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Evaluating the Effect of Diameter-to-Length Ratio in Point Load Index Test on Predicting Uniaxial Compressive Strength

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Abstract
Accurate determination of the strength properties of rock materials is very important in engineering projects. The most important parameter used to express the strength of rocks is the uniaxial compressive strength (UCS). However, in some cases it can be quite difficult to determine the UCS. For example, when it is difficult to obtain rock specimens of the required size for UCS testing, indirect methods such as point load strength and ultrasonic wave velocity are used to estimate UCS. If the UCS is determined incorrectly, this can lead to irreversible design errors, project delays and financial losses. PLI testing is performed on specimens of different shapes as well as on specimens of different sizes. This study investigates the ability of the values obtained as a result of PLI tests on specimens prepared with different diameter/length (D/L) ratios to predict UCS. For this purpose, PLI experiments were performed on seven different carbonate rocks prepared at different D/L ratios. The relationships between the obtained values and the UCS values of the rocks were analyzed. High correlations were obtained between PLI and UCS values and it was observed that D/L ratio has no significant effect on UCS estimation.

1. Introduction

In order to ensure the stability of structures in engineering projects, the strength properties of rock materials should be accurately determined in designs. The most commonly used mechanical parameters for demonstrating the strength properties of rock materials are the uniaxial compressive strength (UCS) and the point load strength index (PLI). These two parameters are commonly used as input for software used in the design of underground and surface engineering structures as well as tunnels. They also feature in numerous rock mass and excavation classification systems.

Rock specimens with the applicable dimensions must be used to determine the UCS according to the International Society for Rock Mechanics [1], [2]. However, the required size rock samples for UCS testing are very difficult to obtain in many cases, such as layered sedimentary rocks, schistosity metamorphic rocks and highly weathered rocks [2]. Therefore, indirect methods such as point load index (PLI) and ultrasonic wave velocity are used to estimate UCS. Incorrect determination of UCS can lead to errors in the design, which can damage the project [3]. There have been numerous studies on the correlations between UCS and PLI and more than 100 equations have been proposed to determine UCS values [4], [5]. To estimate the UCS, a wide range of coefficients from 3 to 71 must be multiplied by the PLI values of the rocks [6]. The reliability of PLI's UCS estimates is called into question due to this wide range of coefficients. There are several reasons for the wide coefficient range, including test method (specimen geometry), test apparatus and rock origin/type.

Determination of the PLI of rocks is a simpler, faster, and cheaper method when compared to the UCS. It is a method that can be used both in the field and laboratory without requiring specimen

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preparation or sampling whatsoever. Despite its advantages, errors arising from the equipment used and the operator are encountered during the determination of PLI. Loading speed and discrete loading, dial gauge (indicator) errors, conical platen geometry, distortion of conical platens from axis can be mentioned as some of these errors [6].

Core specimens (for both radial and axial testing), cut block specimens, or irregularly sized specimens may be used in the determination of the PLI. Due to this difference in available specimens, in order to obtain a unique PLI value for the rock specimen, a size correction must be applied. The size effect in the PLI test has been the subject of extensive investigations.

In their study, Franklin et al [7] found that PLI increased linearly as the length/diameter (L/D) ratio approached 1 in the diameter test and did not change much when $L/D>1$, while PLI decreased as the L/D ratio decreased in the axial test. Therefore, they suggested that the values obtained from axial tests should be corrected with a correction factor for size and shape effects. Wijk et al. [8] determined the tensile strength indirectly from the values obtained by performing PLI tests on granite and determined that the strength value decreases as the specimen volume increases. Al-Jassar and Hawkins [9] performed PLI tests on cube and core specimens of three different sizes and determined that the PLI values decreased as D (diameter=thickness) increased. Brook [10] carried out some tests on different limestone and sandstone specimens to determine the shape and size effect and emphasised the cross-sectional area. He argued that the 50 mm diameter correction factor proposed by Broch and Franklin [11] is difficult to apply in stratified rocks. Greminger [12] conducted experiments on four different rock types to determine how anisotropy affects the PLI due to shape and size effects. He recommended the use of 50 mm diameter specimens where possible, and where not, specimens with a minimum diameter of 30 mm that fulfil the $1 \leq L/D \leq 3$ condition. Forster [13] identified three basic problems for PLI (diametral testing in anisotropic rocks, specimen geometry for axial testing, and UCS/PLI relationship). He performed experiments on 7 different types of rocks with different length/diameter ratios and obtained similar results to previous studies. He stated that $0.5<L/D<1$ and $D>30$ mm for axial testing and proposed two different equations for the cases of $D<50$ mm and $D>50$ mm for axial testing. Broch [14] stated in his study that the method recommended by ISRM [15] should be used in the diametrical test and $0.5\ D<L<D$ in the axial test. Brook [16], in his study, summarised the size and shape correction factors to date and made an evaluation. He used and defined the equivalent diameter expression. Abdallah [17] conducted PLI tests on unshaped (D=10-80 mm) and core (D=10-100 mm) specimens of different thicknesses for four different rock types. They determined that the PLI changed very sensitively in the experiments performed on specimens with a thickness below 10 mm, while there was no change in the specimens with a thickness above 70 mm, and it was independent of the size effect. As a result, they recommended $10\ mm<D<70\ mm$ (where D represents the distance between the conical platens). Chau [18], in his study, tried to determine the stress distributions in the specimen under tensile stress by PLI test. He emphasised that the tensile stress occurring in the middle of the specimens increases for $2L/D<1$, and remains roughly constant for $2L/D>1$. He found that the model he applied was consistent with the results obtained experimentally on marble, granite, and tuff. Wei et al. [19] determined that the widest rock has the lowest PLI for fixed L/D ratio and the thinnest specimen has the lowest PLI for fixed diameter value. In their study, Chau and Wei [20] found that circumferential stress is dominant in long cylinder specimens ($L/D>7$), while axial stresses are more intense in small specimens ($L/D<4$). They stated that the shape effect can be neglected when L/D=0.7. They suggested that specimens with large diameter values should not be used in the PLI test. Zacoeb and Ishibasi [21] recommended a diameter of 50 mm and an L/D ratio of 2 for the PLI test. Li et al. [22] stated that the height of the rock mass has a certain influence on the load point, whether the height is too large or too small has great effects. When using irregular specimens in the tests, they recommended the use of specimens with a height of 30 mm to 50 mm. Forbes et al. [23] through an experimental investigation of both axial and diametral PLI tests involving 374 specimens of Gosford sandstone. As a result of this investigation, they found that the PLI varies increasingly with specimen diameter for all investigated specimens at different length-to-diameter ratios. Masoumi et al. [24] compared the experimental results obtained in their study and concluded that the concept of "generalised size effect" was observed in which the strength decreases with increasing size in all rock types.

Studies in the literature have always sought answers to questions such as how PLI changes and how much it changes. However, in this study, the relationship between uniaxial compressive strength and PLI values obtained from specimens with different D/L ratios was also investigated. For this purpose, PLI experiments were performed on rock specimens prepared with different D/L ratios to determine how the D/L ratio changes the PLI, and then the relationship between UCS and PLI values obtained from specimens prepared with different D/L ratios was examined.

2. Material and Method

2.1. Point Load Index

Core specimens (for diametrical and axial tests), cut block specimens, or irregular lump specimens can be used in the PLI tests. The required specimen dimensions according to the test types are given in Figure 1. The rock specimen, whose dimensions are measured and placed between the conical platens, is broken within a certain time (10-60 s) and the failure load is read from the load indicator. The load at which the rock is broken is recorded. If the test specimen is heterogeneous and anisotropic, the test is repeated 10 times. The lowest and highest two values are discarded. The arithmetic mean of the remaining six values is taken.

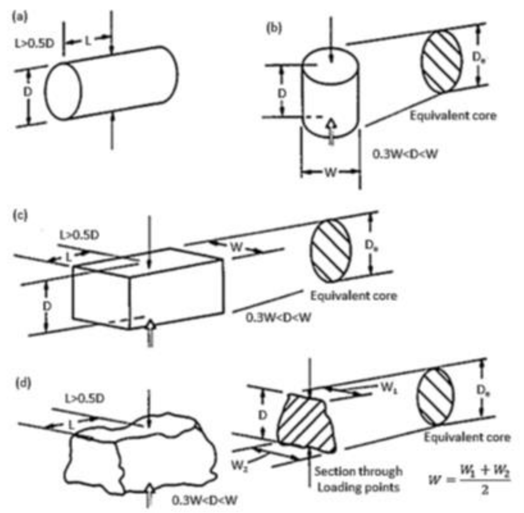

Figure 1. Specimen dimensions and limits for (a) diametral test specimen, (b) axial test specimen, (c) block specimen, and (d) an irregular lump [25].

ISRM [25] gives the types of failure modes for which the test should be considered valid or invalid in Figure 2. In particular, it is sufficient for the failure to be considered invalid if the failure surface does not pass through any loading point.

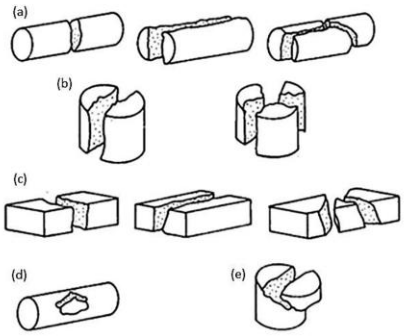

Figure 2. Failure modes for valid tests (a, b, c) and invalid tests (d, e) [25].

The After the test is completed, the uncorrected PLI is calculated by Equation 1:

$$I_s = \frac{P}{D_e^2} \qquad (1)$$

Where I_S is the uncorrected point loading strength (MPa), P is the failure load (kN, kgf, etc.) and D_e is the equivalent core diameter (mm). Equivalent core diameter is calculated by Equation 2 for diametrical specimens:

$$D_e^2 = D^2 \qquad (2)$$

Where D_e is the equivalent core diameter (mm) and D is the core diameter (mm). It is calculated by Equation 3 for axial test, block test, and irregular lumps:

$$D_e^2 = \frac{4 \times A}{\pi} \qquad (3)$$

Where D_e is the equivalent core diameter (mm) and A is the smallest cross-sectional area of the specimen passing through the contact points of the conical heads.

The value of I_S varies as a function of D in the diametral test and as a function of De in other types of tests. Therefore, the I_S value must be corrected for a standard core diameter (D=50 mm). The corrected $I_{S(50)}$ value is determined using a monogram (Figure 3) or graph (Figure 4) prepared for this purpose.

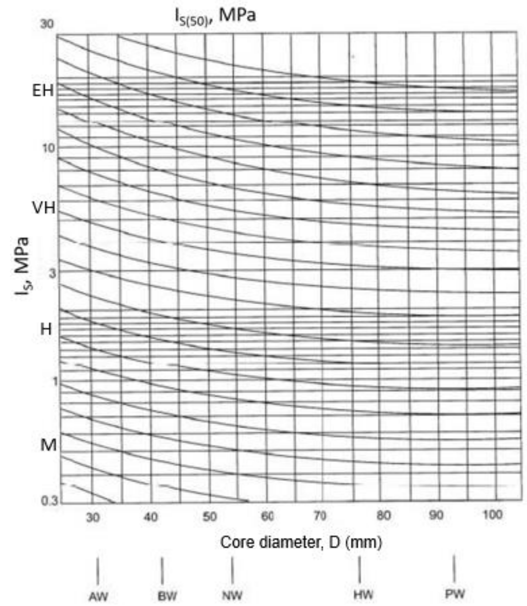

Figure 3. Corrected PLI determination nomogram [11] (M: Medium; H: High; VH: Very high; EH: Extremely high).

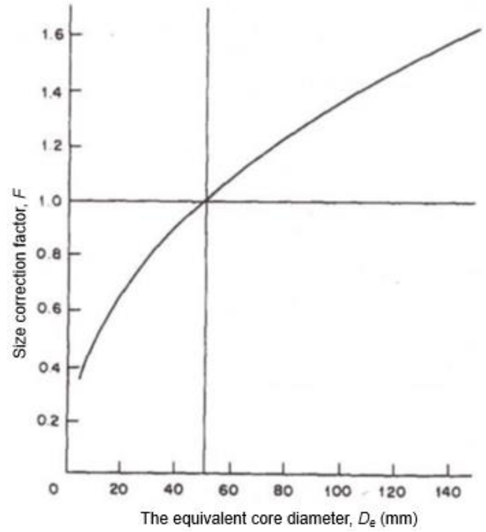

Figure 4. Size correction factor chart [25].

If there is no nomogram, the size correction factor is calculated by Equation 4 and the corrected PLI is calculated by Equation 5:

$$F = \left(\frac{D_e}{50}\right)^{0,45} \quad (4)$$

$$I_{s(50)} = I_s \times F \quad (5)$$

2.2. Experimental Study

In this study, seven different natural stones of sedimentary origin, which are generally used in building cladding and flooring applications, were used (Table 1). Some physical and mechanical properties were determined to characterise the rocks studied. All tests were performed according to the relevant standards recommended by the Turkish Standards Institute (TSE). Unit volume weight (UVW), water absorption percent by weight (WAW), apparent density (AP) of rocks were determined according to the EN 1925 [26]. The ultrasonic wave velocity (*Vp*) tests were measured on specimens cubical in shape having 70 mm edge length as specified in EN 14579 [27]. The UCS tests were conducted on specimens cubical in shape 50×50×50 mm as specified in the principles of EN 1926 [28] standard. The test results are presented in Table 1.

Table 1. Some physical and mechanical properties of the studied rocks

Specimen Code	Origin	Region	UVW t/m^3	AP %	WAW %	*Vp* m/s	UCS MPa
K-1	Sedimentary	Isparta	2.7	0.324	0.120	6168	155
K-2	Sedimentary	Antalya	2.7	0.267	0.099	6117	158
K-3	Sedimentary	Isparta	2.7	0.325	0.120	6154	122
K-4	Sedimentary	Burdur	2.7	0.409	0.151	6160	149
K-5	Sedimentary	Isparta	2.7	0.441	0.163	6286	98
K-6	Sedimentary	Afyon	2.7	0.425	0.157	6234	115
K-7	Sedimentary	Afyon	2.7	0.381	0.141	6258	117

UVW: unit volume weight; WAW: water absorption percent by weight; AP: apparent density; *Vp*: ultrasonic wave velocity; UCS: uniaxial compressive strength

Specimens for PLI tests with different D/L ratios were prepared according to the limit dimensions recommended by ISRM for specimens that can be used in PLI tests [25]. The specimens were placed in the test apparatus as shown in Figure 5 for a simpler expression of the D/L ratio. Specimens with a diameter of 35 mm and a D/L ratio ranging from 0.39 to 1.08 were prepared for diametrical PLI test and specimens with a diameter of 35 mm and a D/L ratio ranging from 0.95 to 2.50 were prepared for axial PLI tests (Figure 6). PLI tests were applied on seven specimens for each test in accordance with the standard recommended by ISRM [25]. At the end of the tests, all specimens were broken in valid failure modes (Figure 7). The test results were presented in Table 2.

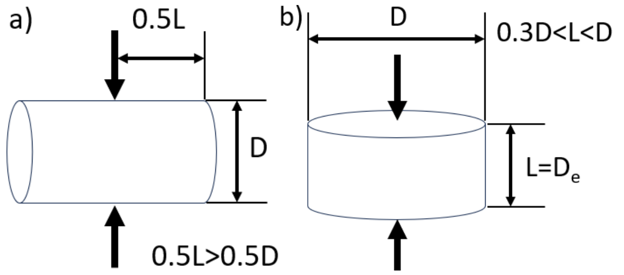

Figure 5. The specimen dimensions and limits for (a) diametral test specimen, (b) axial test specimen (modified from ISRM [25]).

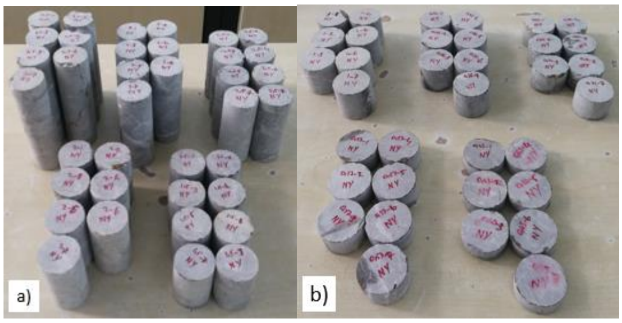

Figure 6. Specimens prepared for PLI tests a) diametral test, b) axial test.

Figure 7. Broken specimens after the PLI tests a) diametral test, b) axial test.

Table 2. The PLI values and D/L of the studied rocks

Specimen code	K-1		K-2		K-3		K-4		K-5		K-6		K-7	
Test type	D/L	PLI MPa	D/L	PLI MPa	D/L	PLI MPa	D/L	PLI MPa	D/L	PLI MPa	D/L	PLI MPa	D/L	PLI MPa
Diametral test	0.39	2.61	0.40	3.12	0.42	2.30	0.40	2.89	0.41	1.05	0.42	1.08	0.40	1.21
	0.55	4.10	0.57	4.10	0.55	3.21	0.56	3.70	0.53	1.41	0.55	1.59	0.55	1.94
	0.71	4.93	0.70	4.72	0.72	3.96	0.72	4.40	0.69	1.85	0.72	2.04	0.67	2.36
	0.79	5.36	0.78	5.46	0.83	4.65	0.82	4.94	0.78	2.28	0.81	2.39	0.80	2.98
	0.89	5.51	0.90	5.64	0.91	4.84	0.91	5.12	0.88	2.31	0.88	2.43	0.93	3.13
	1.04	5.46	1.06	5.62	1.02	4.83	1.08	5.10	1.05	2.33	1.04	2.45	1.05	3.08
Axial test	1.04	5.21	0.99	6.42	1.01	5.52	0.95	4.95	0.95	2.31	0.99	2.44	1.01	2.84
	1.21	4.74	1.23	5.81	1.21	4.82	1.20	4.60	1.23	2.04	1.25	2.10	1.20	2.50
	1.49	4.41	1.46	5.57	1.52	4.47	1.55	4.39	1.54	1.81	1.53	1.87	1.52	2.38
	1.82	4.13	1.82	4.58	1.82	3.59	1.84	4.23	1.76	1.47	1.85	1.40	1.83	2.02
	2.21	3.99	2.22	4.43	2.19	3.63	2.23	3.69	2.18	1.43	2.17	1.32	2.24	1.57
	2.50	3.67	2.39	4.10	2.41	3.12	2.40	3.68	2.38	1.20	2.40	1.05	2.39	1.47

3. Results and Discussion

The relations between PLI values and D/L ratios of the studied rocks were graphically investigated and the plots are shown in Figure 8 and Figure 9. In addition to the effect of D/L ratios, the correlations between PLI values and D/L ratios of the studied rocks were analyzed by simple regression. Significant relationships were found between PLI values and D/L ratios as expected. In diametral test, correlations vary between 0.92-0.97, and in axial test correlations vary between 0.96-0.99. In In Figure 8, the relationship between PLI and D/L ratios indicated that PLI values increased as the D/L ratios of the specimens became larger until D/L ratios of 1. It is observed that the PLI values almost do not change much after the critical D/L ratio of approximately 0.8. In other words, the PLI values increased as the D/L ratio of the specimens became larger—up to the critical D/L ratio of 0.8. After this value, PLI values did not change significantly as the D/L ratio approached towards 1. This ratio is also very close to the value D/L=1.0

ISRM's recommended upper limit for specimen's D/L ratio [25]. As can be seen in Figure 9, the PLI values have decreased as the D/L ratios increased. Moreover, PLI values were observed to increase as the specimen length (height) became near the specimen diameter. Therefore, the results indicated an apparent correlation between PLI and the length (height/thickness) of specimens.

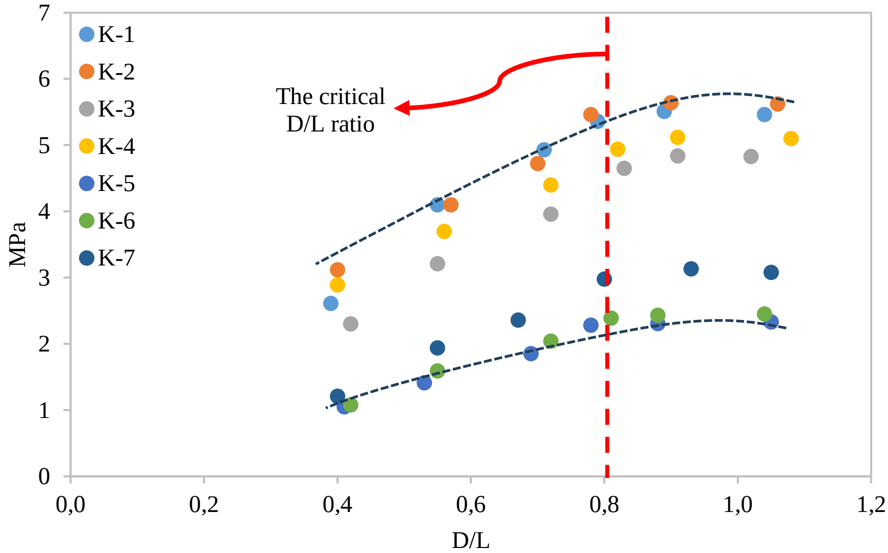

Figure 8. The relationships between the PLI and D/L ratios in diametral test.

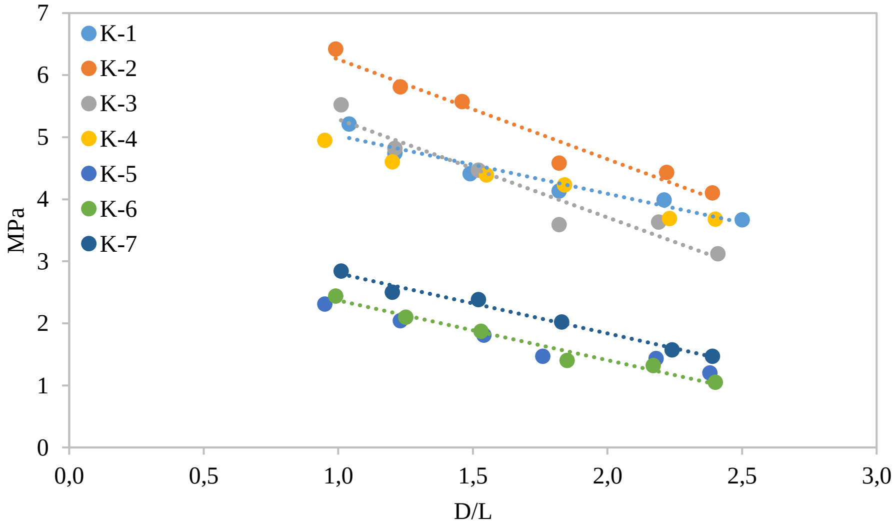

Figure 9. The relationships between the PLI and D/L ratios in axial test.

The study also examined the relationship between UCS and PLI. Similar results to those obtained in previous studies between UCS and PLI were obtained. Strong relationships with high correlation coefficients were found between UCS and PLI for both the diametral and axial tests. In diametral tests, linear relationships were determined between UCS and PLI values obtained from specimens prepared at different D/L ratios with correlation coefficients ranging from 0.91 to 0.94 (Figure 10). As a result of axial tests, correlations ranging from 0.84 to 0.91 were determined between UCS and PLI values obtained from specimens prepared at different D/L ratios (Figure 11). The correlations obtained from the diametral tests are slightly higher than the axial tests.

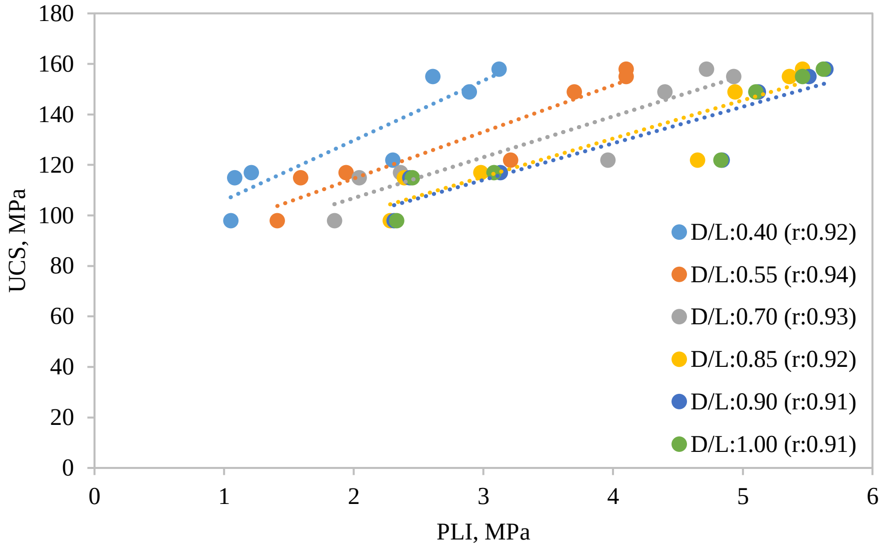

Figure 10. The relationships between the PLI and UCS in diametral test.

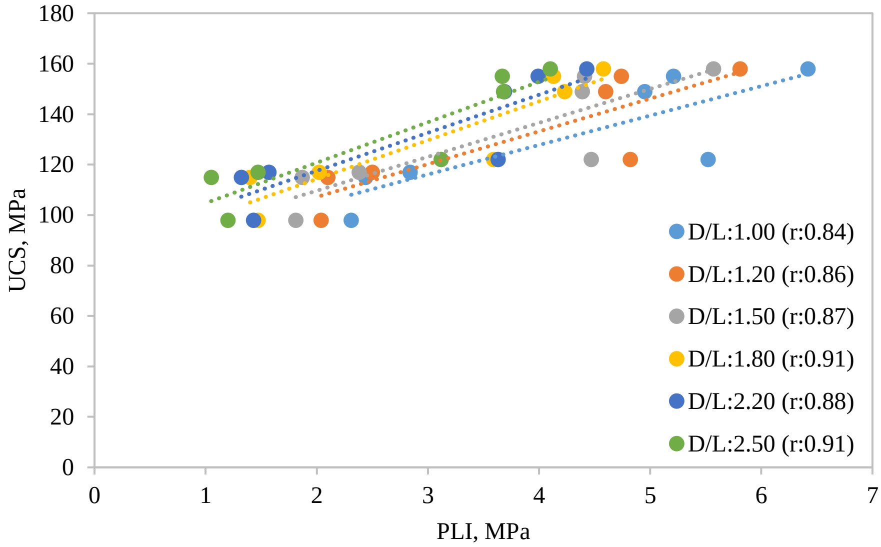

Figure 11. The relationships between the PLI and UCS in axial test.

4. Conclusion and Suggestions

The results obtained in this study show that the D/L ratio of the specimen significantly affects the determination of PLI values and is a parameter that should be taken into account in the evaluations of diametral and axial PLI tests.

It was determined that the PLI increased linearly as the D/L ratio approached 1.0 in the diametral test, and did not change much after 1.0, while the PLI decreased as the D/L ratio increased in the axial test, as stated by Franklin et al. [7] in their study.

The difference in the effect of the D/L ratio on the axial and diametral tests can be explained as diameter is a horizontal distance and length is a vertical distance in the axial tests whereas diameter is a vertical distance and length is a horizontal distance in the diametral tests. In the diametral test, the moment created by gravity due to the mass moving away from the centre as a result of neck elongation creates an additional tensile stress in the centre of the specimen in addition to the loading condition. Due to this extra stress, which is not read on the load indicator, the specimen breaks at low loads. As the D/L ratio approaches 1, in other words, as "L" approaches "D", the value of this extra stress decreases. Therefore, D/L=1 condition for diametrical test is the ideal D/L ratio.

In the axial test, for constant diameter, as the thickness increases, that is, as the length increases, the load required to break the specimen will increase, and as the thickness decreases, that is, as the length shortens, the load required to break the specimen will decrease. When examined in previous studies, the current size correction factor is not sufficient for this situation [21]. The main point to be considered here is that in order for the experiment to be considered valid, the failure must occur between 10-60 seconds as recommended by ISRM. In very long specimens, it takes more than 60 seconds for failure to occur, while in very short specimens it takes less than 10 seconds. In order to determine the ideal ratio, the stress distributions on the specimen at different length and diameter ratios should be analysed.

This study was carried out only on seven types of natural stones of carbonate origin and test specimens were prepared at six different D/L ratios. In future studies, the results of this study will become more meaningful if experiments are carried out on prepared specimens with more D/L ratios (especially the part in the range of D/L=0.8-1.0 can be increased) with rocks of different geologic origin.

When the relationships between the results obtained from the PLI tests on the specimens prepared at different D/L ratios and the UCS values of the rocks were analyzed, high linear relationships were determined for both diametral (r=0.91-0.94) and axial (r=0.84-0.91) tests. It was observed that PLI can be successfully used to predict UCS regardless of the D/L ratio. And also, it could be told that the correlations between the PLI values obtained as a result of the diametral tests only were slightly higher than the correlations between the PLI values obtained as a result of the axial tests.

The findings of this study may be specific to the tested rocks and may not be applicable to rocks of different origins or compositions. Further research is needed to validate the findings on a broader range of rock types.

Statement of Research and Publication Ethics

The study is complied with research and publication ethics.

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