

Empirical Procedure Investigation for Sandstone Anisotropy Evaluation: Part II



Abdelsalam Abugharara and Stephen Butt

Department of Process Engineering, Memorial University of Newfoundland, St. John's, Newfoundland and Labrador, Canada

John Molgaard

Department of Mechanical Engineering, Memorial University of Newfoundland, St. John's, Newfoundland and Labrador, Canada

Charles Hurich

Department of Earth Sciences, Memorial University of Newfoundland, St. John's, Newfoundland and Labrador, Canada

ABSTRACT

A laboratory methodology of an anisotropy evaluation for fine grain sandstone is reported. The methodology involved four types of tests: (i) point load strength (OPLS) and (ii) compliant and non-compliant drilling as two primary tests, and (iii) ultrasonic wave velocity (OUSWV) measurement and (iv) unconfined (uniaxial) compressive strength (UCS) as supporting tests. Each test was conducted on samples produced from the same natural sandstone block in three orientations: vertical, diagonal, and horizontal. The primary tests were conducted for sandstone characterization determined by OUSWV using published anisotropy indices, and correlated with UCS. The tests showed sandstone isotropy, and are part of an ongoing study to develop a rock anisotropy characterization procedure.

RÉSUMÉ

Cette communication examine une méthode de laboratoire utilisée pour l'évaluation anisotropique du grès à grains fins. La méthodologie a impliqué quatre types de tests: (i) l'intensité des charges ponctuelles (OPLS), (ii) forages conformes et non-conformes étant les deux premiers tests effectués et (iii) la mesure de la vitesse des ondes ultrasoniques (OUSWV), (iv) celle de la résistance à la compression uniaxiale (UCS) en tant que tests complémentaires. Chaque test a été mené sur des échantillons provenant de la même roche naturelle de grès selon trois orientations principaux: verticale, diagonale et horizontale. Les tests principaux ont été conduits pour caractériser le grès tel que déterminé par le procédé de la mesure de la vitesse des ondes ultrasoniques (OUSWV) en utilisant les indices d'anisotropie publiés et corrélés avec ceux de la résistance à la compression (UCS). Les tests ont démontré l'isotropie du grès et font partie d'une étude en cours dans le but de développer un procédé de caractérisation de l'anisotropie de la roche.

1 INTRODUCTION

Rocks are classified to be either isotropic, whose properties (i.e. mechanical, physical, etc.) are directional independent or anisotropic, whose properties are directional dependent (Brown et al. 1993, Goodman 1980). Anisotropy can vary between the most basic vertically transversely isotropic / horizontally transversely isotropic, VTI and HTI, respectively and the very highly anisotropy (Brady and Brown 2006)

Rock anisotropy can highly affect various applications, including oil and gas drilling process, well-logging measurements, reservoir evaluation, and mining operations as well as civil structures (Mokhtari et al. 2016, Gu 2018, Abugharara 2019).

Evaluating and determining rock anisotropy assist in controlling well trajectory, enhancing drilling performance, optimizing hydrocarbon production, strengthening civil

structures, and minimizing errors in produced data and results.

The influence of anisotropy of shale, as an example of VTI rocks on oriented drilling by Abugharara et al. (2019) highlighted the importance of studying the anisotropy.

Published studies reported rock anisotropy evaluation methods through several tests of destructive and non-destructive tests.

The aim of the research is to study the tested fine grain sandstone through oriented strength tests (OPLS, OUCS and their correlations) and directional compliant and non-compliant drilling as a part of ongoing research, whose ultimate goal is to develop a comprehensive procedure for rock anisotropy characterization.

2 SAMPLE PREPARATION

63 samples (3 for oriented wave velocity, 30 for OUCS, 26 for OPLI, 3 for oriented drilling) were produced from one

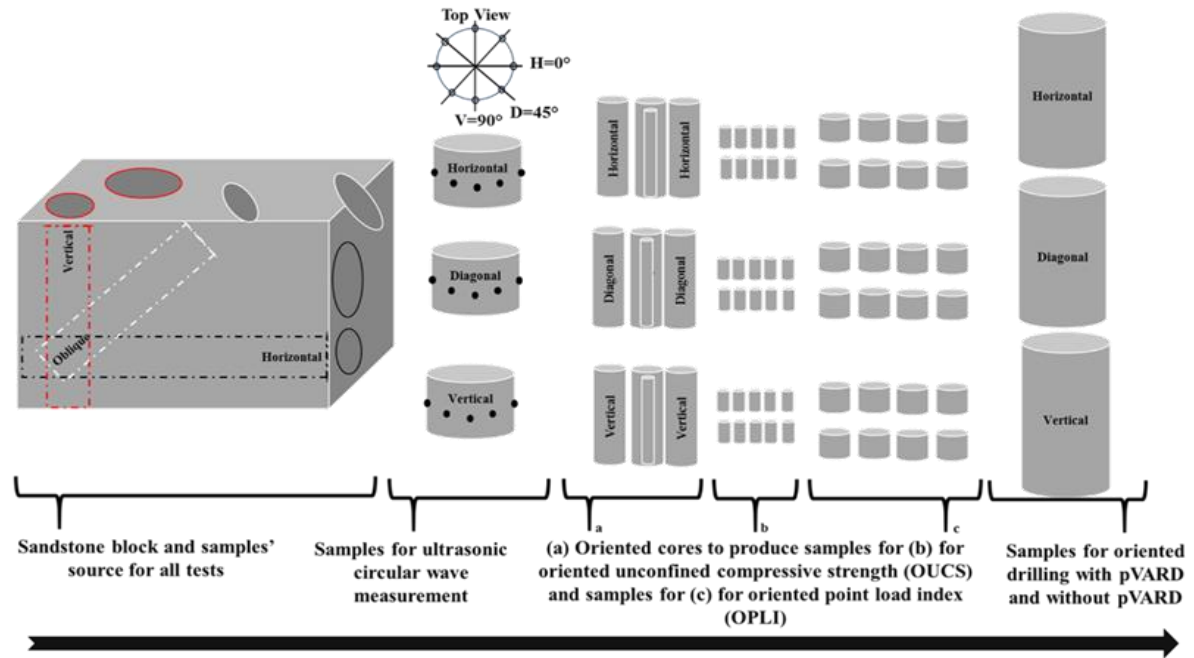


Figure 1. Sandstone coring source and samples sets for all tests of ultrasonic, strength and drilling

fine-grain sandstone block and used for all tests as shown in Fig. 1. Such practice of obtaining all samples from the same block in different orientations is a unique and a novel practice for such high number of tests involved. Samples were obtained in various dimensions in accordance with American Society for Testing and Materials (ASTM) standards and International Society of Rock Mechanics (ISRM) suggested methods. The dimensions of the main block were about 70 cm long, 40 cm wide, and 50 cm high. Different diameter coring bits were used to core sandstone in three orientations: vertical, diagonal, and horizontal.

For OUSWV measurements, samples were cores of 10.16 cm diameter and about 10 cm long as shown in Fig.1 second left, with indications of circular wave velocity measurements as well as samples' top view. For oriented strength measurements, samples were cores of 4.76 cm diameter and about 30 cm long or more depending on the coring directions. Samples in each orientation were then categorized to three groups. Each group was denoted for particular oriented strength testing type.

For the unconfined compressive strength test, samples were cored axially from the 4.76 cm samples using a 2.54 cm coring bit. These samples are shown in Figure 2 (a and b). The samples were then cut to a 2:1 ratio of length to diameter with accordance to standards. For the PLI test, samples were prepared for the point load axial test. Samples were cut from the 2.54 cm cores in accordance with standards (ASTM D5731 – 2016) as shown in Fig. 1(c). Figure 2 shows sample dimension requirements for the point load axial test.

For both compliant and non-compliant drilling, samples were cored using a 10.16 cm coring bit. Samples are shown in Fig. 1 (Right).

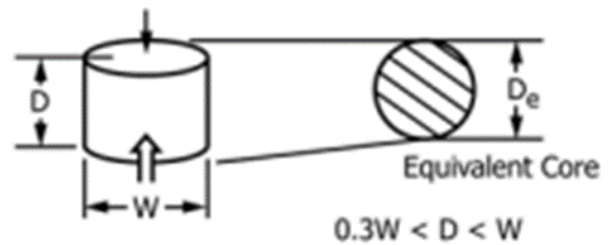


Figure 2. sample dimension requirement for point load test (ASTM D5731 – 2016)

3 EXPERIMENTAL PROCEDURE

Experiments were conducted in the following order. First: for oriented ultrasonic wave velocity (OUSWV) including compressional and shear wave velocity (v_p and v_s respectively). The purpose of this test was to characterize the tested sandstone anisotropy in accordance with some published ultrasonic wave velocity anisotropy indices.

Second, sandstone oriented strength was determined through the destructive strength tests of both OPLS and OUCS.

Third, a compliance drilling using a passive vibration assisted rotary drilling (pVARD) tool, followed by a non-compliant drilling were performed in three orientations. Both drilling types were performed on the same samples, but each drilling from a different side as detailed in.

Fourth, constructing correlations between OPLIS and OUCS for further sandstone anisotropy evaluation and characterization, followed by the fifth step of determination of sandstone anisotropy.

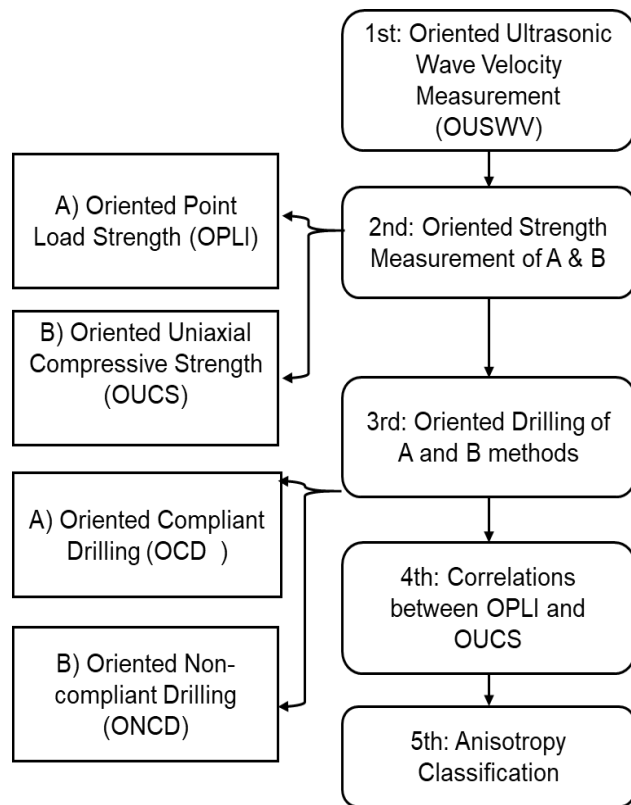


Figure 3. Experimental procedure flowchart.

4 PERFORMED TESTS AND APPARATUS

Several tests were performed to characterize the fine-grain sandstone's anisotropy. These tests included a non-destructive test of oriented ultrasonic compressional and shear wave velocity (OUSWV), and destructive tests of oriented point load Index (OPLI) and oriented uniaxial compressive strength (OUCS).

The purpose of conducting OUSWV, whose apparatus was fully described by Abugharara et al. (2016), was to characterize the anisotropy of the tested fine-grain sandstone using published indices, and then using this anisotropy characterization as a base for the oriented strength tests and oriented compliant and non-compliant drilling experiments.

The purpose of applying destructive strength tests of OPLS and OUCS, whose apparatus is shown in Fig. 4 (point load apparatus for OPLS and modified point load apparatus with flat-end pistons for OUCS), was (i) to determine the anisotropy of the tested rock by oriented strength measurements using the corresponding published strength indices and then compare it with the anisotropy results determined through OUSWV, (ii) to evaluate the sandstone strength anisotropy based on OPLI results, and (iii) to correlate results of OPLS and OUCS and compare their correlation models to the published models.



Figure 4. Point load apparatus and its modified version for OUCS.

Compliant drilling using pVARD and non-compliant drilling were the last tests. Figure 5 shows compliant and non-compliant drilling apparatus with a dual cutter Polycrystalline Diamond Compact (PDC) bit. Figure 6 shows samples PLI and UCS before testing as well as samples after compliant and non-compliant drilling tests using a fully instrumented laboratory scale rotary drilling rig. pVARD tool was used to drill with induced vibrations that makes it different from non-compliant drilling, where pVARD was locked, where the pVARD tool is considered a rigid part of the whole drill string by replacing the springs and demining portions with spacers that eliminate. The reason of not removing. The purpose of using two different drilling modes of compliant and non-compliant was to further evaluate sandstone anisotropy.

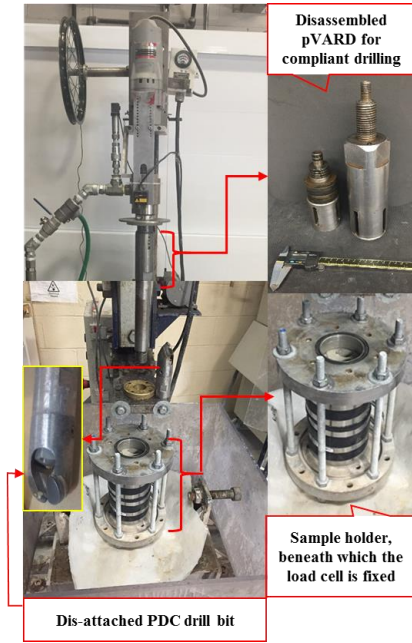


Figure 5. Fully instrumented laboratory scale drilling rig

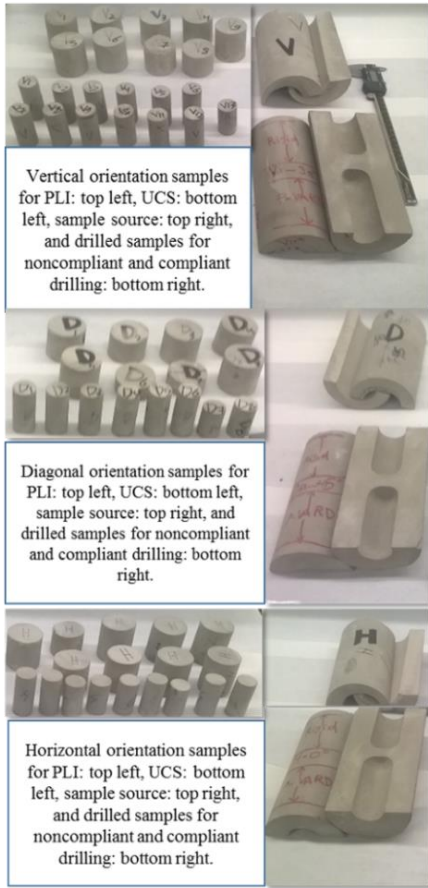


Figure 6. Samples for PLI and UCS before testing as well as drilled samples.

5 RESULTS

This section contains results of OUSWV, OPLS, OUCS, compliant and non-compliant drilling, as well as correlations between OPLS and OUCS.

5.1 Results of Oriented Ultrasonic Wave Measurement and Sandstone Anisotropy classification

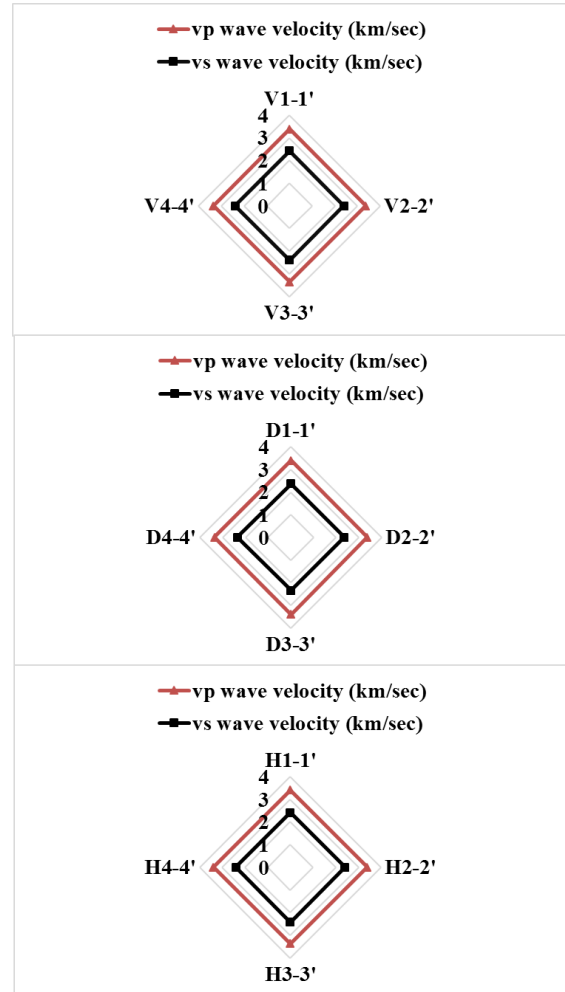


Figure 7. Circular ultrasonic compressional and shear wave velocity measurement (V, D, and H represent orientation, #-# ', represents a set of each two points for each measurement, as shown in the top view of Fig. 1)

Figure 7 shows results of the circular ultrasonic compressional and shear wave velocity measurements from three oriented sandstone cores.

Results of the anisotropy classification of this sandstone according to some of the published anisotropy indices by Tsidzi (1997) and Saroglou (2007) are summarized in Table 1. Table 1 also contains the anisotropy strength indices and the results of their current work.

5.2 Results of Oriented Strength

5.2.1 Oriented Unconfined Compressive Strength

This section shows results of sandstone oriented strength measured by OUCS and OPLS as shown in Fig. 8 and 9, respectively. The average values of strength results measured from both tests show consistency indicating sandstone isotropy.

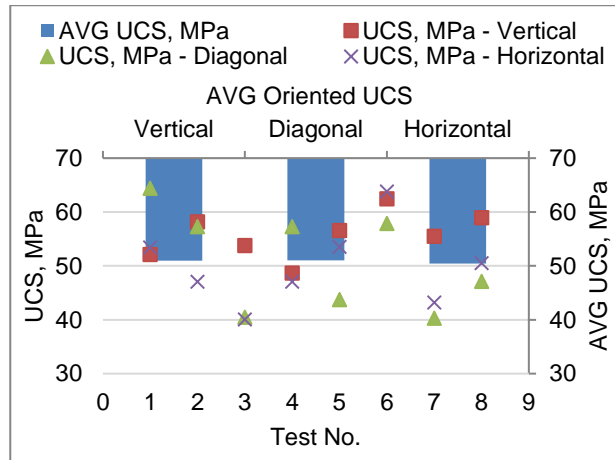


Figure 8. Oriented unconfined compressive strength and their average values.

5.2.2 Oriented Point Load Strength

Results of OPLS and their values are shown in Fig. 9. The average strength values of OPLS and OUCS are shown in Fig. 10.

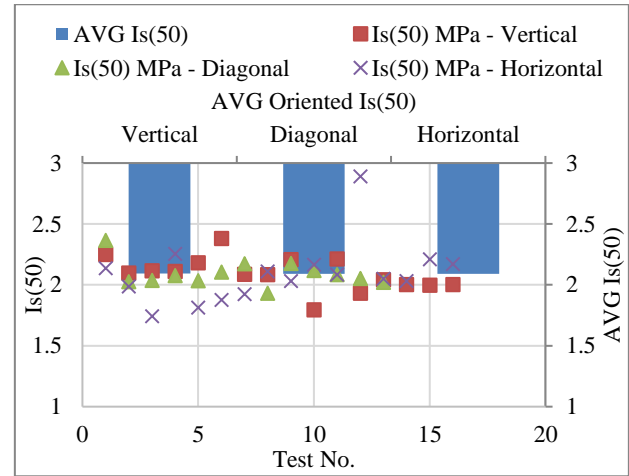


Figure 9. Oriented point load strength and their average values

Table 1. Published wave velocity and strength anisotropy indices with their conditions for isotropy classification and results of current study

Author	Test type	Anisotropy Index	Equation	Criterion	Result of current study	Descriptive term
Tsidzi (1997)	Wave velocity	Velocity Anisotropy (VA) Index	$VA = [(V_{max} - V_{min}) / V_{mean}] (%)$	< 2.0 : Isotropy	0.55 (%)	Isotropy
Saroglou (2007)			$I_{vp} = V_p(0^\circ) / V_p(90^\circ)$			
ISRM (1981)			$I_a(50) = I_s(50)(90^\circ) / I_s(50)(0^\circ)$	1.0 : Isotropy	0.05	Isotropy
ISRM (1985)	PLI	Point load strength anisotropy index				
Tsidzi (1990)						
Ramamurthy (1993)	UCS	Uniaxial compressive strength anisotropy index	$I_{\sigma c} = \sigma_c(90^\circ) / \sigma_c(\min)$	1.0 - 1.1: Isotropy	0.99	Isotropy

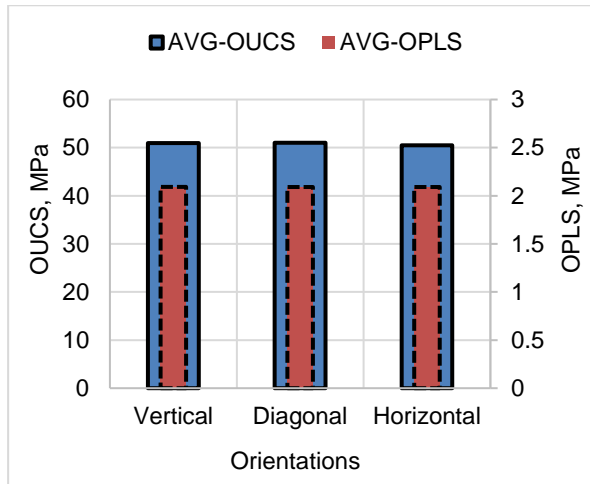


Figure 10. Average values of OUSC and OPLS

According to ISRM (1981), ISRM (1985), and Tsidzi (1990), rock strength anisotropy can be classified using PLI using Eq. 1.

$$Ia(50) = \frac{Is(50)(90^\circ)}{Is(50)(0^\circ)} \quad (1)$$

Where, $Ia(50)$ is a point load strength anisotropy index, $Is(50)(90^\circ)$ and $Is(50)(0^\circ)$ is point load strength anisotropy index applied vertically and horizontally, respectively.

The associated conditions for Eq.1 for a rock to be isotropy is that the value equals 1. For this study $Ia(50) = 0.05$, classifying the tested sandstone as isotropic.

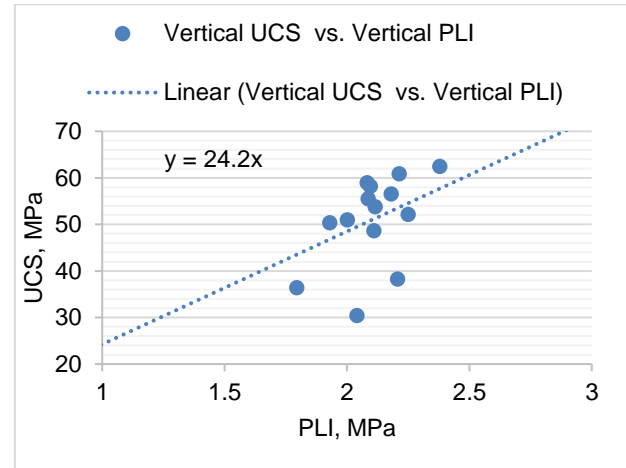


Figure 11. Correlation between vertical PLI and vertical UCS

Considering oriented correlations as a new practice used in this work that was not used before, was for the purpose of evaluating rock anisotropy and for supporting anisotropy results determined by direct testing methods of oriented velocity and oriented strengths. . Figures 11 to 14 are 4 figures of 10 figures in total, whose results are summarized in table 2. They show correlations between

Table 2. Summary of published correlations for PLI and UCS with correlations with the current study

Reported correlations			
Author	Source of rock	Rock type	Correlation
Broch and Franklin (1972)	UK	Various rocks	UCS = 23.7*PLI
Bieniawski (1975)	South Africa	Sandstones	UCS = 23.9*PLI
Hawkins and Olver (1986)	UK	Sandstones	UCS = 24.8*PLI
Vallejo et al. (1989)	USA	Sandstones	UCS = 17.4*PLI
Das (1985)	Canada	Sandstones	UCS = 18*PLI
Smith (1997)	Various locations	Sandstones	UCS = 24*PLI
Current study correlations: Abugharara et al. (2019)			
Vertical UCS vs. Vertical PLI	Canada	Sandstones	UCS=24.3*PLI
Diagonal UCS vs. Diagonal PLI	Canada	Sandstones	UCS=24.3*PLI
Horizontal UCS vs. Horizontal PLI	Canada	Sandstones	UCS=24.1*PLI
Vertical UCS vs. Diagonal PLI	Canada	Sandstones	UCS = 24.3*PLI
Vertical UCS vs. Horizontal PLI	Canada	Sandstones	UCS = 24*PLI
Diagonal UCS vs. Vertical PLI	Canada	Sandstones	UCS = 23.6*PLI
Diagonal UCS vs. Horizontal PLI	Canada	Sandstones	UCS = 25.8*PLI
Horizontal UCS vs. Diagonal PLI	Canada	Sandstones	UCS = 24*PLI
Horizontal UCS vs. Vertical PLI	Canada	Sandstones	UCS = 23.7*PLI
OUCS vs. OPLS (all data in all orientations)	Canada	Sandstones	UCS=24.3*PLI

UCS and PLI in all scenarios of orientations. Figure 11 shows correlations between vertical UCS and vertical PLI. Figure 12 shows correlations between diagonal UCS and diagonal PLI. Figure 13 shows correlations between horizontal UCS and horizontal PLI. Figure 14 shows correlations between OUCS and OPLI.

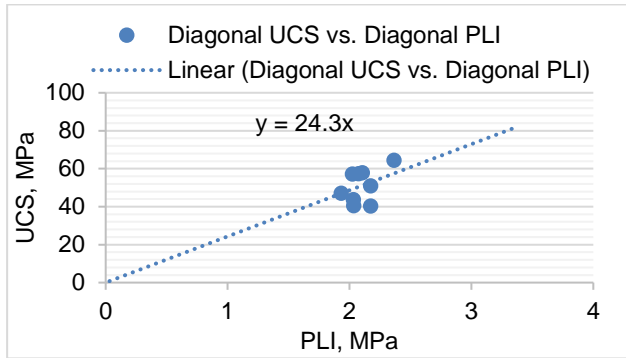


Figure 12. Correlation between diagonal PLI and diagonal UCS

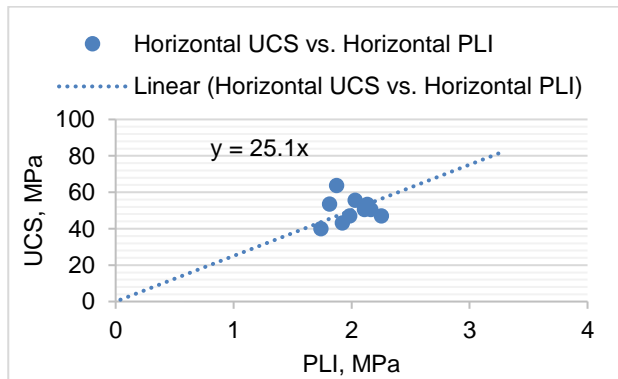


Figure 13. Correlation between horizontal PLI and horizontal UCS

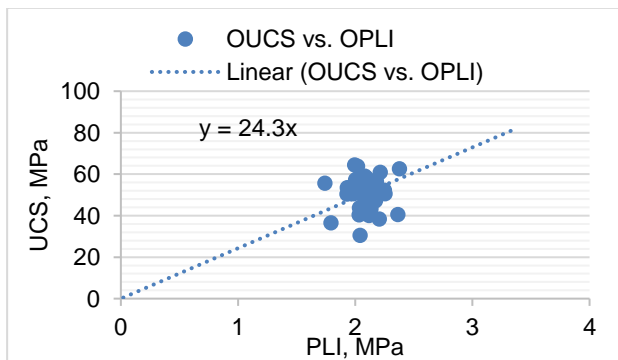


Figure 14. Correlation between OPLI and OUCS involving their data in the three orientations

5.3 Oriented Compliant and Non-Compliant Drilling

This section contains the results of oriented drilling sandstone in three orientations using compliant and non-compliant drilling. The drilling experiments were conducted at atmospheric pressure condition and laboratory (room) temperature using constant flow rate of a clean water. The results involved comparison between the downhole dynamic weight on bit (DDWOB) measured by the load cell attached beneath the sample holder. Drilling using compliant and non-compliant systems induces different levels of vibrations that influence the DDWOB. The purpose here is to conduct a comparative analysis DDWOB in compliant and non-compliant drilling as a function of sandstone orientation and static weight and evaluate their changes with orientation. Differences in results with orientation indicates sandstone anisotropy and similar results indicates sandstone isotropy.

Fig. 15 and 16 show consistency indicating sandstone isotropy. This similarity appears in DDWOB as well as rate of penetration (ROP) compliant and noncompliant drilling as a function of orientation.

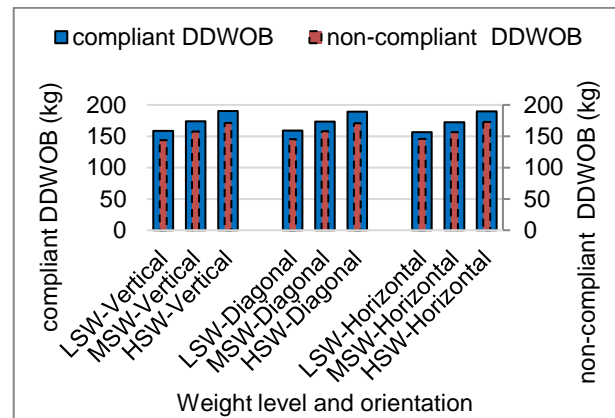


Figure 15. Compliant and non-compliant DDWOB as a function of sandstone orientation and weight levels of low, medium, and high static weight

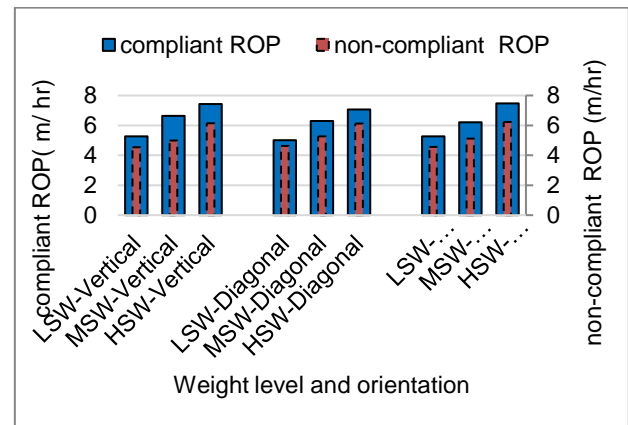


Figure 16. Compliant and non-compliant ROP as a function of sandstone orientation and weight levels of low, medium, and high static weight

6 Discussion

The anisotropy of the fine grain sandstone was studied using the oriented ultrasonic, strength and drilling tests. Ultrasonic method was conducted first on three samples. The results of ultrasonic wave velocity measurement are shown in Fig. 7.

Figure 8 and 9 show oriented strength results and their average values, which were obtained by OUCS and OPLS, respectively. Strength anisotropy indices were determined based on the averaged values of all tests. Although Abugarara (2019) reported the UCS anisotropy for sandstone, the purpose of presenting OUCS in this paper is to have correlation between OUCS and OPLS.

Figure 10 shows the average values of the oriented strengths. These average values were used for the sandstone strength anisotropy classification. For PLI anisotropy index, Eq. 1 was used. Results showed sandstone isotropy as summarized in Table 1.

Figures 11 to 14 show correlations between PLI and UCS in similar orientations: individually as shown in Fig. 11 to 13 and collectively as shown in Fig. 14). Correlations of possible scenarios of all orientations are summarized in Table 1.

Drilling was performed for evaluating sandstone's anisotropy. The two drilling parameters involved were DDWOB and ROP (Fig 15 and 16; respectively). Both parameters were studied as a function of orientation in two drilling modes of compliant and non-compliant. First, the compliant drilling was better in performance and had higher ROP against non-compliant. Second, DDWOB was recorded higher in compliant drilling than that of non-compliant. They various weight levels of low, medium, and high static weight levels were applied to study DDWOB and ROP. The results of DDWOB and ROP show consistency, which could be considered as a sign of sandstone isotropy as was determined by the ultrasonic wave velocity and the strength methods.

7 CONCLUSION

This research reports results of an ongoing project that uses various techniques, among which are compliant and non-compliant drilling as well as strength tests, for rock anisotropy evaluation.

Tests were supporting one another in showing sandstone isotropy, in particular wave velocity and strength tests. The drilling tests showed data consistency, indicating sandstone isotropy.

8 FUTURE WORK

Involving different rock types and performing tests under pressurized conditions 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

CBIE	Canadian Bureau for International Education, Canada
VP	Compressional (Primary) Wave Velocity
IVP	Compressional Wave Velocity Index
DDWOB	Downhole Dynamic Weight on Bit
DTL	Drilling Technology Laboratory
HSW	High Static weight
LSW	Low Static weight
Vmax	Maximum velocity
Vmean	Mean velocity
MSW	Medium Static weight
Vmin	Minimum velocity
OPLS	Oriented Point Load Strength
OUSWV	Oriented Ultrasonic Wave Velocity
OUCS	Oriented Unconfined "Uniaxial" Compressive Strength
pVARD	passive Vibration Assisted Rotary Drilling
PLI	Point Load Index
Ia(50)	Point load strength anisotropy index
Is	Point load strength index
PDC	Polycrystalline Diamond Compacts
ROP	Rate of Penetration
RDC	Research and Development Corporation
VS	Shear (Secondary) Wave Velocity
I _{σc}	Uniaxial compressive strength anisotropy index
VA	Velocity Anisotropy

12 REFERENCES

- Abugarara, A. N., Alwaar, A. M., Butt, S. D., and Hurich, C. A. 2016. Baseline Development on Rock Anisotropy Investigation Utilizing Empirical Relationships Between Oriented Physical and Mechanical Measurement and Drilling Performance, *the 35th International Conference on Ocean, Offshore and Arctic Engineering, Drilling Symposium*, Busan, South Korea. Paper No. OMAE2016-5514.
- Abugarara, A. N., Mohamed, B., Hurich, C., Molgaard, J., & Butt, S. D. 2019. Experimental Investigation of the

- Effect of Shale Anisotropy Orientation on the Main Drilling Parameters Influencing Oriented Drilling Performance in Shale, *Journal of Energy Resources Technology*, 141(10):102904. DOI: 10.1115/1.4043435
- ASTM International. 2016. ASTM D5731-16 Standard Test Method for Determination of the Point Load Strength Index of Rock and Application to Rock Strength Classifications. West Conshohocken, PA.
- Bieniawski Z. T. 1975: Point load test in geotechnical practice. *Engineering Geology*, 9(1), 1-11.
- Brady, B. H. G., and E. T. Brown. 2006. *Rock Mechanics for underground mining*, Kluwer Academic Publishing: 36.
- Broch, E. and Franklin, J. A. 1972. The point load strength test, *International Journal Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, 9 (6): 669-697. Pergamon Press.
- Brown, Edwin T., and John A. Hudson, eds. 1993. *Comprehensive rock engineering: principles, practice & projects. 1. Fundamentals*, Pergamon Press, p.285, DOI: 10.1016/0148-9062(94)90473-1
- Chau, K.T., Wong, R. H. C. 1996: Uniaxial compressive strength and point load strength of rocks, *International Journal of Rock Mechanics and Mining Sciences, Geomechanical Abstract*, 33, 183-188.
- Das, B. M. 1985. Evaluation of the point load strength for soft rock classification, *Proceedings of the fourth international conference ground control in mining*, Morgantown, WV, 220-226.
- Goodman, Richard E. 1980. *Introduction to Rock Mechanics*. No. BOOK. John Wiley:12.
- Gu, M. 2018. Impact of Anisotropy Induced by Shale Lamination and Natural Fractures on Reservoir Development and Operational Designs, *SPE Reservoir Evaluation & Engineering*, 21(04): 850-862.
- Hawkins, A. B., Olver, J. A. G. 1986. Point load tests: correlation factor and contractual use, An example from the Corallian at Weymouth. In: Hawkins, A.B. (Ed.), *Site Investigation Practice: Assessing BS 5930*, Geological Society, London, 269-271.
- INTERNATIONAL SOCIETY OF ROCK MECHANICS (ISRM). 1981. Rock characterization testing and monitoring, *ISRM Suggested methods*, Brown E.T. (ed.), Pergamon Press, Oxford.
- ISRM 1985: Suggested method for determining point load strength. *International Journal of Rock Mechanics and Mining Sciences and Geomechanical Abstract*, 22(2), 51-60. 21)
- Mokhtari, M., Honarpour, M. M., Tutuncu, A. N., & Boitnott, G. N. 2016. Characterization of elastic anisotropy in Eagle Ford Shale: Impact of heterogeneity and measurement scale, *SPE Reservoir Evaluation & Engineering*, 19(03): 429-439.
- Ramamurthy, T. 1993. Strength and Modulus Responses of Anisotropic Rocks, *Comprehensive Rock Engineering*, Pergamon Press, Oxford, 1: 313-329.
- Saroglou, H., and G. Tsiambaos. 2007. Classification of anisotropic rocks, *In 11th Congress of the International Society for Rock Mechanics*. In: Ribeiro e Sousa, Otalla, Grossmann, editors. Taylor & Francis Group, London, p. 191.
- Smith, H. J. 1997. The point load test for weak rock in dredging applications, *International Journal of Rock Mechanics and Mining Sciences*, 34, 295, 3-4.
- Tsidzi, K. 1990. The Influence of Foliation on Point Load Strength Anisotropy of Foliated Rocks, *Bull. Int. Association of Eng. Geology*, 29: 49-58.
- Tsidzi, K. 1997. Propagation characteristics of ultrasonic waves in foliated rocks, *Bull. Int. Association of Eng. Geology*, 56: 103-113.
- Vallejo, L. E., Welsh, R. A., Robinson, M. K. 1989. Correlation between unconfined compressive and point load strength for Appalachian rocks, *Proceeding of 30th US Symposium on Rock Mechanics*, Morgantown, 461-468.