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*Research Article*

# Investigation of the availability of a new point load test device in characterization of rocks

***Deniz Akbay*** [a,*] ***and Raşit Altındağ*** [b]

[a]*Çanakkale Onsekiz Mart University, Çan Vocational School, Department of Mining and Mineral Extraction, Çan, Çanakkale, 17400, Turkey*
[b]*Süleyman Demirel University, Faculty of Engineering, Department of Mining Engineering, Isparta, 32260, Turkey*

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ABSTRACT

Difficulties in determining rock properties have led to the developed and increased use of index test methods predicting them. Index test methods are mostly simple, cheap, and easy to apply but there are some restrictions due to these specifications. The most used method to determine the strength values of rocks indirectly is the point load index. The main aim of this study is primarily investigating the usability of modified test device instead of classical test device. For this, laboratory tests were carried out on rocks with different strength values (3 igneous, 1 metamorphic, 3 sedimentary). The point load index tests were carried on 15 different classical test devices and on a modified test device which the limitations of the classical test device were eliminated. Analysis of the obtained results was carried out by the simple regression method. It was determined the modified test device can be used reliably instead of the classical test devices. Besides, while determining the strength tests the stress distributions on the samples were examined with the finite element method.

## 1. Introduction

Classification of rock mass is very important in engineering projects in terms of project design. Different methods are used to obtain this information in engineering applications. The most preferred one of these is the experimental method. Experimental methods consist of experiments involving index and engineering properties that are used to identify and correlate the rock mass and the ground, which are performed according to the related standards. However, for some experiments, rock procurement, preparation, and testing are costly and time-consuming. In such cases, to predict the required parameter, simpler, faster, easier, relatively cheaper test methods that do not require a sample preparation process may be preferred. The first and most used mechanical parameter that comes to mind to determine the strength properties of rock material is uniaxial compressive strength (UCS). In cases where UCS cannot be determined, the first and most used mechanical parameter that comes to mind to predict UCS is the point loading index (PLI). For this reason, many researchers have been studying on predicting the UCS of rocks using PLI indirectly. As a result of these studies, the researchers presented more than 100 equations that were predicting UCS using PLI [1]. In rocks of different geological origin and structure to predict the UCS of the rock its PLI value must multiply by a coefficient ranging from 3 to 71 [1]. However, it has not been revealed clearly which coefficient will be used for which rock in predicting UCS, so the studies in this area have continued.

For the first time in the literature, Andrea et al. [2] mentioned PLI as point load tensile strength and defined it "point load tensile strengths were obtained by applying a compressive point load to the surface of a cylindrical core perpendicular to the axis of the core". They emphasized as a result of their study that PLI alone can be reliably sufficient to predict UCS. They determined a linear and strong relationship between UCS and PLI. For years after, the researchers used PLI to predict the UCS of the rocks. First Broch and Franklin [3] and Bieniawski [4] investigated the correlation between UCS and PLI in their studies. After that, many studies were carried out in which

* Corresponding author. Tel.: +90-286-416-7705; Fax: +09-286-416-3733.
E-mail addresses: denizakbay@comu.edu.tr *(D. Akbay)*, *rasitaltindag@sdu.edu.tr* *(R. Alındağ)*
ORCID: 0000-0002-7794-5278 *(D. Akbay)*, 0000-0002-5397-7312 *(R. Alındağ)*
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different coefficients were proposed. They carried out the experiments on different rock samples and on different sample shapes. Singh and Singh [5] examined the relations between PLI and UCS using quartzite rocks. Rusnak and Mark [6] made a study that was involving the load frame and PLI tests of coal. Akram and Bakar [7] performed PLI tests on different rock types to consider the relationships between the UCS and the PLI. Basu and Kamran [8] tested usability of PLI to predict UCS on schistose rocks. Heidari et al. [9] aimed to compare all of the PLI test methods and their applicability in practice. Singh et al. [10] made a study to confirm the relationship between PLI and UCS for core samples of igneous, sedimentary, and metamorphic origin rock types. Elhakim [11] used PLI as a describing parameter like UCS for weak and very weak calcareous sandstones. Liang et al. [12] They made experiments on irregular samples to compare and verify the empirical relation between UCS and PLI for different rock types. Alitalesh et al. [13] researched relationships between the PLI and UCS for rock samples. Wong et al. [14] investigated the relations of the UCS with PLI on irregular volcanic rock samples for of different grain sizes and weathering grades. Akbay and Altındağ [15] made experiments on 15 different test devices on the same samples to investigate the errors and the limitations of the PLI test method and device. Al-Jassar and Hawkins [16] studied the correlations between PLI and geotechnical properties on the carboniferous limestone various sized samples. Çobanoğlu and Çelik [17] made a study to estimate UCS from PLI, P-wave velocity and Schmidt hardness using multiple regression analysis. Minaeian and Ahangari [18] examined the relationship between PLI and UCS and tensile strength of weak conglomerates. Ferentinou and Fakir [19] investigated the correlations of the UCS and indirect tests such as PLI for some sedimentary and igneous rocks using the technology of artificial intelligenceTeymen [20] made an experimental study to determine the relations between mechanical properties and index properties such as PLI. Khajevand and Fereidooni [21] used PLI and block punch strength tests to estimate the mechanical properties of rocks in their study. Brook [22] suggested a size correction for PLI test method in his study. Abbs [23] made a statistical study and showed that PLI was poorly suited to weak carbonate rocks. Norbury [24] reviewed published papers reporting test procedures and case histories and underlined PLI is a useful test as a cheap reliable index test. Khanlari et al. [26] researched on different experimental techniques to classify the strength of anisotropic foliated rocks and pointed at that porosity and water absorption are the dominant parameters on the mechanical properties of rocks such as PLI. Smith [27] investigated the usability of the PLI for weak rocks in dredging applications. Look and Griffiths [28] looked for an answer in their study the usability of PLI to provide guidance on design parameters for various tunnels and bridge foundations. Quane and Russel [29] developed rock strength as an ancillary tool for mapping variations in welding intensity using PLI. Basu and Aydin [30] researched the properties of cone penetration test with weathering in granitic samples, to improve the prediction ability prediction of UCS of PLI. Kabilan et al. [31] examined the relationships between UCS and PLI based on joint asperity and orientation of rocks. Also, there are many studies in the literature that were researched the relationships between PLI and other rock properties. Ren et al. [32] established a correlation of failure load between half-core and core samples with a fit size suggestion and size correction factor. Mesutoğlu and Özkan [33] made a study to determine the material characteristics of coal and inner burdens using relationships between the Schmidt hardness and PLI values. Guevara-Lopez et al. [34] developed prediction models for the UCS of rocks based on the PLI. Jamshidi et al [35] suggested a new parameter (PMP) based on physical and mechanical properties of rocks to estemate the brittleness of sandstones and calculated the PMP of sandstones based on the ratio of PLI to porosity. Şahin et al. [36] studied on prediction models for the UCS from the PLI on half-cut core samples.

In this study, the PLI tests were carried out on 15 different classical PLI test devices and a modified PLI test device which the limitations were removed (Figure 1). Seven different rock types (three sedimentary, one metamorphic, three igneous) used in the experiments. The classical PLI test device was modified to eliminate the limitations and errors determined by Akbay and Altındağ [31]. Thus, the ability of PLI obtained from the modified PLI test device to predict physical and mechanical properties was analyzed.

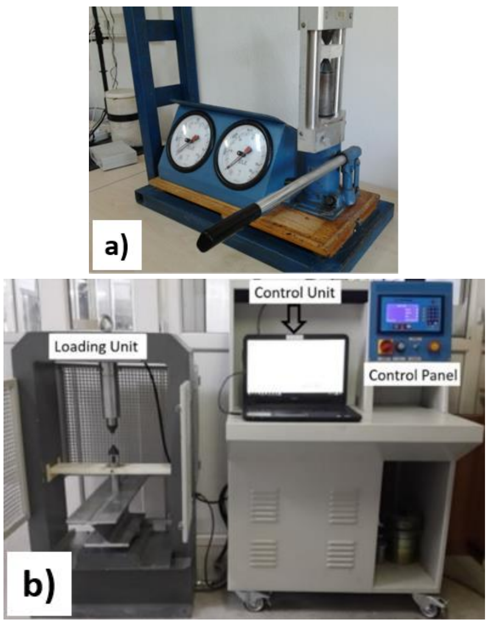


Figure 1. a) The classical test device and b) the modified test device

In the studies carried out so far, the results obtained from a single test device (with known errors/limitations) have been compared with the other properties of the rocks. The main reason is using a test device with known errors/limitations why the results obtained in these studies, in which heterogeneous rock material was investigated, showed such a large distribution from each other.

In such a situation, the number of samples should be increased and even the experiment should be repeated in different devices in order to reach the closest results to the real. In this study, it was shown that the results to be obtained by using a test device that was eliminated from its errors/ limitations instead of these would be sufficient. You should repeat the PLI tests on at least 15 different devices to achieve the nearest true PLI. This will take a lot of time and will be costly and you will need a large number of test samples. Or it will be enough to carry out tests just on the modified test device to reach the reliable results on a limited number of samples in less time.

## 2. Materials and Methods

Seven different rock types were used in this study and rock blocks were taken from marble processing plants located in different regions of Turkey (Table 1). The investigated natural stones show a wide range of strength and are generally used for building, facing, and flooring applications. All the test specimens were prepared according to the related standards recommended by the International Society for Rock Mechanics and Rock Engineering (ISRM) and Turkish Standards Institution (TSE). For the mineralogical and petrographic examinations of the rock samples used in the study, thin sections were prepared in the laboratory and mineralogical analyses were made with a microscope. The fresh surface images of the rocks used in the analyses are given in Figure 1.

### *2.1 Sample Description*

For the mineralogical and petrographic examinations of the rock samples used in the study, thin sections were prepared in the laboratory and mineralogical analyses were made with a microscope. The fresh surface images of the rocks used in the analyses are given in Figure 2.

*Limestone-1:*

The dominant mineral is calcite. Calcites are anhedral fine-grained and occasionally found in medium grains. There are randomly formed thin and medium cracks in the rock. The cracks observed in the rock are mostly filled by thin and medium-sized secondary calcites. The rock shows the micritic character (Figure 2a).

Table 1. Geographical and geological origins of the rocks used in this study

| Sample | Sample Code | Origin | Region |
|---|---|---|---|
| Limestone-1 | LS-1 | Sedimentary | Isparta |
| Limestone-2 | LS-2 | Sedimentary | Isparta |
| Limestone-3 | LS-3 | Sedimentary | Antalya |
| Marble | M | Metamorphic | Muğla |
| Andesite | A | Igneous | Isparta |
| Granite | G | Igneous | Aksaray |
| Diabase | D | Igneous | Kayseri |

*Limestone-2:*

The dominant mineral in the rock is dolomite. Crystals are semi-essentially shaped. The crystals are medium-grained and there are coarse grains in places. Dolomite is also observed as vein filling in less observed cracks in the rock. The rock shows micritic and sparitic texture (Figure 2b).

*Limestone-3:*

The dominant mineral is calcite. Calcite crystals are generally rhombic and euhedral and sometimes seen as subhedral. Calcites are fine and medium grain size. The rock has a massive appearance, and no fractures or cracks are observed. However, it may contain some melt gaps. The rock consists of sparitic texture (Figure 2c).

*Marble:*

The rock consists of calcite minerals. Calcites are observed in medium and coarse grain sizes. Crystals exist in subhedral and anhedral forms. Rhomboedric cleavage and polysynthetic twinning are commonly observed in calcites. The rock generally shows a homogeneous feature without fractures or cracks. The rock is in granoblastic texture (Figure 2d).

*Andesite:*

The rock is phenocrystalline mainly composed of amphibole (hornblende), plagioclase, and pyroxene (augite) minerals. On the other hand, there are sanidine and opaque minerals. The rock shows porphyritic, pilotaxic, and glomeroporphyric texture characteristics. Amphiboles are euhedral and subhedral. They are generally hexagonal in shape and cleavage. Brownish interference-colored amphiboles have brownish and dark brown pleochroism. Most of these crystals have become opaque by oxidizing along the edge planes. Pyroxene crystals are observed in the form of thin, long, rod-like crystals. These crystals with a greenish interference color have low pleochroism. Plagioclases have been observed as phenocrysts, generally semi-shaped, plate-like crystals. While it typically shows polysynthetic twinning, it rarely shows zoned extinction. Kaolinization is evident in the rock, in the phenocrysts of sanidine, and in the whole section (Figure2e).

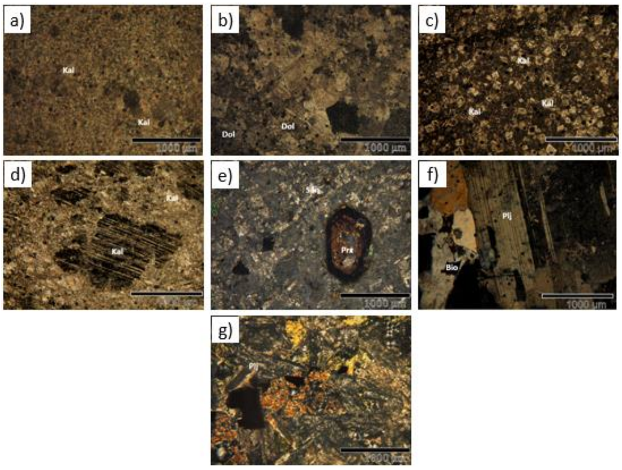


Figure 2. The images of the samples under the polarizing microscope a) limestone-1, b) limestone-2, c) limestone-3, d) marble, e) andesite, f) granite, g) diabase

*Granite:*

Dominant minerals in the rock are plagioclase (oligoclase), alkali feldspar (orthoclase), and quartz. There are fewer amounts of biotite and hornblende. Plagioclases are euhedral and subhedral. It commonly shows polysynthetic twinning and rarely shows zoned extinction. It is generally separated, and clay formation is observed. Orthoclase mineral is less common than plagioclase. Biotites are thin and long rod-like and plate-like shapes. Biotites with brown interference color have brownish pleochrism. Quartz is in the form of anhedral crystals. It is seen as transparent and transparent. They rarely show undulating extinction (Figure 2f).

*Diabase:*

The dominant mineral in the rock is plagioclase and amphibole. There are opaque minerals scattered around. Plagioclases mostly do not show their optical properties due to alteration, but they are grayish-brown in color. They have been observed as long and rod-like crystals. They rarely show polysynthetic twinning. Amphiboles are subhedral and anhedral. Chloritization is generally observed in amphibole minerals (Figure 2g).

### *2.2 Physical and Mechanical Properties*

To describe the investigated rocks in this study some physical and mechanical properties tests were performed in the laboratory. Density, unit volume weight; apparent porosity, and total porosity [37], water absorption percent by weight [38], sound speed propagation [39], Bohme abrasion strength [40], the uniaxial compressive strength [41], Brazilian tensile strength [42], flexural strength under concentrated load [43], and flexural strength under constant moment [44] of the investigated rocks were determined with the related standards and suggested methods. All tests were carried on at least ten samples. The test results were presented in Table 2 and Table 3.

## 3. Point Load Index Tests

Seven different rock types were used in this study and rock blocks were taken from marble processing plants located in different regions of Turkey (Table 1). The investigated natural stones show a wide range of strength and are generally used for building, facing, and flooring applications. All the test specimens were prepared according to the related standards recommended by ISRM [45]. Figure 3 shows the PLI values obtained from 15 different devices and modified devices together. It is seen in Figure 3 how far the values obtained from 15 different devices deviate from each other. The dashed line on the figure is a line drawn from the modified device value. It can be said that this line approximately represents the average of the values obtained from 15 different devices. In Table 4, average PLI values and standard deviation values obtained from 15 different devices and modified device are given. It is seen that especially the standard deviations of the PLI values obtained from the modified test device are smaller than the standard deviations of the PLI values obtained from 15 different test devices.

Table 2. The physical properties of rocks [1]

| Sample Code | $d_0$ (g/cm$^3$) | | UVW (g/cm$^3$) | | WAW (%) | | AP (%) | | TP (%) | *Vp* (m/s) | | BAR cm$^3$/50cm$^2$ | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | x̄ | SD | x̄ | SD | x̄ | SD | x̄ | SD | x̄ | x̄ | SD | x̄ | SD |
| LS-1 | 2.770 | 0.007 | 2.756 | 0.016 | 0.124 | 0.053 | 0.343 | 0.148 | 0.484 | 6627 | 38 | 10.5 | 0.6 |
| LS-2 | 2.851 | 0.009 | 2.714 | 0.009 | 1.173 | 0.119 | 3.183 | 0.313 | 4.788 | 5456 | 688 | 10.0 | 0.7 |
| LS-3 | 2.734 | 0.005 | 2.561 | 0.012 | 2.375 | 0.290 | 6.081 | 0.720 | 9.311 | 5038 | 451 | 14.6 | 0.2 |
| M | 2.725 | 0.002 | 2.713 | 0.001 | 0.076 | 0.015 | 0.206 | 0.040 | 0.440 | 6144 | 723 | 9.1 | 0.9 |
| A | 2.608 | 0.002 | 2.303 | 0.019 | 3.281 | 0.297 | 7.552 | 0.632 | 11.704 | 4875 | 91 | 9.9 | 0.1 |
| G | 2.673 | 0.005 | 2.644 | 0.002 | 0.218 | 0.004 | 0.576 | 0.011 | 1.082 | 5367 | 156 | 4.5 | 0.4 |
| D | 2.994 | 0.012 | 2.904 | 0.030 | 0.656 | 0.076 | 1.902 | 0.204 | 3.011 | 5101 | 152 | 4.5 | 0.5 |

$d_0$: density; UVW: unit volume weight; WAW: water absorption percent by weight; AP: apparent density; TP: total porosity; *Vp*: ultrasonic wave velocity; BAR: Bohme abrasion resistance; x̄: average; SD: standard deviation

Table 3. The mechanical properties of rocks [1]

| Sample Code | $\sigma_c$ (MPa) | | $\sigma_t$ (MPa) | | $\sigma_{fs(cl)}$ (MPa) | | $\sigma_{fs(cm)}$ (MPa) | |
|---|---|---|---|---|---|---|---|---|
| | x̄ | SD | x̄ | SD | x̄ | SD | x̄ | SD |
| LS-1 | 110.6 | 11.1 | 8.4 | 1.3 | 11.6 | 2.5 | 14.2 | 2.7 |
| LS-2 | 103.9 | 12.3 | 8.0 | 1.8 | 8.0 | 1.7 | 13.1 | 2.2 |
| LS-3 | 64.2 | 10.8 | 8.9 | 0.9 | 10.8 | 1.1 | 17.4 | 1.4 |
| M | 72.1 | 5.0 | 8.5 | 1.7 | 13.5 | 2.0 | 21.0 | 0.8 |
| A | 102.4 | 11.5 | 10.0 | 0.6 | 15.7 | 0.8 | 22.9 | 1.4 |
| G | 154.0 | 8.6 | 10.0 | 1.3 | 17.7 | 1.1 | 31.7 | 2.5 |
| D | 144.5 | 15.8 | 11.6 | 1.4 | 17.2 | 2.3 | 24.9 | 1.7 |

$\sigma_c$: uniaxial compressive strength; $\sigma_t$: Brazilian tensile strength; $\sigma_{fs(cl)}$: flexural strength under concentrated load; $\sigma_{fs(cm)}$: flexural strength under constant moment; x̄: average; SD: standard deviation

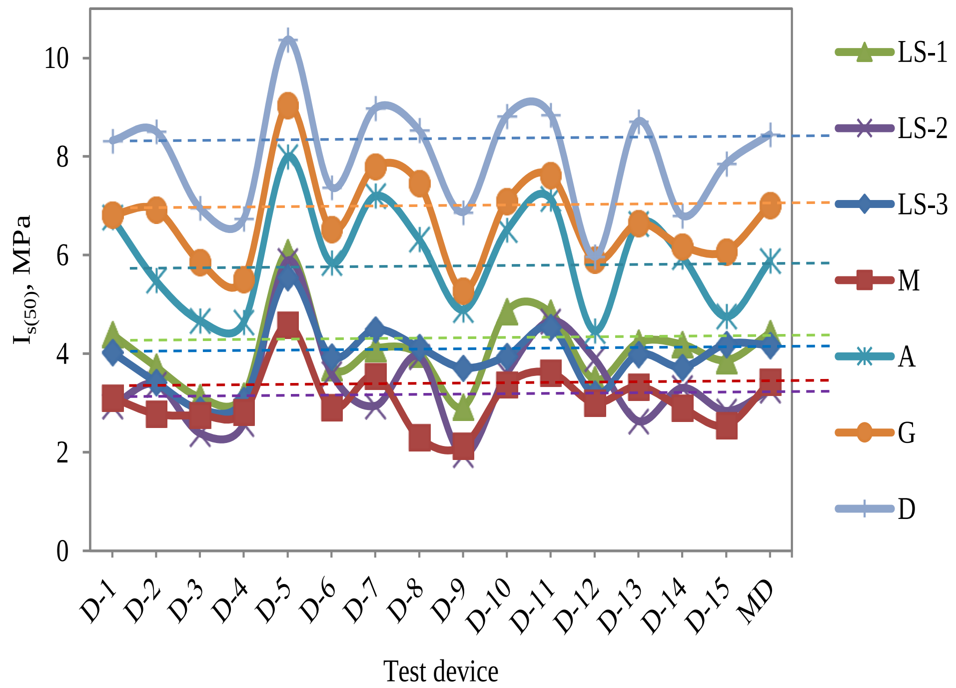


Figure 3. PLI values of the rocks obtained from 15 different PLI test devices and modified test device (D: test device; MD: modified test device)

## 4. Results and Discussions

### *4.1 Experimental Study*

Relationships between PLI values and physical and mechanical properties of the studied rocks were analyzed by the simple regression method and distribution graphs were created (Figure 4 and 5). Significant relationships were found between PLI values (obtained from both 15 different test devices and modified test device) and physical and mechanical properties as expected. It is seen in Table5, the correlation coefficients of the relationships between PLI values obtained from both 15 different test devices and modified test device and determined rock properties were very close. When Figures 4-5 are examined, it is seen that the strongest relationship is between PLI and Brazilian tensile strength with a correlation coefficient of r = 0.96, the weakest relationship is between PLI and *Vp* with a correlation coefficient of r = 0.52 and r = 0.46. The correlation coefficients and their direction and type of relationships between PLI and physical and mechanical properties are given in Table 5. Brazilian tensile strength, flexural strength under concentrated load, and flexural strength under constant moment experiments apply for predicting the tensile strength of rocks. In this study when Table 5 is examined it is seen the correlation coefficients (r) between PLI and Brazilian tensile strength, flexural strength under concentrated load, and flexural strength under constant moment values of the studied rocks are higher than the correlation coefficient (r) between PLI and UCS. This should be interpreted as PLI is more capable of predicting tensile strength than predicting UCS.

Table 4. The PLI values obtained from different test devices [1]

| Sample Code | The average values obtained from 15 different test devices | | Modified test device | | Difference between $I_{s(50)}$ values | Difference between SD values |
|---|---|---|---|---|---|---|
| | $\bar{x}$ $I_{s(50)}$ (MPa) | SD | $\bar{x}$ $I_{s(50)}$ (MPa) | SD | % | % |
| LS-1 | 3.95 | 0.86 | 4.22 | 0.24 | 7 | **-72** |
| LS-2 | 3.29 | 1.27 | 2.76 | 0.98 | **-16** | **-23** |
| LS-3 | 3.84 | 0.40 | 4.14 | 0.22 | 8 | **-45** |
| M | 2.97 | 0.31 | 3.31 | 0.20 | 11 | **-35** |
| A | 5.87 | 0.72 | 5.77 | 0.73 | **-2** | 1 |
| G | 6.64 | 0.63 | 6.96 | 0.23 | 5 | **-63** |
| D | 7.92 | 0.92 | 8.25 | 0.66 | 4 | **-28** |

$\bar{x}$: average; SD: standard deviation

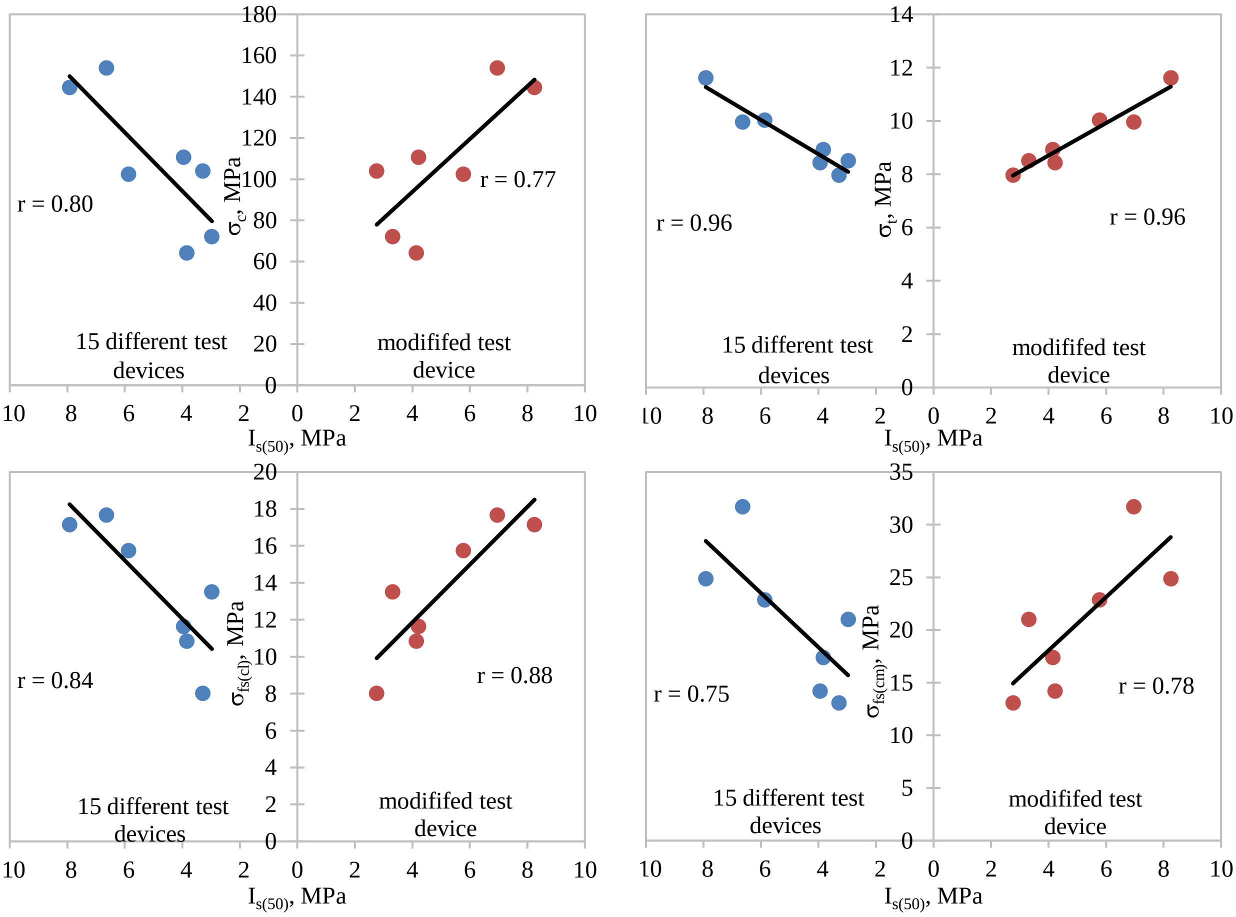


Figure 4. Relationships between PLI and some mechanical properties

### *4.2 Numerical Study*

In the strength tests applied to rock samples in different shapes and sizes, the stress distributions formed on the rock samples were analyzed with ANSYS Workbench 2020 R1. For Young's modulus and poison's ratio values required for static stress analysis, the default values defined for the limestone embedded in the software were used. For Young's modulus and poison's ratio values required for static stress analysis, the default values defined for the limestone embedded in the software were used. The elastic modulus was to be assumed 38 GPa and Poisson's ratio was assumed to be 0.3 [45]. In the analysis, all different shaped and sized samples were subjected to load of the amount required to achieve maximum stress of 5 MPa on cross-section, since the software used was academic version and there were limitations. While performing static stress analysis, Von mises stresses give good results in ductile materials, whereas principal stresses should be considered for brittleness materials such as limestone, marble, granite, etc. As a result of the analysis, maximum principal stress distributions on the surface and inside of the sample for each different test sample are given in Figure 6-10. The positive values show tensile stresses and the negative ones show compressive stresses.

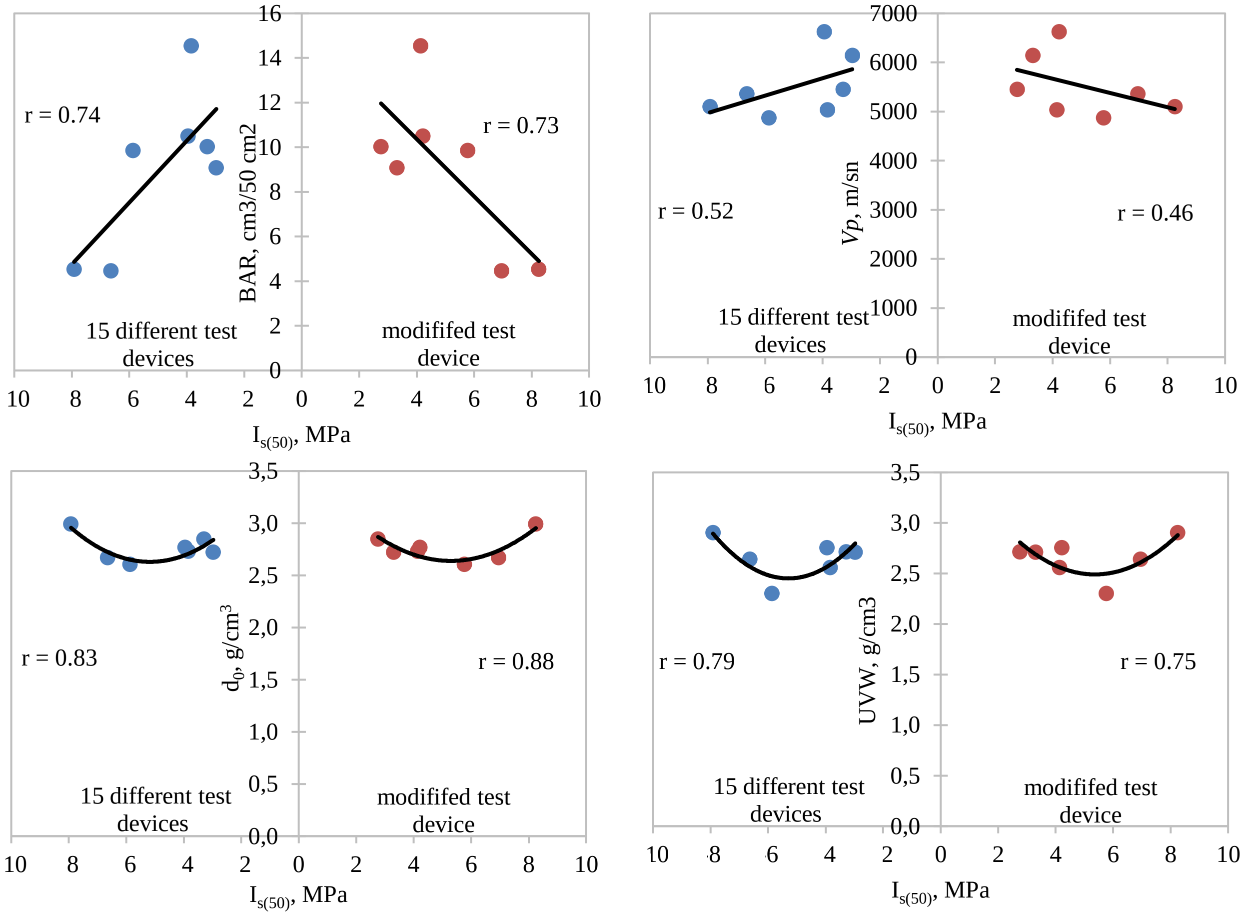


Figure 5. Relationships between PLI and some physical properties

Table 5. Correlations between PLI and physical and mechanical properties of rocks

| Associated property | Correlation coefficient (r) | | Form - direction |
|---|---|---|---|
| | 15 different test devices | Modified test device | |
| $I_{s(50)}$- $\sigma_c$ | 0.80 | 0.77 | Positive linear |
| $I_{s(50)}$- $\sigma_t$ | 0.96 | 0.96 | Positive linear |
| $I_{s(50)}$- $\sigma_{fs(cl)}$ | 0.84 | 0.88 | Positive linear |
| $I_{s(50)}$- $\sigma_{fs(cm)}$ | 0.75 | 0.78 | Positive linear |
| $I_{s(50)}$-BAR | 0.74 | 0.73 | Negative linear |
| $I_{s(50)}$-*Vp* | 0.52 | 0.46 | Negative linear |
| $I_{s(50)}$-$d_0$ | 0.83 | 0.88 | Second-degree polynomial |
| $I_{s(50)}$-UVW | 0.79 | 0.75 | Second-degree polynomial |

$I_{s(50)}$: point load index; $\sigma_c$: uniaxial compressive strength; $\sigma_t$: Brazilian tensile strength; $\sigma_{fs(cl)}$: flexural strength under concentrated load; $\sigma_{fs(cm)}$: flexural strength under constant moment; BAR: Bohme abrasion resistance; *Vp*: ultrasonic wave velocity; $d_0$: density; UVW: unit volume weight

In Figures 6 and 7, it is seen that the vertical applied load induces horizontal tensile stress and the distribution of this tensile stress occurs along a plane running parallel to the load application direction. The failure occurs at the centre of the specimen when the maximum tensile strength of the rock is exceeded. Since the tensile strength of rocks is lower than their compressive strength.

In Figures 8 and 9, a vertical load from the middle of the specimen standing on two supports or vertical loads are applied from two different points close to the middle point. Here, both compression and tensile forces occur in the sample. Compression force occurs on the upper surface of the sample where the load is applied, while tensile stress occurs on the lower surface of the sample. Since the tensile strength of the rocks is lower than the compressive strength, the failure occurs when the tensile strength of the rock is exceeded.

However, when Figure 10 is examined, it is seen that tensile stresses are concentrated in a region close to the lower surface of the sample due to the vertical force applied to the upper surface of the sample.

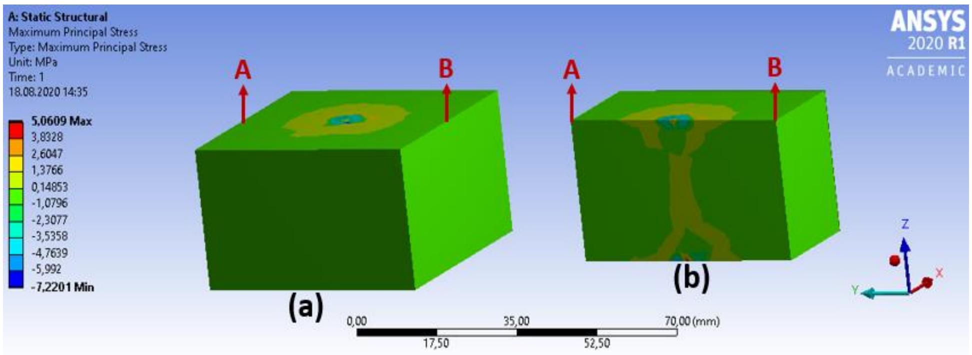


Figure 6. The stress distribution in block point index load tests; a) sample surface, b) section A-B

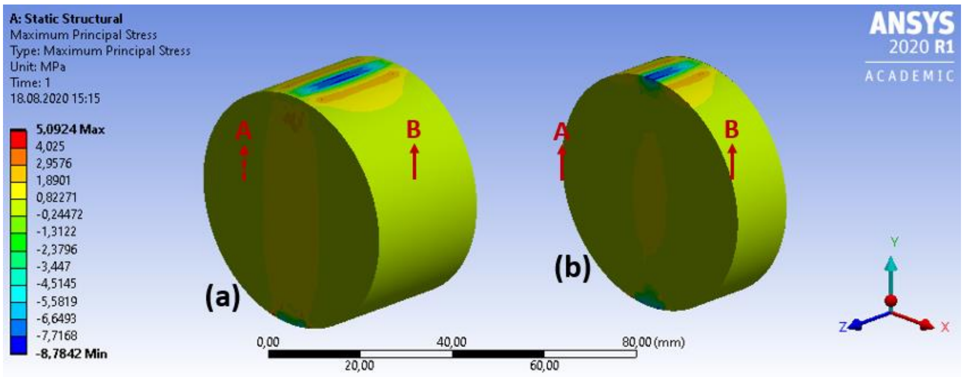


Figure 7. The stress distribution in Brazilian tensile strength tests; a) sample surface, b) section A-B

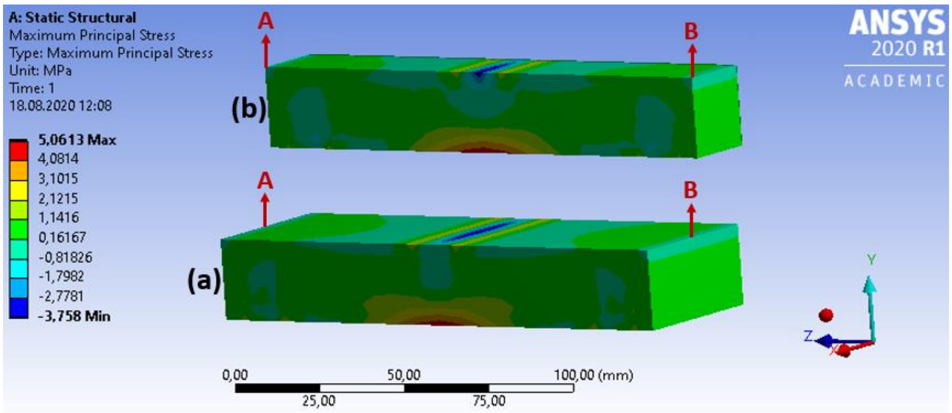


Figure 8. The stress distribution in flexural strength under concentrated load tests; a) sample surface, b) section A-B

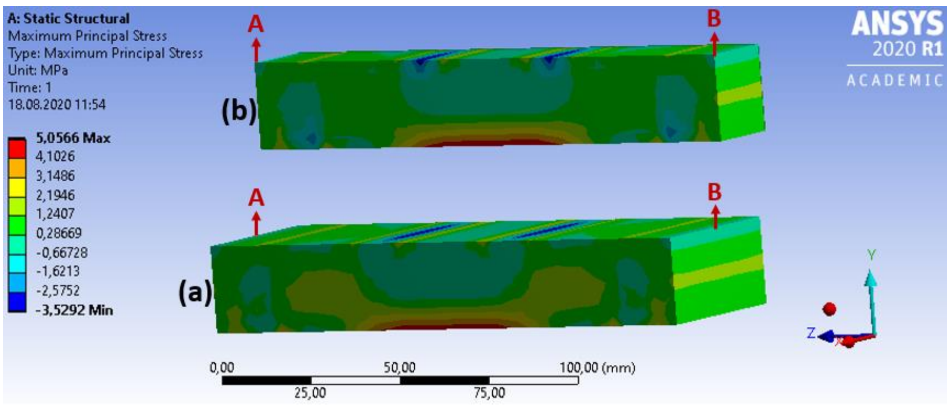


Figure 9. The stress distribution in flexural strength under constant moment tests; a) sample surface, b) section A-B

But in the compressive strength test, the failure occurs when the compressive strength of the rock exceeds along a failure plane. In other words, unlike the test methods mentioned above, the compressive strength of the sample must be exceeded for the failure to occur.

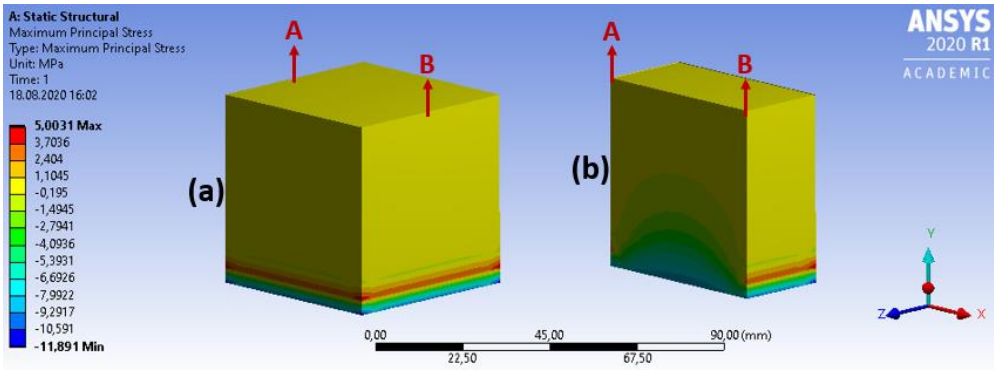

Figure 10. The stress distribution in uniaxial compressive strength tests; a) sample surface, b) section A-B

## 5. Conclusions

The aim of this study is primarily investigating the useability of modified test device instead of classical test device.

As a result of this study, you should repeat the PLI tests on at least 15 different devices to achieve the nearest true PLI. This will take a lot of time and will be costly and you will need a large number of test samples. Or it will be enough to carry out tests just on the modified test device. Also, significant relationships were found between PLI values (obtained from both 15 different test devices and modified test device) and physical and mechanical properties as expected. It is noticed, the correlations of the relations between PLI values obtained from both 15 different test devices and modified test device and determined rock properties were very close. These results also prove the PLI values obtained from the modified test device can be used reliably in predicting rock properties.

Several regression analyses were conducted between the PLI and some physical and mechanical properties using the laboratory test results of this study. According to the results obtained from the analysis, it is established that the strongest relationship is between PLI and Brazilian tensile strength. The performance of each correlation has been measured using linear and nonlinear regression analyses.

The results of the numerical analysis also support the analytical results obtained. The numerical analysis explains the failure mechanisms of each strength test.

## Declaration

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## Author Contributions

D. Akbay and R. Altındağ contributed to the formation of the idea. D. Akbay performed the design and literature review. D. Akbay and R. Altındağ provided the materials used and examined the results. R. Altındağ checked the spelling and checked the article in terms of content.

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