

Development of Leeb hardness field test methodology to be used during rock core logging

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Abstract

This study investigates the use of non-destructive Leeb hardness testing as an alternative to conventional rock strength evaluation field tests including using geological hammers and point load testing devices. Conventional methods are noted to be subjective and/or potentially dangerous, resulting in rock fragment ejecta attributed to causing injury including blindness. Leeb hardness testing offers a safer approach with the potential for improved reliability and data, and standardisation of results. Testing is performed on diorite, andesite and dolerite igneous rocks retrieved as NQ size rock core during diamond drilling at the Newmont Boddington Gold Mine. A field-testing methodology is developed through a detailed data-driven familiarisation process to determine the sensitivity of Leeb hardness test results. Hardness testing is undertaken using the Equotip 550 device. Initial evaluation includes assessment of circumferential and longitudinal test results, separation between test locations and number of repeat tests per location, statistical evaluation, comparison of proximal results on vein structures (i.e. quartz) and country rock, effect of inclination of test device, applied pressure during testing and wet versus dry conditions. The effect of sample seating is also evaluated, comparing results of testing core laying within plastic core tray grooves to core laying in steel v-notch grooves often used during orientation of rock core.

Using the empirically derived methodology, testing is undertaken at metre marks along rock core in plastic core tray grooves. Results from multiple drill holes are included in the study. Testing is also performed on core samples sent to the laboratory for determination of parameters including uniaxial compressive strength (UCS). Correlational factors between Leeb hardness and UCS, density test results are derived through assessment of the field and laboratory test results and compared with published data. The methodology offers a relatively quick, safe and reliable way of determining and understanding rock strength and parameter variation along the length of rock core and, more widely, within the rock mass ultimately being evaluated.

Keywords: *Leeb hardness, Equotip, field test, UCS, non-destructive, rock core, safety, strength*

1 Introduction

Field tests to evaluate rock strength during the logging of rock core include hitting the core with a geological hammer and testing small samples of rock using point load test (PLT) devices. Safety concerns have been raised for both techniques, including an increased risk of hand and eye injuries. The use of non-destructive hardness testing has been put forward in the literature as an alternative to standard destructive testing (Ghorbani et al. 2023). This study evaluates a methodology for hardness testing to be used to collect standardised test results in the field and relate these back to uniaxial compressive strength (UCS). First, a familiarisation process is followed to help gain a better understanding of the sensitivity of the hardness test device when used on NQ size rock core. A correlation factor is then derived by comparing hardness test results with laboratory UCS test results on collected rock samples. An example of the application of the correlation factor at 1 m intervals along logged/tested rock core is also provided. Tests were undertaken on igneous rock core retrieved during diamond core drilling at the Newmont Boddington Gold Mine. Correlation factors may vary according to different lithologies present at particular geographical locations.

Field index strength test results for logged intervals during rock core logging are used to assign rock mass rating values that are considered during material characterisation. International Society for Rock Mechanics and Rock

Engineering (ISRM) grades shown in Table 1 below are assigned during logging, often through evaluation by hitting rock with a geological hammer (Read & Stacey 2009). Tests using geological hammers are understood to be subjective in nature, relying on the experience of the person undertaking rock core logging to assign a strength grade. PLT is a destructive form of testing whereby small rock core samples are squeezed between two metal points using a hand-pumped jack until the rock breaks. The pressure at breaking point is recorded and then correlated to equivalent UCS test value. Although general correlation factors are available, it is best practice to derive site-specific correlation factors. Figure 1 presents images of the geological hammer, PLT device and the Proceq Equotip 550 portable hardness test device used in this study.

Where suitability is determined, use of the portable hardness test device can offer advantages including:

- Greater safety during use.
- Increased standardisation of the testing technique.
- Non-destructive testing.
- Greater ease of use compared to destructive techniques.
- Collection of digital readings in CSV File Format 2.
- Opportunity to collect data more easily at increased intervals along rock core.
- Ability to correlate hardness values with other rock characteristics such as density.

Depending on the strength of the correlation factor, hardness testing at narrow intervals may offer other advantages such as greater resolution of rock strength at depth with potential applications to refine the geotechnical model and feed into decision-making processes such as those related to slope stability or drilling and blasting (Hoek & Brown 1997). It is noted, for example, that the R5 ISRM grade has a range between 100 MPa and 250 MPa. Being able to determine variations along rock core may highlight weaker or stronger areas of rock with additional precision.

Table 1 Description of rock strength and assigned ISRM grade with equivalent uniaxial compressive strength (UCS) value

ISRM grade	Term	Description of field estimate of strength	Is ₅₀ (MPa)	Equivalent UCS (MPa)
R0	Extremely weak	Indented by thumbnail.	***	0.25–1
R1	Very weak	Material crumbles under firm blows of geological pick, can be shaped with knife.	***	1–5
R2	Weak	Knife cuts material but too hard to shape into triaxial specimens.	***	5–25
R3	Medium strong	Firm blow with geological pick indents rock to 5 mm, knife just scrapes surface.	1–2	25–50
R4	Strong	Handheld specimens broken by a single blow of a geological hammer.	2–4	50–100
R5	Very strong	Requires many blows of a geological hammer to break intact rock specimens.	4–10	100–250
R6	Extremely strong	Rock material only chipped under repeated hammer blows, rings when struck.	>10	>250

***Values are insignificant.

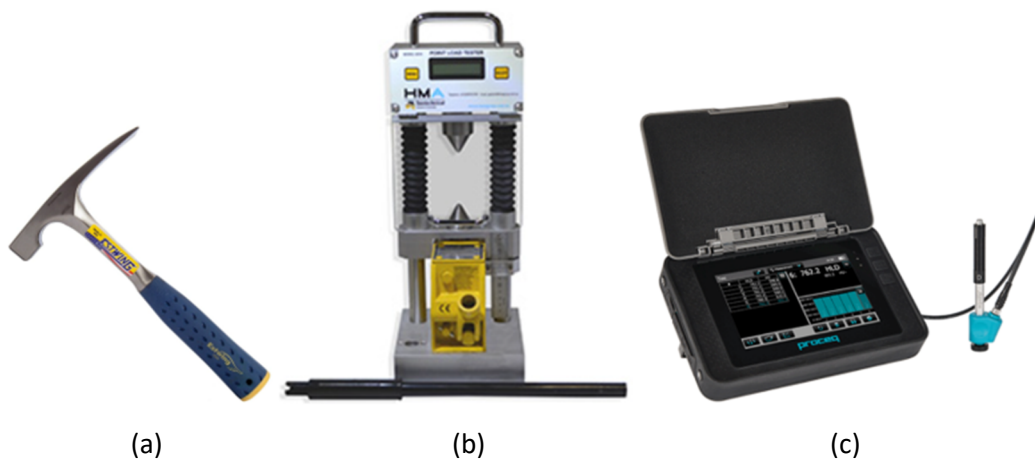


Figure 1 (a) Geological hammer; (b) PLT device; (c) Proceq Equotip 550 portable hardness test device

2 Description of Leeb hardness test device

Hardness testing is a rebound test method that uses a spring-loaded 3 mm diameter spherical tungsten carbide test tip on an impact tool contained within hard housing. The device used (Figure 2) has a type Z (25–50) support ring adapted for seating on cylindrical specimens of NQ core diameter. To determine hardness of the rock core sample, the release button is pressed and the velocity of the impactor is measured before and after impact. Measurements are collected when a permanent magnet passes through a coil of wire inducing a voltage proportional to velocity. The ratio of rebound velocity to the impact velocity provides the dynamic Leeb hardness result. Harder materials induce greater rebound, giving higher Leeb hardness values.

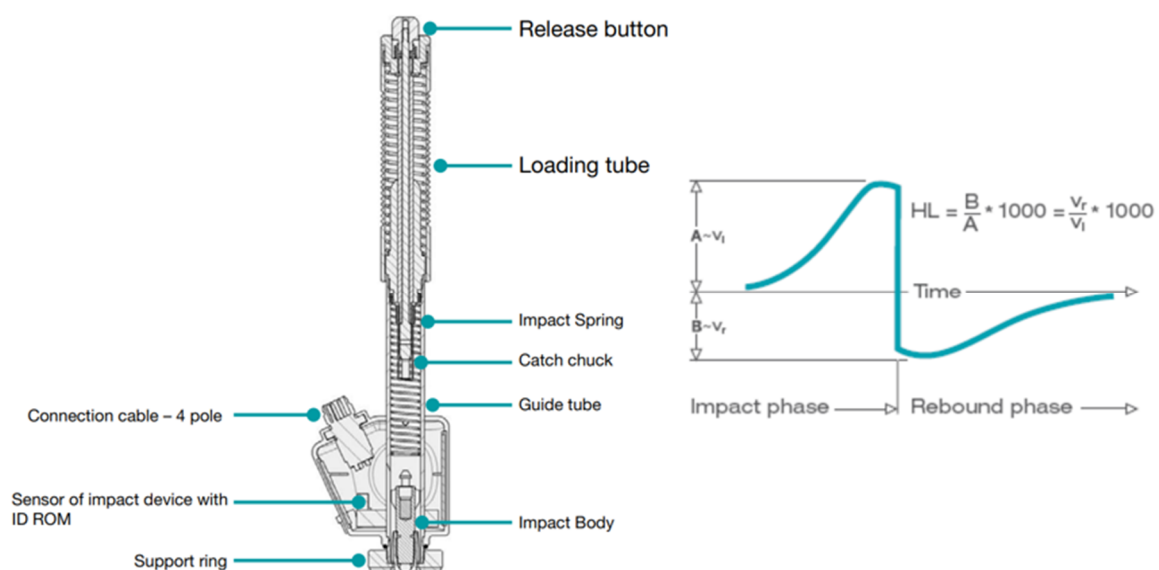


Figure 2 Schematic image of Equotip impact device (Proceq Equotip)

3 Possible influence factors and application to in-tray core testing

Different factors can influence Leeb hardness results. Ghorbani et al. (2023) and Proceq (2015) note the following as having the potential to influence results:

- Shape of the rock (i.e. block/cylinder).
- Sample size (recommend min core L/D of 1.6).
- Roughness of surface.

- Temperature.
- Specimen vibration.
- Porosity of rock.
- Proper seating of test device on sample.

To help assess the practicalities involved in testing rock core in the field, the current study evaluates the potential additional influence factors listed below. The study also compares hardness testing performed on rock core seated in a v-notch steel frame to testing of the same core seated in plastic core trays. Testing core in trays is considered practical and quick, and, where justified, considers:

- The effect of local variability in rock fabric (e.g. foliation, veining).
- The results gathered diametrically around the rock core.
- Moisture content of the core samples.
- Testing with application of added applied pressure on the testing device.
- Inclination of the test device during testing (i.e. poor practice).
- The medium seating of the test samples (e.g. steel v-notch versus plastic core tray).

4 Evaluation of sensitivity of hardness testing on rock core

Hardness testing was performed on NQ diameter rock core in an outdoor core shed at Boddington during summer/autumn of 2023. Testing focused on becoming familiar with the sensitivity of the hardness testing device and using this information to determine the best approach to test rock core at 1 m intervals along recovered drillcore. During this phase of the study all rock core was tested when seated in a steel v-notch frame used to orientate core in core yards. This was done to limit potential vibrations during testing and in accordance with recommendations by Yilmaz & Goktan (2018). Hardness testing was performed to evaluate influence factors as noted in Section 3. Figure 3 shows the set-up used to test rock core on the steel v-notch frame. The frame was brushed clean of any detritus during set-up to alleviate any potential influence on results. All sample cores were tested three times at 10-cm intervals, and the average and standard deviations (SD) were determined for analysis.

The following sub-sections provide more detailed information related to each step taken when evaluating hardness test sensitivity.

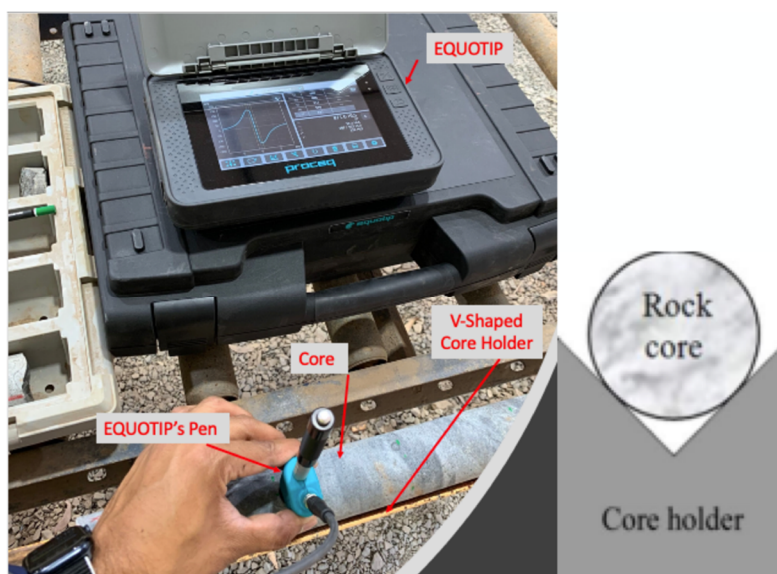


Figure 3 Experimental set-up & v-notch core holder side view (Yilmaz & Goktan 2018)

4.1 Orientation sensitivity of hardness testing around the core

To better understand the sensitivity of Leeb hardness test readings on dry rock core, circumferential test results were collected on sample rock and compared to readings taken singularly along the orientation line. Circumferential measurements were collected at 10-cm intervals along the sample core. At each testing location, three readings were taken at 90° intervals, as illustrated in Figure 4, and their average was computed. Longitudinal measurements were obtained along the singular orientation line, with three readings recorded at each 10-cm interval.

Both circumferential and orientation (ori) line readings were taken on the same section of the core and shared the same testing locations. Results indicate relatively parallel Leeb hardness average readings for both testing methods. However, the circumferential testing method produced results with reduced SD compared to the testing along the orientation line method. Although there is a slightly higher variance in results for the orientation line method, it is preferred over circumferential testing as it offers practicality with faster testing technique for roughly the same results. As such, a longitudinal technique was adopted when performing subsequent testing within the study.

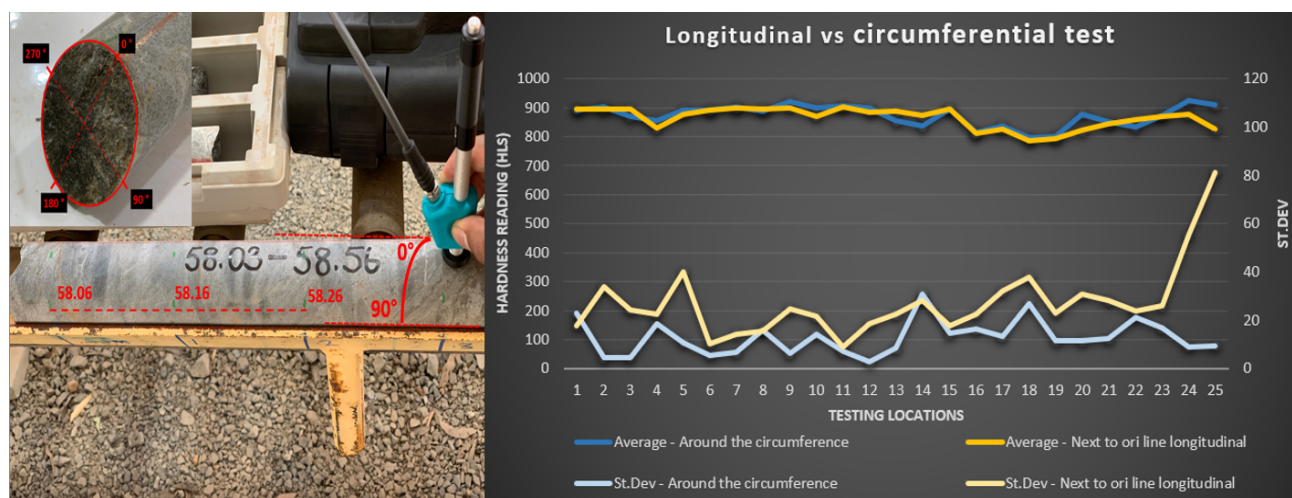


Figure 4 Illustration of the data collection points, and comparison between circumference and longitudinal testing

4.2 Orientation sensitivity of the testing probe at an incline at 5°, 10° and 15°

Due to the manual aspect of the testing technique, it is possible that different users apply variations during testing. One such variation is related to potential inclination of the probe. To better understand the influence of probe inclination and to help develop a robust field-testing methodology, testing was undertaken at probe inclinations of 5°, 10° and 15° from perpendicular. Results were compared to standard perpendicular inclination tests performed at similar locations along the rock core. For uniformity and consistency, all core samples were washed, air dried and assessed on steel v-notched racks, and any dust or debris was wiped away using a cloth prior to testing. Figure 5 shows the Equotip probe at a 5° incline from perpendicular and presents test results attained.

During the testing, it was proven that any core inclination of more than 10° resulted in a 'bad measure' on the Equotip reader and no data was collected. As such, results were only obtained for 5° inclinations. As can be seen from the graph in Figure 5, the average of testing at 0° angle, given gold, resulted in less erratic results between test locations, whereas at a 5° angle, results were slightly more erratic at the later test locations. A slight deviation can be expected in the HLS (rebound hardness unit) readings due to the non-homogenous nature of rock. At around testing location 18 there was a large outlier in the data which affected the SD (light yellow) and consequently the average HLS reading. Considering the available results, and in order to obtain the most consistent and accurate results, it is recommended to position the probe perpendicular to the core during testing.

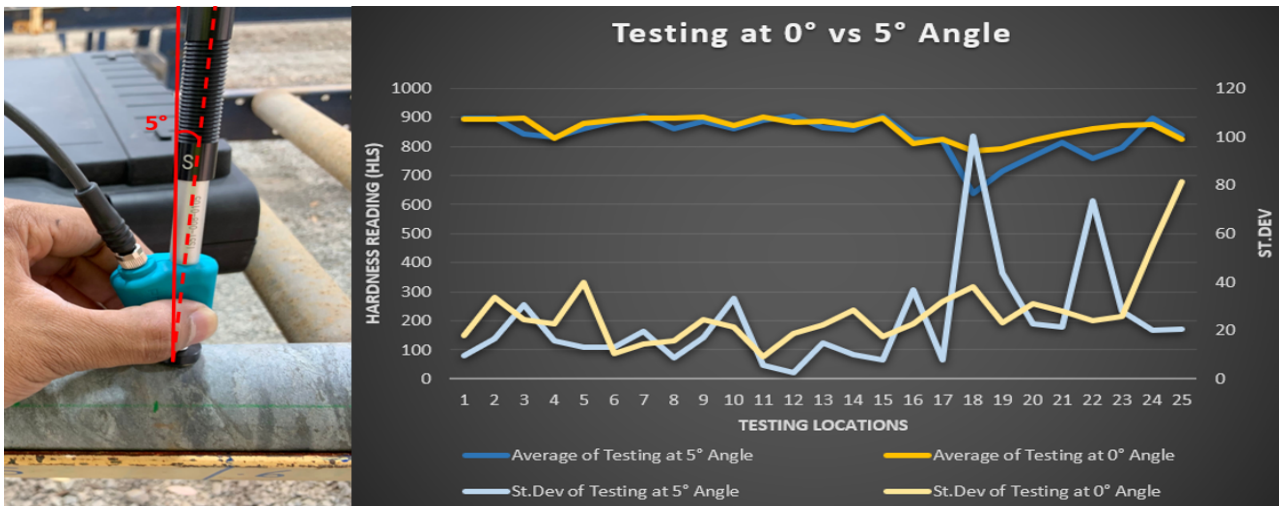


Figure 5 Effect of inclination of the probe during core testing, with the reference data

4.3 Reading sensitivity to external incline probe pressures

During this test, the probe was manually forced down onto the specimen to induce pressure and to analyse the differentiation it has on the HSL readings received from the Equotip 550 reader. Figure 6 shows the analysis between the normal and the applied pressure testing that showed a lower SD for the applied pressure, which suggests more consistent data. This could be due to the applied pressure permitting a better connection at the contact point between the probe and the specimen; thus more consistent data, with only two testing locations (6 and 8) where the SD for applied pressure was higher than for normal testing. It is worth noting that the averages for both datasets are almost parallel and concise with each other. By simply analysing the data it can be concluded that use of the Leeb hardness tester with applied pressure would result in improved data accuracy.

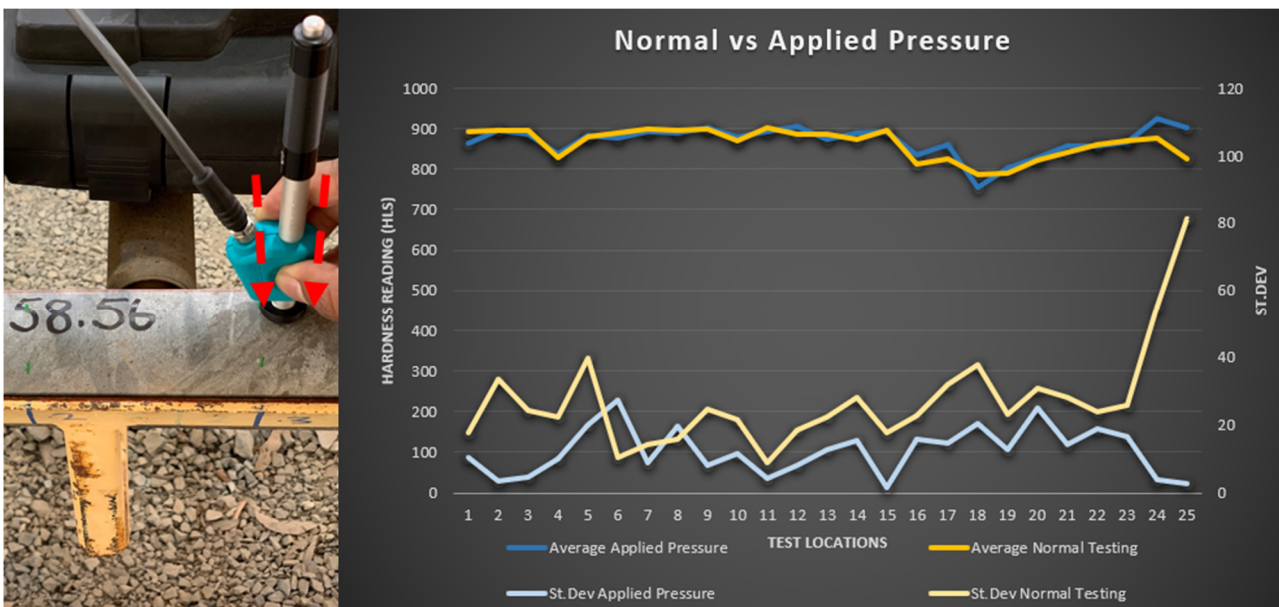


Figure 6 Effects of applied pressure while using the Leeb hardness tester, with the reference data

But a major drawback of the applied pressure method would be the difficulty in quantifying the level of applied pressure as it would vary from person to person. Although the data obtained by pressing down onto the probe is more concise with the reference data collected earlier, pressing the probe down without a quantifiable amount of force makes the test quite impractical and dependent upon the user, which ultimately makes this test subjective and similar to Schmidt’s hammer test conducted by Akbay & Ekincioglu (2022) and

Kovler et al. (2018). Therefore it is best to avoid additional pressure applied down with the testing probe into the core, as normal testing would give similar average HLS values.

4.4 Readings taken from wet core

In this scenario the core samples were sprayed with water until they achieved a wet surface and HSL readings were then taken. This was conducted to imitate groundwater conditions and to analyse whether the wet surface influences the data attained by comparing it with the referenced dry surface using the Equotip 550 Leeb hardness testing device.

The results, shown in Figure 7, illustrate a lower hardness reading (HLS) on average for most testing locations along the core samples, especially with the readings taken at the 18th location, which had the greatest differentiation by an almost 280 HLS difference between the dry and wet surfaces. This could be due to the presence of water on the surface which acts as a slight dampener that creates a lubricating effect, reducing the resistance to indentation and affecting the rebound or indentation depth measurements; ultimately resulting in a lower hardness level which is apparent by the consistently lower HLS average for wet surface versus dry surface (Li & Bradt 1992). Furthermore, analysing the standard deviation of the data illustrates the irregular behaviour of the readings attained when the sample surface was wet, especially for testing locations 14 to 22, which would suggest a higher inaccuracy. Therefore, it is suggested that to achieve an accurate and a correct hardness reading, users must ensure that the surface of the core is dry before taking the hardness reading using the Leeb hardness tester.

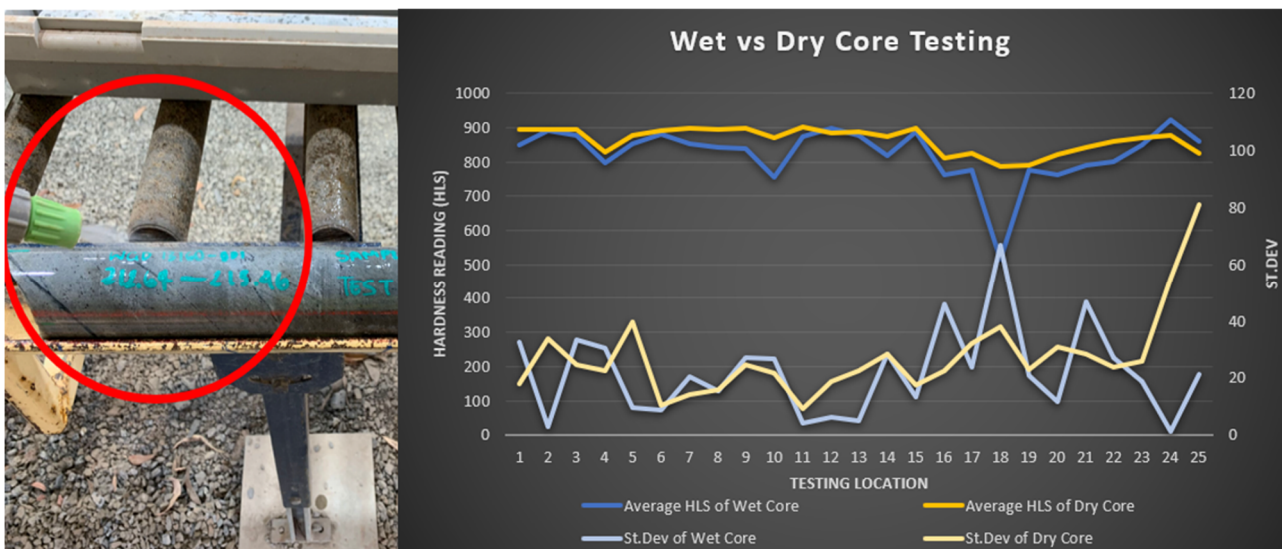


Figure 7 Effects of wetting the surface of the core, with reference to the dry core data

4.5 Saturated readings

In this variation of testing the samples were submerged in water for 24 hours to imitate the concept of rock structures which are naturally below the groundwater table and the effects this has on their HLS values. The number of samples and location of tests conducted were restricted by the size of the water bucket that held the specimens. As such, due to the limited depth of the bucket, only three samples were tested, with four downhole test locations per specimen. Weight of the specimen was taken before and after the 24-hour soak period to calculate water content absorbed by the core samples. On average, all three samples had a weight differential of 1 g, which was considered to be largely associated with water coating the surface of the core. The dolerite and andesite are considered to have limited porosity. The samples were then subjected to the Leeb hardness testing. The results attained from the soaked core samples are presented in Figure 8. From testing locations 1 to 5 the dry core samples had a higher average HLS, but from 6 to 12 the soaked core samples showed a harder surface on average. The lower SD for the soaked core from 6 to 12 would suggest that the core had a higher accuracy of data. However, at the same time, the test locations from 1 to 5 had

lower average HLS for soaked cores and higher SD, meaning a higher variance in data. Due to this bipolar relationship produced by the soaked cores it would be advisable to simply dry the rock core before conducting Leeb testing as otherwise it could introduce variation in the results.

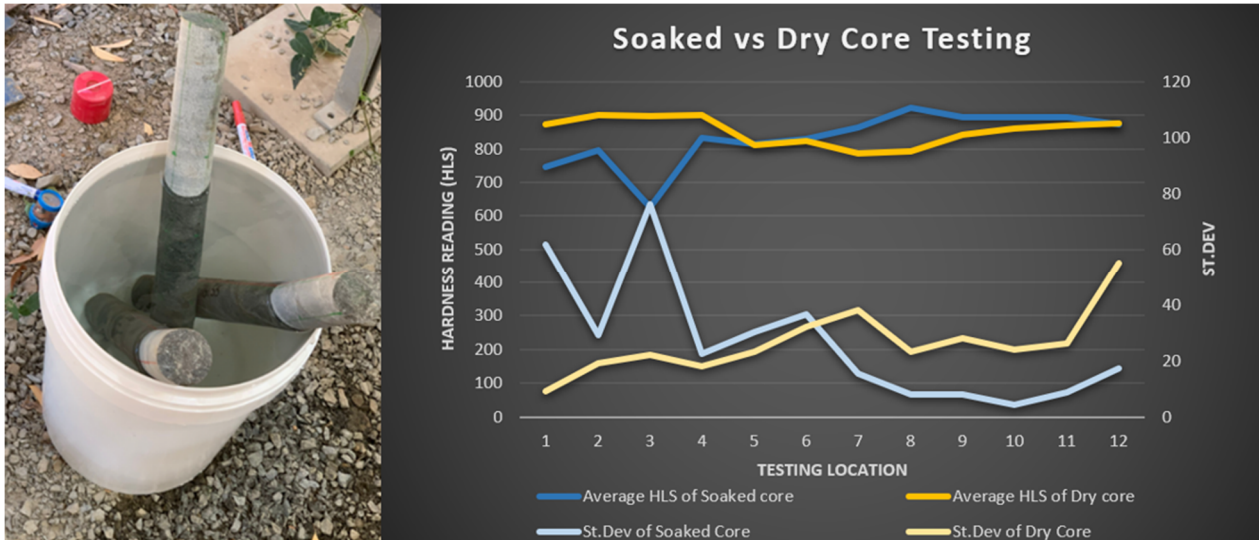


Figure 8 Effects of soaking the cores for 24 hours, with the dry reference data

4.6 Readings taken at various testing locations and at various repeats per location

This style of testing looked at two separate ways of conducting the test around the metre mark to evaluate the variability of the results. The two types of testing included evaluating the around the metre mark with the Leeb probe five times. The first type of testing required striking the metre mark five times to attain the HLS values. Comparatively, the second Leeb test was repeated for the same metre mark but the five trials were stretched across 5 cm over the metre mark as shown in the image attached to Figure 9. This data would allow us to deduce the variability in the results from the Leeb hardness testing using Equotip 550 device.

Firstly, analysing the averages for both tests shown in Figure 9 demonstrate that they are roughly on par with each other, showing some degree of a parallel relationship with each other. Although the standard deviation for these tests shows a higher variance in data for the test 'spaced 1 centimetre apart', in contrast the test 'on the centre point' has a far lower standard deviation on average. In this scenario, the higher standard deviation for the test based on 'spaced 1 centimetre apart' is preferred because it gives a more comprehensive overview around the metre mark with on par average HLS value to 'on the centre point'.

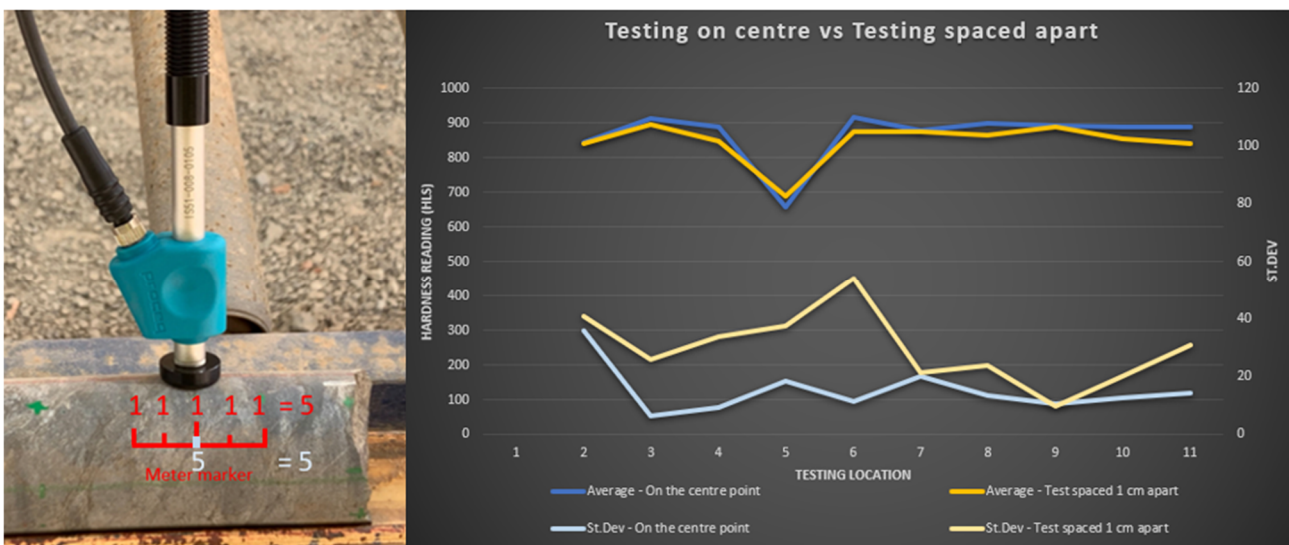


Figure 9 Shows the testing on the centre versus testing spaced apart

4.7 Final methodology

The finalised method to conduct Leeb hardness testing is to strike the probe at every metre mark 15 times (three trials at five locations, spaced 1 cm apart), adjacent to the orientation line on the rock core. Figure 9 (in red ink) illustrates the proposed method, but instead of one trial, three trials are conducted at each location for more accurate data. From the testing it was concluded that when conducting the Leeb test, users must avoid striking on a quartz vein as it results in an inaccurate hardness reading due to the strong properties of quartz. Similarly, users must avoid striking on the pencilled-in wax marks as it results in a lower hardness reading as the wax creates a dampening effect like the wet water surface, and produces false hardness readings. Furthermore, users should hold the probe perpendicular to the core, should not apply external pressure down onto the probe, and should make sure that the core is dry and alleviated from any moisture which could impact the results. These findings, which are all possible due to the multiple trials and investigations conducted, all lead to a proposed methodology: one which can accurately determine the structural properties of diamond drilled rock core on-field and provide an estimated UCS reading.

5 Results

5.1 Correlation between bulk density and rock's mechanical properties

Once the data was collected from all the samples using Leeb hardness testing, these samples were sent to a laboratory to determine their maximum UCS. To increase the accuracy of the data obtained, the Leeb hardness data was later filtered out for the section of the core where the UCS testing took place. Comparing these sets of data allowed for a correlation to be established.

Figures 10 and 11 represent the relationship between the UCS and the Leeb hardness results against the material property of rock core: the bulk density. While the UCS data represents the rock's ability to support loads and resist deformation, the Leeb hardness reading provides insights into the rock's material structure. Both mechanical properties are compared to the bulk density, which provides information about the porosity and compactness of the rock. Plotting these data would show the relationship of the rock with respect to its strength and density. A positive correlation would indicate that the denser rocks generally exhibit higher strength and hardness value, while a lower correlation would suggest the opposite. No correlation would suggest that the two parameters may be influenced by other factors and are not directly related.

From Figure 10 we can assess that most of the dolerite rock had a bulk density of more than 3 t/m^3 with only two outliers in the data and with relatively high UCS values of 300 MPa or above, which is due to its igneous and homogenous rock properties. For andesite, the majority of the data showed a bulk density of less than 3 t/m^3 , aside from two outliers, but it had a huge variance in its UCS data with a peak of 356.93 MPa and a low of just 63.91 MPa. These huge differences may be due to the vast number of variations and foliations associated within the non-homogenous rock properties of andesite rock type. Furthermore, the quartz sericite in general had a lower UCS and bulk density with respect to dolerite and andesite, with one outlier bulk density of above 3 t/m^3 , which is expected due to the variable non-homogenous nature of the rock.

In contrast, Figure 11's Leeb hardness testing and bulk density showed a similar relationship to that of the Figure 10 relationship discussed earlier between UCS and bulk density. But the Leeb hardness values were significantly higher than UCS, between 700 to 900 HLS from the Equotip reader. Both dolerite and andesite showed a similar pattern of results between the two diagrams. Sericite had 50% of its data suggesting higher HLS values, which could be due to multiple factors such as different rock property or incorrect measurements. More data on sericite could have led to a more accurate data, as this report only had four points of reference for sericite. The similarities in patterns between Figures 10 and 11 suggests that there is a correlation between UCS laboratory test results and the Leeb hardness test results attained using the Equotip 550 device.

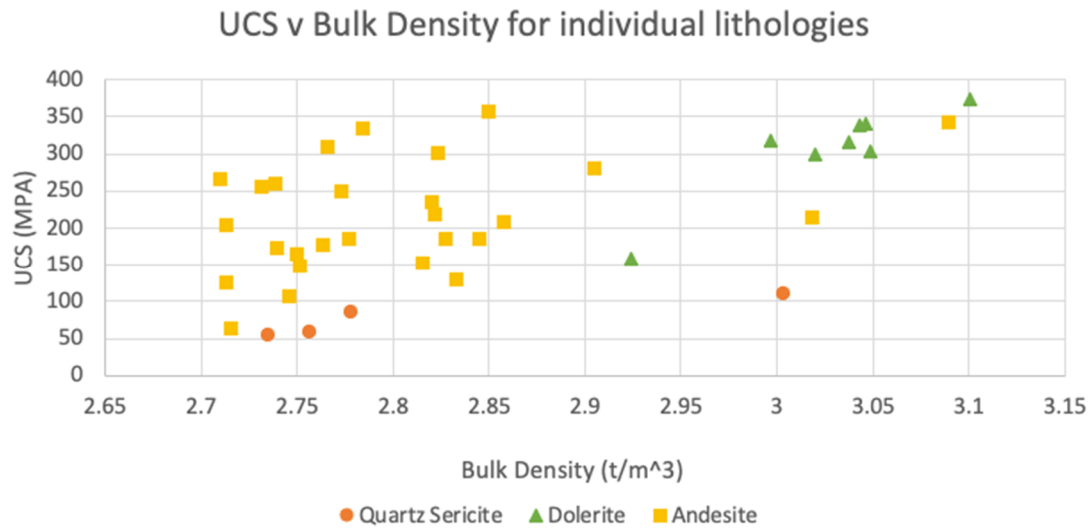


Figure 10 Graph illustrating the relationship between UCS and bulk density

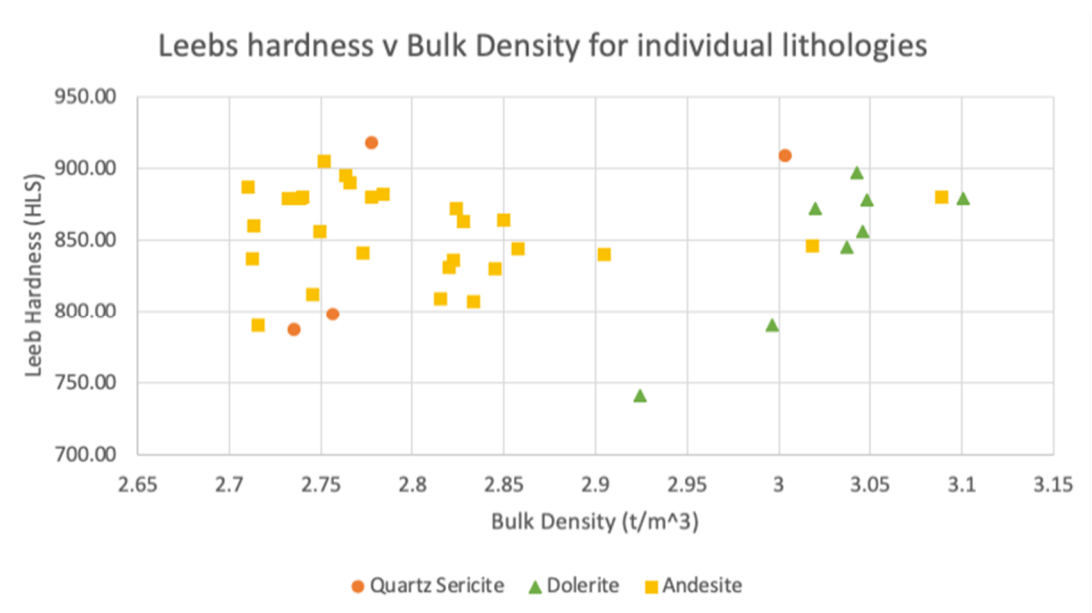


Figure 11 Graph illustrating the relationship between Leeb hardness testing and bulk density

5.2 Correlation between UCS and Leeb hardness testing

To establish this correlation, in Figure 12 the relationship between UCS laboratory data and the Leeb hardness data obtained using the Equotip 550 device was plotted for all lithologies of different rock types used in the samples. The scatter plot data shown in Figure 12 suggested a weak correlation of 0.1294 between the UCS data against the Leeb hardness data. It was discovered that combining and plotting various rock's lithologies on a singular graph resulted in reduced accuracy of the correlation coefficient.

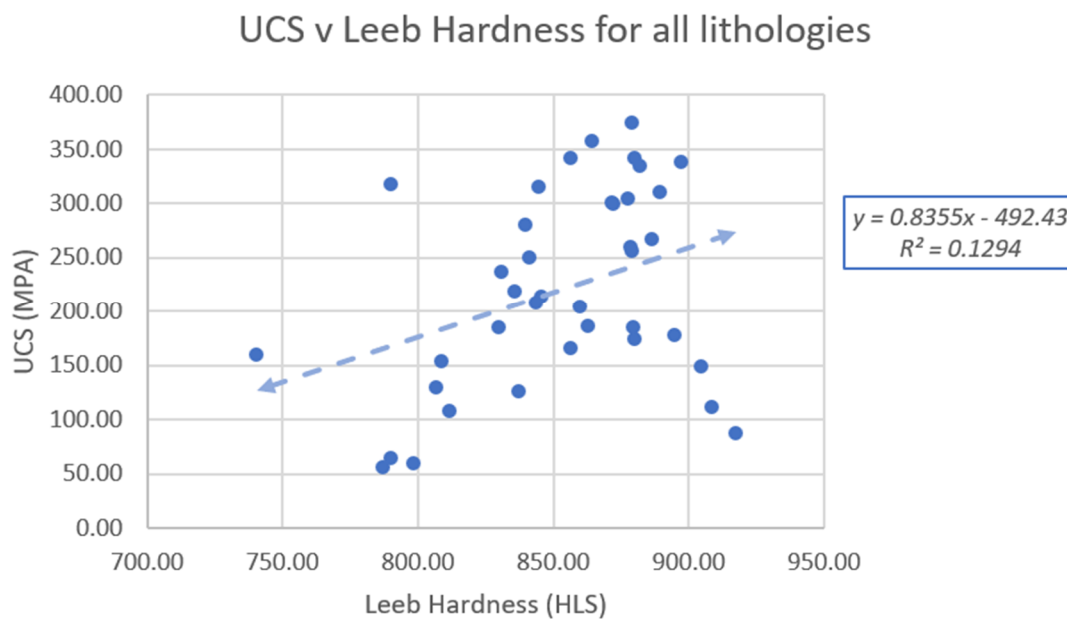


Figure 12 Relationship between UCS laboratory testing and Leeb hardness testing for all lithologies combined

By separating the data into individual lithologies, a better correlation was attained for each lithology of rock type, as shown in Figure 13. Andesite graphed a correlation of 0.2813, which can be considered as a weak correlation, but it is still higher than the combined average attained for all lithologies by 117%. Dolerite had a correlation factor of 0.6288 between its UCS testing and Leeb hardness value, showing a strong correlation and an increase by almost 0.5 coefficient factor with respect to all the lithologies. Quartz sericite had the most significant, and a very strong, correlation factor of 0.8127.

A reason for the low correlation coefficient for andesite could be due to its non-homogenous properties. During Leeb testing, caution was taken to avoid testing on the quartz veins and foliations present in andesite rock. However, local variations in the rock fabric led to invalid testings and variations in the data, hence the lower correlation coefficient. The homogenous nature of intrusive dolerite resulted in more consistent data, hence the better correlation coefficient than for andesite rock. Finally, quartz sericite had the highest correlation among the various rock types tested, which can be deduced down to the quartz content which offers a high resistance to deformation and can withstand significant compressive force that results in a higher UCS value and higher Leeb hardness readings. Also, quartz sericite offers homogeneity, like dolerite, and this uniformity in mineral composition can contribute to a consistent mechanical property leading to a strong correlation between UCS and Leeb hardness measurements.

By separating and plotting all the lithologies, the correlation factor for all different rock types increased significantly and gave a more accurate correlation dependent on the rock's mechanical and physical properties. Graphing the individual lithologies allows for higher confidence in the data attained from Leeb hardness testing. These correlation factors are used to calibrate the Leeb hardness testing device for the different rock types, giving site-specific correlation coefficients. These site-specific correlation coefficients facilitate more accurate data collection than the traditional field hammer index strength test and provide a field estimate UCS.

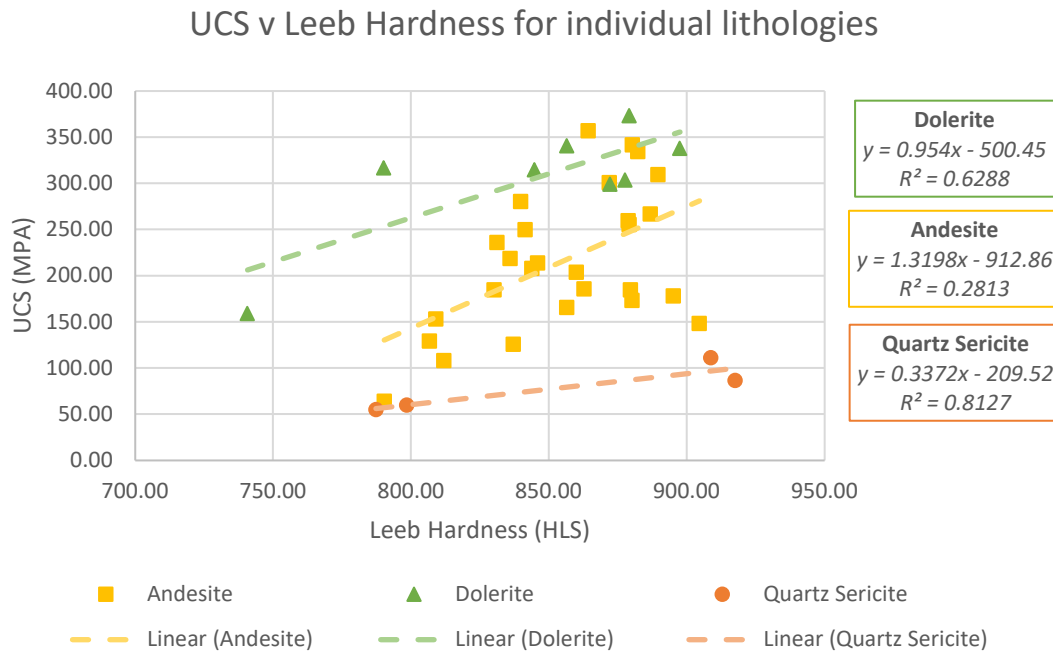


Figure 13 Relationship between UCS laboratory testing and Leeb hardness testing for separate lithologies

5.3 Leeb hardness testing on a tray against the v-notched frame

To further develop the study and the testing methodology it is vital to study the correlation and differentiation Leeb hardness testing has with testing of the core resting on various surfaces. Performing Leeb hardness testing on both a tray and the v-notch frame broadens the range of surfaces that can be assessed using the Equotip 550 hardness reading instrument. It allows for comparative analysis, validation and flexibility of hardness measurements across different orientations and surface configurations.

Figure 14 given below plots the relationship between the Leeb hardness values with respect to the downhole length of the core logs. The graph displays the average of 15 HLS values recorded per metre mark for both the tray (shown in dark blue) and the v-notch frame (shown in yellow). It also shows the correlated UCS data attained using the correlation coefficient from Figure 13 for the respective lithology down the length of the drilled core. Visually the data attained shows quite volatile behaviour, with rapid changes per metre down the hole, which could suggest ambiguity in the data collected. But since both sets of data display similar volatile behaviour, this confirms the reliability of the data collected. As the line-graphs for ‘HLS tray average’ and ‘HLS v-shaped average’ are almost succent and parallel with each other, attributing a correlation between the two sets of data points.

Furthermore, the solid line at the 500 HLS mark indicates the lithology of the rock downhole, and the majority of this hole is andesite with few metres of dolerite at the bottom of the core’s end. Analysing the graph, the UCS values in the region of dolerite display the highest strength reading of above 300 MPa, with a peak of 356 MPa. For the andesite region it is consistently below the 300 MPa mark. This relationship correlates with the mechanical properties of these rocks as dolerite has proven to be stronger than andesite. Figure 13 confirms this relationship as it can be seen from the sample tested in the laboratory, that almost all the dolerite had a UCS value of above 300 MPa. This relationship and the correlation coefficient factors achieved from the Leeb hardness testing ultimately give an estimated UCS and prove that Leeb hardness testing can be used as field-based practice to estimate a rock’s UCS value.

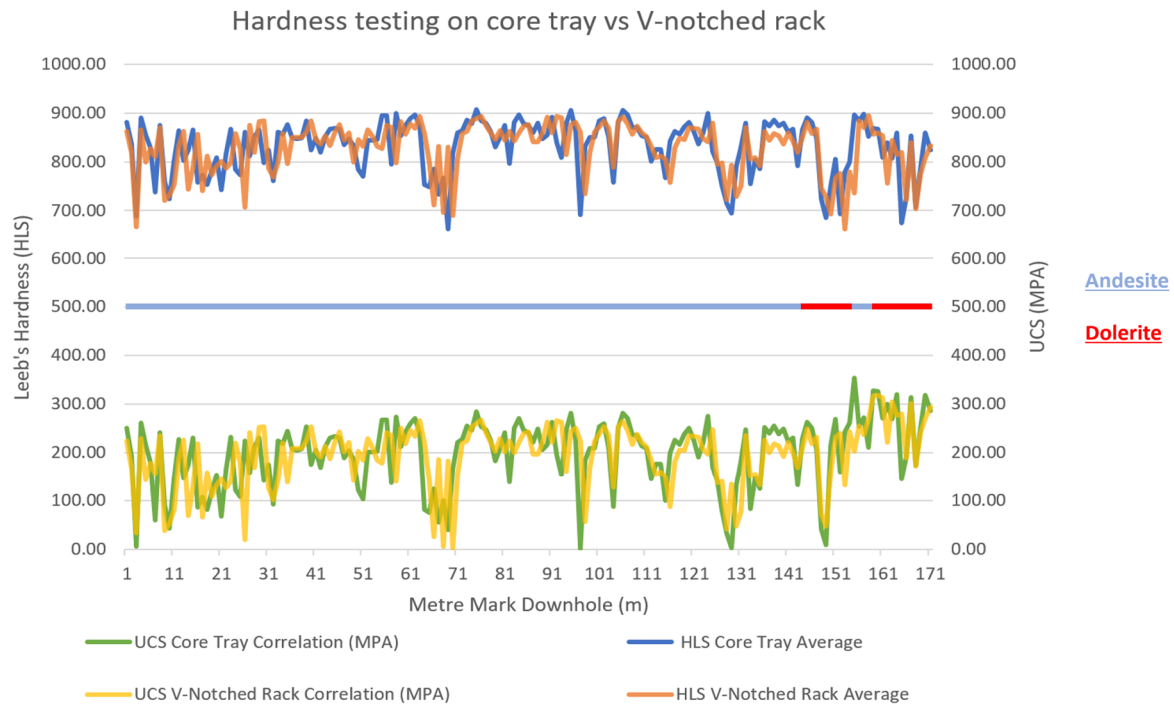


Figure 14 Relationship between Leeb hardness testing on a tray against v-notched racks

6 Conclusion

This study aimed to investigate the use of non-destructive Leeb hardness testing as an alternative to conventional field-testing techniques to evaluate rock strength such as using a geological hammer or a point load testing device. While conventional methods can be subjective and potentially dangerous due to rock fragment ejecta, Leeb hardness testing offers a safer approach with improved reliability, ease of use, higher resolution of data collection and better standardisation of results. By performing Leeb hardness testing on rock core samples that were later sent for UCS testing, correlation factors were successfully derived for various lithologies encountered during drilling. The correlation factors were then applied to Leeb hardness test results collected along the entire length of drillcore at metre mark intervals. The authors believe the methodology of collecting hardness test data, determining correlation factors and rendering data into UCS-equivalent values presents a practical and safe approach to collecting non-destructive field test data during logging of diamond drill rock core. The authors encourage interested parties to use and adapt the methodologies put forward, and improve on learnings, including within different geological settings and lithologies.

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