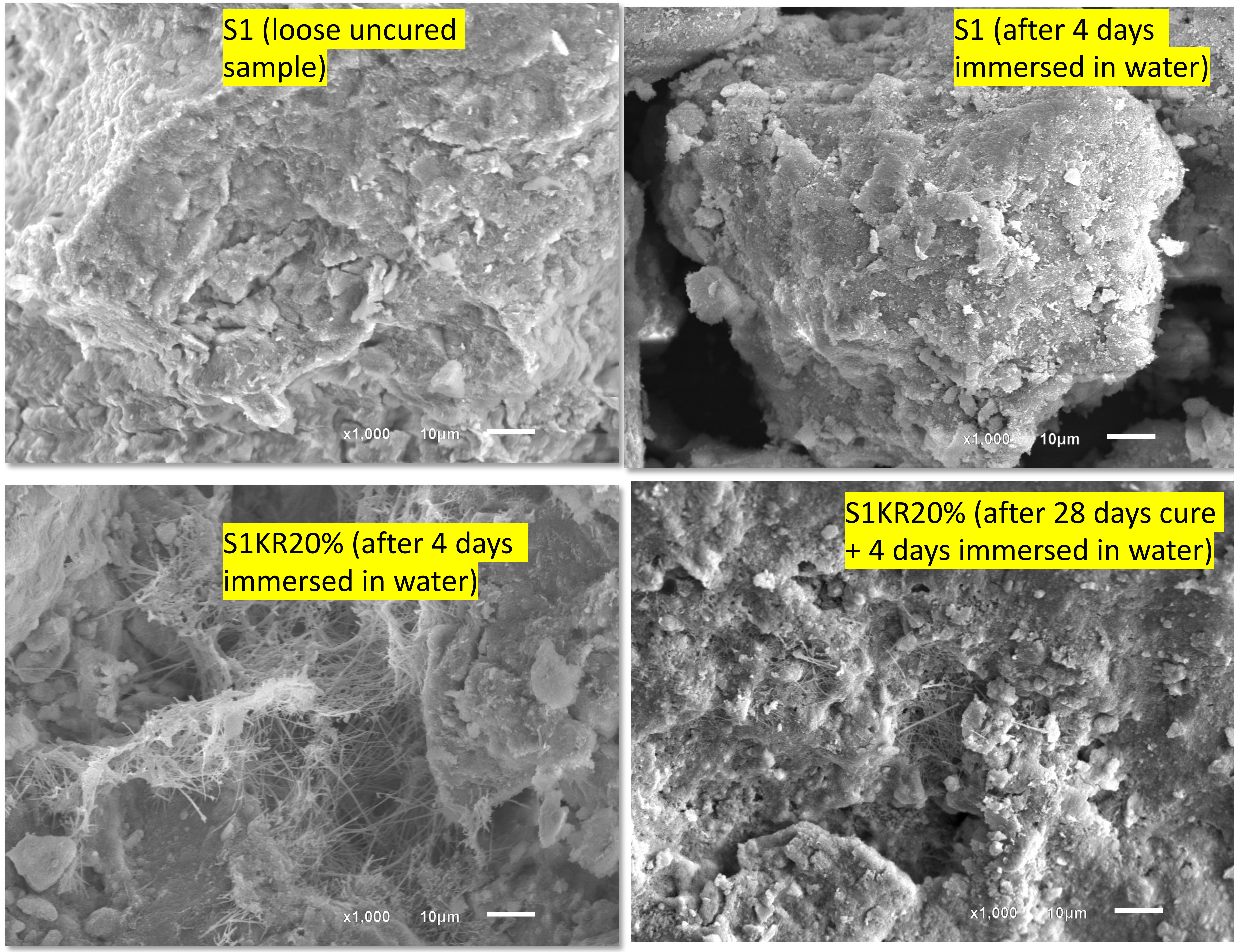
Cation Exchange Capacity (CEC)

	KR	PC	HL
Total Cation Exchange Capacity (pH 7.0) ($cmol_c/dm^3$)	47.1	63.7	61.3
Saturation Index Ca^{2+} (%)	99.3	99.0	97.8
Saturation Index Mg^{2+} (%)	0.2	0.2	0.2
Saturation Index K^{+} (%)	0.5	0.8	2.1
Saturation Index Na^{+} (%)	4.2	1.3	0.2
Base Saturation Index (%)	100	100	100
pH	12.2	12.4	12.4

- KR slag presents an expressive **total cation exchange capacity (CEC)** value, similar to Portland cement and hydrated lime.

- **Contribution of the Ca^{2+} cation is more predominant.**





The presence of **fibrillar** or **needle-shaped structures** at early ages can be attributed to the **formation of C-S-H (**calcium silicate hydrate)**.**

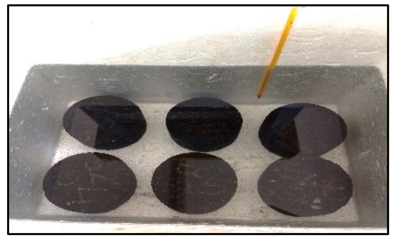
*Bastos. **Bridi.** Teixeira. and Pires. TRB 2024.*

3

ASPHALT BINDER-SLAG ADHESION: BLAST FURNACE SLAG *VS* STEEL FURNACE SLAG

03 | Blast Furnace Slag Vs Steel Furnace Slag

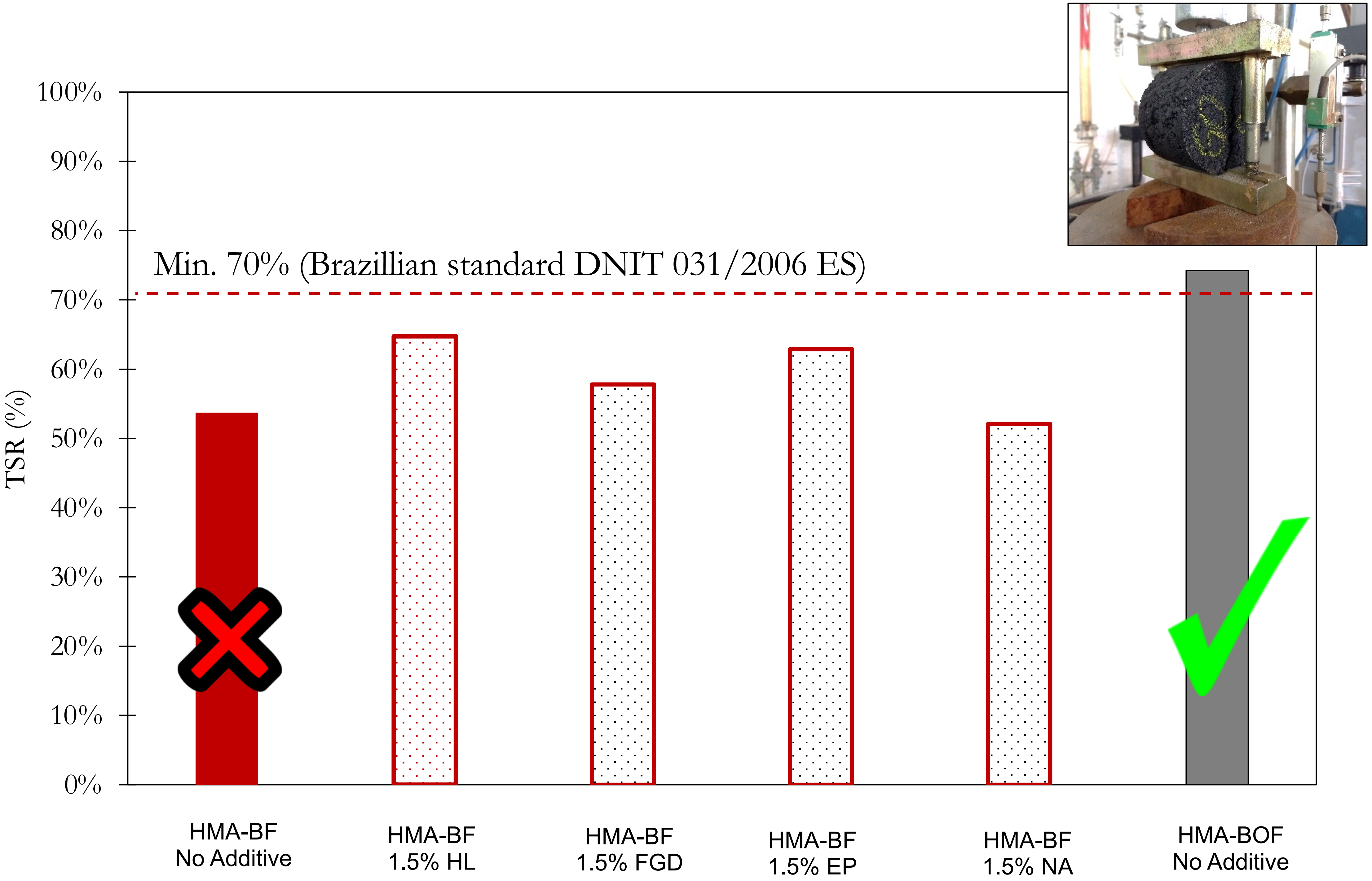
Boiling Test Visual Observation



AASHTO T-283, TSR values:

HMA_0%Slag= 53% ✗
HMA_25% BF = 54% ✗
HMA_25% BOF = 74% ✓

03 | Blast Furnace Slag Vs Steel Furnace Slag: HMA Results



Moura et al. (2020). Construction and Building Materials

03 | Evaluation of Binder-Slag Adhesion

(AC)BF slag

BOF Steel Slag

Physical

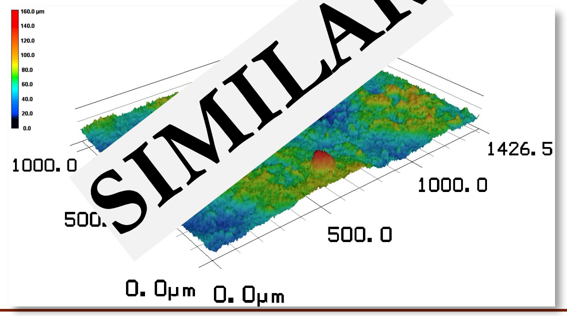
Aggregate Image Analysis (AI

T... angularity

SIMILAR

Laser Scanning Microscopy (LSM)

Rugosity



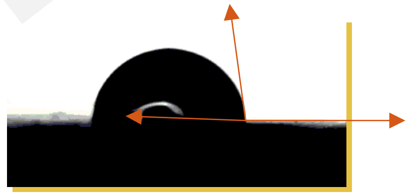
SIMILAR

Thermodynamical

Surface Free Energy (SF

S... tact Angle

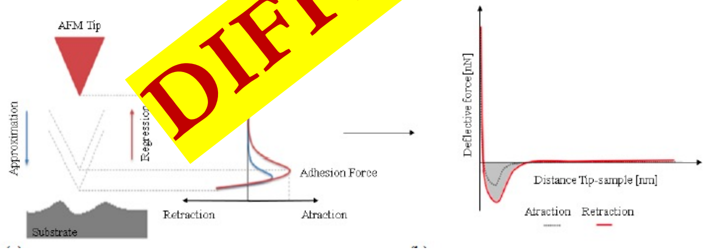
SIMILAR



Atomic Force Microscopy (AFM)

Work o... on

DIFFERENT



Chemical

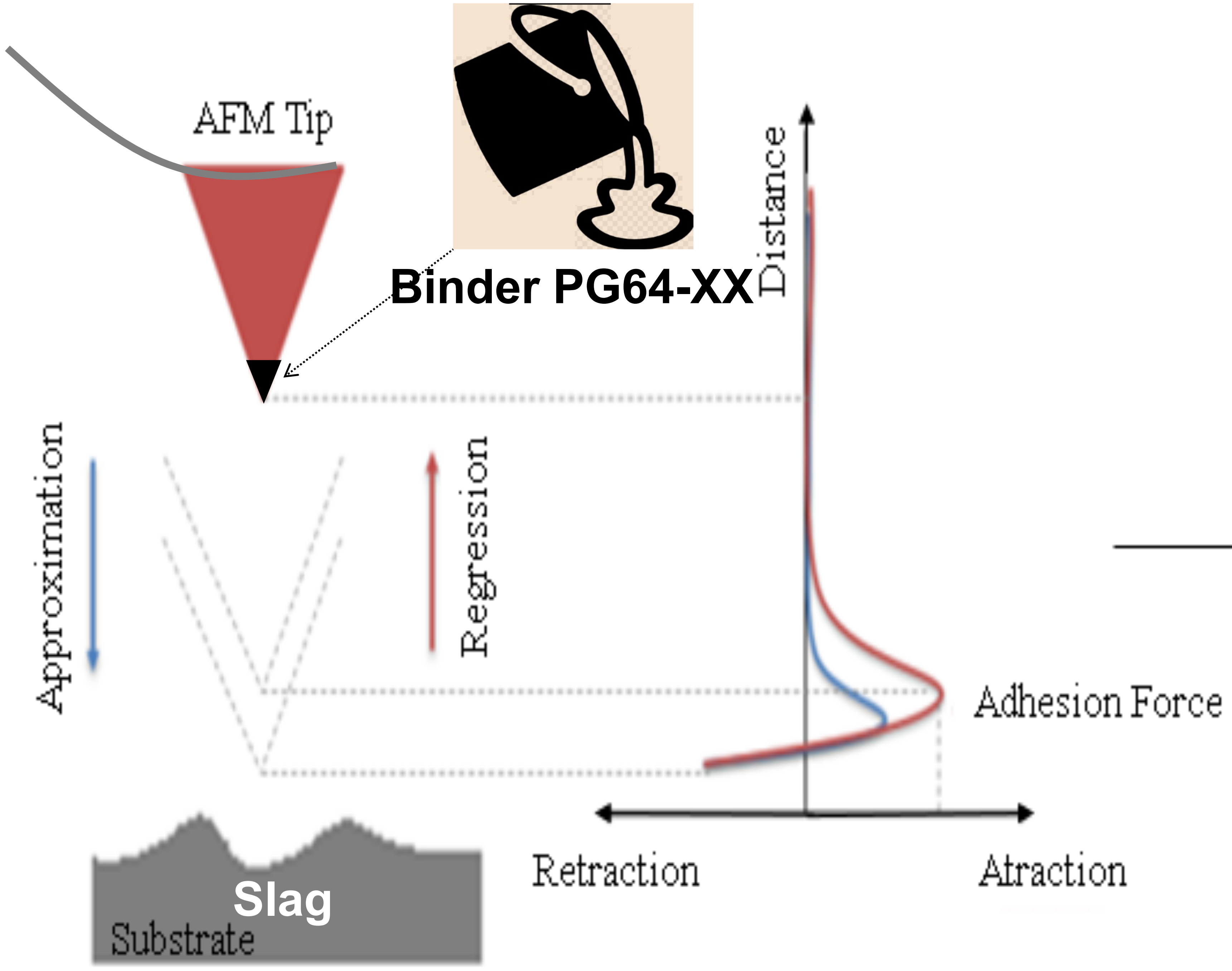
X-ray fluorescence (XRF)

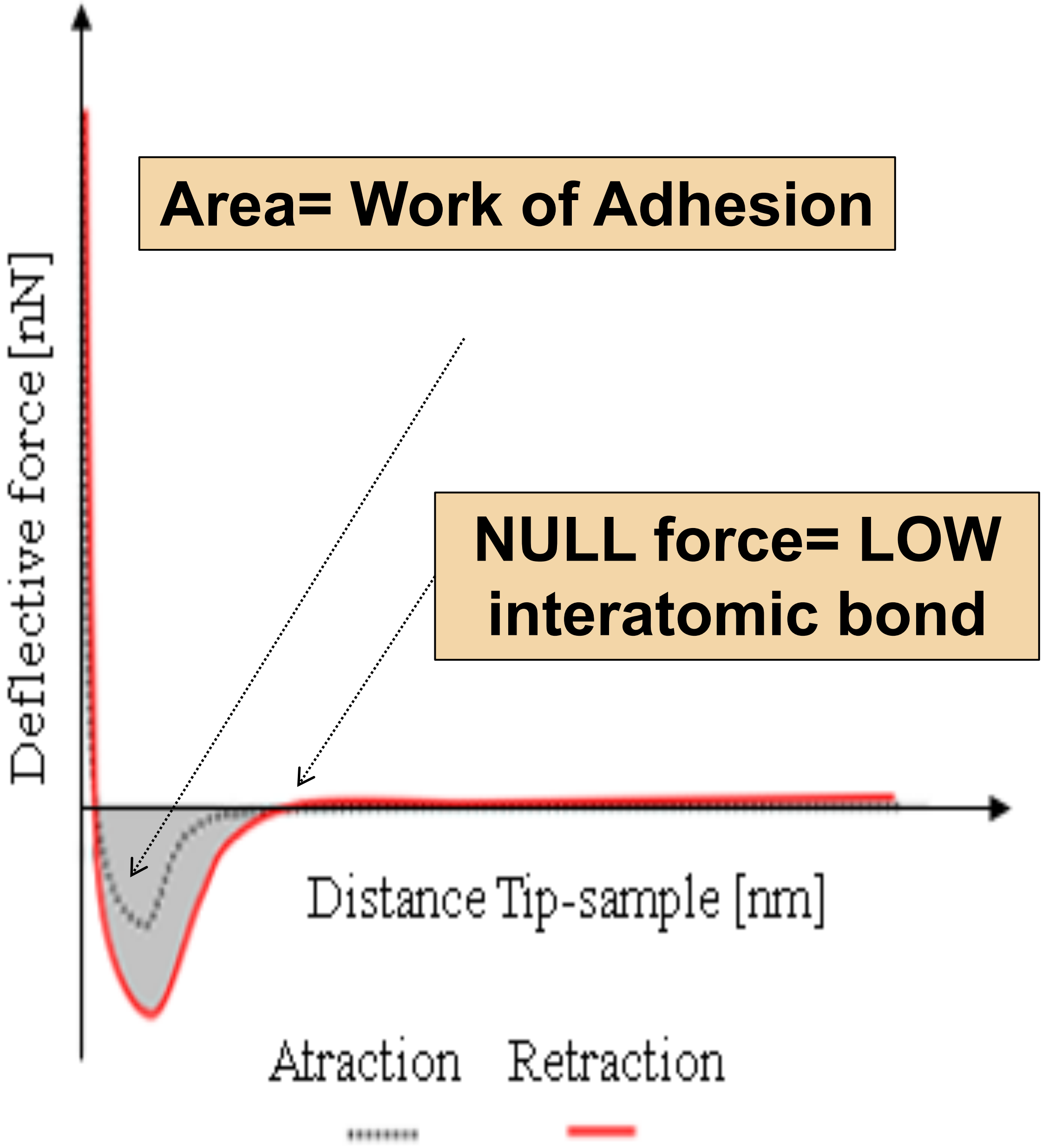
Chemical Composition

DIFFERENT

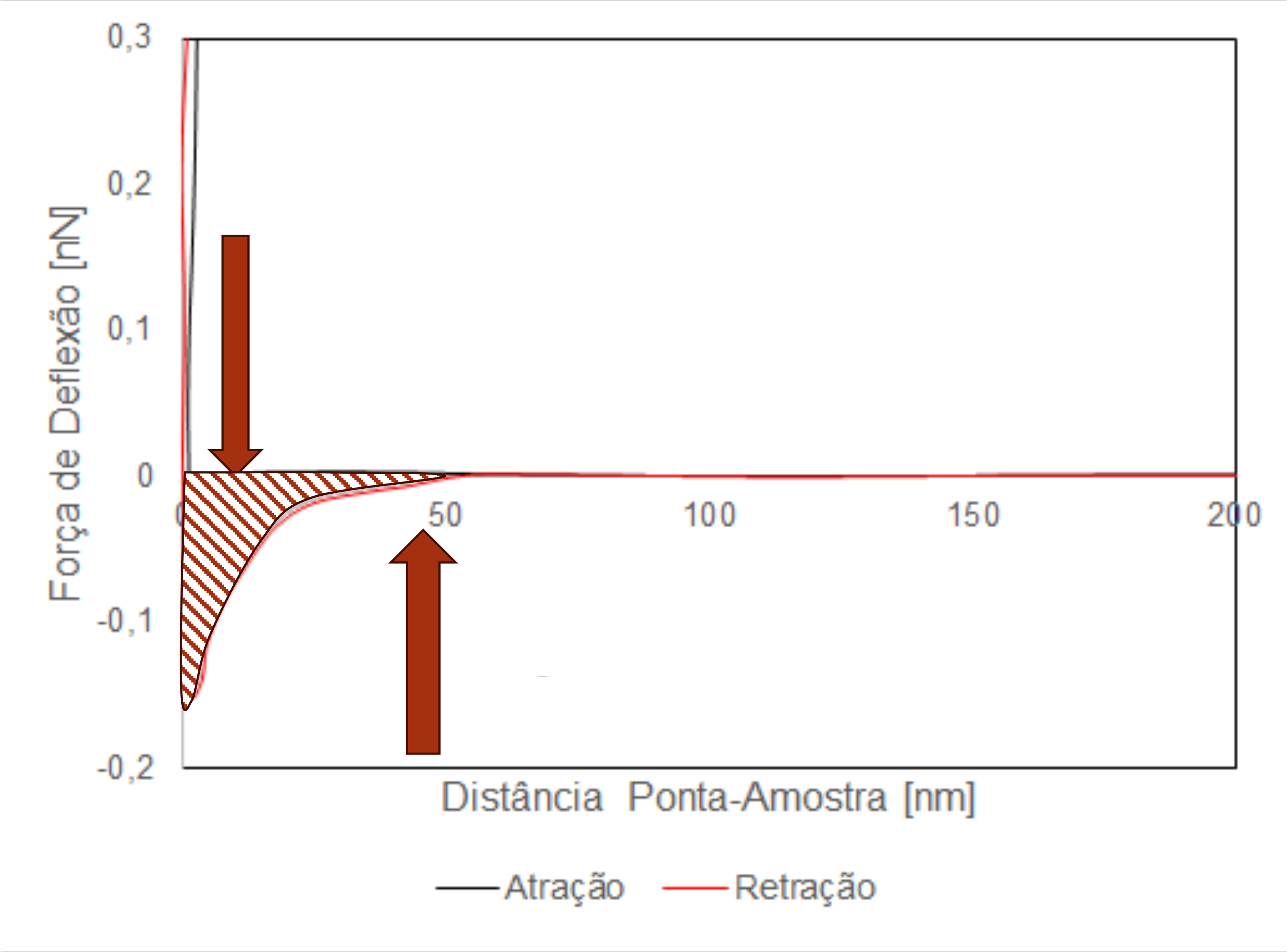
Moura et al. (2020). Construction and Building Materials

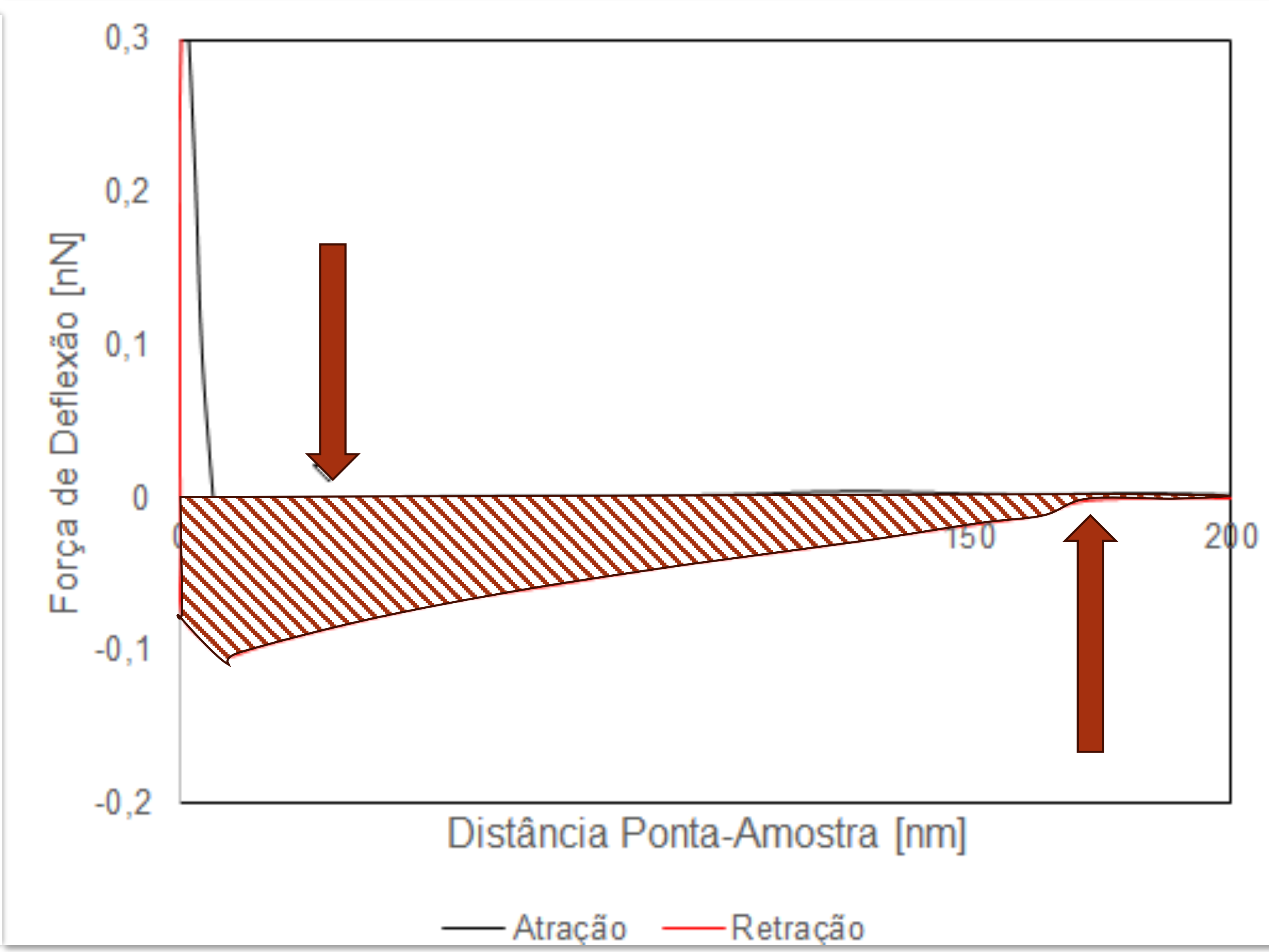
03 | Evaluation of Binder-Slag Adhesion: AFM





03 | Evaluation of Binder-Slag Adhesion: AFM





- Interatomic forces start earlier in the BOF-Binder system than in the BF-Binder systems.
- Interatomic forces last longer in the BOF-Binder system than in the BF-Binder systems.
- The work of adhesion is higher in the BOF-Binder system.

03 | Evaluation of Binder-Slag Adhesion: XRF

Oxides	ACBFS (%)	LD (%)
Na_2O	0.28	0.17
MgO	5.2	5
Al_2O_3	9.3	4.9
SiO_2	32.4	12.7
P_2O_5	0.1	1.3
SO_3	4.5	0.16
K_2O	0.32	<0.1
CaO	41.2	43.4
TiO_2	0.49	0.36
MnO	0.55	3.2
Fe_2O_3	2.7	26.4
SrO	0.11	0.1

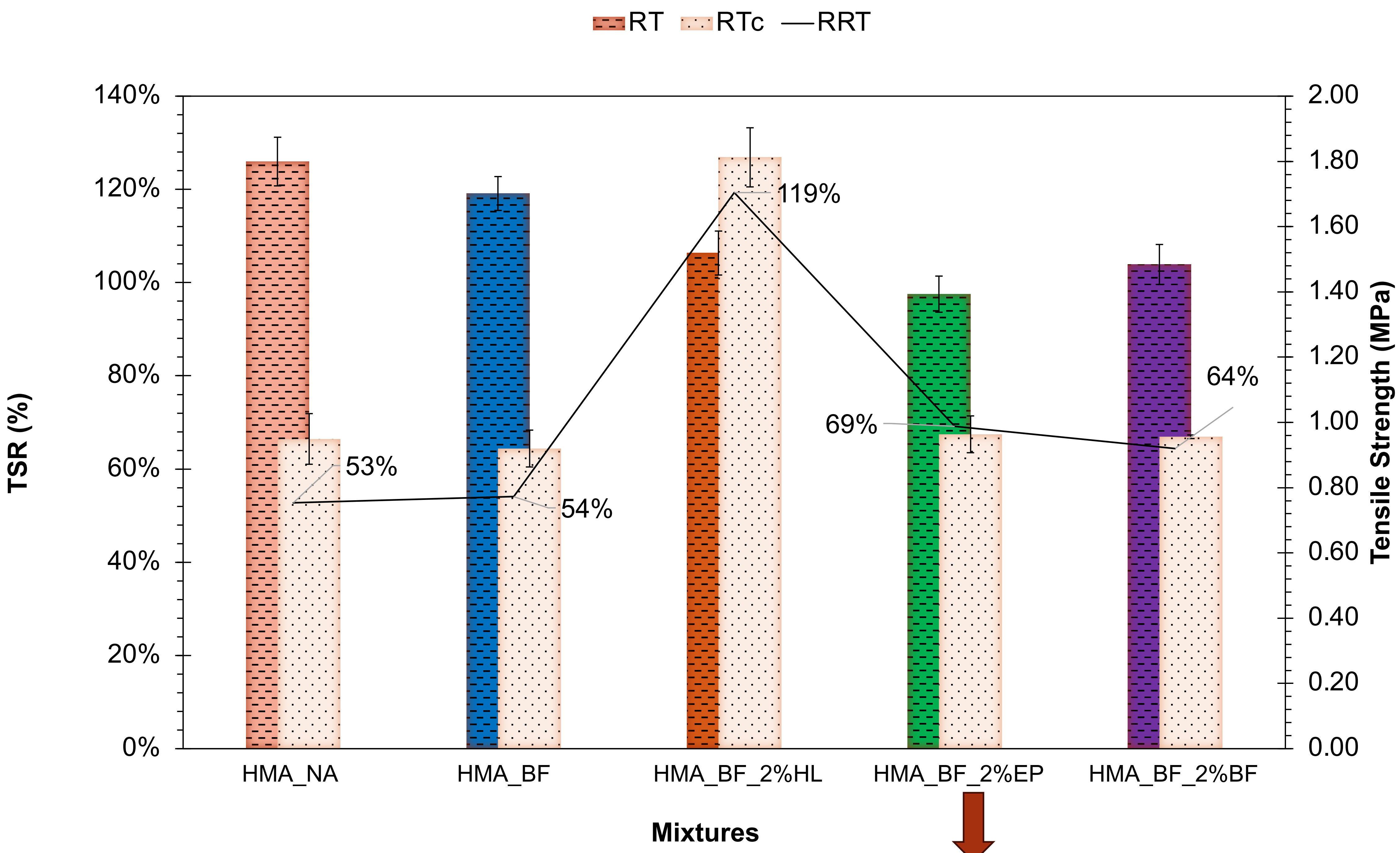
SILICA: ↑ BF ↓ BOF

High %**Ca** on both SSA

IRON: ↓ BF ↑ BOF

Moura et al. (2020). Construction and Building Materials

03 | HMA with 25% BF Slag + 2% Additives



EP (steel by product)	
Fe_2O_3	62.94%

Frossard et al. (2022). Transp. Research Record

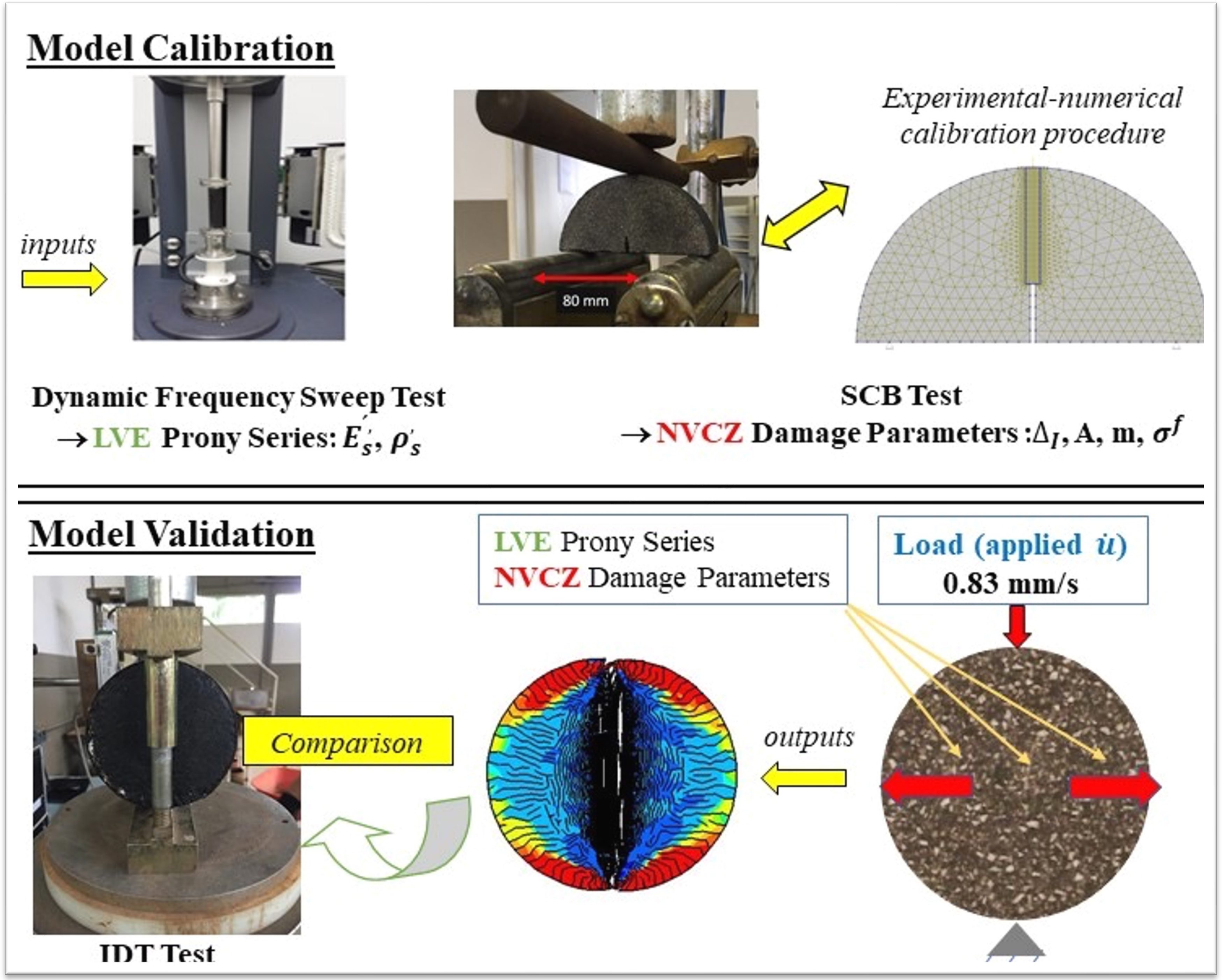
4

ASPHALT CONCRETE CONTAINING SLAGS AND ITS FRACTURE RESISTANCE

04 | Fracture Resistance Assessement using Numerical Modeling

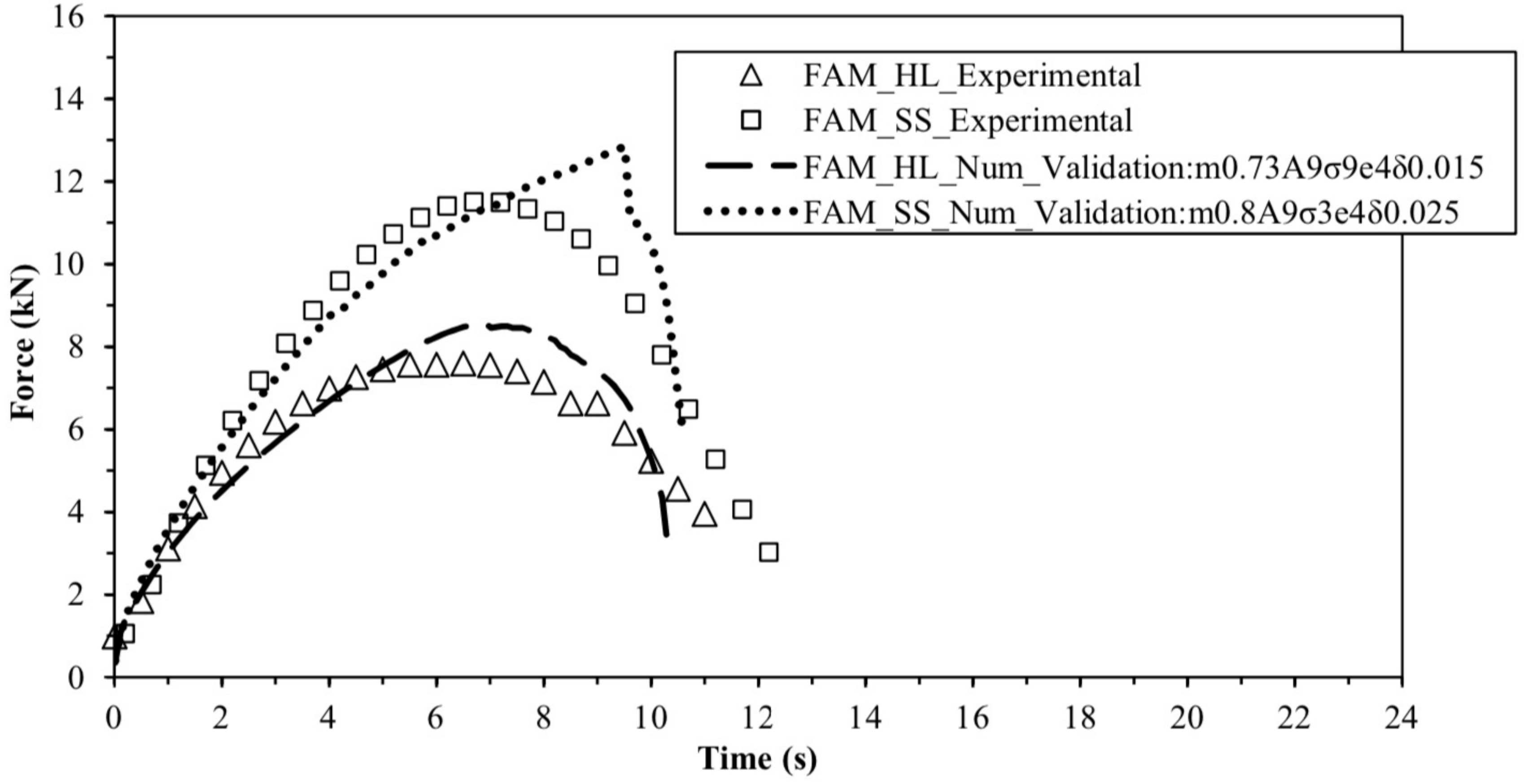
Does the type of filler (slag vs. HL) influence the ***rate of crack initiation and propagation***?

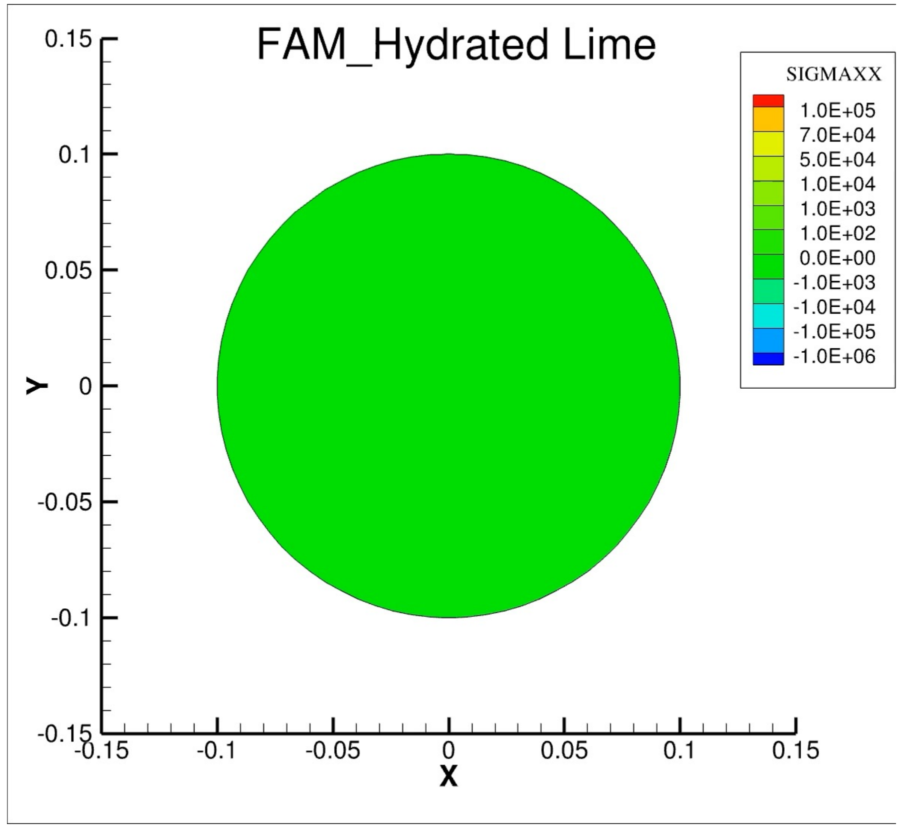
What parameters and laboratory tests are required as ***input*** to allow the use of numerical Nonlinear Viscoelastic Cohesive Zone Model NVCZ?

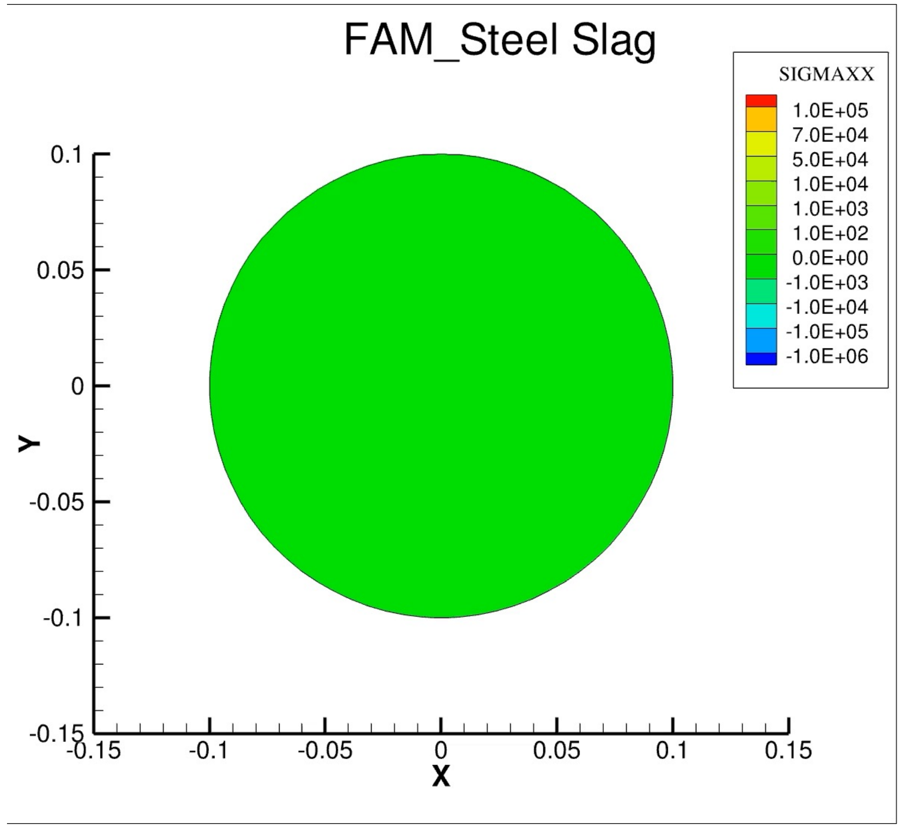


Rodrigues et al. (2019). Construction and Building Materials

04 | Fracture Resistance Assessement using Numerical Modeling



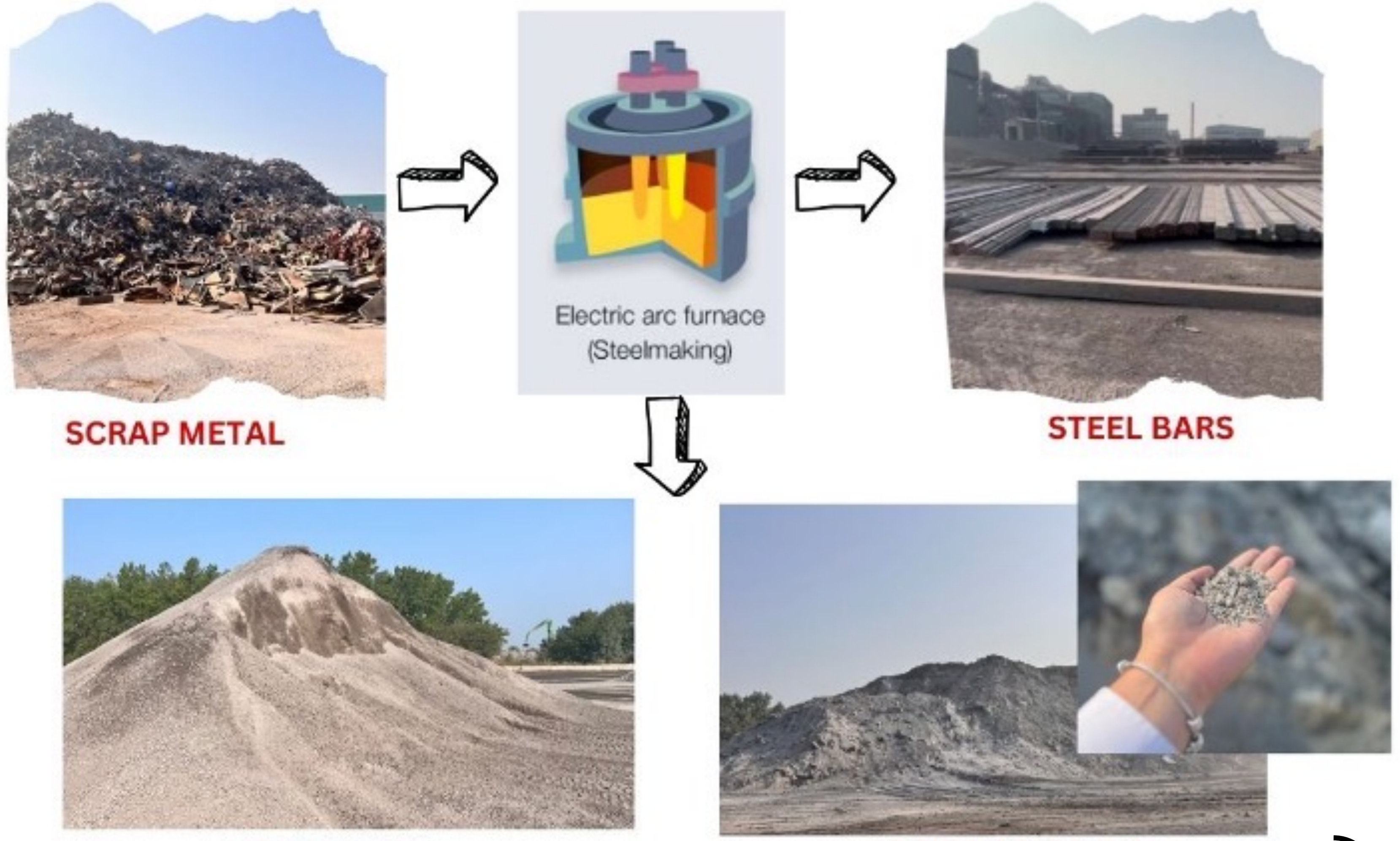




5

What comes next? Nebraska UNL Research on Slag

05 | EAF in Nebraska



EAF SLAG

- Sizes ranging 0 to 25mm
- Availability at Norfolk-NE: Approx. 100,000 tons/year

CASTER SLAG

- fine material <0.15mm
- Availability: each ton of EAF generates about 10% of caster slag

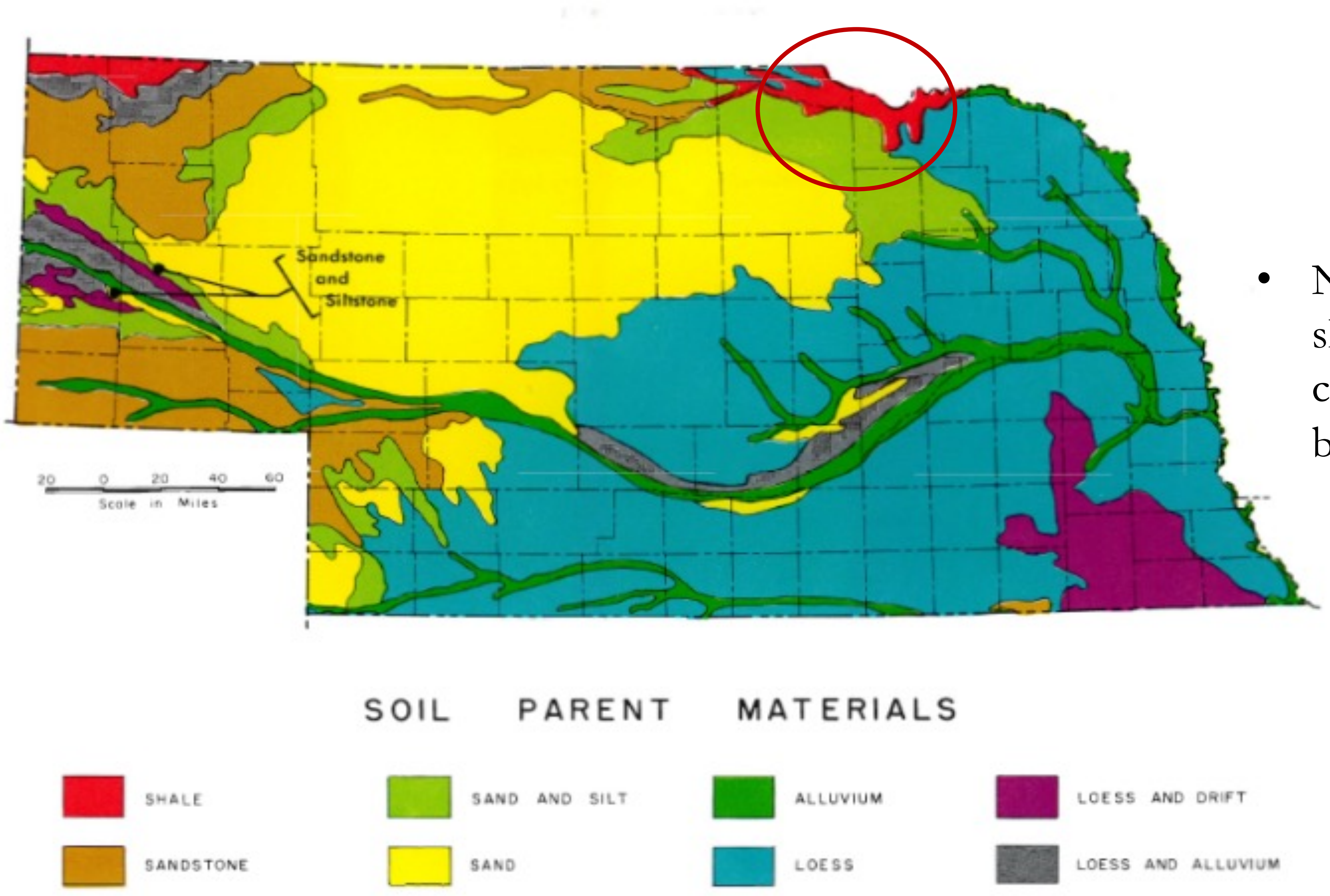
! Current disposal at landfills (no value)

Preliminary site visit at **Norfolk-NE**

NEBRASKA Good Life. Great Resources. Department of Environment and Energy — Air, Water, Land, Energy

In NE, slag is **not** considered a solid waste. According to Nebraska Department of Environment and Energy: "008.23 Slag, a **product** that is a result of the steel manufacturing process and is managed as an item of value in a controlled manner and not as a discarded material."

05 | EAF in Nebraska



- Northeastern Nebraska presents shale soil (Niobrara). This type of clay soil has high plasticity and low bearing capacity.

05 | EAF in Nebraska: Research Questions

Currently, there is no specification to apply Electric Arc Furnace (EAF) slag in Nebraska. The NDOT allows the use of other calcium-rich stabilizers, such as **fly ash, lime, or Portland cement**. Due to its local availability and expected physical-chemical properties, EAF slag can be an alternative for soil stabilization in Nebraska. However, NDOT has several questions that we aim to address:

- **What are the main recommendations and state-of-practice of EAF slag as a paving material in the US?**
- **What are the physical, chemical, mineralogical, and morphological characteristics of the two locally (Nebraska Steel Industry) generated EAF slags?**
- **Do the slag characteristics varies much depending on the slag batch sample?**
- **Is the leaching of hazardous heavy metals a concern when using these materials for stabilizing NE clay soils?**
- **What is the optimum combination of slag (EAF and Caster/Ladle slag) with clay soils + other additives that leads to a stabilized material for pavement application?**
- **What happen when Soil-Slag material is subject to freezing/thawing cycles?**
- **What happen when Soil-Slag material is subject to dynamic (cyclic load)?**
- **What is the environmental impact - conduct Life Cycle Assessment (LCA) to evaluate the environmental impacts associated with all stages of a product's life?**

Other medias:

- **Use of EAF for asphalt? And at Gopolymer applications?**

6

CONCLUDING REMARKS

TAKEAWAYS

- ✓ The results obtained herein confirms the technical feasibility of using steel slag aggregates.
- ✓ It's important to understand the physical. chemical. and mineralogical characteristics of each coproduct to ensure the efficiency of its use.
- ✓ KR slag appears to be a promising alternative for soil stabilization (CEC+hydration products observed).
- ✓ Steel (BOF) and blast furnace (BF) slags seem to be alternative aggregates for asphalt mixtures. Good bonding of BOF with asphalt binder can be attributed to its chemical composition as well as its thermodynamical properties.
- ✓ The use of adhesion modifiers can make the use of BF viable.

The UNL research team on Infrastructure and Pavement materials is interested in delving into the studies of alternative materials and obtaining sustainable and resilient pavement solutions. We are researching other types of slags (EAF, Norfolk-NE), as well as other potential solutions for infrastructure application (waste plastics, RAP, vegetable oils, RCA, GRT, etc).

UNL/COLLEGE OF ENGINEERING: ENGINEERING RESEARCH CENTER

CEE RHEOLOGY AND MATERIALS LAB

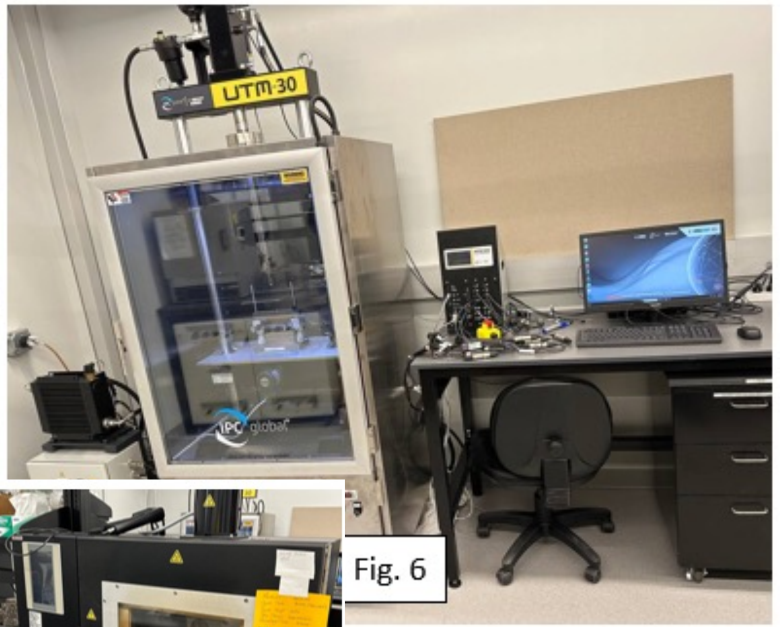


Fig. 6

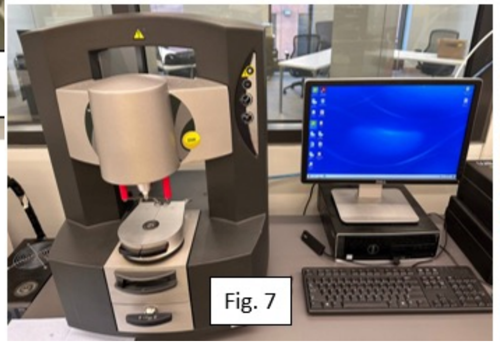


Fig. 7

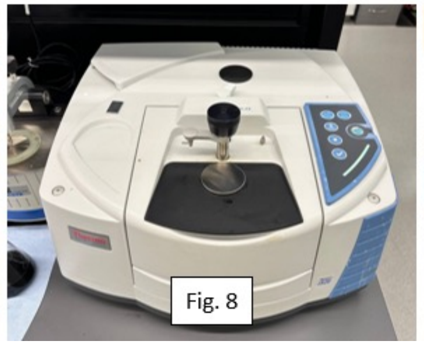


Fig. 8

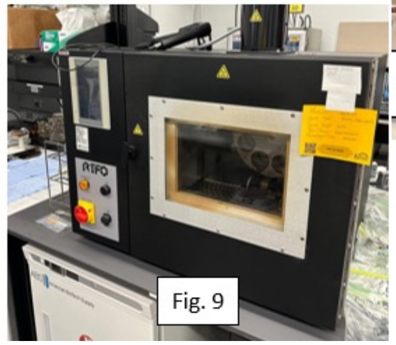


Fig. 9

OF ENGINEERING

Acknowledgements

- Special contributions from Prof. Patricio Pires and graduate students from Geotechnical Lab at UFES/PPGEC/Brazil.

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Towards Sustainable Pavement Construction Practice

Thank You!
Any question or comment?

DR. TEIXEIRA'S PUBLISHED PAPERS ON SLAG

- R. M., Frossard, **J. E. S. L. Teixeira**, Y. Kim. (2022). "Effects of Aggregate's and Filler's Characteristics on the SCB Fracture Parameters Obtained from Asphalt Concrete Subject to Moisture Damage." Transportation Research Record, DOI: 10.1177/03611981221093329.
- S. Izoton, **J. E. S. L. Teixeira**, P. J. M. Pires, V. S. Dias. (2021). " Evaluation of the effects of LD slag expansion on the mechanical behavior of asphalt mixtures subjected to aging and moisture damage."(in portuguese). Transportes (Rio de Janeiro), v. 29, DOI: 10.14295/transportes.v29i2.2442
- B. L. R. Moura, **J. E. S. L. Teixeira**, R. A. Simao, M. Khedmati, Y. Kim, P. J. M. Pires. (2020). "Adhesion between steel slag aggregates and bituminous binder based on surface characteristics and mixture moisture resistance." Construction and Building Materials, v. 264, p. 120685, DOI: 10.1016/j.conbuildmat.2020.120685
- J. A. Rodrigues, **J. E. S. L. Teixeira**, Y. Kim, D. N. Little, F. V. Souza. (2019). "Crack modeling of bituminous materials using extrinsic nonlinear viscoelastic cohesive zone (NVCZ) model." Construction and Building Materials, v. 204, p. 520-529, DOI: 10.1016/j.conbuildmat.2019.01.215
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- P. J. M. Pires, **J. E. S. L. Teixeira**, D. V. Nepomuceno, E. C. Furieri. (2019). "Laboratory and Field Evaluation of KR Slag-Stabilized Soil for Paving Applications." Journal of Materials in Civil Engineering, v.31, Issue 9, DOI: 10.1061/(ASCE)MT.1943-5533.0002811
- J. F. Fonseca, **J. E. S. L. Teixeira**, V. T. F. Castelo Branco, Y. Kim. (2019). "Evaluation of Effects of Filler By-Products on Fine Aggregate Matrix Viscoelasticity and Fatigue-Fracture Characteristics." Journal of Materials in Civil Engineering, v. 31, Issue 10, DOI: 10.1061/(ASCE)MT.1943-5533.0002891
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- J. L. Calmon, F. A. Tristao, M. Giacometti, M. Meneguelli, M. Moratti, **J. E. S. L. Teixeira**. (2013). "Effects of BOF steel slag and other cementitious materials on the rheological properties of self-compacting cement pastes." Construction and Building Materials, v. 40, p. 1046-1053, DOI: 10.1016/j.conbuildmat.2012.11.039