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2023 Sandia FORCEE Summer Research Symposium

# Effect of Printing Orientation on Geomechanical and Geophysical Properties of Gypsum-Based 3D Printed Geomaterials

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Future of Research Climate, Earth & Energy
2023 SANDIA FORCEE

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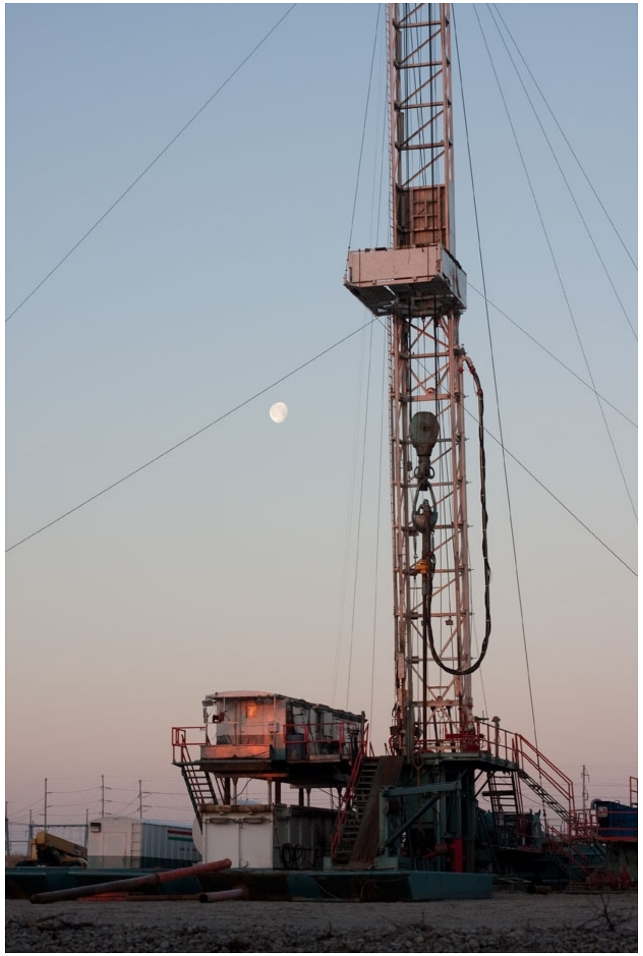
# Experimental Repeatability Concerns with Natural Rock

- Natural heterogeneities in rock causes repeatability challenges in experimental testing.
- 3D printed rock can be produced in testable configurations with reproducible microstructures. However, its elastic behavior and microstructure needs to represent that of natural rock.
- Proposed method: Use ultrasonic velocities and mechanical testing to investigate the response of 3D printed rock to loading and evaluate its degree of anisotropy.

https://news.unl.edu/

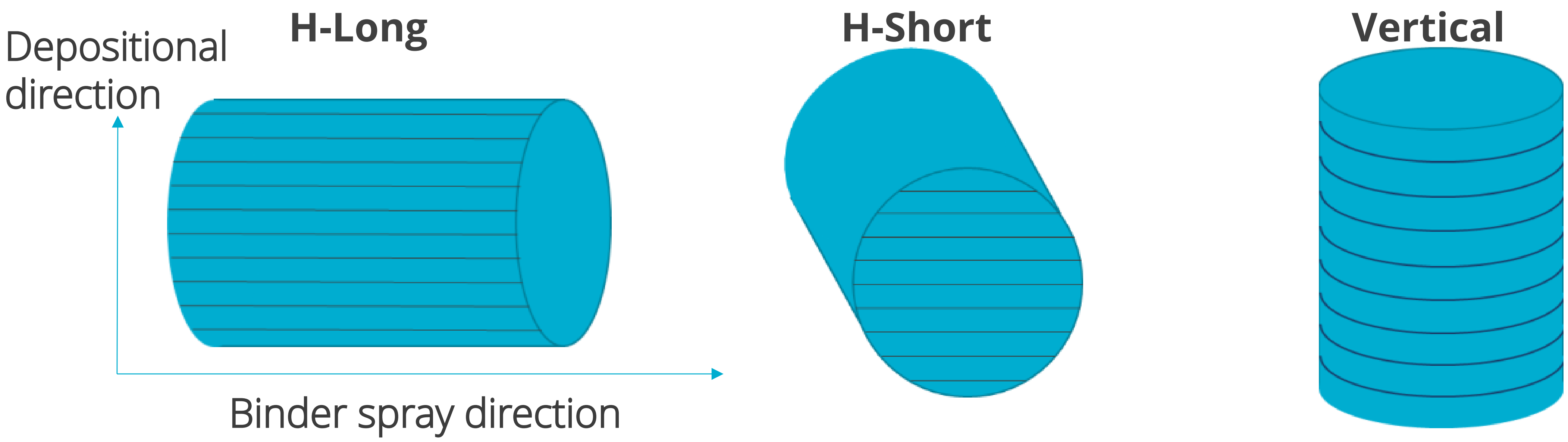


*Carbon-storage project combines innovation and outreach*
https://news.illinois.edu/view/6367/205138

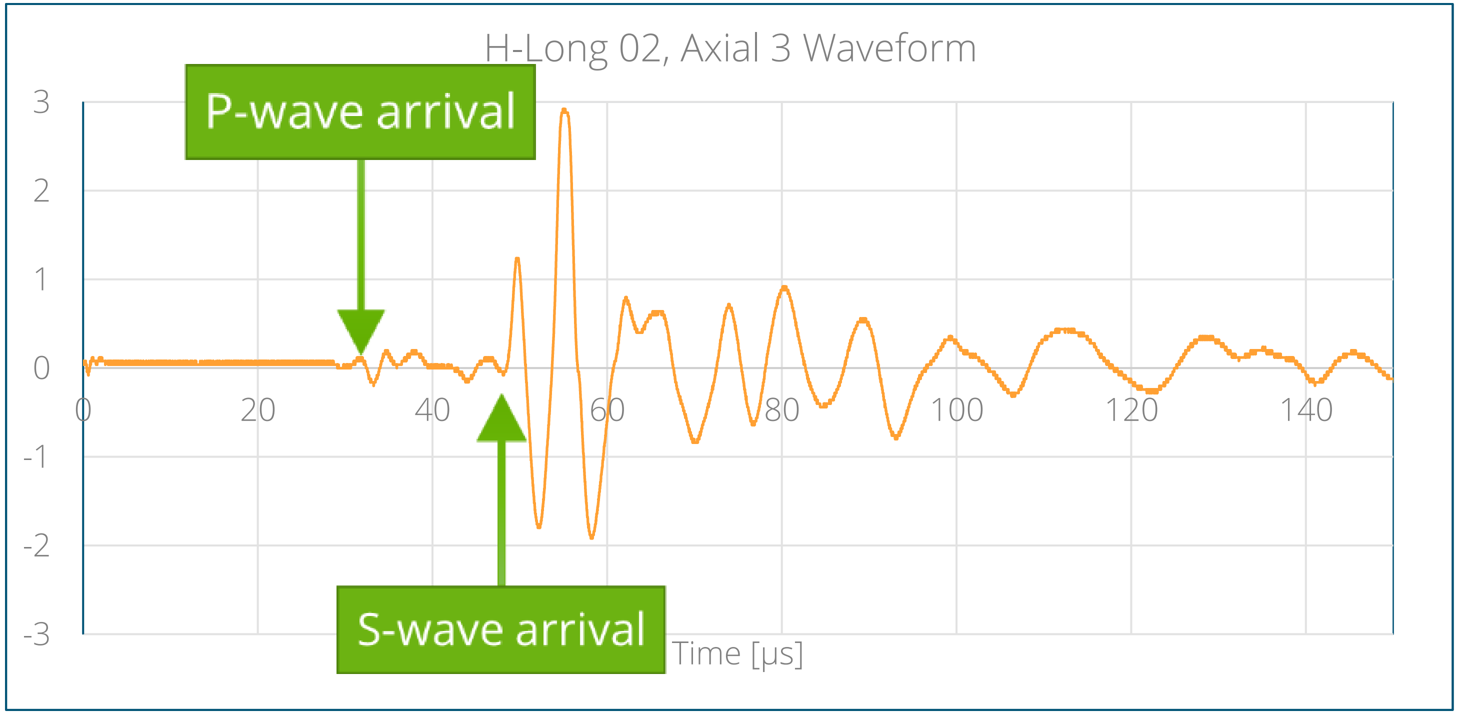
## Prior Work Done

- Design for repeatable 3D printing configurations.
- Bassanite + Binder forms Gypsum: $CaSO_4 \cdot 0.5H_2O + 1.5H_2O = CaSO_4 \cdot 2H_2O$.
- Determining that printing orientation, binder spray direction, and post-printing humidity have an effect on mechanical properties.

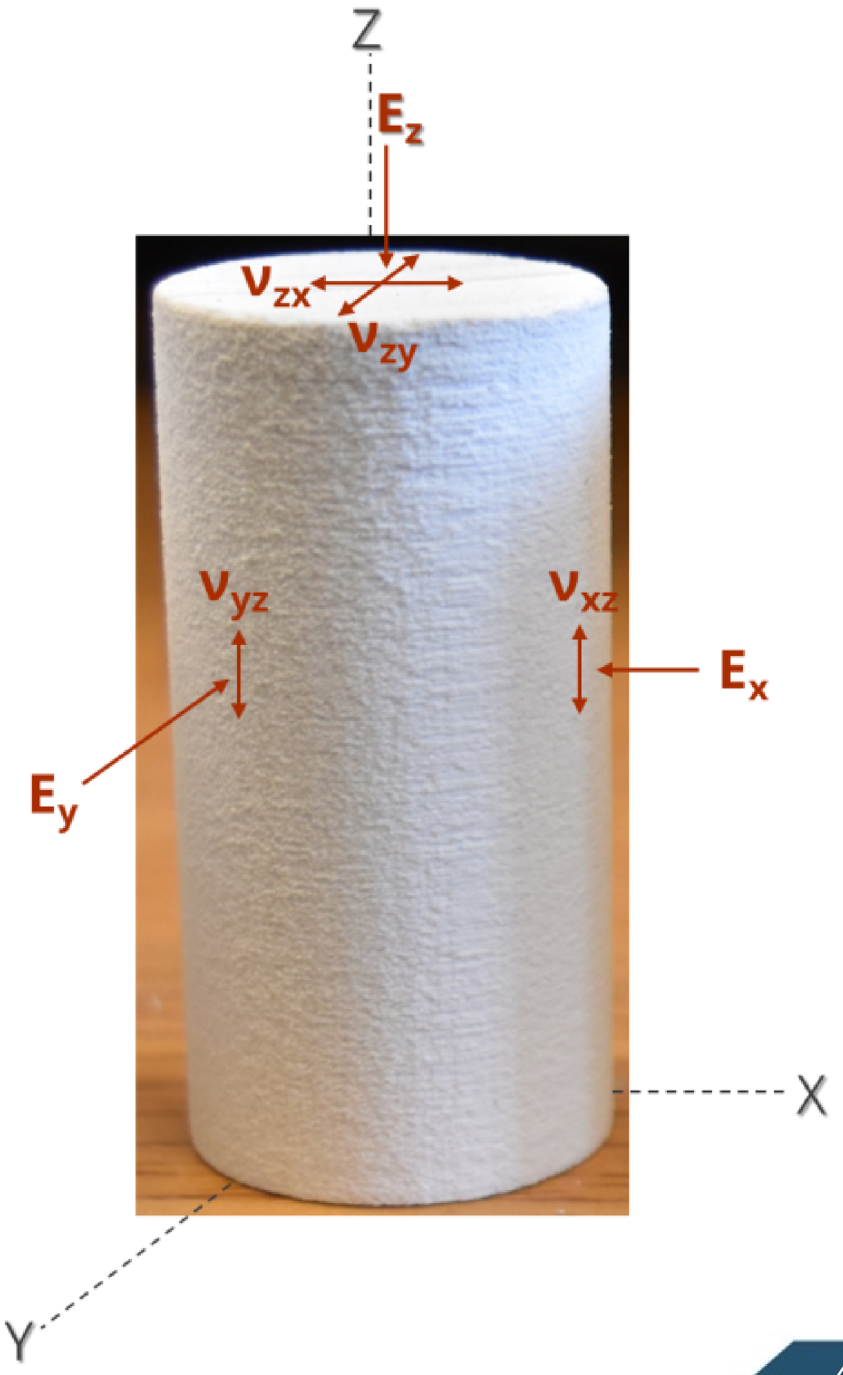
**Humidity states:** Dry (10% RH), Oven Dry (0% RH), and Humid (80% RH)



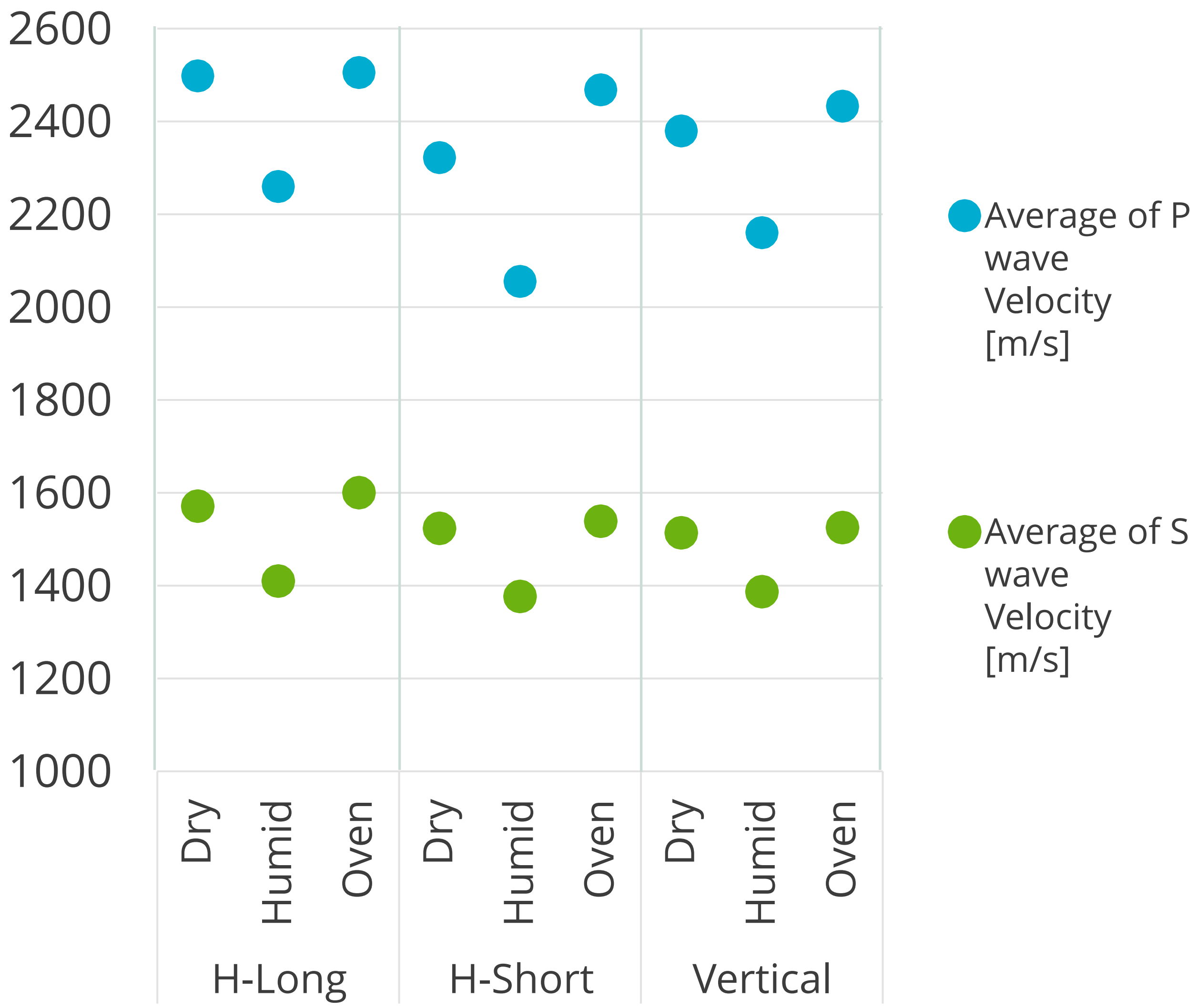
# Procedure: Ultrasonic Velocity




- Velocity measurements taken prior to loading.
- S-wave transducers were used to identify first arrival of P- and S- waves.
- Velocity indicates elastic properties.



# P and S Velocity Averages




| Configuration | Avg. P wave Velocity [m/s] | Avg. S wave Velocity [m/s] |
|---|---|---|
| H-Long | 2453 ± 177 | 1543 ± 97 |
| H-Short | 2282 ± 230 | 1516 ± 110 |
| Vertical | 2324 ± 211 | 1475 ± 69 |

| Material | P wave Velocity [m/s] | S wave Velocity [m/s] |
|---|---|---|
| Chalk | 2300-2600 | 1100-1300 |
| Sandstone | 1400-3300 | 700-2800 |
| Concrete | 3600 | 2000 |
| Granite | 5500-5900 | 2800-3000 |

https://pburnley.faculty.unlv.edu

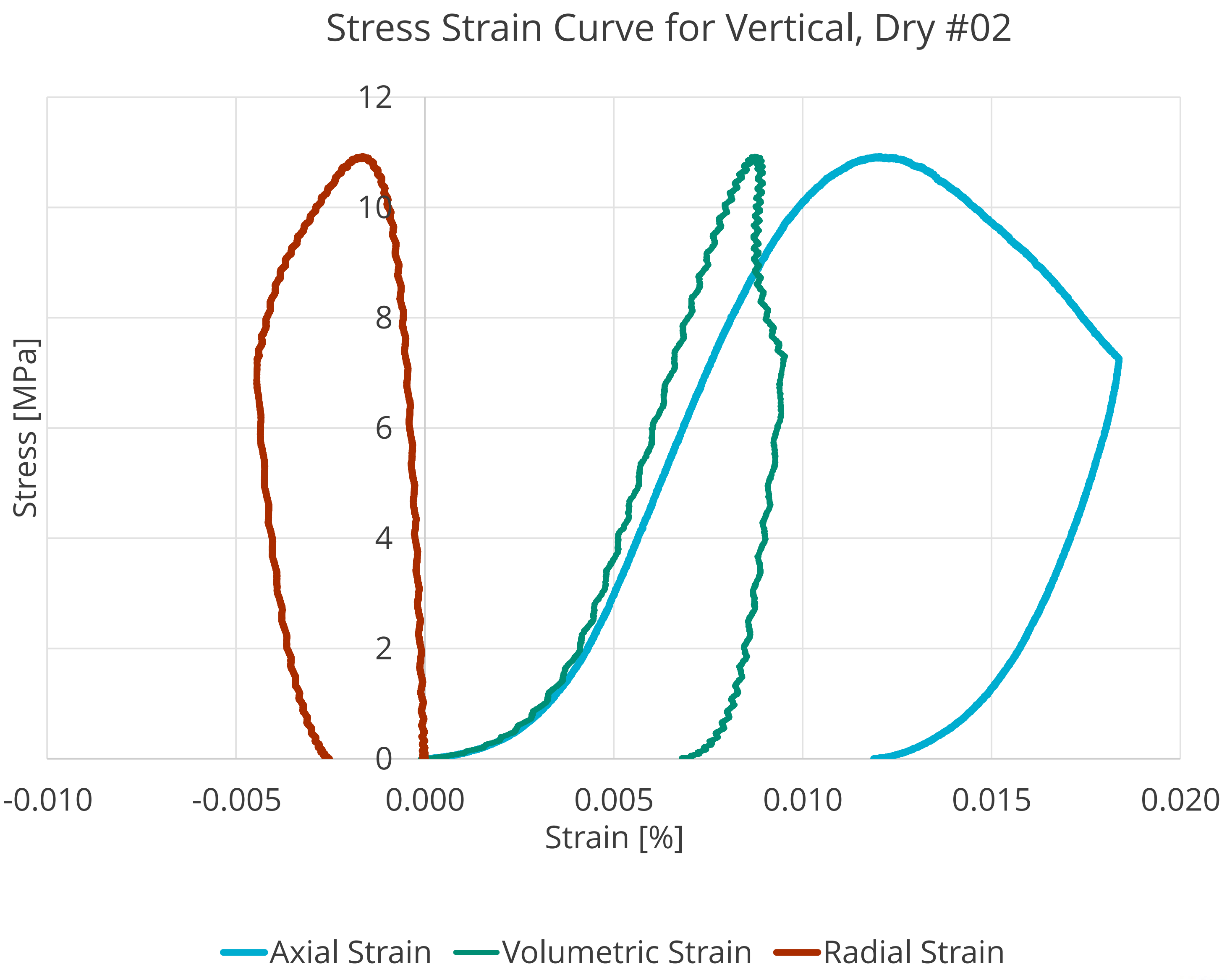
# Procedure: Unconfined Compression Strength (UCS)

UCS Tests

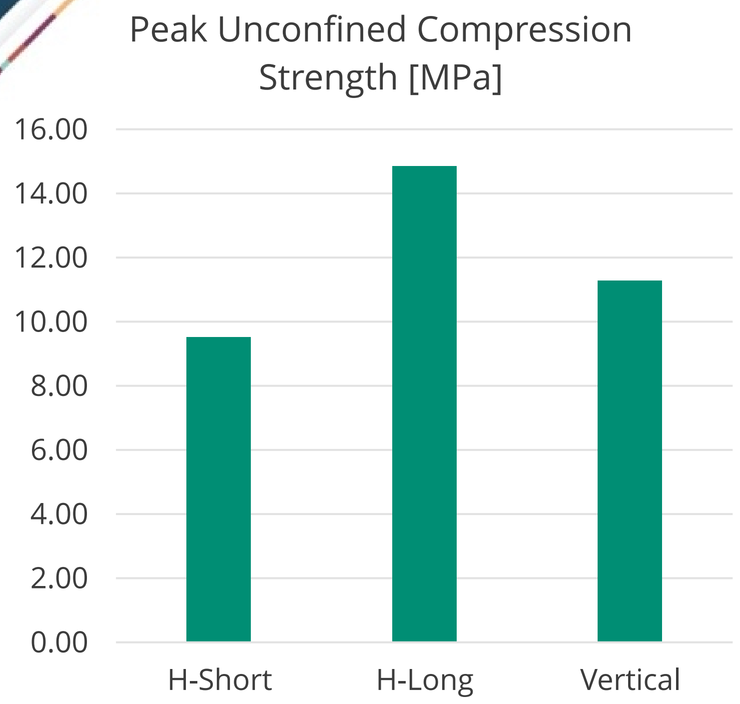
- 3" x 1.5" cylindrical samples
- Axial and radial LVDTs are used to measure strain.

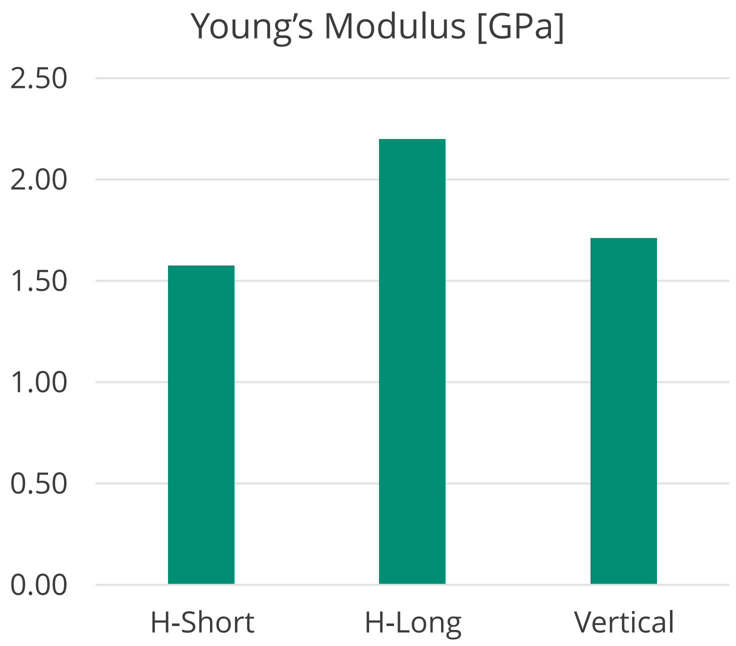
Measured properties:

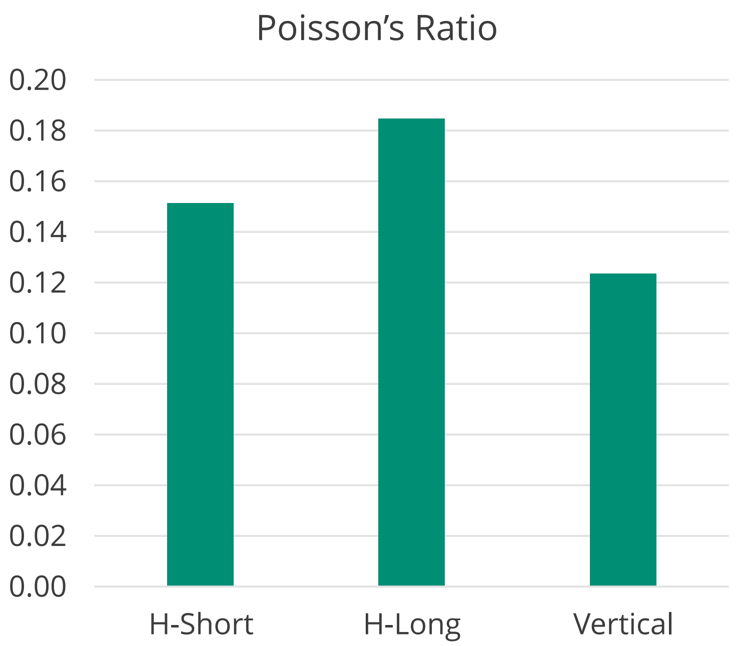
- Peak UCS strength.
- Young's (Elastic) Modulus
- Poisson's Ratio

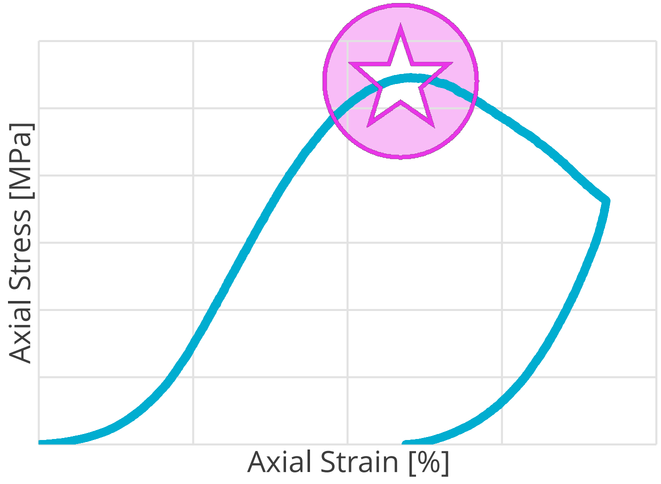


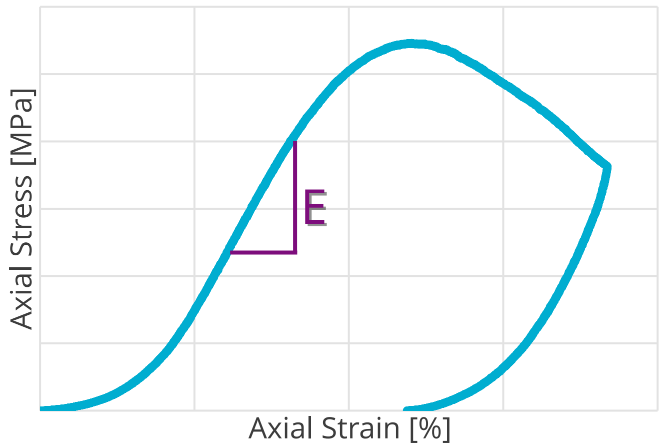
# UCS Test Results by Printing Orientation

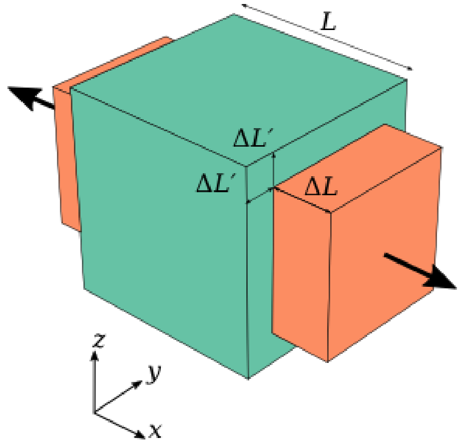


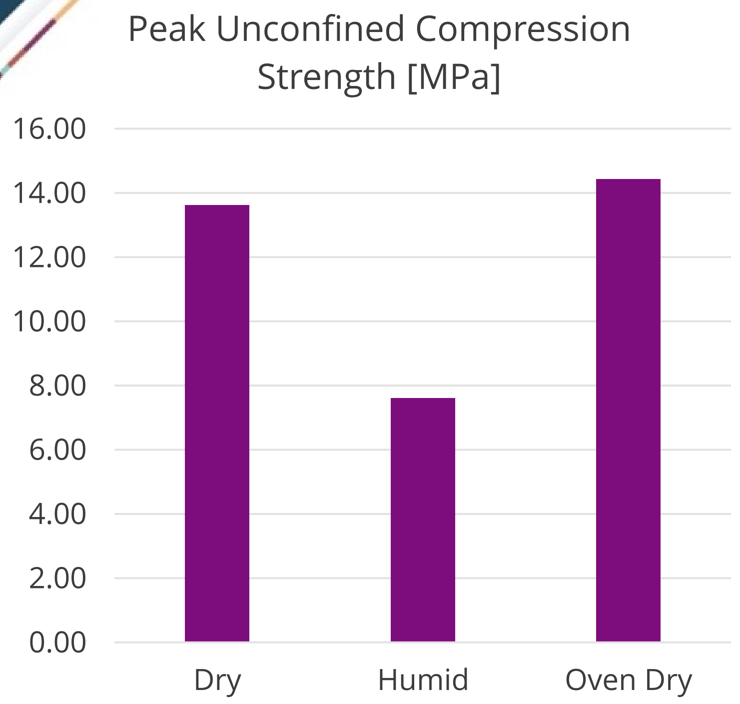



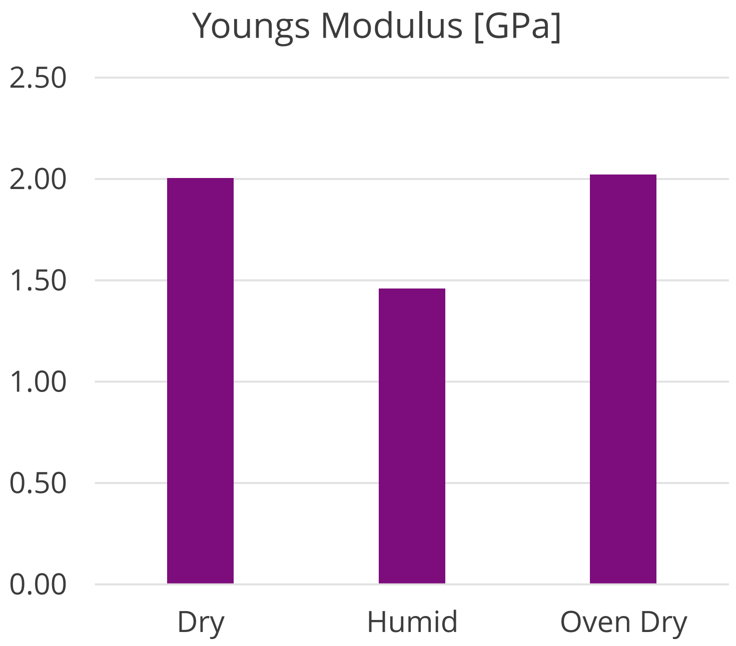



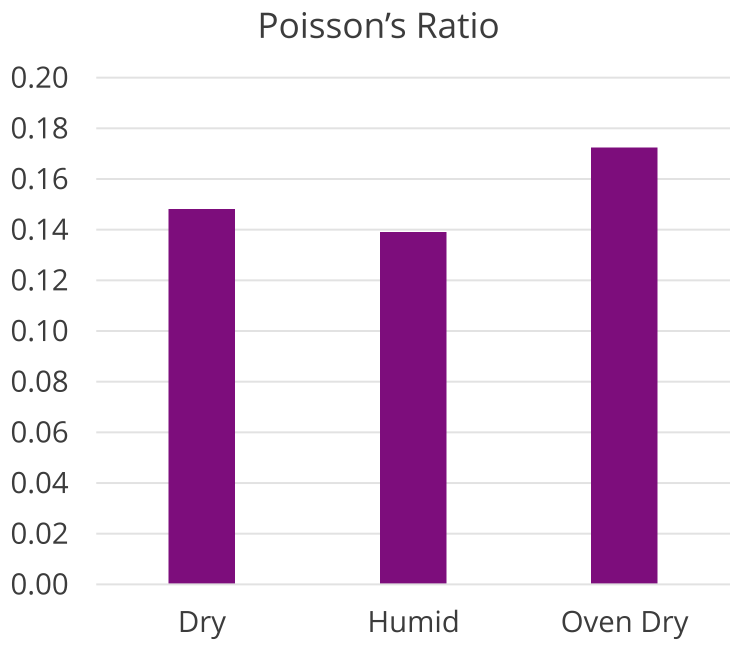



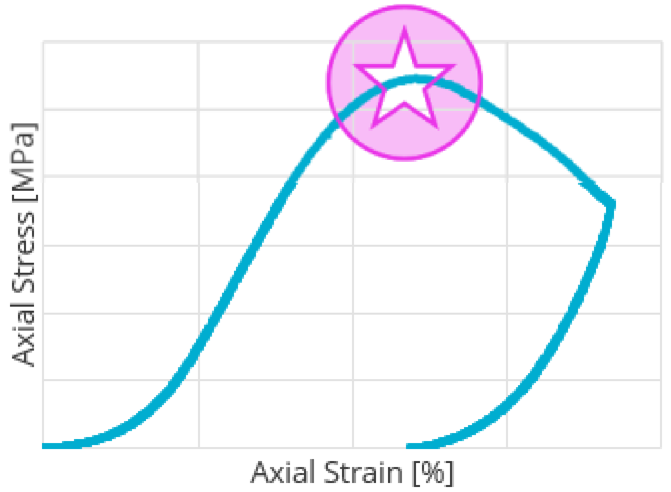



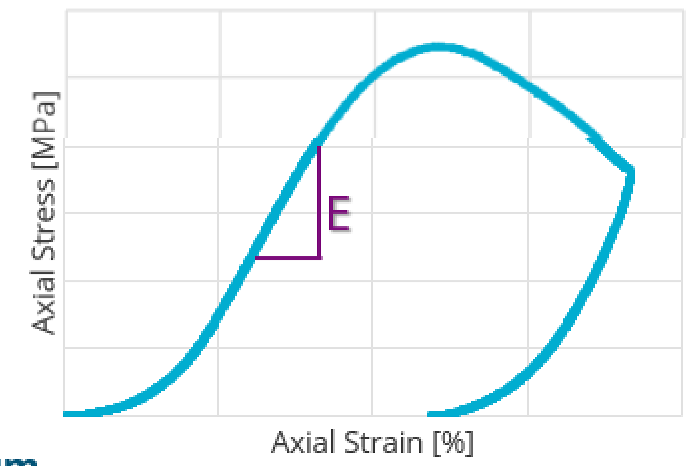
# UCS Test Results by Post-Printing Humidity

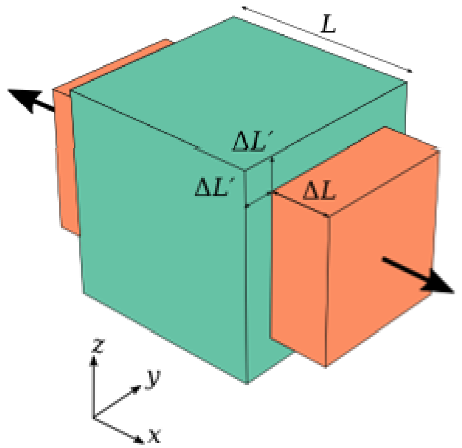


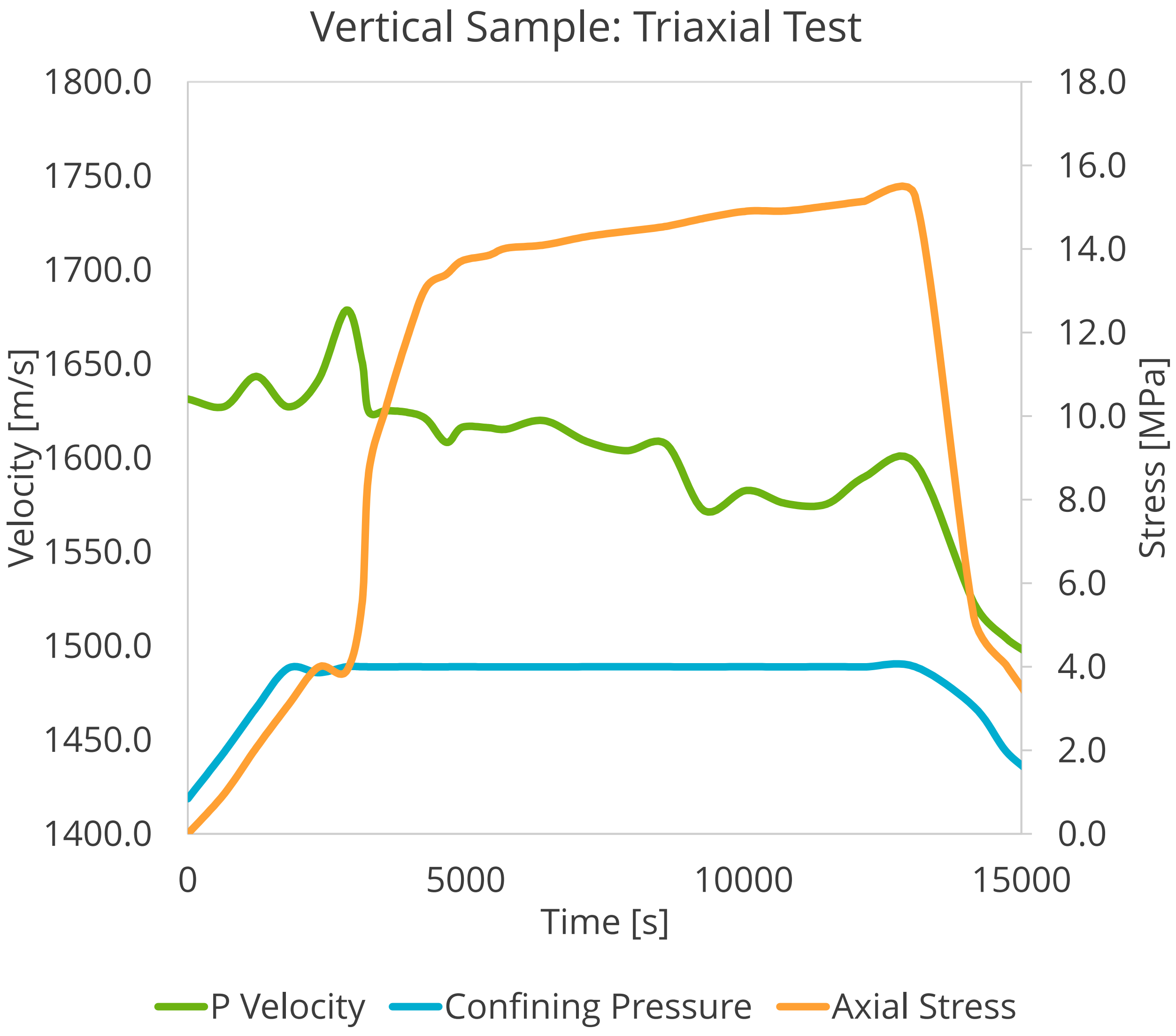
# Triaxial Test with P-wave Measurement

Observe velocity change with damage.

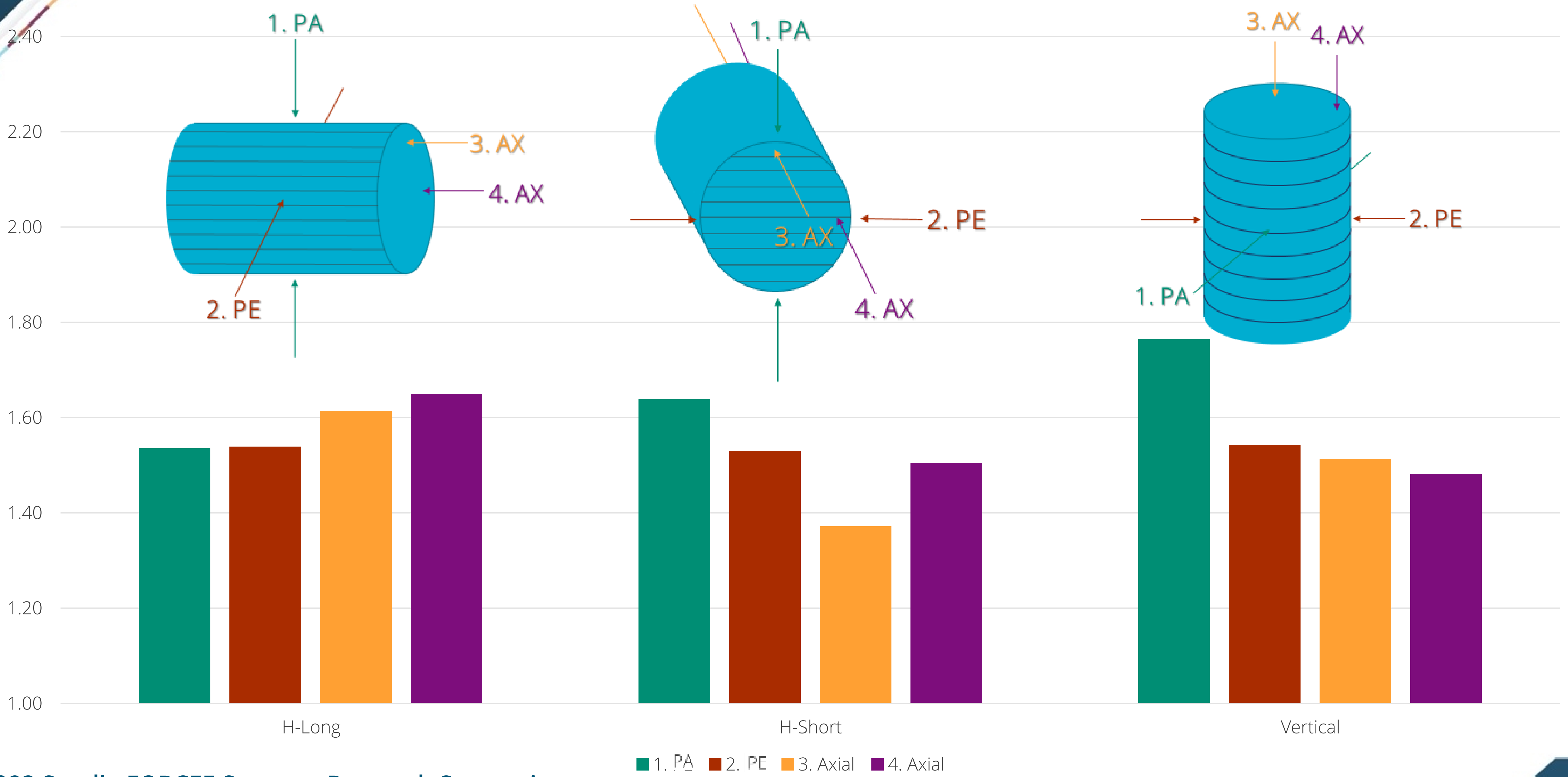
- Confining pressure: 4 MPa.
- Sample loaded at constant axial strain rate.
- Throughout loading, Vp decreases.

Elastic properties (and velocities) are stress dependent.

- Velocity is lower under confinement
- E = 14.18 GPa.
- $\nu = 0.06$.



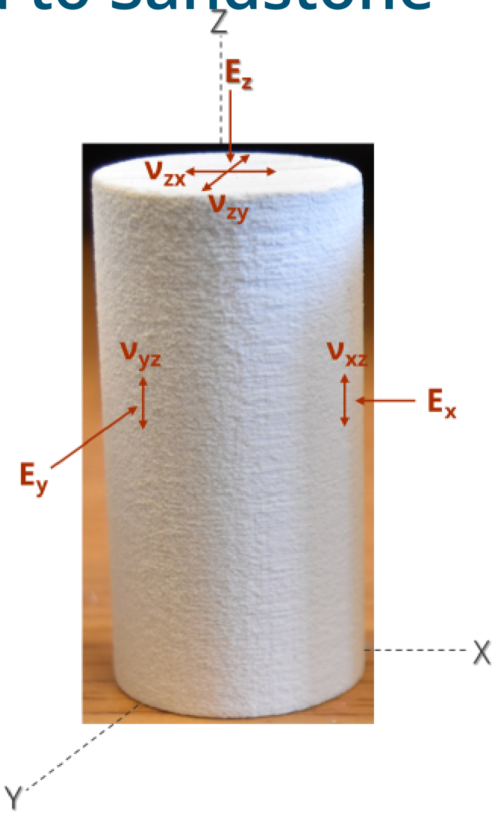
# P:S Velocity Ratio by Print Orientation



# Elastic Properties of 3D Printed Rock Compared to Sandstone

- Velocity correlates to the dynamic elastic properties.
- In an isotropic rock, 1 value of each elastic constant is needed to characterize the behavior. 3D printed rocks are not isotropic.
- Confinement influences the elastic properties.

| H-Long & Oven Dry: | Dynamic Young's Modulus [GPa] | Dynamic Poisson's Ratio |
|---|---|---|
| X direction | 8.8 | 0.12 |
| Y direction | 7.8 | 0.13 |
| Z direction | 9.3 | 0.18 |
| Argenta Sandstone (Dry, Lab Tested) | 14.3* | 0.19* |




$$\nu = \frac{\left(V_P/V_S\right)^2 - 2}{2\left[\left(V_P/V_S\right)^2 - 1\right]}$$

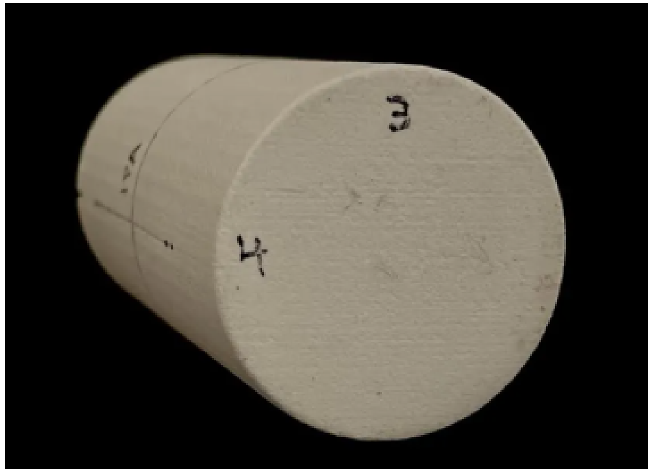
$$E = V_P^2 \rho \left[\frac{(1+\nu)(1-2\nu)}{(1-\nu)}\right]$$

*Bondarenko et al, 2022

# Conclusions and Recommendations

These results highlight the importance of directional anisotropy and post-printing environmental conditions on the mechanical properties of 3D printed materials.

- Orientation: H-Long
- Curing Humidity: Oven Dry
- Stress-dependency exhibited.
- Velocities for 3D printed rock are similar to chalk or loose sandstone.
- Geometry is likely orthotropic, meaning that 9 independent parameters are needed.



**Hooke's Law for Orthotropic Material**

$$\begin{bmatrix} \epsilon_{xx} \\ \epsilon_{yy} \\ \epsilon_{zz} \\ 2\epsilon_{yz} \\ 2\epsilon_{zx} \\ 2\epsilon_{xy} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{yx}}{E_y} & -\frac{\nu_{zx}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xy}}{E_x} & \frac{1}{E_y} & -\frac{\nu_{zy}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xz}}{E_x} & -\frac{\nu_{yz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{yz}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{zx}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{xy}} \end{bmatrix} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{yz} \\ \sigma_{zx} \\ \sigma_{xy} \end{bmatrix}$$

<u>Printing Directions:</u>

- H-long
- H-short
- Vertical

<u>Post Printing Humidity:</u>

- Ambient
- 80% Humid
- Oven Dry

# Acknowledgements

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## Thank you for your attention!

**Questions?** Email me at juljone@sandia.gov | jajones046@gmail.com*