Empirical Procedure Investigation for Sandstone Anisotropy Evaluation: Part I

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ABSTRACT

An experimental procedure to examine fine-grain sandstone rock anisotropy is reported. The procedure involved several tests. Each test was conducted in three main orientations: vertical, diagonal, and horizontal. Tests included ultrasonic wave velocity and strength. The oriented ultrasonic compressional and shear wave velocity measurements were performed to characterize the anisotropy of the tested sandstone using reported anisotropy indices. The oriented unconfined compressive strength was followed by a multidirectionally oriented indirect tensile strength. Correlations between the unconfined and the indirect tensile strength tests were constructed and compared to published correlations. Results showed isotropy of the tested sandstone, throughout the conducted tests.

RÉSUMÉ

Cette communication traite d'une expérimentation pour examiner l'anisotropie des roches de grès à grains fins. La procédure a impliqué plusieurs tests. Chaque test a été mené selon trois orientations principales : verticale, diagonale et horizontale. Les tests ont inclus la mesure de la vitesse et la résistance de l'onde ultrasonique. On a procédé à des mesures axées sur la vitesse des ondes de compression et de cisaillement pour caractériser l'anisotropie du grès testé, en utilisant les indices d'anisotropie rapportés. Le test de résistance à la compression uniaxiale orientée a été suivi par un test multidirectionnel de résistance à la compression diamétrale. Les corrélations entre les tests de compressions simples et ceux des compressions diamétrales ont été élaborées et comparées à des résultats ont été publiés. Les résultats ont indiqué une isotropie du grès analysé tout au long des tests réalisés.

1 INTRODUCTION

Rock strength was studied using numerous methods both destructive and nondestructive. Selective of the destructive methods include confined and unconfined compressive strength, CCS and UCS, respectively, (Syed et al. 2018). UCS can be estimated from several other testing types such as indirect tensile test (IT) or Brazilian tensile test (BTS) (Sheory 1997; Asadi 2015; Kharaman et al. 2012; Diederichs 2007) and point load index (PLI) (Broch and Franklin 1972; Mendieta 2012; Tsidzi 1990), which have been proved to have reliable correlations with UCS.

Many factors including time consuming sample preparation and test procedure complications, data variability, as well as the high cost of the destructive tests, which can vary from one method to another are behind the demand for alternative methods to estimate rock strength.

Ultrasonic wave propagation is one main nondestructive method for rock strength estimation. It gained its high recognition and attention with the increase of studies correlating measured rock strength from destructive methods with the estimated rock strength from the nondestructive methods.

Rock anisotropy classification is another main topic of research, where the destructive and nondestructive rock strength methods have been used. Several indices have been produced to evaluate rock anisotropy through the variation of the ultrasonic wave velocity (Tsidzi 1997; Saroglou 2007). Other indices were produced to classify rock anisotropy based on their strength variation in different directions using UCS (Ramamurthy 1993). Such methods vary in their cost, time consumed, and complexity.

Rock strength determination has been intensively studied in both laboratories and through simulation under various conditions providing a massive amount of data and methodologies within various range of inclinations (degree increments). However, the indirect tensile strength determined multidirectionally, has not been applied for rock anisotropy / isotropy classification. One reason for choosing such application is the ease of sample preparation, low cost, simple apparatus and experimental procedure.

Rock tensile strength is determined through both direct and indirect tensile tests (ASTM 2008a; ISRM 1987; Chen et al. 1998; Li and Wong 2013; Perras and Diederichs 2014).

An experimental procedure was previously developed by the authors, Abugharara et al. (2015), which was implemented to evaluate anisotropy of rock like material and granite. However, the indirect tensile strength (ITS) was not included. This study can support the procedure as a practical method for rock anisotropy evaluation.

The work of this paper concentrates on using indirect tensile strength (IT), conducted in multiple orientations to classify the anisotropy of the tested fine-grain sandstone.

2 SAMPLE PREPARATION

One sandstone block was the source for samples used for all tests. Samples were obtained in various dimensions in accordance with the American Society for Testing and Materials (ASTM) and International Society of Rock Mechanics (ISRM) suggested methods. The dimensions of the main block were about 70 cm * 40 cm * 50 cm (length * width * height). Samples of various diameters were cored in the three main orientations of vertical, diagonal, and horizontal.

Samples for oriented ultrasonic measurements were cores of 10.16 cm diameter and about 10 cm long. Figure 1 shows the sandstone block, core samples for OUSWV, and the top view of each sample indicating the degree increments for the circular wave measurement from left to right, respectively.

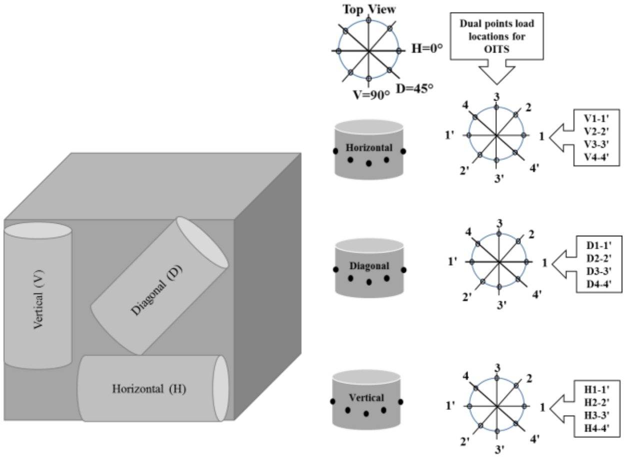

Figure 1. Sandstone block, core samples for OUSWV, and top view of each sample indicating the degree increments for the circular wave measurement from left to right, respectively. The locations of the sensors used to measure the wave velocities were precisely prepared using advanced equipment at the university technical service to ensure accuracy and precise alignment.

Samples for oriented strength measurements were cored using a natural diamond coring bit to obtain cores of 4.76 cm diameter samples and about 30 cm long or more depending on the coring directions. Several cores were obtained in each orientation to produce sufficient number of samples recommended for each test according to standards. Samples in each orientation were then categorized into three groups. Each group was denoted for particular oriented strength testing type.

For the unconfined compressive strength test, samples where cored axially from the 4.76 cm samples using a 2.54 cm coring bit. These samples are shown in Figure 2, (middle). The samples were then cut to 2:1 ratio of length to diameter (Fajer 2013).

For the indirect tensile test, disk samples were cut to after colour-coding the original cores as shown in Fig. 2 (left), to denote three secondary orientations within each primary orientation.

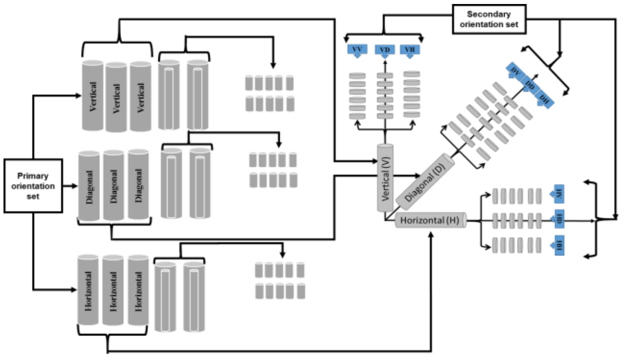

Figure 2. Oriented cores of sandstones (left), OUCS samples (middle), and OITS disks (right)

3 EXPERIMENTAL PROCEDURE

Experiments were performed in the following order. First: for oriented ultrasonic wave velocity (OUSWV) including compressional and shear wave velocity, vp and vs, respectively. The purpose of performing the OUSWV first was to determine the anisotropy of the sandstone through the non-destructive tests using some existing anisotropy indices.

Second, the multidirectional oriented indirect tensile strength test (OITS) as well as the oriented unconfined (uniaxial) compressive strength test (OUCS) were performed. The OITS was conduced on disk samples prepared according to two orientation sets: primary and secondary as shown in Fig. 3. The OUCS was performed on samples prepared according to the primary set of vertical, diagonal, and horizontal. The purpose of these tests was to confirm the sandstone anisotropy classification obtained by OUSWV with the oriented strength tests.

Third, a comparative analysis between the results of this work and work reported elsewhere was performed.

4 PERFORMED TESTS AND APPARATUS

This section shows the tests that were conducted for sandstone anisotropy investigation including ultrasonic wave and strength measurements.

4.1 Oriented Ultrasonic Wave Velocity

The purpose of this measurement was mainly to classify the sandstone anisotropy through a nondestructive method.

Compared to other sound wave velocity measurements (e.g. low frequency sonic wave method and the frequency resonant method), the high frequency ultrasonic method is more reliable and practical. A reason for using this method that it is the associated non-destructive, low cost, and the high precision measurement. In this test the compressional and shear wave velocities (vp and vs, respectively) were measured across eight spots around a circumference of each sample with an increment of 45 degrees as shown in Fig 1.

The ultrasonic wave velocity apparatus used for this measurement was fully described by Abugharara et al. (2016).

4.2 Oriented Strength

This section shows the two main types of strength tests used: the oriented indirect tensile strength (OITS) and the oriented uniaxial compressive strength (OUCS). Figure 3 shows the apparatus used for all strength tests including the oriented indirect tensile (OIT) test and the oriented unconfined compressive strength (OUCS) test. The apparatus was modified to suit the OIT and OUCS tests by replacing the conical pistons to flat-end pistons.

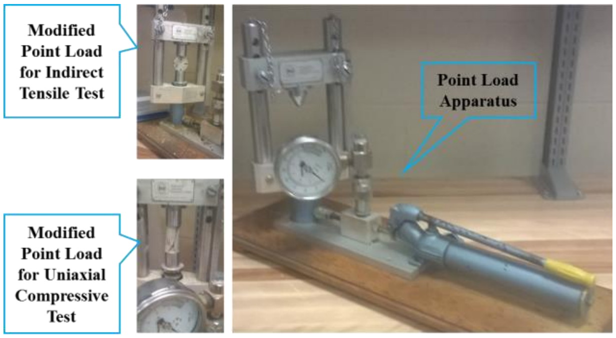

Figure 3. PLI tester Apparatus modified for OITS and OUCS strength measurement with flat-end pistons

4.2.1 Oriented Indirect Tensile Strength

For this test, 90 sandstone disk samples were prepared and classified into three groups as described in Fig. 2. Following a colour code, three smaller groups of about 10 samples were representing three orientations. Each group consists of about 30 samples representing three secondary orientations (VV, VD, VH), (DV, DD, DH), and (HV, HD, and HH) within each primary orientation of vertical (V), diagonal (D), and horizontal (H). The purpose of this classification of the disk samples into primary and secondary was for investigation of the sandstone anisotropy. Figure 4 shows the procedure of testing the disk samples following the colour code for the secondary orientations.

Figure 4. Procedure of OITS test on sandstone disk sample

As many studies reported the influence of rock anisotropy on the fracture direction deviation from the two load points, splitting (fracturing) of sandstone disk samples was monitored while testing. The straight and direct fracture between the two load points in all OITS testing was another was determined as shown in Fig. 6. and was considered as another sign of sandstone isotropy. Figure 5 and 6 show the oriented disk samples before and after OITS, respectively.

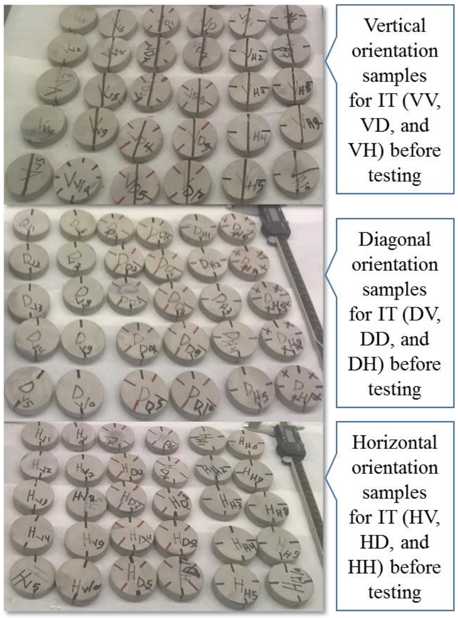

Figure 5. Sandstone disk samples before OITS testing

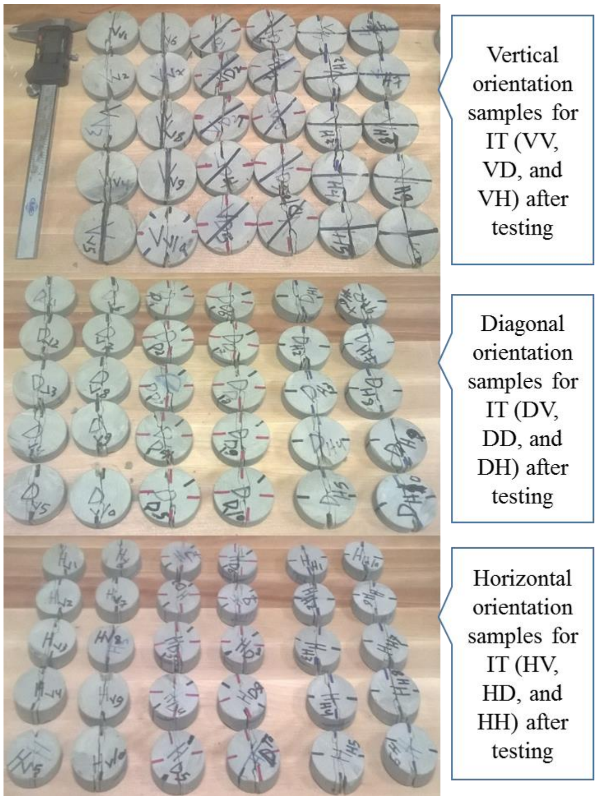

Figure 6. Sandstone disk samples after OITS testing

4.2.2 Oriented Unconfined Compressive Strength

30 samples were tested for the OUCS. Samples were classified into three groups to represent three orientations. Figure 7 shows the samples before (top) and after (bottom) conducting the UCS test.

Figure 7. Sandstone core samples before (top) and after (bottom) OUCS testing

5 RESULTS

This section contains the results of the measurement of the oriented ultrasonic, by which the isotropy of sandstone was firstly confirmed. It also contains the results of the oriented IT, UCS, and their correlations.

5.1 Oriented Ultrasonic Wave Measurement and Anisotropy Classification

Using the ultrasonic apparatus reported by Abugharara et al. (2016), oriented compressional and shear wave velocities were measured from the three sandstone cores (vertical, diagonal, and horizontal) as described in Fig. 1.

Compressional and shear wave velocities were measured around the complete circumference of three cylinders. The measuring locations were 45 degrees apart. The purpose of this measurement was to evaluate the sandstone isotropy and calculate its strength using existing numerical models. Such calculated strength would be compared with the measured sandstone strength of this paper. Figure 8 shows results of OUSWV measurements as well as the density of the samples used.

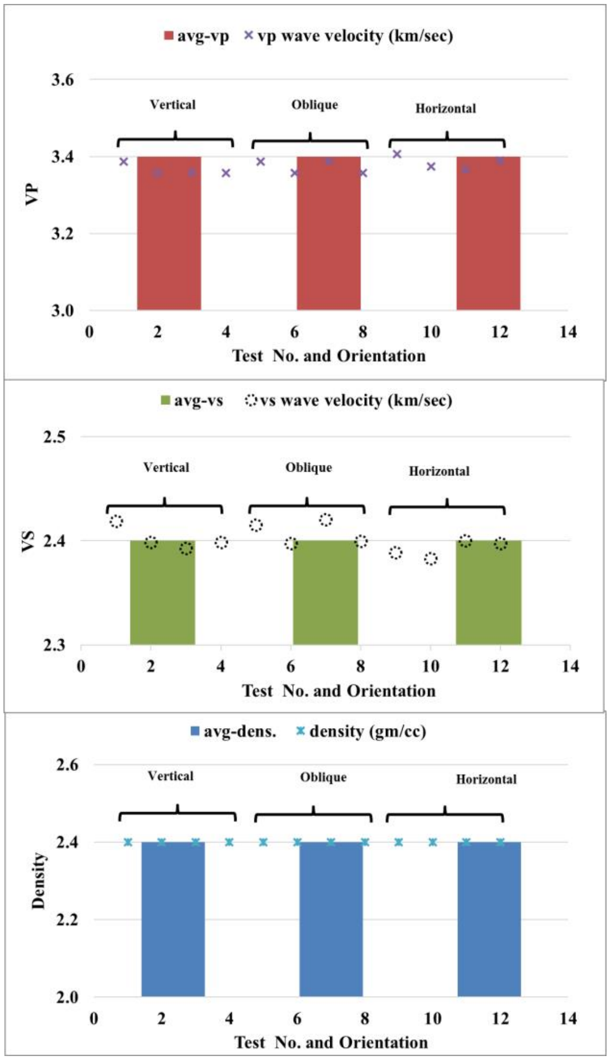

Figure 8. Oriented compressional (top) and shear (middle) wave velocities using ultrasonic method with oriented density (bottom)

Ultrasonic wave velocity anisotropy (VA) was classified by Tsidzi (1997) and Saroglou (2007). This classification was also used by Birch (1961) for description of seismic waves.

Tsidzi (1997) reported the velocity anisotropy index (VA) based on Eq. 1. Table 1 shows the anisotropy classification according to Tsidzi (1997).

$$VA = \frac{\mathrm{Vmax} - \mathrm{Vmin}}{Vmean}\ (\%) \qquad (1)$$

Where Vmax: the maximum ultrasonic velocity, Vmin: the minimum ultrasonic velocity, and Vmean: the mean velocity.

Table 1. Degree of velocity anisotropy VA (%) (Tsidzi 1997).

Degree of velocity anisotropy VA (%)	Descriptive term
< 2	Isotropy
2 to 6	Fairly Anisotropy
6 to 20	Moderately Anisotropy
20 to 40	Highly Anisotropy
> 40	Very highly Anisotropy

Saroglou (2007) proposed Eq. 2 for rock anisotropy classification.

$$\mathrm{Ivp} = \frac{\mathrm{Vp}(0°)}{\mathrm{Vp}(90°)} \qquad (2)$$

Results of this study using Eq. 1 and 2 including the criterion of each author's index are shown in Table 2.

Table 2. Results of sandstone isotropy using OUSWV measurement

According to	Criterion	Description	Result of this study
Tsidzi (1997)	Less than 2(%)	Isotropy	0.55 (%)
Saroglou (2007)	Equal or less than 1	Isotropy	1.006

5.2 Oriented Strength and Strength Anisotropy Classification

This section contains results of (i) strength anisotropy classification and (ii) the calculated sandstone strength using OITS and OUCS.

According to Ramamurthy (1993), a strength anisotropy index was proposed as presented in Eq. 3.

$$\mathrm{I}\sigma\mathrm{c} = \frac{\mathrm{I}\sigma\mathrm{ci}\ (90°)}{\mathrm{I}\sigma\mathrm{ci}\ (min)} \qquad (3)$$

Where Iσc is the uniaxial compressive strength (UCS) anisotropy, Iσci (90º) is the maximum UCS, and Iσci (0º) is the minimum UCS. The tested sandstone was determined as an isotropy rock according to the criterion described in Table 3.

Table 3. Uniaxial compressive strength anisotropy (Ramamurthy 1993)

According to	Criterion	Description	Result of this study
Ramamurthy (1993)	1.0 to 1.1	Isotropy	1.01

Through the OUCS test, the strength was measured at three primary orientations. However, the OITS test was measured in the three secondary orientations within the three primary orientations.

After performing each of the OITS and OUCS tests, their results were correlated. The purpose this correlation was for a comparative study analysis with some reported results elsewhere for further evaluation of sandstone isotropy.

5.2.1 Collective Results of OITS vs. OUCS

Strength results of all OITS tests verses OUCS tests were plotted collectively with respect to each primary orientation and are shown in Fig. 9. The average values of these tests are shown in Fig. 10.

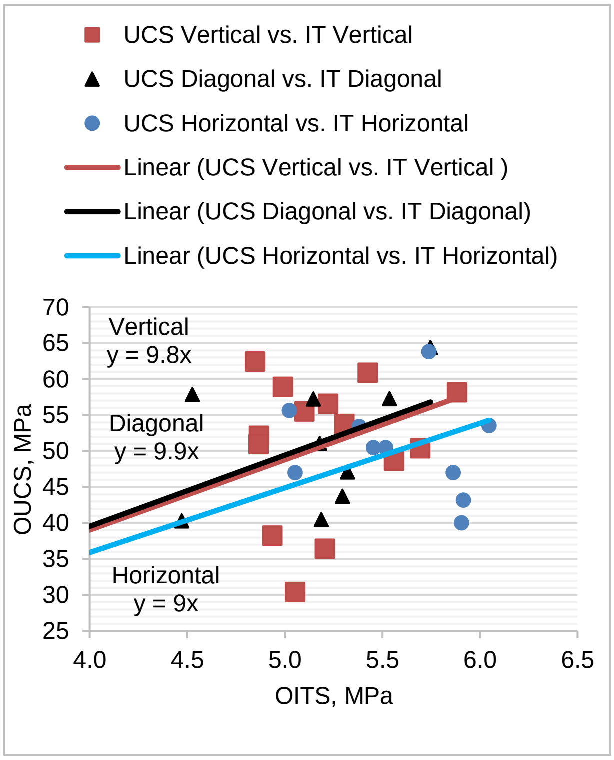

Figure 9. Strength values of OUCS vs. OITS

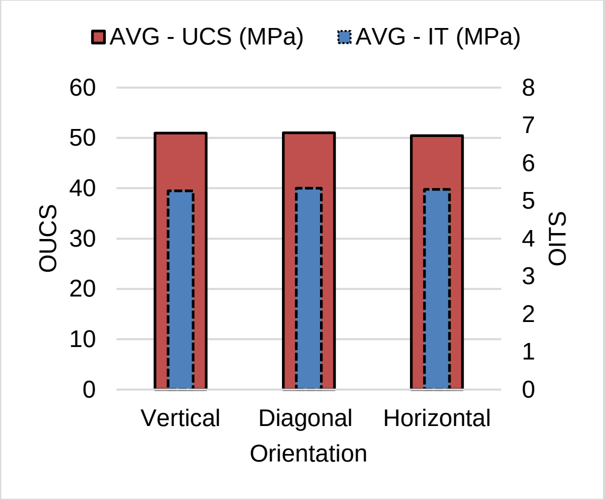

Figure 10. Average strength values of OITS and OUCS

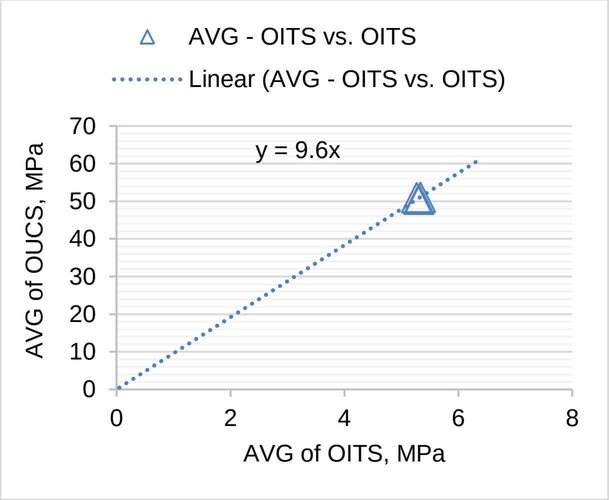

Figure 11. Correlation between the average values of OITS and OUCS

Figure 11 shows the correlation between the average values of OITS versus average values of OUCS demonstrating sandstone isotropy. The three average values of OITS and OUCS represent the three primary orientations of vertical, diagonal, and horizontal.

5.2.2 Individual Results of OITS vs. OUCS

Data of each orientation was considered in separate graphs of OUCS vs. OITS for each orientation, as shown for one orientation in Fig. 12. Results of all correlations between OUCS and OITS are summarized in Table 2 (bottom) with some published models (top).

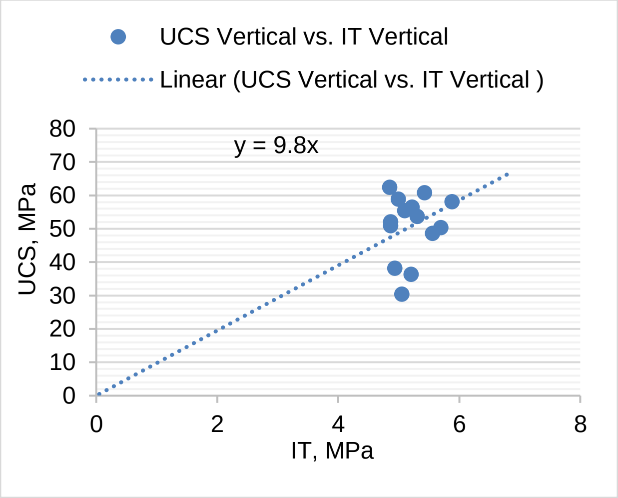

Figure 12. Correlations between vertically oriented strength of IT vs. UCS

6 DISCUSSION

Sandstone anisotropy was evaluated first, by OUSWV according to reported wave velocity indices. Second, by OUCS. Finally, by OITS.

After anisotropy classification, which was determined by OUSWV as indicated in Table 1, OUCS tests were conducted to provide more data for correlation with OITS. Figure 9 contains all data of OITS performed on disk samples vs. OUCS performed on standard samples that are shown in Fig. 7.

Oriented correlations between the results of different strength tests conducted in different directions as new practice, which was not used before for rock anisotropy evaluations is used in this research to enrich the laboratory procedure being developed for rock anisotropy evaluation. Correlating equations shown in Fig. 9 showed sandstone isotropy following the same conclusion that was determined by oriented wave velocity measurements. Sandstone isotropy is also shown when correlating AVG-OITS with AVG-OUCS producing a similar equation as shown in Fig. 10 and 11.

7 CONCLUSION

This is a report of an ongoing study of methodology for evaluating rock anisotropy. The following points can also be concluded:

- The practiced methodology connected several tests whose results can be supporting one another.
- As the work still before maturation, the involved procedure could be of practical methodology collectively or partially.

Table 4. Summary of correlations between OITS and OUCS in all scenarios of multiple and singular orientation

Correlations between IT and UCS of Previous studies

Ref.	Author	Equation	Rock Type	Orientation
1	Kahraman et al, 2012	UCS=10.61*BTS	Different rock types including sandstone	Regardless the orientation
2	Altidag and Guney, 2010	UCS=12.308*TS^1.0725	Different rock types including sandstone	Regardless the orientation
3	Altidag and Guney, 2010	UCS=12.38*TS^1.025	Different rock types including sandstone	Regardless the orientation

Correlations between IT and UCS of this study

Ref.	Author	Equation	Rock Type	Orientation
4	Abugharara et al, 2019, Current study	UCS = 9.7596*IT	Fine-grain Sandstone	UCS Vertical vs. IT Vertical
5		UCS = 9.7955*IT	Fine-grain Sandstone	UCS Diagonal vs. IT Vertical
6		UCS = 9.6437*IT	Fine-grain Sandstone	UCS Horizontal vs. IT Vertical
7		UCS = 9.8863*IT	Fine-grain Sandstone	UCS Vertical vs. IT Diagonal
8		UCS = 9.5817*IT	Fine-grain Sandstone	UCS Diagonal vs. IT Diagonal
9		UCS = 9.6625*IT	Fine-grain Sandstone	UCS Horizontal vs. IT Diagonal
10		UCS = 8.9771*IT	Fine-grain Sandstone	UCS Vertical vs. IT Horizontal
11		UCS = 9.0219*IT	Fine-grain Sandstone	UCS Diagonal vs. IT Horizontal
12		UCS = 9.2662*IT	Fine-grain Sandstone	UCS Horizontal vs. IT Horizontal
13		UCS = 9.6165*IT	Fine-grain Sandstone	Multi-orientation of UCS vs. IT
14		UCS = 9.5848*IT	Fine-grain Sandstone	AVG of AVG OUCS vs. OITS

8 FUTURE WORK

- Considering smaller orientation increments in all parts of the study.
- Involving various types of rocks to enrich the current procedure for broader anisotropy evaluation.
- Further study for rock anisotropy evaluation under various conditions such as pressurized condition will be considered.

9 ACKNOWLEDGEMENT

This work was performed at the drilling technology laboratory (DTL) at Memorial university of Newfoundland, St. John’s, Newfoundland and Labrador, Canada.

10 FUNDING DATA

- Atlantic Canada Opportunity Agency (AIF contract number: 781-2636-1920044), involving Husky Energy, Suncor Energy and Research and Development Corporation (RDC) of Newfoundland and Labrador.
- The Ministry of Higher Education and Scientific Research, Libya, through the Canadian Bureau for International Education, Canada (CBIE-Canada).

11 NOMENCLATURE

BTS	Brazilian Tensile Strength
CBIE	Canadian Bureau for International Education, Canada
VP	Compressional (Primary) Wave Velocity
IVP	Compressional Wave Velocity Index
DTL	Drilling Technology Laboratory
IT	Indirect Tensile Strength
OITS	Oriented Indirect Tensile Strength
OUSWV	Oriented Ultrasonic Wave Velocity
OUCS	Oriented Unconfined "Uniaxial" Compressive Strength
RDC	Research and Development Corporation
VS	Shear (Secondary) Wave Velocity
ST	Splitting Strength
VA	Velocity Anisotropy

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