

Quasistatic Crack Propagation in Cement-Based-Materials Induced by Pyrrhotite Oxidation

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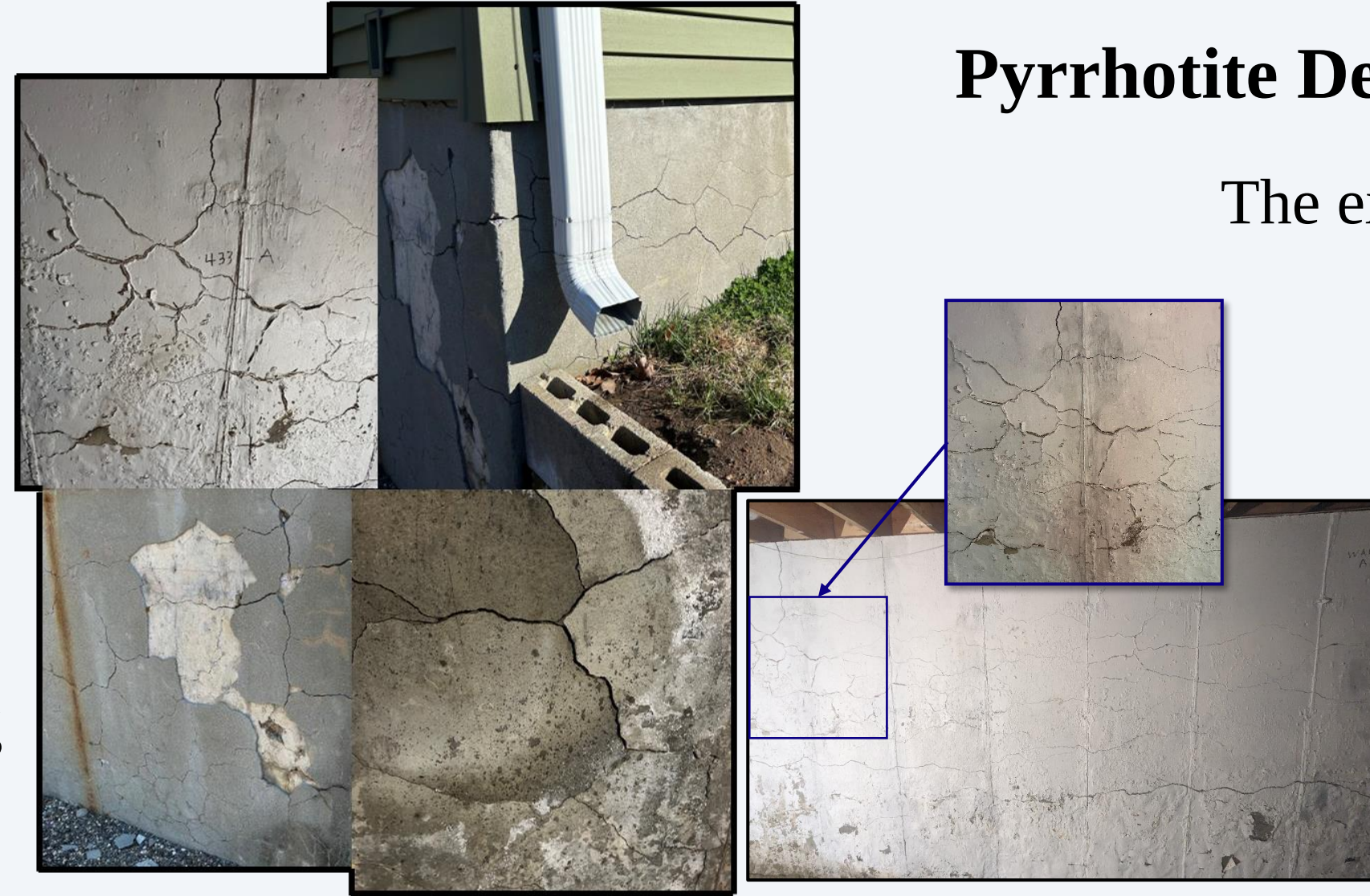
1 Pyrrhotite in Concrete

Background

- **Pyrrhotite-bearing aggregate** was used in the construction of **tens of thousands** of homes in Connecticut and Massachusetts in 1980s - 2000s
- **Pyrrhotite oxidation** occurred over several decades after construction, which led to foundation cracking and deterioration (**crumbling foundations**)
- Damage often requires **full foundation replacement**, costing over \$150K per home

Study Objectives

1. Understand chemical reactions and **cracking mechanisms**
2. Develop protocols to reliably measure sulfur content in aggregates
3. Quantify microstructural and mechanical properties of damaged foundations
4. Evaluate mitigation strategies for existing and new structures containing pyrrhotite-bearing aggregate



Deteriorated house foundation caused by pyrrhotite oxidation

Pyrrhotite Deterioration Mechanisms

The expansion is attributed to:

- i) **Pyrrhotite Oxidation**
- ii) **Internal Sulphate Attack**

Consequences :

1. Aggregate expansion
2. Cement paste damage
3. Concrete cracking
4. Strength reduction
5. Altered microstructure

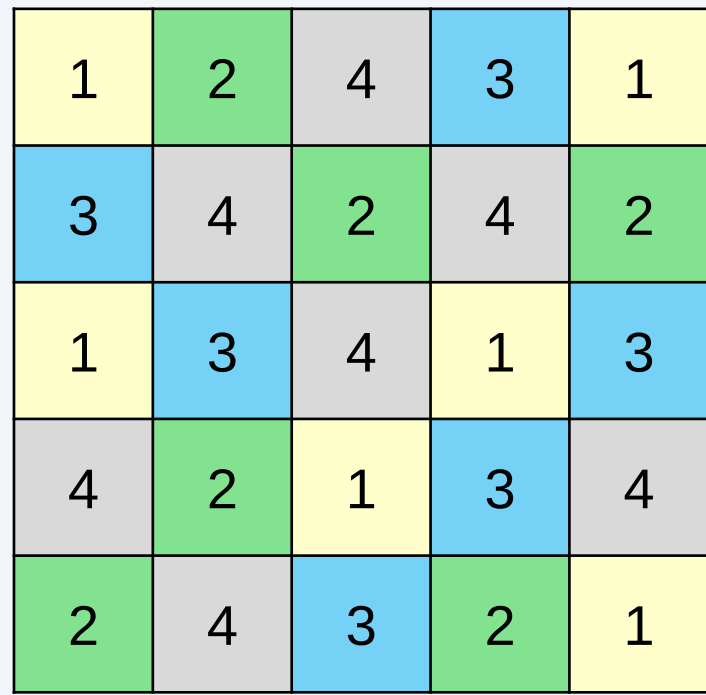
2 Quasistatic Crack Formation Model

First Digital Image

- Created by Russell Kirsch, who scanned a 5×5 cm photo of his 3-month-old son, Walden (176×176 pixels)



The first digital image, created in 1957, first invented by National Institute of Standards and Technology (NIST).

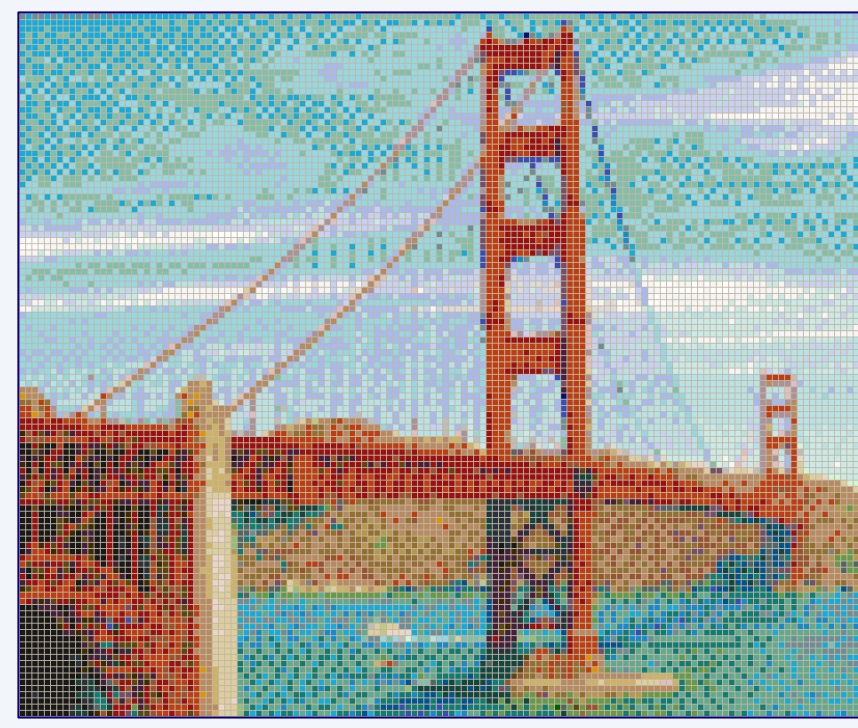


5 × 5 Grid

Legend
1: Aggregate
2: Cement paste
3: Voids
4: Crack

Pixelated Approach

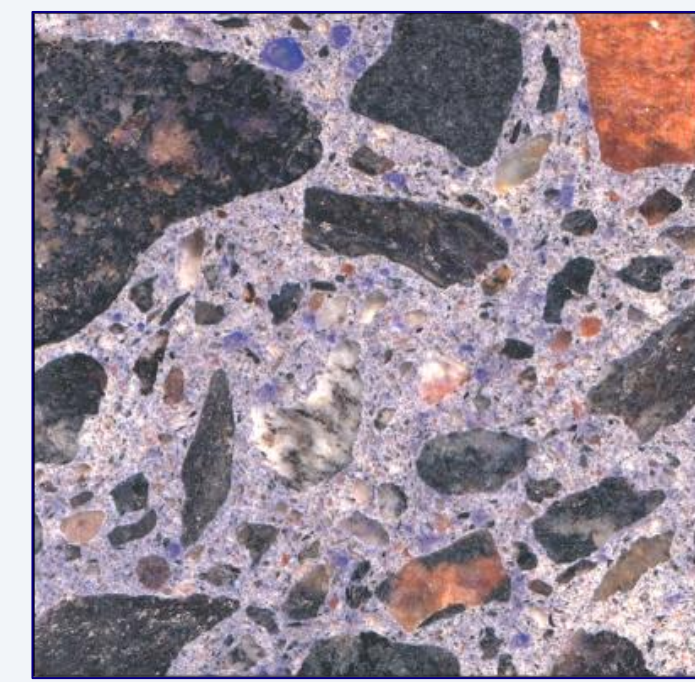
- A computational model based on Finite Element Method (FEM) was developed to simulate the quasistatic crack formation.
- This model is applied to pyrrhotite-rich aggregate concrete, which has not been previously modeled.
- A pixelated approach is used to account for the distinct mechanical behaviors of different phases with expansive strain being applied to a selected phase (e.g., pyrrhotite)



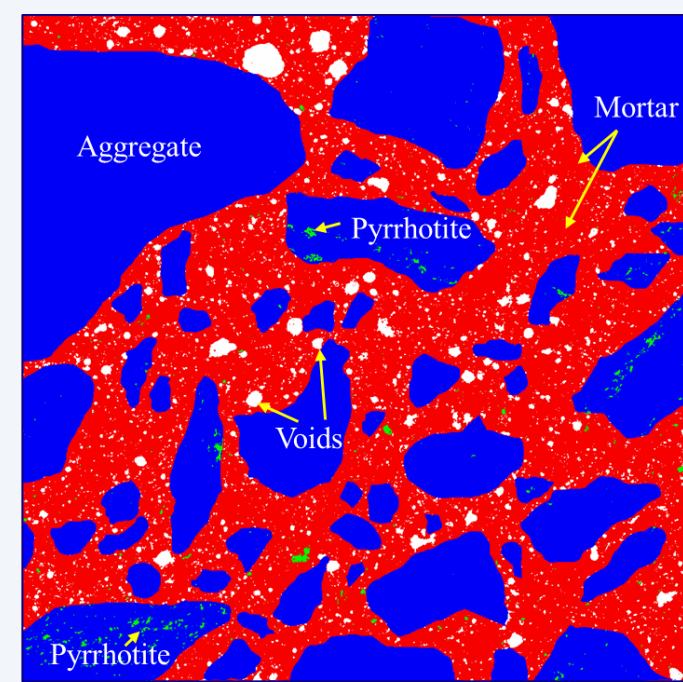
Golden Gate Bridge pixelated image (top) vs. photograph (bottom)

4 Application

- Modeling microstructural degradation due to sulfide diffusion from a pyrrhotite source.

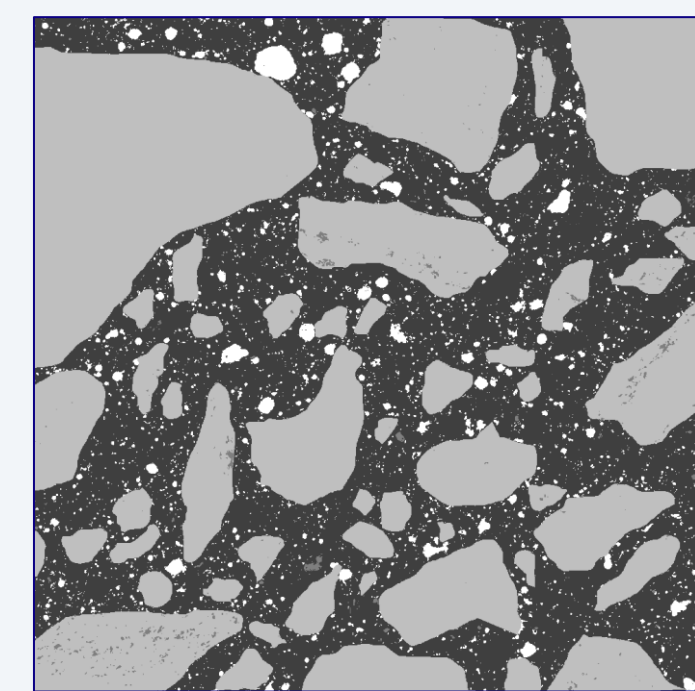


Polished core cross-section from foundation wall of Connecticut house

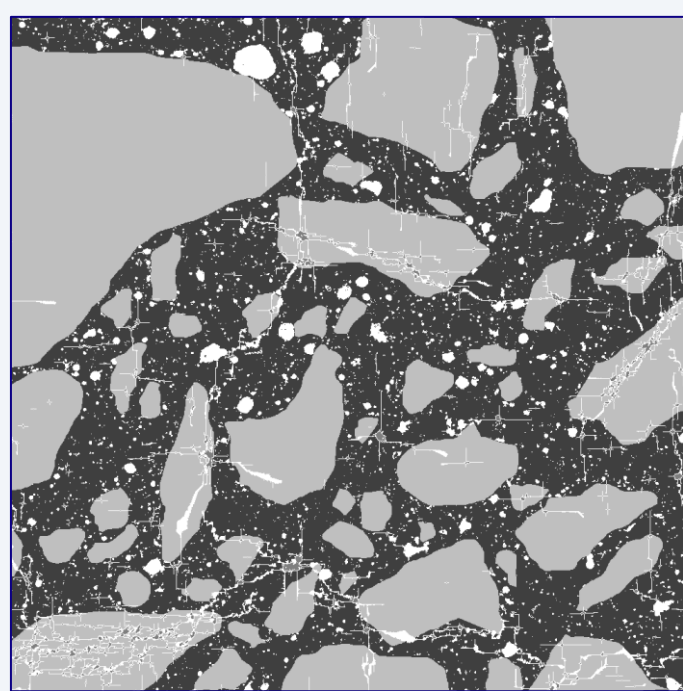


Scanned Electron Microscopy (SEM) Segmented Image

Crack Formation



Digital image without cracks



Simulated crack formation

Cracks Propagation Observations:

1. Initiation at pyrrhotite sites
2. Expansion to nearby pyrrhotite regions
3. Propagation through aggregates into cement paste (CP)
4. Continued growth within CP due to internal sulphate attack

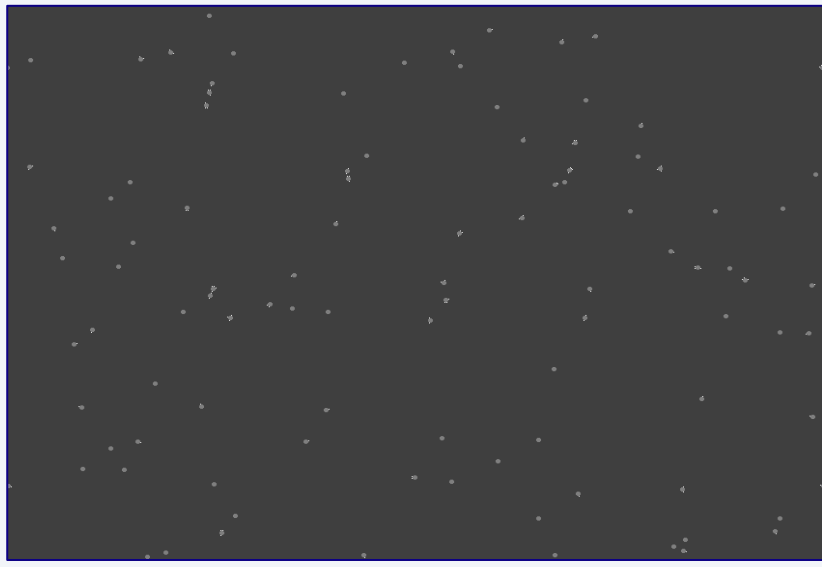
3 Model Development

Density of Expansion Sites

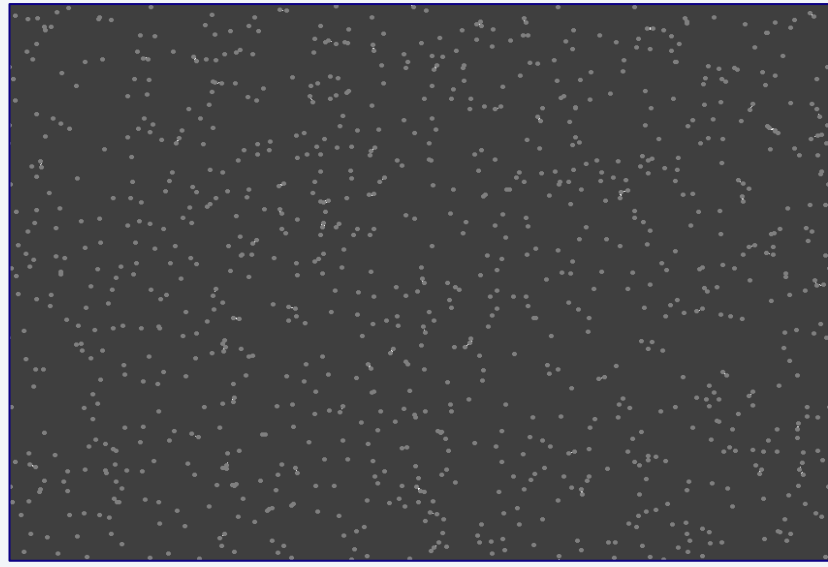
A. Crack Sites (origins)

Assume two phases:

- (1) Cement paste (black); (2) Expansion phases (white)

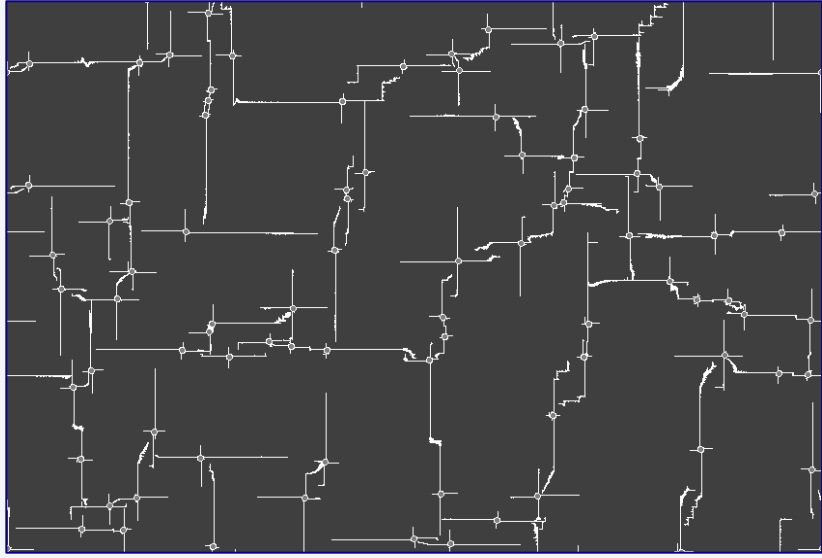


100 Sites (0.5% Area)

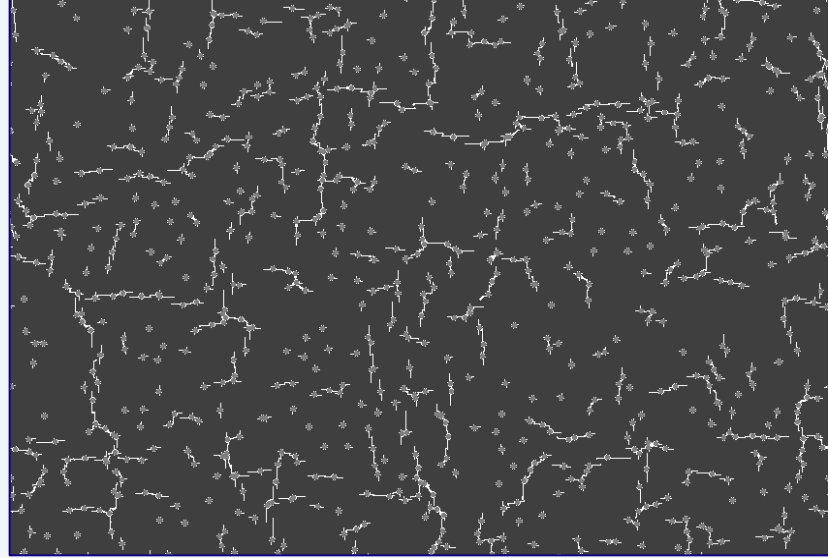


1000 Sites (5% Area)

B. Crack Formation



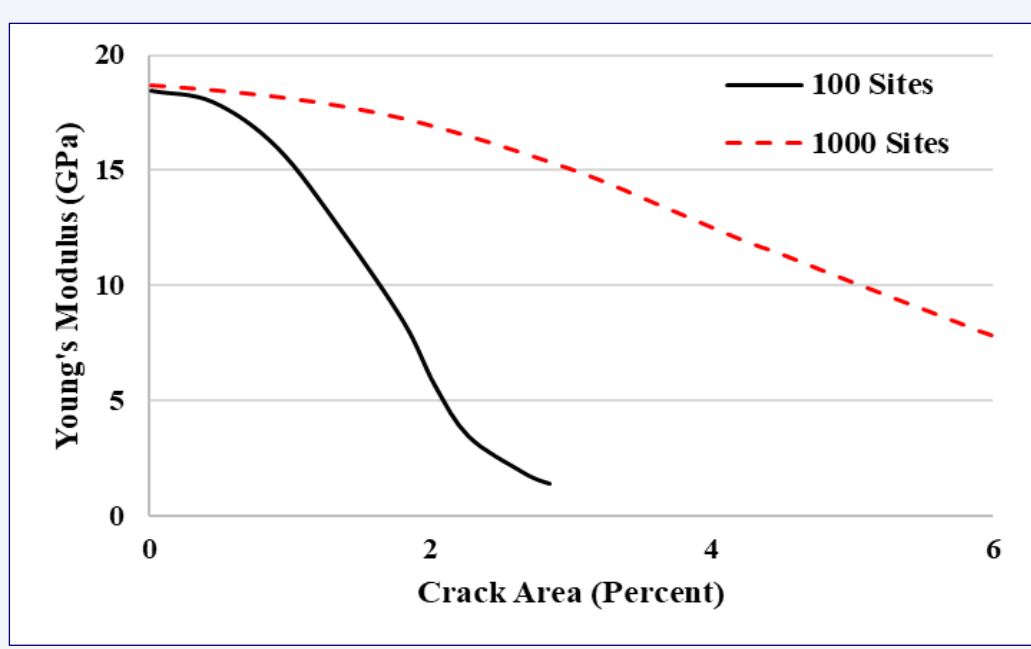
100 Sites (0.5% Area)



1000 Sites (5% Area)

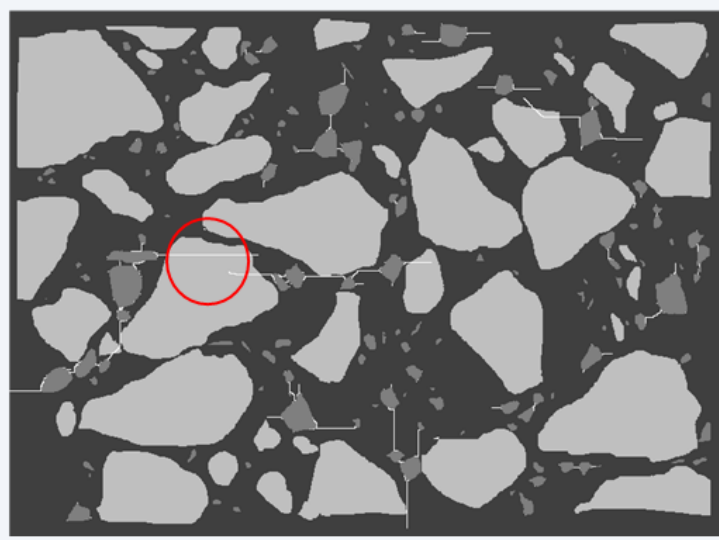
Crack formation Vs. Crack Sites

C. Elastic Modulus

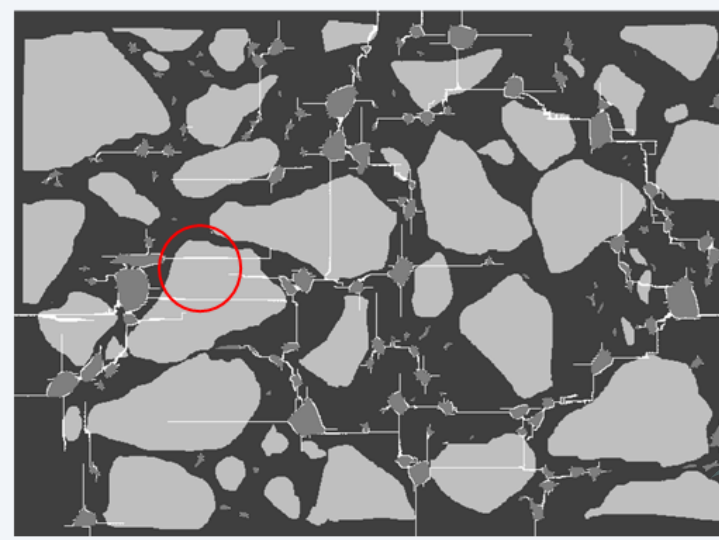


Young's Modulus Vs. Crack Area

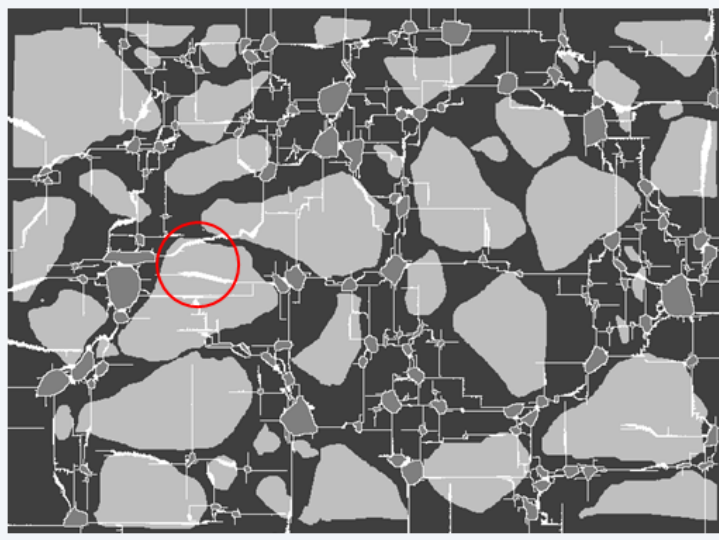
Number of Cracks Per Iteration



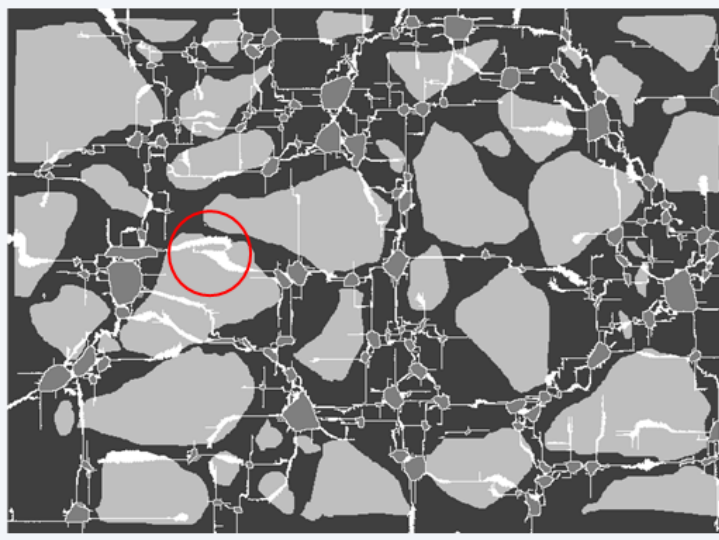
(a) 1 crack per iteration



(b) 10 cracks per iteration



(c) 100 crack per iteration



(d) 400 cracks per iteration

Crack propagation for different number of cracks per iteration

The developed model can be initialized using a real image.

More cracks per iteration lead to wider (thicker) crack formations.

Elastic Properties

- The model calculates elastic moduli (Young's, shear, bulk) and Poisson's ratio

Semi-Empirical Model

- 10 cracks/iteration yields much faster computation than 100 or 400 cracks
- Enables extrapolation to predict results for higher crack densities

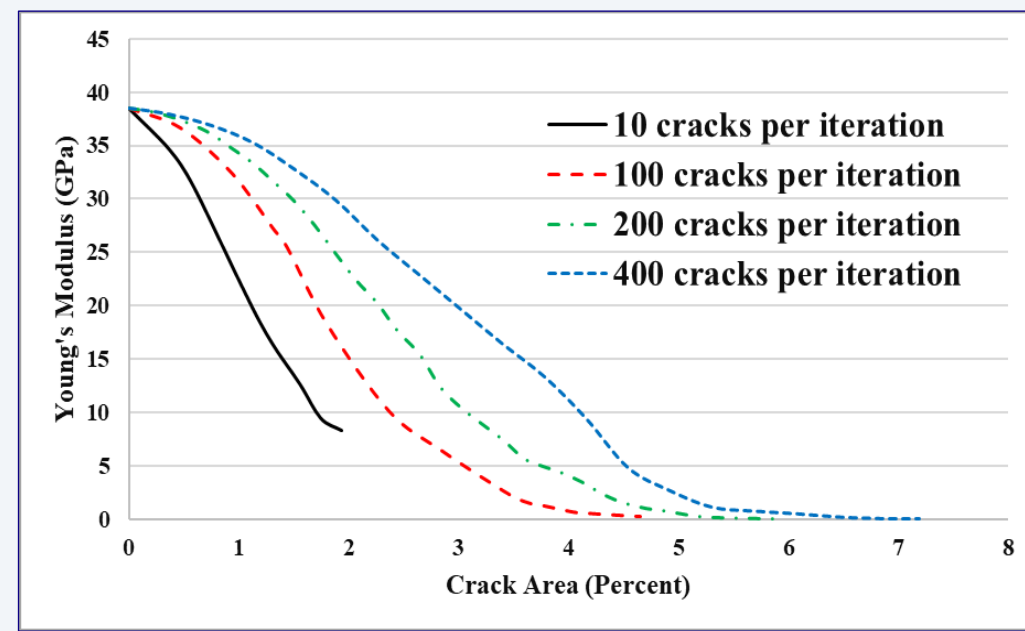
$$M = A^k \cdot C$$

M : designated mechanical property

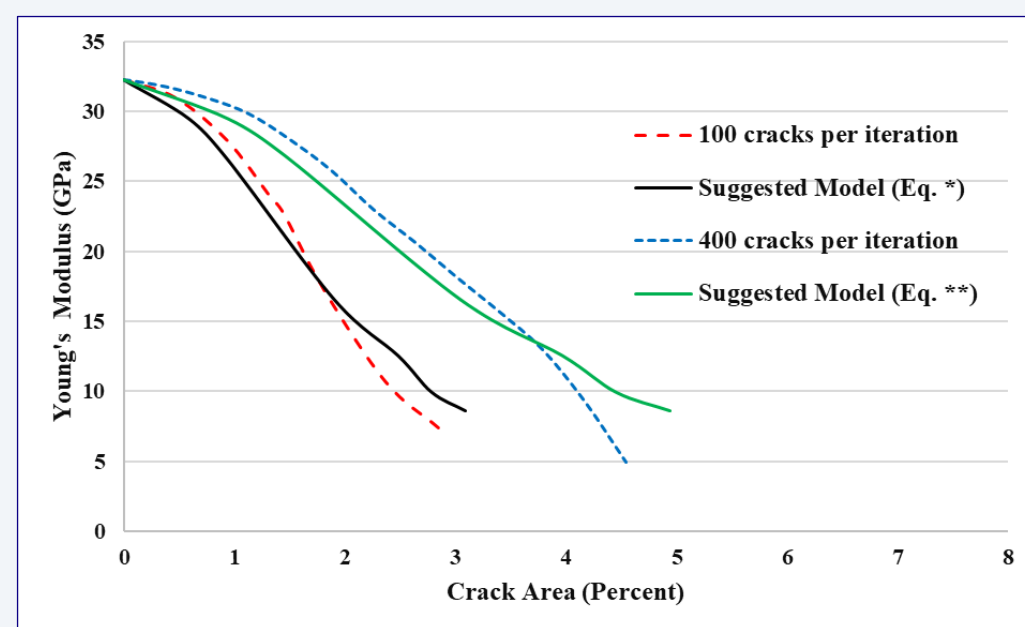
C : crack area percentile for 10 cracks/iteration

A and k are model constants

$M = 1.6 \cdot C$	(*)
$M = 1.6^2 \cdot C$	(**)



Young's Modulus Vs. Crack Area



Young's Modulus Vs. Crack Area

Model Simulation

Scan to view crack propagation



References

- E. J. Garboczi, "Finite element and finite difference programs for computing the linear electric and elastic properties of digital images of random materials.," NIST Internal Report (NISTIR) - 6269. p. 198, 1998.
- Golden Bridge Gate Pixelated image, Kaamar Ltd, 2011