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Correlation between Uniaxial Compression Strength and Point Load Index for Irish Caledonian granites

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ABSTRACT: While the Uniaxial Compression Strength (UCS) test is the gold standard for determining the UCS of rock for geotechnical and mining applications, empirical correlations between UCS and other test measurements are useful in situations where intact cores are difficult to retrieve and/or the scope of UCS testing is constrained by budget. UCS is most commonly correlated with the cheaper and more accessible Point Load Index (PLI) measurement. In ASTM D5731-16 (2016), it is recommended that site-specific correlations are developed between UCS and $I_{s(50)}$, the point load index adjusted to a specimen diameter of 50 mm, as a means of estimating UCS indirectly. However, in the absence of site-specific data, a UCS/$I_{s(50)}$ ratio in the range 18 to 24.5 (dependent on core diameter) may be used. In this paper, the relationship between UCS and $I_{s(50)}$ is explored for Caledonian granites from three regions in Ireland. The effects of variables such as the direction of point load application (diametral versus axial), UCS core diameter and aspect ratio and Rock Quality Designation are also considered. These data supplement the very limited information on UCS-PLI relationships published for granite internationally, while complementing a similar study recently conducted for Calp Limestone in the greater Dublin area.

KEY WORDS: geotechnical engineering, granite, mining, Point Load Index (PLI), rock, Uniaxial Compression Strength (UCS).

1 INTRODUCTION

The design of geotechnical and mining infrastructure such as building and bridge foundations, excavations, shafts and tunnels in rock are heavily dependent on reliable values of the rock's Uniaxial Compression Strength (UCS). While direct UCS measurements are preferable, difficulties in retrieving intact rock cores and budget limitations often compel engineers to resort to empirical correlations between UCS and other rock test parameters, which are simpler to perform and less expensive. It has been shown that UCS is most successfully correlated with $I_{s(50)}$, the Point Load Index (PLI) test result corrected to a specimen diameter of 50 mm [1,2]. ASTM D5731-16 [3] advises that UCS predictions should be based on site-specific UCS/$I_{s(50)}$ correlations, in the absence of which 'generalised' UCS/$I_{s(50)}$ values may be used; these vary in the range 18 (for a core diameter 21.5 mm) to 24.5 (core diameter 60 mm). In practice, UCS/$I_{s(50)}$=24, originally proposed by Broch and Franklin [4], is in widespread use. Neither of these empiricisms advocate any dependence on rock type.

The ASTM D5731-16 [3] preference for site-specific correlations is justified by the wide UCS/$I_{s(50)}$ variations observed in the literature; UCS/$I_{s(50)}$=3.1 for Arabian-Persian Gulf calcarenites [5] and UCS/$I_{s(50)}$=31 for Calp Limestone in Dublin, Ireland [6], for example. Moreover, some of the linear correlations proposed in the literature have a UCS intercept (i.e. a non-zero UCS corresponding to $I_{s(50)}$=0), and others are non-linear. In addition, many are based on scant data and/or scatterplots offering poor statistical reliability, and most studies do not explore factors on which UCS/$I_{s(50)}$ may depend.

The aforementioned Casey and Fleming [6] paper provided the first UCS-PLI study for an Irish rock formation (Calp limestone), relevant to construction in the greater Dublin area of Ireland. UCS-$I_{s(50)}$ relationships for Irish Caledonian granites are explored in this paper; granite is also commonly encountered in the vicinity of Dublin and at other locations in Ireland. The effects of variables such as the direction of point load application (i.e. axial versus diametral), UCS core diameter and aspect ratio and Rock Quality Designation are also considered. These data supplement the relatively limited information on UCS-PLI relationships published for granite internationally, which is summarised in Section 2 as context.

2 REVIEW OF UCS-PLI CORRELATIONS IN GRANITE

A literature review of UCS-PLI relationships for granitoid rocks has yielded the following findings, ordered by year:

- A best fit of UCS/$I_{s(50)}$ = 12.5 (coefficient of regression R = 0.73) was reported by Chau and Wong [7] for Hong Kong granite and tuff, with weathering grades from fresh to moderately decomposed (n=21). The PLI tests were performed in the axial direction.
- Kahraman and Gunaydin [8] presented the following correlation for Turkish igneous rocks: UCS = 8.2$I_{s(50)}$+ 36.43 (R^2 = 0.68), covering a range of UCS values from 50 MPa to 200 MPa approx. However, only eight of the 17 points in the correlation pertain to granite. The PLI tests were diametral.
- Based on data (n = 19) from Malanjkhand, India, Mishra and Basu [9] proposed the following relationship for granite: UCS = 10.9$I_{s(50)}$+ 49.3 (R^2 = 0.8). UCS values typically fell in the range 100-200 MPa; the direction of PLI tests was axial.
- Tandon and Gupta [10] proposed the following expression for Himalayan granitoid rocks (n=9): UCS = 5.602I_s+ 4.38 (R^2 = 0.94), although it is unclear whether

the I_s value is $I_{s(50)}$. The UCS values range to 100 MPa approx., with the PLI tests conducted on irregular lumps.

- Armaghani et al. [11] conducted UCS and PLI tests on granite (n = 71) from the PSRWT tunnel site in Malaysia, yielding the following power relationship: UCS = $49.337I_{s(50)}^{0.713}$ ($R^2 = 0.711$), representing UCS values up to 200 MPa. The PLI test version was not specified.
- Yin *et al.* [12] conducted 53 diametral, 54 axial and 547 irregular lump PLI tests on Hong Kong granite. A size correction factor was proposed for the irregular lumps. A correlation of UCS/$I_{s(50)}$ ≈22 (R^2 in the range 0.73-0.82) was proposed, essentially independent of whether the PLI tests were diametral, axial or on irregular lumps.

Other authors have incorporated granitoid rocks in their databases, but ultimately the correlations are based on multiple rock categories/types, which is not particularly helpful.

The correlations presented above, which almost exclusively relate to Asia, vary very widely, and although R or R^2 values are reasonable, the datasets are extremely small for the most part. The correlations with a UCS intercept may be difficult to justify if they are to be applied to weak rocks. The UCS range represented is limited in some cases, and important details of the UCS and PLI testing regimes are often missing. Some of these shortcomings are addressed for the study in this paper.

3 IRISH GRANITES

3.1 General

The distribution of granitic rocks on the island of Ireland is shown in Figure 1, after Chew and Stillman [13]. The granites can be divided into two main subgroups: Caledonian granites (Galway, Ox Mountains, Donegal, Newry and Leinster) and Palaeogene granites (Mourne Mountains, Slieve Gullion and Carlingford, all in NE Ireland; shown as uncoloured (white) areas to the east of the Newry granite on Figure 1).

The Caledonian orogeny relates to events that took place from the Ordovician to Early Devonian, 490-390 million years ago (Ma). Caledonian granites are associated with post-orogenic collapse and with the major SW-NE trending faults that were undergoing left-lateral movement at the end of that period. In stark contrast to the post-orogenic origins of the Caledonian granites, the Palaeogene granites owe their origin to the opening of the North Atlantic circa 60 Ma. The UCS/PLI data presented in this paper pertain to Caledonian granites only.

3.2 Irish Caledonian granites

At 1500 km², the Leinster batholith (417-405 Ma) is the largest in the UK or Ireland and comprises five plutons. Its chemistry and mineralogy differs from other Irish Caledonian granites in containing both biotite and muscovite mica, reflecting the origin of the magma (possibly related to its position on the south side of the Iapetus Suture, see Figure 1). While magma generation is believed in all cases to be due to decompression melting as a subducted slab detached under the Caledonian orogenic belt, the source rocks for the Leinster granite would appear to be the aluminium-rich schists and other meta-sedimentary rocks that now host the granite.

In contrast, the other Irish batholiths were generated from melting of igneous rocks, and show more evidence of the involvement of mafic magmas in their generation, as evidenced by the presence of mafic enclaves, the lack of muscovite (therefore lower in aluminium) and the presence of hornblende and titanite. The Galway batholith (410-380 Ma) is ~900 km² in area, but extends under Galway Bay, so it is likely to be twice that size in areal extent. It comprises multiple, varied, individual plutons, generally granodioritic in nature (i.e. lower quartz content than true granite). The 'main' body is distinctly porphyritic, with large (up to 10cm long) pink K-feldspar phenocrysts in a coarse groundmass. Biotite, hornblende and titanite are common. A key feature is a (presumed axial) band circa 4 km wide of intense magma mixing and mingling between granites and more mafic rocks. Geobarometry suggests intrusion depths of between 18 km and 4 km for the plutons of this batholith.

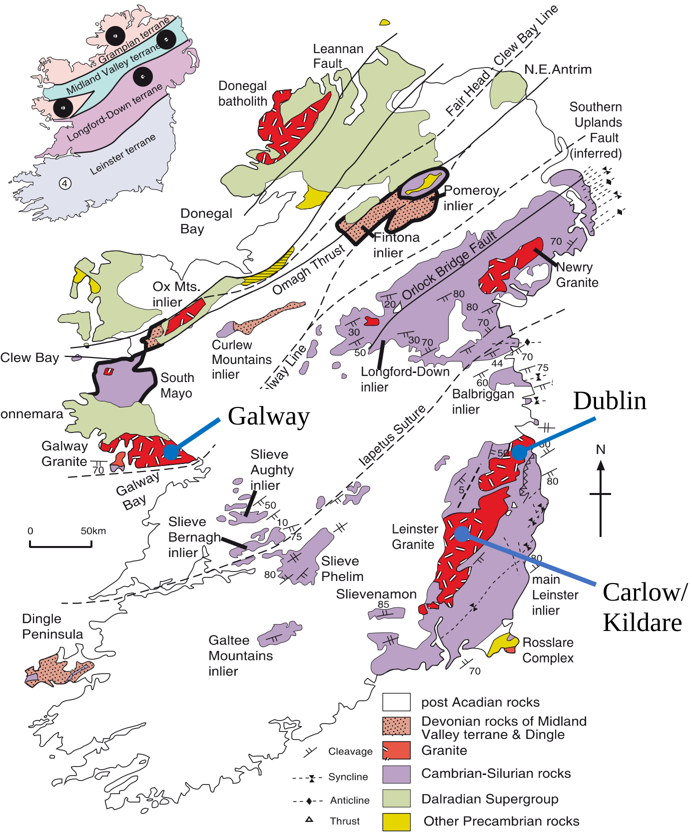


Figure 1. Distribution of granite in Ireland [13]

4 UCS-PLI DATABASE

The UCS-PLI database was compiled from historical ground investigation (GI) reports in the files of AGL Consulting, and some publicly available from the Geological Survey of Ireland (GSI). These reports date from 1996 to 2021 and are attributable to nine separate GI contractors. The database incorporates the following information, where available:

- UCS tests: specimen depth, height, diameter, bulk density, UCS value.
- PLI tests: specimen depth, height, diameter, width, whether tests were diametral, axial, on blocks or irregular lumps, direction of testing (parallel or perpendicular to planes of weakness, unknown/random), $I_{s(50)}$ value.
- The geological formation/unit name, according to the GSI 100k series mapping.

- Description of granite strength, grain size, mineralogy, bedding and weathering.
- Quantification of Discontinuity Spacing, Fracture Spacing, Fracture Intensity (FI), Total Core Recovery (TCR), Solid Core Recovery (SCR) and Rock Quality Designation (RQD).

The main database comprises a total of n=244 UCS-PLI pairs, with UCS and PLI specimen depths within 0.5 m in almost all cases, and the $I_{s(50)}$ measurement based on diametral results. Diametral PLI data dominated the database, and are generally preferred over axial PLI data for geometric sensitivity reasons [4]. The dataset can be attributed regionally as follows: Dublin (n=141) and Carlow/Kildare (n=50) (both from the Leinster batholith) and Galway (n=53). A secondary (and largely separate) dataset of PLI data for Dublin (n = 728) was developed for the purpose of comparing axial and diametral $I_{s(50)}$ values only. Most of these data do not have the comparative UCS tests necessary for inclusion in the main database. For the small number that do, only the diametral ones are included, for reasons already described, and given that the association of a single UCS value with two different $I_{s(50)}$ values would be statistically inappropriate.

5 UCS-PLI CORRELATIONS

5.1 UCS and $I_{s(50)}$ distributions

Statistical data for UCS, $I_{s(50)}$ and bulk density are shown in Figure 2 in the form of *box and whisker* plots (illustrating minimum, lower quartile, median, upper quartile, maximum values and outliers, in the standard way) for the entire database and differentiated by region. The mean value is also included (marked ×). A wide range of UCS values (up to ~240 MPa) and $I_{s(50)}$ values (up to ~13 MPa) is represented overall, in contrast to the more limited ranges on which some of the correlations in Section 2 are based.

It is apparent from Figure 2 that the overall database is somewhat skewed by regional variations. While the mean UCS for the Dublin data follows the overall mean fairly closely (0.88 of the overall mean), the mean UCS values for the Galway and Carlow/Kildare data are 1.83 and 0.44 times the overall mean respectively. Corresponding ratios for $I_{s(50)}$ means are 0.96 (Dublin), 1.64 (Galway) and 0.43 (Carlow/Kildare). Single factor analysis of variance (ANOVA) suggests that these regional differences in UCS and $I_{s(50)}$ are statistically significant in all three cases. The (also statistically significant) higher bulk densities for Galway granite (Figure 2c) are likely to have influenced the higher UCS and $I_{s(50)}$ values. Such differences are probably a reflection of the chemical and mineralogical differences between the Galway and Leinster batholiths discussed in Section 3. However, the differences in UCS and $I_{s(50)}$ between Dublin and Carlow/ Kildare granites, both within the Leinster batholith, are not explained by bulk density (i.e. differences in bulk density not statistically significant) and requires further investigation.

5.2 UCS-PLI linear relationships

A plot of UCS against $I_{s(50)}$ for the entire database is provided in Figure 3, with the Broch and Franklin [4] correlation and the granite correlations presented in Section 2 superimposed. The data in Figure 4 incorporate scatter typical of large rock measurement datasets; the Chau and Wong [7] relationship appears to represent the data best on average. The Broch and Franklin [4] correlation grossly over-predicts UCS for the majority of cases. Also, given that most of UCS cores included in database are 60 mm in diameter or greater, ASTM D5731-16 [3] also overpredicts UCS (very similar to the Broch and Franklin [4] line, so not shown in Figure 3 for clarity). None of the other correlations represent the data well either, although the Armaghani et al. [11] and Tandon and Gupta [10] offer reasonable upper and lower bounds respectively. It is worth noting that while correlations such as those in Figure 3 aspire to produce mean trends (for the purposes of foundation design, for example), upper bounds/over-predictions of UCS can be useful where rock excavatability predictions are sought, such as for shaft and tunnel construction [14].

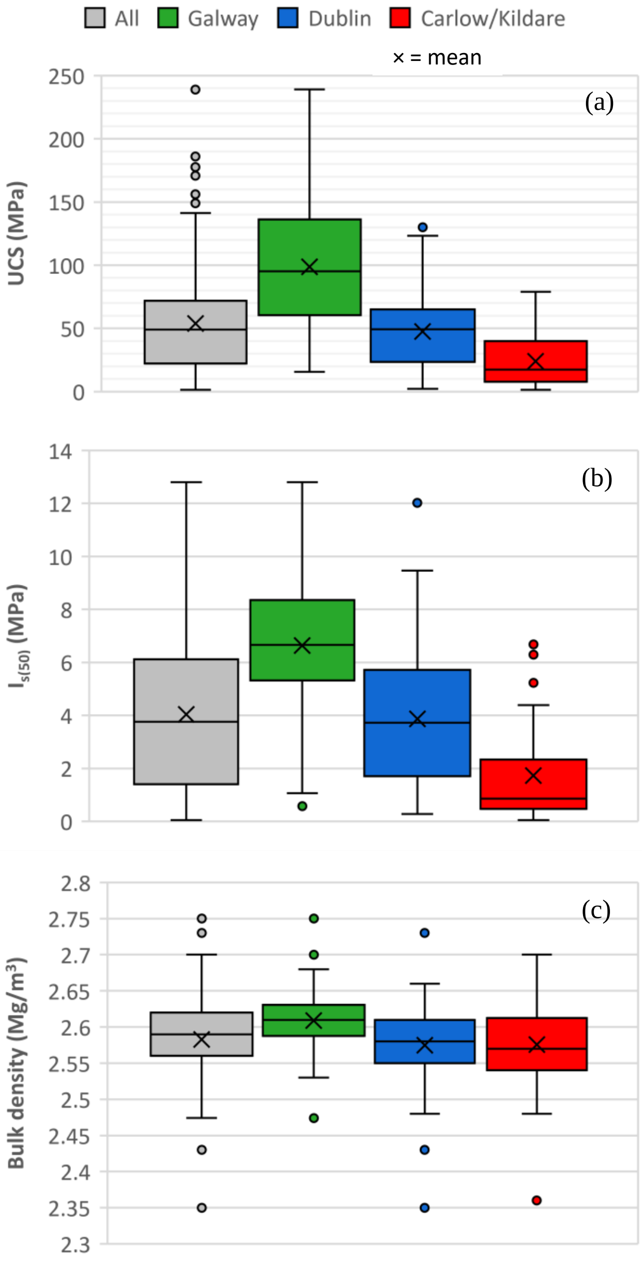


Figure 2: Box and whisker plots for (a) UCS (b) $I_{s(50)}$ and (c) bulk density for entire database and differentiated by region

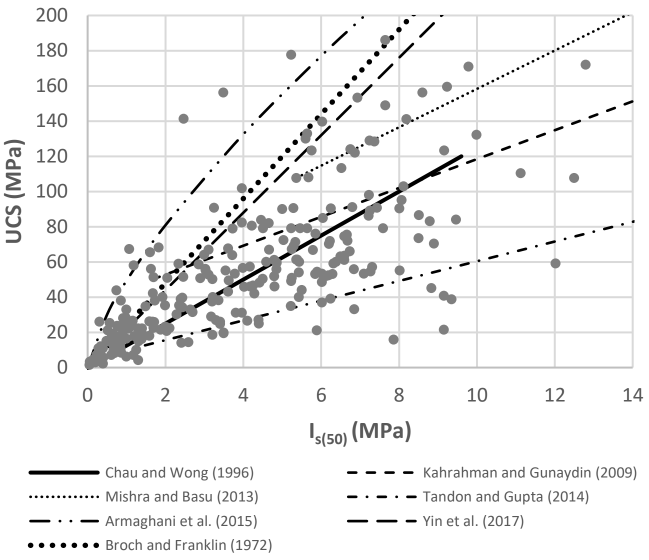
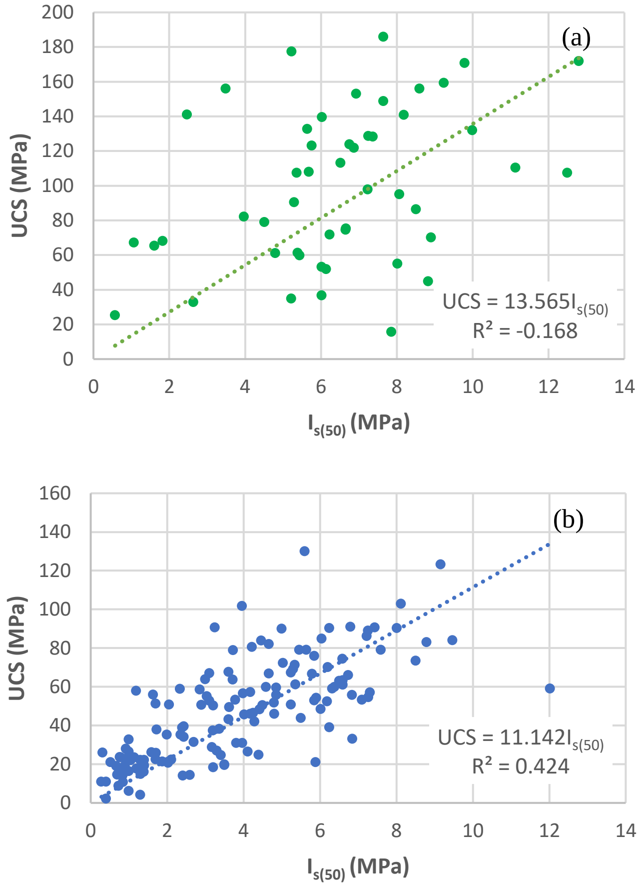


Figure 3: UCS against $(I_s)_{50}$ for the entire granite database (n=244) with correlations from the literature superimposed.

Separate plots of UCS against $I_{s(50)}$ are presented in Figure 4 for the three regions: (a) Galway, (b) Dublin and (c) Carlow/Kildare. Initially, simple linear correlations (zero UCS intercept) were investigated. The best fit for the entire database was found to be UCS/$I_{s(50)}$= 12.3 (R^2=0.45), with UCS/$I_{s(50)}$ values of 13.6 (R^2=-0.17), 11.1 (R^2=0.42) and 11.4 (R^2=0.60) for Galway, Dublin and Carlow/Kildare respectively.



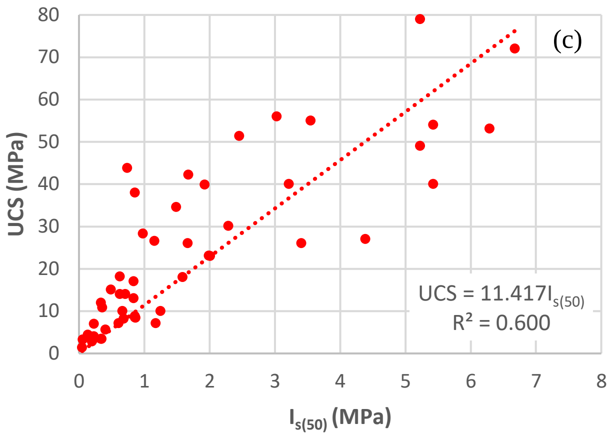


Figure 4: Individual UCS-$I_{s(50)}$ relationships for (a) Galway, (b) Dublin and (c) Carlow/Kildare granites

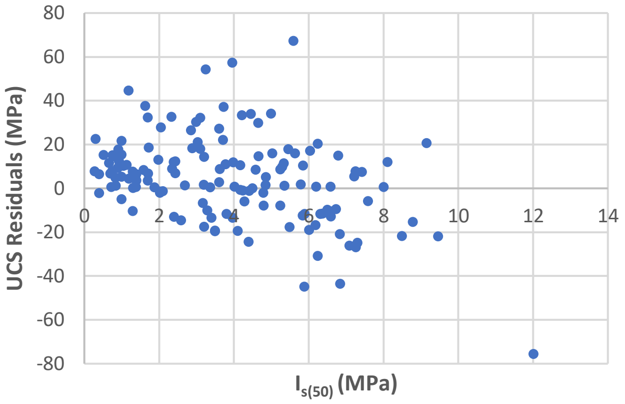


Figure 5: UCS residuals plotted against $I_{s(50)}$ data for Dublin: linear relationship

Individually, these ratios are relatively similar (the Galway value is slightly higher) and broadly in keeping with UCS/$I_{s(50)}$ = 12.5 (for axial PLI specimens) in Hong Kong granite/tuff [7]. However, the negative R^2 for the Galway data implies that the increasing relationship shown in Figure 4(a) does not embody the trend of the data, and therefore its use is not advised until the reason for the spread is better understood.

The UCS residuals (the difference between predicted and observed UCS values in a regression analysis) corresponding to the linear relationships presented in Figure 4 were plotted against $I_{s(50)}$; an example for Dublin granite is shown in Figure 5. These residual plots revealed that the data are not well represented by the linear relationships at lower UCS and $I_{s(50)}$ values; the residuals are predominantly positive up to $I_{s(50)}$ of at least 3 MPa in both Dublin and Carlow/Kildare granites. On this basis, bi-linear relationships were considered for both sets of data, in order to capture the lower strength realm better. However, these were not particularly successful and have the potential to be misused in practice.

5.3 UCS-PLI non-linear relationships

Non-linear (polynomial and power) relationships between UCS and $I_{s(50)}$ were explored for the Dublin and Carlow/Kildare granite data. The following power relationships, similar in general form to that of Armaghani et al. [11] (i.e. $UCS = AI_{s(50)}^B$, where A and B are constants), were ultimately preferred:

Dublin: $UCS = 19.06\ I_{s(50)}^{0.66}\ (R^2 = 0.55)$ (1)
Carlow/Kildare: $UCS = 16.12\ I_{s(50)}^{0.75}\ (R^2 = 0.71)$ (2)

Equations (1) and (2) are displayed in context of the underlying data in Figures 6a and 6b respectively. The corresponding residual plots illustrate that these non-linear correlations model the data more appropriately than the linear ones; the example for Dublin granite in Figure 7 clearly depicts a more equitable spread about the zero residual axis than in Figure 5. A power relationship was not explored for the Galway granite given the poor R^2 value in the linear correlation.

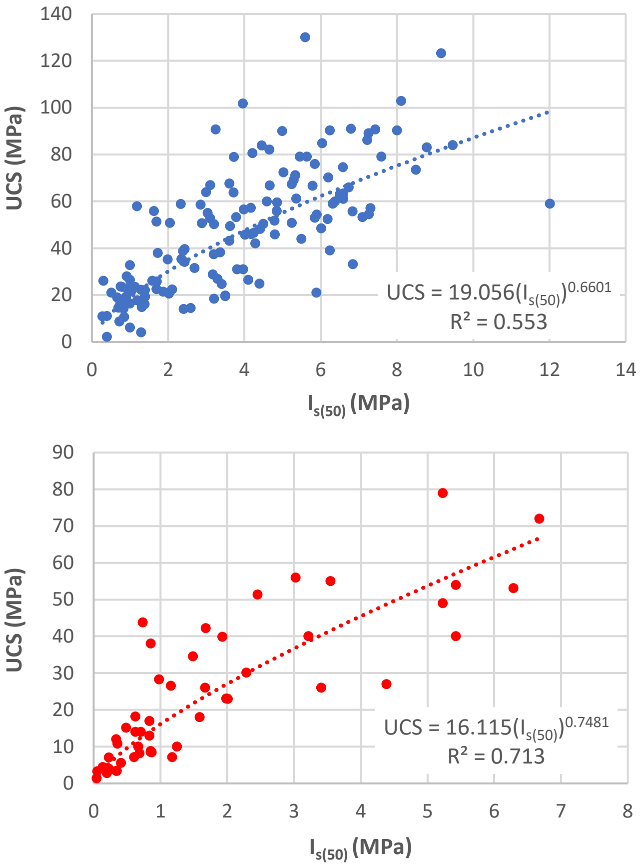


Figure 6: Non-linear UCS-$I_{s(50)}$ relationships for (a) Dublin, (b) Carlow/Kildare granites

5.4 *$I_{s(50)}$ values: axial versus diametral*

In the aforementioned study, Yin *et al.* [12] conducted 53 diametral and 54 axial PLI tests on Hong Kong granite. Their correlation of $UCS/I_{s(50)} = 22$ was found to be independent of whether diametral or axial tests were considered.

Axial $I_{s(50)}$ values are plotted against diametral $I_{s(50)}$ values (n =752) for Dublin granite in Figure 8, where both measurements correspond to the same depth within the same core. The slope of the best fit line is virtually unity, suggesting, despite the scatter (R^2=0.49), a general equivalence between $I_{s(50)}$ measurements from the two loading directions, in keeping with previous findings [12]. The $I_{s(50),axial}/I_{s(50),diametral}$ ratio appears to be related to anisotropy of the rock; with igneous rocks more likely to yield a 1:1 ratio than sedimentary rocks incorporating bedding planes. For instance, $I_{s(50),axial}/I_{s(50),diametral}$ ratios of 2 to 2.5 were reported for a Western Australian shale, and 1 to 2.5 for a banded-iron formation, with higher ratios reflecting greater weathering in the latter case [15].

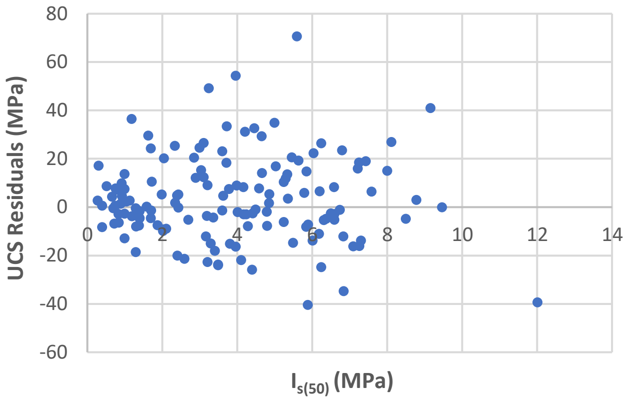


Figure 7: UCS residuals plotted against $I_{s(50)}$ for Dublin: power relationship

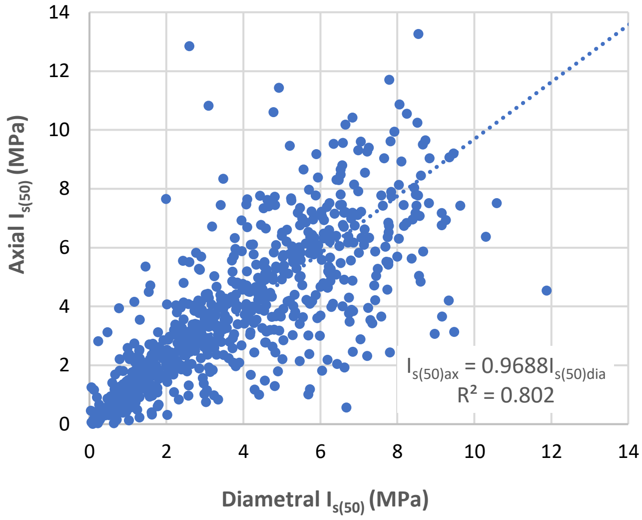


Figure 8: Axial $I_{s(50)}$ plotted against diametral $I_{s(50)}$ for Dublin granite (n=752)

5.5 *Other variables*

Thuro *et al.* [16] found no significant dependence of UCS on (i) core diameter, in the range 45-80 mm for limestone samples and 50-117 mm for granite samples, and (ii) aspect ratio, in the range 1 to 3 for (igneous) kersantite samples. Notwithstanding the bias in the data due to the much higher UCS for the Galway specimens, no relationship between UCS and core diameter (in the range 34-93 mm) or aspect ratio (mostly the recommended 2-3 range) was evident in this database either. Such comparisons could be considered more broadly with an enhanced dataset, without the requirement of proximal UCS and $I_{s(50)}$ values.

The significant dependence of $UCS/I_{s(50)}$ on core diameter implied in ASTM D5731-16 (2016) relates to core diameters in the range 21.5 mm to 60 mm. However, no relationship was apparent between UCS/$I_{s(50)}$ and either diameter or aspect ratio (over the ranges quoted above) for the Irish granites considered.

RQD, defined as the percentage of intact drill core pieces longer than 10 cm recovered during a single core run, is a measure of jointing or fracture in a rock mass. Some studies (e.g. [17] in sandstone) have indicated a positive correlation between UCS and RQD. Despite a wide range of RQD values in the database (8%-100%), UCS or UCS/$I_{s(50)}$ for the granites appeared to be insensitive to RQD, perhaps in part due to differences in individual drilling styles across multiple GI companies.

6 CONCLUSIONS

A new UCS-PLI database for Irish Caledonian granites (n=244, i.e. more data than most other granite studies reviewed) has indicated that the commonly-quoted correlation UCS=24$I_{s(50)}$ is likely to overpredict the UCS of these granites by a factor of two on average. Despite the fact that much higher UCS values (and $I_{s(50)}$ values) were encountered in Galway granite than in Leinster granites, probably attributable to significant chemical and mineralogical differences, the best-fit UCS/$I_{s(50)}$ ratio was only slightly higher for Galway data, but with the important caveat of only moderate R^2 values (and very poor in the case of Galway).

A statistical examination of residual UCS values has led the authors to prefer a non-linear (power) relationship between UCS and $I_{s(50)}$ to the more common linear ones. The usual caution is advised in applying these correlations. This research also highlights the danger of applying correlations from other granites worldwide to Irish conditions; only one of the published correlations considered compared favourably to those developed in this paper.

A separate Dublin granite database (n=728) has suggested that the axial and diametral PLI test results are statistically equivalent, in theory rendering either version suitable for the development of local UCS/$I_{s(50)}$ correlations in granite.

There was no apparent effect of other variables such as core diameter, aspect ratio and RQD on UCS and UCS/$I_{s(50)}$ values in the database (although a larger UCS-only database may be more informative in this regard). There is scope to consider geological unit, rock grain size, weathering state and other variables in a further development of this work. In addition, granite UCS-PLI data from other regions (both Caledonian and Palaoegene) will be considered.

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