ROCK STRENGTH PREDICTION DURING CORING OPERATION

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ABSTRACT

Coring operations have become more challenging as tougher conditions are encountered more frequently. Hole stability, rock strength, temperature, depth, mud weight and other parameters directly affect core recoveries and quality. It is therefore important to have reliable information during the pre-planning phase. Rock strength and mechanical specific energy (MSE) can help to improve coring system and core bit selection to aim towards a better recovery and higher core quality for more representative tests.

There are different factors that can affect drilling efficiency and core recovered. Some of these factors are fixed and cannot be changed such as lithology, rock strength and downhole insitu stresses. The factors that are variable and can be optimized are drilling processes and parameters. To optimize the drilling process and overall core recovery, the variable factors have to be analyzed. Gstalder and Raynal [1] noted however that drillability of rocks cannot be defined absolutely or using a single test because of the many variables during drilling.

The main purpose of this study is to validate the analytical predictive strength model used as input to aid in coring technology selection and compare to strength measurements in the laboratory. Analytical rock strength is derived from acoustic and bulk density data in real-time in order to do a coring analysis. Unconfined compressive strength (UCS) and indirect tensile strength (BTS) were measured in the laboratory for three different lithologies and cement to determine the rock strength. The measured laboratory UCS correlates very well to the analytical predicted UCS from our model for low to medium strength rocks, giving high confidence in our prediction to optimize the drilling process for better core recovery.

Unique realtime downhole measurements from a specific formation can also be used to estimate MSE and the output used for the planning stage of coring operations. The total energy required to remove a unit volume of rock is the MSE. Parameters such as weight on bit (WOB), torque, rate of penetration (ROP) and rotation per minute (RPM) can be controlled during drilling to help minimize MSE to improve efficiency. This study is an effort to characterize strength in different lithologies and use this knowledge in planning coring operations in increasingly difficult environments and to improve the drilling efficiency, optimize performance and reduce cost per foot with minimized non-productive time (NPT).

INTRODUCTION

Reliable knowledge of rock strength is important for successful coring operations especially in areas where no previous coring knowledge is available. Therefore rock strength estimation from logs becomes very vital and must use formation specific empirical strength correlations to guide in obtaining intact core samples. Complicating this rock strength empirical correlation are the dependence of rock strength on mineralogy and microstructure of the rock. Khaksar et al. [2] discussed in detail the importance of using multiple variables, as using a single variable alone might not sufficiently capture the rock strength. We have made an attempt to use different coring parameters and rock mechanical properties estimated from logs and laboratory measurements to look at trends that can guide in optimizing coring efficiency. The coring operation was conducted at the Baker Experimental Test Area (BETA) well located in Okmulgee County, Oklahoma. Logging information was available during the drilling process previously done in the well in the Glenpool field and recently in 2016 when the whole cores were obtained in the sandstone, shale and in the basement granite. The well had previously been cemented with light gray oilfield cement at the shallow depths between 400-462 ft. and this was also cored and tested. The sandstone, shale and sandy shale formations were cored between 490-521 ft. as shown in the lithology in Figure 1 and the granite from the basement rock was cored from 5385-5388 ft. The predominant rock type cored in this well is shale. Figure 2 shows a set of four samples prepared from the whole core in each lithology tested.

CORING OPERATION

Parameters such as lithology, porosity, rock structure (fracture or consolidated) and rock strength are key inputs needed for successful coring operation using the best coring technology selection available.

All of these parameters are taken into consideration during the planning phase of a coring operation to make the best selection for core bit, coring technology and barrel length.

If proper selection is made, core recovery (core recovered/core cut) and core efficiency (core recovered/barrel length) will be optimized. Time spent on a coring operation is directly related to barrel length, the bigger the length the more time that will be required for every stage of the coring operation (making-up, coring downhole, breaking-out and recovering the core). UCS, lithology and formation properties play a key role to decide the most suitable barrel length to improve core efficiencies.

UCS is particularly useful for core bit selection to optimize core quality and ROP. Predicting reliable UCS can help in selection of different features such as:

1. Cutter size: Appropriate cutter size selection for the UCS range of the target formation will help to improve core quality by delivering a smooth cutting action to reduce reactive torque and vibrations that may cause induced fractures. New generation cutters provide high wear and impact resistant PDC cutters which is important for extended coring runs.
2. Blade count: Although the main objective in a coring operation is to acquire high quality samples, ROP plays an important role on rig time and is always desired to

be as high as possible without compromising quality. Normally the harder the formation, the bigger the blade count in a PDC core bit. Efficient cuttings removal brings higher ROP and is normally easier to achieve efficient removal with a low blade count. This is why it is important to look into new generation core bits that incorporate the latest technology, new matrix materials (core bit body) improvement to reduce erosion, CFD (Computational Fluid Dynamics) analysis to optimized blade count and next generation cutters to find the right balance between durability and ROP.

3. Gauge Pads: Plays an important role to minimize torsional and lateral vibrations to help deliver a high quality core. Gauge protection materials need to be taken into consideration as well, a high UCS formation would normally require premium protection to perform at its best for a longer period of time.

ROCK MECHANICAL PROPERTIES (RMP)

Acoustic log data for the determination of formation elastic properties has been widely used due to its known physical relationships, Coates and Denoo [3]. A direct calculation of elastic properties (Young's Modulus, Shear Modulus, Bulk Modulus and Poisson's ratio) based on physical relationships to the direct measurement of formation density and acoustic wave velocities exists.

To calibrate the log-derived rock mechanical properties (RMP), testing consisting of unconfined triaxial tests for static elastic properties and rock strength, X-Ray diffraction (XRD) to identify and quantify minerals present in the samples and indirect tensile strength (BTS) for rock strength. Compressional and shear wave ultrasonic velocity measurements as a function of hydrostatic stress testing for dynamic elastic properties determination were also conducted. All the samples were tested as received with the bulk density estimated from the physical dimensions and weight. Almost all the available log data correlations to rock strength are typically derived from acoustic wave velocities, porosity and formation density, Chang et. al. [4] and Zoback, M. [5]. The compressional slowness (DTC) and shear slowness (DTS) gives a good correlation to UCS. It should also be noted that DTS is less affected by formation fluid (gas) than compressional slowness (DTC). Mason [6] also showed an excellent correlation between shear velocity and UCS and then developed a bit selection method based on DTS from log data. When high quality processed DTS is available, it gives a better correlation to UCS. Irrespective of the rock type it is obvious that the trend obtained is UCS decreasing with increase in acoustic slowness with either DTC or DTS.

A proprietary correlation is used to estimate the strength based on acoustic slowness and gives a good match both on the DTC and DTS for the shale lithology but seems to under predict the strength in the sandstone as shown in Figure 3. The proprietary correlation is the DTC_UCSLOG and DTS_UCSLOG in Figure 3. In this case, the acoustic slowness relationship with the laboratory measured strength for the sandstone and granite seems to be better predicted by Freyburg [7] correlation. It should be noted however that the Freyburg [7] correlation is based on the compression velocity. The relationship between laboratory measured UCS and ROP is shown in Figure 4 with the ROP increasing with lower strength. The RPM was kept constant throughout the coring process and as expected there is lower ROP and higher strength in the sandstone and granite samples, while the shale and cement samples exhibited higher ROP and lower strength. Curry et al. [8] showed that penetration rate is sensitive to both borehole pressure and formation fluid as well. The laboratory measured results of the triaxial and ultrasonic tests are shown in Table 1. Correlation of UCS with Young’s modulus (Stiffness) shows the correlation as expected in Figure 5 with low to medium strength region for cement and shale, and high strength region for sandstones and granite (Coates and Denoo [3]). Correlation between dynamic Young’s modulus (Ultrasonic laboratory testing) to static Young’s modulus (Triaxial laboratory testing) on cement, shale and granite is shown in Figure 6. It shows a good correlation with the dynamic values higher than the static values as expected, however only three ultrasonic tests were available, no ultrasonic measurements were done on the sandstone sample.

The similar strength in the sandstone and granite shown in Table 1 might be due to the mineralogical composition between the two rock samples. The XRD shows the sandstone to be predominately quartz (90%) whereas the granite consists predominately of feldspar (54%), quartz (29%) and chlorite (10%). The low strength in the granite might be due to the presence of chlorite, Yatabe et al. [9] found the presence of weak clay minerals like chlorite and smectite to lower strength. Correlation between Young’s modulus and ROP is shown in Figure 7, showing increase in ROP with decrease in Young’s modulus, implying as expected that stiffer rock is harder to core.

XRD was conducted only on six samples, four shale samples and one each of sandstone and granite. Consequently, the grain modulus was estimated from the mineralogical composition of each rock type tested and its relationship to ROP is shown in Figure 8. The correlation between Grain modulus and ROP shows a good trend with lower grain modulus corresponding to increase in ROP. The use of wireline mineralogical logs for weight and volume percent of the mineralogical composition of the rock might come in handy due to the findings in Figure 8 and may be used to estimate ROP during coring process. This relationship needs to be explored more with a larger dataset.

For QA/QC, the bulk density is also plotted with UCS and Indirect tensile strength in Figures 9 and 10 showing increase in strength as expected in both plots as formation bulk density increases. The ratio of indirect tensile strength to UCS seems low in this formation, as low as 3-5 times the UCS in the three lithologies.

MECHANICAL SPECIFIC ENERGY (MSE)

Teale proposed the concept of Mechanical Specific Energy (MSE) in the 60’s and discovered that minimizing MSE would maximize drilling and result in maximum rate of penetration (Teale [10]). The total energy required to remove a unit volume of rock is the MSE. Parameters such as weight on bit (WOB), torque, rate of penetration (ROP) and rotation per minute (RPM) can be controlled during drilling to help minimize MSE to improve efficiency.

Pessier and Fear [11] showed that when specific energy is approximately equal to the UCS of a rock, then the minimum specific energy has been reached. This principle holds in oil and gas drilling under confining pressure. The efficiency hardly reaches 35% and under ideal conditions it reaches the UCS if drilling is efficient.

Minimizing MSE will therefore improve drilling efficiency as shown in equation (1). Pessier and Fear [11] also developed a bit specific coefficient (μ) to express torque as a function of WOB as shown in equation (2).

$$MSE = WOB\left(\frac{1}{B_A} + \frac{13.33\mu * RPM}{B_D * ROP}\right) \tag{1}$$

$$\mu = 36\frac{T}{B_D * WOB} \tag{2}$$

MSE was calculated based on the drilling and coring surface data in the different lithology and correlated to ROP. MSE correlation to ROP during drilling of the well is shown in Figure 11, note that drilling data was only available for shale and sandstone. MSE is high at low ROP and decrease as ROP increases. MSE seems to be higher in shale and therefore reducing drilling efficiency as compared to the sandstone, this could be due to the mineralogy of the shale and it has also been shown by Pessier and Fear [11] that higher sand content increases ROP and reduces specific energy. Hamrick [12] also showed that if rocks are broken into pieces smaller than necessary, this would lead to more energy expenditure than required. It should also be noted that in the 60 ft. of data analyzed in Figure 11, it is predominantly a shale to sandy–shale lithology and only ~14ft. of sandstone layer. MSE correlation to ROP during the coring operation is shown in Figure 12 and covers the four samples cored in this well. Similar trend is obtained as during drilling.

Average rate of penetration, unconfined compressive strength and static Young's modulus is shown in Table 2 for cement, shale, sandstone and granite. Even though the strength is not significantly different between the sandstone and granite, the average ROP significantly drops in the granite. The very low ROP in the granite might also be due to the bit available for this coring which is not the main choice for this type of hard formation but was used so as to be able to make comparison between the lithology. As explained previously also, the presence of chlorite in the granite might have caused the lower strength but the presence of feldspar and quartz still made it significantly difficult to core with this bit even with lower strength than usual for a granite.

CONCLUSION

The use of log based rock mechanical properties can help to determine coring parameters as both strength (UCS) and stiffness (Young's modulus) correlates well with ROP.

The log predicted UCS based on DTS correlates well with the laboratory measurement as the maximum UCS predicted during the coring was 3500 psi and 14000 psi, respectively for shale and granite. However additional empirical correlation was needed for the sandstone, this might be due to few sandstone cored and tested. Grain modulus seems to show a good correlation with ROP, however we have limited data and this needs to be further investigated as a parameter to predict ROP through wireline mineralogical logging or XRD analysis when core samples are available. Figure 11 showed that when MSE decreased in the deeper shale, ROP increased. Drilling efficiency can be optimized by changing parameters such as WOB and RPM, so as to increase the ROP. Unique realtime downhole measurements from specific formations will be explored further in future work to estimate MSE based on the initial trends observed in this study.

NOMENCLATURE

B_A = Cross sectional area of bit (in^2)
B_D = Bit Diameter (in)
MSE = Mechanical Specific Energy (psi)
WOB = Weight On Bit (lbf)
ROP = Rate of Penetration (ft/hr)
RPM = Rotations Per Minute (rev/min)
Torque = Rotational torque (ft-lbf)
μ = Bit Specific Coefficient of Sliding Friction
BTS = Indirect tensile strength

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Table 1: Triaxial and Ultrasonic laboratory Test Results

Lithology	**Triaxial (Static)**							**Ultrasonic (Dynamic)**					
	Bulk Density	**Unconfined compressive strength**	**Poisson's Ratio**	**Young's Modulus**	**Shear Modulus**	**Bulk Modulus**	**Lame's Constant**	**Compressional slowness**	**Shear slowness**	**Poisson's Ratio**	**Young's Modulus**	**Shear Modulus**	**Bulk Modulus**
	DEN	**UCS**	**ν**	**E**	**G**	**K_b**	**λ**	**DTC**	**DTS**	**νd**	**Ed**	**G**	**K**
	g/cc	**psi**		**Mpsi**	**Mpsi**	**Mpsi**	**Mpsi**	**us/ft**	**us/ft**		**Mpsi**	**Mpsi**	**Mpsi**
Cement	1.73	2421.5	0.12	1.16	0.52	0.51	0.17						
	1.66	1741.5	0.09	0.91	0.42	0.37	0.09						
	1.72	1421.0	0.09	0.88	0.40	0.36	0.09						
	1.71	1589.2	0.13	1.15	0.51	0.52	0.18						
	1.67	1930.5	0.10	1.06	0.48	0.44	0.12						
	1.81	2217.6	0.22	1.01	0.41	0.61	0.34						
	1.81	2234.5	0.13	1.00	0.44	0.45	0.16						
	1.77	2463.6	0.11	1.25	0.56	0.53	0.16						
	1.73	1628.4	0.12	1.03	0.46	0.45	0.14						
	1.78	1666.1	0.07	0.90	0.42	0.35	0.07	136.0	251.00	0.29	1.02	0.40	0.81
Shale	2.51	3206.0	0.11	0.76	0.34	0.33	0.10	167.0	312.00	0.30	0.89	0.34	0.74
	2.49	3859.9	0.06	1.00	0.47	0.38	0.06						
	2.49	3030.5	0.10	1.04	0.47	0.43	0.12						
	2.43	3037.8	0.02	0.98	0.48	0.34	0.02						
Sandstone	2.62	13718.5	0.07	4.78	2.23	1.87	0.38						
	2.48	10421.2	0.09	3.44	1.58	1.39	0.34						
	2.61	12406.2	0.05	4.25	2.03	1.58	0.22						
Granite	2.74	12325.0	0.09	5.40	2.48	2.19	0.54						
	2.65	12309.1	0.12	6.02	2.68	2.66	0.88						
	2.65	10722.8	0.11	6.95	3.12	3.00	0.92						
	2.62	13505.3	0.16	7.12	3.07	3.50	1.46						
	2.63	14040.4	0.14	6.55	2.88	3.01	1.09						
	-	13881.0	0.29	2.69	1.04	2.13	1.44	91.0	163.00	0.28	3.42	1.34	2.59

Table 2: Average Coring Data and Rock Properties in the Samples

Lithology	**Avg. ROP**	**Avg. UCS**	**Avg. Static Young's Modulus**
	Ft./hr.	**psi**	**Mpsi**
Cement	129	1919	1.04

Shale	65	3365	0.95
Sandstone	58	12182	4.16
Granite	0.5	13773	6.83

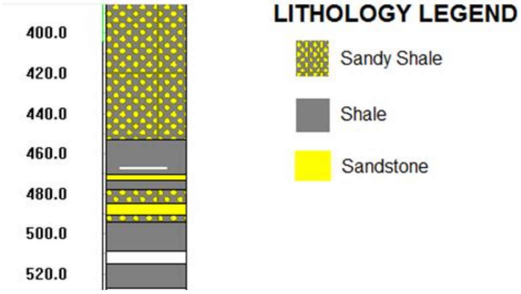

Figure 1: Lithology and Depth of Rocks Cored

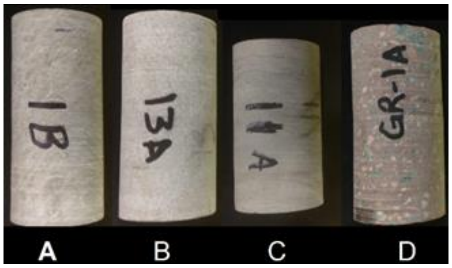

Figure 2: (A) Cement (B) Sandstone (C) Shale and (D) Basement Granite

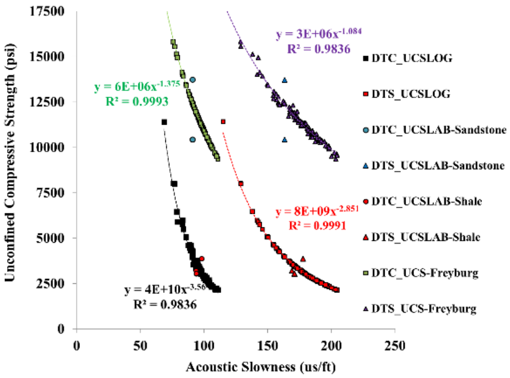

Figure 3: Unconfined Compressive Strength and Acoustic Slowness

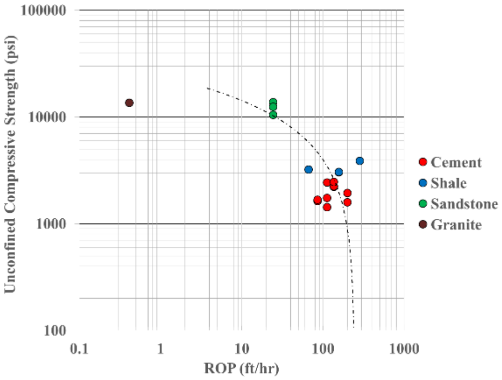

Figure 4: Laboratory Measured Unconfined Compressive Strength and Rate of Penetration during Coring

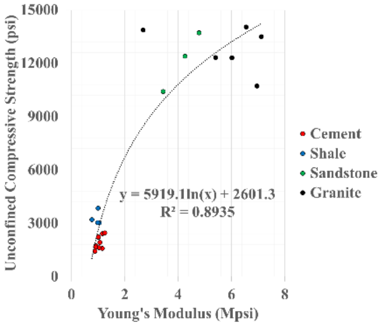

Figure 5: Unconfined Compressive Strength and Young's Modulus Correlation

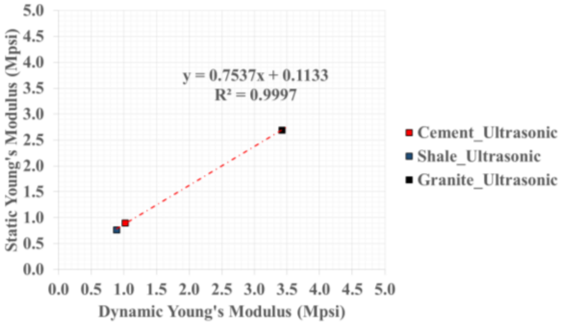

Figure 6: Dynamic to Static Young's Modulus Correlation

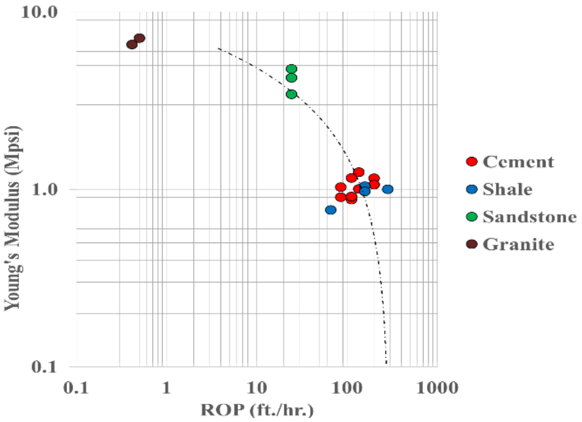

Figure 7: Young's Modulus and Rate of Penetration

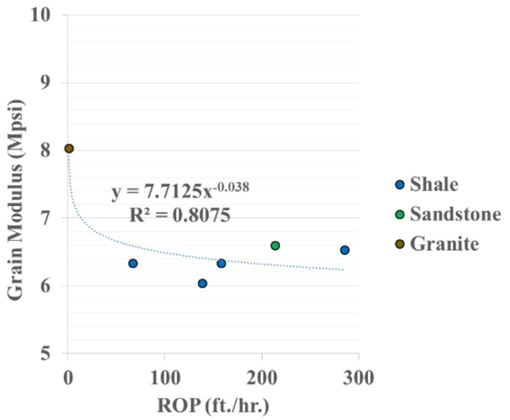

Figure 8: Grain Modulus and Rate of Penetration

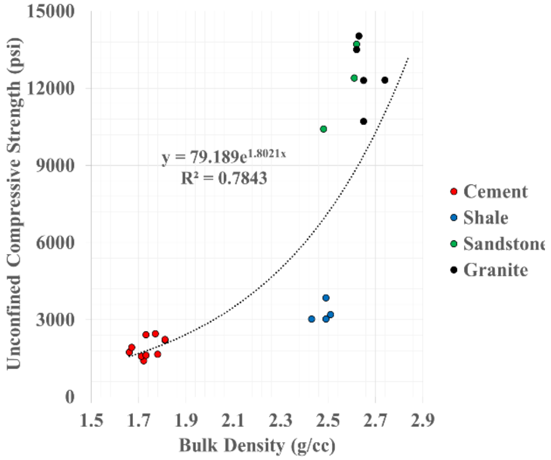

Figure 9: Unconfined Compressive Strength and Bulk Density Correlation

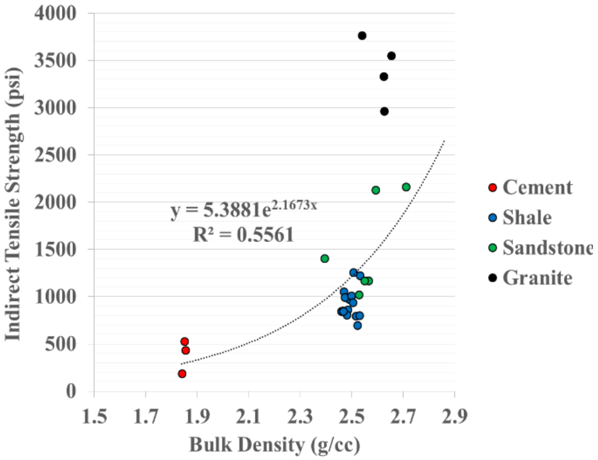

Figure 10: Indirect Tensile Strength and Bulk Density Correlation

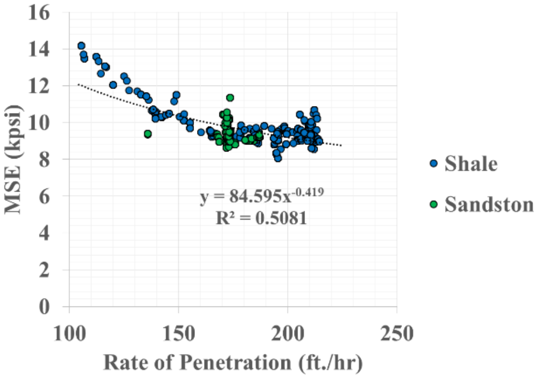

Figure 11: MSE Change with Rate of Penetration (ROP) in Shale and Sandstone during Drilling

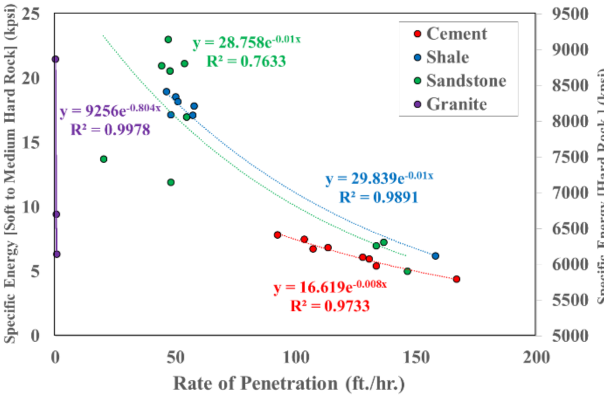

Figure 12: MSE Change with Rate of Penetration (ROP) during Coring Operation