Material Characterization while Drilling on the Moon: Analyzing the atmospheric and cryogenic drilling data. D. R. Joshi[1] , A. W. Eustes III[2], J. Rostami[3], C. Dreyer[4], J. Hanson[5], [1]Petroleum Engineering Department, Colorado School of Mines, 1600 Arapahoe St, Golden, CO. 80401. deepjoshi@mines.edu, [2]Petroleum Engineering Department, Colorado School of Mines, 1600 Arapahoe St, Golden, CO. 80401. aeustes@mines.edu, [3]Mining Engineering Department, Colorado School of Mines, 1600 Illinois St, Golden, CO. 80401. rostami@mines.edu, [4]Center for Space Resources, Colorado School of Mines, 1310 Maple St, Golden, CO. 80401. cdreyer@mines.edu, [5]Petroleum Engineering Department, Colorado School of Mines, 1600 Arapahoe St, Golden, CO. 80401. jennamaehanson@mines.edu.

Introduction: In last five years, several agencies and companies have shown interest in prospecting and extracting resources from the Moon, Mars and other celestial bodies. Current assessments of the water-ice in the lunar Permanently Shadowed Regions (PSR) come from the orbital measurements[1,2] with only one ground truth data point recorded during the LCROSS mission[3]. The orbital data and the LCROSS mission shows wide variance in the composition, quantity, form, and distribution of water-ice in the lunar PSRs. This severely hinders design and execution of extraction technologies. More ground truth data acquired by drilling 'exploratory boreholes' is required.

This paper discusses the development of algorithms that analyzes the trend in the drilling data to estimate the geotechnical properties and characteristics of subsurface water-ice in the lunar regolith. These algorithms use drilling data to estimate the uniaxial compressive strength, density, and subsurface stratigraphy. These algorithms are also used to estimate the quantity and distribution of water-ice on the lunar subsurface. This paper compares the analyzed drilling data for both atmospheric and cryogenic drilling tests.

Experimental Setup: A test drilling rig with a high-frequency drilling data acquisition system was designed and fabricated[4]. Figure 1 shows the test drilling rig. The drilling tests were conducted with commercially available masonry bits. Homogenous and layered analog grout samples with a basaltic simulant were designed to record the drilling response. The compressive strength of the analog samples was changed by varying cement-water ratio. Figure 2 shows the analog samples used for drilling tests. Drilling parameters such as torque, thrust, rotation speed were recorded and parameters like penetration rate and mechanical specific energy were calculated. A data processing schema was implemented to remove the outliers and the noise. The data set from each borehole was individually labeled to identify the operation being conducted (drilling or not drilling), any drilling dysfunctions (vibration, auger choking etc.), and changes in the formations.

To test the applicability of the algorithms at cryogenic conditions expected in lunar PSRs, a cryogenic apparatus was designed and fabricated. In the next month, three cryogenic tests in homogenous simulant sample with 3%-9% water content are planned.

Figure 1: Test drilling unit

Results: The labeled drilling data from each wellbore was randomly split into 80% training and 20% validation dataset. Various classification algorithms were trained to predict the rigstate, drilling dysfunctions and varying formation . Various regression algorithms were developed to estimate the UCS, and moisture content while drilling. The algorithm performance was compared to identify the most efficient algorithm and optimum hyper-parameters. The optimum algorithms were blind tested on the analog samples and will be tested on the cryogenic samples.

Such algorithms can be vital in identifying the rig state and drilling dysfunctions both of which can help optimize the drilling operations by identifying the drilling parameters resulting in minimum vibration or optimum power consumption. These algorithms can also help estimate the quantity, distribution, and subsurface stratigraphy of water available on the lunar poles which will be essential in planning any human and robotic missions in the coming years.

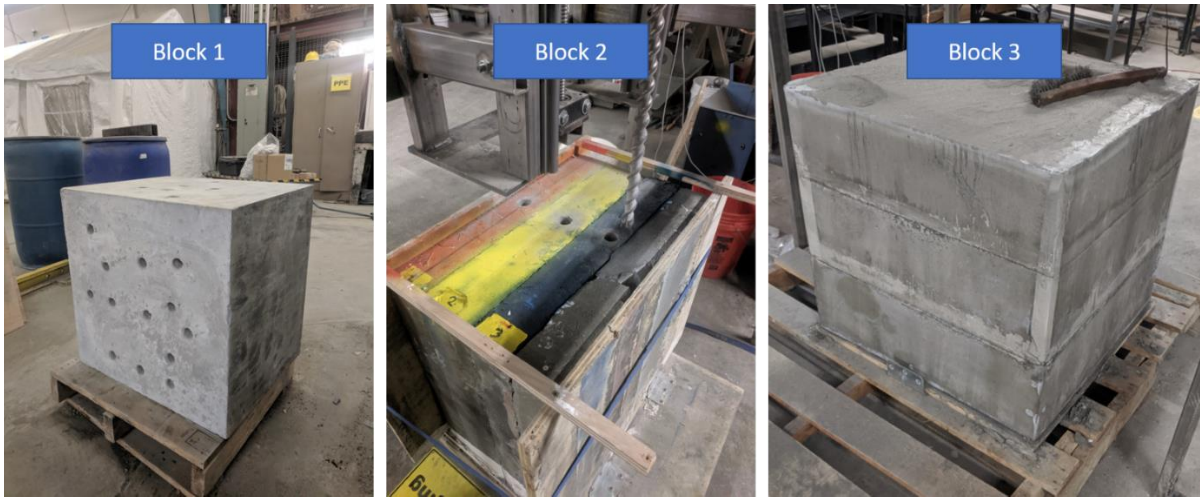

Figure 2: Analog samples cast for the drilling test,
Block 1, homogeneous sample, Blocks 2 & 3 variable strength grout layers

References: [1] Heldmann, J. L., Colaprete, A., Elphic, R., Mattes, G., Ennico, K., Fritzler, E., Marinova, M., (2015) *"Real-Time Science Operations to Support a Lunar Polar Volatiles Rover Mission."* Advances in Space Research 55, no. 10 (2015): 10. [2] Li S., Lucey P. G., Milliken R. E., Hayne, P. O., Fisher E., Williams J., Hurley D. M., Elphic R. C*. (2018) "Direct Evidence of Surface Exposed Water-Ice in the Lunar Polar Regions."* PNAS*.* [3] Colaprete A., Schultz P., Heldmann J., Wooden D., Shirley M., Ennico K., Hermalyn B., et al (2010) *"Detection of Water in the LCROSS Ejecta Plume."* Science 330, no. 6003 (2010): 463-68 [4] Joshi D., Eustes A. W., Rostami J., Gottschalk C., Dreyer C., Liu W., Zody Z., Bottini C., (2019) *"How Can Drilling Engineers Help Revolutionize Space Transport and Colonize the Solar System: Focusing on Lunar Water-Ice."* In SPE Annual Technical Conference and Exhibition. Calgary, Alberta.