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EVALUATION OF GRANITE DEFORMATION THROUGH NON-COMPLIANT VERSUS COMPLIANT INDIRECT TENSILE STRENGTH APPLICATION

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ABSTRACT

Rock deformation evaluation as an essential approach for rock characterization and property determination has been examined via several methods through experimental and simulation studies. Such methods are reported to be conventional techniques applied to define the rock stress-strain relationship that consists of several regions including elastic and plastic regions. The load-displacement relationship also determines the yield and the breakage limits and shows the overall rock deformation behavior. The focus of this research is to evaluate the rock deformation behaviour through the implementation of compliant loading versus non-compliant. In this new approach and unconventional testing technique, the ultimate rock strength through rigid compression and the trend of the load-displacement curve were firstly determined. Secondly, Belleville springs were utilized in various stacks as per their full compression loads to determine the compression levels of 50% and 100% compression ranges of the non-compliant loading application. Results of testing about 150 samples of granite as high strength formation by indirect tensile tests, the compliant loading using Belleville conical disc springs compared with the non-compliant "rigid" loading was observed to influence the load-displacement curve to shift and the ultimate rock main failure to delay in the favor of compliant loading. Results also showed changes in granite fracture mode from pure and clean tensile in the case of non-compliant to a combination of tensile with rupture fractures in the 50% and the 100 compliant application. Such curve shift, rock failure delay, fracture modes, and overall deformation behaviour allow providing valuable data for controlling and predicting rock failure. This could also be used in optimally applying drilling parameters to evaluate rock fragmentation, improve the rate of penetration, and for safely designing civil structures

Keywords: Load-displacement curve, compliant loading, indirect tensile strength, rock deformation, drilling engineering.

NOMENCLATURE

σ_{IT}	Indirect Tensile Strength
BDS	Belleville Disc Springs
CCS	Confined Compressive Strength
DAQ-SYS	Data Acquisition System
DTL	Drilling Technology Laboratory
GLF	Geomechanics Loading Frame
IT	Indirect Tensile
LDS	Large-scale Drilling Simulator
MC	Material Characterization
MUN	Memorial University of Newfoundland
rpm	Revolution per minutes
ROP	Rate of Penetration
PDC	Polycrystalline Diamond Compact
pVARD	passive Vibration Assisted Rotary Drilling
TkWCB	Thick Wall Coring Bit
TnWCB	Thin Wall Coring Bit
UCS	Unconfined Compressive Strength

1. INTRODUCTION

Rocks can be characterized through determining their properties of physical, mechanical, electrical, etc. Material characterization of rocks through mechanical measurements can be conducted through either destructive or nondestructive tests. The destructive tests are performed to determine the mechanical properties including strength and hardness. Furthermore, rock strength can be determined either directly through destructive application or indirectly through nondestructive testing and correlation applications. Under the rock strength directive methods comes the two widely recognized and well-known tests, which include the Confined Compressive Strength test and the Unconfined Compressive Strength tests, CCS and UCS, respectively. Nevertheless, rock strength can be indirectly estimated through correlations, which can be constructed between strength indices that include Point Load Strength Index (PLSI) and Indirect Tensile strength test (IT) with UCS and CCS strength results.

The Indirect Tensile strength test follows the ASTM D3967-16 [1] and its correlations with UCS and other strength methods is widely adopted [2-10].

Numerous laboratory and numerical studies have been conducted on granite for various purposes including monitoring sample deformation and crack propagation [2, 9], examination of rock anisotropy [9-13], and study of influence of different pistons shapes on IT strength results [8].

Granite formation used in this research has been characterized at Drilling Technology Laboratory (DTL) at Memorial University of Newfoundland (MUN) Canada [12-18].

A passive Vibration Assisted Rotary Drilling (pVARD) tool was developed by DTL-MUN to assist in enhancing drilling and coring Rate of Penetration (ROP). One main section that pVARD consists of is Belleville Disc Spring (BDS) section. BDS are designed to uphold preset loads in a balanced mode. BDS also went under numerical, analytical and experimental examination for better understanding the spring behavior under loads [19-21]. As rocks fracture following either shear, tensile, or combined fractures, and due to the enhancement of ROP reported by DTL publications [22-24], the aim of this research was developed.

The objective of this research focuses on evaluating the rock strength and deformation through compliant and non-compliant IT application.

2. MATERIALS AND METHODS

All materials for this research are categorized into three main groups including (i) isotropic and high strength granite blocks, retrieved granite cores, and prepared disc samples, ii) Fully instrumented Laboratory Drilling and coring Simulator (LDS) and coring bits, and iii) Geomechanics Loading Frame (GLF), Belleville conical disc springs, and GLF Data Acquisition System (DAQ-Sys).

2.1 Granite blocks

Blocks of previously characterized granite formation was selected formation for this research for its pre-determined properties including isotropy and high strength [15-18]. Such properties are recommended in the field of research to be considered as a baseline for research that adopts new techniques, methodologies, and approaches for rock characterization and fracture pattern evaluation. The isotropic property of granite provides balanced and symmetric distribution of physical, mechanical, etc. properties regardless the testing direction or orientation [12,14,25]. The high strength property of granite provides wide range data collection interval before concluding the tests, which may include drilling, coring, mechanical and physical testing, etc. The size of the granite blocks used to provide cores for this research was ~ 45 cm long, ~ 45 cm wide, and ~ 20 cm thick (Figure 1).

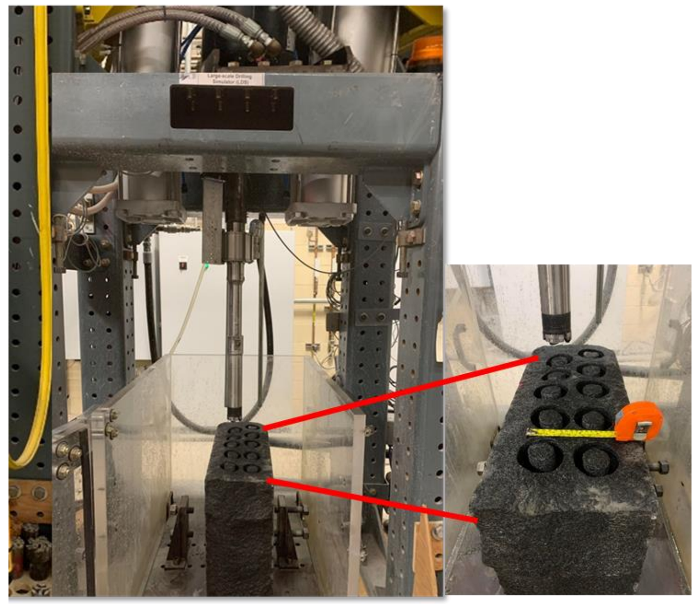

FIGURE 1: LABORATORY DRILLING AND CORING SIMULATOR

2.2 Laboratory drilling and coring simulator

A fully instrumented Large-scale laboratory Drilling Simulator (LDS) (Figure 1) was the equipment utilized for obtaining granite cores. Although the equipment was designed for drilling, it is fully capable for coring in various rotary speeds ranging from 1 revolution per minutes (rpm) to 1000 rpm. The LDS can produce pneumatic and hydraulic applied Weight On Bit (WOB) exceeding 90 kN. LDS also can be operated manually or automatically as required and can record real-time sent by all attached sensors using Data Acquisition System (DAQ-SYS) with LabVIEW software. Following a pre-set conditions and applied parameters such as WOB, rpm, and stroke travel limit, the LDS can be automatically operated and controlled.

One main coring bit was used for obtaining all cores prepared for the Indirect Tensile (IT) strength test. A Polycrystalline Diamond Compact (PDC) coring bit with four teeth made from tungsten carbide was used for the coring experiments (Figures 1)

Several cores were obtained through the coring operation using the LDS (Figure 2). Cores were cut using a wet saw table utilizing a 7-inch (17.78 cm) diamond blade. About150 disk-shape samples (Figure 2) were prepared as per the ASTM

D3967-16 standard [1]. All dimensions and weight measurements were taken for post testing analysis.

FIGURE 2: PREPARED SAMPLES FOR IT STRENGTH TESTS

2.3 Geomechanics Loading Frame

The Geomechanics Loading Frame (GMF) was the main testing equipment used for conducting the Indirect Tensile (IT) "splitting" strength test in three testing modes (Figure 3). The modes of the three tests were having different configurations for testing the granite disc samples and they were (i) non-compliant (rigid) IT where the upper and bottom pistons were completely rigid as conventional compression, (ii) 50% compliant IT, and (iii) 100% non-compliant IT.

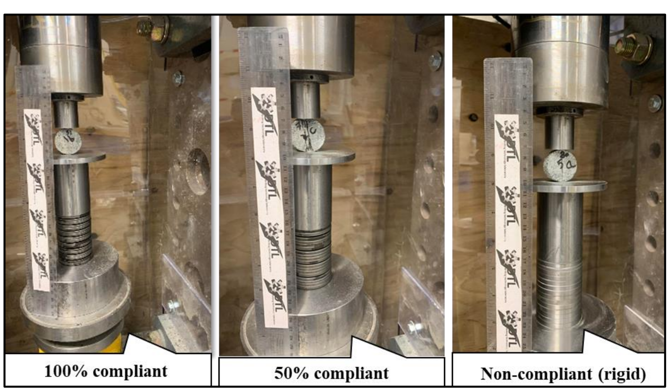

FIGURE 3: THREE MAIN IT TESTING CONFIGURATIONS

For the non-compliant compression (Figure 3-right) no springs were used and the compression was rigid. Spacers were used to provide the same initial displacement as the non-compliant. For the 50 % and 100 % compliant configuration (Figure 3-middle and left, respectively), Belleville Disc Springs (BDS) No.: 9712k31 were used. The BDS dimensions were 1-inch (2.54 cm) ID, 2-inch (5.08 cm) OD, and 0.142 inch (0.361 cm) Thick.

3. RESULTS AND DISCUSSION

This section provides the results of all three types of IT strength tests. The tests were conducted as per the ASTM D3967-16 standard [1]. Equation 1 is the main equation used for the IT strength calculations.

$$\sigma_{IT} = 2*P/\pi*D*T \quad (1)$$

Where σ: Indirect tensile strength (MPa), P: Max load recorded at sample IT strength test (N), which is equal to load at sample splitting, D: sample diameter (mm), and T: Sample thickness (mm).

The difference between the three sets of the compression setups was the exclusion or the inclusion of the Belleville Disc Springs (BDS) (Figure 3). Figure 3-right shows the non-compliant (rigid / conventional) setup. This setup does not involve BDS, where the flat spacers were added instead to make the pistons elevation and the sample position similar to that in the compliant setups. In the non-compliant compression, about one thirds of the prepared disc samples (Figure 2-top) were tested and their recorded testing data were analyzed for comparison study with the data of the compliant IT tests.

The compliant compression is categorized into 2 sets including (i) 50 % compliance and (ii) 100 % compliance (Figure 2-bottom and middle, respectively). The selection of 50% and 100% was based on the BDS compression percentage to the full compression level. In other words, the 100% compression means that the BDS are fully compressed at the load equal to the maximum load at which the sample breaks in the noncompliant IT strength test. Where the 50 % compression means that the BDS are 50% compressed at the maximum load at which the sample breaks in the noncompliant IT strength test. Furthermore in numerical explanation, if the average maximum load of sample split at the non-compliant compression was 10 kN, then for the 100 % compression, the BDS stacking has to be fully compressed at 10KN. Likewise, for the 50% compression, the BDS stacking has to be 50 % compressed at 10 kN and has to be fully compressed at 20 kN.

The BDS for the compliant compression setups were selected based on their compression data, calculations, and properties that have been intensively examined in our research group. These BDS have been intensively tested, experimentally, analytically, and numerically for the application of the passive Vibration Assisted Rotary Drilling (pVARD) tool in the Drilling Technology Laboratory (DTL) at Memorial University of Newfoundland (MUN), Canada [19-24].

It is important to state that the IT strength test is well-known as a testing methodology adopted to estimate the strength of rocks and rock like materials [3-7]. As the rule of thumb, materials' unconfined compressive strength is about 10 times of their IT. In this research; however, the testing approach by involving the compliant versus the non-compliant testing setups was to evaluate the influence of such adoption on the overall load-displacement curve that can describe the behaviour of the tested materials, as well as to examine the post fracture modes for the purpose of implementing the outcomes in the next generation of pVARD drilling and coring tests. As none of the work using this research approach of noncompliance vs. compliant IT has been found to be previously conducted, this study could be elevated to a new or a novel testing approach.

Prior to conducting the IT strength tests, measurements of dimensions and weights of all prepared samples (Figure 2) were taken for the post IT calculations and for the density estimation. Dimension measurements determined the density of granite, which is the source material of all samples as 2.82 (gr/cc) (Figure 4).

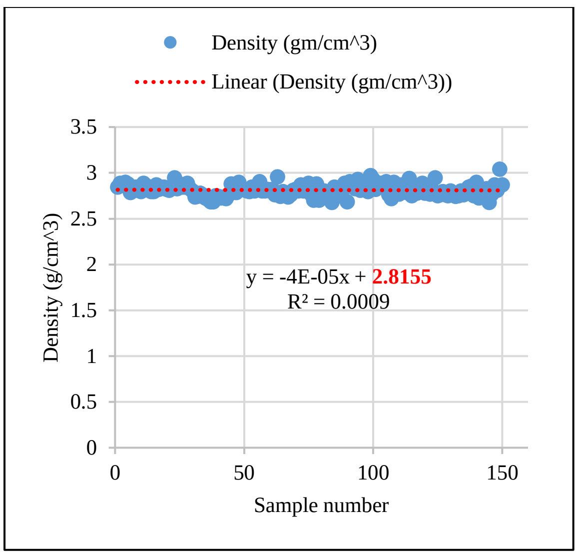

FIGURE 4: INDIVIDUAL AND AVERAGED DENSITY MEASUREMENT

Figure 5 shows samples after conducting the IT tests under the three testing modes and configurations including (i) non-compliance, (ii) IT 100% compliance, and (iii) IT 50% compliance (Figure 5, top, middle, bottom; respectively).

IT strength results were categorized into three main groups based on the compression mode applied in terms of the fractured samples (Figure 5) and the IT strength results (Figure 6).

By further looking at the fractured samples in Figure 5, there was valuable information concerning the lost material that scattered from the main two halves of samples and could not be collected after conducting each test. Such observation was further looked at through correlating the weight of the lost materials to the IT compression mode. This observation is subjected for more studies and will be reported in future publications. Such observation could also be linked to the applicability of energy stored by BDS that was released at the moment of splitting and; therefore, causes the enlargement of sample fractures.

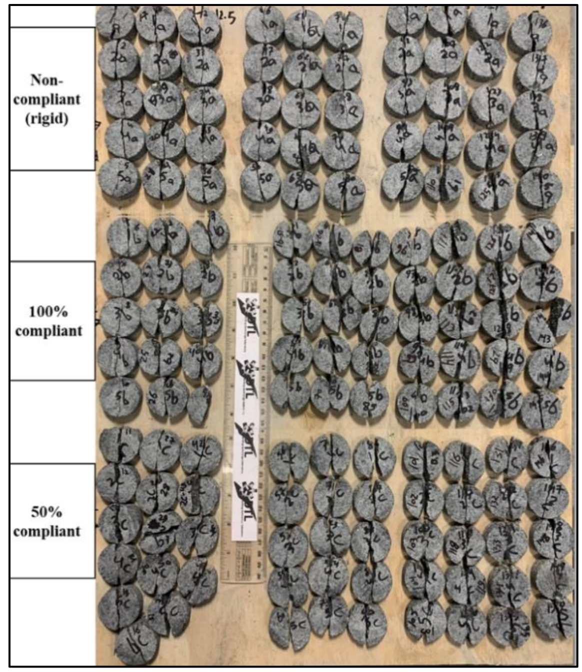

FIGURE 5: ALL SAMPLES AFTER IT STRENGTH TESTS

Figure 6 shows all IT strength results as per the test number and the test compression mode. The results show negligible strength value differences in the collective result representation (Figure 6) and in the average result representation (Figure 7) as per this research conditions.

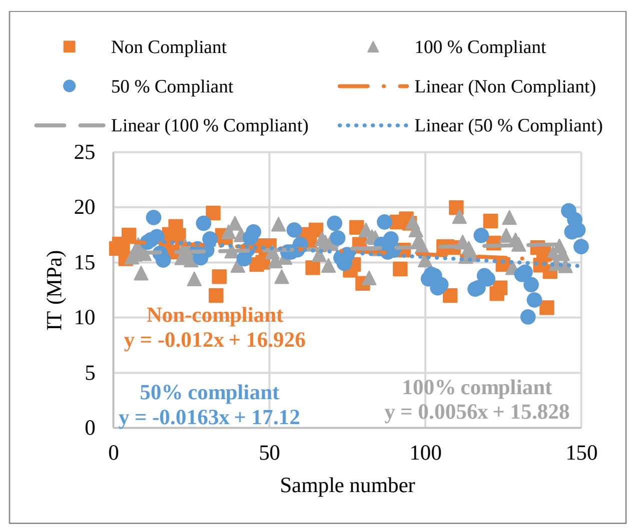

FIGURE 6: RESULTS OF IT STRENGTH TESTS UNDER ALL THREE TESTING CONFIGURATIONS

The variations in the strength values generated in the models shown in Figure 7 (16.926, 17.12, and 15.828 for IT-noncompliant, IT 50% compliant, and 100% IT compliant, respectively) are the values of intersect of the trend of the IT strength of each group with the IT axis.

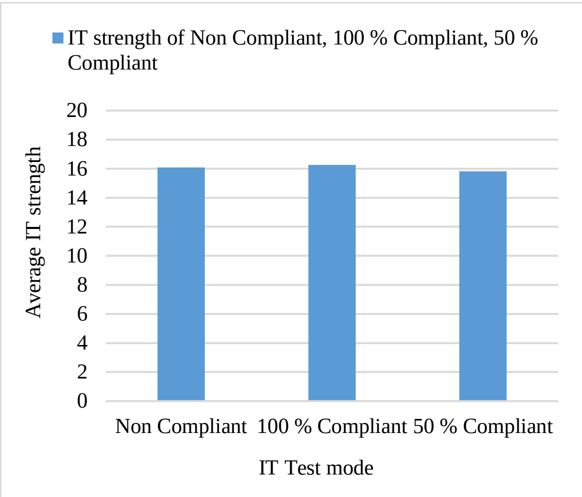

FIGURE 7: AVERAGE IT STRENGTH FOR NON-COMPLIANT, 50% AND 100% COMPLIANT APPLICATIONS

Correlations between results of IT non-compliant strength versus IT 50% compliant and 100% compliant strength were constructed (Figure 8). Correlations showed that the involvement of compliant compression in IT tests have low or no significant effect on the IT strength results at least as per the conditions applied in this research. Furthermore, the minor variation in the IT strength results, which is considered negligible could be changed if the conditions surrounding the tests of this research changed such as the loading rate, controlled loading versus manual loading, etc.

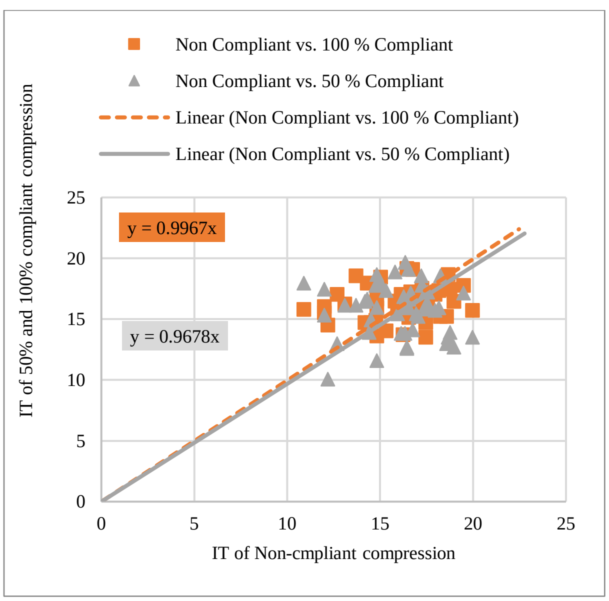

Figure 8: CORRELATIONS OF IT RESULTS OF 50% AND 100% COMPLIANCE WITH IT OF NON-COMPLIANT

On the other hand, a longer testing time due to the BDS load absorption to the level of the predetermined sample fracture region by the non-compliant was observed (Figure 9). The following provides more explanation on the displacement variations.

IT of non-compliant compression was determined first. By obtaining the averaged IT non-compliant strength (Figure 7), then the 50% and the 100% compliant compression were performed on the bases of that the sample should break at the 50% BDS compression in the 50% compliance and should break at 100% BDS compression in the 100% compliance.

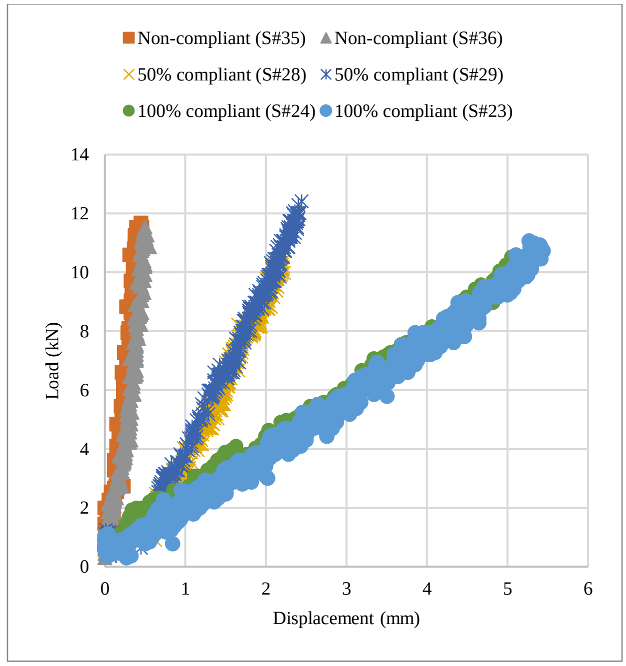

FIGURE 9: LOAD VERSUS DISPLACEMENT OF TWO DATA EXAMPLES OF EACH TESTING CONFIGURATION

For the non-compliant IT compression (Figure 3-right), as there were no BDS involved, the samples split after a purely non-compliant displacement occurs. The average of the maximum load reached in the IT compression

For the 50% BDS arrangement, the total number of springs was 2 parallel in 9 series (Figure 3-middel), which means that the total number of springs used was 18 springs. As per the predetermined calculations of this spring configuration, the stiffness is 5.52 kN/mm, the maximum spring deflection is 3.89 mm, and the maximum working load is 21.44 kN. As per the averaged compression load reached in the IT non-compliant test was around 10.75 kN, then it was assumed that the 10.5 kN should be reached at 50% DBS deflection at (3.89/2). This means that the displacement occurs due to DBS deflection by (3.89/2) plus the deflection normally occurs before splitting the samples at the non-compliant compression should be the total displacement before the sample fracture occurs in this 50% compliant configuration. For the 100% BDS arrangement, the total number of springs was 1 parallel in 17 series (Figure 3-left), which means that the total number of springs used was 17 springs.

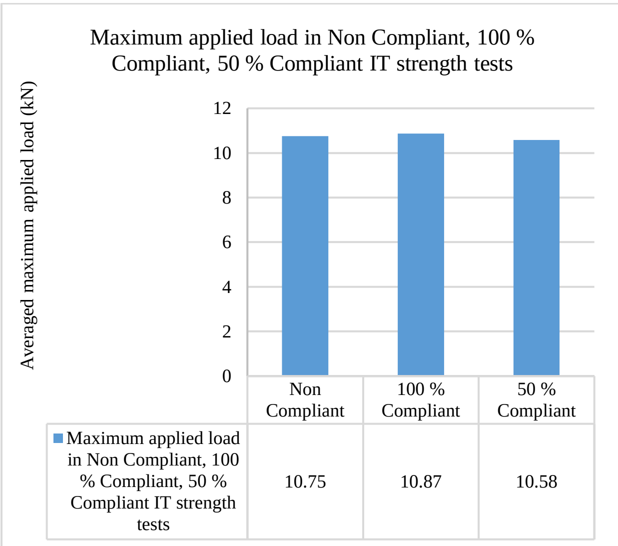

FIGURE 10: MAXIMUM APPLIED LOAD IN ALL IT TESTING MODES

As per the predetermined calculations of this spring configuration, the stiffness is 1.46 kN/mm, the maximum spring deflection is 7.34 mm, and the maximum working load is 10.72 kN. As per the averaged compression load reached in the IT non-compliant test was around 10.75 kN, then it was assumed that the 10.5 kN should be reached at about 100 % DBS deflection at (7.34). This means that the displacement due to the DBS deflection by (7.34) plus the deflection normally occurs before splitting the samples at the non-compliant compression should be the total displacement before the sample fracture occurs in this 100% compliant configuration.

By considering the pre calculations of the displacement before sample splitting at the three IT compression configurations including the non-compliant, the 50% compliant, and the 100% compliant, results were found to agree with the calculations as shown in Figure 9. Figure 9 shows the results of two tests for each IT test more as a representation for the involvement of the displacement of BDS deflections.

The fracture mode occurred in all three IT tests was also examined as per the testing configuration implemented (Figure 10). The examination was focused on a visual inspection of the pattern of the fractures, size magnitude of the broken pieces, the possibility of involvement of ruptures rather than only pure splitting, the weight of the lost materials, etc.

Samples of some fractures from each IT configuration are presented in Figure 11. Figure 11-top shows split samples after the IT non-compliant compression, Figure 10-middle shows split samples after the IT 50% compliant compression, and Figure 10-bottom shows split samples after the IT 100% compliant compression. By the visual inspection of the fracture mode, it was noted that a pure tensile split mode was observed after the IT non-compliant test. This mode is usually occurs as a result of conventional (rigid) IT strength test. Specific examples of the most pure split fractures can be seen in sample number 4a in Figure 11-top.

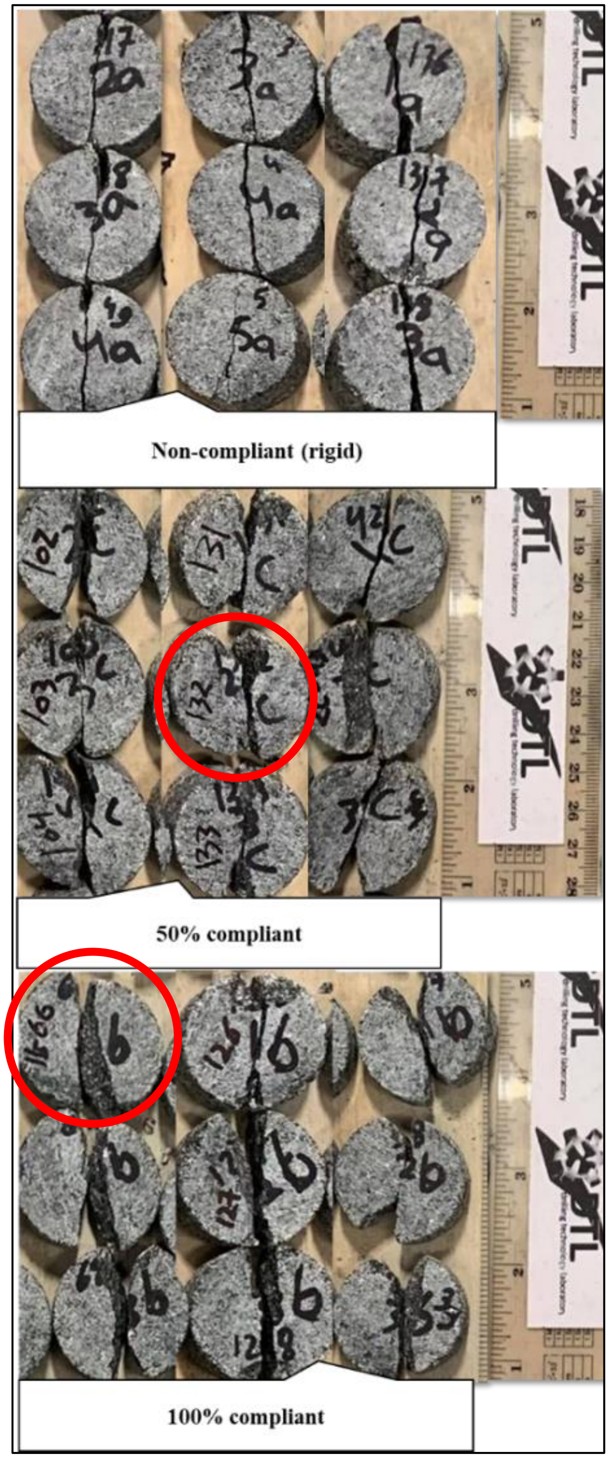

FIGURE 11: SAMPLES REPRESENTING THREE IT COMPRESSION MODES

This fracture mode was also observed as part of the sample fractures in the other two types of the IT compliant tests.

However, the pure splitting was noticed also to be combined with other types of fracturing such as rupturing as can be seen in samples number 132 and 66 in Figure 11-middle and bottom, respectively.

4. CONCLUSION

IT tests were performed following relevant ASTM standards. Three modes of IT tests were conducted including the IT non-compliant strength test, IT 50% compliant strength test, and 100% compliant strength test. Some of the conclusions of this work are reported below:

- As none of similar to this work was found in the literature, this approach is adopted in this research as new testing procedure to evaluate the inclusion of compliance in rock strength results. Also to correlate such results with the application of passive Vibration Assisted Rotary Drilling (pVARD), which involves compliance compression in the Bottom Hole Assembly (BHA) as means of enhancing ROP. [23, 24].
- The IT tests showed the applicability of adopting various compression levels in the tests.
- No significant strength variation was found as per the used apparatus as per Figures 6 and 7, but important fracture patterns and modes are observed (Figure 11).
- The results presented in Figure 11, deserve more attention and a follow up. Such fracture pattern differences are noted to be more splitting fractures in the non-compliant partially splitting with rupture at top and bottom of samples in the 50% compliant, to dominantly rupture mode in the 100% compliant.
- As the load was manually applied using the geomechanics frame, the current results could be inconclusive and could be influenced by the inconstant and variable loading rate, which is planned to be constant in a future follow up.

5. FUTURE WORKS

The following points are among the planned research to be conducted and reported in future publications:

- IT tests of non-compliant vs. compliant compression can be further carried out involving smaller percentile increments such as 25%, and 75%.
- IT tests of non-compliant vs. compliant compression can also be performed under controlled loading rate for deeper data representations.
- Non-compliant vs. compliant compression can be performed on other types of strength tests such as Unconfined Compressive Strength (UCS), Point Load Strength Index (PLSI), etc.
- Microscopic analysis of the fractures can be performed for further investigation of the fractures patterns when required.
- Evaluation of the lost materials (i.e. weight, pieces shapes, fractures type and patterns, etc.) and correlation with IT compression configurations will be carried out.

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REFERENCES

[1] ASTM D3967 − 16 - Standard Test Method for Splitting Tensile Strength of Intact Rock Core Specimens

[2] Hoek, E., & Martin, C. D. (2014). Fracture initiation and propagation in intact rock–a review. Journal of Rock Mechanics and Geotechnical Engineering, 6(4), 287-300.

[3] Nazir, R., Momeni, E., Armaghani, D. J., & Amin, M. M. (2013). Correlation between unconfined compressive strength and indirect tensile strength of limestone rock samples. Electron J Geotech Eng, 18(1), 1737-1746.

[4] Arman, H. (2021). Correlation of uniaxial compressive strength with indirect tensile strength (Brazilian) and 2nd cycle of slake durability index for evaporitic rocks. Geotechnical and Geological Engineering, 39(2), 1583-1590.

[5] Momeni, E., Nazir, R., Armaghani, D. J., & Mohamad, E. T. (2015). Prediction of unconfined compressive strength of rocks: a review paper. Jurnal Teknologi, 77(11).

[6] Kılıç, A. L. A. E. T. T. İ. N., & Teymen, A. (2008). Determination of mechanical properties of rocks using simple methods. Bulletin of Engineering Geology and the Environment, 67(2), 237-244.

[7] Erarslan, N., Liang, Z. Z., & Williams, D. J. (2012). Experimental and numerical studies on determination of indirect tensile strength of rocks. Rock Mechanics and Rock Engineering, 45(5), 739-751.

[8] Komurlu, E., & Kesimal, A. (2015). Evaluation of indirect tensile strength of rocks using different types of jaws. Rock Mechanics and Rock Engineering, 48(4), 1723-1730.

[9] Li, R., Zhu, J., Qu, H., Zhou, T., & Zhou, C. (2022). An experimental investigation on fatigue characteristics of granite under repeated dynamic tensions. International Journal of Rock Mechanics and Mining Sciences, 158, 105185.

[10] Chen, C. S., Pan, E., & Amadei, B. (1998). Determination of deformability and tensile strength of anisotropic rock using Brazilian tests. International Journal of Rock Mechanics and Mining Sciences, 35(1), 43-61.

[11] Barla, G., & Innaurato, N. (1973). Indirect tensile testing of anisotropic rocks. Rock mechanics, 5(4), 215-230.

[12] Abugharara, A., Butt, S., Molgaard, J., & Hurich, C. (2019). Empirical Procedure Investigation for Sandstone Anisotropy Evaluation: Part I. Influence Of Formation Anisotropy And Axial Compliances On Drilling Performance, 369. Ph.D. Thesis.

[13] Quan, W., Rasul, G., Abugharara, A., Zhang, Y., Rahman, M., & Butt, S. (2021, September). Tensile and Shear Fracture Examination for Optimal Drilling Performance Evaluation: part-II. In proceedings for the 74th Canadian Geotechnical Society Annual Conference.

[14] Abugharara, AN, Alwaar, AM, Butt, SD, & Hurich, CA. "Baseline Development of Rock Anisotropy Investigation Utilizing Empirical Relationships Between Oriented Physical and Mechanical Measurements and Drilling Performance." *Proceedings of the ASME 2016 35th International Conference on Ocean, Offshore and Arctic Engineering*. *Volume 8: Polar and Arctic Sciences and Technology; Petroleum Technology*. Busan, South Korea. June 19–24, 2016. V008T11A016. ASME. https://doi.org/10.1115/OMAE2016-55141

[15] Abugharara, A, Mafazy, S, & Butt, S. "A New Approach for Rock Strength Estimation Through a Semi-Point Load Strength Index and Correlation With Destructive and Nondestructive Tests." *Proceedings of the ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering*. *Volume 10: Petroleum Technology*. Hamburg, Germany. June 5–10, 2022. V010T11A092. ASME. https://doi.org/10.1115/OMAE2022-81556

[16] Premraj, P., Li, Z., Abugharara, A., & Butt, S. Evaluation of indentation on high strength and isotropic formations. Proceedings of the 75th Canadian Geotechnical Conference. Banff, AB, Canada, from September 29 to October 1, 2022.

[17] Quan, W., Rasul, G., Abugharara, A., Zhang, Y., Rahman, M. A., & Butt, S. (2021, September). Empirical Correlations and A New Approach for Strength Evaluation of Isotropic Rocks. In proceedings for the 74th Canadian Geotechnical Society Annual Conference, was held September 26-29 in Niagara Falls, ON, Canada.

[18] Premraj, P, Li, Z, Abugharara, A, & Butt, S. "Indentation Test Implementation for Rock Strength Correlation by Experimental Method and Simulation Using Distinct Element Method." *Proceedings of the ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering*. *Volume 9: Offshore Geotechnics*. Hamburg, Germany. June 5–10, 2022. V009T10A015. ASME. https://doi.org/10.1115/OMAE2022-79227

[19] Shaha, M. S., Maharjana, D., Abughararaa, A., Imtiaza, S., & Butt, S. Numerical and Experimental Study on Belleville Springs as Vibrational Element of Passive Vibration Assisted Rotary Drilling (pVARD) Tool for Drilling Performance Applications. Proceedings of the Canadian Society for Mechanical Engineering International Congress 2020 CSME Congress 2020 June 21-24, 2020, Charlottetown, PE, Canada.

[20] Abugharara, A, & Butt, S. "Evaluation of Belleville Springs and Damping Through Static Cyclic Loading "Hysteresis" for pVARD Optimization: Part-I." *Proceedings of the ASME 2021 40th International Conference on Ocean, Offshore and Arctic Engineering*. *Volume 10: Petroleum Technology*. Virtual, Online. June 21–30, 2021. V010T11A071. ASME. https://doi.org/10.1115/OMAE2021-61985

[21] Maharjan, D, Shah, S, Abugharara, A, & Butt, S. "Calculating Frictional Losses in Belleville Springs by Geometrical Interpolation." *Proceedings of the ASME 2020 39th International Conference on Ocean, Offshore and Arctic Engineering*. *Volume 11: Petroleum Technology*. Virtual, Online. August 3–7, 2020. V011T11A024. ASME. https://doi.org/10.1115/OMAE2020-18856

[22] Abugharara, A, Jamil, S, & Butt, S. "Empirical Evaluation of Influence of pVARD on Drilling Performance Through Static, Dynamic, and Drilling Applications." *Proceedings of the ASME 2022 41st International Conference on Ocean, Offshore and Arctic Engineering*. *Volume 10: Petroleum Technology*. Hamburg, Germany. June 5–10, 2022. V010T11A088. ASME. https://doi.org/10.1115/OMAE2022-79349

[23 Abugharara, AN, Molgaard, J, Hurich, CA, & Butt, SD. "Study of the Influence of Controlled Axial Oscillations of pVARD on Generating Downhole Dynamic WOB and Improving Coring and Drilling Performance in Shale." *Proceedings of the ASME 2019 38th International Conference on Ocean, Offshore and Arctic Engineering*. *Volume 8: Polar and Arctic Sciences and Technology; Petroleum Technology*. Glasgow, Scotland, UK. June 9–14, 2019. V008T11A017. ASME. https://doi.org/10.1115/OMAE2019-96189

[24] Alwaar, A, Abugharara, AN, & Butt, SD. "PFC-2D Numerical Study of the Influence of Passive Vibration Assisted Rotary Drilling Tool (pVARD) on Drilling Performance Enhancement." *Proceedings of the ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering*. *Volume 8: Polar and Arctic Sciences and Technology; Petroleum Technology*. Madrid, Spain. June 17–22, 2018. V008T11A014. ASME. https://doi.org/10.1115/OMAE2018-78057

[25] Abugharara, AN, Hurich, CA, Molgaard, J, & Butt, SD. "Implementation of Circular Wave Measurements and Multiple Drilling Parameter Analysis in Rock Anisotropy Evaluation." *Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering*. *Volume 8: Polar and Arctic Sciences and Technology; Petroleum Technology*. Trondheim, Norway. June 25–30, 2017. V008T11A012. ASME. https://doi.org/10.1115/OMAE2017-62088