# Evaluation of rock properties using ultrasonic pulse technique and correlating static to dynamic elastic constants

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## Abstract

Formation elastic parameters including Young's modulus, Poisson's ratio and shear modulus are the input parameters for wellbore instability and sanding prediction analysis. These parameters are customarily estimated from laboratory experiments on core samples and called static elastic properties. This is an expensive and time consuming approach, as intensive care required for sample preparation and handling. An alternative laboratory approach is to measure the dynamic moduli on a core sample through Acoustic Travel Time (ATT) method. This method is advantageous in being non-destructive and fast; however, the static moduli are required to be obtained for any geomechanics related studies.

As a result, a correlation between static to dynamic moduli needs to be developed. In general, static moduli are smaller than that of dynamic moduli due to higher level of strain applied to the rock. Several correlations have been proposed in the literature for this purpose, although each has been developed in a specific formation and hence not appropriate to be used in other areas.

In this paper, a large number of ATT tests were conducted on a variety of rock types in conjunction with measurement of other rock physical and mechanical properties including density, porosity, water absorption, uniaxial compressive strength and indirect tensile strength.

Statistical analysis of the results enabled developing some good correlations between velocity of elastic waves and physical/mechanical properties of rock. Also dynamic elastic moduli measured using ATT and static moduli calculated through UCS tests, were analyzed and used to develop a correlation between static to dynamic moduli. Using these equations, physical and mechanical properties of rock and static elastic constants can be estimated by peforming non-destructive ATT test.

## Introduction

Nowadays, laboratory sonic velocity techniques, socalled ultrasonic tests, are becoming very popular due to their non-destructive nature, high precision and low cost. In rock mechanics, these techniques are regularly used for determination of rock dynamic elastic constants. In addition, these techniques are applied to evaluate rock quality and identify cracks and defects in the rock matrix. In these techniques, transition time of a traveling elastic pulse is measured between two points in a core plug and compressional and shear waves (P & S waves) velocities are calculated. Having obtained these values, the dynamic elastic constants of rock can be determined.

Three types of sonic velocity methods are available: ultrasonic technique, low frequency sonic wave technique and frequency resonant technique. Among these methods, the ultrasonic technique is more convenient to be used in rock mechanics.

The velocity of elastic waves in rock depends on various parameters including mineralogy, grain size, density, porosity, weathering, stress level, water absorption, water content and temperature.

This study aims in making correlations between elastic wave velocities and some of the rock properties. Moreover, attempt has been made to estimate rock's static elastic constants from the dynamic elastic constants measured with ultrasonic technique, using laboratory derived correlations. The main objective is to investigate the possibility of replacing the ordinary destructive tests (such as UCS) with cheap non-destructive methods in order to determine physical and mechanical properties of rock.

## Ultrasonic technique

Ultrasonic test is used as a method to determine the velocity of propagation of P and S waves in laboratory rock samples. In this technique, the frequency of wave should be high and rock specimens should have infinite extent compared to the wavelength of the pulses. The specimens can be rectangular blocks, cylindrical cores or even spheres (for determination of elastic symmetry of anisotropic rocks). This test is performed in accordance with the ISRM suggested methods or the ASTM D2848 standard.

## Experimental study

Ultrasonic tests were carried out on about 200 core plugs in order to correlate the velocity of P and S waves with some physical and mechanical properties of different rock types including sandstone, siltstone, conglomerate, claystone, granite, andesit, basalt, diabas, quartzite, slate, micro conglomerate, limestone, and marl. Subsequently, the plugs were used in order to determine bulk density, porosity, water absorption, UCS and tensile strength. All these tests were carried out in accordance with the ISRM suggested methods. In UCS tests, axial and lateral strains were measured using electric resistant strain gauges. The dynamic Young modulus and Poisson's ratio were calculated using $V_p$, $V_s$ and bulk density data.

## Analyzing the results

### *$V_s$ to $V_p$ correlation*

As the first step, a correlation between compressional and shear wave velocities were established showing a linear relationship (Figure 1). The high regression coefficient (i.e. $R^2$ = 0.9) reveals a strong correlation between the two velocities which enebales estimation of one velocity having another one. The following equation defines this relationship:

$$V_s = 0.456\ V_p + 264.3 \qquad [1]$$

where both $V_p$ and $V_s$ are in m/s.

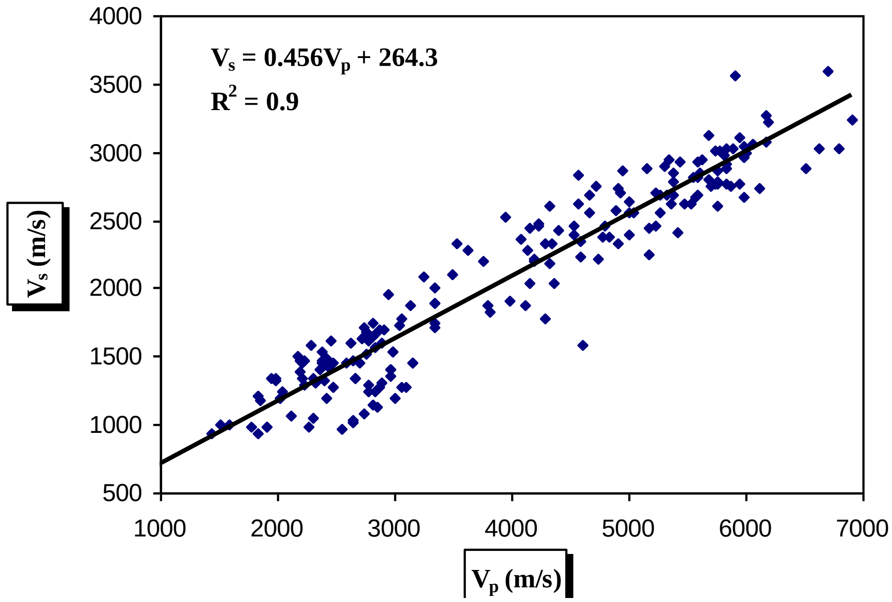


Figure 1: $V_s$ versus $V_p$ plot showing a linear relationship

*Density versus elastic wave velocity*

Around 190 data obtained from laboratory tests and were analyzed in order to correlate bulk density with $V_p$ and $V_s$. Figures 2 and 3 show these correlations where both cross-plots illustrate quadratic relationship between density and wave velocities with a reasonable regression coefficient:

$$\rho = -2 \times 10^{-8} V_p^2 + 0.0002 V_p + 1.93 \quad [2]$$

$$\rho = -6 \times 10^{-8} V_s^2 + 0.0004 V_s + 1.94 \quad [3]$$

where $\rho$ is density in gr/cm$^3$.
It is noted that equations 2 and 3 are valid only in the ranges shown in the cross-plots.

According to the plots, compressional and shear wave velocities increase with increasing density as expected, due to the fact that sonic velocity in higher in solids than fluids.

As a results, having $V_p$ or $V_s$ of a certain rock, it is possible to estimate bulk density with an acceptable accuracy.

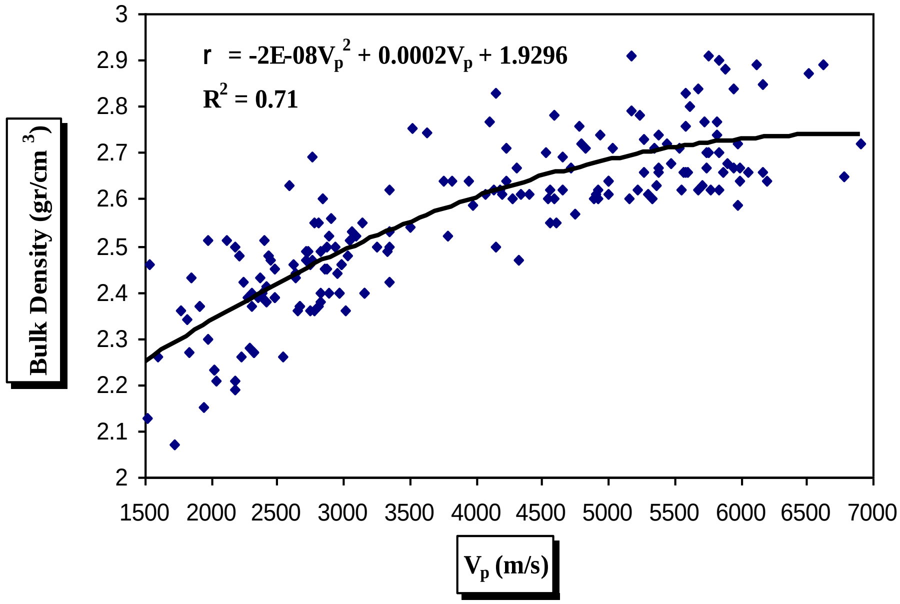


Figure 2: Quadratic correlation between density and $V_p$

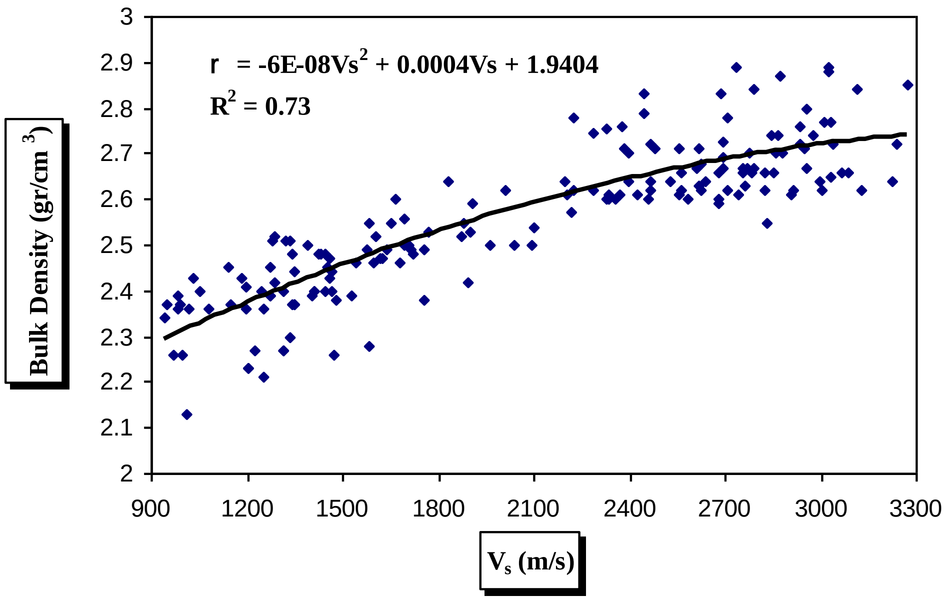


Figure 3: Quadratic correlation between density and $V_s$

*Water absorption versus elastic wave velocity*

Water absorption, $I_w$, is an important rock index depending on mineralogy and porosity of rock. These are the characteristics that sonic velocity also depends on them. Therefore, the correlation between them expect to be strong. The results of study, which are shown in Figures 4 and 5 for $V_p$ and $V_s$ respectively, sort of substantiate this. Figures 4 depicts a good relationship between $I_w$ and $V_p$ with $R^2$=0.81. It is a logarithmic relationship which shows a decrease in $I_w$ as a result of increasing $V_p$.

There is a similar relationship between $I_w$ and $V_s$ (Figure 5) but with a smaller correlation coefficient ($R^2$=0.75). In overall, the following equations can be used to estimate water absorption from $V_p$ or $V_s$, with a reasonable accuracy.

$$I_w = -4.184 \ln (V_p) + 36.56 \quad [4]$$
$$I_w = -4.390 \ln (V_s) + 35.28 \quad [5]$$

where $I_w$ is in percent.

It is notable that these equations are valid for $V_p$ in the range of 1400 m/s to 7000 m/s and $V_s$ in the range of 900 m/s to 3300 m/s.

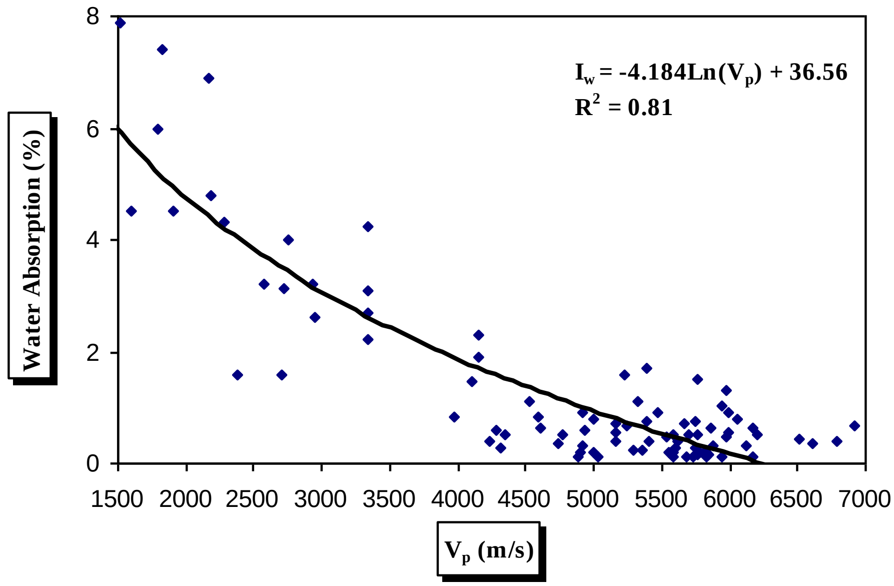


Figure 4: Logarithmic correlation between water absorption and $V_p$

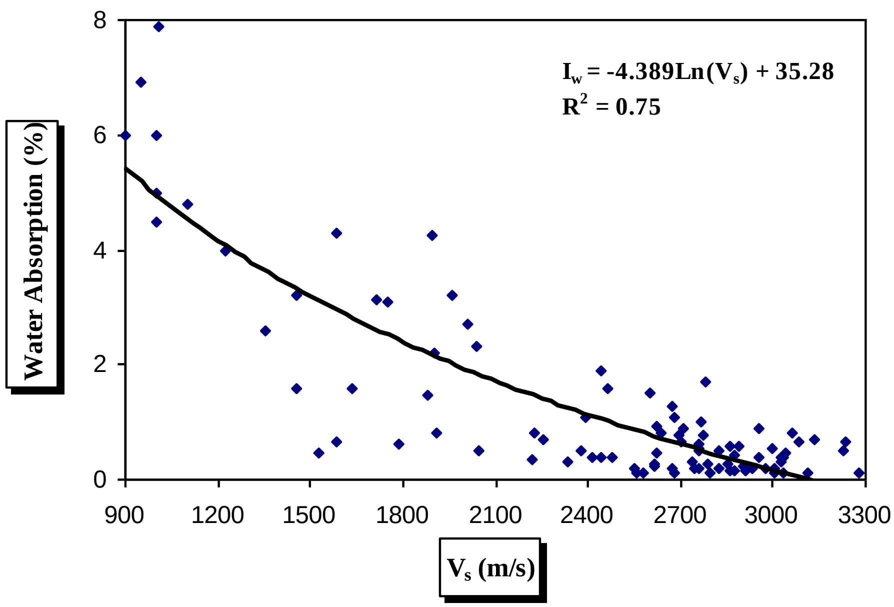

Figure 5: Logarithmic correlation between water absorption and $V_s$

*Porosity versus elastic wave velocity*

Contrasting the general idea that porosity can be estimated from sonic data with a high accuracy, the results of our tests showed an intermediate correlation between these parameters. The reason for that was found to be due to discrepancy in rock types used for correlations. When the data were plotted separately for similiar rock types, the correlation coefficients increased appreciably.

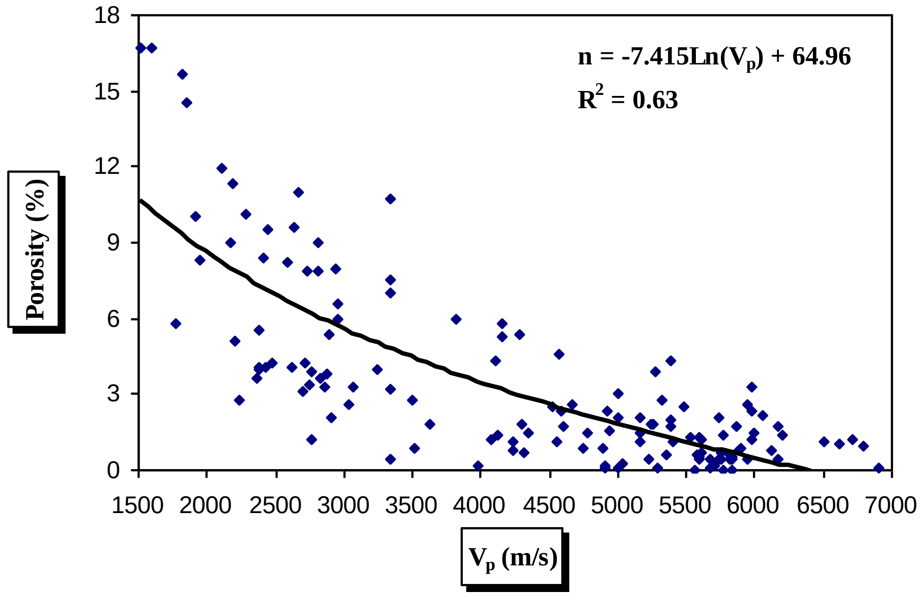


Figure 6: Logarithmic correlation between porosity and $V_p$

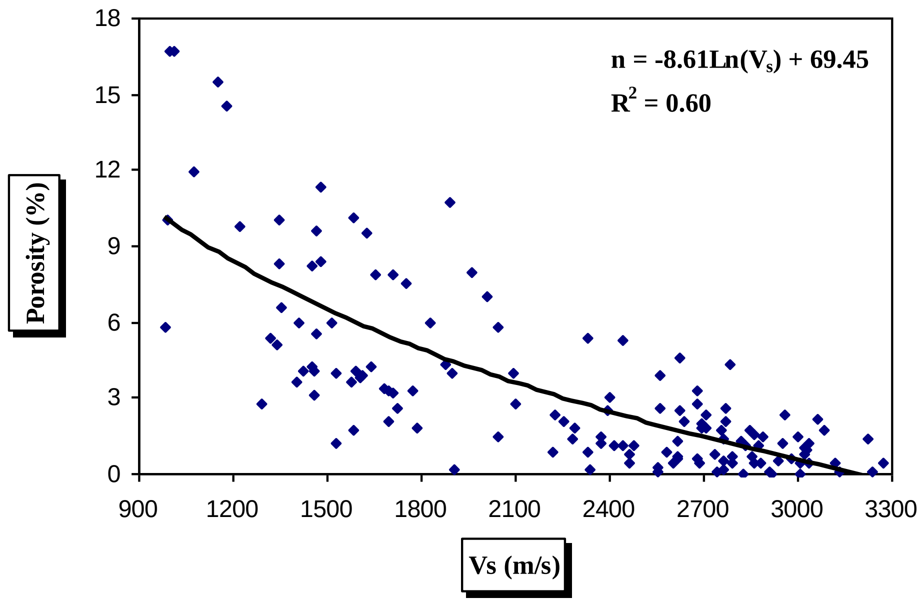


Figure 7: Logarithmic correlation between porosity and $V_s$

*UCS versus elastic waves velocity*

All abovementioned parameters have some influences on rock strength. Therefore, UCS is expected to show a relationship with elastic wave velocity. To scrutinize this, results of a testing program on 115 rock plugs were analysed and cross-plots between UCS and $V_P$ and $V_s$ were plotted (Figures 8 and 9, respectively). These cross-plots showed rather weak correlations due to dispersion of data. Of cpurse it is possible to draw a direct line through the maximum values of UCS under which most of points will be placed. These line enables estimation of a maximum value for UCS. These lines can be defined by equations 8 and 9:

$$UCS_{max} = 43V_p + 1000 \quad [8]$$
$$UCS_{max} = 16\ V_s + 900 \quad [9]$$

where UCS is in MPa.

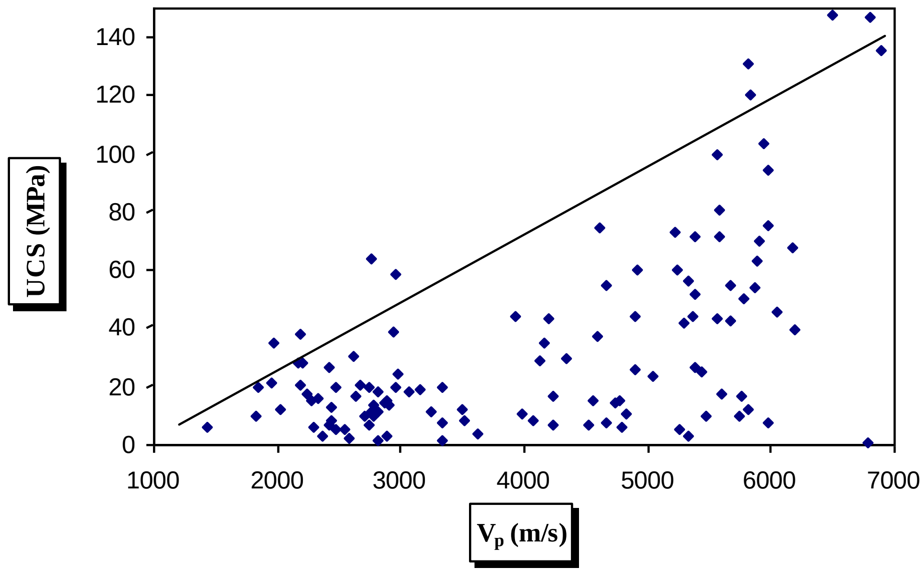


Figure 8: Uniaxial compressive strength versus $V_p$

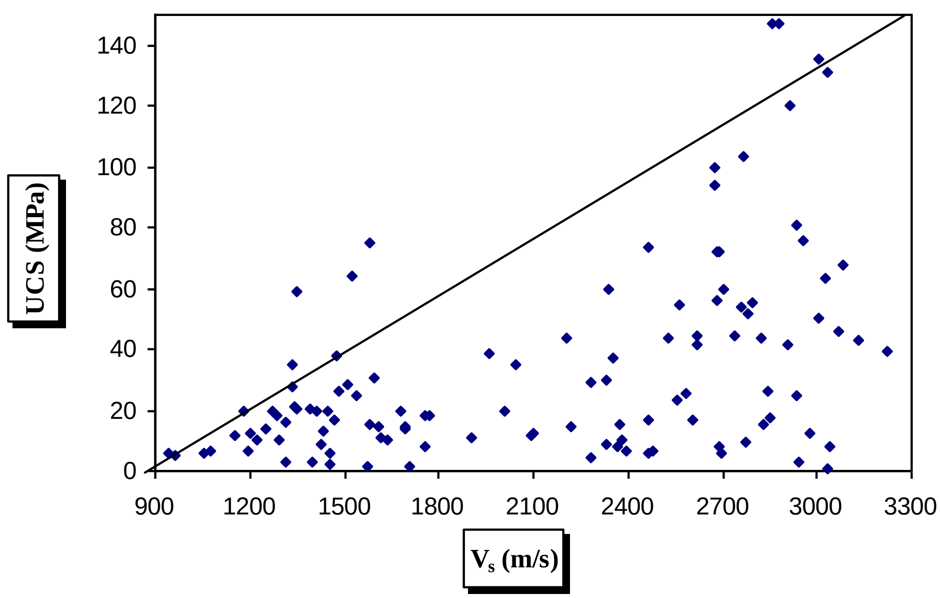

Figure 9: Uniaxial compressive strength versus $V_s$ plot

The main reason for scattering the data in this case is the wide variation in the studied rock types. In order to eliminate this effect, data from similiar rock types (e.g. claystone, conglomerate, marl, sandstone and slate) were analyzed separately and resulted in significantly better correlations (Figure 10). Unfortunately the number of data for each rock type was not enough to enable us suggesting any equations for UCS calculation. It is suggested to repeat this analysis with more data and establish reliable correlations for each rock.

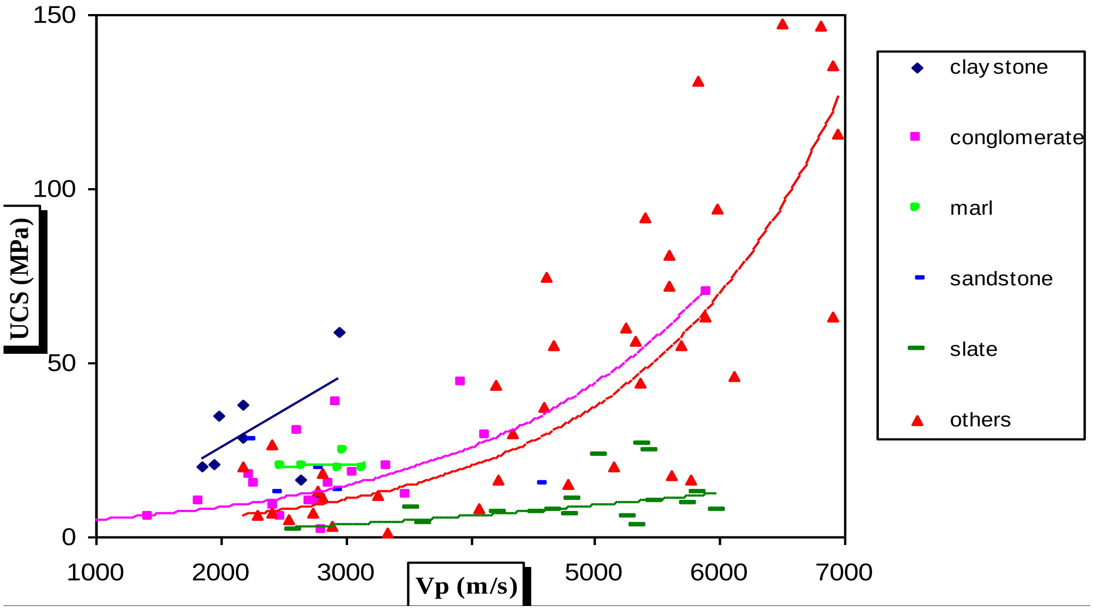


Figure 10: UCS correlation with $V_p$ in some rock types

*Tensile strength versus elastic waves velocity*

Brazilian test were conducted on 70 core plugs from different rock types in order to determine tensile strength. The results were used to establish correlations between tensile strength (T) and elastic waves velocity. Figures 11 and 12 show the results for $V_p$ and $V_s$ respectively. They showed intermediate correlations between T and waves velocities as follow:

$$T = 0.348e^{0.0004\ Vp} \quad [10]$$

$$T = 0.277\ e^{0.0008\ Vs} \quad [11]$$

where T is tensile strenght in MPa.

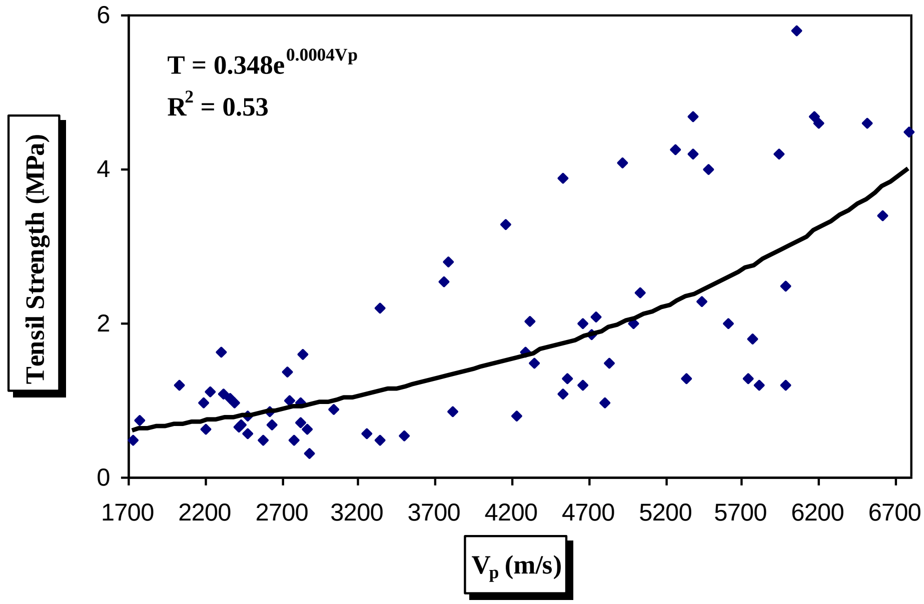


Figure 11: Tensile strength versus $V_p$ plot

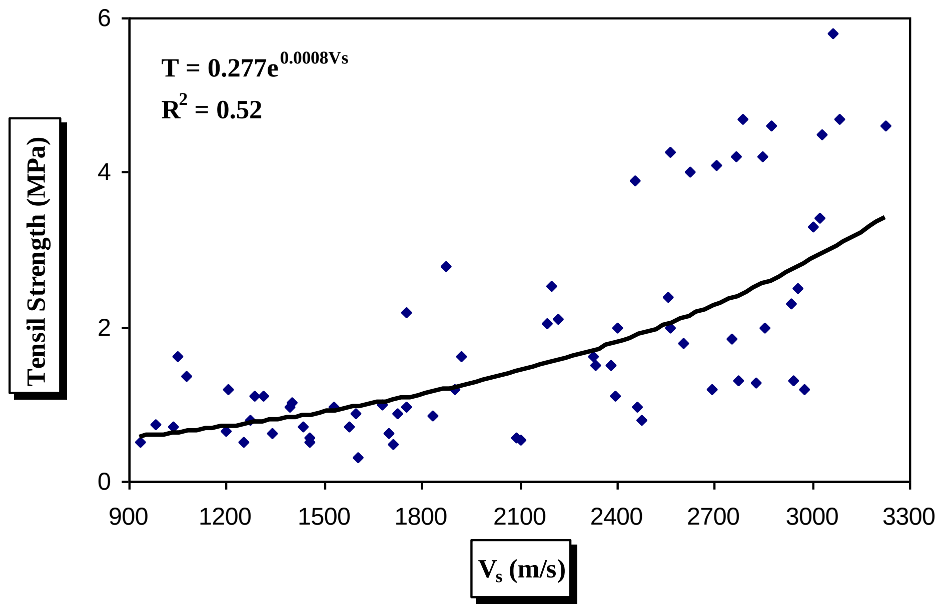


Figure 12: Tensile strength versus $V_s$ plot

*Correlation between Ed and Es*

The most important correlation, which was the aim of this research, ia the correlation between static and dynamics Young modulus ($E_s$ and $E_d$). The importance of this correlation, specially in oil and gas industry, is because of the fact that sonic data are usually available in oil and gas wells which makes it possible to calculate dynamic modulus; however, obtaining cores in order to measure static modulus in the lab is an expensive and cumbersome process. Finding a good correlation between $E_s$ and $E_d$ enables estimation of $E_s$ without requirements to perform expensive and time-consuming compressive strenght tests. Figure 13 shows the result of analyzing 114 data obtained from UCS laboratory tests on variety of rock types. This figure reveals a fairly appropriate exponential relationship between $E_s$ and $E_d$ with $R^2 = 0.72$ as:

$$E_d = e^{0.0477Es} \qquad [12]$$

This equation is recommended strongly in order to estimate static Young modulus by conducting ultrasonic test in cases which this value is not very critical. It is notable that precision of this equation in low values is high and decreases with increasing $E_d$.

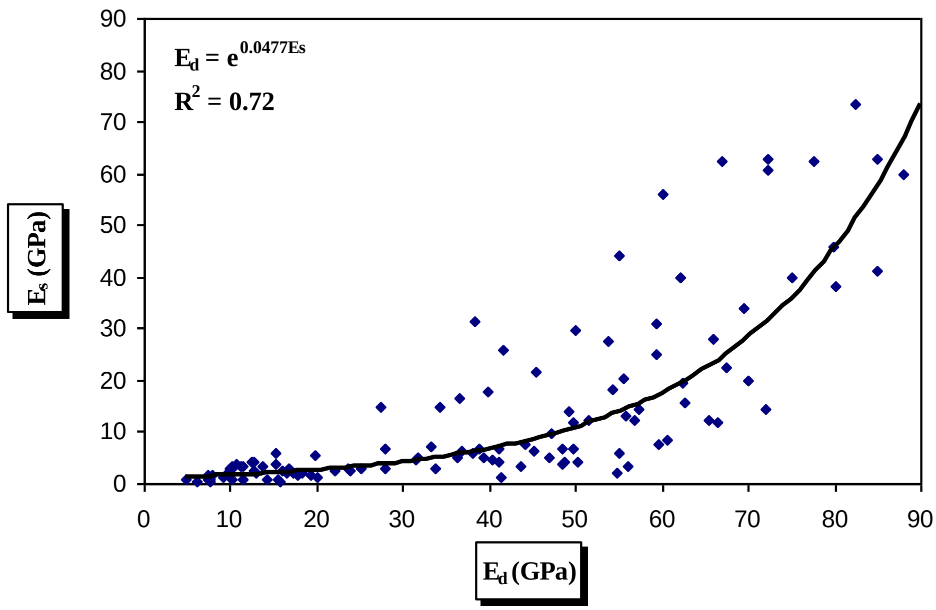


Figure 13: Es versus Ed plot shows an exponential equation

*Correlation between $G_d$ and $G_s$*

Another important correlation, which was performed on obtained data, was the correlation between static shear modulus ($G_s$) and dynamic shear modulus ($G_d$). Having found a good equation between $G_s$ and $G_d$, we can evaluate $G_s$ using $G_d$ without doing expensive and time-consuming static tests. The result of analyzing 114 data obtained from laboratory tests is shown in Figure 14. This figure shows that there is a rather appropriate power relationship between these two parameters with $R^2 = 0.72$. This regression coefficient is less than one for elasticity modulus. The relationship can be defined as:

$$G_s = 0.047G_s^2 - 0.69G_s + 3.08$$

This equation is recommended in order to estimate static shear modulus by conducting ultrasonic test in cases, which the high precision is not necessary. It is notable that precision of this equation in low values is high and decreases with increasing $E_d$.

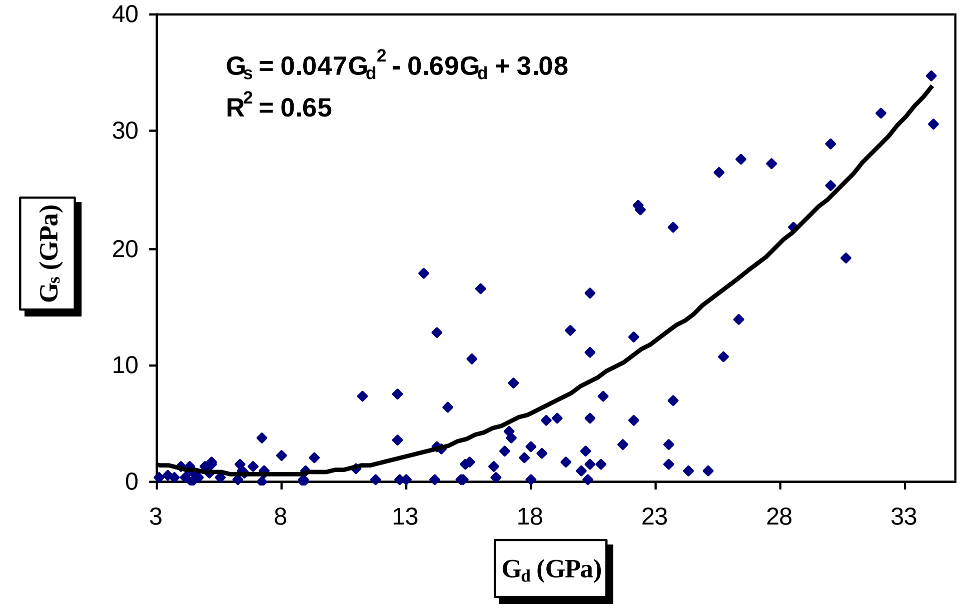


Figure 13: Gs versus Gd plot shows a power equation

*Correlation between $\nu_d$ and $\nu_s$*

Analyzing 114 data mentioned above shows that there is not any specific relationship between static and dynamic Poisson's ratio ($\nu_s$ & $\nu_d$). The dispersion of data is illustrated in Figure 14.

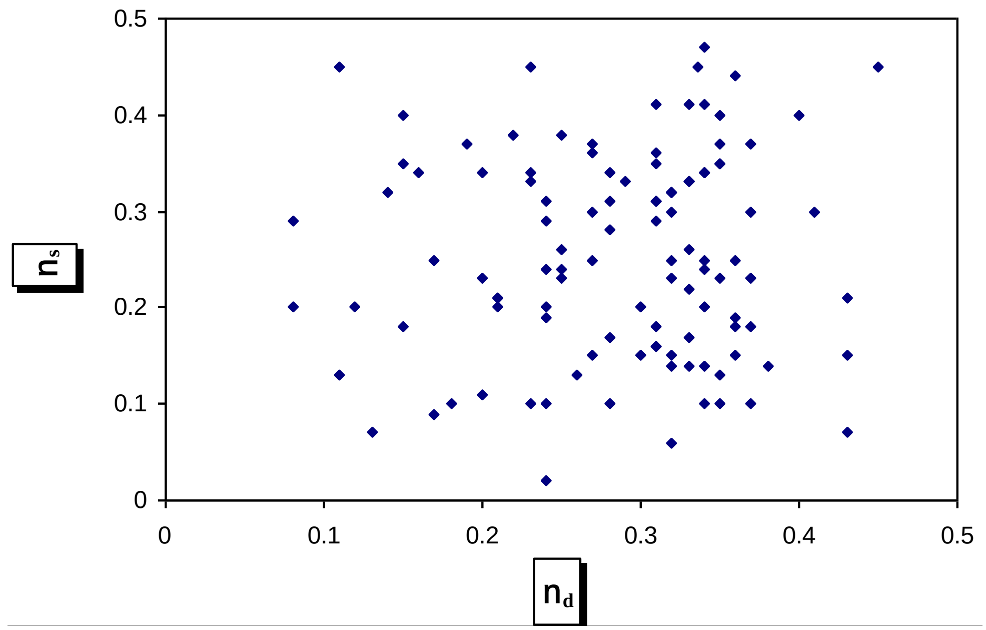


Figure 14: $\nu_d$ versus $\nu_s$ plot showing dispersion of data

**Conclusions**

It can be concluded from laboratory tests and the results that in some cases we can replace many expensive and complex tests with a cheap and quick non-destructive test (e.g. ultrasonic test). These cases and also other results of this research can be summarized as follow:

- Density of rock can be estimated by ultrasonic test with a rather good precision.
- Water absorption percentage of rock can be determined by ultrasonic test with a high precision.
- Porosity of rock can be estimated by ultrasonic test with a moderate precision.
- It is possible to evaluate a maximum value of rock strength by ultrasonic test.
- Tensile strength has a rather exponential relationship with elastic velocities.
- Static elasticity modulus can be estimated by having dynamic elasticity modulus with a rather high precision.
- Static shear modulus can be estimated by having dynamic shear modulus with a moderate precision.
- Static Poisson's ratio has no relationship with dynamic one.

## References

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