Modeling Moisture Infusion in Ceramic Tiles: A Numerical Simulation Study

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INTRODCUTION

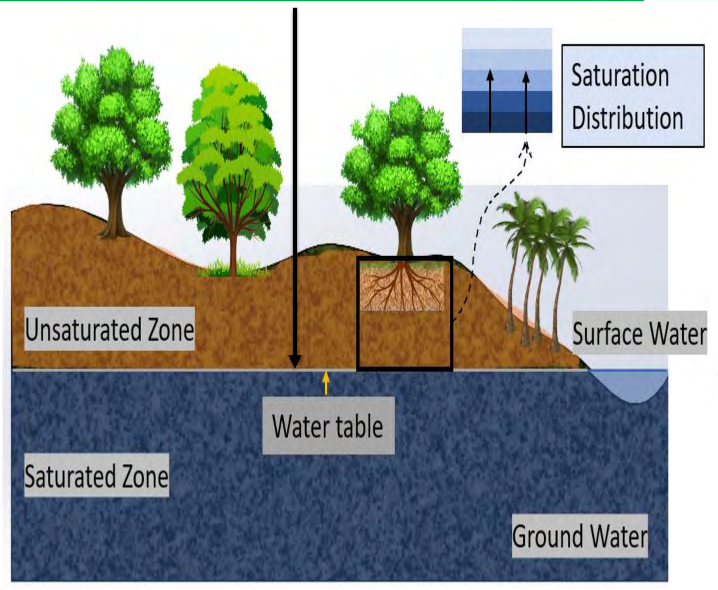
- Ceramics are widely used in filtration system, residential tiling, biomedical engineering etc.
- Understanding how water affects the physical and mechanical properties of ceramics is crucial.
- Moisture modeling is essential for this.
- Moisture resistance is crucial for durable building materials.
- Modeling moisture infusion have implications for development of new materials and technologies.
- Fields like biomedical and energy storage could benefit from a better understanding of moisture infusion in ceramics.

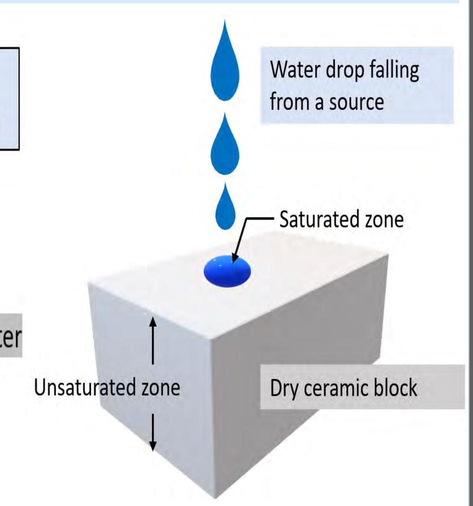
BACKGROUND

- Advanced Cement-Based Materials Laboratory at UWM recently conducted research on developing superhydrophobic ceramic material.
- Water imbibition modeling was required to aid comprehension of water absorption in ceramics with and without coatings.

Richards' equation models moisture movement and saturation distribution from the water table to unsaturated soil.

Present study modifies Richards' equation for water incorporation in ceramic.



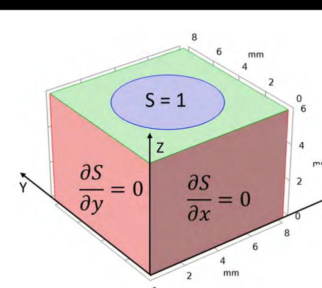


Unsaturated zone towards the surface ⇧ Water table

Water droplet on top surface ⇩ Dry ceramic block towards bottom

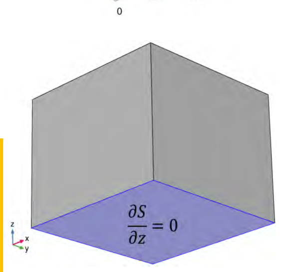
PHYSICAL DESCRIPTION

- Dimension of ceramic block is (8 x 8 x 6) mm along x, y, z axis.
- Saturation of water denoted by S.



Boundary Conditions

Surfaces	Top Circular area	Bottom surface	XZ planes	YZ planes
Saturation	$S = 1$	$\frac{\partial S}{\partial z} = 0$	$\frac{\partial S}{\partial y} = 0$	$\frac{\partial S}{\partial x} = 0$



MATHEMATICAL MODELLING

Governing Equations

- Mass balance: $\epsilon \frac{\partial S}{\partial t} + \nabla \cdot \langle \vec{v}_w \rangle = 0$
- Momentum balance:

$$\langle \vec{v}_w \rangle = -k_r\, K_h \cdot \nabla \left(\frac{\langle p_w \rangle^w}{\rho g} + z \right)$$

- Pore averaged pressure: $\langle p_w \rangle^w = p_{atm} - \langle p_c \rangle$

- Above equations gives Richards equation [1]:

$$\epsilon \frac{\partial s}{\partial t} = \nabla \cdot k_r \frac{K}{\mu} \left(- \frac{d\langle p_c \rangle}{dS} \right) \nabla S + \frac{k \rho g}{\mu} \left(\frac{dk_r}{dS} \right) \frac{\partial S}{\partial z}$$

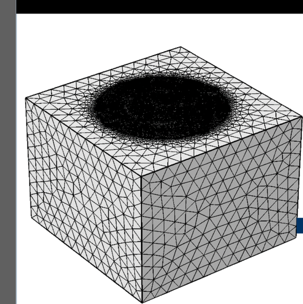
- Richards equation for ceramic tile:

$$\epsilon \frac{\partial s}{\partial t} = \nabla \cdot \frac{0.04\, K}{\mu} \frac{S^{1.75}}{1-S} \nabla S + \frac{K \rho g}{\mu} 3S^2 \frac{\partial S}{\partial z}$$

k_r = relative permeability
K_h = Hydraulic conductivity
$\langle p_c \rangle$ = Capillary pressure
K = Permeability
ϵ = Porosity

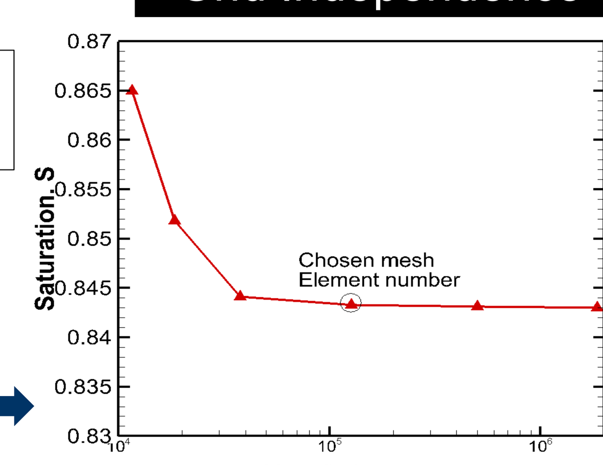
NUMERICAL SIMULATION

Mesh Generation



Mesh type: Hybrid
Mesh elements: 126,948

Grid Independence



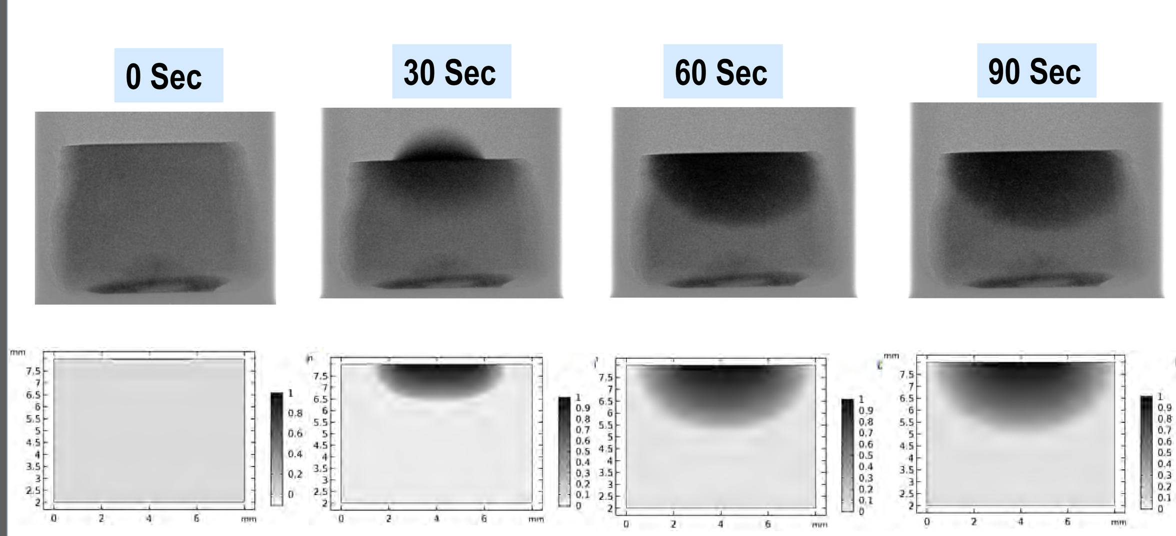
Variation of saturation value (S) at (4, 4, 5.5) at time, t = 1 min

Simulations use COMSOL Multiphysics, a commercial software, with the Finite Element Method (FEM) [2]

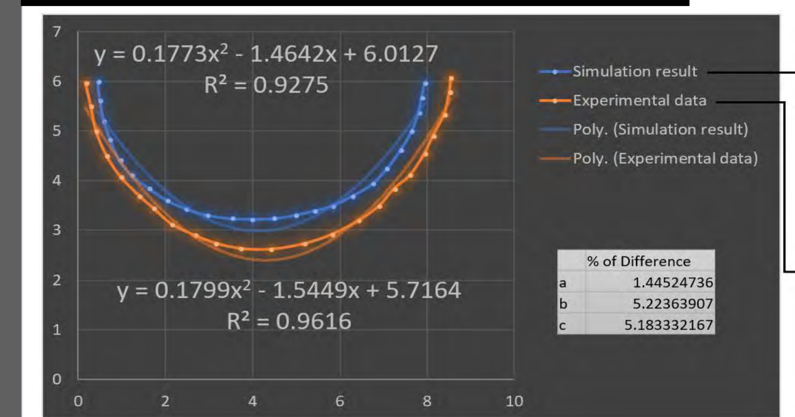
CODE VALIDATION

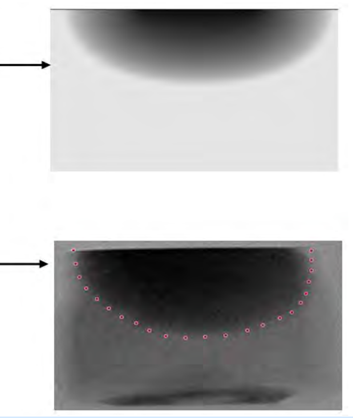
Validate code via experiment comparison

- Neutron Microscope imaging (NMI) experiments were performed on a ceramic tile sample at the Paul Scherrer Institute in Switzerland [3].
- Sample underwent neutron beam exposure while water droplet was added.
- Experimental results (top) is compared to the simulation results of water saturation (bottom).



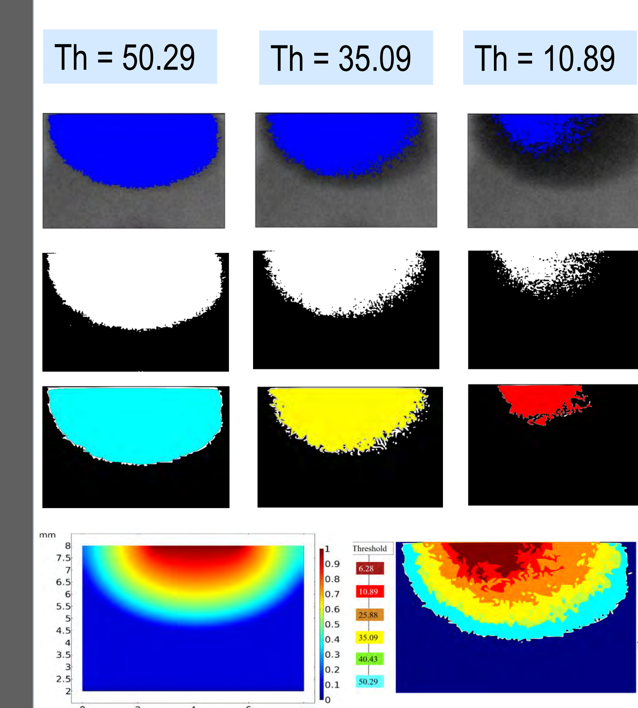
Saturation front comparison



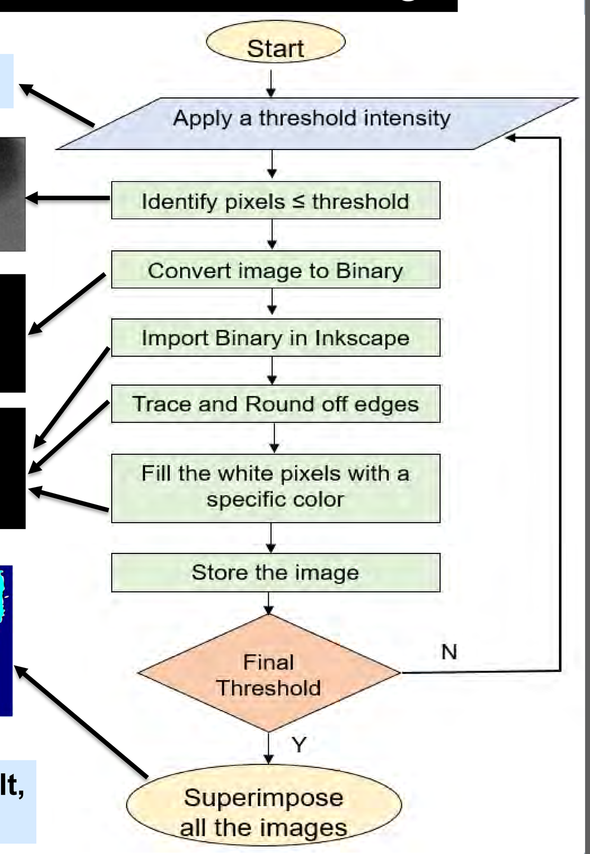


A comparison of the experimentally observed and numerically predicted saturation fronts. Bold blue line and bold orange line denotes the simulation and experimental data respectively. Faded blue and faded orange lines respectively denote second order polynomial trendline for the simulation font and experimental font.

Saturation distribution from NMI -Thresholding



Saturation level for - a) Simulation result, b) extracted in image thresholding

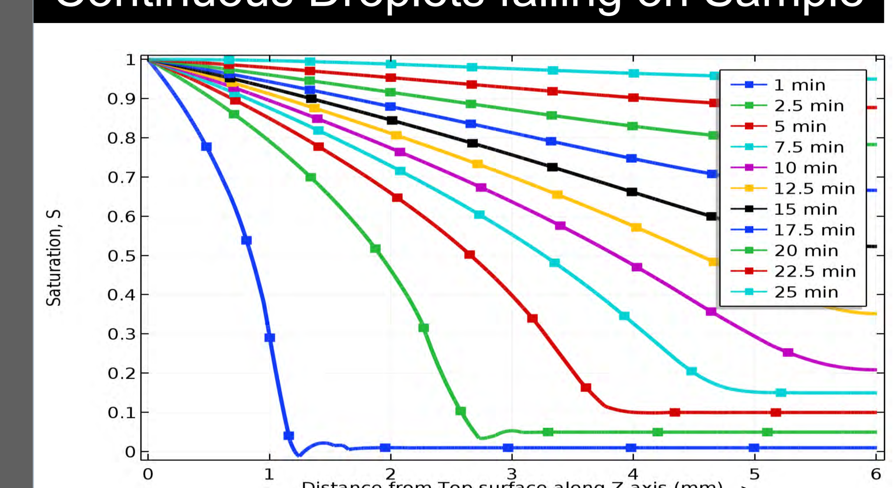


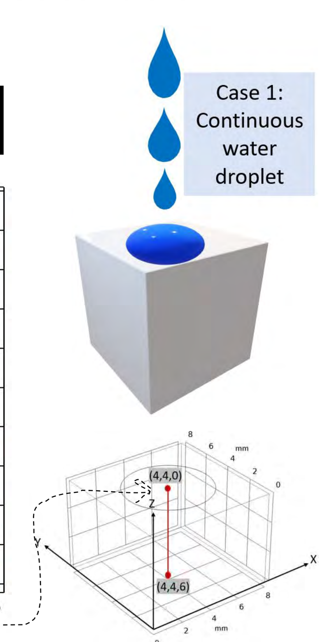
All three comparisons are in excellent alignment with the experimental result.

RESULTS

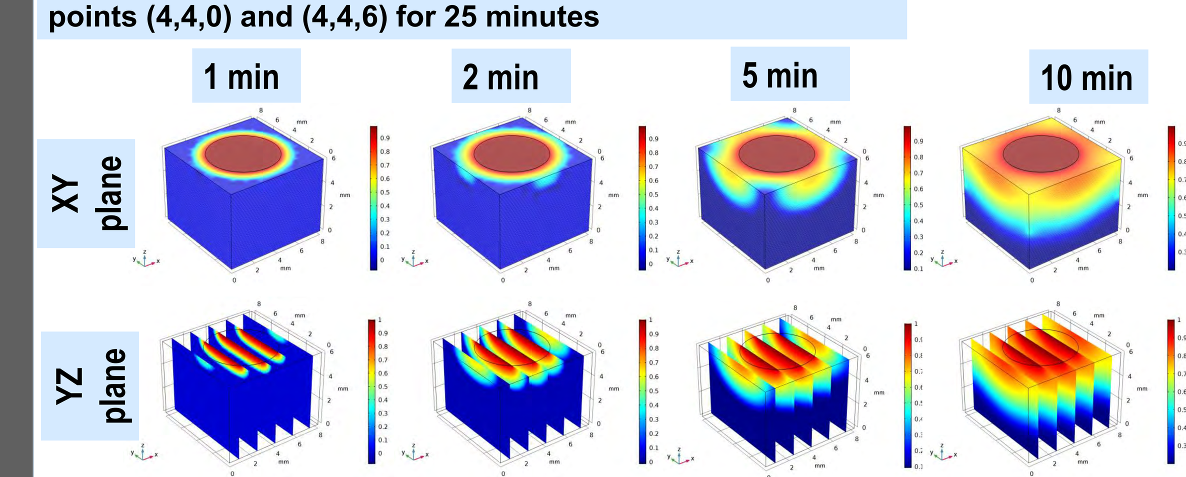
Three cases were investigated for the saturation distribution over time.

Continuous Droplets falling on Sample



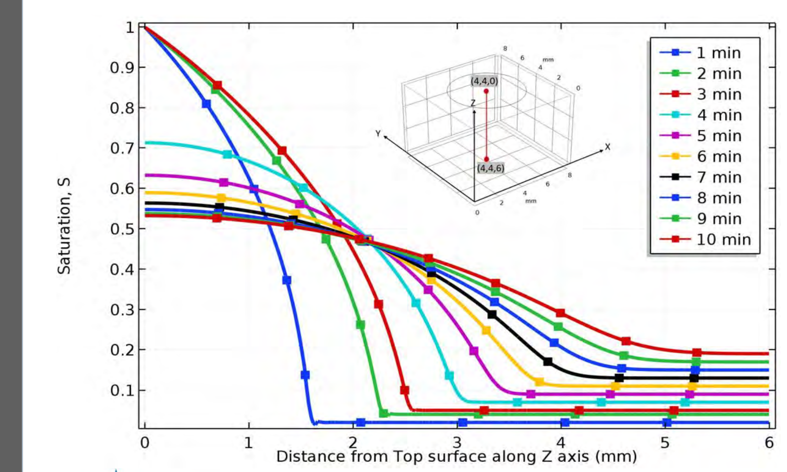


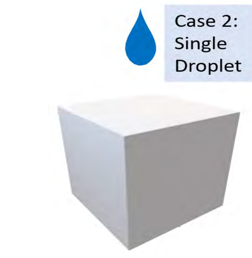
Saturation distribution along the line passing through the points (4,4,0) and (4,4,6) for 25 minutes



Saturation distribution for continuous droplets of water (time lapse between the droplets is negligible)

Spread of Single Droplet

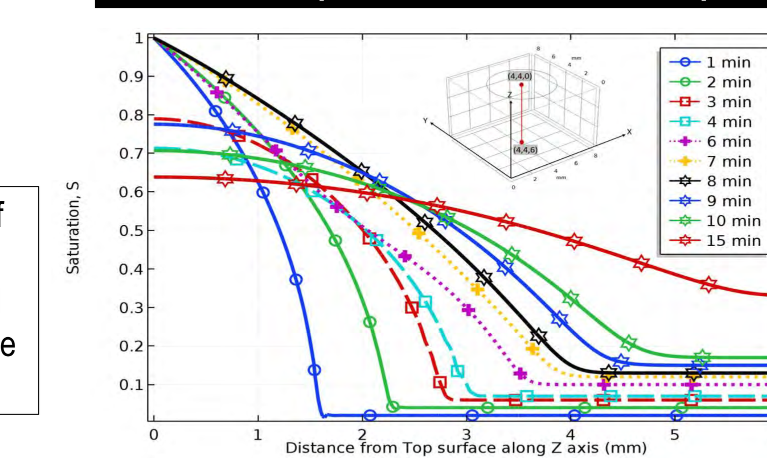




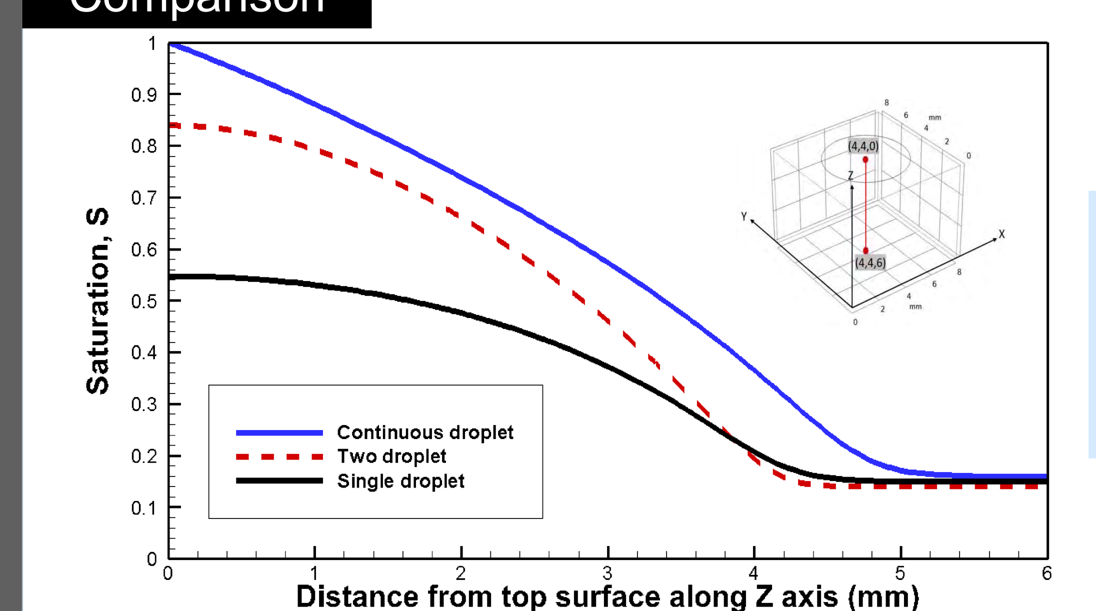
Single droplet saturation distribution for a period of 10 minutes.

Two Droplets with Time Lapse

Saturation distribution of two droplets for 15 minutes with the second droplet hitting the surface at t=5 min.



Comparison



CONCLUSION

- The saturation level of water is influenced by the amount of water received over time.
- Saturation levels in the first 2.5 minutes are the same for all cases.
- The first scenario maintains a constant saturation level of 1 on the top surface.
- 2nd case demonstrates a continuous drop of saturation at the top surface.
- In the third scenario, saturation levels fluctuate, beginning at 1 and dropping gradually, before returning to 1 and lowering again.

REFERENCES

1. R. Masoodi and K. M. Pillai, Wicking in porous materials: traditional and modern modeling approaches. CRC Press, 2012.
2. COMSOL Multiphysics user manual.
3. Zemajtis, Filip, Abul Borkot Md Rafiqul Hasan, Krishna M. Pillai, Pavel Trtik, Okan Yetik, and Konstantin Sobolev. "From superhydrophobicity to superhydrophobicity. Neutron microscope imaging and water imbibition modeling of porous surfaces treated with surface changing nano-coatings."(In review)