Evaluation of indentation on high strength and isotropic formations

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ABSTRACT
High-performance drilling tool design requires a deep understanding of rock mechanical properties of strength and hardness. The indentation test is an indirect rock strength measurement test. Rock fracturing behaviors and responses under indentation tests represent rock hardness index that follows patterns and modes that also are produced similarly by drilling, cutting, and boring either in petroleum drilling processes or mining operations. This work concentrates on conducting indentation tests on high-strength granite of a highly isotropic nature. Many samples of 2-inch diameter cores of different length to diameter ratios were tested using different indenter-tip diameters with varying confinements to evaluate the influence of all variables in the test on rock cuttability. The tests resulted in curves with varying load-displacement responses and specific energy.

RÉSUMÉ
La conception d'outils de forage performants nécessite une connaissance approfondie des propriétés mécaniques de la roche, à savoir sa résistance et sa dureté. L'essai d'indentation est un test indirect de mesure de la résistance de la roche. Les comportements et les réponses de fracturation de la roche lors des essais d'indentation représentent l'indice de dureté de la roche qui suit des modèles et des modes qui sont également produits de manière similaire par le forage, la coupe et l'alésage dans les processus de forage pétrolier ou les opérations minières. Ce travail se concentre sur la réalisation d'essais d'indentation sur du granite à haute résistance de nature hautement isotrope. De nombreux échantillons de carottes de 2 pouces de diamètre de différents rapports longueur/diamètre ont été testés en utilisant différents diamètres de pointes d'indentation avec des confinements variables afin d'évaluer l'influence de toutes les variables de l'essai sur la capacité de coupe de la roche. Les essais ont donné lieu à des courbes présentant des réponses charge-déplacement et une énergie spécifique variables.

1 INTRODUCTION

Drilling and boring involve excavation of the earth's crust which requires a lot of energy. These are processes that are time-consuming and thus an expensive part of the mining and petroleum industry. Excavation of the rocks is a subsurface activity that can be learned, planned, and performed using rock engineering principles. Before and after visualization is the only way to study rock tests due to their opaque nature (Swain, 1976). Effective tool design requires the strength of rock as a physical parameter Denkena (2022). These values are obtained by direct rock tests such as unconfined compressive strength (UCS), Brazilian tensile strength (BTS), etc. devised by the ASTM standards. Direct tests are usually expensive, time-consuming, complicated, and less adaptable to field conditions (Kallu, 2015). Also, the sample preparation must be precise, crack-free, and discontinuity free.

In conditions when the rock samples to be studied are not available in bigger sizes and sophisticated requirements so as to perform standardized tests, Szwedzicki (1998) came up with a draft to help engineers categorize rocks based on their hardness. with less sophisticated sample preparation. In the next two decades, indentation tests underwent many modifications and changes. Though the process varied, the output from the tests gave similar justifications. Kalyan (2015) presented a review comprised of all the work done and advancements made in the indentation tests for rock hardne ss evaluation. The study is augmented with various correlations obtained from experimental work to match and predict the strength of the rocks.

Ranman (1985) described the process of indentation as a cycle that can be divided into three sections. It begins with the indenter stored with elastic energy that subsequently causes crushing and cracking (Fig. 1). The further increase in load extends the crack formation until the load drops significantly and another cycle begins. Pang (1990) categorized cracks less than 2 mm as micro-cracks, and the ones larger than that to be macro-cracks.

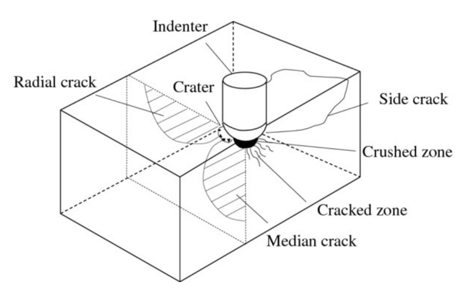

Figure 1: Fracture pattern occurring in rocks by indentation (Saadati, 2018).

The categorization was done using strain extension theory. This means failure in the rocks occurs when indentation strain exceeds a critical strain which is the ratio of ultimate tensile strength to Young's Modulus. The work focused on crack propagation and its extent but, due to heterogeneity in rocks, the predictions cannot always be accurate. The main objectives of the indentation tests were to primarily understand rock breakage, predict the rate of penetration and optimize excavation tool development, and secondarily find rock strength.

Kaharman (2012) developed comprehensive correlations between the indentation hardness index (IHI) with UCS and BTS including all three types of rocks occurring in nature: igneous, metamorphic, and sedimentary. This work highlighted the strong correlation between the IHI and UCS. The experimental setup and procedures are very well described and a statistical study added to the experimental work provided more confidence in the conclusions. Copur (2003) utilized indentation tests for predicting cutter performance and mechanical properties of the rocks. As the disc excavation mechanism matches the indentation process, the indentation indices are obtained for the studies from his apparatus. Copur (2003) used the term brittleness index, however, it is calculated the same way as the widely used IHI. He also observed that indentation occurs suddenly for hard nonporous rocks as compared to progressively for soft porous rocks.

During the indentation test, porous rocks have the property that do not let the load increase constantly, resulting in crushing rather than chipping. Leite (2001) developed a model to estimate the UCS of sandstones with a porosity between 44% and 68% and observed that the UCS estimated from indentation testing was more reliable than the actual UCS tests due to the sensitivity of these tests to sample preparation. Mateus (2007) utilized the indentation testing technique on irregularly shaped rock specimens to predict rock parameters utilizing the Kaharman (2012) correlations. This work concluded that, since there are no adopted standards for indentation tests, different researchers often yield conflicting results due to differences in selecting test parameters. Haftani (2014) proved that the cross-sectional area perpendicular to the direction of loading does not matter as much as the thickness of the sample since results showed that greater thickness resulted in higher IHI. His experimental apparatus applied lateral confinement to the rock sample leading to higher indentation loads at crater formation and sample failure by splitting. Yin (2014) conducted disc cutter indentation experiments with confinement on granite and marble. He found that increasing the confinement increases the force required to initiate a crack and the size of the crushed zone, and as confinement around the rock surface increases, there is a transition from brittle to ductile fracturing. Hood (1977) concluded that cone indenters require more penetrating force than wedge indenters to break through the rock, but an added shear or transverse force reduces the penetrating force, making cutting easier and more efficient. This principle is used in designing tools that utilize roller cones and disc cutters. Benjumea (1969) studied the responses of indentation on non-isotropic rocks by keeping the indenter geometry the same. He also carried out experiments on rock breakage parameters based on penetrating through the bedding of the rock with an indenter in directions perpendicular and parallel to the bedding. The work also discussed a technique to calculate specific energy utilized in the indentation process by measuring the crater volume by filling it with a displacing fluid from a burette. Zou et al. (2022) measured specific energy using a laser crater profiling method and observed that increasing confining pressure around the sample increased the specific energy for crater formation.

Thiercelin and Cook (1988) used scanning electron microscope images of porous rocks under indentation to explain the observed rock fracturing patterns. A transition from tensile micro-cracks to shear bands was observed in porous limestones during indentation. Zhu (2020) carried out a comprehensive study on the crack formation and propagation in rocks under an indentation test, finding a total of 4 types of cracks in rocks, namely: Intra grain shear, intra grain tensile, inter grain tensile, and inter grain shear Out of all of these types, the most prevalent type of crack observed during indentation is the inter grain tensile crack. The mechanism of crack formation will vary based on rock structure and grain size distributed inside the bulk of the rock.

Morris (1969) began the work on drilling rate prediction by generating a model utilizing the reciprocal of the slope from the indentation curve. He called the reciprocal of the indentation slope the drillability index. In his study, he came up with the criteria that the drillability ratio below 0.00002 in/lb can be drilled using steel roller cone bits while a value above it requires the use of tungsten carbide inserts. With parameters such as the number of inserts, weight on the bit, bit rotational speed, and the drillability index, he devised a formula for predicting the rate of penetration. In addition to that, the index also gave an estimate of the bit life for drilling a certain type of formation for which the indentation was performed. To Morris's (1969) work of finding the equation for predicting the rate of penetration, Kahraman (2000) added some modifications and conducted tests using conical and spherical tips. Kahraman (2000) utilized indentation test load-penetration curve slopes for the rate of penetration prediction successfully which was validated with field drilling data for carbonaceous rocks with strength above 40Mpa. His work also commented on how increasing the angle and tip thickness influences the indentation index. Bilgin (2003) made a remark in his critical review that the unconfined compressive strength, point load strength and BTS exhibit a great correlation with the rate of penetration in a rock type. Most of the penetration prediction was accurate for rocks with more than 25MPa strength.

In this paper, granite core samples of 2-inch diameter with varying length to diameter ratios are used in the indentation test. Various combinations of the metal indenters' spherical tip diameter and the confinement pressure around the rock side surface are included in the test sample matrix. The test is performed utilizing a servo-controlled frame with a constant loading rate. The rock cuttability is discussed based on the slopes of the curve, the load levels at which the samples break, and the specific energy spent in breaking them.

2 MATERIALS AND METHODS

2.1 Servo Controlled Loading Frame

Figure 2: Servo controlled loading frame.

Memorial University Materials Lab's servo control frame has a maximum load capacity of 250kN (Fig. 2). It can conduct compressive and tensile strength tests at specified custom loading rates, which may be regulated by either displacement or load control. The displacement control loading is used in this work to avoid quick indentation, which causes a substantial fracture propagation in the rock sample. A loading rate of 0.01mm/sec was selected based on the previous experimental procedures devised by various researchers including Copur (2003) and Haftani (2014, 2015).

2.2 Metallic Indenters for the Test

Figure 3: Metallic indenters with varying tip diameters. From left to right 7mm, 5mm, and 3mm.

The tips of the indenters are spherical and the tests utilize 3 geometries with tip diameters of the sphere as 7 mm, 5 mm, and 3 mm (Fig. 3). All the indenters are made from hardened steel with a hardness of 58 HR. As shown in Fig. 4, angle α is called the apex angle which is set at a

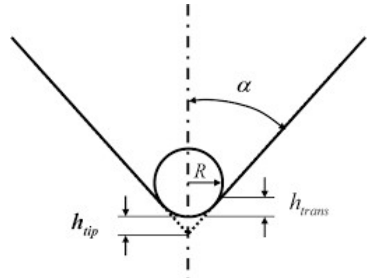

Figure 4: Geometry of a conical metallic indenter (Szwedzicki,1998).

Figure 5: Granite core samples and confining metal straps for the experiment.

constant value of 60° for all the indenters in this study and R is the radius of the spherical tip of the indenter.

2.3 Rock samples and confinement setup

Granite core samples were utilized after being cored from blocks of the rock using a 2-inch coring bit. The long core samples were later cut into disk samples with heights of 1 inch and 2 inches respectively. The intention of this was to prepare samples with dimensional criteria with a length to diameter ratio of 0.5 and 1. Both types of rock samples are saw-cut and are ensured to have a smooth and flat surface. This is done to the samples to ensure they yield accurate results. Two metal straps of different heights were manufactured to cover the circumference of each of the samples (Fig. 5). The strap was tightened by nut and bolt to offer selected confinement values while testing using a torque wrench.

3 EXPERIMENTAL PROCEDURE

The prepared granite core samples are placed on a core platen on the servo-control loading frame and the indenter is lowered until the tip of the indenter contacts the smooth rock surface with a minimum load of 12 N force (Fig. 6). This ensures that the rock is engaged and the testing can proceed. A constant loading rate of 0.01mm/sec was applied to the indenter at the beginning of the test. The test is continued for 3 minutes which accounts for a 1.8mm

Figure 6: Sample with length to diameter ratio of 0.5 undergoing indentation subjected to confinement using a metal strap.

displacement. All the tests split before 3 minutes, but the same procedure was repeated for all the samples. The servo control loading frame produced a real-time load-displacement plot while the experiments were performed. There were 15 tests done on the smaller 1-inch long samples and 32 tests on the bigger 2-inch long samples, with and without the metal strap confinements. A torque wrench is utilized to tighten the metal straps to the required torque on the nut-bolt assembly. The torque values used in this experimental work are 0 Nm, 7.35 Nm, and 8.48 Nm respectively.

We use specific energy as a parameter to evaluate the rock penetration efficiency. The specific energy is affected by the variation of other parameters, such as indenter tip diameter and confinement around the rock. Specific energy in this work (Joules) is calculated by dividing the work done in breaking the rock under the load-displacement curve by the volume of the spherical tip of the indenter which is displaced into the surface while loading.

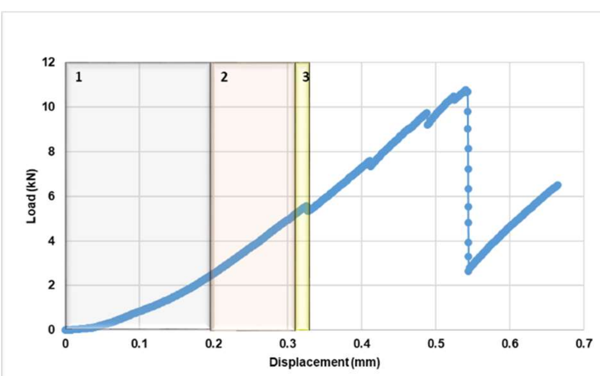

Figure 7: Indentation curve highlighting zone transition with loading.

In Fig. 7, the plot achieved from the loading of the granite rock is highlighted in 3 different zones. Zone 1 denotes the section where rocks behave elastically. Zone 2 highlights the part where that elastic nature turns into plastic and the slope starts to become more linear; this is the zone of

Figure 8: All samples with L:D of 0.5 post indentation.

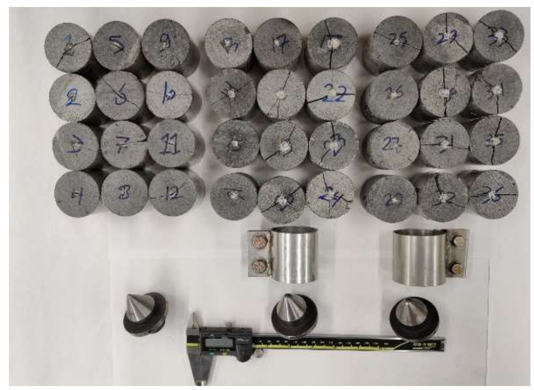

Figure 9: All samples with L: D of 1 post indentation.

interest from which the indentation index is calculated. Zone 3 is the neck of the curve where the rock no longer is crushed and a crater is produced along with a drop in the load.

4 RESULTS AND DISCUSSIONS

A total of 47 tests were performed. From Fig. 8, the six samples to the left had been indented with no confinement, and the nine to the right were confined with a torque value at the nut and bolt at 8.48 Nm.

In Fig. 9, the samples are arranged in such a way that there are 3 sets of 3 columns. The samples are arranged into 3 sets to represent the confinement the samples were subjected to. As the first one does not have the metal strap below, it says 0 Nm confinement. The second and third are 7.35 Nm and 8.48 Nm respectively. The 3 columns represent the different indenter tips used for testing in the order of increasing tip diameter from 3 mm to 7 mm respectively.

The indentation test gives a result of the load-displacement response for a certain rock type, which is influenced by other variables involved in the test. These variables can be loading rate, rock type, rock mineralogy composition, indenter geometry, and sample confinement. In this work, the rock sample is obtained from granite, which is a typical isotropic rock. The indenters tip diameter and confinement around the samples are varied and their influence on the indentation test result is then analyzed.

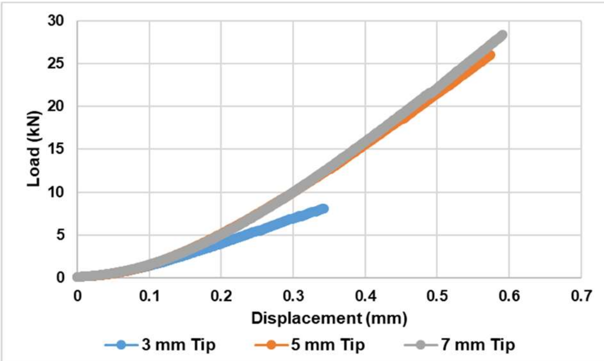

Figure 10: Indentation test slope response for different indenter tip diameters without any confinement with L:D of **1**

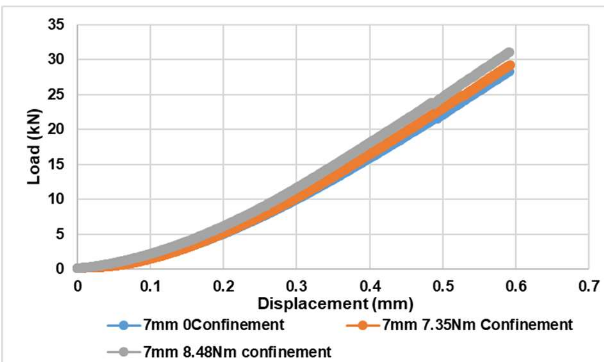

Figure 11: Indentation curve for 7mm indenter tip diameter with varying confinements for samples with L:D of 1.

4.1 Effect of Indenter tip diameter and Confinement around the core sample

As we go from a smaller tip diameter to a higher tip diameter, experimentally, the cratering of rock becomes difficult. This means that more load is required in breaking the rock. This is analytically observed from the rock's loading curve. The flatter the curve, the easier it is to break it, and the farther it goes away from the horizontal axis, the more the difficulty to break the rock increases. The slope is calculated from the transition of elastic to the plastic zone where the curve is linear and straight and is called the indentation hardness index. In Fig. 10, all the rock samples are subjected to no confinement around them. A significant difference in slope is noted when the 3 mm tip diameter of the indenter is used. The curve is very flat but as we move to a 5 mm tip diameter, the value of the slope of the curve and the indentation index jump up by 2.5 times. The slope of the 7 mm tip is 10% more than the 5 mm tip diameter results. It is seen that with increasing tip diameter, the angle of slope keeps increasing. The slopes from 5 mm and 7 mm tip diameter are very close to each other, but the 3 mm diameter tip breaks the rock easily with a much narrower tip. A total of 4 experimental slopes were averaged for the analysis for Fig. 10 on samples with a length to diameter ratio of 1.

The tightening from the torque wrench provided more confinement to the rocks laterally. Any solid body when subjected to vertical stress tries to compensate laterally. Rocks do have an elastic nature in their early indentation zone. Confinement around the rock prevents that action. According to Mohr's circle, a confined body of uniform composition has a delayed fracture that fails the rock rather than a rock with no confinement (Rajagopal, 1998). For understanding, samples with a length to diameter ratio of 1 were subjected to different confinement levels and indented using a 7 mm tip diameter indenter. The results are expressed in Fig. 11. Another fact noticed is that the point at which the rock fails and splits is shifted to a higher load value. In Fig. 11, we can notice the slopes - depicted by different colors – are shifted positively in the vertical axis. Also with increased confinement, the linearity in the plot increases. This gives us more confidence in the slope value of the curve. (Premraj, 2022).

Tables 1 and 2 numerically present the results from the tests with a very small standard deviation. This proves that the tests were very consistent and repeated with an average standard deviation of 1.194kN/mm.

The peak value of indentation is the value at which the rock splits when subjected to a certain amount of load corresponding to the displacement of the indenter into the rock surface. The peak value achieved at a 5 mm tip is twice the peak value at a 3 mm tip diameter, whereas with

Table 1: Indentation test results for samples with L:D of 0.5.

Tip Diameter	Confinement	Average slope	Std dev
mm	Nm	kN/mm	kN/mm
3	0	25.01	2.91
5	0	51.35	2.20
7	0	59.05	3.67
3	8.48	27.12	0.24
5	8.48	54.54	2.52
7	8.48	65.48	0.07

Table 2: Indentation test results for samples with L:D of 1.

Tip Diameter	Confinement	Average slope	Std dev
mm	Nm	kN/mm	kN/mm
3	0	22.91	1.63
5	0	56.62	2.40
7	0	63.99	2.66
3	7.35	25.22	3.02
5	7.35	56.96	1.41
7	7.35	59.75	1.21
3	8.48	27.69	2.17
5	8.48	58.28	0.75
7	8.48	65.83	1.87

a 7 mm tip, the value is 2.4 times that achieved from a 3 mm tip diameter. This means the results from 5 mm and 7 mm are very similar and also very different from 3 mm tip diameter.

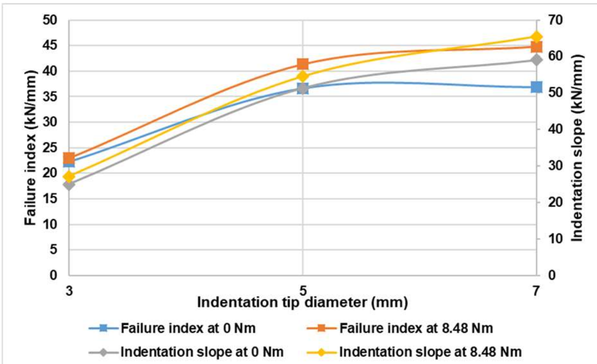

Figure 12: Influence of confinement and indenter tip diameter on indentation indices for L:D of 0.5.

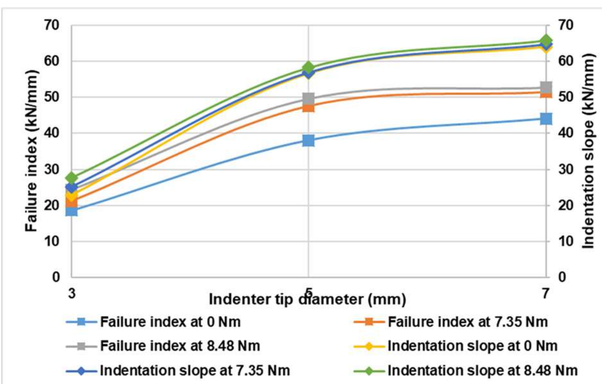

Figure 13: Influence of confinement and indenter tip diameter on indentation indices for L:D of 1.

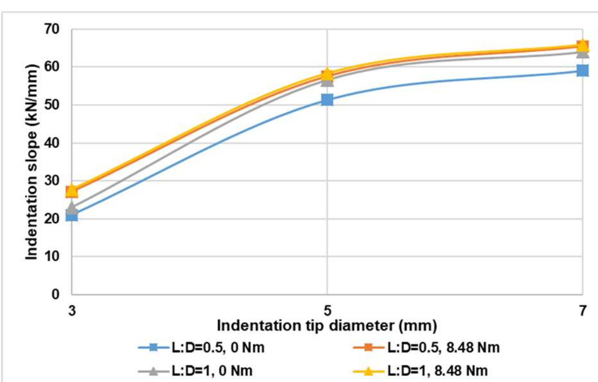

Figure 14: Effect of confinement on size of the sample.

The failure index is the peak value with a load and corresponding displacement value at which the rock fails and splits in half. This index denotes failure of rock and helps to correlate failure with parameters of indentation such as slope. In these two graphs from Figs. 12 and 13, the variation in tip diameter of the indenter and the confinement around the rock are correlated with the slope of the indentation curve as well as the failure index. The shift is consistent and is in the positive axis with increasing tip diameter and confinement.

4.2 Effect of size of the rock core sample

The size of the sample influences the outputs of the indentation tests (Haftani, 2014). Smaller samples with a length to diameter ratio of 0.5 break earlier and easier than samples with a length to the diameter of 1. As the height of the sample increases, the extension of the median crack that breaks the rock is delayed. This is graphically evident. Because of the ease with which the smaller samples break, their slopes and peak index are 10% smaller than the larger samples.

Median cracks, as shown in Fig. 1, are the type of cracks that travel to the base of the sample from the bottom of the tip indenter when loading occurs. Shetty (1985) concluded in his work that the length of the median crack is linearly proportional to the Indentation load. This means it requires more load to produce a long median crack. From the experiments, we found out that the samples with a length to diameter ratio of 1 failed under loads higher than the samples with a length to the diameter of 0.5. This is experimentally verified in this study.

There is an interesting observation made from the test using confinement at a torque value of 8.48 Nm around both the core samples with different heights. The slopes using this confinement give a similar value and, as a result, from Fig. 14 we can see the slopes of the two types of samples overlapping each other. In this condition, the effect of the size of the sample is eliminated as the slope is the parameter that is most useful to us.

4.3 Effect of Specific energy

Specific energy is the work done to excavate a unit mass of rock by the tool. This study helps understand a pattern of how the specific energy varies with confinement around the core sample and the varying tip diameter of the indenter. The higher the confinement around the rock, the more energy that has to be spent to excavate a unit volume. This means that specific energy at no confinement is lesser than that at confinement from a torque value of 8.48 Nm.

On the other hand, as we move from a smaller tip diameter to a higher tip diameter, the specific energy drops down. This is because a bigger tip diameter corresponds to more volume of the metallic indenter displaced into the rock surface at the same displacement value. Ma (2016) drew conclusions from his work on confining granite for tunnel boring machine performance. TBM primarily breaks the rock by indentation or forces normal to the rock surface. He found out that with increasing penetration, the specific energy values decreased for a very long range. In this experimental work moving from smaller to higher tip diameter, the penetration has constantly increased while the specific energy has decreased. Also, with increased confinement, the specific energy utilized for rock breakage keeps rising. Zou (2020) experimentally and numerically proved that specific energy is negatively correlated to the indentation hardness index. Finally, eexperiments conducted by Zhang (2021) on limestone had the same pattern where the specific energy invested was more on confined samples than the unconfined samples.

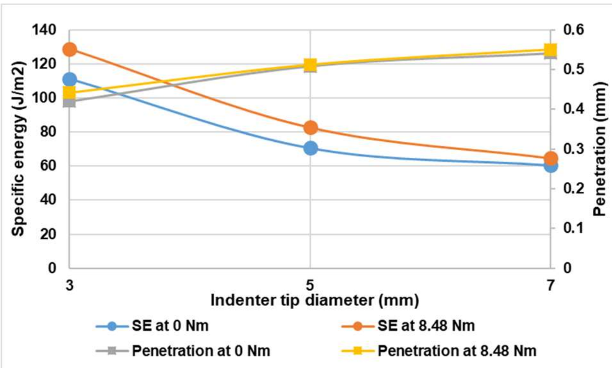

Figure 15: Effect of indenter tip on specific energy and penetration for samples with L: D of 0.5

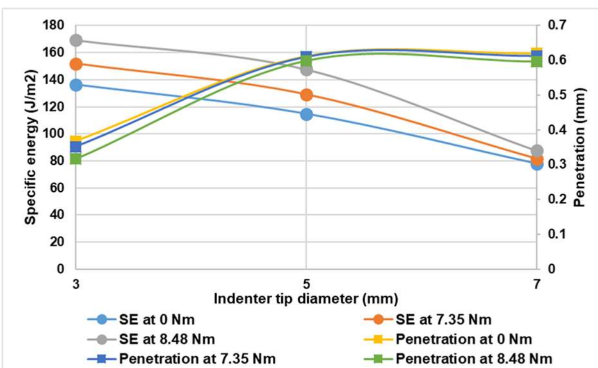

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Figure 16: Effect of indenter tip on specific energy and penetration for samples with L: D of 1.

Table 3: Specific energy analysis from indentation

Torque	Tip diameter	Height indented	Indented volume	Work	Specific Energy
Nm	mm	mm	mm^3	J	J/m^2
0.00	3.00	0.368	10.35	1411.4	136.40
7.35	3.00	0.352	9.91	1504.2	151.82
8.48	3.00	0.416	11.69	1977.9	169.22
0.00	5.00	0.611	47.75	6962.7	145.81
7.35	5.00	0.610	47.68	7348.8	154.14
8.48	5.00	0.599	46.84	6917.0	147.68
0.00	7.00	0.620	95.18	7417.7	77.94
7.35	7.00	0.613	94.08	7402.7	78.69
8.48	7.00	0.597	91.69	7663.0	83.58

5 CONCLUSIONS

The effect of varying indenter tip diameter, confinement around the sample, and the height of the samples were studied on granite. The major conclusions drawn from the work are:

- With increasing tip diameter, the angle of the slope keeps increasing hence the load required to indent into the rock by unit distance increases.
- The slope of the indentation curve jumps up to almost twice the value as we transition from 3 mm to 5 mm and 7 mm tip diameters.
- The confinement hinders the rock breakage and delays the fracture. This is because the lateral expansion while a crater is generated is obstructed by stiff walls, hence the median crack does not propagate to the bottom to break the rock. Therefore, the difficulty in penetrating through a confined rock increases the rock indices.
- Increase in the size of the sample works the same way. The crack requires more load to travel to the other end of the rock sample to break it, therefore the slope and the failure are shifted ahead while moving from a shorter sample to a taller sample.
- There is an interesting fact found that the slopes of the curves of indentation overlap for the smaller and the bigger samples when both were subjected to confinement at 8.48 Nm torque around the core. This eliminated the size dependency.
- With increasing tip diameter, the specific energy utilized to break the rock kept decreasing. On the other hand, for the same indenter type, the specific energy increased with increased confinement.
- With the increasing penetration of the indenter, the specific energy kept dropping down consistently.

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