Innovative Materials and Advanced Technologies for a Sustainable Pavement Infrastructure

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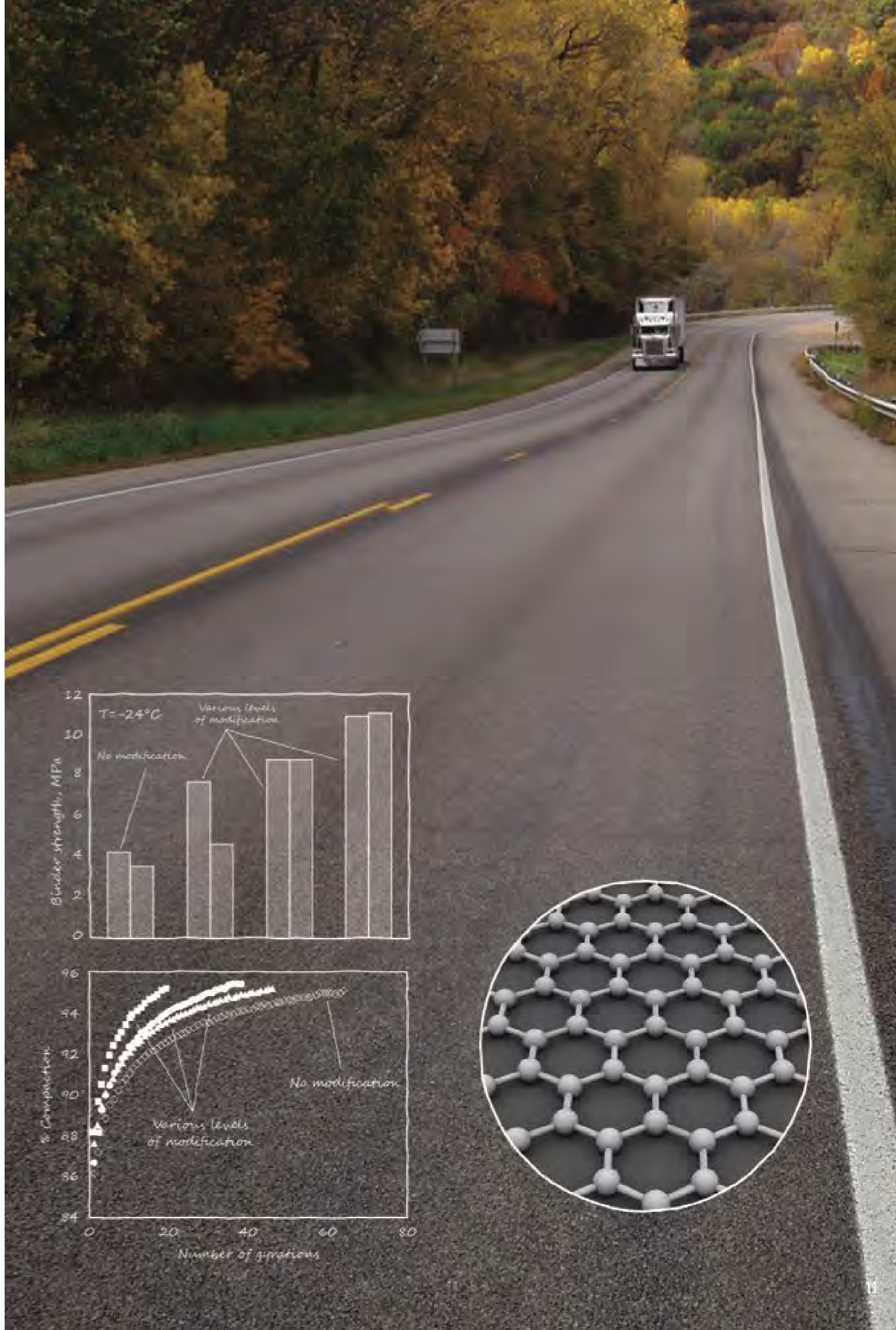
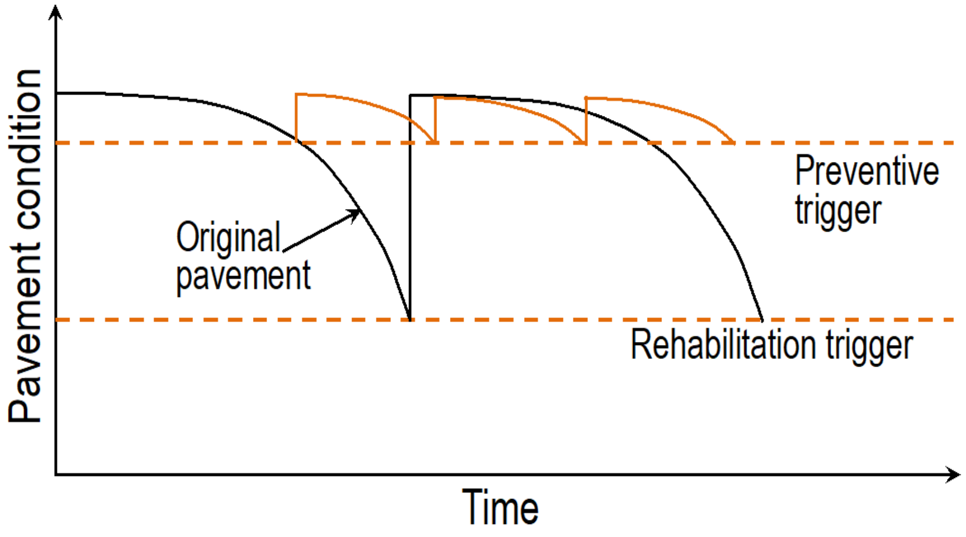
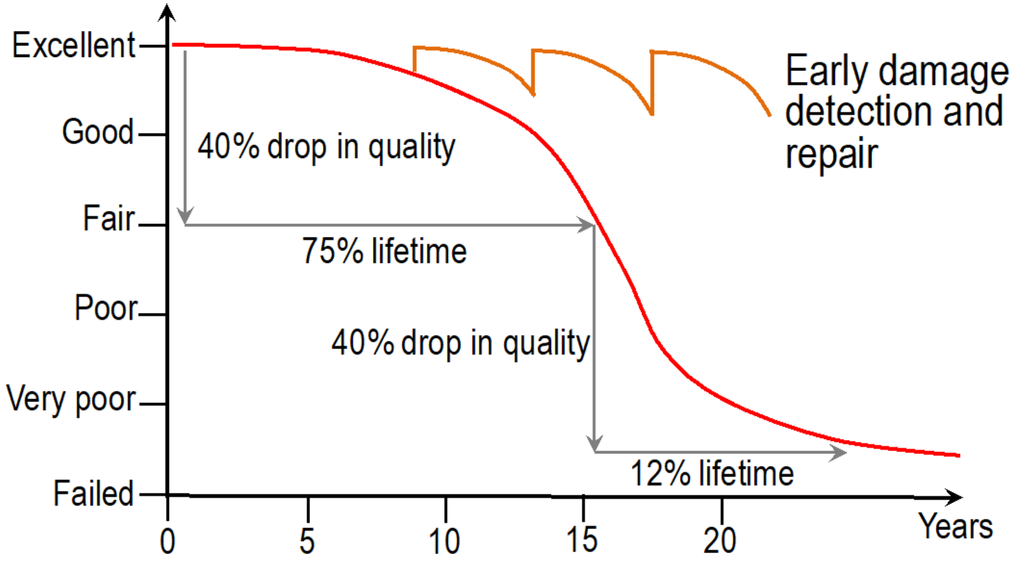


Background and Motivation

Proactive pavement preservation and rehabilitation:

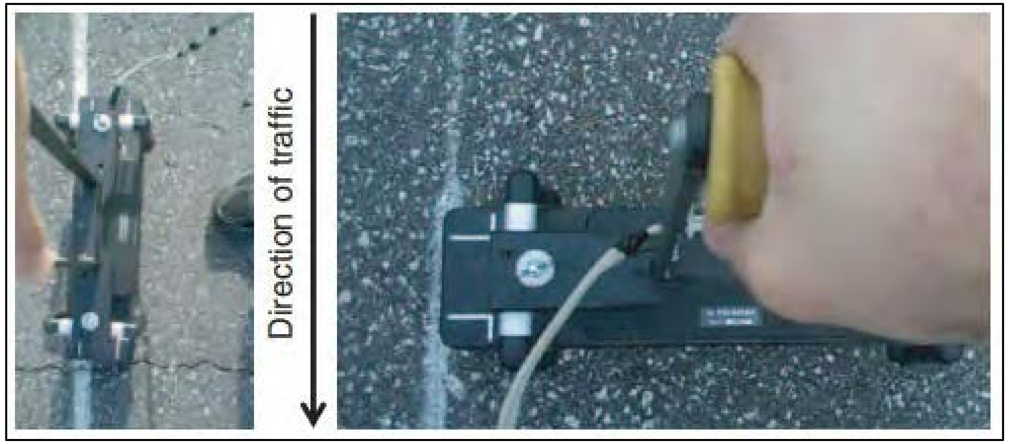
- Each dollar spent on the early-stage pavement preservation could eliminate or delay spending $6 to $10 in future on rehabilitation or reconstruction (Galehouse et al. 2003).
- Efficient detection of damage and repair are critical for cost-effective pavement preservation plan.





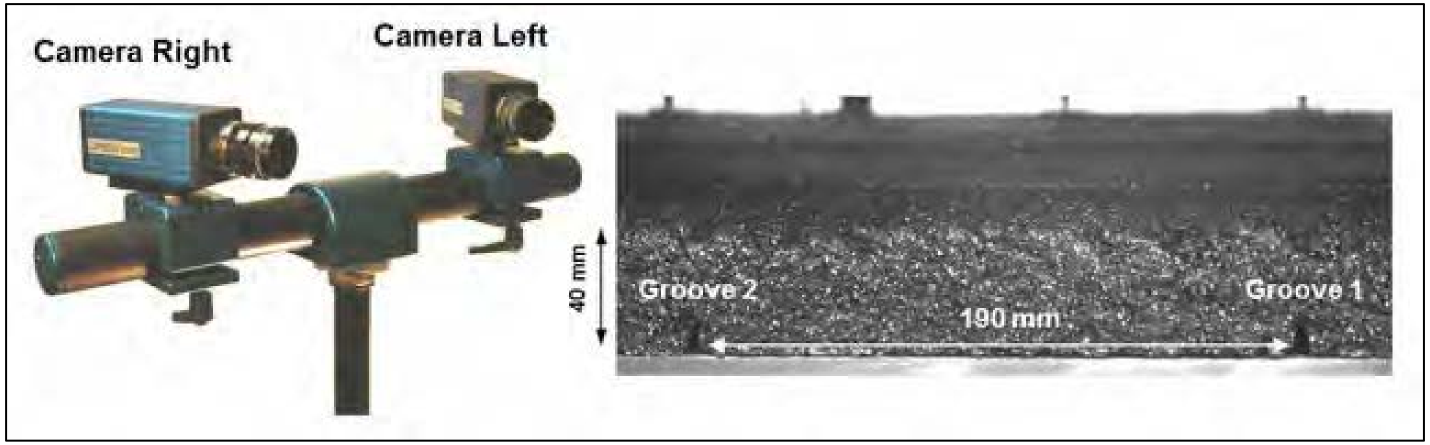
Background and Motivation – Nondestructive Testing

Ultrasonic test



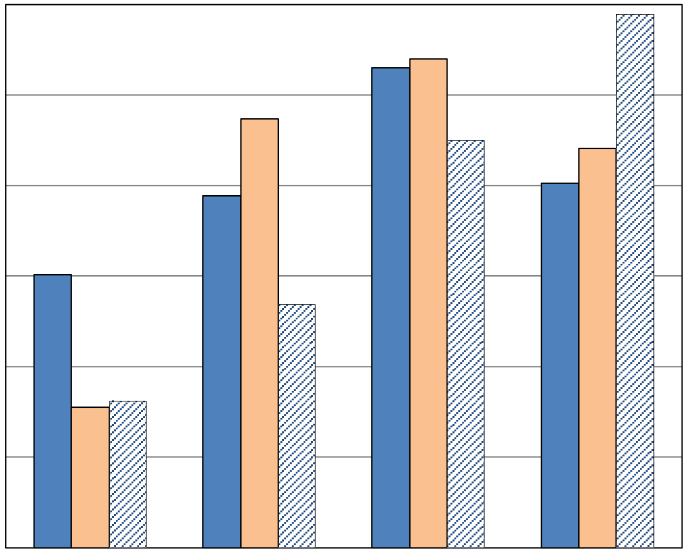
MIRA (Hoegh et al. 2012)

Rolling density meter

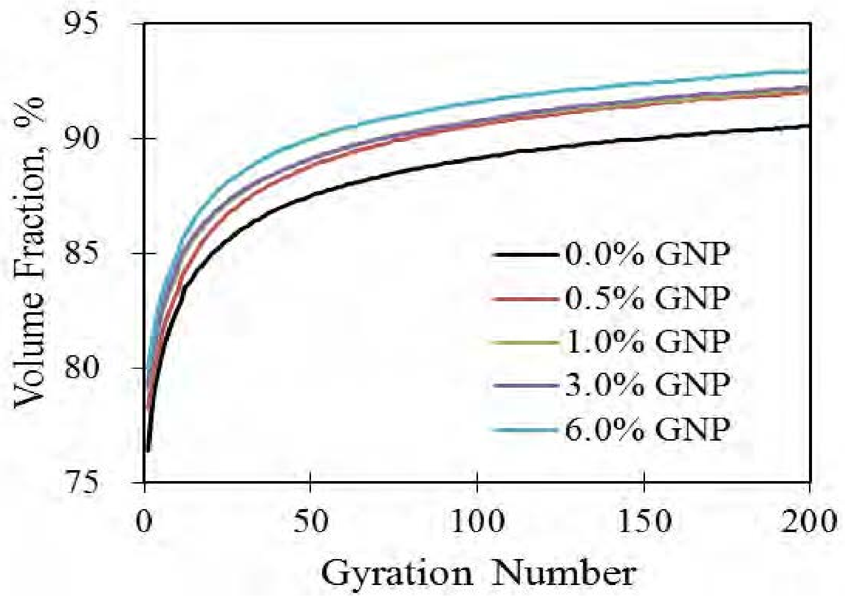


Digital image correlation (Bueno & Arraigada 2016)

Background and Motivation –
GNP modified asphalt materials



- Research team at UMN developed graphite nano-platelet (GNP) modified asphalt materials, which exhibits various attractive properties, e.g. strength and fracture properties at low temperatures, compactability.

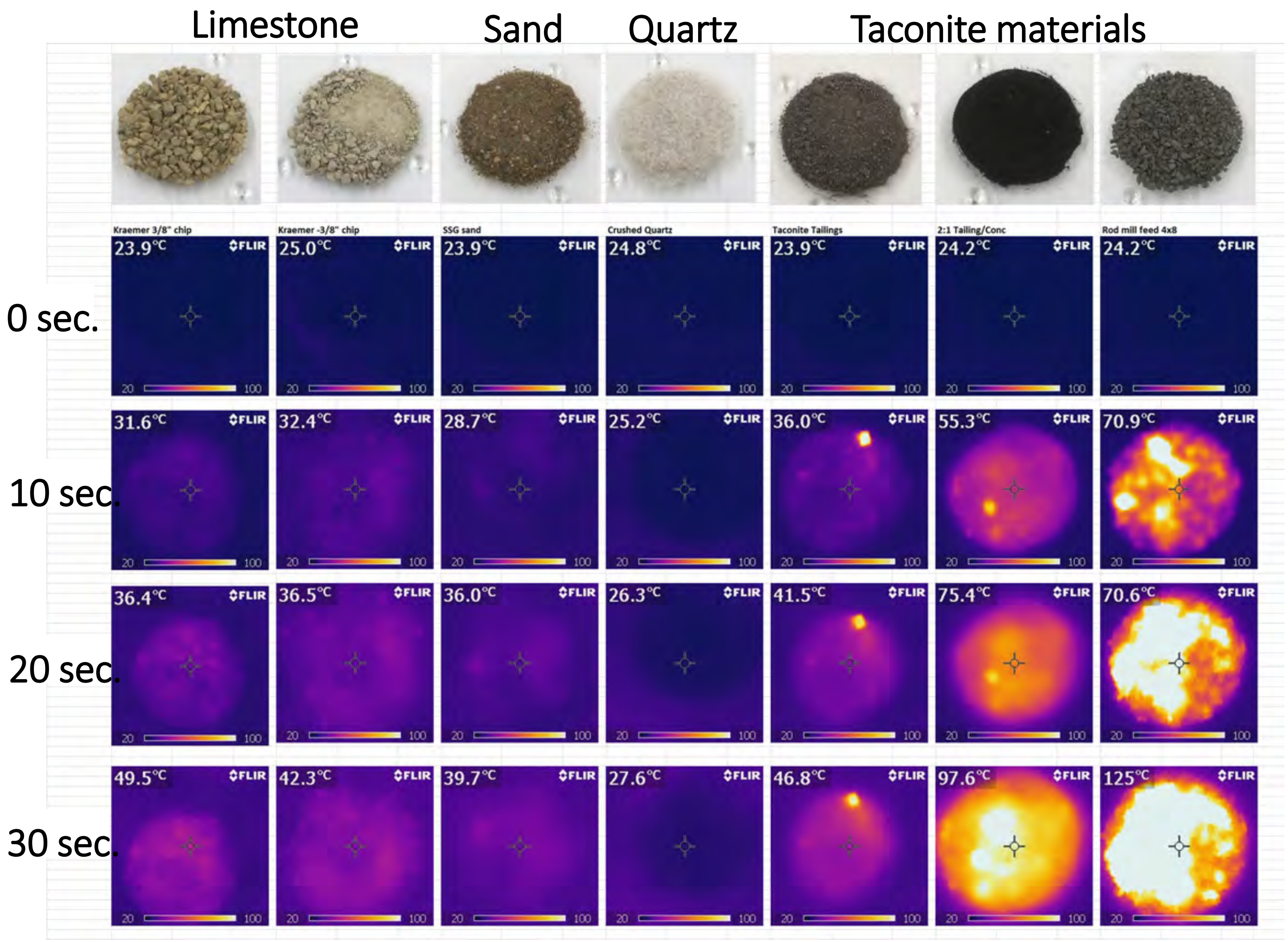


Background and Motivation – GNP modified asphalt materials

- GNP materials are highly microwave energy absorbing and are also electrically conductive.

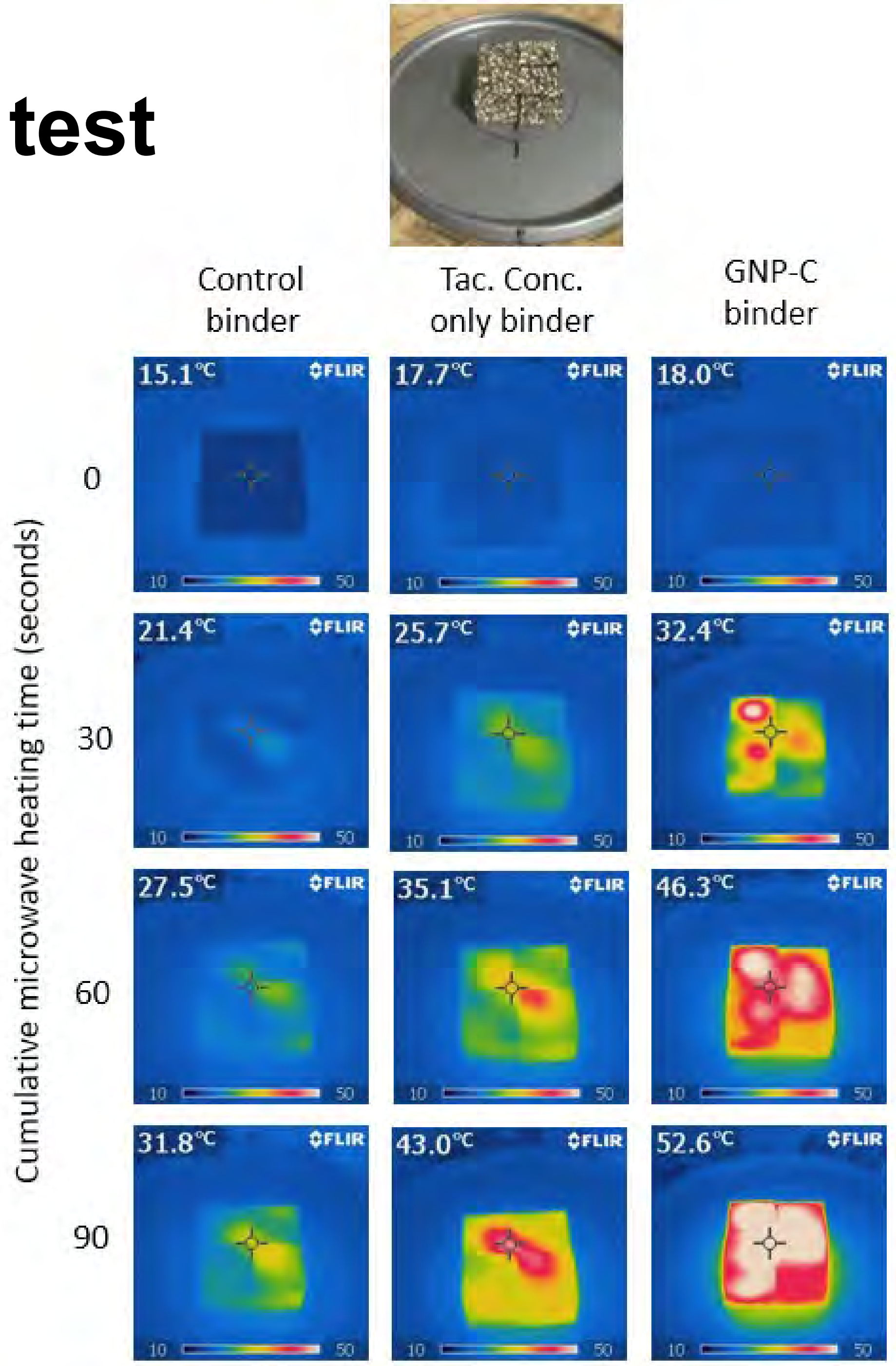
Background and Motivation – Taconite modified asphalt materials

- Natural magnetite in taconite is an outstanding microwave absorber
- It enhances microwave energy absorption in asphalt materials



Asphalt cube microwave heating test

- Asphalt specimen cubes:
  - control binder
  - taconite concentrate-only binder
  - GNP+taconite concentrate binder
- For the test, 4 cubes were arranged in a 2 x 2 array
- Cubes were microwave-heated in three 30-second increments (cumulative heating time of 90 seconds) using a custom-built 1 kW, 2450 MHz microwave heating device
- Thermal imaging camera was used to record specimen heating and spot temperatures

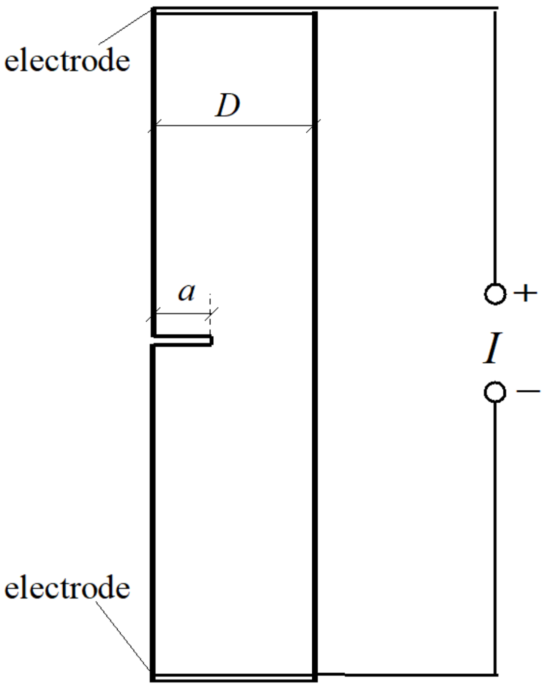


Research Objectives

- Damage detection through the measurement of electrical conductivity
- Investigation of electrical conductivity of GNP-taconite modified asphalt materials
- Damage healing capability via microwave heating
- Application to tack coat

I. Damage Detection using Electrical Conductivity

Analytical Modeling – Mathematical Analogy Between Electrostatic Field and Elastostatic Field



Electrostatic field

Electric potential: Φ

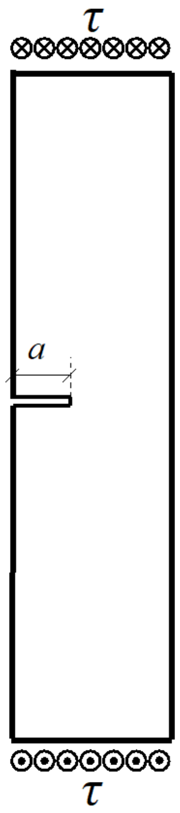
Electric field: $E_x = -\Phi_{,x}$ $E_y = -\Phi_{,y}$

Current density: $J_i = \sigma E_i$

Equation of continuity:

$$\partial J_x/\partial x + \partial J_y/\partial y = -\partial \rho/\partial t$$

$\rho =$ Charge density



2D anti-plane shear problem:

Displacement: u_z

Strain: $\gamma_{zx} = u_{z,x}$

$\gamma_{zy} = u_{z,y}$

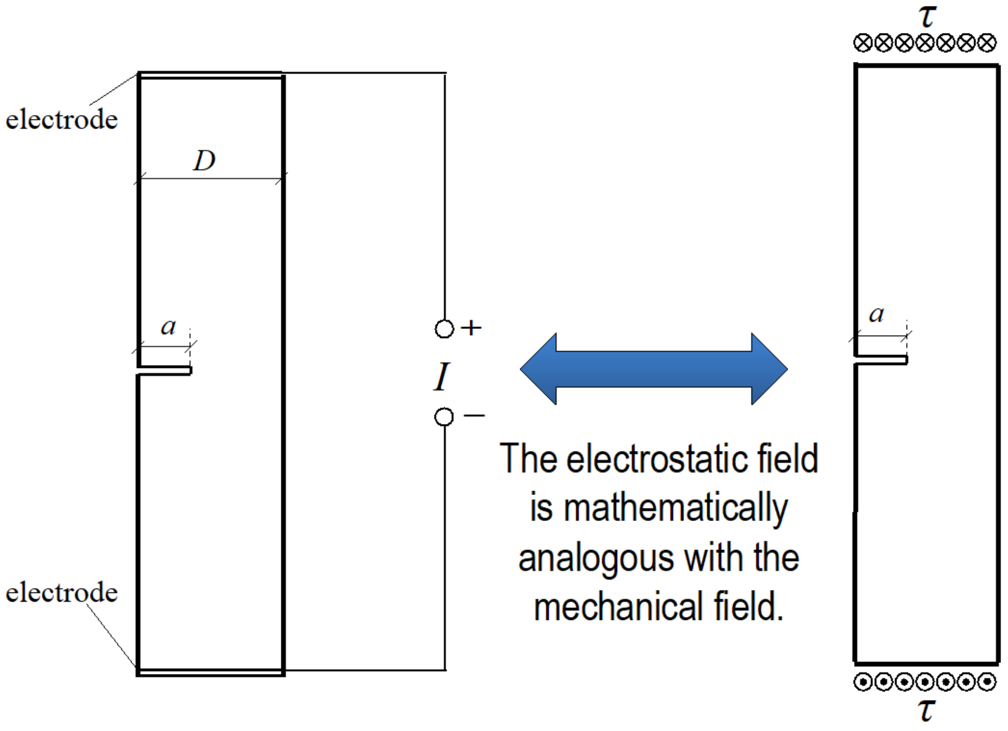
Stress: $\tau_{zi} = G\gamma_{zi}$

Equilibrium Equation:

$$\partial \tau_{zx}/\partial x + \partial \tau_{zy}/\partial y = -f$$

$f =$ Body force

Analytical Modeling – Mathematical Analogy Between Electrostatic Field and Elastostatic Field



$$R = V/I \quad \Rightarrow \quad \Delta u_z/P = C_\tau$$

Electrical resistance is analogous to the elastic compliance under anti-plane shear loading.

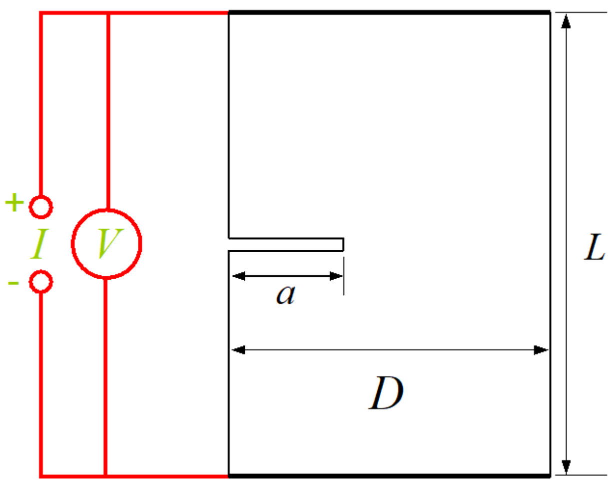
$$R(a)/R_0 = C_\tau(a)/C_0 = F(a)$$

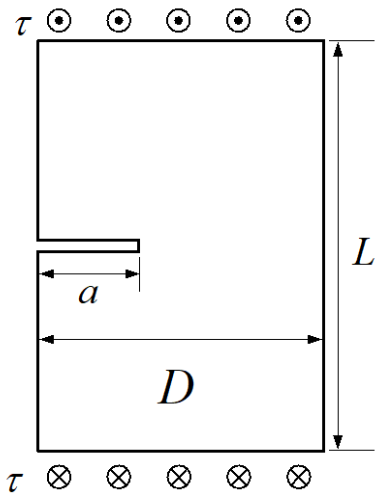
Based on linear elastic fracture mechanics, we have

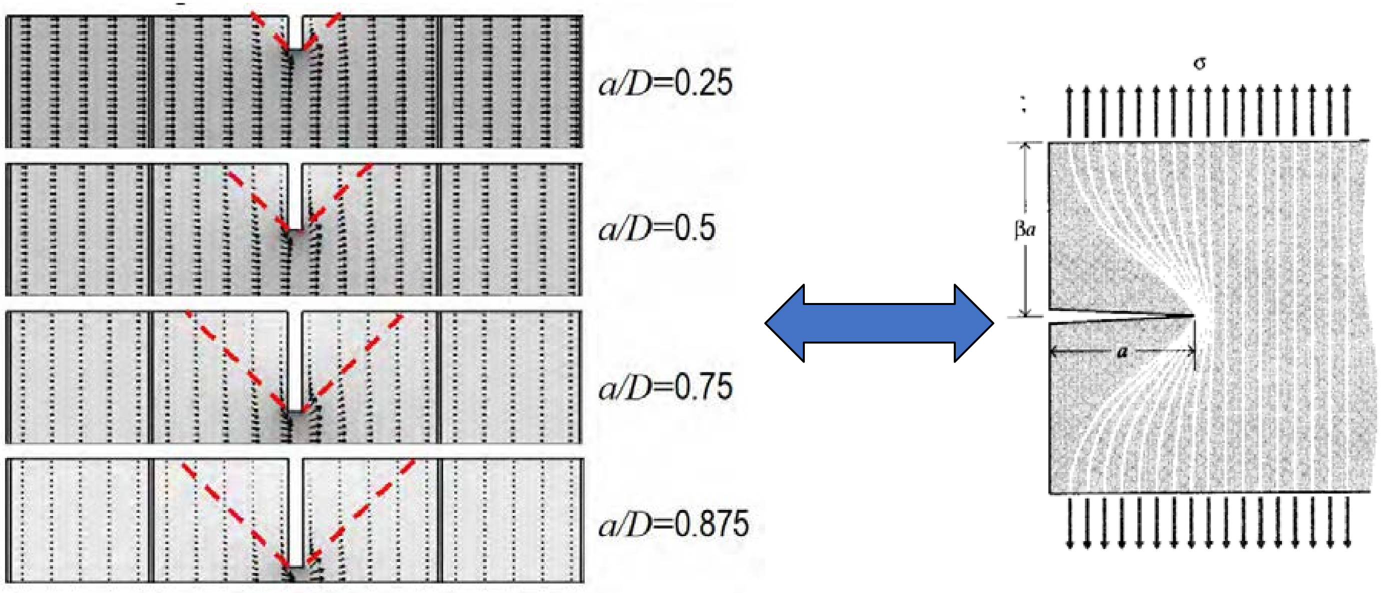
$$C_\tau(a) = C_0 + \frac{b}{P^2}\int_0^a \frac{K^2(a')}{G}\mathrm{d}a'$$

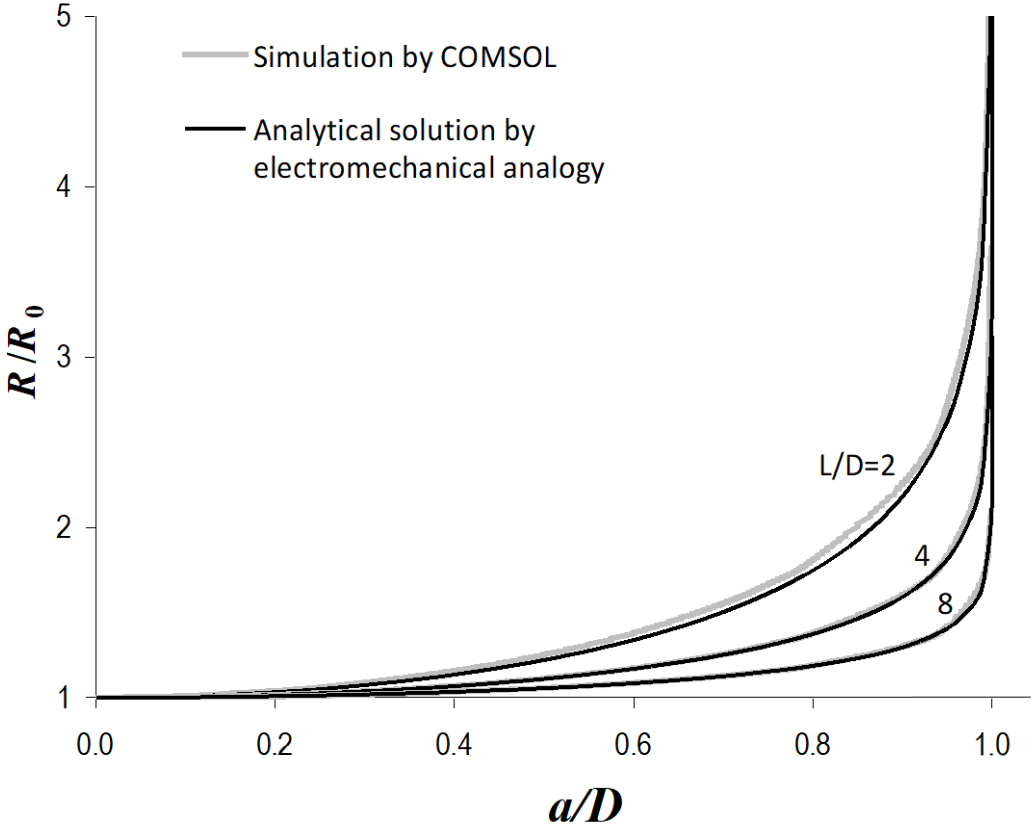
Le et al. *Comp. B*, 2014

Numerical Validation









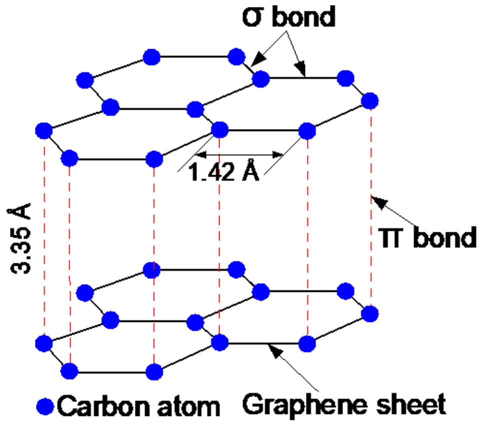
Le et al. *Comp. B*, 2014

II. Electrical Conductivity of GNP-Taconite Modified Asphalt Materials

Experimental Investigation of Electrical Conductivity

Graphite nano-platelet materials

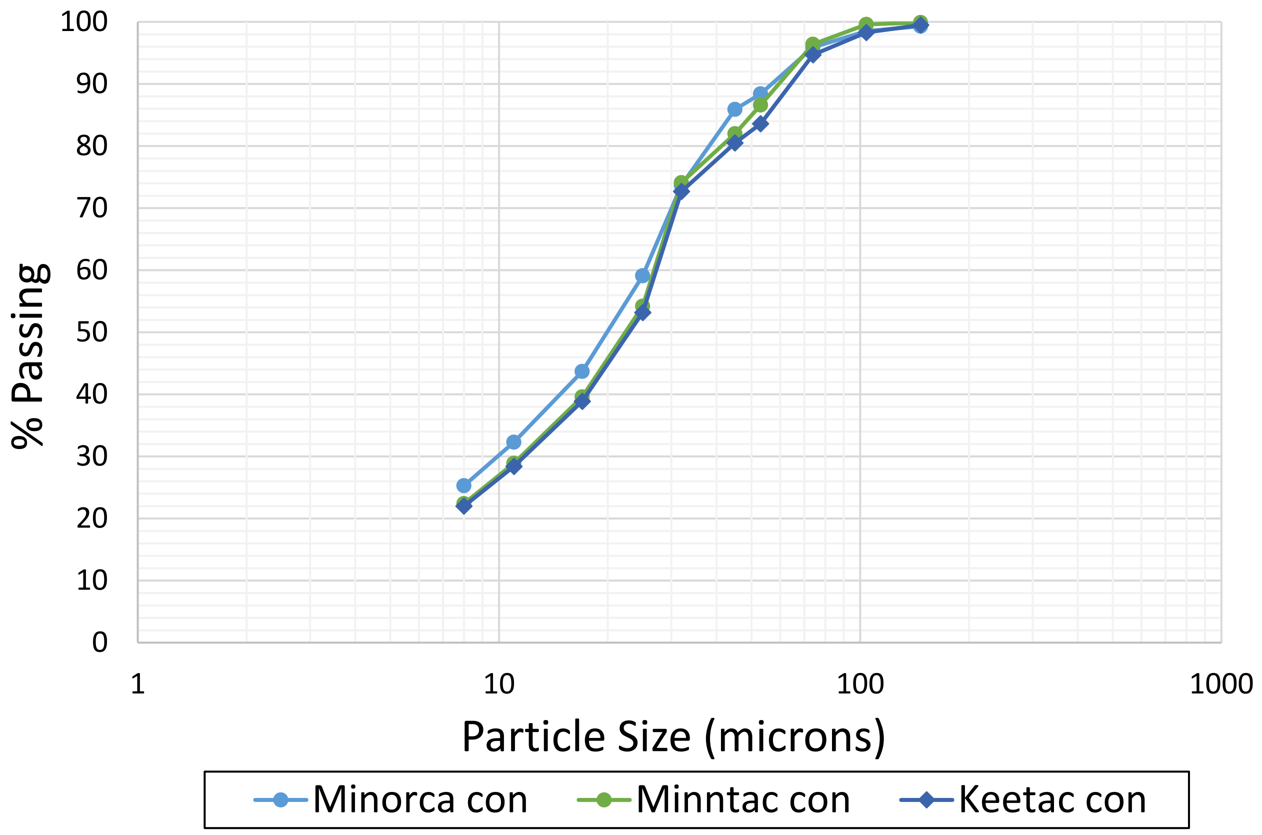
Type	Description	Carbon content	Surface area (m^2/g)	Cost ($/lb)
M850	Graphite nano-flake powder	99.54%	13	3.53
4827	Surface-enhanced synthetic graphene material	99.66%	250	4.14



Experimental Investigation of Electrical Conductivity

Taconite concentrate

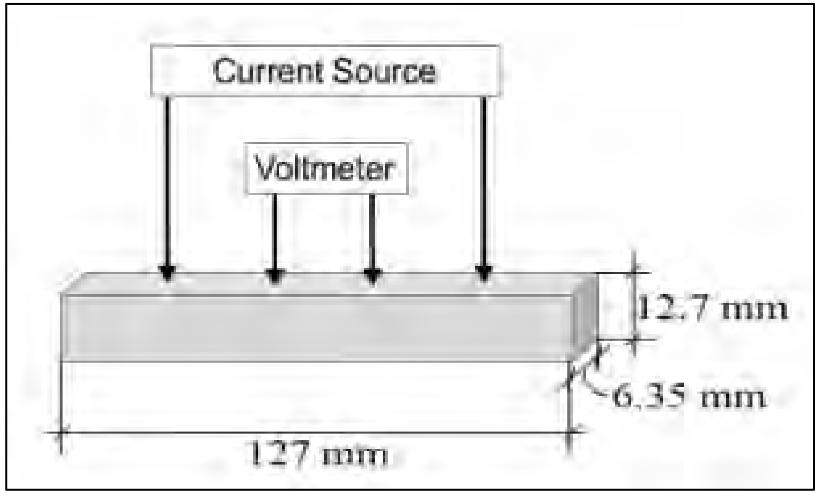
The concentrate produced by the taconite operations typically contains 65% to 66% Fe, mostly as magnetite, before the addition of flux material.

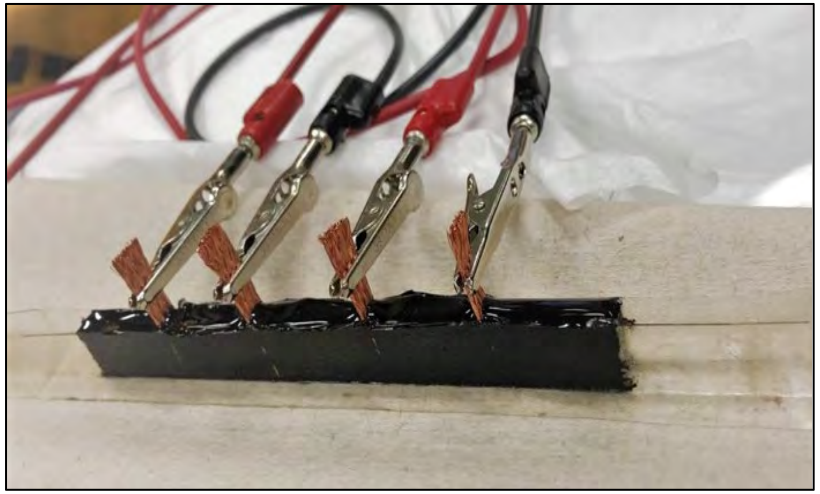


Experimental Investigation of Electrical Conductivity

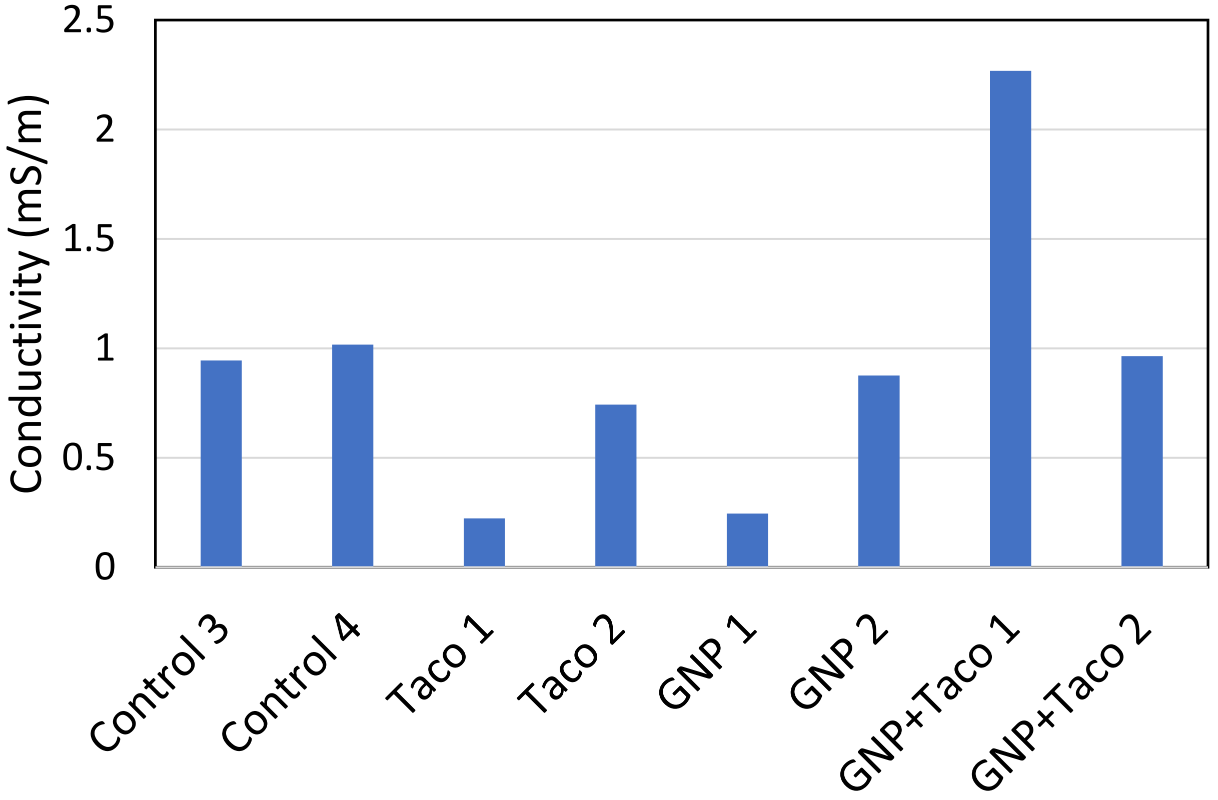
Sample No.	Mix Design
1	Control
2	Control + 6% Taconite Concentrate
3	Control + 6% GNP 4827
4	Control + 6% Taconite Concentrate + 6% GNP 4827

Four-probe test





Experimental Investigation of Electrical Conductivity



The combination of GNP and taconite (6% GNP+6% taconite concentrate) leads to the most improvement in the electrical conductivity.

It is speculated that the addition of taconite on top of GNP may provide a medium that enhances the dispersion of GNPs, and thus creates a more effective electron hopping network.

Influence of Humidity on Electrical Conductivity

- The experiments showed a significant influence of humidity on the measured electrical conductivity.

- For the same mix, test performed in the winter (dry condition) measures a much lower electrical conductivity than that performed in the summer (humid).

- For the purpose of damage detection, special care is needed to ensure a nearly constant humidity for measuring the electrical conductivity.

III. Damage Healing via Microwave Heating

Damage Healing Through Microwave Heating

- Previous studies showed that both GNP and taconite modified asphalt materials are excellent absorbers of microwave energy.

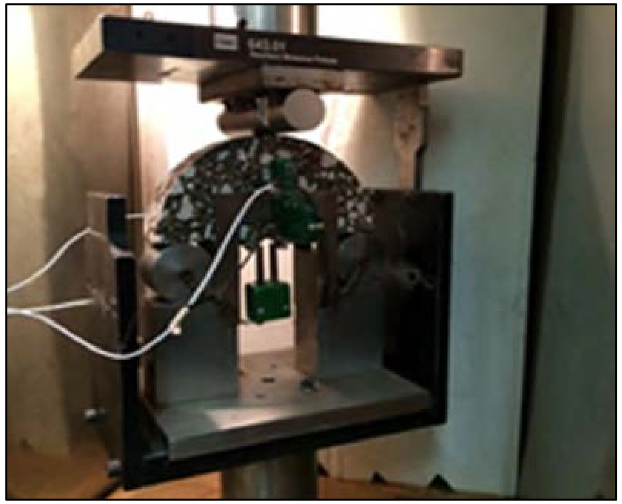
- We investigate the possibility of damage healing (e.g. microcracks) via the application of microwave heating.

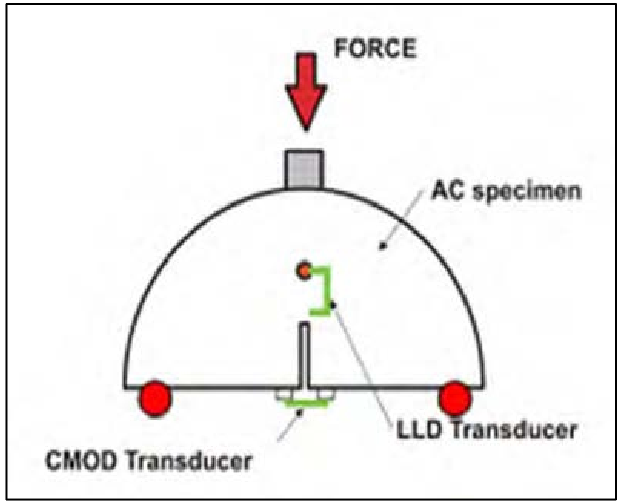
Microwave heating → Viscous flow asphalt binder at elevated temperatures → Sealing crack upon cooling

Experimental Program

- The experimental program used notched semi-circular bend specimens.

- One Superpave loose asphalt mix was used to prepare the specimen. Two types of mixtures were considered:
  -- Mixture 60-SPL (loose mix + 6% GNP)
  -- Mixture 61-SPL (loose mix + 6%GNP + 1% concentrate)



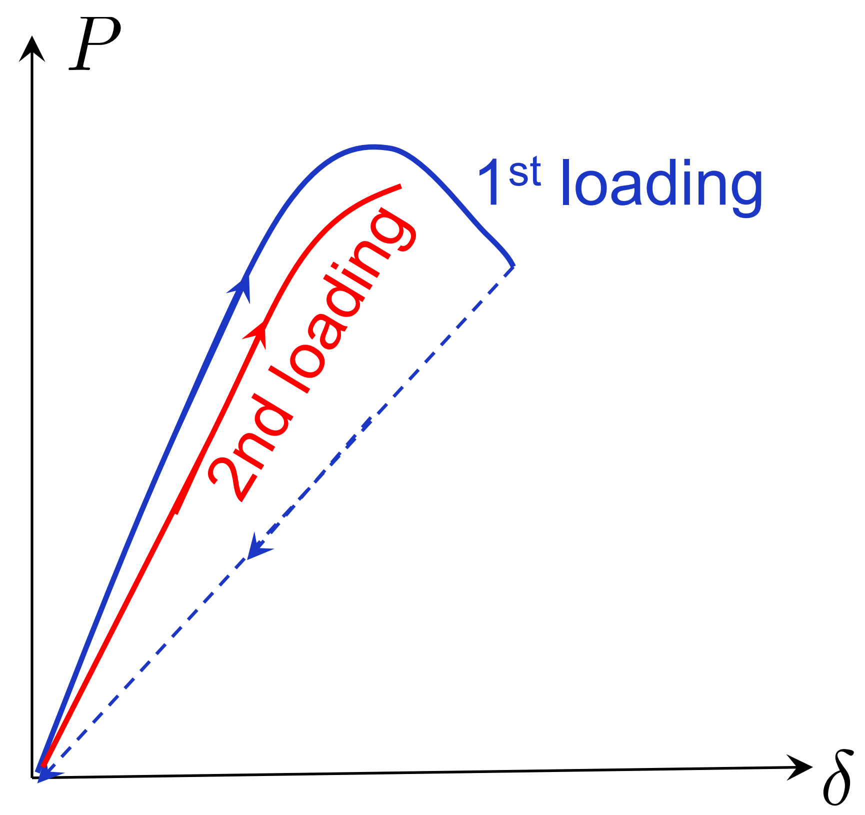


Experimental Program

- Description of the experiment:
  1) The specimen is loaded using CMOD control mode at –12ºC and the test is stopped at 80% post-peak strength.

  2) The specimen was heated in microwave oven for one and half minutes. The surface temperature in the notch region reaches about 50ºC.

  3) After specimen cools down in the fridge, the specimen was retested at –12ºC under controlled load.

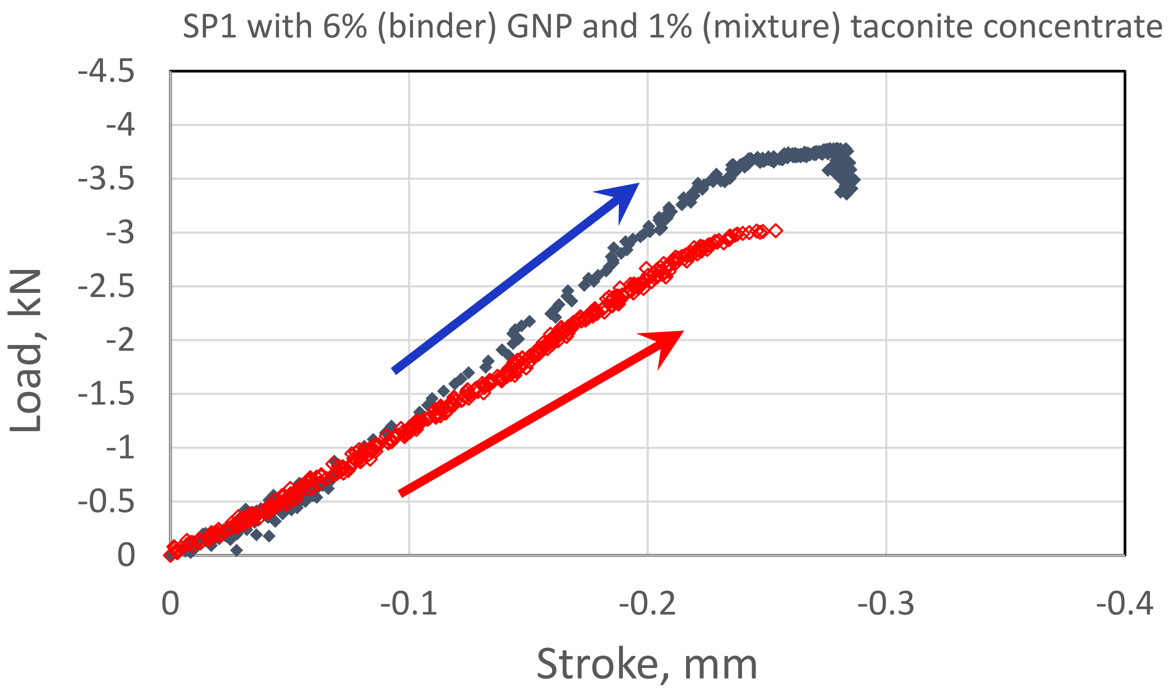


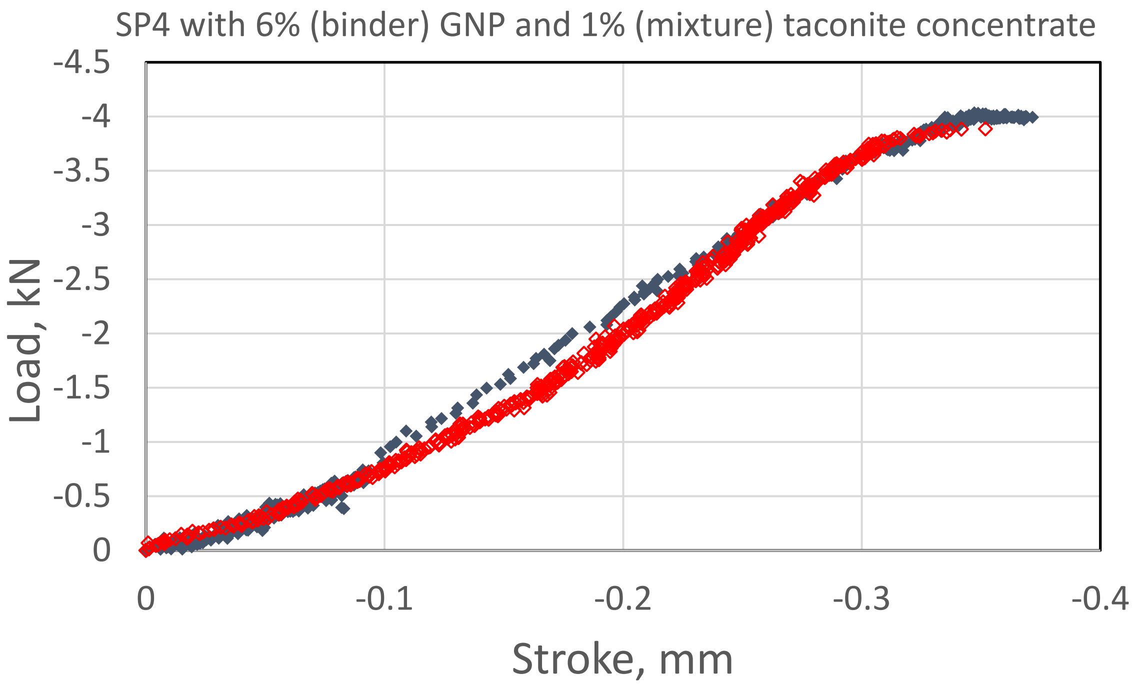
Peak Load Capacity After 2nd Loading

Sample	Treatment	Average peak load at fracture /load at 80% post-peak
ALL 60-SPL Micro	Microwave	1.133
ALL 60-SPL NON	NONE	1.043
ALL 61-SPL Micro	Microwave	1.116
ALL 61-SPL NON	NONE	0.95

- Without microwave heating, the peak load capacity of the specimen during the 2nd loading is similar to the load level at which it was unloaded. This indicates ***no strength recovery***.
- Upon microwave heating, the specimen is able to ***regain its strength*** (~90% of the peak load of the intact specimen)

Load-Displacement Response



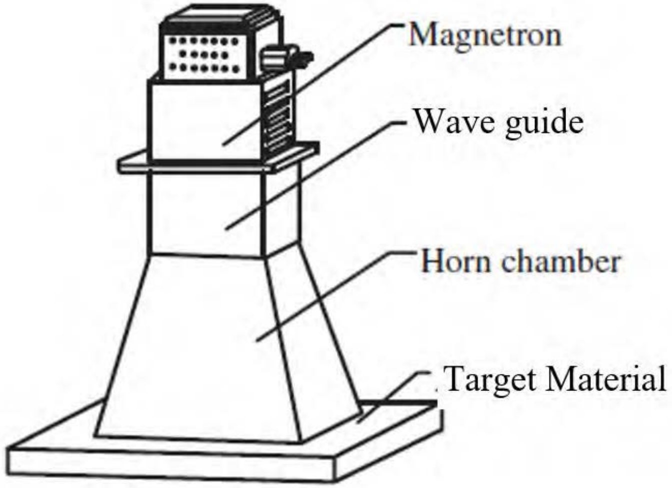


- Without microwave heating, considerable stiffness degradation is observed.
- Microwave heating leads to stiffness recovery, a key indicator of healing of microcracks.

Microwave Systems

- Microwave heating system components
  - Power unit
  - Applicator
  - Control circuitry

- Microwave system types
  Domestic microwave oven
  Horn antenna system

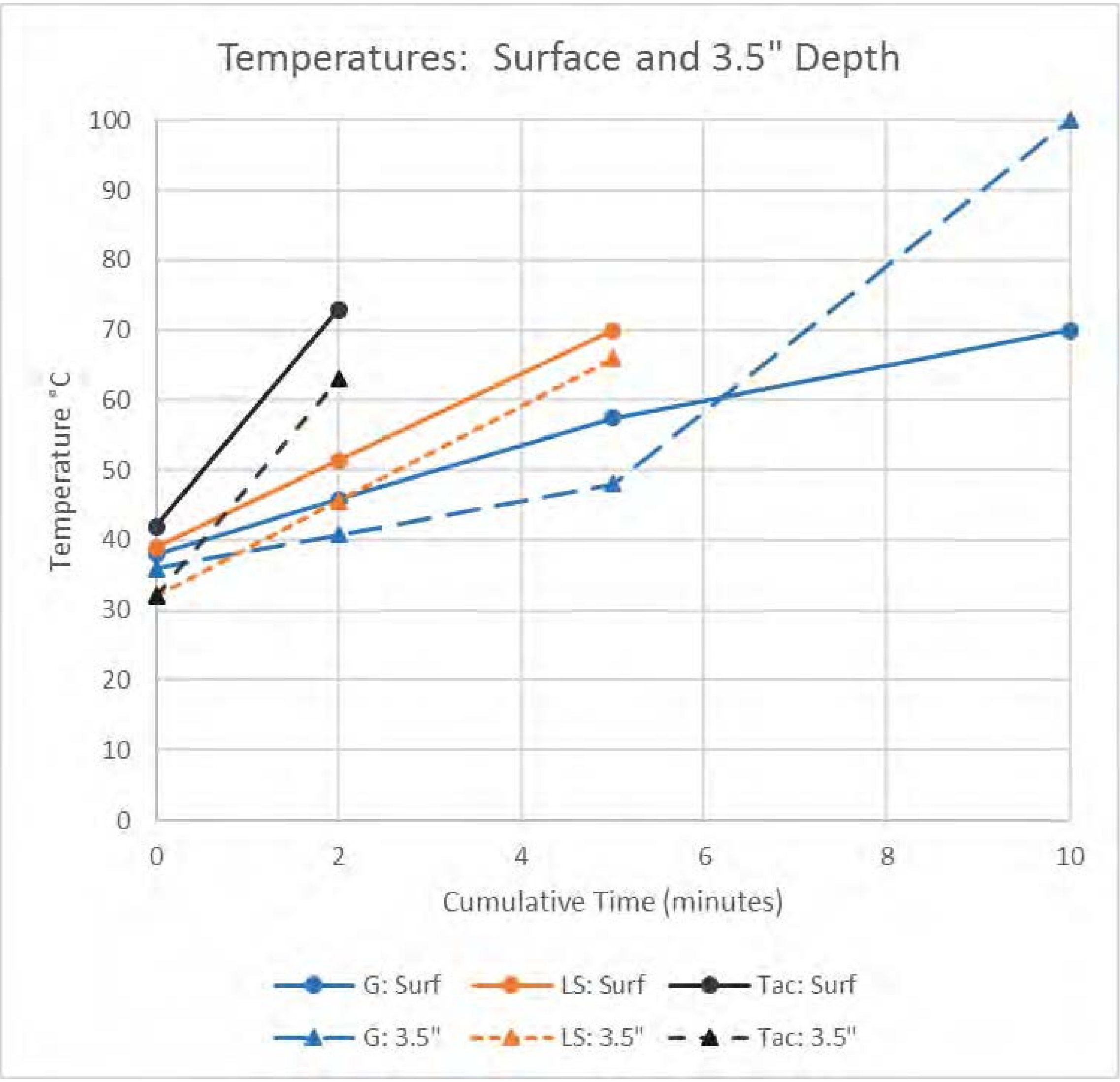


Microwave Heating in the Field

Assess the heating effect on three different hot mix asphalt pavement sections made with three major aggregate types:

- Granite
- Limestone
- Mesabi Aggregate (crushed taconite waste rock)

Microwave Heating in the Field



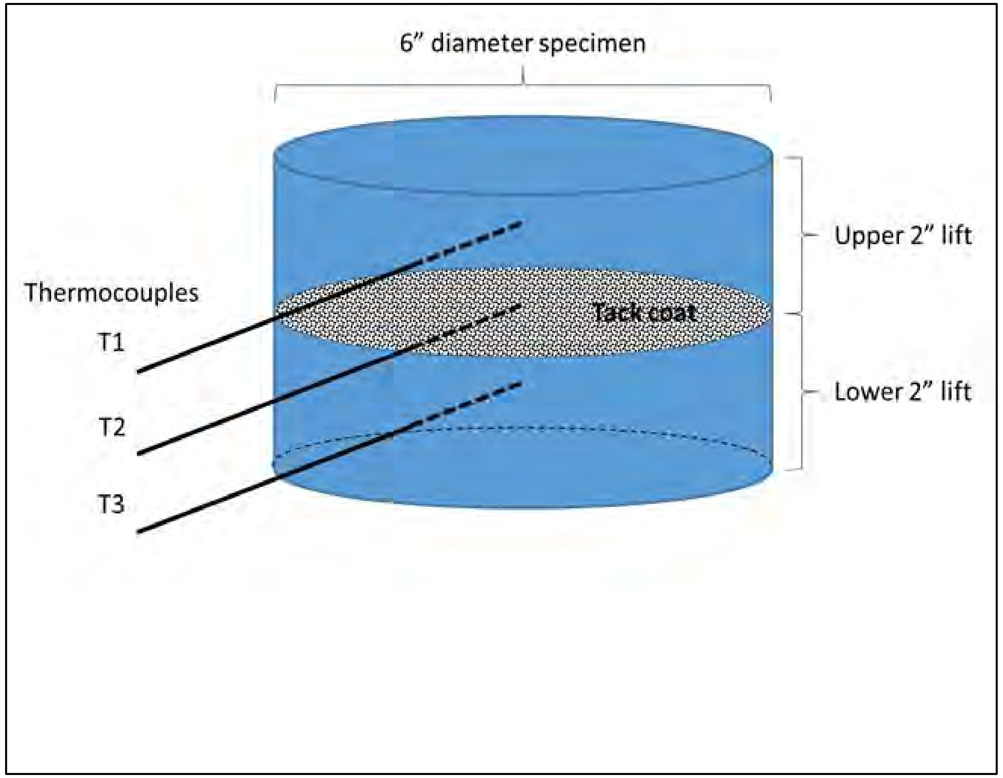
Key Findings:
The pavement containing taconite aggregate absorbed microwave energy much more efficiently than the limestone and granite-containing pavements (2 mins to achieve ~70° C, versus 5 mins for limestone and 7 to 10 mins for granite)

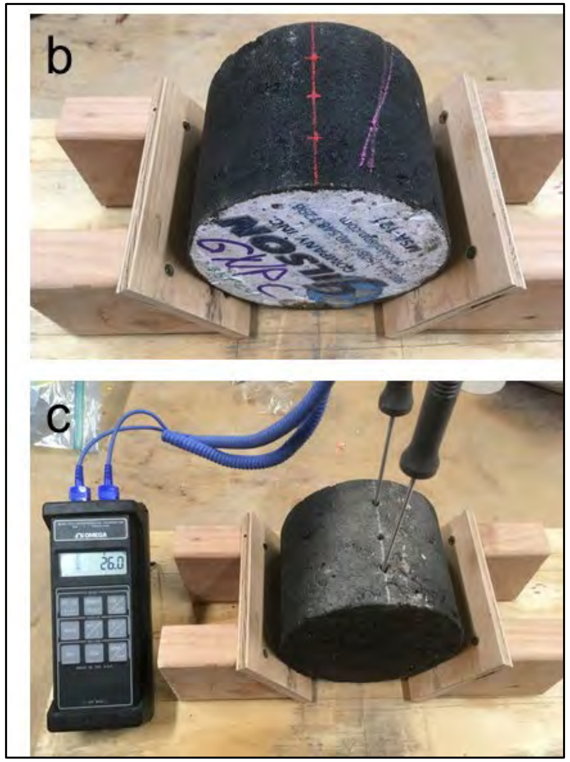
The granite-containing pavement was less microwave-absorbing and more microwave-"transparent“.

IV. Application to Tack Coat

Application to Tack Coat

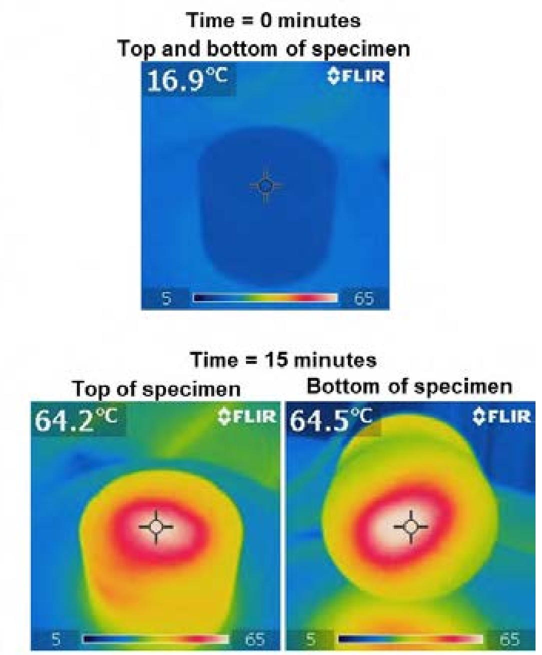
- Investigation of improved interfacial bond strength of GNP-taconite modified tack coat after subjecting to microwave heating.





Experimental Program

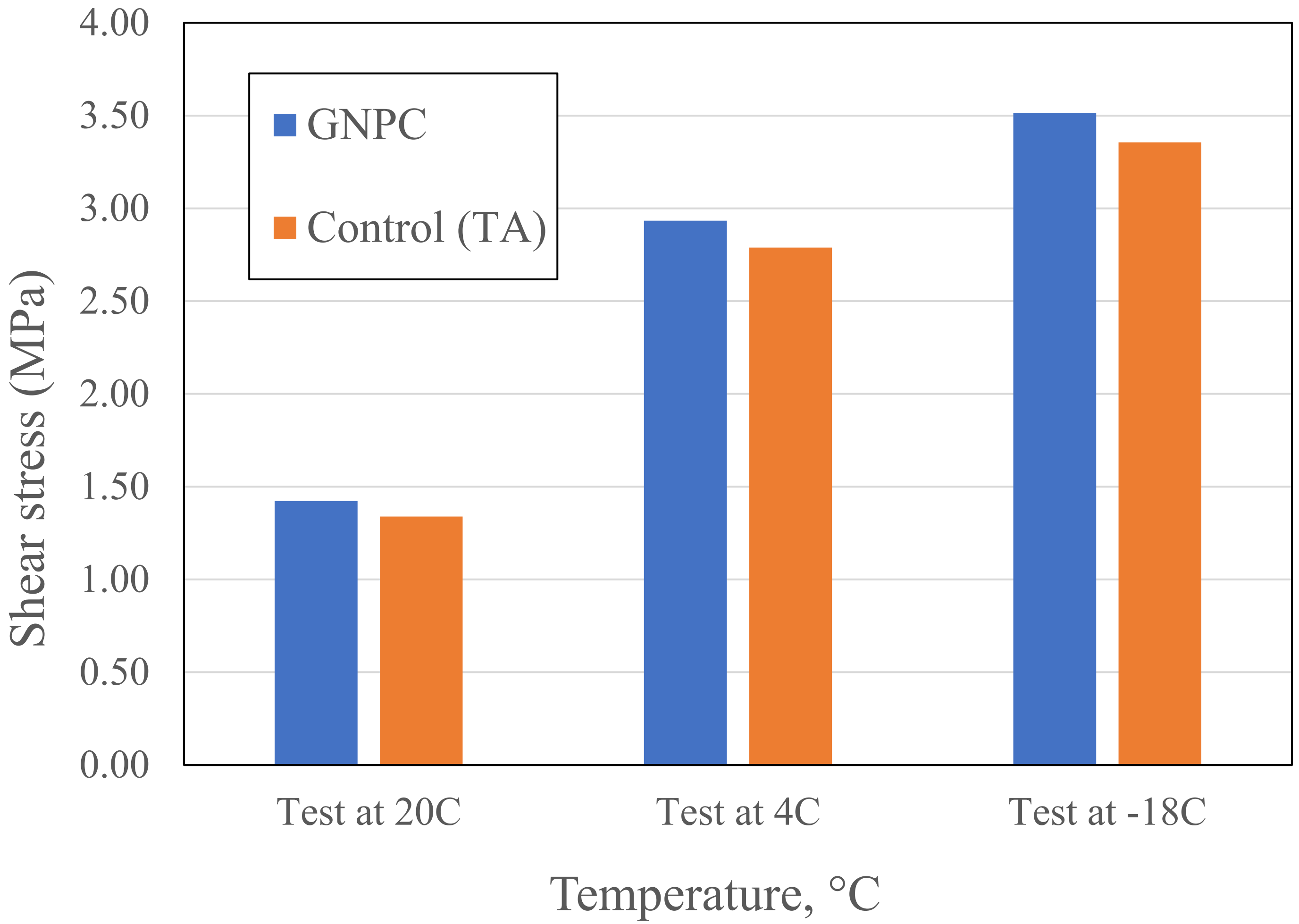
- Tack coat materials: 1) normal tack coat, and 2) GNP-taconite mixture.
- The GNP-taconite tack coat is subjected to microwave energy.
- Tack bond shear strength test is performed.



Experimental Results

Specimen failed at tack coat interface

- The microwave treated GNP-taconite mixture leads to about 6% improvement of the interfacial shear strength of the tack coat.



Conclusions

- The GNP-taconite modified asphalt binder exhibited the most significant improvement in electrical conductivity. It is believed that this improvement was attributed to the enhanced electron hopping mechanism.

- The humidity of the testing environment can have a strong influence on the measured electrical conductivity.

- Based on the fact that the electrostatic field is mathematically analogous to the elastostatic field under anti-plane shear loading, theoretical relationship between the electrical conductivity and damage extent can be established.

- The GNP-taconite modified asphalt mixtures can effectively absorb microwave energy, which provides an effective means for damage healing. This attractive property can also be exploited to improve the interfacial bonding of the tack coat.

Recommendations

- This research clearly demonstrates the potential benefits of using newer technologies and materials, such as the application of microwave energy for asphalt healing and for interlayer bonding enhancement.
- At the same time, some limitations were also identified, such as the use of new materials for sensing applications, which can be significantly affected by environmental conditions.
- The work performed was done in laboratory conditions. Therefore, to fully investigate the potential benefits of using these newer technologies and materials, a series of field trials are recommended.
- A limited number of proof-of-concept field experiments can be performed first, before embarking in any large-scale investigations.

Acknowledgment

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- Glenn Engstrom and Ben Worel, who supported the idea of the critical need for innovation and new materials in pavement applications.

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- Undergraduate students:

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