Michelle Williams
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Geomechanical Characterization of Geo-architectured Rock Specimens using Gypsum-based 3D Printing

Abstract

Due to natural heterogeneity in rock specimens, classifying rock characteristics can present difficulties. 3D printing geo-architectured rock specimens has the potential to reduce the heterogeneity and help evaluate characteristics with reproducible microstructures, bedding, and strength to advance mechanical interpretations. This testing focused on 3D printing effects on strength and rock behavior by varying amount of binder, printing direction, and atmospheric conditions. A powder-based Gypsum 3D printer was used to create 1.5-inch diameter cylindrical samples. Unconfined compressive strength (UCS) testing was completed on these samples to gather failure plots and peak strength. Multiple batches of cylindrical samples were printed with varying printing direction, binder amount, and atmospheric conditions.

UCS results show that the strongest samples were those that were printed perpendicular to the loading direction compared to those printed parallel or 45 degrees. Due to reactions of the printing material with water, those at dry conditions were the strongest. Samples with the most binder amount proved to also be stronger than those with less. 3D printing of rock samples has to the potential to reduce heterogeneity rock presents, however additional factors introduced by the printing process can affect overall rock strength and behavior. Test results of the 3D printed geo-architected rock specimens demonstrated reasonable reproducibility and appear to be a promising path towards increasing the ability to characterize natural rock.

Introduction

Due to natural heterogeneity in rock, classifying rock characteristics can be difficult. Difficulty can arise when trying to capture and test a particular feature or microstructure in a rock, or due to availability of time (3) and funds to prepare and test a natural specimen or numerous specimens. Advancing 3D printing technology has the potential to help evaluate characteristics with reproduceable microstructures, bedding, and strength to advance mechanical interpretations.

There are many characteristics of interest when it comes to classifying rock including: strength, density, porosity, microstructure, mineralogy, and geophysical and mineralogical interactions. Common methods used to define these characteristics include testing on a load frame, like UCS and triaxial testing; or using a microscope analysis such optical, confocal, SEM; as well as CT, micro-CT, geochemical testing, permeability testing, and rock mass classification methods. Some of the natural heterogeneities in rock that can make this classification difficult are fractures, joints, bedding, mineralogy, and mineral inclusions.

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3D printed rocks are created using a 3D printer which reads a computer input and combines a gypsum-based powder and binder to form cylindrical or block samples. This method is relatively quick and less expensive compared to preparation of natural rock samples, man-made cements, or other materials (2) and has the potential to help characterize rock by reducing heterogeneity by reproducing microstructure, bedding, strength, and complicated geometries.

Interest has grown in using 3D printing technology to help solve a variety of scientific problems from aerospace and medicine to geomechanical applications (2). Fereshtenejad et al., tested powder-based 3D printing applications by varying the inclined angle of printing layer, layer thickness, binder level, and heating temperatures to see how those properties of printing affected overall strength. Farzadi et al., while their applications are on bone tissue engineering and not geomechanics, used similar powder-based printing to analyze accuracy for porous samples and characterized printing direction with closeness of pore size, porosity, and pore interconnectivity to the CAD file instructing the printer (1). Numerous examples exist, and as these types of analysis processes are tested and improved, the usefulness to geomechanics will increase.

The research described below took place at Sandia National Laboratories and was funded by Laboratory Directed Research and Development (LDRD) program. Hongkyu Yoon was the PI on this project and led research efforts. Related work on this project include: SAND2019-11256 (technical report, 7), SAND2019-14916C (conference poster, 5), and SAND2017-13305C (conference poster, 6).

Methods

Testing focused on 3D printing effects on strength and rock behavior by varying the amount of binder, printing direction, and atmospheric conditions. Cylindrical samples were printed, and velocity measurements and pre-photos were taken prior to testing. Samples that were part of the atmospheric testing were baked or placed in the relative humidity (80%) chamber. Samples were then prepped for testing. Uniaxial compressive strength (UCS) tests were then carried out on an MTS 22kip frame, and the resulting data analyzed to extract out material characteristics of interest.

A commercially available powder-based Gypsum 3D ProJet360 printer was used to create cylindrical samples 1.5in diameter by 3.0in long. This printer has a HP11 printhead and uses VisiJet PXL Clear binder (7). There were three sets of variation in testing including amount of binder, printing direction, and atmospheric conditions, in an interest to determine how those variations affected peak strength of the samples. A total of 36 samples were printed and 27 samples tested, nine of each printing direction. The samples with varying amount of binder were printed with low, medium, and high amounts of binder. Samples with varied printing direction included horizontal-long (H-long, which had a ‘horizontal’ bedding and was printed parallel to axial load), horizontal-short (H-short, which had a ‘vertical’ bedding and was printed perpendicular to axial load), and vertical (‘horizontal’ bedding printed perpendicular to load) (5). Figure 1, adapted from SAND2019-14916C (5), shows how samples were printed horizontal to the printing tray. Samples were treated with varying atmospheric conditions included ambient, Dry (baked), and relative humidity- 80%.

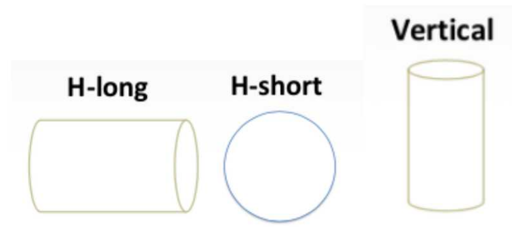

Figure 1: Printing direction with respect to horizontal tray. Adapted from SAND2019-14916C.

After samples were printed and confined to appropriate humidity and oven conditions, pre photos and velocity measurements were taken. Velocity measurements were taken in 4 directions along each sample, as can be seen in Figure 2. These measurements were taken with a table top velocity system that uses a compressed air apparatus to hold transducers in place on the samples.

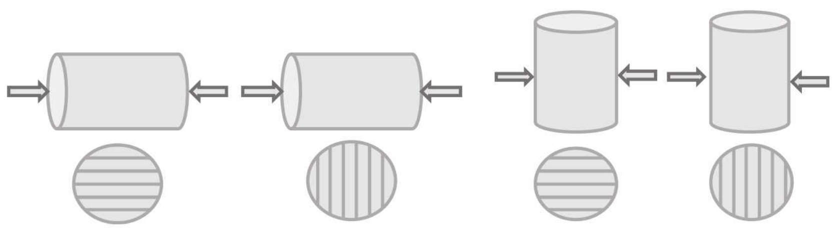

Figure 2: Direction and location of velocity measurements

Samples were then placed and taped between two end-caps prepared with a stearic acid mixture recommended by Labuz et al. to reduce the friction coefficient that can be found between rock/material and metal endcaps or load frame platens. Figure 3 shows 3D printed sample stack instrumented with lateral linear voltage displacement transducers (LVDTs) between the load frame platens.

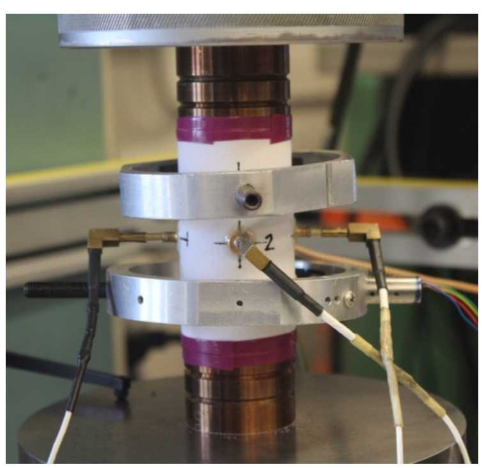

Figure 3: 3D printed sample stack with LVDTs

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In these experiments an MTS 22kip load frame, shown in Figure 4, was used to complete uniaxial compressive strength (UCS) tests on 3D printed cylinders to determine peak strength of the material. This machine is paired with a National Instruments data acquisition system and raw data is collected to analyze post-test.

Figure 4: MTS 22kip load frame used for UCS testing at Sandia National Lab

Most of the data analysis plotting is currently completed by hand, but research is being conducted on machine learning techniques. Python code was created in this case to uniformly process the data, plot the processed data, and pick P and S velocity arrival times. The program accomplishes this by filtering noise, adjusting for bias, and identifying consistent trend indicators of the onset of the P and S waves. Figure 5 shows a plot generated with the Python code with a red marker indicating the P arrival and a green marker indicated the S arrival.

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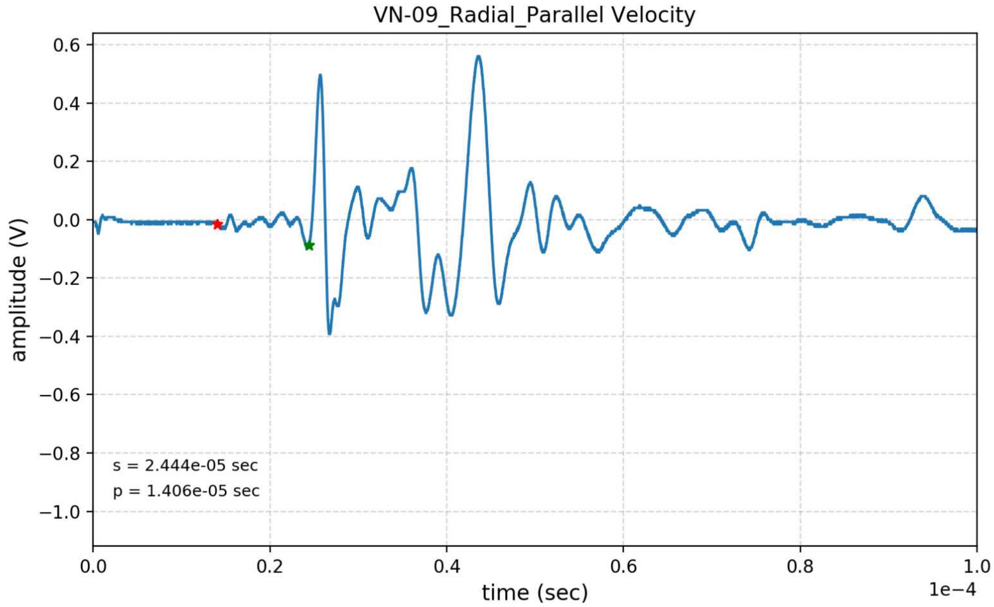

Figure 5: Python generated velocity plot with P and S arrivals

Results

The plotted results of the printing variation UCS tests of stress vs. strain curves can be found in Figures 6, 7, and 8. The samples that were printed in the H-long direction were the strongest, followed by the vertically printed samples. The weakest printed samples were the H-short samples. These 3D printed samples are relatively weak, between 1000-3000psi. The weakest few samples in each plot are a result of the relative humidity chamber and will be discussed below.

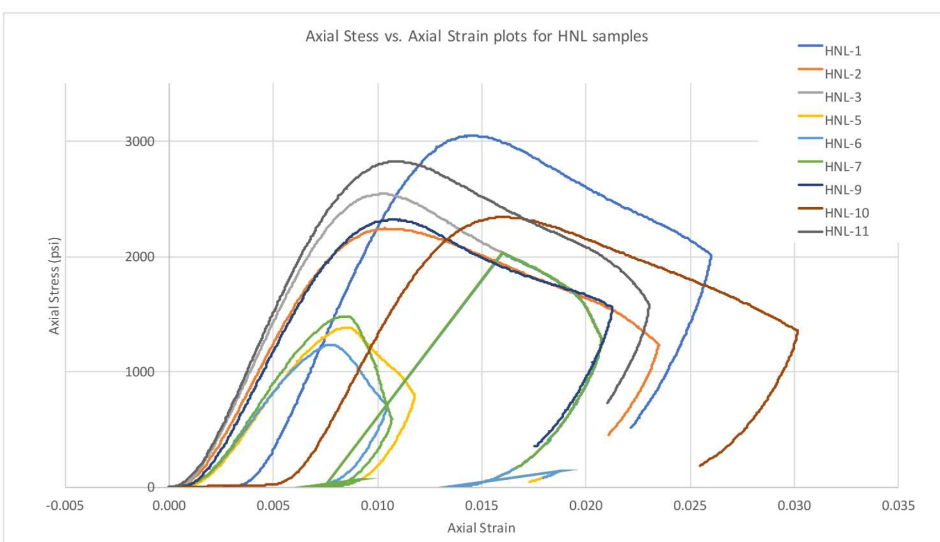

Figure 6: H-long samples-strongest, stress vs. strain plots

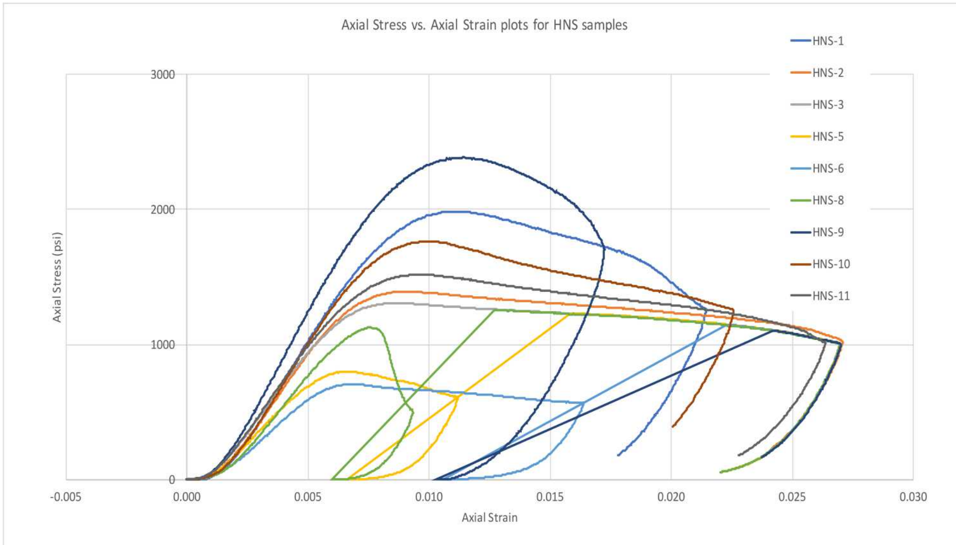

Figure 7: H-short samples-weakest, stress vs. strain plots

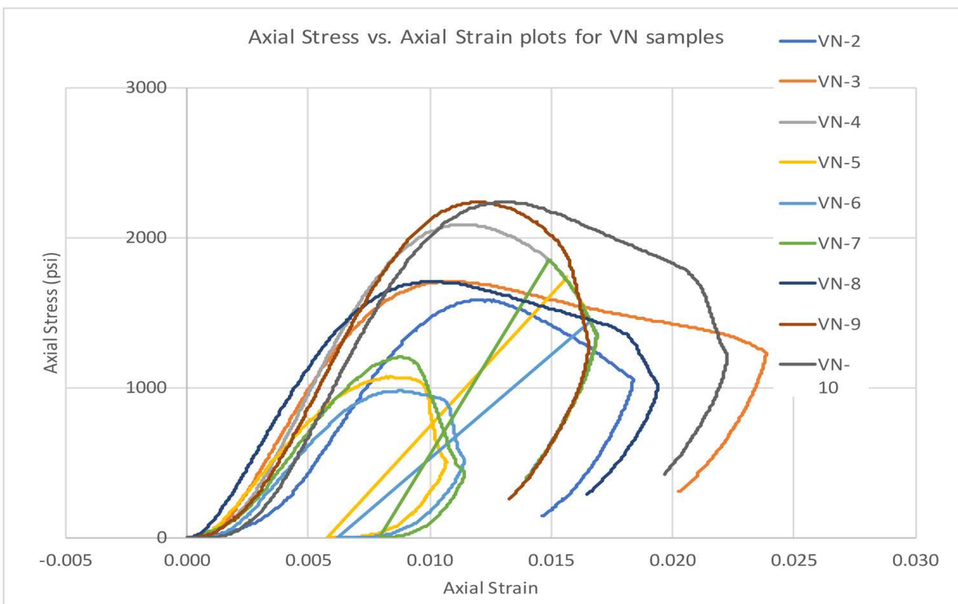

Figure 8: Vertical samples-middle strength, stress vs. strain plots

The results of the binder amount can be found below. With varying amount of binder, the larger amount (blue) resulted in the strongest rock during UCS testing (Figure 9). This is equivalent to adding more glue, so this result makes sense. In Figure 8, the orange trace is the medium amount of binder which had medium strength, and green is the least amount which was the weakest. Density was also measured to ensure additional binder amount, and the higher density sample is the sample with the larger amount of binder (Figure 10).

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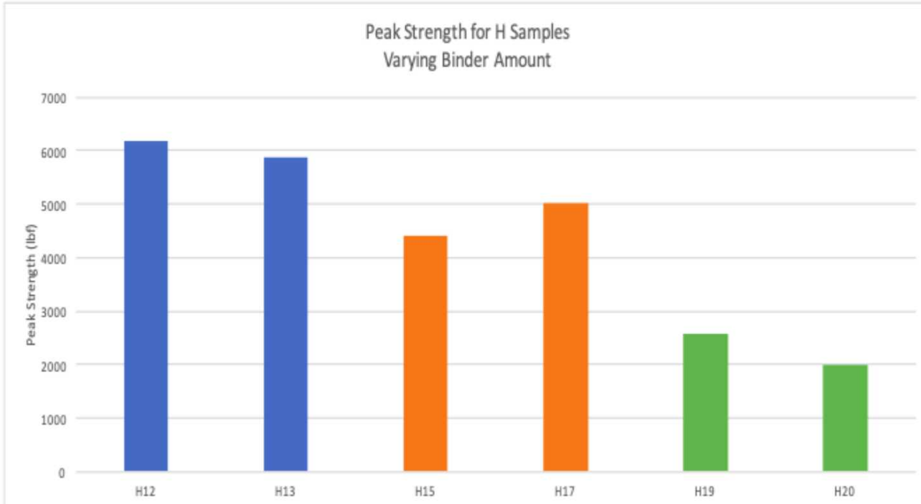

Figure 9: Peak strength vs. varying amount of binder

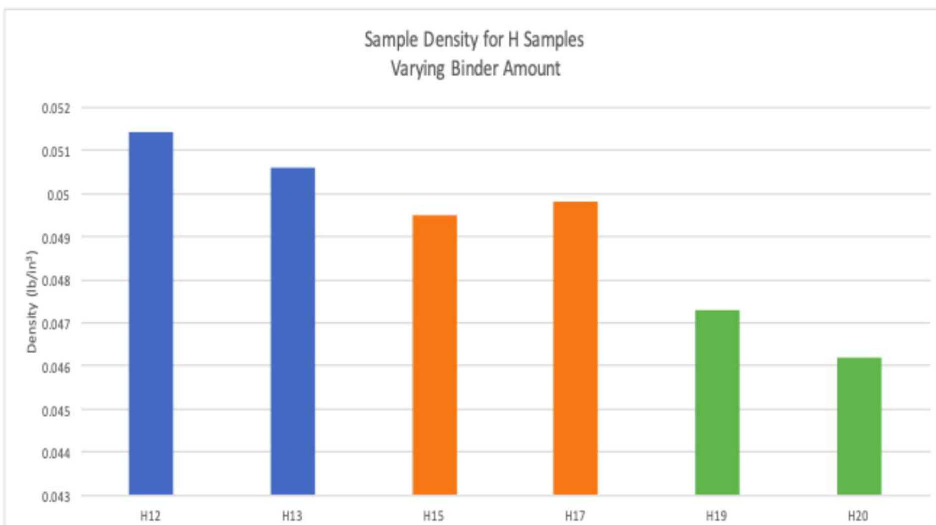

Figure 10: Density vs. varying binder amount

Figure 11 shows the variation in strength as a result of the varied atmospheric conditions. The samples that were dry (baked) were the strongest, and the weakest were those that were exposed to relative humidity of 80%. The middle strength were those at ambient conditions found on the far left. Due to the reactions of printing material with water, the samples at dry conditions were the strongest.

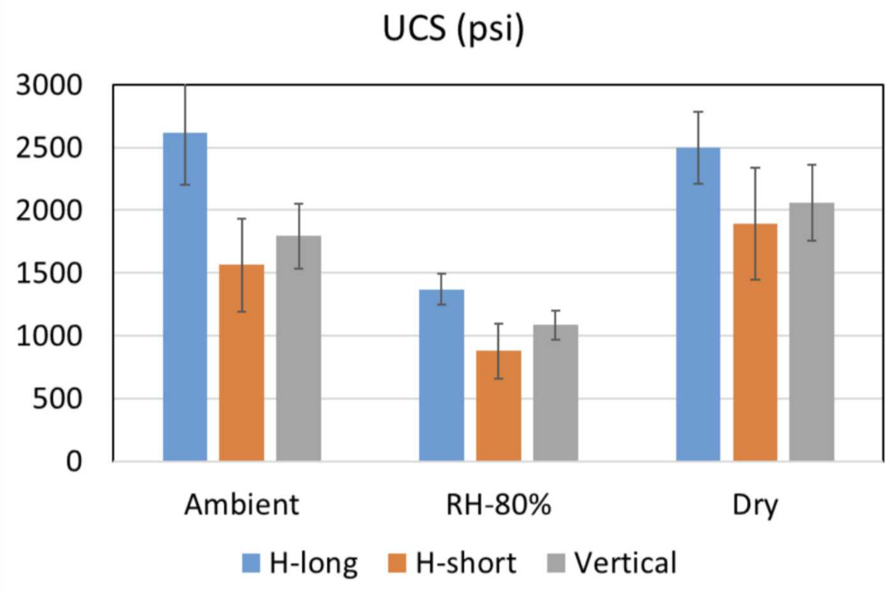

Figure 11: UCS of varied atmospheric conditions

The combined results show peak strength obtained from UCS data and show a strong correlation between strength and varied printing direction, binder, and change in atmospheric conditions. These results also show the additional factors that are introduced in the printing process and that they can affect overall rock strength and behavior. As 3D printing technology advances, these effects may be reduced and better defined.

Conclusions

Due to natural heterogeneity in rock specimens, classifying rock characteristics can present difficulties. A gypsum-based powder 3D printer was used to print specimens with varying printing direction, amount of binder, and atmospheric conditions. These samples were prepared and then UCS tested on an MTS 22kip load frame to collect peak strength data. The results showed that the strongest printing direction was that of the H-long sample, followed by the vertical, and H-short was the weakest. The samples with the most amount of binder were the strongest as well as the most dense. Finally, the samples that were at dry (baked) conditions were the strongest, followed by ambient conditions, and the relative humidity at 80% resulted in the weakest samples. Test results of the 3D printed geo-architected rock specimens demonstrated reasonable reproducibility and appear to be a promising path towards increasing the ability to characterize natural rock.

Future work could improve the Python code to also calculate and compare Young's Modulus from the UCS data versus that from the velocity measurements. Due to the high impact of the 3D printing, advances in the technology appear inevitable. Such advances may help control sample microstructure, which will increase the value of this technology for understanding classification of rock characteristics.

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Presentation: *SAND2019-14994 PE*