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 an intrinsic property of all materials including sedimentary rocks. The variables responsible for a sedimentary rock's hardness are not completely understood. By understanding which variables control hardness, we may gain a better understanding of related rock strength. Rock strength, defined as a rock's resistance to plastic deformation under loading, is an important parameter for many industries such as mining, civil engineering, and hydrocarbon exploration.

Numerous tests such as triaxial tests or uniaxial tests are used to quantify rock strength. However, these tests are often expensive, time consuming, or require substantial investment in laboratory setup. To circumvent these issues, 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 materials such as concrete, steel, and ceramics. These hardness values have been used to determine material strength. Selected studies on rocks empirically correlate between Bambino-derived hardness value (called Leeb hardness) and uniaxial compressive strength (UCS). However, significant scatter in the data suggest that certain intrinsic (e.g., density, bulk mineralogy, etc.) or extrinsic factors (e.g., sample volume, surface the sample rests on) need to be considered for a better correlation.

In this study, I examined the relations between Leeb hardness and UCS values, while accounting for lithologic variations and other properties such as bulk mineralogy, water loss, volume, density, and effective porosity. I found that intrinsic properties such as bulk mineralogy, density, and effective porosity correlated with a sample's mechanical hardness. Also, I determined that a sample's UCS is related to its density, effective porosity, and mechanical hardness. Ultimately, these data validated previous studies and shed new insight on the controlling properties of a rock's hardness and strength.

Introduction & Background

- 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:

$$\mathbf{HLD = (V_i / V_f)*1000}$$

Where: Vi = initial velocity, Vf= final velocity

- Numerous studies prove relationship between hardness and a material's unconfined compressive strength (UCS), and examine how these are controlled by intrinsic properties:
  - Porosity (Aoki and Matsukura, 2008; Brooks et al., 2016)
  - Density
  - Water Saturation (Desarnaud et al., 2019)
  - Mineralogy (Verwaal and Mulder, 1993; Daniels et al., 2012; Ritz et al., 2014; Dong et al., 2017, Celik and Cobanoglu, 2019)
  - Sample Volume (Demirdag et al., 2009; Lee et al., 2014; Brooks et al., 2016)

- Multiple statistical methods have been used for data analysis
  - Linear Correlations (Meulenkamp and Grima, 1999)
  - Multivariate Exploratory Methods (Grima and Babuska, 1998; Meulenkamp and Grima, 1999; Manouchehrian et al., 2012)
  - Artificial Neural Networks (Meulenkamp and Grima, 1999; Manouchehrian et al., 2012)
  - Fuzzy Logic (Grima and Babuska, 1999)

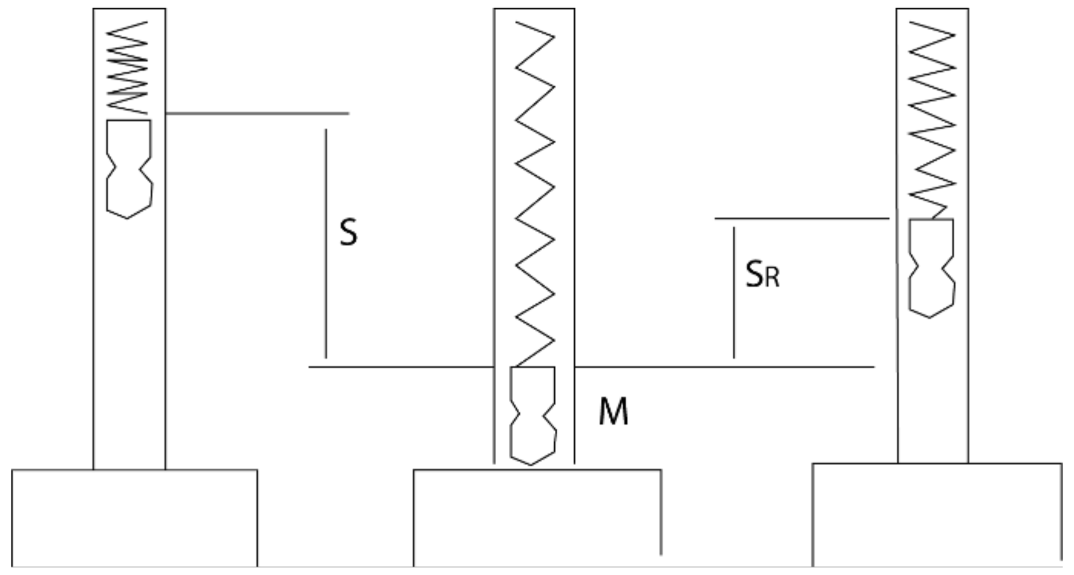


Figure 1: Bambino operation. "S" is the striking phase, "M" is the impact phase, and "SR" is the rebound phase.

Methods

Sample Collection
- Samples were collected throughout southwest (Figure 2)
- All samples named, marked with vertical orientation, and GPS location

Bambino
- Non-destructive method of measuring hardness
- 20 measurements taken perpendicular and parallel to bedding to characterize sample (Celik and Cobanoglu, 2019)

UCS Methods
- Samples cored perpendicular to bedding
- Core lengths must not exceed 2.5 times their diameter
- Used GCTS load cell within Geology department

Physical Properties
- Measured core density and effective porosity using water immersion
- Whole rock volume calculated from density, and rock moisture content measured via mass lost during drying

X-Ray Diffraction
- Used Rigaku Smartlab SE
- Scan range= 5-50 degrees at 40kV
- Match! Software used for Rietveld Refinement
- Samples grouped by: silicates, carbonates, and clays

Statistics
- Past4 used for all statistical analyses
- Spearman's Rank Order Correlation used to compare the correlations between medians of several measurements (Wilhelm et al., 2016)
- Principal Components Analysis used to find natural groupings within datasets, helping to develop better predictive datasets (Tiryaki, 2008)
- Multiple Linear Regression used to find main inputs based on an output (Meulenkamp and Grima, 1999)

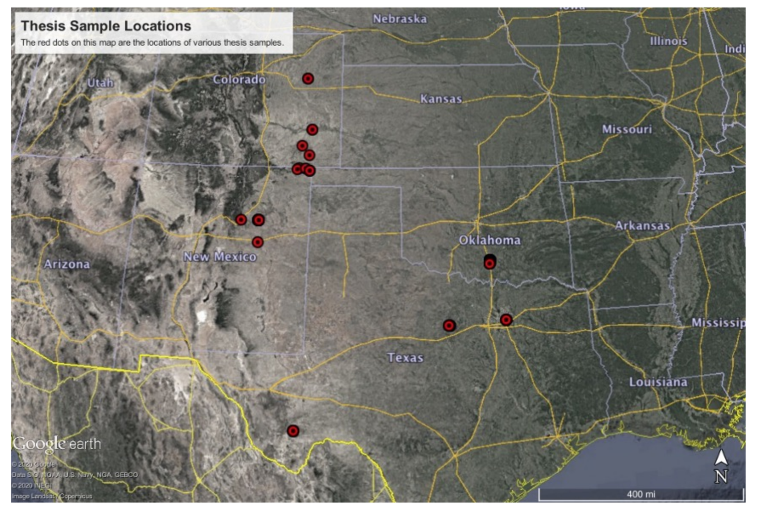


Figure 2: Sample locations.

Figure 3: Bambino rebound hammer.

Results

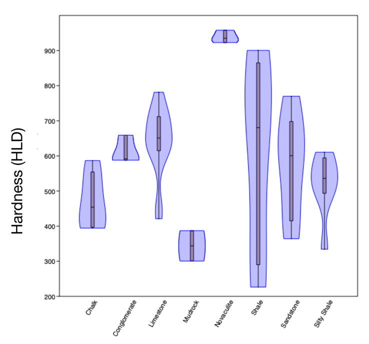


Figure 4a.

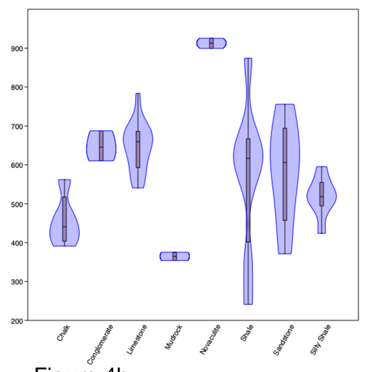


Figure 4b.

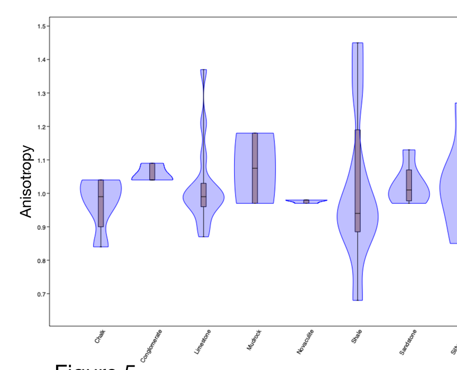
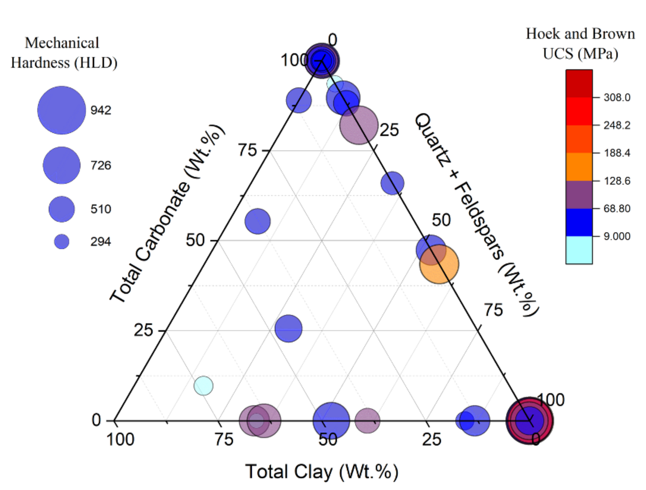


Figure 5.



Figure

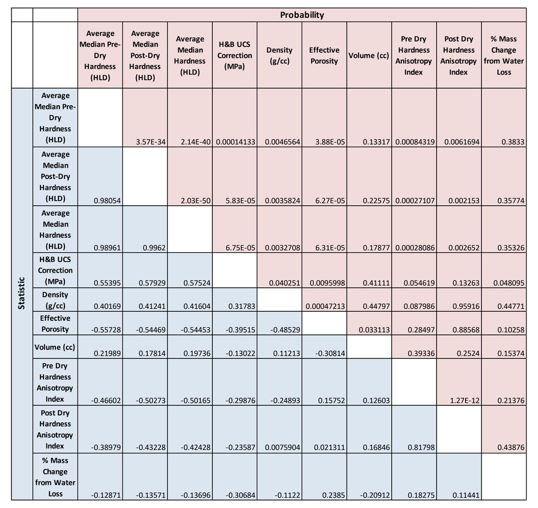


Figure 11a.

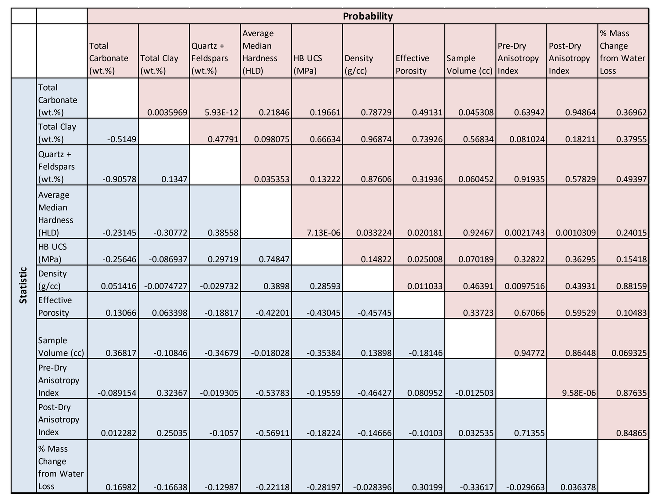


Figure 11b.

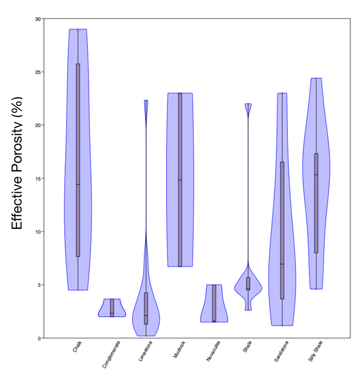


Figure 6.

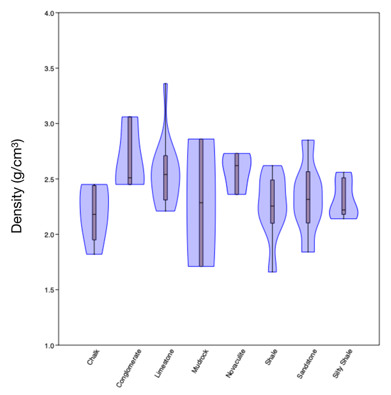


Figure 7.

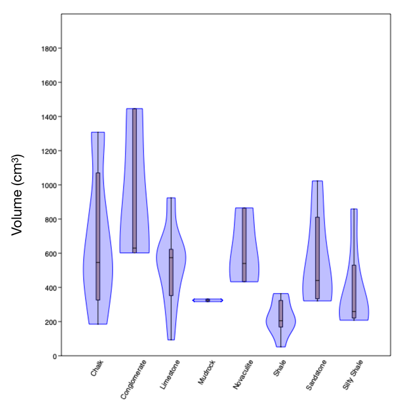


Figure 8.

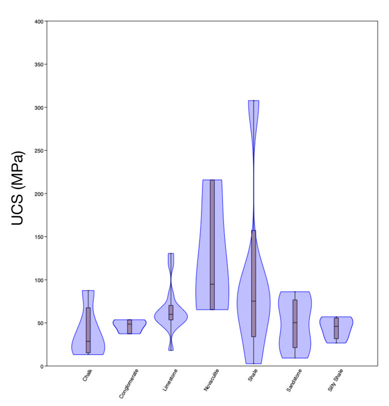


Figure 9.

- Hardness generally increased after drying (Figure 4a; Figure 4b)
- Anisotropy varied by lithology (Figure 5)
- Effective porosity non-zero in almost all samples, large median values in chalks, mudstone, sandstone, and silty shales (Figure 6)
- Density values variable (Figure 7)
- Volume is not an intrinsic variable; rocks were cut to desired volume, but this data was used in future analyses (Figure 8)
- UCS variable for each lithologic group; mudrocks are the only group without data (Figure 9)
- Silicates and carbonates generally harder/stronger than clay-rich samples (Figure 10)
- Correlations between independent variables validate previous studies (Figure 11a; Figure 11b)

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 I explicitly show this with XRD analysis. Thus, XRD analysis should become a standard practice.
- Unlike other studies which trim outliers, I 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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