Intact Strength Determination of Rock Containing Mesodefects using the Leeb Hardness Test

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ABSTRACT: The strength of rock blocks containing structural flaws and defects, such as veins and healed fractures (mesodefects) is particularly important for sparsely jointed rock masses under high stress. The conventional UCS test is often unsuitable for providing an accurate measure of the intact strength for rock containing mesodefect and it is difficult to conduct tests on suitably large specimens to account for mesodefects. The Leeb Hardness (LH) test is proposed to provide a quantifiable estimate of intact strength for mesodefected rock. The LH test is a lightweight, compact rebound test that has been correlated to rock strength with a large database (~400 test records) of various rock types over a wide strength and hardness range. The effects of conducting LH tests in the proximity of mesodefects has been examined and the LH test has been used in this study to estimate the true intact rock strength of defected rock cores.

Keywords: Leeb Hardness test, defects, intact rock strength, DFN.

1 INTRODUCTION

For over 20 years, practitioners have recognized that estimates of rock mass strength should account for flaws and defects within the intact block portion of the rock mass. As noted by Hoek and Brown (2019) in their discussion of intact rock strength estimation for the Hoek-Brown rock mass shear strength criterion: "…in many rock masses, defects such as veins, micro-fractures and weathered or altered components can reduce the intact rock strength in unconfined compressive strength (UCS) tests. This is particularly important to address for sparsely jointed rock masses containing defects under high stress. Ideally, tests should be carried out on specimens large enough to include representative sections containing these defects…". Because the collection and testing of large samples is often impractical, other methods have been developed to account for the effects of defects in rock mass classification and rock mass strength estimates:

- The Modified Rock Mass Rating (MRMR) system (Jakubec & Laubscher, 2000; D. H. Laubscher, 1990; D. Laubscher & Jakubec, 2001) accounts for these defects in applications for underground mine design and block caving fragmentation.

- Martin et al. (2012) used the SRM method (Mas Ivars et al., 2011) with the software code *PFC2D* to evaluate the scale effect implications of defects on rock block strength. This study revealed a tendency for an asymptotic lower limit of 80% of the standard laboratory unconfined compressive strength (σ_c) with increasing specimen size.
- Stavrou & Murphy (2018) also conducted a numerical modelling-based study of microdefects and macrodefects related to specimen scale. They used *UDEC* Voronoi tessellated micromechanical modelling methods to simulate unconfined compressive strength (UCS), triaxial and Brazilian tests on various specimens. The simulation results were used to develop a modified classification system based on the GSI called the micro GSI (μGSI). Day et al. (2019) have modified the geological strength index (GSI) to account for defects. Their method utilizes a harmonic weighted calculation to account for both interblock defects and intrablock defects to determine a Composite GSI (CGSI). The CGSI is then used to estimate rock mass strength via the Hoek-Brown rock mass strength criterion.

A summary of various scales of rock defects is provided in Table 1 and core samples containing these flaws and defects are shown in Figure 1.

Table 1. Proposed micro, meso, and macro defect definitions.

Defect scale	Description	References
Micro	At or between mineral grains or crystals of the intact rock. May be visible at drill core scale as closed/healed foliation, schistosity, cleavage, bedding.	Jakubec,2013; Stavrou et al., 2019
Meso	Healed, closed, or incipient weaknesses in the intact rock visible at drill core scale. Occur within intact blocks of the rock mass. Veins, non-throughgoing fractures.	Jakubec, 2013;
Macro	Open discontinuities separating individual blocks of the rock mass. Observable at core, outcrop, and excavation scales. Open or cemented block forming discontinuities; joints; open joints parallel to bedding or foliation, etc.; faults.	Jakubec, 2013;

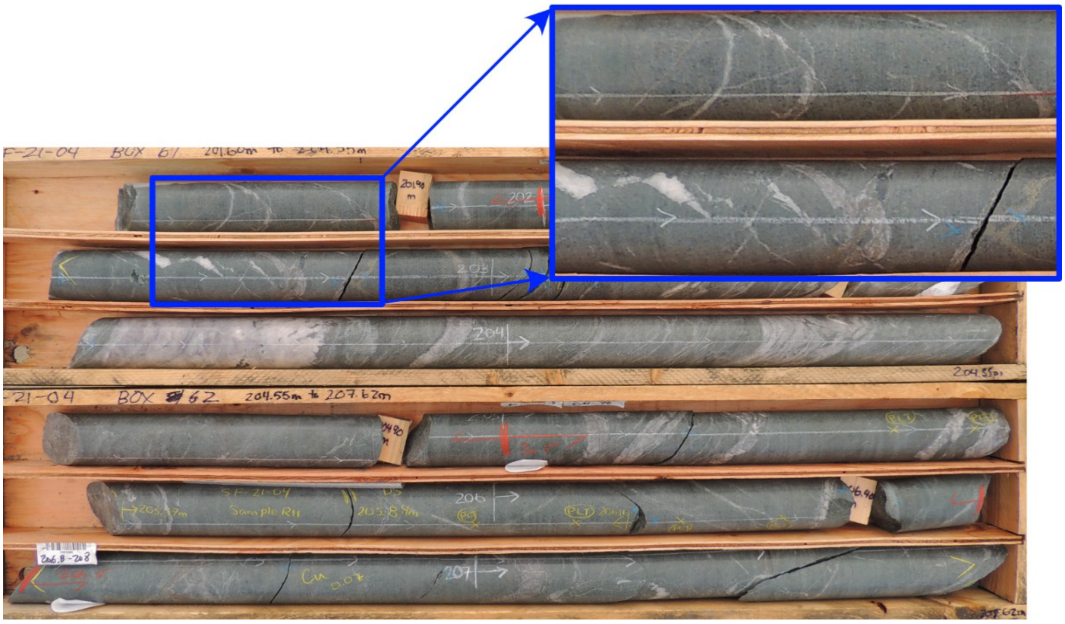


Figure 1. Core containing open and closed intrablock, structural mesodefects can be easily seen at the core scale. Microdefects and flaws are also typically present, but are not typically visible at the core scale.

These methods provide alternative means to estimate rock mass strength based on characterization of the defects. However, each of these methods require an accurate estimate of the intact rock strength without the impact of defects to avoid accounting for these defects twice: 1. in the reduced intact strength, and again 2. as defects contained within rock blocks. Where defects are widely present, the standard UCS test conducted on core specimens does not reflect the true strength of the intact component when failure is structurally controlled involving defects. In some instances, careful selection of specimens that do not include defects can be done; however, this introduces another issue of biased, unrepresentative test specimen selection.

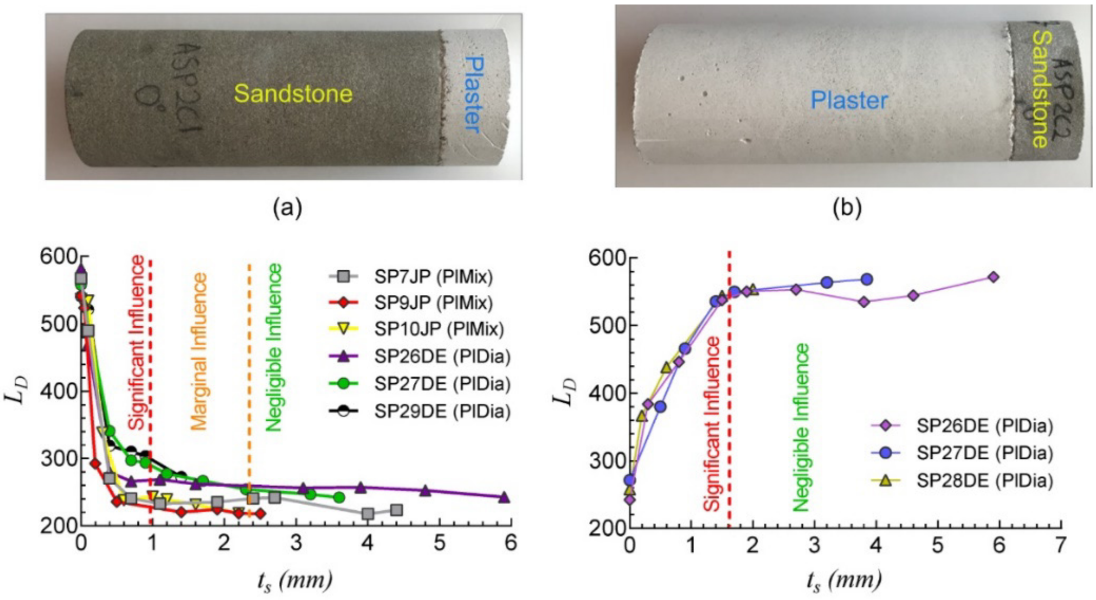
The definition of rock defects, from the smallest microcracks through to large-scale faults and all intermediate scales, is not currently clearly defined in rock engineering. Hencher (2014) discussed this issue and proposed a classification based on both scale and defect tensile strength relative to the intact rock strength. For the purposes of this paper, the definitions in Table 1 will be utilized.

The focus of this study is determining the intact σ_c for rock blocks containing mesodefects, as described in the Table 1, using the Leeb Hardness test (LH). The LH device is a lightweight, compact, non-destructive rebound tester that has been correlated to rock strength with a large database (~400 test records) of various rock types over a wide hardness range. The LH test is proposed to provide a quantifiable estimate of intact rock strength that is insensitive to the presence of mesodefects in rock.

2 LEEB HARDNESS TEST TO ESTIMATE INTACT ROCK STRENGTH

To evaluate the suitability of the LH test for estimating the intact rock strength of rock containing mesodefects, an assessment was made on the effect of seams of differing hardness on the intact components. An *Influence Zone* has been recognized by (Hack et al., 1993; Jeans, 2021) where the LH test reading (termed L_D) is influenced by the nearby material. A laboratory program was conducted by Jeans (2021) to evaluate the thickness of the Influence Zone (t_{iz}) for weathered and altered joint surfaces. The findings of the study can be applied to the case of rock specimens containing mesodefects for cases where rock blocks or core pieces contain relatively well constrained (narrow) mesodefects comprised of closed, cemented curvilinear structures. In other words, defects that are relatively contained as separate materials from the surrounding intact rock similar to the artificial composite specimens. Conditions where intact rock is highly variable due to weathering or alteration, would not be suitable candidates for the method.

The study utilized the preparation of composite specimens containing two materials of known hardness. Wallace sandstone (hard material) from Nova Scotia, Canada, and a plaster mix (soft material). The materials were cast together forming single, strongly adhered composite specimens, as shown in Figure 2. The LH test tests were conducted on the surface materials (referred to as the Secondary) with a contrasting underlying material (referred to as the Primary). Two composite specimen configurations were prepared: SS (Secondary Softer) and SH (Secondary Harder). Full details regarding the materials and methods can be found in: (Jeans, 2021). To determine t_{iz}, the Secondary component of the specimens were sequentially and carefully ground down in 1 to 2 mm increments with LH tests conducted on each subsequent new surface. Profiles of L_D and Secondary thicknesses (t_s) are shown in Figure 3 for several plaster mixtures. The results for SS and SH are similar with respect to t_{iz}. Based on the findings of the study it is concluded that the thickness of t_{iz} is between 1 and 2 mm. A value of $t_{iz} = 2$ mm is suggested by the results.

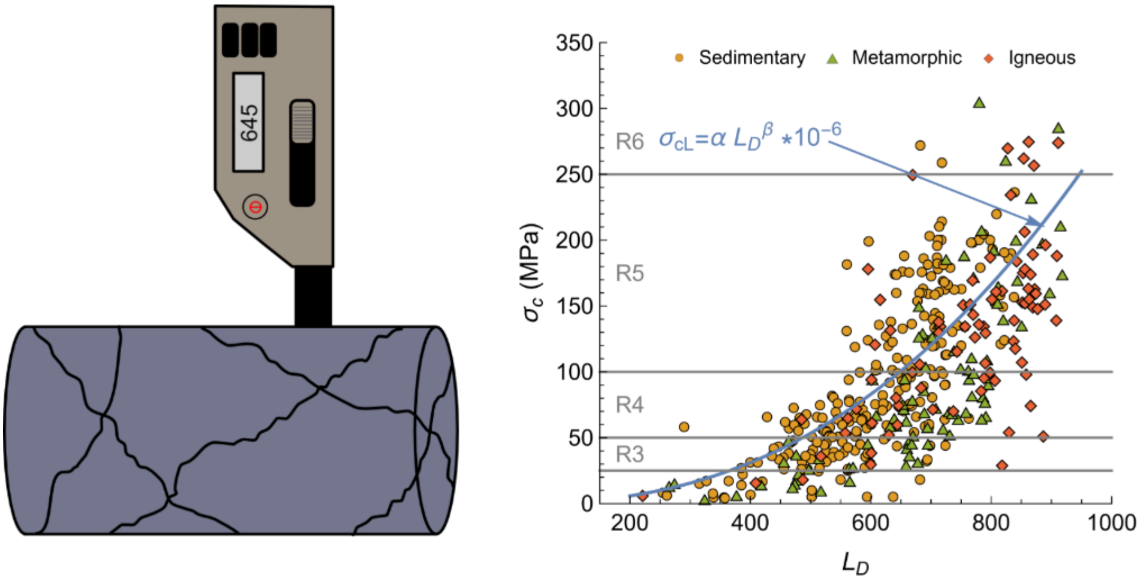


(a) (b)

(c) (d)

Figure 2. Examples of artificial composite specimens comprised of plaster mix and Wallace sandstone cast together in a mould with a strongly adhered interface. In these examples the larger component is the Primary material and the LH test was performed on the top surface of the Secondary. (a)(c) are SS, (b)(d) are SH.

Based on a study of rock specimen size effects and LH test readings in Wallace Sandstone, Corkum et al. (2018) determined that specimens with volume greater than 90 cm^3 show no indication of size effects on L_D. The composite specimen study indicates that tests done a distance greater than 2 mm from a zone of differing hardness, do not have a substantial impact on L_D. Therefore, it seems likely that for specimens containing fully closed (e.g., cemented) defects of variable hardness, where tests are done on specimens with volume greater than 90 cm^3 and at a distance greater than 2 mm from any defects, the LH test value of L_D should provide a valid representation of the intact rock hardness. An example is shown in Figure 3a.



(a) (b)

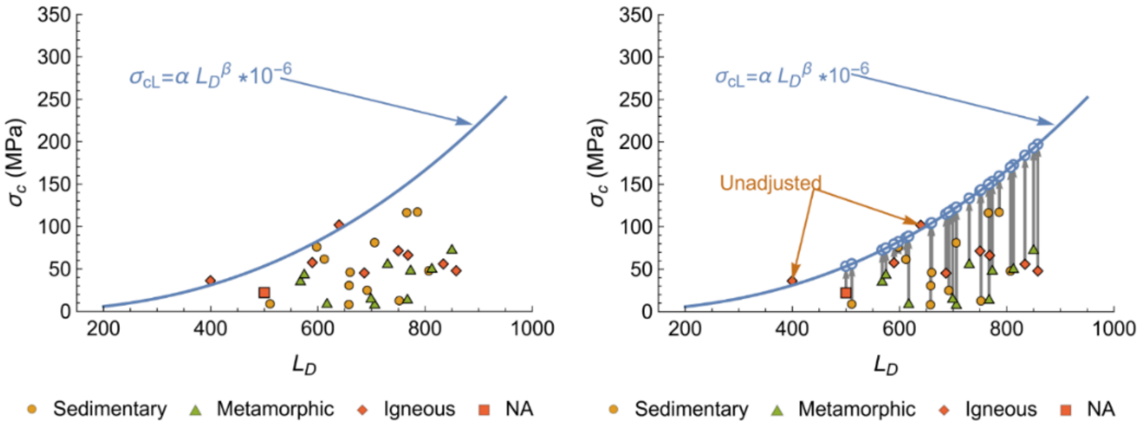
Figure 3. (a) Use of the LH test on an intact block within a mesodefected core specimen at suitable distance from mesodefect traces. (b) Database of L_D and σ_c values from Séguin et al. (2022) along with the regression curve for *All Rock Types* from Corkum et al. (2018).

A dataset of specimens with both UCS and LH tests conducted has been collected by the authors. The most recent dataset update has been published by Séguin et al. (2022) and includes 412 valid data entries. The dataset includes a wide range of rock types, hardness and strength values. The dataset is shown in Figure 3b along with the regression curve for *All Rock Types* from (Corkum et al. 2018). Further discussion of the dataset and regression is provided in the original publication. Note that the regression curve has not been updated to reflect the most recent dataset.

3 TRUE INTACT ROCK STRENGTH ESTIMATED FROM LEEB HARDNESS

In addition to the 412 valid records of UCS and LH tests, an additional 31 records were considered *invalid* due to structural failure; where the UCS test resulted in failure influenced by a structural defect (mesodefect) within the specimen. The data for these 31 specimens containing mesodefects are shown in Figure 4a along with the *All Rock Type* regression curve. These invalid UCS breaks may not all fit the geological descriptions of mesodefected rock; however, the failure influenced by structural features makes them a good direct analogy of rock containing mesodefects.

The regression curve predicts the mean σ_c value for each corresponding value of L_D based on the underlying dataset. All but two of the data points fall below the curve, which is unlikely if this were simply a random set of test results. Given the scatter in the full dataset of valid breaks about the regression curve in Figure 4b, the magnitude by which any single measured value of σ_c may have been reduced by the mesodefects' influence cannot be determined. However, if the regression curve can be considered the predicted mean σ_c without defects, then this predicted σ_c value on the regression curve is likely a better estimate of the actual intact rock strength than is the UCS test value itself (σ_c), which is influenced by failure involving the structural mesodefect. In Figure 4b, the arrows pointing from the test data to the corresponding circles on the regression line illustrate this proposed correction approach.



(a) (b)

Figure 4. (a) Data points for observed invalid failure (structurally influenced) tests. (b) A proposed correction for σ_c based on the regression curve (Corkum et al., 2018).

This approach can be applied to UCS test specimens to provide an estimate of the true σ_c. As demonstrated by the scatter in the correlation data, it will provide only an estimate of σ_c and not an accurate value. However, based on the data in Figure 4, the estimate obtained in this way will be a significant improvement over the values obtained from the invalid UCS tests.

4 CONCLUSION

Estimating the strength of rock containing mesodefects is needed as failure of sparsely jointed rock masses under high stresses in deep mining environments is becoming increasingly important. The LH test has been proposed as a suitable method to provide an accurate estimate of intact rock strength in cases where suitably representative specimens are scarce or unavailable. Findings from a recent study on the effect of contrasting hardness materials on the LH test on rock surfaces can be applied to the case of rock containing mesodefects. The findings indicate that LH test conducted a distance greater than 2 mm from a well-constrained, closed mesodefect/infilling on a specimen with overall volume > 90 cm^3 can provide a valid result. The correlation between L_D and σ_c can be used to provide an improved estimate of the intact σ_c compared to the UCS test itself when invalid structural failures occur on mesodefects. This approach could be used to support other evaluation methods such as micromechanical modelling to determine rock block strength and mining fragmentation evaluation.

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