Estimation of rock strength using scratch test by a miniature disc cutter on rock cores or inside boreholes

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ABSTRACT

Accurate estimation of rock properties is crucial for performing realistic analyses in geomechanics, especially for assessment of rock mass strength. The conventional methods for strength measurement require testing on core samples, which are not always available or are time consuming/expensive to obtain. In addition, sample preparation can be an arduous task, and finally special equipment are required to perform the tests. This process offers the strength values with a time lag and not representing the in-situ conditions. Estimation of rock strength by scratching the surface of cores has been implemented with reasonable success in recent years. The need for application of this concept for assessment of rock strength in a borehole has led to development of a special probe that can scratch the borehole wall and offer an estimate of rock strength. This is accomplished by comparing the recorded forces with the strength of the known rock samples. To develop a relationship between cutting forces and rock strength, 27 different rocks covering a wide range of strengths, grain size, and origins have been tested by a miniature disc cutter and the results are discussed in this paper. The results show a promising correlation with R-square values of around 80% between the average normal force and the compressive (UCS) and tensile strengths (BTS) of the sedimentary/metamorphic rocks. However, no significant correlation was observed for igneous rocks. This could be attributed to the impacts of rock texture, grain orientations, and grain size. General equations are also introduced to estimate the UCS and BTS of sedimentary/metamorphic rocks by using average normal force and cutting depth with reasonable accuracy. These outcomes can pave the way for field application of the borehole strength measurement probe, which is currently under development for field trials.

1. Introduction

Assessment of rock mass properties is an essential input for analysing stability of any surface or underground structure in rock. Availability of geological information including condition and frequency of discontinuities as well as rock strength are the main components of rock mass classification systems and related strength and stability analysis. One of the important parameters in evaluating rock mass properties is the intact rock strength. This parameter is usually measured by testing the core samples, which are obtained from exploration borings, coring boulders collected from outcrops, or cores from within the structure. These core specimens are subsequently tested in Rock Mechanic laboratories. The test results offer limited information about the rock at the few locations along the borings for all the efforts, time, and costs allocated for such rock strength evaluation. However, despite all the efforts made to prepare and test the samples,

the results may not necessarily be representative of the behaviour of the rock in the field since the test cannot provide assessment of the in-situ conditions and related impacts on rock strength in the ground. The ideal solution is to be able to estimate the rock mass properties in-situ, and inside exploration borings or other drilled holes in an underground space that is being excavated for mining or civil applications. Therefore, the objective of the current study was to develop a method for evaluating rock strength in various type and size boreholes and measure in-situ rock strength.

Scratch test method has proven to be a promising approach and offer the ability to estimate the rock strength by testing small area of the rock surface. Scratch test offers several advantages including minimum to no sample preparation, small pieces or surfaces can be tested which are for the most part easy to obtain, and finally, the test could offer a continuous measurement of strength along the length of the scratch. As such, the scratch test allows for continuous recording of rock strength

along the core sample, which is preferred over the discrete measurement of strength along a core sample where the UCS specimen is obtained. These features have made this method appealing in various areas of application. One of the main benefits of the scratch test, which was the key reason for being considered for this study, is the adoptability to be used in the field for measuring in-situ strength of rock inside narrow/upward/dry boreholes. This is mainly due to the fact that most of the available borehole strength measurement systems have been primarily developed for larger downward holes that are filled with water or other fluids, as is often the case in petroleum and water well drilling.

Scratch test is based on the rock cutting mechanisms and is related to the cut geometry, cutting forces, and mechanical properties of rock. This relationship has been extensively studied for decades.[1,2] This paper will cover the background of scratch test method, followed by the description of methodology and equipment employed to run scratch test for this study. A quick review of the results of full scale cutting tests will be offered. The relationship between depth of penetration, measured forces, and rock strength which is based on a preliminary statistical analysis of the available data will be discussed. The results of this study have been used for the design of a borehole probe that can implement scratch test principals for estimating rock strength in a small hole drilled for installation of rock bolt or blast holes. The conceptual design of scratch probe is also briefly described at the end of this paper.

2. Background

Scratch test was developed in 1990's in University of Minnesota based on the initial studies on the cutting models of drag bits[3] and PDC cutters.[4] The initial work was followed by correlating the rock strength to the cutting test results,[5,6] which then resulted in development of a device called "Rock Strength Device (RSD)".[7,8] Scratch test was the subject of several studies, which produced a method for rock strength measurements on core samples from the oil field drilling operations.[9–17] More recent studies on scratch test, is focused on estimation of fracture toughness.[18–24] Naeimipour et al. also studied estimation of UCS through scratch test using a miniature disc cutter.[25]

Scratch test basically consists of a system for measuring the cutting forces required to scratch a rock core (along its axis) with a Polycrystalline Diamond Compact (PDC) cutter. The scratch test is kinematically controlled, i.e. both the depth of cut "d" and the cutter speed "v" are maintained constant during the test. The depth of cut typically varies between 0.1 and 2 mm, while the cutter speed is usually set at a few mm/s, (e.g. 0.1–12 mm/s).[8] Both components of the force acting on the cutter are measured. This includes the component "F_t" in the direction of motion of the cutter, and "F_n" normal to the scratched surface. From the force measurements, the specific energy "SE" can be calculated. In addition "F_n/F_t" is estimated to evaluate the wear of the cutter.[26] More than 350 different rock samples,[27] mainly sedimentary rocks, as well as construction materials, such as bricks, cement and plaster, refractories,[28,29] mortars,[30,31] and iron ore[32] were tested by this method.

In addition to the uniaxial compressive strength of the rock, Young's Modulus was estimated from scratch test.[26] Another parameter that can be estimated by this method is the internal friction angle of the rock, which can be estimated through friction coefficient by scratching the surface of the rock with a blunt cutter.[33]

Suárez-Rivera et al., employed scratch test method to assess core heterogeneity, and to compare scratch results with the mechanical properties predicted by logging of reservoir sandstone, mainly to improve analyses such as sand prediction.[34,35] Germay and Richard, also have recently evaluated the correlation between the strength and petrophysical properties.[36] The alteration of concrete strength as a result of contamination and the effect of temperature on refractory brick are also investigated by scratch test method and promising outcome has been reported.[35] Both cases take advantage of continuity of scratch test

results. Dagrain and Germay, and Dargrain et al., employed the minimum sample preparation/requirement feature of scratch test and estimated the strength of rocks such as shale.[35,37] Attempts are also made to estimate the properties of the masonry mortars of a heritage building in Belgium, in order to stabilize its foundation,[30,31,35] and more recently scratch test was used in order to estimate the lump to fine ratio and mineralogy of iron ores through their strength.[32]

A substantial amount of studies has been conducted on cutting of rock with disc cutters and they show a good correlation between the cutting forces and rock properties. All the previous studies on the disc cutters has been in larger disc sizes that are used in tunnelling industry for TBM applications and they are in the range of ~430–480 mm. An extensive study of the rock cutting by disc cutter has been presented by Rostami in various publications.[38–40] The range of disc diameters in previous studies include 75–483 mm and variety of rock strength. No test was conducted with smaller discs with diameter of about 20 mm, which was the selected size disc for development of a borehole probe that could fit in smaller boreholes with diameters ranging from 30 to 50 mm. The testing units for larger discs (linear cutting machine or LCM) did not have the precision for measuring forces in lower range of penetration of 0.2–1 mm, nor do they have the precision for implementing such low penetration ranges. Similarly, the reviewed scratch test machines were all using drag or wedge type tools, and not roller type cutters. Therefore, one of the steps for conducting current studies was to develop a miniature LCM that could implement high precision cuts with a small disc and measure cutting forces.

3. Theory and developed devices

The cutter–rock interaction is generally characterized by the coexistence of two processes, namely rock fragmentation in front of the cutting face of the tool and frictional contact along the wear flat/rock interface.[3] Moreover, two different cutting or failure mechanisms, ductile and brittle, are observed in the process. The mechanism of the failure is controlled by the depth of cut.[10,8,13] In the ductile mode, the energy consumed is related to the volume of the rock removed and as a result the strength of the rock. In brittle mode, however, the amount of consumed energy depends on the surface of the cracks that forms chips, which in turn, is correlated to the fracture toughness and ultimately tensile strength of rock.[8]

Scratch test is based on a phenomenological model of cutter/rock interaction in the ductile regime, which was proposed by Detournay and Defourny.[3] This model is based on three key assumptions applicable to a particular cutter– rock combination, irrespective of the cutter wear, namely (i) the forces on the cutting face, averaged over a distance which is large compared to the depth of cut, and is proportional to the cross-sectional area of the groove traced by the cutter; (ii) the inclination of the average force on the cutting face is constant (in other words, angle of resultant force); and (iii) there is frictional contact at the wear-flat rock interface. Such a model is characterized by three parameters: the intrinsic specific energy (ε) associated with the cutting process, the inclination of the force acting on the cutting face, which is based on the ratio of drag to normal forces, and the friction coefficient mobilized across the wear flat. Phenomenological model assumes that "ε" is indeed independent of the depth of cut and it is a constant quantity characterizing a particular combination of cutter geometry and rock. It is important to reiterate the difference between the intrinsic specific energy "ε" and the specific energy "SE". The latter quantity, SE, accounts for both the energy expended in cutting the rock and the energy dissipated at the frictional contact between the wear flat and the rock, while the former, ε, only characterizes the energy used to fragment the rock ahead of the cutter.

Since the introduction of scratch test, scratch test devices have been evolved and some companies have developed their own devices with different names. Currently, there are three commercially available apparatus including Rock Strength Device (RSD),[7] profiler core scratch

test system,[41] and Wombat.[32]

Rock Strength Device (RSD) is the first scratch test apparatus, which was introduced by University of Minnesota in 1990s.[7] RSD is gradually optimized and a number of prototypes have been developed over the years.[29] Despite gradual improvements, the main components of RSD seem to be the same in all prototypes. It consist of a frame, a load sensor, a drive motor and a data acquisition system.[37] Its cutting element, sharp or blunt, accepts replaceable polycrystalline diamond cutters of 10 mm width and back-rake angle of 15°.[26] Blunt cutters have a wear flat length varying from a fraction of mm to a couple of mm,[27] with a small forward inclination about 2° to ensure conforming contact with the rock.[7] The range of force measurements is from 10 N to 4000 N, and is recorded with a resolution of about 1 N.[8] The data acquisition rate is up to 1000 Hz[8] and the scanning rate is typically at 25 samples/mm.[27]

Another device is "profiler core scratch test system", which is a patented technology developed by Schlumberger for continuous measurements of rock strength by cutting (scratching) the rock surface.[41] Wombat is a new apparatus, which is manufactured by Epslog SA and is commonly used in the petroleum industry.[32] Wombat seems to have very similar components as the RSD. If the sample is sufficiently competent, this device can scratch and analyse up to 3 m of core per hour.[36]

4. Methodology

The scratch methods that were discussed earlier use rock core from the diamond drilling to estimate the rock strength. Although this approach has addressed some of the issues related to rock testing regarding the sample preparation and continuous strength results, it still has the disadvantages of not being truly in-situ, providing small amount of information from the relatively scattered boreholes and being relatively costly and time consuming from the initial stage of coring and handling, to setting up the samples for running the scratch test. While this system is suitable for its current applications, it cannot offer rock strength measurements that meets work flow of many mining and tunnelling applications.

A scratch probe device can overcome these shortcomings by testing the rock inside drilled boreholes in the underground openings. This system is based on using the holes that would be drilled in the normal operation cycle for development of tunnels, drifts, mine entries, or a stope, including roof bolting or blast rounds. No sample preparation is needed for this method other than drilling boreholes, which is several times faster than diamond/core drilling. Also, the evaluated strength values are continuous along the borehole, and can be readily obtained on site by real time analysis of the probing data with specialized software.

Moreover, unlike the other scratch devices, which use wedge shape scribes to scratch the surface of the rock core, this study has used miniaturized disc cutters as the means to scratch the surface of the borehole wall, as shown in Fig. 1. This disc cutter is made of Tungsten Carbide and has two ball bearings on each side. The disc diameter is about 7/8″ (~ 22 mm) and its thickness is roughly 1/16″ (~ 1.6 mm). This will help the operator run the probe inside the borehole with much less effort and minimizes the chance of the probe getting stuck inside

Fig. 1. Miniature disc cutter used for this project (ruler in inches).

the borehole. Disc cutters require higher normal force than drag type tools, which makes the measurement of forces easier, while it takes less rolling force, thus making it easy to operate the device in terms of pushing the probe in the borehole and its retrieval. Therefore, the first step for this study was to develop the background data to establish correlations between measured scratch forces and mechanical properties of the rock by using a disc scribe. Fig. 2 shows the overall picture of the linear cutting device used for testing.

There are various parameters involved in scratch test, including tool velocity, scratch depth, distance between the scratches, type/geometry of scribe, rock type, and bit wear. During the tests, the cutting velocity was kept constant to about 2.6 m/min. This value is measured by a precise digital readout positioning system mounted on the cutting machine. One of the main parameters involved in this test is the scratch depth. In this study, cutting depth varied between 0.2 mm and 1 mm with an interval of 0.2 mm. In order to minimize the effect of the adjacent scratches, a distance or cut spacing of 10 mm was used, which is at least 10 times more than the depth of maximum penetration used in the testing. No cross chipping between two adjacent cuts was observed and therefore cuts can be considered isolated.

The cutting tests were performed on various samples ranging from soft (coal), medium strength (i.e. limestone), to hard rocks (granite). Some of the samples were collected from the coal/limestone mines in Pennsylvania, and the majority of samples were obtained from quarries around the world as part of scanning available dimension stones in the construction market. The samples can be categorized as limestone, marble, travertine, and igneous rocks (commercially called granite for tiling or countertop), which represent sedimentary, igneous and metamorphic rocks. There are also some other sedimentary rocks, namely siltstone, coal and conglomerate. These samples were subject to standard rock mechanic tests before running cutting tests. This includes Uniaxial Compressive Strength (UCS) and Brazilian Tensile Strength (BTS). The test results are summarized in Table 1.[42–44] The UCS and BTS results for Siltstone were not readily available and, as a result, these two parameters were estimated based on the point load (PLT) tests. The mean grain size (MGS) of most samples were evaluated and are also listed in this table. Under the "rock type" column, CL, CT and CM are abbreviations for Limestone, Travertine and Marble; MF, MM and MC are Igneous rocks with fine, medium and coarse grain sizes; and CG, CO and SL are conglomerate, coal and siltstone, respectively. In Fig. 3, the typical igneous rocks with fine, medium and coarse grain sizes are illustrated.

Since cutter tip wear can impact the results, an attempt was made to identify the issues and address such impacts by maintaining a consistent cutter profile during the tests. As such, possibility and extent of disc tip wear was examined by cutting the surface of S2-GL sample, which is a relatively hard and abrasive limestone and checking the tool wear by means of a microscope and a precise 3D scanner. Negligible or no bit wear was observed after making ten 1-mm-deep scratches on these samples and therefore, it was assumed that the test results weren't affected by bit wear in this study. However, the disc cutters were also replaced occasionally to eliminate any possible wear effect on the results and malfunctioning due to bearing resistance.

The miniature linear cutting test device was designed and fabricated at Penn State University, as elaborated in reference,[45] by using a milling machine and instrumenting it to measure displacements and forces. Precise instruments and load sensing components were used to manufacture this device to meet the required high accuracy. The cutting tool was mounted on a frame where the load cell was also mounted to force measurements. This mounting system was designed in a way to maximize the range of penetration for the cutter into the sample and to minimize the probability of the holder getting stock by cutting fragments. The rock sample is cast in concrete to provide a confining support for the specimen. The sample is then mounted and fixed on the machine's table by a vise. The position and speed of the table can be adjusted and controlled with relatively high accuracy in all three dimensions.
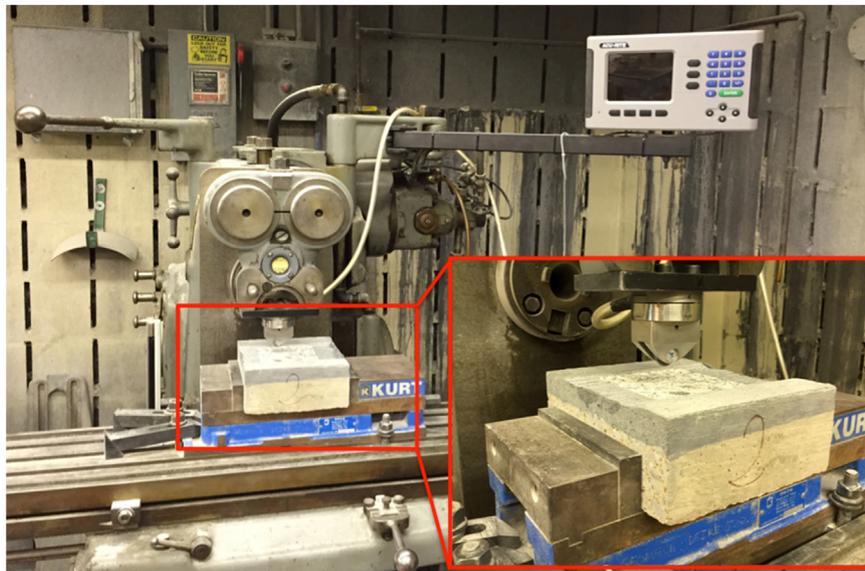
Fig. 2. Linear cutting device developed to run the scratch tests.

Table 1
Geomechanics test results on selected rock samples.[42–44].

| Rock type	ID	UCS (MPa)	BTS (MPa)	MGS (mm)	Rock Type	ID	UCS (MPa)	BTS (MPa)	MGS (mm)
MC	S1	176.00	9.06	15.18	CM	S13	75.00	3.72	0.57
MM	S2	145.00	8.20	4.89	CM	S14	54.00	4.70	0.47
CL	S2-GL	154.69	6.83	NA	CL	S15	86.00	8.45	0.005
MM	S3	186.00	11.72	6.36	CT	S16	58.00	3.43	0.085
CG	S3-CG	154.14	8.55	NA	CL	S17	87.00	7.40	0.067
CO	S3-CO	28.98	1.98	NA	CL	S18	93.00	8.57	0.005
SL	S3-SL	(42.50)[a]	(4.25)[a]	NA	CL	S19	95.00	5.81	0.004
MC	S5	163.00	9.66	11.97	CM	S20	48.00	3.72	1.4
MM	S6	134.00	6.88	7.86	CM	S22	75.00	6.83	0.67
MF	S7	151.00	11.02	2.91	CT	S23	75.00	4.47	0.004
MM	S8	164.00	14.15	7.97	CT	S24	51.00	3.93	0.006
MM	S9	194.00	8.21	4.52	CT	S25	58.00	4.19	0.077
MC	S10	174.00	9.48	27.73	MC	S26	150.00	12.50	23.14
MF	S11	249.00	8.70	1.47					

[a] Estimated based on the PLT Axial result.
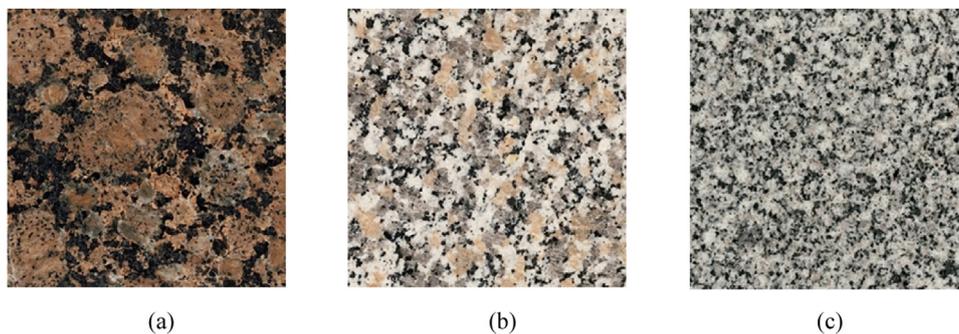
Fig. 3. Pictures of typical igneous rocks with (a) coarse, (b) medium, and (c) fine grain size.

A round triaxial load cell with 3000 Ibs (~ 14000 N or 1360 Kgf) capacity measures the cutting forces in three directions. The load cell consists of four-leg strain gage bridges in three directions with full-scale output of 4 mV/V and is resistant to dusty/wet environment. Although the load cell was factory calibrated, it is re-calibrated on regular basis in the laboratory after the scribe structure was mounted on the load cell by applying a set of predetermined loads to the tip of the cutting tool through a small hydraulic jack and a manual hydraulic pump.

The load cell data was recorded by a NI USB-6341 × series data acquisition system (DAQ). The cutting test apparatus shows and records

the position of the cutting tool. The positioning data is collected from a readout system installed on the milling machine and connected to the DAQ system. This readout system shows the absolute and relative position of the cutting tool relative to the milling machine table in X (cutting direction), Y (perpendicular to cutting direction), Z (vertical) directions with the accuracy of 0.0001 mm.

The high accuracy of the testing device and fine control of the scratch depth requires very precise sample preparation. The sample surface needs to be flat and level relative to the machine table. A special flat PCD bit with the width of about 20 mm was used to level the surface
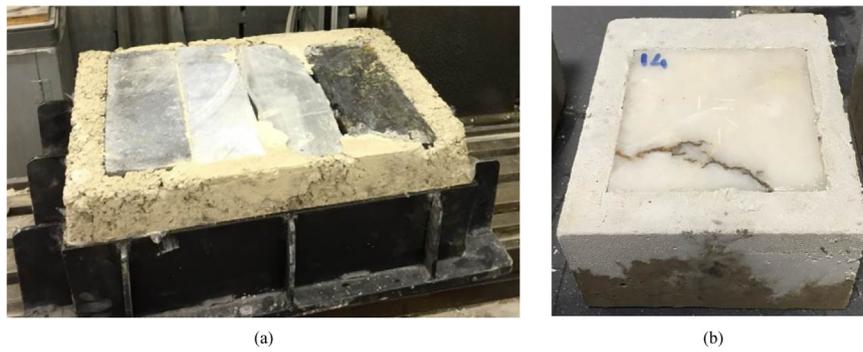
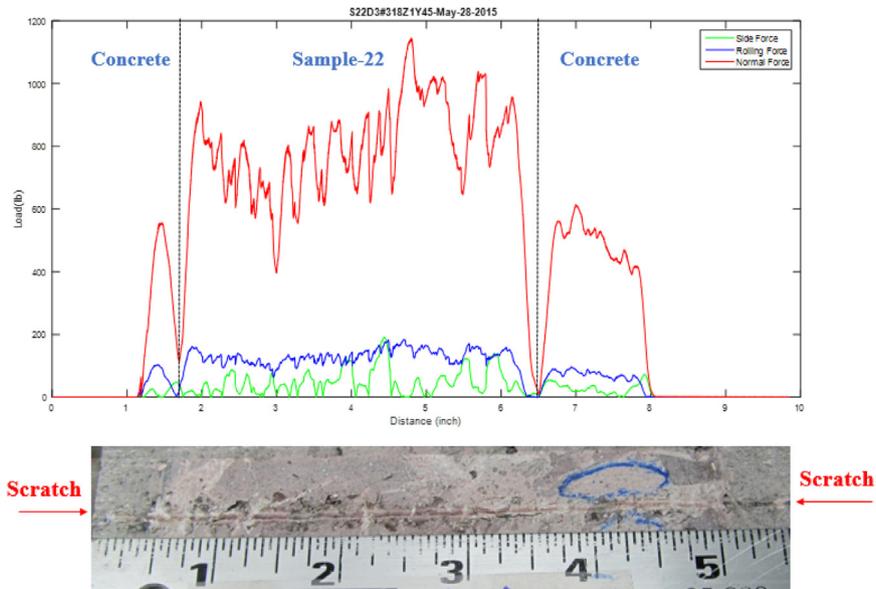**Fig. 4.** Picture of rock samples prepared for cutting test.

Fig. 5. Typical result of cutting test and the picture of the cut on the sample S-22 surface.

Table 2
Scratch test results (three repetitions for each cutting depth) for sample S-22.

Sample ID	Cut depth (mm)	Mean normal force (Ib)	Mean rolling force (Ib)	Average normal force (Ib)	Average rolling force (Ib)
S22	0.2	52.21	3.26	48.43	3.10
		45.35	2.86		
		47.73	3.19		
	0.4	239.47	25.20	243.36	24.97
		247.43	25.84		
		243.18	23.86		
	0.6	414.95	51.92	468.93	55.07
		463.18	58.23		
		528.66	65.98		
	0.8	778.33	118.37	722.90	111.21
		716.46	114.82		
		673.90	100.44		
	1	863.43	165.38	834.28	144.39
		804.21	131.02		
		835.19	136.77		

of the sample by shaving the top of the sample with the scribe. After the load cell/cutting disc assembly was mounted, the vertical reference point in Z direction for each test (cutting path) was reset using the displacement sensor and verified by passing a piece of paper under the cutter. Zero depth was where the paper could not pass through the gap between the disc and the sample surface.

For scratch tests, some of the rock blocks were cut into

approximately 75 mm (3″) wide to 250 mm (10″) long pieces, and placed side by side in a steel box, then cast by using concrete. This allowed for simultaneous testing of the samples and to see if the system can distinguish between various rock types in a composite sample. Fig. 4(a), shows the prepared sample consisted of limestone, siltstone, coal and conglomerate. Most of the available samples, however, were cast in smaller moulds with no steel frame as shown in Fig. 4(b).

As noted earlier, all the samples were subject to cutting test and cut depth of 0.2–1 mm with 0.2 mm intervals. Each identical test was repeated 3 times for most of the rock samples and in some cases with highly variable force measurements, the test was repeated 10 times. Fig. 5, shows a typical result of cutting test and the change of cutting forces in X (rolling), Y (side) and Z (normal) directions at the depth of 1 mm on S-22 sample. For each test, the controlling variables and results such as rock type, the average of normal, rolling and side forces are measured, and description of the sample surface was recorded. The correlations between these parameters and strength properties of the rock samples, UCS and BTS, were subsequently examined, as will be discussed in following sections. Additional details on testing procedures and processing of data is available in reference.[45]

5. Test results and discussion

So far, more than 500 tests have been run in different rock samples with various strength, type, and structure. For each test, the appropriate data window that represents the rock signature is selected and then the mean value of normal and rolling forces are calculated within that
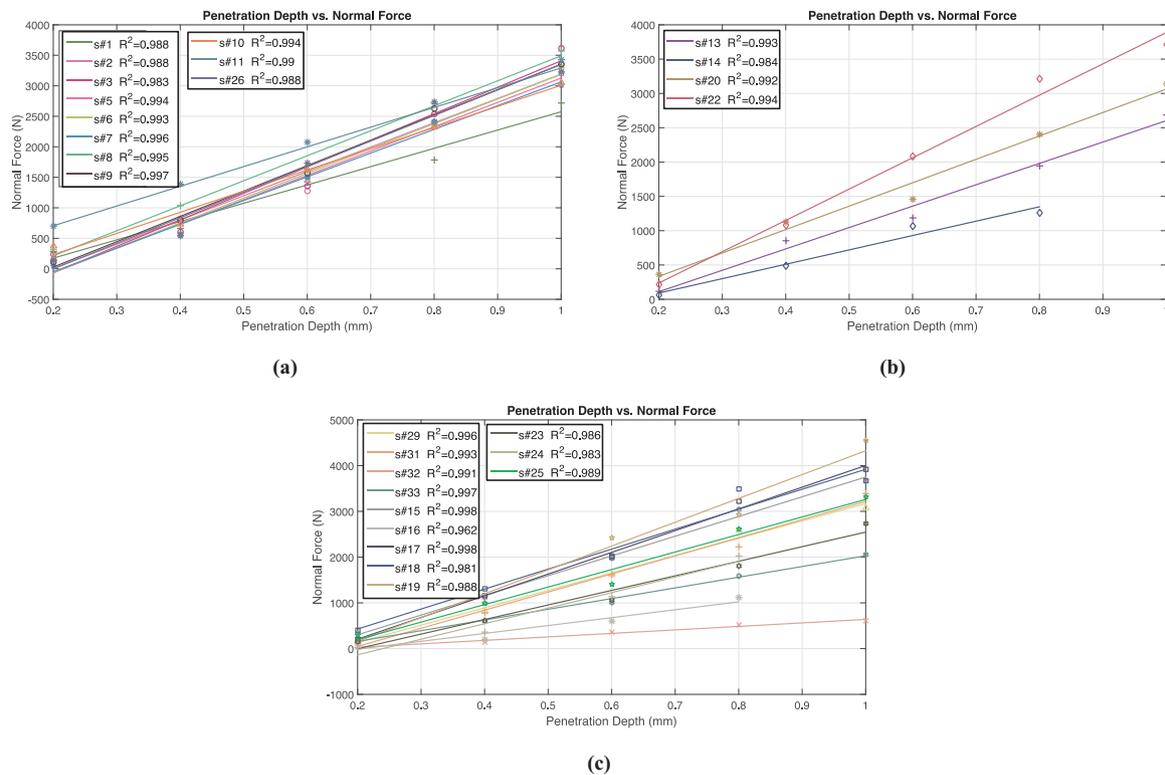
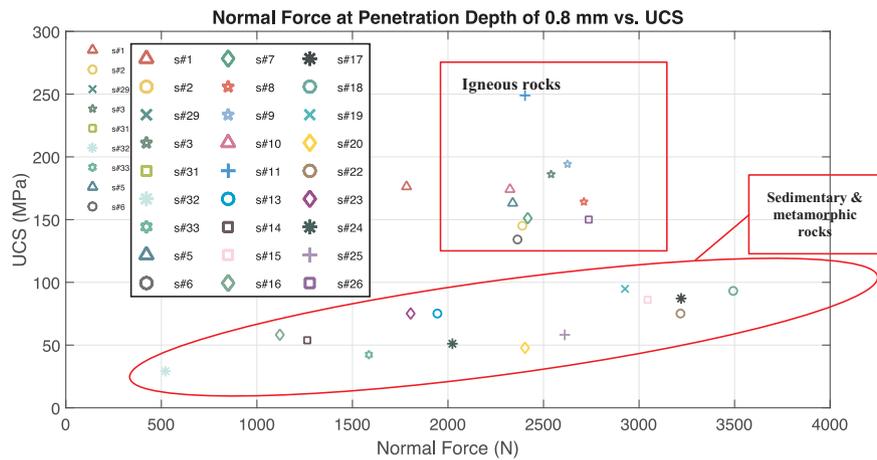**Fig. 6.** Normal force vs. penetration depth for (a) igneous, (b) metamorphic, and (c) sedimentary rock samples.

Fig. 7. Scattering of the samples on UCS vs. average normal force graph for cutting depth of 0.8 mm.

Table 3
Details of regression analysis to estimate UCS vs Normal forces of sedimentary and metamorphic rock samples for the penetration depth of 1 mm.

Equation	Model summary		
	R Square	F[1]	Significance[2]
Linear	0.715	22.582	0.001
Logarithmic	0.626	15.077	0.004
Inverse	0.494	8.800	0.016
Quadratic	0.719	10.223	0.006
Power	0.738	25.407	0.001
Exponential	0.767	29.652	0.0003

range. This was done by a MATLAB code that was developed for data analysis. The results for each penetration depth were subsequently evaluated and the outliers were discarded. For the tests with 3 or 5 repetitions, the outlier cuts were selected based on the apparent closeness of the results using interquartile range method. The average of normal and rolling forces were calculated for the acceptable results of each penetration depth.

Table 2 is an example of the scratch test results for sample S22. As shown in this table, the rolling force values are significantly lower than the normal forces, which means that much less force is needed to move the cutter along the sample unlike the relatively high normal force that is needed to penetrate into the rock. Also, the relative closeness of test results in each penetration depth, demonstrates the repeatability of this test for this sample.

Fig. 6 shows the measured forces at various depth of penetration for different rock types. For convenience, in the rest of this paper average of normal and rolling forces are simply called normal and rolling forces and are referred to as FN and FR, respectively. A quick review of charts in Fig. 6 points to linear correlations between the measured forces and the penetration for all the sample with good R-square values. Similar

Table 4
Summary of the best curve fitting results based on the normal force for various penetrations for sedimentary and metamorphic rock samples.

Strength	Scratch depth	Equation type	Model summary		
			R Square	F[1]	Significance[2]
Compressive UCS	0.2	Power	0.337	6.107	0.029
	0.4	Power	0.512	12.579	0.004
	0.6	Linear	0.674	24.78	0.000
	0.8	Power	0.654	22.64	0.000
	1	Exponential	0.767	29.652	0.000
Tensile BTS	0.2	Power	0.331	5.924	0.032
	0.4	Power	0.627	20.141	0.001
	0.6	Power	0.79	45.267	0.000
	0.8	Exponential	0.815	52.824	0.000
	1	Exponential	0.702	21.225	0.001

[1] F-test value.
[2] p-value associated with F-test.

Table 5
Summary of the best curve fitting results obtained from SPSS software.

Rock type	Strength type	Force type	Scratch depth	Equation type	Model summary				Validity	Equation
					R Square	Adj. R Square	F	Sig.		
Sedimentary and metamorphic	UCS	FN	1	Exponential	0.767	0.741	29.65	0.000	Yes	25.099. Exp (0.0003 FN)
		FR	1	Power	0.728	0.698	24.07	0.001	Yes	1.897. (FR$^{0.574}$)
	BTS	FN	0.8	Exponential	0.815	0.799	52.82	0.000	Yes	1.943. Exp (0.0004 FN)
		FR	0.8	Exponential	0.798	0.782	47.53	0.000	Yes	2.007. Exp (0.003 FR)
Igneous with coarse grains	UCS	FN	0.8	Linear	0.740	0.611	5.704	0.140	No	226.031 −0.03 FN
		FR	0.8	Exponential	0.856	0.783	11.85	0.075	No	232.258. Exp (−0.001 FR)
	BTS	FN	0.8	Exponential	0.732	0.598	5.466	0.144	No	4.873. Exp (0.0003 FN)
		FR	0.8	Exponential	0.905	0.857	19.02	0.049	Yes	5.063. Exp (0.002 FR)
Igneous with medium grains	UCS	FN	0.8	Power	0.534	0.379	3.437	0.161	No	3.91E-05. (FN$^{1.946}$)
		FR	0.8	Power	0.444	0.258	2.394	0.220	No	0.152. (FR$^{1.167}$)
	BTS	FN	1	Exponential	0.884	0.846	22.93	0.017	Yes	0.013. Exp (0.002 FN)
		FR	1	Exponential	0.730	0.641	8.127	0.065	No	0.364. Exp (0.005 FR)

correlations seem to exist between the penetration and rolling forces. It should be noted that the force vs. penetration (F-P) relation is a curve that follows a power function, but for the sections beyond the initial penetration or so called "Threshold Penetration", the F-P relationship can be considered to be linear in a limited range and the resulting error is low, relative to the variability of the forces in rock cutting. If a F-P curve were to be constructed that extends to penetration near zero or very high penetration rates, then the use of non-linear function would be more suitable.

Since the main objective of the study has been the estimation of the UCS from cutting forces, the UCS versus normal force graph is developed as shown in Fig. 7. This figure shows a reasonable correlation between cutting forces and UCS values in certain rock types for cutting at a depth of 0.8 mm. One can observe that the igneous rocks show no noticeable pattern between cutting forces and UCS, unlike the sedimentary and metamorphic rocks where a rather linear trend can be identified. However, if the igneous rocks are classified based on their mean grain size, in some cases, models with acceptable results can be found based on the data analysis.

As a result, for each penetration depth, statistical analysis (SPSS software package) was used to examine the correlation between the normal and rolling forces and UCS or BTS values by using various regression functions. This includes linear, power, polynomial, and exponential function. As an example, Table 3 presents the results for the regression analysis to find the best correlation between UCS and normal forces for sedimentary and metamorphic rock samples at the penetration depth of 1 mm. Based on Table 3, exponential model provides the highest R^2, F-test value and significance in the aforementioned case. In this table, "F" and

"Significance" parameters are F-test value and the p-value associated with it, respectively. F-test can be calculated from dividing the Mean Square of Regression by the Mean Square of Residuals.

Table 4 summarizes the best fit of each case for sedimentary and metamorphic rock samples. A quick review of this table shows that UCS and BTS of sedimentary and metamorphic rocks can be generally best predicted by normal force when the scratch depth or penetration is more than 0.4 mm. This might be because at certain depth of cut, significant amount of rock is crushed, and therefore, cutting forces would be good representatives of rock strength properties. For igneous rocks, there is no significant correlation between the normal and rolling forces and UCS or BTS. The best correlations found for the tested rock samples are those summarized in Table 5.

Table 5, presents the models that best estimate the UCS or BTS for each rock group. Since, there are just 2 igneous samples with fine grain size, they are not analysed in this iteration. Based on this table UCS or BTS of sedimentary and metamorphic samples can be predicted with a relatively high confidence and R-square. For igneous rocks, BTS can be estimated with fairly good correlations. The UCS, however, cannot be estimated with an acceptable confidence range. This matter is worse for samples with medium size grains.

In most cases, exponential functions offer the best fit and the data from 8-mm deep tests gives the highest R-square in majority of cases. The results also show that generally BTS is more predictable with this method. Normal and rolling forces both gives acceptable formula for the sedimentary and metamorphic rocks. For igneous rocks with coarse and medium grain size, rolling and normal forces, respectively, provide more suitable formulas.
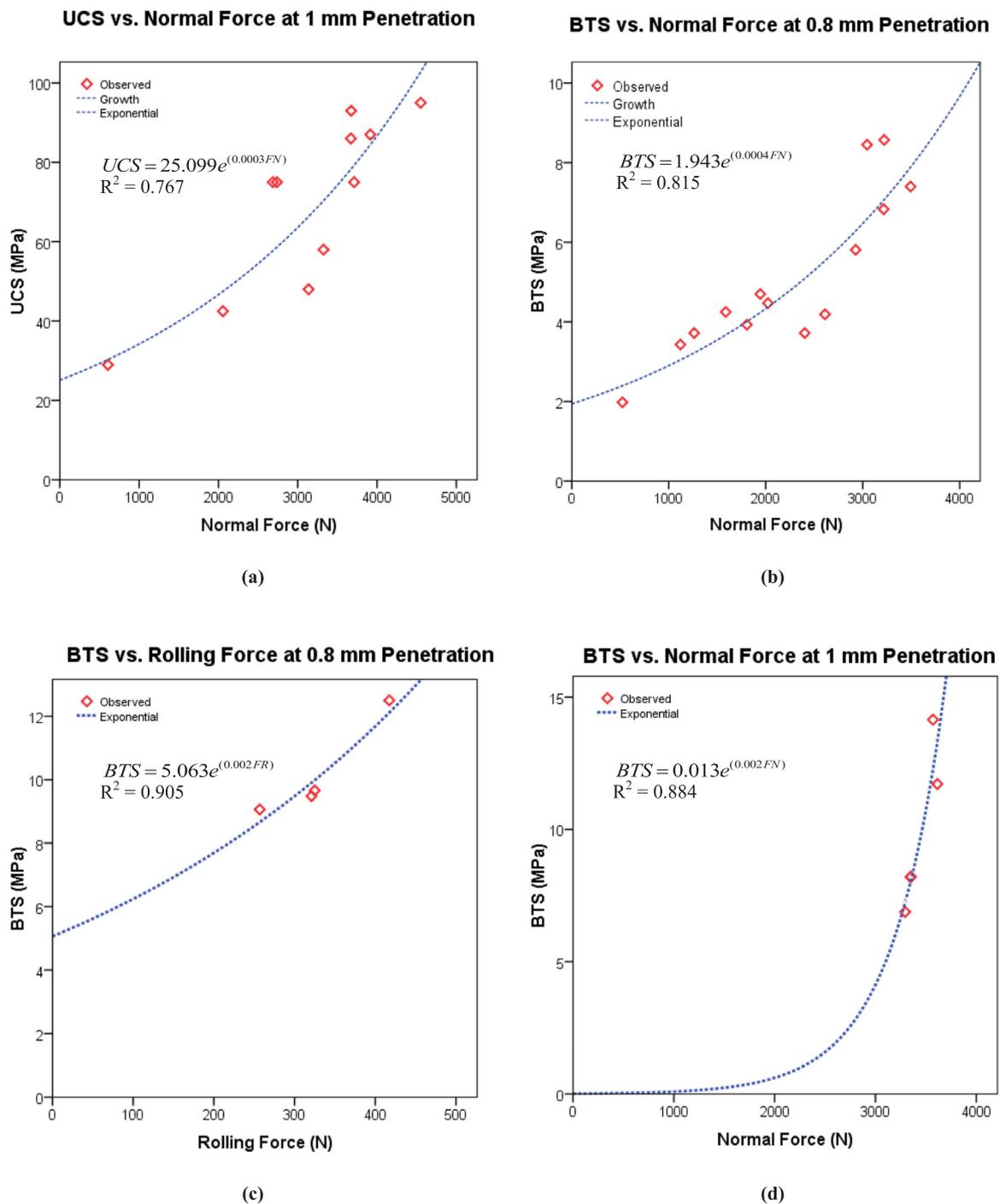
Fig. 8. Best curve fits and their formulas for (a) UCS, and (b) BTS, of sedimentary and metamorphic rocks; (c) BTS of igneous with coarse grains, and (d) BTS of igneous rocks with medium size grains.

Fig. 8 shows the graphs of curve fits that best estimate the UCS and BTS of sedimentary and metamorphic rock samples as well as the best estimate of BTS for coarse and medium grain size igneous rock samples.

Although it is of high interest to know which depth(s) of cut gives the best estimation of the UCS and BTS, it is more practical to find a more general correlation that involves penetration as a variable. This is because for borehole probe application it is not possible to keep the depth of the scratch penetration constant. Therefore, it would be desirable to predict the UCS/BTS based on the recorded penetration depth and forces at each point. Consequently, statistical analysis was used to establish a set of linear regressions for estimation of UCS and BTS from penetration and measured cutting forces. Table 6 summarizes the

results of these analyses for the sedimentary and metamorphic rocks.

In this table, F_N, F_R and P represent average normal and rolling forces, and penetration depth, respectively. The first two equations for UCS and BTS show that F_N provides better estimates of rock strength compared to F_R. Also, the last two equations for each parameter are the optimum correlations between UCS or BTS, F_N and P. As it can be noticed, all the statistical parameters, including R-square and adjusted R-square, of each set of these equations are the same, although one is correlated to the logarithm (Log_{10}) of the parameter and the latter to the natural logarithm (Ln). However, since some equations require the least number of components, the suggested equations are as follows:

Table 6
Best fit formulas for estimation of UCS and BTS for various penetration depths.

| #	Strength type	Equation	R-Square	Adj. R-square	Sig.	F
1	UCS	$UCS = 77.748 + 0.021(F_N) - 71.554(P)$	.482	0.466	0.000	29.774
2		$UCS = 81.851 + 0.107(F_R) - 64.773(P)$	.365	0.345	0.000	18.374
3		$UCS = 37.430 + 0.016(F_N) + 18.245 Log(FN) - 81.971(P)$	.538	0.516	0.000	24.492
4		$Log(UCS) = 0.766 + 7.385E - 5(F_N) + 0.105 Ln(F_N) - 0.716 Log(P)$	.569	0.548	0.000	27.694
5		$Ln(UCS) = 1.764 + 0.243 Ln(F_N) - 1.648 Log(P)$	.569	0.548	0.000	27.694
6	BTS	$BTS = 6.242 + 0.002(F_N) - 7.064(P)$	.493	0.477	0.000	31.077
7		$BTS = 6.646 + 0.011(F_R) - 6.386(P)$	.372	0.352	0.000	18.964
8		$BTS = 2.565 + 0.002(F_N) + 0.723 Ln(F_N) - 8.012(P)$	.542	0.52	0.000	24.812
9		$Log(BTS) = -0.585 + 9.443E - 5(F_N) + 0.127 Ln(FN) - 0.883 Log(P)$	.636	0.619	0.000	36.741
10		$Ln(BTS) = -1.347 + 0.294 Ln(F_N) - 2.032 Log(P)$	.636	0.619	0.000	36.741

(a) **(b)**

(c)
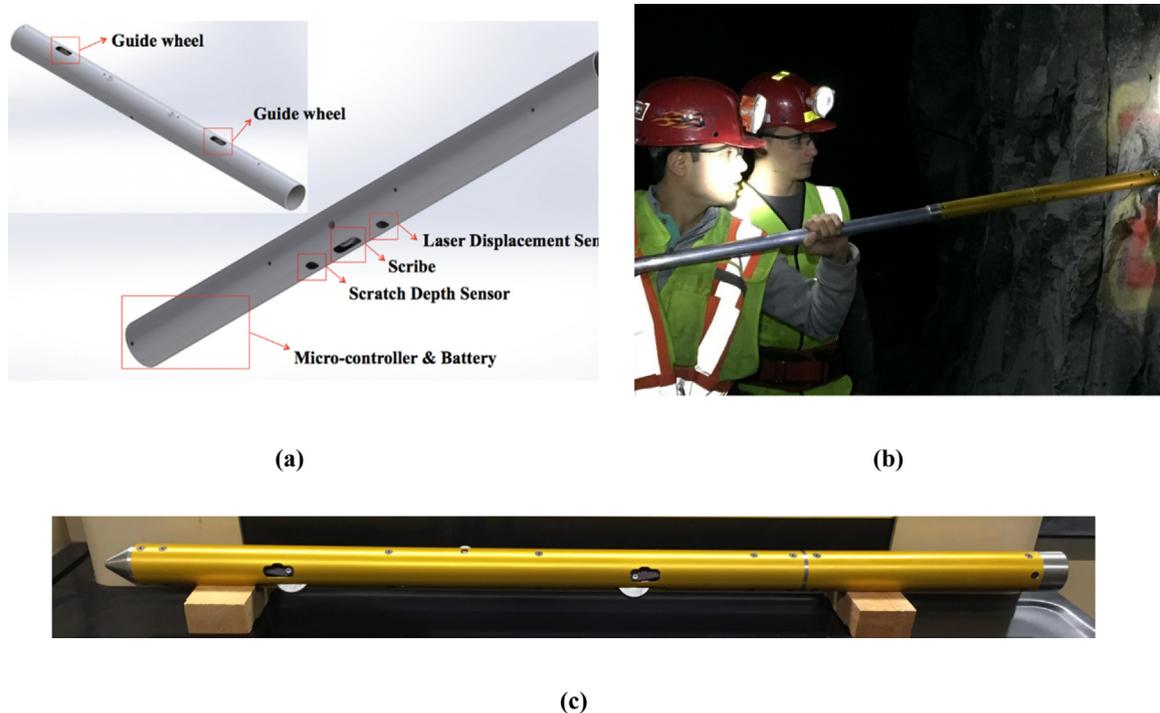
Fig. 9. (a) conceptual design of scratch probe; (b) field trial of first prototype in an underground limestone mine in PA, USA; and (3) photo of the first prototype of scratch probe.

$$UCS = 5.84 \times \frac{F_N^{0.243}}{P^{0.716}}; \ R^2 = 0.569 \tag{1}$$

$$BTS = 0.26 \times \frac{F_N^{0.294}}{P^{0.882}}; \ R^2 = 0.636 \tag{2}$$

It should be mentioned that although these results are from a broad range of rock types, more rock samples are required to be tested to verify these outcomes. Moreover, since the purpose of these tests is to estimate the rock strength by scratching the borehole wall, it is necessary to also examine the scratch result for a condition more similar to the borehole and run a series of tests on curved surfaces with varied curvature radii.

6. Rock Strength Borehole Probe (RSBP)

As mentioned earlier, the results of cutting tests will be used for the design of Rock Strength Borehole Probe (RSBP), which is the final goal of this project. This probe should be able to operate in a 25–50 mm (1 – 2 in) diameter upward boreholes with the length of 2–10 m (7–30 ft.). The probe is designed to be easy to use and also light enough for an average person to operate. This probe will measure normal/rolling forces on the scribe with a load sensing device, and monitors linear

displacement, scratch depth, and the borehole profile using optical sensors and a micro controller. All the data will be stored on a SD card for subsequent analysis. The scribe is pressed against the borehole walls by a set of spring loaded guide wheels, which runs along the hole and maintains the disc cutter at constant depth relative to the outer surface of the probe. This system allows for controlling the depth of cut and the applied forces can be used to evaluate rock strength. The operator can adjust the amount of normal force or depth of cutting head by control screws. Fig. 9(a)–(c) show the conceptual design of rock strength borehole probe, its field trial at an underground limestone mine in PA, USA and photo of scratch probe first prototype, respectively.

7. Conclusion

The results of the current study show that the measured forces while scratching the surface of different sedimentary and metamorphic rocks with disc shape cutter can provide good estimates of rock strength properties. The preliminary results show good correlations between the average normal/rolling force and the compressive and tensile strengths of the sedimentary and metamorphic rocks, meaning that UCS and BTS of the samples can be predicted from the measured cutting forces. No significant correlation was found between measured forces and rock

strength in igneous rocks. The igneous rock samples consist of different type and percentage of minerals, the mean grain size of these minerals in the tested samples ranged from 5 micrometres to 25 mm. Also, igneous rocks have mostly heterogeneous and anisotropic structure in the scale of cutting with the miniature disc cutter. Therefore, obtaining a significant relationship between the normal and/or rolling forces and the mechanical properties of igneous rocks was not possible. Analysis of the test results lead to development of formulas for estimation of UCS and BTS of the sedimentary and metamorphic rock samples with R-square in the range of 80%. This was for the tests with cutting depth of 1 and 0.8 mm. Additional equations are introduced to estimate UCS or BTS values of sedimentary and metamorphic rocks from cutting forces and penetration depth. These equations are not meant to be universal for estimation of UCS and BTS from the scratch test by small discs, and there are other laboratory or in situ conditions such as rock moisture content, stresses, condition of cutting surface that can impact the test results. The main focus of the study has been to evaluate the feasibility of measuring rock strength by such means, and the results show a pathway forward for further development of the concept. More tests are underway to evaluate the scratch test results on the curved surfaces and under variable cutting velocities. Also, final design and fabrication of the borehole probe is underway for application in boreholes drilled in the roof/rib of an underground opening for estimation of rock strength properties.

Acknowledgment

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