# CORRELATIONS OF POINT LOAD INDEX AND PULSE VELOCITY WITH THE UNIAXIAL COMPRESSIVE STRENGTH FOR ROCKS

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## ABSTRACT:

Rock engineers widely use the uniaxial compressive strength (UCS) of rocks in designing surface and underground structures. The procedure for measuring this rock strength has been standardized by both the International Society for Rock Mechanics (ISRM) and American Society for Testing and Materials (ASTM), **Akram and Bakar(2007)**.

In this paper, an experimental study was performed to correlate of Point Load Index ( $I_{s(50)}$) and Pulse Wave Velocity ($V_p$) to the Unconfined Compressive Strength (UCS) of Rocks. The effect of several parameters was studied. Point load test, Unconfined Compressive Strength (UCS) and Pulse Wave Velocity ($V_p$) were used for testing several rock samples with different diameters.

The predicted empirical correlations based on various test results indicate that the UCS could be obtained directly from measured ($V_p$), and then the Index $I_{s(50)}$ can be calculated by back substitution.

## الخلاصة:

إن مهندسي الصخور يستخدمون بشكل واسع مقاومة الانضغاط المحوري للصخور (UCS) في تصميم المنشات المقامة فوق و تحت سطح الأرض. إن الطريقة الرئيسية لقياس مقاومة الصخور تمت معايرتها دولياً من قبل المجتمع الدولي لميكانيك الصخور (ISRM) و المجتمع الأميركي للفحوص و المواد(ASTM)، **أكرم و بكر(2007)**.

في هذا البحث تم إجراء برنامج عملي لغرض معرفة العلاقة بين دليل الحمل النقطي لنماذج ذو قطر 50 ملم ($I_{s(50)}$) و سرعة الموجات الطولية المارة بالنموذج($V_p$) مع مقاومة الانضغاط اللا محصور (UCS) للصخور. الفحوص دليل الحمل النقطي($I_{s(50)}$)، سرعة الموجات الطولية المارة بالنموذج($V_p$) و مقاومة الانضغاط اللا محصور(UCS) تم إجراءها على نماذج مختلفة من الصخور ذو أقطار مختلفة.

إن العلاقات التجريبية المستنتجة و المستندة على الفحوص المذكورة سابقاً تدل على أن مقاومة الانضغاط اللا محصور يمكن حسابها مباشرة من سرعة الموجات الطولية المقاسة للنماذج و بالتالي يمكن حساب دليل الحمل النقطي لنماذج ذو قطر 50 ملم بالتعويض العكسي.

**KEY WORDS:- Rocks, Uniaxial Compressive Strength (UCS), Modulus of Elasticity($E_s$), Point Load Index ($I_{s(50)}$), Pulse Wave Velocity ($V_p$).**

## INTRODUCTION:

The most two important engineering characteristics of a rock mass are its strength and the discontinuity spacing. In engineering terms, rock strength may be defined as the inherent strength of an isotropic rock under specific conditions, notably wet or dry, Hawkins(1998). The UCS is the geotechnical property that is most often quoted in rock engineering practice.

These methods are time consuming and expensive. Indirect test such as point load index ($I_{s\ (50)}$) as a quick estimation of the UCS is used. The test is easier to carry out because it does not need sample preparation and the testing equipment is less sophisticated, **Akram and Bakar(2007).**

## Scope of the Study:

Unconfined compression tests and point load tests were carried out on different samples taken from Taq Taq Dam project and were used to obtain correlations between unconfined compressive strength UCS versus point load index, and UCS versus longitudinal wave velocity, $V_P$.

The researcher has been done all the tests including Point load index, unconfined compressive strength and ultra sonic waves on different rock core samples.

## Engineering Properties of Rock:

### Strength Test:

1. **Point-Load Index:**

   **Definitions and Calculations:**

   **Broch and Franklin (1972)** started with a simple formula taking an idealized failure plane of a diametric core sample into account **Fig. (1)**.

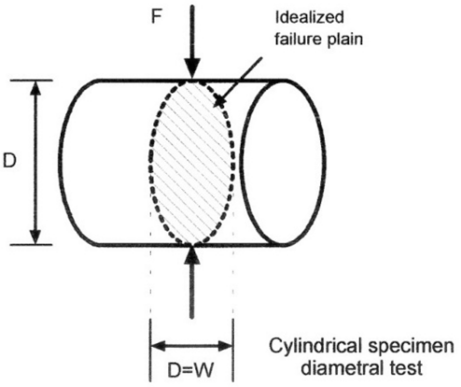

**Fig.(1):** Core specimen's dimensions for a diametric point load test.

$$I_s = \frac{F}{D_e^2} \qquad \text{Eq. (1)}$$

*Where:*

$I_s$ = *point load strength*
$F$ = *load*
$D_e$ = *equivalent core diameter*

Since then, this formula varied little. Taking into account the cross sectional area of the core, the formula rewritten as:

$$I_s = \frac{4F}{\pi D^2} \qquad \text{Eq. (2)}$$

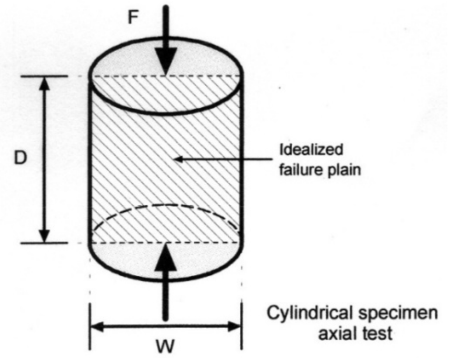

**Fig.(2):** Core Specimen dimensions for an axial point load test.

Users of this test noticed, that the results of a diametric test **Fig.(2**) were about 30% higher the results for an axial test using the same specimen dimensions. **Brook (1985)** and the **ISRM (1985)** suggest a size correction and introducing the "equivalent core diameter":

$$I_s = \frac{F}{D_e^2} = \text{ And}$$

$$W.D = A = \quad \text{Eq. (3)}$$

Where

$I_s$ = point load strength
F = load
$D_e$ = equivalent core diameter
D = thickness of specimen
W = width of specimen
A = minimum cross sectional area of a plane through the platen contact points.

Using the simple physical law σ = F/A, the formula for determining point load strength **(ASTM D 5731-95)** should be:

For cores:

$$I_s = \frac{4F}{\pi D^2} \qquad \text{Eq. (4)}$$

And for blocks and irregular lumps:

$$I_s = \frac{F}{W.D} \qquad \text{Eq. (5)}$$

Given the deficiencies in the derivation by the quoted authors, **Eq. (3)** used for determining the point load index for sake of comparisons.

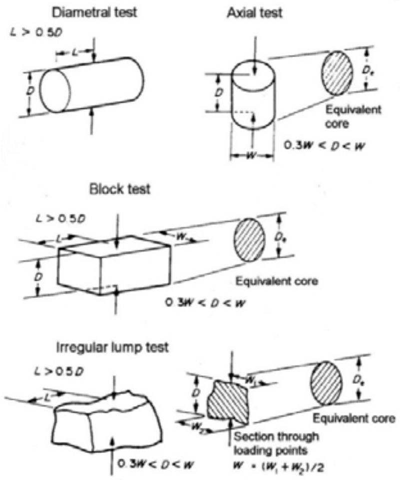

**Fig.(3):** Specimen shape requirements for different test types after **Brook (1985)**,**ISRM (1985)**and **ASTM (D 5731-95).**

## Approaches to Overcome Scale Effects:

Known from the onset of testing, the point load strength is highly dependent on the size of the specimen as well as the shape.

Using thick instead of tall specimens for the block and the irregular lump test and standardizing the general shape of the specimens were steps forward **Broch and Franklin (1972)**, **Brook 1985**. Specimen shape requirements are given in **Fig.(3)** to obtain more reliable testing results with a smaller standard deviation. However, analysis and evaluation were limited by size variation and the lack of a reliable and easy-to-comprehend method for size correction.

**Broch and Franklin (1972)** offered a Size Correction Chart with a set of curves to standardize every value of the point load strength $I_s$ to a point load strength index ($I_{(50)}$) at a diameter of D = 50 mm. The purpose of the function was to describe the correlation between I and D and to answer the question, whether this function is uniform for all rock types or if it depends on the rock type together with grain size, composition of mineral bonds, grain cleavage etc.

**Brook (1985)** and the **ISRM (1985)** suggest three options to evaluate the results of a test set:

1. Testing at D=50 mm only (most reliable after **ISRM (1985)**).
2. Size correction over a range of D or $D_e$ using a log-log plot, **Fig.(4)**. The most reliable method of size correction is to test the specimen over a range of D or $D_e$ values and to plot graphically the relation between P and $D_e$. If a log-log plot is used, the relation is a straight line (see **Fig. 4**). Points that deviate substantially from the straight line may be disregarded (although they should not be deleted). The value of $Is_{(50)}$ corresponding to $D_e$ =50 mm can be obtained by interpolation and use of size-corrected point load strength index calculated as shown in Eq.(7).**ASTM (D 5731-95)**.
3. when testing single-sized core at a diameter other than 50 mm or if only a few small pieces are available, size

correction may be accomplished using the formula containing the"Size Correction Factor" *f*:

$$I_s = f.\frac{F}{D_e^2} = f.\frac{\pi.F}{4.W.D} \qquad \text{Eq. (6)}$$

Where:

$$f = \left(\frac{D_e}{50}\right)^{0.45} = \left(\frac{D_e}{2500}\right)^{0.225} \qquad \text{Eq. (7)}$$

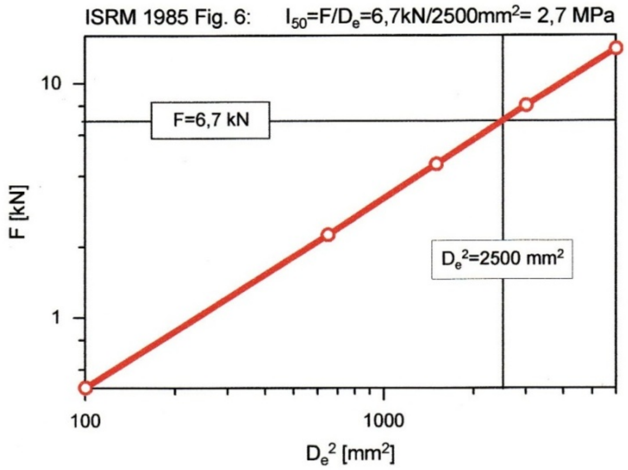

**Fig.(4):** Procedure for graphical determination of I $_{(50)}$ from a set of results at $D_e$ values other than 50 mm **( ISRM 1985).**

## 2. Unconfined Compressive Strength Test (UCS):

Intact rock strength is mostly defined as the strength of the rock material between the discontinuities. Strength values used are often from unconfined compressive strength (UCS) tests **(ASTM D 2938-95)**. **Hack, R and Huisman, M.(2002)** stated the Problems caused by the definition of intact rock strength and using strength values based on UCS laboratory tests are:

1. The UCS includes discontinuity strength for rock masses with small discontinuity spacing. The UCS test sample is most often about 10 cm long and if the discontinuity spacing is, less than 10 cm the core may include discontinuities.
2. Samples tested in the laboratory tend to be of better quality than the average rock because poor rock is often disregarded when drill cores or samples break **(Laubscher, 1990)**, and cannot be tested.
3. The intact rock strength measured depends on the sample orientation if the intact rock exhibits anisotropy.

Unconfined Compression test is the most frequently used strength tests for rocks, yet it is simple to perform properly and results can vary by a factor of more than two as procedures are varied. The test specimen should be a rock cylinder of length to width ratio in the range 2 to 2.5 with flat, smooth, and parallel ends cut perpendicularly to the cylinder axis, **Goodman(1980)**. In the standard laboratory compression test, however, cores obtained during site exploration are usually trimmed and compressed between the crosshead and platen of a testing machine. The compressive strength ($q_u$) is expressed as the ratio of peak load (p) to initial cross-sectional area (A).

$$q_u = \frac{P}{A} \qquad \text{Eq. (8)}$$

## Strength – Deformation Characteristics:

### 1. Elastic Modulation:

For an isotropic and elastic material, the relation between shear and bulk module and Young's modulus and Poisson's ratio are:

$$G = \frac{E}{2(1+\upsilon)} \qquad \text{Eq. (9)}$$

$$k = \frac{E}{3(1-2\upsilon)} \qquad \text{Eq. (10)}$$

Where:

G = shear modulus,
k = bulk modulus,
E = Young's modulus, and
$\upsilon$= Poisson's ratio.

The engineering applicability of these equations is not good if the rock is anisotropic. When possible, it is desirable to conduct tests in the plane of foliation, bedding, etc., and at right angles to it to determine the degree of anisotropy. It is noted that equations developed for isotropic materials may give only approximate calculated results if the difference in elastic module in any two directions is greater than 10 % for a given stress level.

The axial Young's modulus, E, (**ASTM D 3148 – 02)** may be calculated using any of several methods employed in engineering practice. The most common methods are as follows:

1. Tangent modulus at a stress level that is some fixed percentage (usually 50 %) of the maximum strength.
2. Average slope of the more-or-less straight-line portion of the stress-strain curve. The average slope may be calculated either by dividing the change in stress by the change in strain or by making a linear least squares fit to the stress-strain data in the straight-line portion of the curve.
3. Secant modulus, usually from zero stress to some fixed percentage of maximum strength.

## 2. Ultrasonic Testing

Measurement of velocity of sound waves (longitudinal and shear waves) in core specimen **(ASTM D2845-00)** is relatively simple and done by means of Pundit apparatus as shown in **Plate (1).**

**Plate (1):** Ultrasonic testing Apparatus (Pundit Apparatus).

The most popular method pulses one end of the rock with a piezoelectric crystal and receives the vibrations with a second crystal at the other end. The travel time is determined by measuring the phase difference with an oscilloscope equipped with a variable delay line. It is also possible to resonate the rock with a vibrator and then calculate its sonic velocity from the resonant frequency, known dimensions, and density. Both longitudinal and transverse shear wave velocities can be determined.

However, the index test described here requires the determination of only the longitudinal velocity, $V_p$, which proves the easier to measure. **ASTM D2845-00 (2003)** describes laboratory determination of pulse velocities and ultrasonic elastic constants of rock.

Theoretically, the velocity with which stress waves are transmitted through rock depends exclusively upon their elastic properties and their density. In practice, a network of fissures in the specimen superimposes and overriding effect. This being the case, the sonic velocity can serve to index the degree of fissuring within rock specimens.

## Correlation Between uniaxial compressive strength and point load index for rocks:

The point load test has been reported as an indirect measure of the compressive or tensile strength of the rock. **D'Andrea et al (1964)**, performed uniaxial compression and the point load tests on a variety of rocks. They found the following linear regression model to correlate the UCS and $I_{s\,(50)}$:

$$q_u=16.3+15.3I_{s(50)} \quad \text{Eq. (11)}$$

Where:

$q_u$ = Uniaxial Compressive Strength of rock.

$I_{s(50)}$ = Point load index for 50 mm diameter core.

**Broch and Franklin(1972)** reported that for 50 mm diameter cores the uniaxial compressive strength is approximately equal to 24 times the point load index. They also developed a size correction chart so that core of various diameters could be used for strength determination.

$$UCS=24I_{s(50)} \quad \text{Eq. (12)}$$

**Bieniawski(1975)**suggested the following approximate relation between UCS, $I_s$ and the core diameter (D).

$$UCS=(14+0.175D)I_{s(50)} \quad \text{Eq. (13)}$$

**Pells (1975)** showed that the index-to-strength conversion factor of 24 could lead to 20% error in the prediction of compressive strength for rocks such as Dolerite, Norite, and Pyroxenite.

According to **ISRM** commission on standardization of laboratory and field test report **(1985)**, the compressive strength is 20-25 times $I_s$. However, it is also reported that in tests on many different rock types the range varied between 15 and 50, especially for anisotropic rocks. So errors up to 100% should be expected if an arbitrary ration value is chosen to predict compressive strength from point load tests.

**Hassani et al(1985)**performed the point load test on large specimens and revised the size correlation chart commonly used to reference point load values from cores with differing diameters to the standard size of 50mm. with this new correction, they found the ration of UCS to $I_{s(50)}$ be approximately 29.

The dependence of the UCS versus $I_{s(50)}$ correlation on rock types was demonstrated by **Cargill and Shakoor (1990)**. They found the following correlation equation:

$q_u=13+23I_{s(50)}$ Eq. (14)

$q_u=9.08I_s+39.32$ Eq. (17)

**Akram and Baker(2007)**confirm from their study that UCS estimation equations are rock dependent. The UCS was found to be into two groups according to rocks types:

**Group A: (** Jutana Sandstone, Banghanwala Sandstone , Siltstone, Sakessar Massive Limestone, Khewra Sandstone and Dolomite).

$UCS=22.7921Is_{(50)}+13.295$ $R^2=0.88$ Eq. (18)

**Group B: (**Dandot Sandstone, Sakessar Nodular Limestone and Marl)**.**

$UCS=11.076Is_{(50)}$ $R^2=0.8876$ Eq. (19)

**Chau and Wong (1996)** proposed a simple analytical formula for the calculation of the UCS based on corrected $I_s$ to a specimen diameter of 50mm $I_{s(50)}$. The index-to-strength conversion factor (k) relating UCS to $I_{s(50)}$ was reported to depend on the compressive to tensile strength ratio, the Poisson's ratio, the length and the diameter of the rock specimen.

Their theoretical prediction for k = 14.9 was reasonably close to the experimental observation k = 12.5 for Hong Kong rocks.

**Rusnak and Mark (2000)** reported the following relations for different rocks:

For coal measure rocks:

$q_u=23.62I_{s(50)}-2.69$ Eq. (15)

For other rocks:

$q_u=8.41I_{s(50)}+9.51$ Eq. (16)

**Fener et al. (2005)** reported the following relation between Point load index and UCS:

$UCS=143.000\times e^{-0.035t}$ Eq. (20)

Where:
UCS in psi and t is the travel time of the P-wave in micro sec/ft.

## Vp (Longitudinal Waves) with UCS Tests:

Sonic logging has been routinely used for many years in Australia to obtain estimates of coalmine roof rock strength for use in roof support design **(McNally, 1987 and 1990)**. The estimates are obtained through measurements of the travel time of the compression or P wave, determined by running sonic geophysical logs in core holes, which are then correlated with uniaxial compressive strength measurements made on core samples form the same holes.

In **McNally's** classic original study, conducted in **1987**, sonic velocity logs and drill core were obtained from 16 mines throughout the Australian coalfields.

The overall correlation equation **McNally** obtained from least-squares regression was:

**David et.al(2008)**,for the entire data set of coal mine roof rocks in Australia, the relationship between UCS and sonic travel time is expressed by the following equation, where UCS is in psi and t is the travel time of the P-wave in micro sec/ft.

$$UCS=468.000\times e^{-0.054t} \qquad \text{Eq. (21)}$$

The r-squared value($R^2$) for this equation is 0.87, indicating that a strong correlation between sonic travel time and UCS can be achieved with this technique.

## Experimental Work:

### General

Rock core samples were taken from Taq Taq Dam project and used for mechanical properties tests (Point- load, Unconfined Compressive strength, and Ultrasonic Pulse velocity). The project was done between August and November of 2006. This dam site is situated in Lesser Zab River, upstream from Taq Taq Dam, and the roadway from Kirkuk to KoisanjEq.

### 1. Point load tests Data:

Point load tests were carried out and the results were listed in **Table (1)**. This table illustrates Bore hole No., Depths, Diameter and $I_{50}$. An attempt was made to correlate ($I_{50}$) with many variables such as Depth, water content and Diameter. The following **Figures (5), (6),** and **(7)** which shows the relations between ($I_{50}$) and water content, ($I_{50}$) and depths, ($I_{50}$) and diameter. For each graph $R^2$-values was taken into account.

### 2.Unconfined compressive strength tests Data:

Unconfined compressive strength tests were carried out and the results were listed in **Table (2)**. This table illustrates Borehole No., Depths, Unconfined compressive strength, and Modulus of Elasticity. In addition, an attempt was made to correlate (UCS) with many variables such as depths, water content, ($I_{50}$) and Modulus of elasticity. The following **Figures(8),(9)** and **(10)** show the relations between(UCS) and water content, (UCS) and depths, (UCS) and Modulus of elasticity, (UCS) and ($I_{50}$).

### 3.Ultrasonic Pulse Velocity tests Data:

Ultrasonic Pulse velocity tests were carried out and the results are listed in **Table(3)**. This table illustrates Borehole No., Depths, water content, and Pulse velocity.

Here, an attempt was made to correlate. ($V_p$) with many variables such as Depths, water content and UCS. The following **Figures (11), (12),** and **(13)** which show the relations between $V_P$ and water content, $V_P$ and Depths, $V_P$ and UCS.

**Table (1):** Point Load Index of Rock Cores.

| Borehole No. | Depth(m) | P(kN) | D(mm) | $w_n$,% | $\gamma_t$(kN/m$^3$) | $I_s$, MPa | Factor* | $Is_{(50)}$, MPa |
|---|---|---|---|---|---|---|---|---|
| BR-5 | 10-12 | 4.5 | 85 | 3.80 | 22.80 | 0.623 | 1.2697 | 0.791 |
| | 12-14 | 4.71 | 81.33 | 0.54 | 22.40 | 0.712 | 1.2447 | 0.886 |
| | 37-39 | 3.299 | 78.86 | 5 | 22.97 | 0.530 | 1.2276 | 0.651 |
| | 67-69 | 4.71 | 67.50 | 4.5 | 21.51 | 1.034 | 1.1446 | 1.183 |
| BR-6 | 30-33 | 5.298 | 77.73 | 4.44 | 22.66 | 0.877 | 1.2196 | 1.069 |
| | 40-42 | 5.892 | 84.6 | 3.03 | 22.75 | 0.823 | 1.2670 | 1.043 |
| | 48-50 | 4.223 | 82.72 | 10.4 | 22.33 | 0.617 | 1.2543 | 0.774 |
| | 53-55 | 5.298 | 83.89 | 2.85 | 23.02 | 0.753 | 1.2622 | 0.950 |
| BR-9 | 28-29 | 6.484 | 82.86 | 9.25 | 21.84 | 0.944 | 1.2552 | 1.185 |
| | 48-50 | 3.299 | 82.17 | 2.17 | 22.85 | 0.489 | 1.2505 | 0.611 |
| | 87-89 | 1.33 | 83.26 | 2.56 | 20.29 | 0.192 | 1.2579 | 0.241 |
| BR-10 | 12.5-14.45 | 1.489 | 79.75 | 4.83 | 21.32 | 0.234 | 1.2337 | 0.289 |
| | 22-24 | 1.112 | 80.27 | 6 | 20.87 | 0.172 | 1.2374 | 0.213 |
| | 58.8-61 | 0.5776 | 69.62 | 9.5 | 21.37 | 0.119 | 1.1606 | 0.138 |
| BR-12 | 52.5-54.3 | 4.806 | 62.70 | 6.06 | 23.00 | 1.222 | 1.1072 | 1.353 |
| | 58-60 | 1.501 | 62.70 | 11.25 | 22.00 | 0.382 | 1.1072 | 0.423 |
| | 61.5-63 | 2.376 | 65.70 | 5 | 24.30 | 0.550 | 1.1307 | 0.622 |
| | 75.4-76.7 | 6.188 | 66.80 | 3.4 | 23.10 | 1.387 | 1.1392 | 1.579 |
| | 84.3-85.7 | 6.188 | 68.70 | 11.1 | 23.38 | 1.311 | 1.1537 | 1.513 |
| BR-14 | 26-28 | 3.421 | 81.79 | 1.449 | 21.89 | 0.511 | 1.2479 | 0.638 |
| | 30-32 | 3.8159 | 78.45 | 1.33 | 22.574 | 0.620 | 1.2247 | 0.759 |
| | 46.3-48 | 5.133 | 82.88 | 1.17 | 22.914 | 0.747 | 1.2553 | 0.938 |
| | 52-54 | 4.5877 | 82.75 | 3 | 22.237 | 0.669 | 1.2545 | 0.840 |
| BR-15 | 9.5-12 | 4.709 | 74.90 | 12.85 | 21.94 | 0.839 | 1.1994 | 1.007 |
| | 13.2-14.2 | 3.445 | 81.92 | 2.86 | 22.44 | 0.513 | 1.2488 | 0.641 |
| | 19-21 | 3.202 | 79.38 | 4.41 | 21.95 | 0.508 | 1.2312 | 0.626 |
| | 25-27 | 5.8918 | 81.76 | 5 | 21.49 | 0.881 | 1.2477 | 1.099 |
| | 40-42 | 2.522 | 78.80 | 9.21 | 20.88 | 0.406 | 1.2271 | 0.498 |
| BR-16 | 6-8 | 1.1609 | 78.37 | 13.33 | 20.14 | 0.189 | 1.2241 | 0.231 |
| | 9-11 | 6.485 | 82.58 | 5.80 | 22.74 | 0.951 | 1.2533 | 1.192 |
| | 34.5-35.9 | 8.857 | 81.90 | 7.30 | 23.87 | 1.320 | 1.2486 | 1.649 |
| BR-18 | 13-15 | 2.206 | 76.60 | 4.54 | 22.5 | 0.376 | 1.2116 | 0.455 |
| | 21.2-23 | 9.747 | 84.90 | 5.35 | 23.56 | 1.352 | 1.2690 | 1.716 |
| | 27-28.5 | 1.088 | 80.40 | 7.5 | 22.5 | 0.168 | 1.2383 | 0.208 |
| BR-19 | 12-14 | 5.892 | 67.92 | 3.389 | 22.76 | 1.277 | 1.1478 | 1.466 |
| BR-21 | 25.6-27 | 4.223 | 78.48 | 6.55 | 22.93 | 0.686 | 1.2249 | 0.839 |
| | 36.5-38.6 | 4.7056 | 82.0 | 9.09 | 24.457 | 0.699 | 1.2493 | 0.874 |
| | 40-41.7 | 2.7163 | 78.6 | 8.75 | 23.28 | 0.440 | 1.2257 | 0.539 |
| | 43.6-45 | 1.744 | 77.78 | 8.823 | 22.68 | 0.288 | 1.2199 | 0.352 |
| | 48-50 | 2.424 | 85.7 | 8.57 | 22.56 | 0.330 | 1.2744 | 0.421 |
| BR-26 | 12-13.35 | 1.403 | 62.54 | 8.57 | 22.05 | 0.359 | 1.1059 | 0.397 |
| | 24-27 | 4.5148 | 64.49 | 3.16 | 23.274 | 1.085 | 1.1213 | 1.217 |
| BR-28 | 27-30 | 3.105 | 65.5 | 3.33 | 21.98 | 0.724 | 1.1292 | 0.817 |
| BR-29 | 10.5-12.5 | 1.696 | 78.00 | 8.196 | 22.41 | 0.279 | 1.2215 | 0.340 |
| | 21-22.9 | 6.485 | 79.40 | 4.225 | 22.81 | 1.029 | 1.2313 | 1.267 |
| | 40.6-42.6 | 0.893 | 71.40 | 1.29 | 19.03 | 0.175 | 1.1739 | 0.206 |
| BR-30 | 21-22.6 | 14.195 | 80.60 | 1.56 | 24.13 | 2.185 | 1.2397 | 2.709 |
| | 34-35.4 | 10.637 | 84.00 | 1.90 | 23.35 | 1.507 | 1.263 | 1.904 |

*: Factor was calculated using Eq.7.

**Table (2):** Unconfined Compressive Strength of Rock Cores.

| Borehole No. | Depth(m) | $w_n$,% | $\gamma_t$(kN/m$^3$) | UCS(kPa) | Modulus of Elasticity, $E_s$, kPa |
|---|---|---|---|---|---|
| BR-5 | 10-11 | 3.80 | 20.65 | 10601.35 | 76821.37 |
| | 11-12 | 4.68 | 21.613 | 12216.58 | 143724.47 |
| | 12-14 | 0.54 | 22.23 | 9846.05 | 209490.42 |
| | 12-14 | 1.163 | 22.20 | 9211.22 | 237708.87 |
| | 37-39 | 3.45 | 25.84 | 12531.81 | 305653.90 |
| | 67-69 | 4 | 22.736 | 16711.25 | 263169.29 |
| | 67-69 | 4.477 | 22.87 | 19312.88 | 603527.5 |
| BR-6 | 30-33 | 8.33 | 22.608 | 13517.72 | 318064.0 |
| | 40-42 | 5.8 | 22.76 | 13600.85 | 261554.8 |
| | 48-50 | 8.5 | 22.74 | 13052.8 | 326320.0 |
| | 53-55 | 6.25 | 22.65 | 8739.387 | 268904.2 |
| BR-9 | 28-30 | 5.45 | 22.32 | 11663.4 | 466536.0 |
| | 48-49 | 8.69 | 22.82 | 12461.32 | 377615.75 |
| | 49-50 | 5.71 | 22.61 | 7228.94 | 301205.9 |
| | 87-88 | 2.439 | 19 | 3473.011 | 231534.06 |
| | 88-89 | 2.56 | 20.56 | 3301.016 | 165050.8 |
| BR-10 | 22-24 | 6 | 22.15 | 11395.02 | 245054.19 |
| | 58.8-60 | 9.09 | 21.034 | 1160.17 | 45274.77 |
| | 60-61 | 8.5 | 23.69 | 8203.99 | 468799.43 |
| BR-12 | 52.5-54.3 | 8.62 | 23.076 | 7896.64 | 382867.2 |
| | 58-60 | 10.526 | 21.98 | 9707.13 | 351707.6 |
| | 61.5-63 | 5 | 24.46 | 7229.68 | 444903.26 |
| | 75.4-76.7 | 5.4 | 21.91 | 5024.56 | 341806.66 |
| | 75.4-76.7 | 3.389 | 23.695 | 19246.80 | 466589.09 |
| | 84.3-85.7 | 8.51 | 23.50 | 6216.40 | 382547.4 |
| | 84.3-85.7 | 6.25 | 24.12 | 6769.08 | 338453.95 |
| BR-14 | 26-28 | 2.3 | 22.138 | 13005.44 | 394104.24 |
| | 30-32 | 2.0408 | 24.107 | 17772.37 | 253891.0 |
| | 46.3-48 | 2.0408 | 22.5 | 8021.836 | 320873.44 |
| | | 3.508 | 21.768 | 7969.121 | 306504.65 |
| | 52-54 | 3.1 | 22.906 | 19120.98 | 354092.22 |
| BR-15 | 9.5-12 | 4.59 | 21.52 | 4170.99 | 196466.6 |
| | 19-21 | 4.3 | 22.306 | 16818.41 | 538188.8 |
| | 25-26 | 10.42 | 21.55 | 6841.88 | 273675.2 |
| | 26-27 | 5.36 | 21.81 | 14093.83 | 281876.6 |
| | 40-42 | 3.45 | 22.53 | 6639.58 | 295749.71 |
| BR-16 | 6-8 | 12.90 | 20.14 | 7629.10 | 142068.93 |
| | 9-11 | 3.225 | 24.165 | 8189.46 | 314979.11 |
| | 34.5-35.9 | 7.31 | 22.083 | 9883.18 | 299490.5 |
| BR-18 | 13-15 | 8.1 | 23.09 | 10772.89 | 319196.7 |
| | 21.2-23 | 5 | 22.44 | 10032.43 | 209008.9 |
| | 27-28.5 | 9.43 | 22.99 | 10224.75 | 176287.93 |
| BR-19 | 12-14 | 3.846 | 22.60 | 20998.04 | 430729.02 |
| BR-21 | 25.6-27 | 6.97 | 23.18 | 13175.71 | 274493.96 |
| | 25.6-27 | 7.69 | 23.07 | 2362.926 | 315056.8 |
| | 36.5-38.6 | 7.55 | 23.75 | 11395.77 | 633098.3 |
| | 40-41.7 | 9.302 | 22.95 | 12868.43 | 419168.73 |
| | 43.6-45 | 9.876 | 22.159 | 10717.26 | 297701.6 |
| | 48-50 | 9.305 | 22.905 | 12768.42 | 283742.67 |
| BR-26 | 12-13.35 | 7.35 | 23.502 | 10149.36 | 563853.33 |
| | 24-27 | 5.714 | 23.96 | 12578.9 | 314472.5 |
| BR-28 | 27-30 | 2.5 | 22.338 | 11355.99 | 239073.47 |
| | 27-30 | 2.23 | 21.988 | 11653.64 | 448216.92 |
| BR-29 | 10.5-12.5 | 6.78 | 22.76 | 4544.37 | 186435.69 |
| | 21-22.9 | 5.88 | 21.96 | 8866.92 | 73891.0 |
| | 40.6-42.6 | 2.857 | 24.014 | 8503.94 | 219456.5 |
| BR-30 | 21-22.6 | 1.4 | 22.66 | 18422.68 | 1842268.0 |
| | 34-35.4 | 1.56 | 23.75 | 14907.70 | 425934.28 |

**Table (3):** Ultrasonic Velocity of Longitudinal Wave.

| Borehole No. | Depth(m) | L(mm) | D(mm) | $w_n$,% | $\gamma_t$ (kN/m³) | $V_p$(km/s) |
|---|---|---|---|---|---|---|
| BR-5 | 10-12 | 168 | 83.9 | 3.80 | 22.70 | 1.486 |
| | 12-14 | 224 | 82.12 | 4.60 | 22.22 | 1.583 |
| | 37-39 | 202 | 79.81 | 3.50 | 23.22 | 1.909 |
| | 67-68 | 98.52 | 66.16 | 4.00 | 22.35 | 1.753 |
| | 68-69 | 147.47 | 65.26 | 4.50 | 22.62 | 1.559 |
| BR-6 | 30-33 | 196.68 | 77.73 | 4.44 | 22.66 | 1.633 |
| | 40-42 | 194.12 | 84.6 | 3.03 | 22.74 | 1.596 |
| | 48-50 | 212 | 82.72 | 10.4 | 22.33 | 1.867 |
| | 53-55 | 202.28 | 83.89 | 2.85 | 23.02 | 2.015 |
| BR-9 | 28-29 | 203.42 | 82.85 | 3.92 | 22.50 | 2.209 |
| | 29-30 | 193.43 | 82.86 | 9.25 | 21.84 | 2.203 |
| | 48-49 | 190.32 | 82.06 | 6.72 | 22.82 | 2.239 |
| | 49-50 | 201.68 | 81.79 | 8.69 | 22.74 | 2.112 |
| | 48-49 | 116.45 | 82.17 | 2.17 | 22.85 | 2.065 |
| | 87-88 | 197.82 | 83.32 | 2.56 | 20.49 | 1.199 |
| | 87-88 | 161.64 | 83.27 | 2.7 | 20.516 | 1.013 |
| | 88-89 | 145.32 | 83.26 | 2.6 | 20.298 | 1.056 |
| BR-10 | 12.5-14.45 | 81.55 | 80.05 | 5 | 21.32 | 1.742 |
| | 22-24 | 140.46 | 80.27 | 6 | 20.87 | 1.027 |
| | 58.8-61 | 157.75 | 62.18 | 9.1 | 23.69 | 1.860 |
| BR-12 | 52.5-54.3 | 15.3 | 62.7 | 6.3 | 23.1 | 0.245 |
| | 58-60 | 160 | 62.4 | 12 | 22.2 | 2.435 |
| | 58-60 | 160 | 62.7 | 12.7 | 22.3 | 2.363 |
| | 61.5-63 | 160 | 65.7 | 13 | 24.3 | 2.689 |
| | 75.4-76.7 | 160 | 66.8 | 6.4 | 24.1 | 2.488 |
| | 84.3-85.7 | 162 | 68.7 | 11.1 | 23.38 | 2.70 |
| BR-14 | 26-28 | 201 | 81.79 | 1.45 | 21.89 | 1.595 |
| | 30-32 | 141.44 | 78.45 | 1.33 | 22.57 | 1.704 |
| | 46.3-48 | 195.03 | 82.88 | 1.17 | 22.914 | 1.923 |
| | 52-54 | 161.28 | 82.75 | 3 | 22.237 | 1.708 |
| BR-15 | 9.5-12 | 148 | 74.9 | 13 | 21.94 | 1.465 |
| | | 130 | 77.8 | 12.5 | 21.19 | 2.063 |
| | 13.2-14.2 | 75.99 | 81.92 | 2.85 | 22.695 | 2.524 |
| | 19-21 | 168.78 | 79.38 | 4.41 | 21.956 | 1.582 |
| | 25-27 | 166.75 | 81.76 | 5 | 21.497 | 1.799 |
| | 40-42 | 120 | 78.8 | 8.1 | 20.88 | 1.832 |
| BR-16 | 6-8 | 130.44 | 78.37 | 13.4 | 20.136 | 0.162 |
| | 8-9 | 118.55 | 82.58 | 5.88 | 22.74 | 1.39 |
| | 11-12 | 127.53 | 83.63 | 6.12 | 21.99 | 0.658 |
| | 34.5-35.9 | 198.97 | 79.57 | 6.8 | 22.08 | 1.93 |
| | 34.5-35.9 | 199 | 81.9 | 7.1 | 23.875 | 2.149 |
| BR-18 | 13-15 | 150 | 76.6 | 4.5 | 22.51 | 1.961 |
| | 21.2-23 | 195 | 84.9 | 5.1 | 23.56 | 2.281 |
| | 27-28.5 | 100 | 80.4 | 6.5 | 22.55 | 1.244 |
| BR-19 | 12-14 | 171.35 | 67.92 | 3.39 | 22.76 | 1.875 |
| BR-21 | 25.6-27 | 196.52 | 78.48 | 6.55 | 24.457 | 2.568 |
| | 36.5-38.6 | 200.5 | 82 | 9.09 | 22.93 | 2.724 |
| | 40-41.7 | 160.18 | 78.6 | 8.75 | 23.28 | 2.625 |
| | 43.6-45 | 169.25 | 77.78 | 8.82 | 22.68 | 1.6625 |
| | 48-50 | 200 | 80 | 8.57 | 22.56 | 2.164 |
| BR-26 | 12-13.35 | 129.62 | 62.54 | 8.57 | 22.05 | 1.865 |
| | 24-27 | 150.44 | 64.49 | 3.16 | 23.27 | 1.97 |
| BR-28 | 27-30 | 150.32 | 65.02 | 3.33 | 22.4 | 1.886 |
| BR-29 | 10.5-12.5 | 128 | 78 | 8.33 | 22.41 | 1.164 |
| | 21-22.9 | 192.3 | 79.4 | 4.25 | 22.81 | 1.966 |
| | 21-22.9 | 207 | 77.4 | 6.25 | 22.95 | 1.026 |
| | 40.6-42.6 | 161.3 | 71.4 | 1.3 | 19.09 | 1.078 |
| BR-30 | 21-22.6 | 190 | 80.6 | 1.45 | 24.14 | 2.378 |
| | 34-35.4 | 215 | 84 | 1.6 | 23.35 | 2.183 |

## RESULTS AND DISCSSIONS:

### 1. Relations between ($I_{50}$) and water contents, depths, and diameters:

#### A. Relationship between Point-load Index and water content:

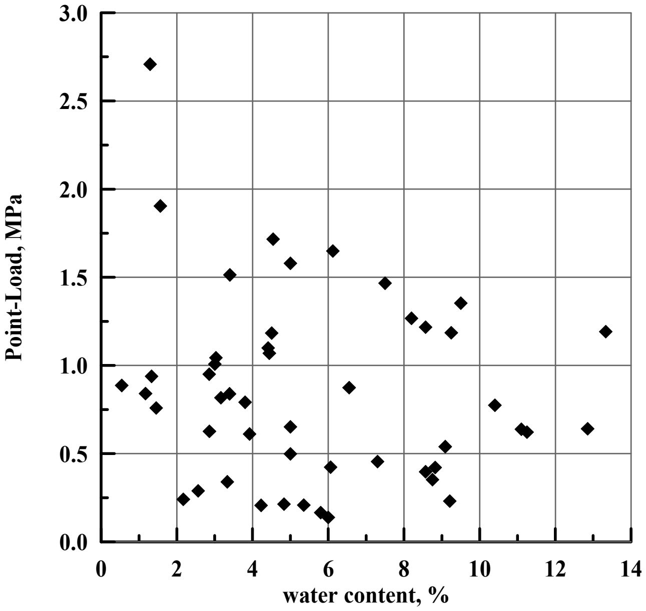

**Fig.(5):** Relationship between Point-load Index and water content.

#### B. Relationship between Point-load Index and depths:

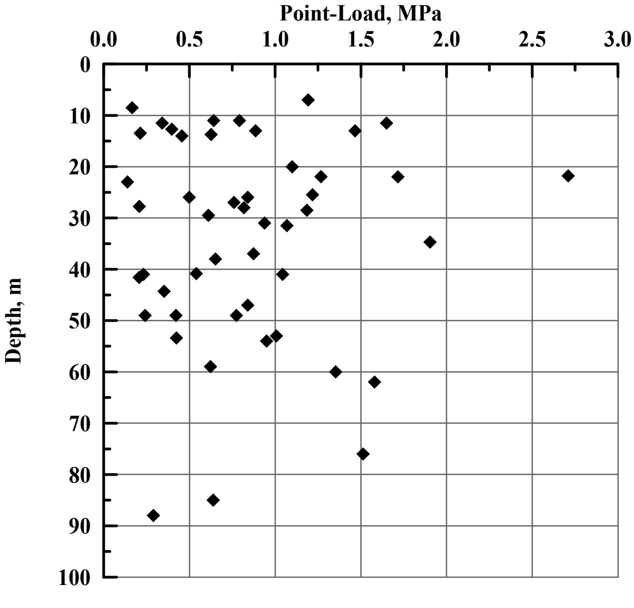

**Fig.(6):** Relationship between Point-load Index and depths.

From the previous graphs, despite the scatter in the data, the following points may be concluded:

1. There is a marked decrease in point load index with increasing water content up to 14% which reflect the field conditions as cited by **Hawkins(1986)**.
2. The point load index decreased with increasing depth.
3. The lower values of the point load index of all tested rock core samples are classified as sedimentary rocks which mainly consist of feldspar, Calcite, gypsum, chert, Mica,Biotite and Iron oxide.

### 2. Relations between UCS and water contents, depths, and (I50):

#### A. Relations between UCS and water content:

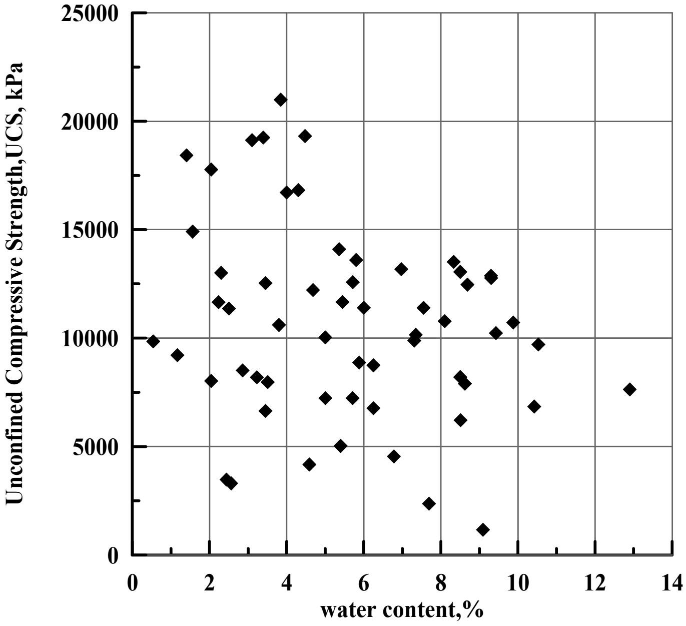

**Fig.(7):** Relationship between UCS and water content.

### B. Relations between UCS and depth:

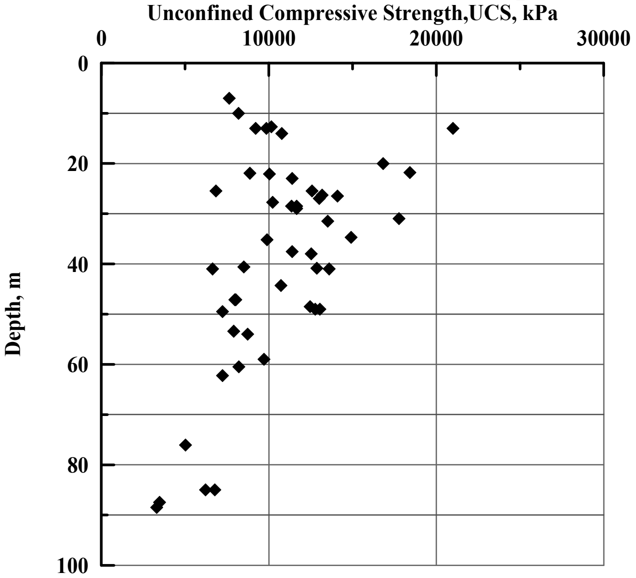

**Fig.(8):** Relationship between UCS and depth.

### C. Relations between UCS and ($I_{50}$):

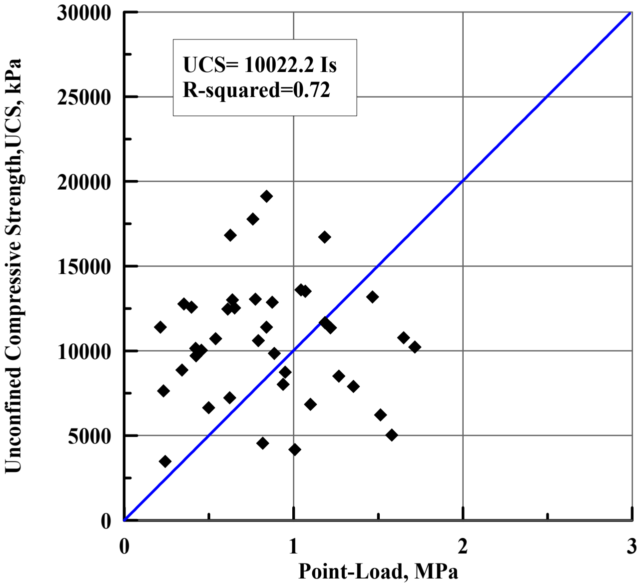

**Fig.(9):** Established Relationship between UCS and Point-load Index.

From the previous graphs, the following points may be derived:

1. The UCS decreased as the water content increased.
2. The UCS decreased as the depth increased which is similar to point load behaviour.
3. The UCS can be related with the point load index by:

$UCS(kPa)=10022.2I_{s(50)}(MPa)$ $R^2=0.72$ Eq. (22)

This low strength range might be influenced by physical characteristics, such as size, saturation, weathering and mineral content. These results reveal that the sensitivity of rock strength due to changes in moisture content seems to vary from rock to rock. As cited by **Agustawijaya (2007)**,this sensitivity depends on the clay content of the rock being investigated. Also **Agustawijaya (2007)** pointed out that weaker sandstones are more sensitive to changes in moisture content than harder rocks and concluded that the texture of the rock, that is the proportion of grain contact, is responsible for reductions in the strength of sandstone. Further, he found that an increase in moisture content tends to decrease the range of elastic behaviour of sandstone.

It was concluded that variability in occurrences of quartz intragranular cracks and in Biotite percentage, distribution and orientation might have played a key role in accelerating or decelerating the failure processes, **Basu, Celestino and Bortolucci (2008)**.

### 3.Relations between $V_p$ and water contents, depths, and UCS:

#### A. Relations between $V_p$ and water contents:

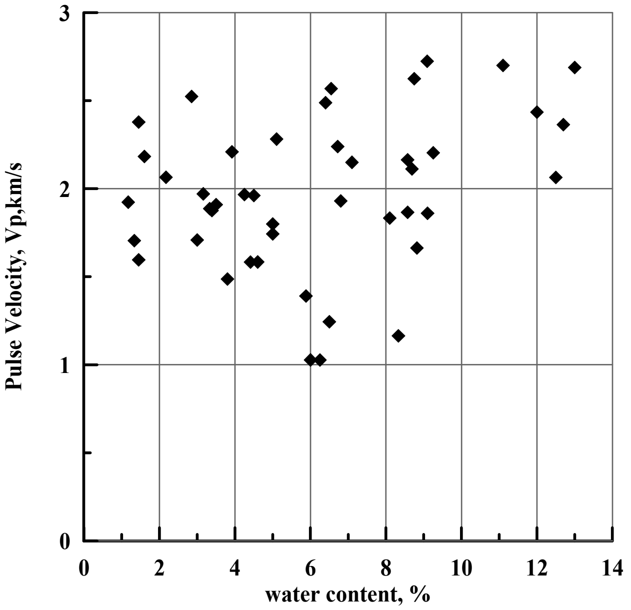

**Fig.(10):** Relationship between $V_p$ and water content.

### B. Relations between $V_p$ and depths:

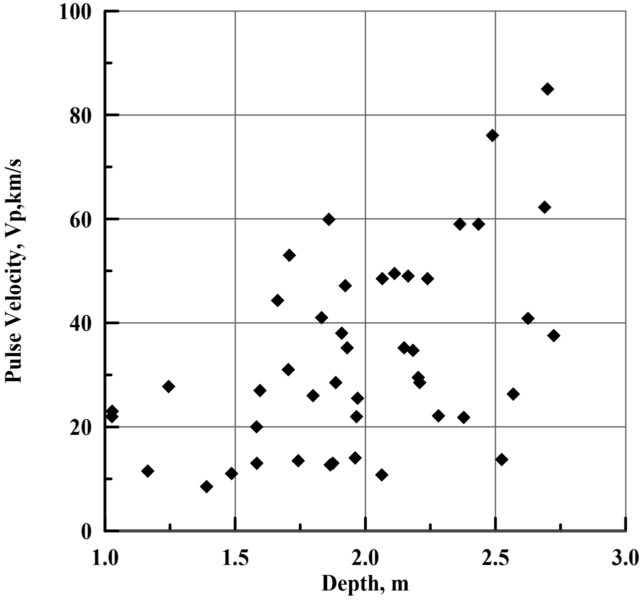

**Fig.(11):** Relationship between $V_p$ and depths.

### C. Relations between $V_p$ and UCS:

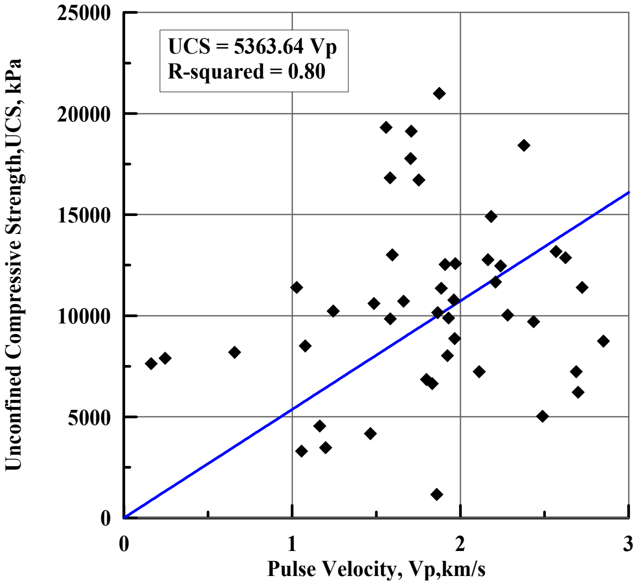

**Fig.(12):** Established Relationship between UCS and $V_p$.

From the previous graphs, the following points may be derived:

1. There is no obvious trend showing $V_p$, pulse velocity increase or decrease with increasing water content.
2. The pulse velocity, $V_p$ increases with increasing depth due to densification and stratification of layered sedimentary rocks.
3. The UCS can be also related with pulse velocity:

   UCS (kPa) = 5363.64 $V_p$ (km/sec) $R^2$= 0.80 Eq. (23)

## CONCLUSIONS AND RECOMMENDATIONS:

1. An attempt has been made to correlate UCS with ($I_{50}$).
2. The pulse velocity, $V_p$, increased with increasing water content and depths.
3. An equation has been found to correlate UCS with $V_p$.
4. For the correlations obtained, it is obvious that when $V_p$ measured, the UCS can be calculated immediately, and then can be determined by back substitution of UCS in point load correlation.
5. There is no obvious trend for some relations.
6. Further study is needed to study the effect of discontinuity of rock on point load Index, UCS and $V_p$. Effect of saturation of rocks on engineering properties, and to study the possibility of using Schmidt hammer as an indication of UCS test result.

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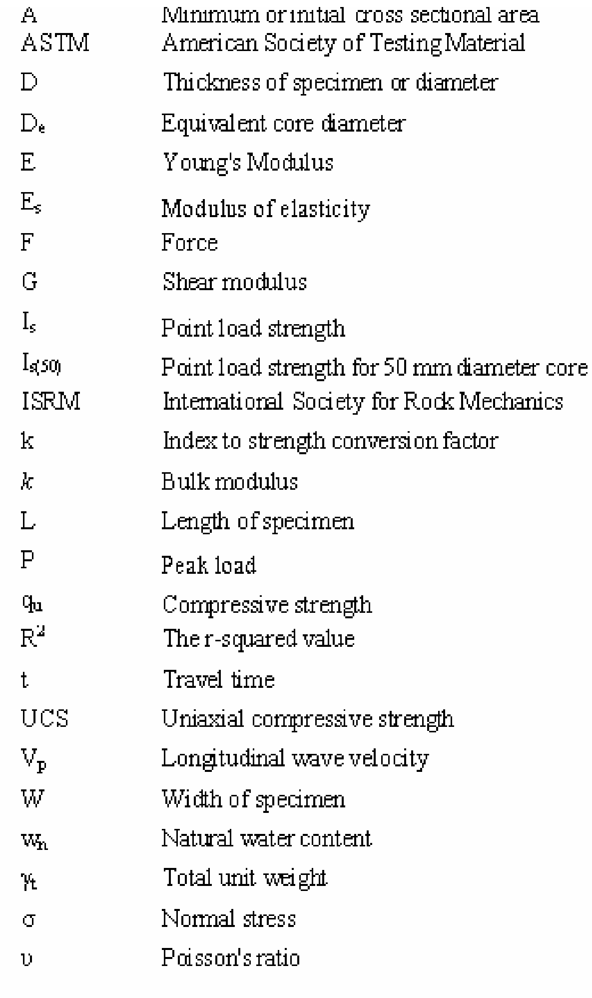
## ABBREVIATIONS AND NOTATIONS:



| | |
|---|---|
| A | Minimum or initial cross sectional area |
| ASTM | American Society of Testing Material |
| D | Thickness of specimen or diameter |
| $D_e$ | Equivalent core diameter |
| E | Young's Modulus |
| $E_s$ | Modulus of elasticity |
| F | Force |
| G | Shear modulus |
| $I_s$ | Point load strength |
| $I_{s(50)}$ | Point load strength for 50 mm diameter core |
| ISRM | International Society for Rock Mechanics |
| k | Index to strength conversion factor |
| $k$ | Bulk modulus |
| L | Length of specimen |
| P | Peak load |
| $q_u$ | Compressive strength |
| $R^2$ | The r-squared value |
| t | Travel time |
| UCS | Uniaxial compressive strength |
| $V_p$ | Longitudinal wave velocity |
| W | Width of specimen |
| $w_n$ | Natural water content |
| $\gamma_t$ | Total unit weight |
| $\sigma$ | Normal stress |
| $\upsilon$ | Poisson's ratio |