DETERMINING LEEB HARDNESS AND ITS CONTROLLING FACTORS TO ASSESS THE STRENGTH OF SEDIMENTARY ROCKS

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Abstract

Hardness, defined as resistance to surface deformation, is intrinsic to all materials including sedimentary rocks. The variables controlling sedimentary rock hardness are not completely understood. By understanding these factors, we may better understand related rock strength. Rock strength, defined as a rock's resistance to brittle failure under loading, is important to many industries such as mining, civil engineering, and petroleum exploration.

Rock strength is typically quantified by triaxial load cell tests, which are expensive, time consuming, and require substantial investment in laboratory setup. To circumvent this, other devices have been employed to determine rock strength. For example, the Proceq Equotip Bambino micro-rebound hammer (Bambino) has been used for decades to test the hardness of manmade materials, and to determine strength. Geologic studies empirically correlate Bambino-derived hardness (called Leeb hardness) and uniaxial compressive strength (UCS). However, significant scatter in the data suggest that certain intrinsic (e.g., density) or extrinsic factors (e.g., sample volume) need to be considered for a better correlation.

In this study, we examined relations between Leeb hardness and UCS values, accounting for properties such as: lithology, bulk mineralogy, water loss, volume, density, and effective porosity. Intrinsic properties such as bulk mineralogy, density, effective porosity, and water content correlate with Leeb hardness. Also, sample UCS is related to its density, effective porosity, and mechanical hardness. Ultimately, this study validates previous studies and sheds insight on the controlling factors of a rock's hardness and strength.

Introduction & Background

Bambino Rebound Hammer

- Dietmar Leeb invented the Bambino in 1977 to test hardness of manmade materials (e.g. steel) by measuring the ratio of impact velocity to rebound velocity (Figure 1)
- Bambino yields Leeb hardness (HLD) values defined as:

$$HLD = (V_i / V_f)*1000$$

Where: HLD= Leeb hardness, Vi = initial velocity, Vf= final velocity

Factors Controlling Hardness

- Previous studies have found an empirical link between rock hardness and its corresponding UCS
- The properties found to have an effect on rock hardness include:
  - Porosity
  - Density
  - Water Saturation
  - Mineralogy
  - Sample Volume
  - Grain Size
  - Sedimentary structures

Statistical Methods

- Multiple statistical methods have been used for data analysis
  - Some methods used trimmed means and parametric statistics
  - Other methods examined non-parametric methods
  - Questions arise about data preservation when using trimmed means
  - The best statistical method to analyze hardness data

Sample Collection

- Sedimentary rock samples were collected in Colorado, New Mexico, Oklahoma, and Texas (Figure 2)
- All samples named, marked with vertical orientation, and GPS location

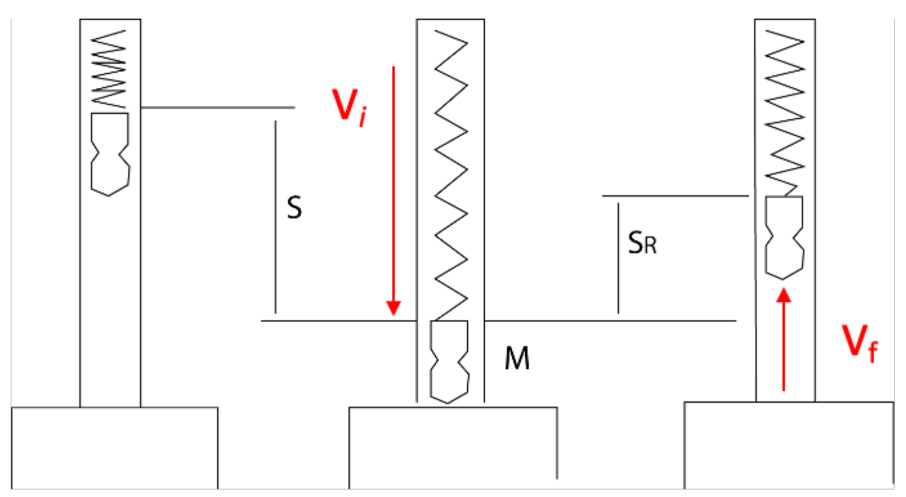

Figure 1: Bambino operation. "S" is the striking phase, "M" is the impact phase, and "SR" is the rebound phase.

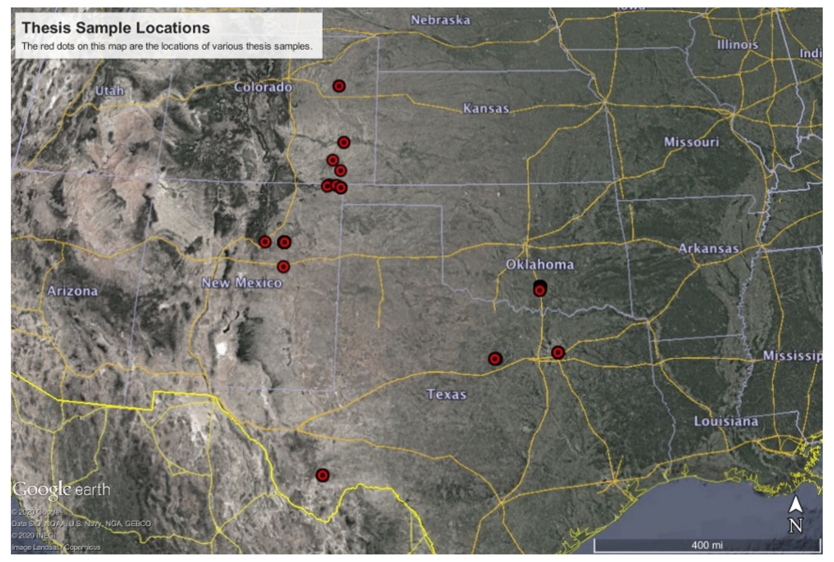

Figure 2: Sample locations.

Methods

Calibration Verification

- Various sample mounts (Figure 3) tested including: tabletop, vise, sandbox, table clamped, table with cardboard layer, and wood block
- Manufacturer provides an engraved hardness on each side of the calibration block
- Purpose was to determine if a sample mount could affect hardness, examine data distribution, and whether true hardness or relative hardness was measured

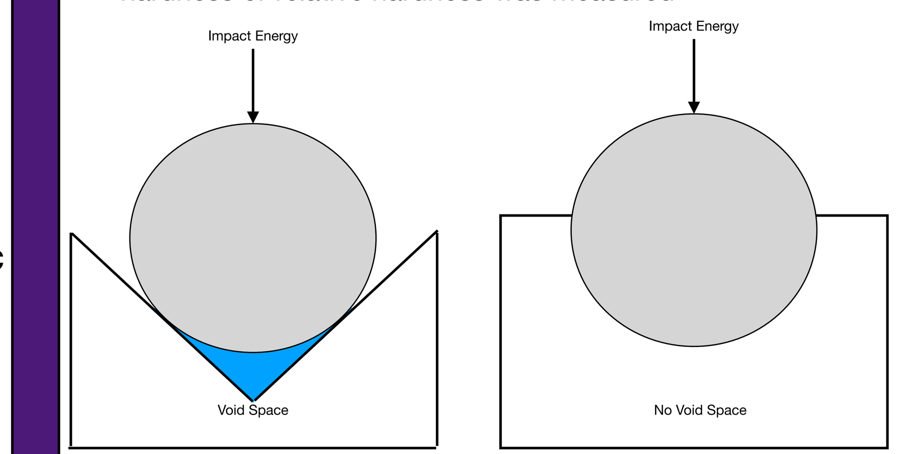

Figure 3: Cartoon depicting different sample mounts and the potential introduction of void space when measuring hardness.

Anisotropy

- Measured hardness perpendicular and parallel to bedding planes (black lines, Figure 4)
- Equation taken from Saroglu and Tsiambaos (2007) and modified to reflect hardness:

I(a)m=HLD(m)Perpendicular / HLD(m)Parallel

- Isotropic mediums should have a value of 1, reflecting no difference in hardness with respect to measurement direction

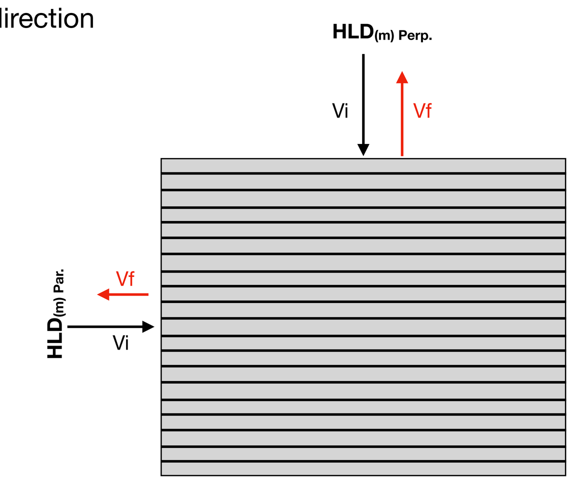

Figure 4: Model showing hardness measurements with respect to bedding geometry for anisotropy calculations. Black lines represent bedding or layering.

UCS Correction

- Hoek and Brown (1980) proposed a correction factor for cores that are not 50mm in diameter (Figure 5)
- Larger cores have higher probability of flaws than smaller cores, leading to lower UCS values (Figure 5)
- Correction equation from Hoek and Brown (1980):

$$\sigma_D = \sigma_{D50}(50/D)^{0.18} = [\sigma_D/(50/D)^{0.18}] = \sigma_{D50}$$

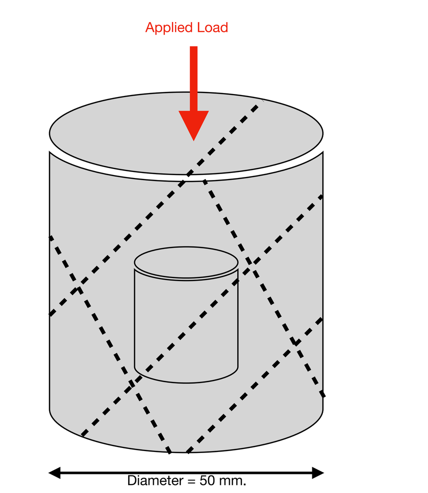

Figure 5: Illustration of how core size can influence UCS measurement values. The dotted lines represent flaws within the core.

X-Ray Diffraction

- XRD analysis helped identify the bulk mineralogy of samples
- Used Rigaku Smartlab SE
- Scan range= 5-50 degrees at 40kV
- Match! Software used for Rietveld Refinement
- Samples grouped by: silicates, carbonates, and clays

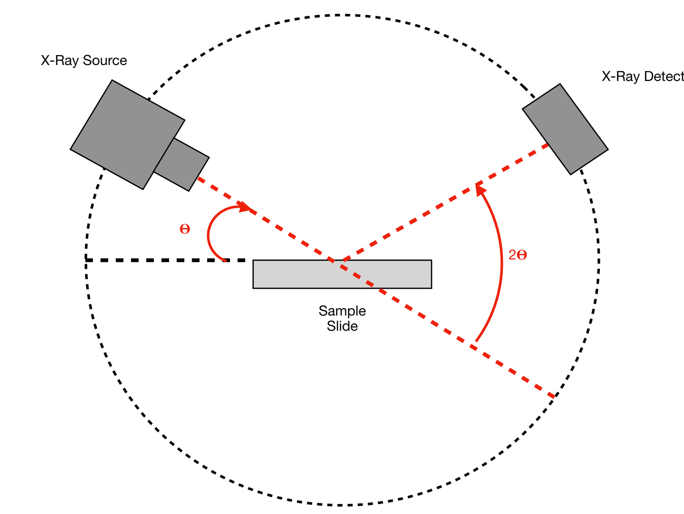

Figure 6: Diagram illustrating X-Ray diffraction analysis. A source emits an x-ray which hits the sample slide and the refracted beams are then measured by the detector.

Results

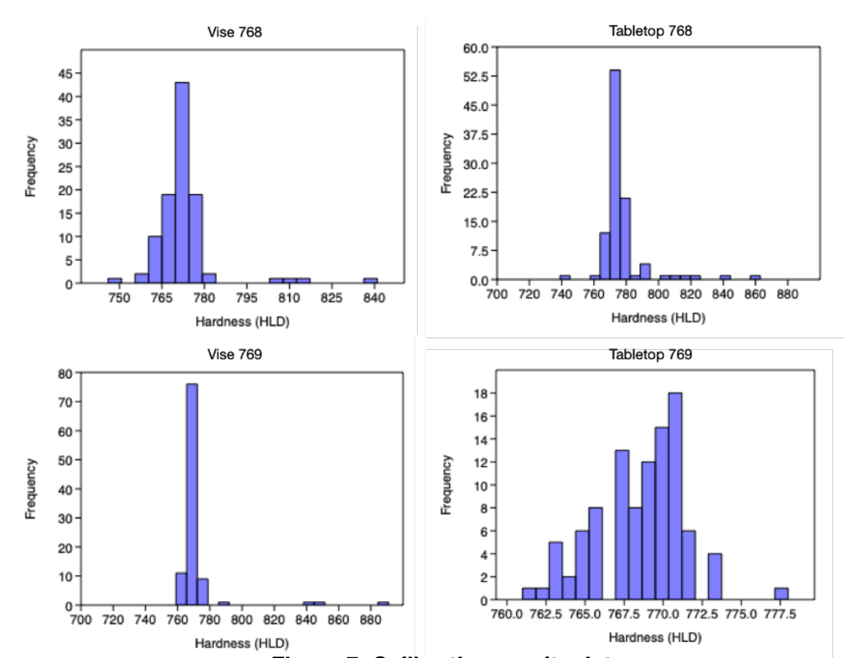

Figure 7: Calibration results data

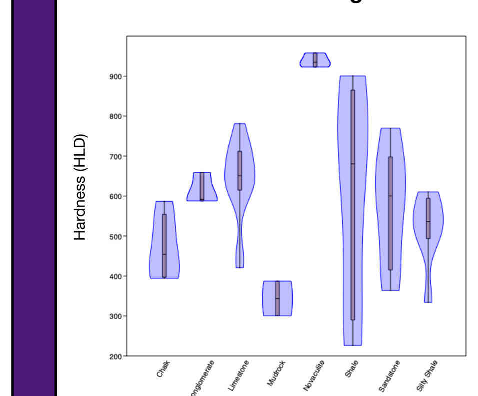

Figure 8: Hardness by lithology

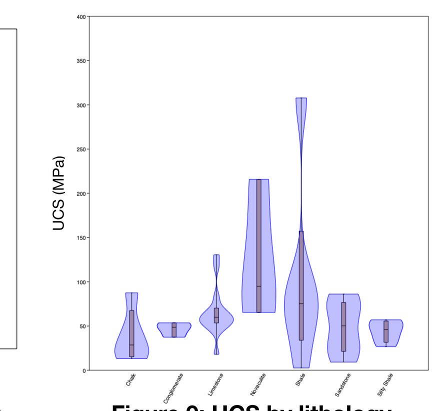

Figure 9: UCS by lithology

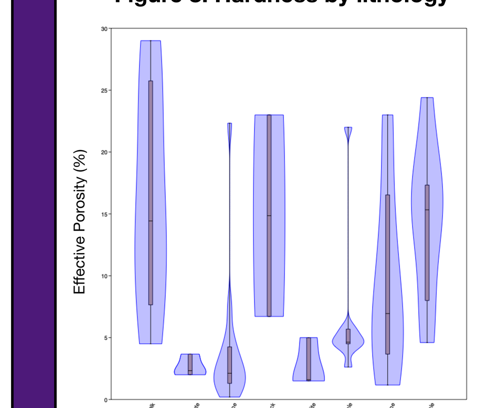

Figure 10: Porosity by lithology

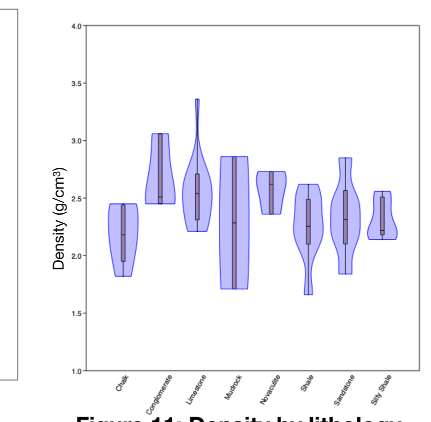

Figure 11: Density by lithology

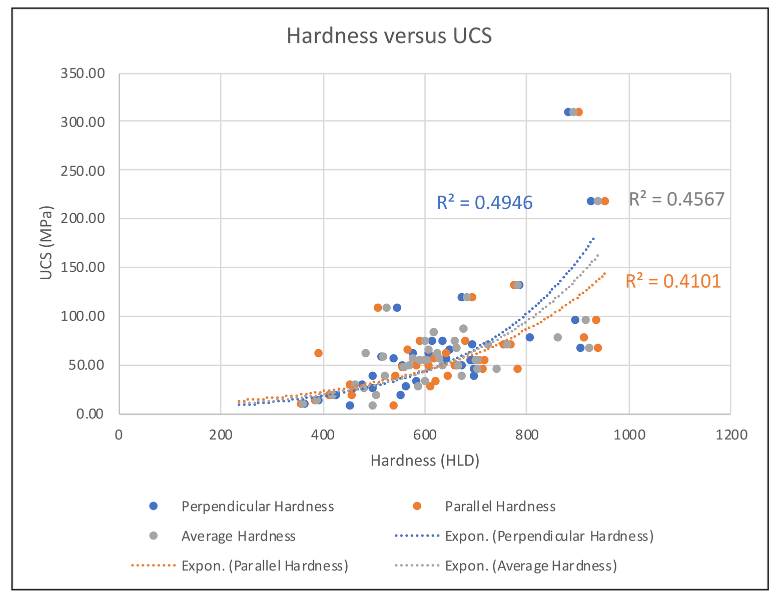

Figure 12: Graph showing hardness vs UCS while accounting hardness measurement direction.

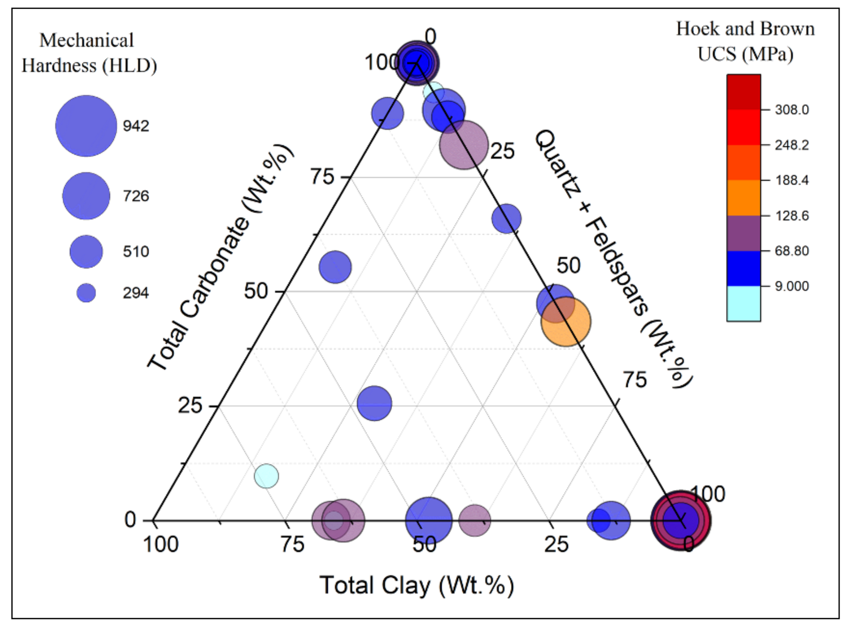

Figure 13: Ternary diagram depicting bulk mineralogy, hardness, and UCS for each sample. Note that hardness values are depicted by circle size, while UCS is depicted by color.

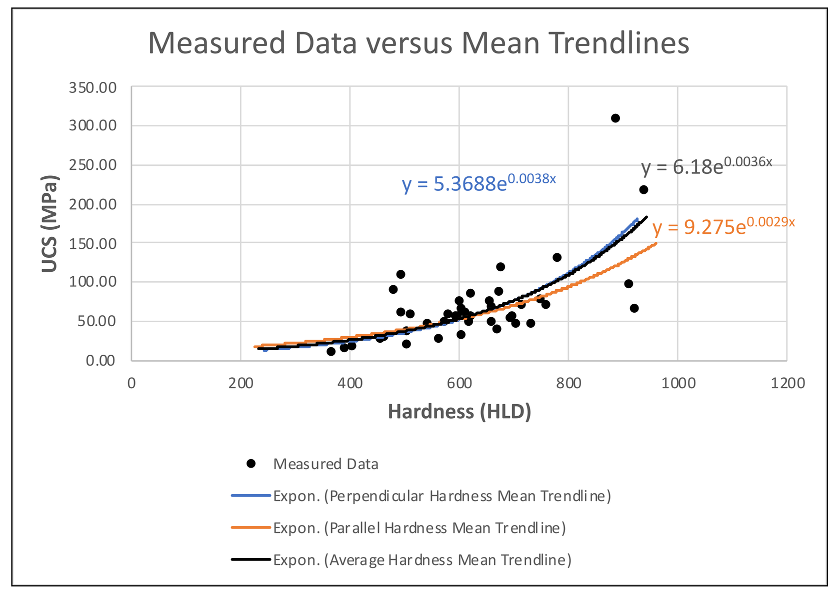

Figure 14: This graph shows each UCS model and its equation derived from hardness data. Each model predicts UCS based on hardness measurement relative to bedding orientation.

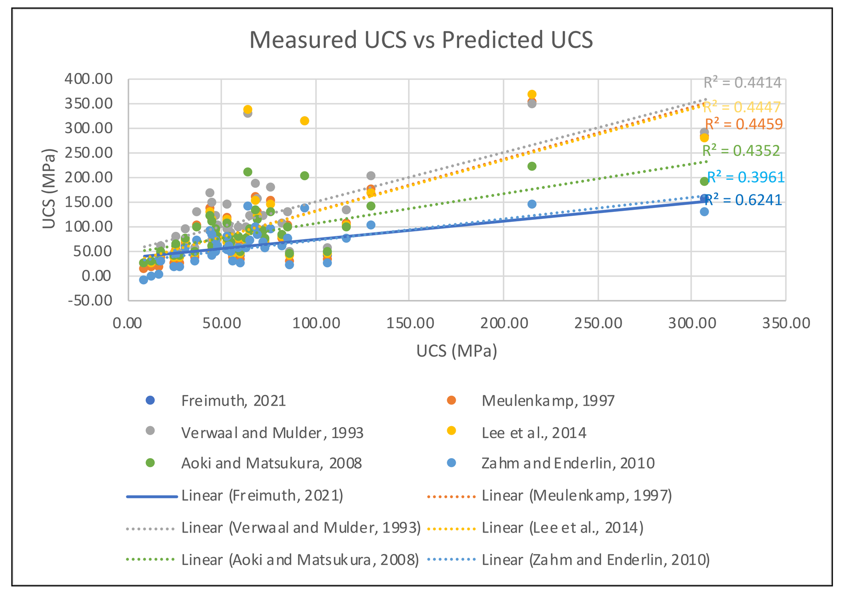

Figure 15: UCS model comparisons between prior studies and this study. The model from this study has the highest fit between measured and predicted values.

Statistic \ Probability	Average Median Pre-Dry Hardness (HLD)	Average Median Post-Dry Hardness (HLD)	Average Median Hardness (HLD)	H&B UCS Correction (MPa)	Density (g/cc)	Effective Porosity	Volume (cc)	Pre Dry Hardness Anisotropy Index	Post Dry Hardness Anisotropy Index	% Mass Change from Water Loss
Average Median Pre-Dry Hardness (HLD)		3.5x10^-34	2.1x10^-40	1.4x10^-4	4.6x10^-3	3.8x10^-5	1.3x10^-1	8.4x10^-4	6.1x10^-3	3.8x10^-1
Average Median Post-Dry Hardness (HLD)	0.98		2.0x10^-50	5.8x10^-5	3.5x10^-3	6.2x10^-5	2.2x10^-1	2.7x10^-4	2.1x10^-3	3.5x10^-1
Average Median Hardness (HLD)	0.99	1.00		6.7x10^-5	3.2x10^-3	6.3x10^-5	1.7x10^-1	2.8x10^-4	2.6x10^-3	3.5x10^-1
H&B UCS Correction (MPa)	0.55	0.58	0.58		4.0x10^-2	9.6x10^-3	4.1x10^-1	5.4x10^-2	1.3x10^-1	4.8x10^-2
Density (g/cc)	0.40	0.41	0.42	0.32		4.7x10^-4	4.4x10^-1	8.8x10^-2	9.5x10^-1	4.4x10^-1
Effective Porosity	-0.56	-0.54	-0.54	-0.40	-0.49		3.3x10^-2	2.8x10^-1	8.8x10^-1	1.0x10^-1
Volume (cc)	0.22	0.18	0.20	-0.13	0.11	-0.31		3.9x10^-1	2.5x10^-1	1.5x10^-1
Pre Dry Hardness Anisotropy Index	-0.47	-0.50	-0.50	-0.30	-0.25	0.16	0.13		1.2x10^-12	2.1x10^-1
Post Dry Hardness Anisotropy Index	-0.39	-0.43	-0.42	-0.24	0.01	0.02	0.17	0.82		4.3x10^-1
% Mass Change from Water Loss	-0.13	-0.14	-0.14	-0.31	-0.11	0.24	-0.21	0.18	0.11	

Figure 16: Spearman Rank Order Correlation results of all data excluding mineralogy.

- Violin plots (Figures 8 - 11) were used not only to depict data ranges, but also the data density for each lithology.
- Calibration tests show that the vise and tabletop suffice as mounting methods (Figure 7). Thus, the vise is used in future rock hardness measurements due to their irregular geometries, and because it allows for level testing surfaces.
- Hardness varies by lithology; novaculite ware the hardest overall and mudrocks the softest (Figure 8).
- UCS also varies with lithology (Figure 9). Novaculites have the highest median UCS, whereas chalks have the lowest (Figure 9). Mudrocks have no data because they disaggregated during coring (Figure 9).
- Effective porosity is non-zero in almost all samples (Figure 10). Large median values occurr in chalks, mudstones, and silty shales (Figure 10).
- Density values are variable between lithologies with considerable overlap present (Figure 11).
- UCS positively correlates with hardness, but the quality of fit is dependent on hardness measurement direction (Figure 12).
- Silicates and carbonates are generally harder and stronger than clay-rich samples (Figure 13).
- Hardness measurement direction with respect to bedding plays a role in a model's ability to predict UCS (Figure 14).
- Predictions of UCS from hardness data is empirical; equations from previous studies are not as well suited to predicting UCS compared to the equation from this study (Figure 15).
- Correlations between independent variables validate previous studies (Figure 16).

Interpretations

- The relationship between hardness, UCS, and a rock's intrinsic properties validate previous studies.
- Both hardness and UCS have similar relationships to independent properties indicating that a change in an independent property (e.g. porosity) could drive similar responses in both mechanical properties.
- The relationship between mineralogy and mechanical properties in this study validates previous studies; high quartz or carbonate content is found in harder/stronger rocks; clay content shows the opposite trend.
- Some studies imply the relationship between mineralogy and mechanical properties through lithology, but we explicitly show this with XRD analysis. Thus, XRD analysis should become a standard practice.
- Unlike other studies which trim outliers, we showed that Spearman's RS characterizes the samples just as well, but without altering data to make it parametric. Thus, non-parametric statistics should be used in future studies to best characterize the data because they are more robust to natural variations.

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