USING THE POINT LOAD TEST TO DETERMINE THE UNIAXIAL COMPRESSIVE STRENGTH OF COAL MEASURE ROCK

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ABSTRACT

Point load testing is used to determine rock strength indexes in geotechnical practice. The point load test apparatus and procedure enables economical testing of core or lump rock samples in either a field or laboratory setting. In order to estimate uniaxial compressive strength, index-to-strength conversion factors are used. These factors have been proposed by various researchers and are dependent upon rock type. This study involved the extensive load frame and point load testing of coal measure rocks in six states. More than 10,000 individual test results, from 908 distinct rock units, were used in the study. Rock lithologies were classified into general categories and conversion factors were determined for each category. This allows for intact rock strength data to be made available through point load testing for numerical geotechnical analysis and empirical rock mass classification systems such as the Coal Mine Roof Rating (CMRR).

INTRODUCTION

The point load test (PLT) is an accepted rock mechanics testing procedure used for the calculation of a rock strength index. This index can be used to estimate other rock strength parameters. The focus of this paper is to present the data analysis used to correlate the point load test index (Is_{50}) with the uniaxial compressive strength (UCS), and to propose appropriate Is_{50} to UCS conversion factors for different coal measure rocks. The rock strength determined by the PLT, like the load frame strengths that they estimate, are an indication of intact rock strength and not necessarily the strength of the rock mass.

THE UNIAXIAL COMPRESSIVE STRENGTH TEST

The UCS is undoubtedly the geotechnical property that is most often quoted in rock engineering practice. It is widely understood as a rough index which gives a first approximation of the range of issues that are likely to be encountered in a variety of engineering problems including roof support, pillar design, and excavation technique (Hoek, 1977). For most coal mine design problems, a reasonable approximation of the UCS is sufficient. This is due in part to the high variability of UCS measurements. Moreover, the tests are expensive, primarily because of the need to carefully prepare the specimens to ensure that their ends are perfectly parallel.

THE POINT LOAD TEST

The PLT is an attractive alternative to the UCS because it can provide similar data at a lower cost. The PLT has been used in geotechnical analysis for over thirty years (ISRM, 1985). The PLT involves the compressing of a rock sample between conical steel platens until failure occurs. The apparatus for this test consists of a rigid frame, two point load platens, a hydraulically activated ram with pressure gauge and a device for measuring the distance between the loading points. The pressure gauge should be of the type in which the failure pressure can be recorded. A state of the art point load testing device with sophisticated pressure reading instrumentation is shown in Figure 1.

Figure 1. The Point Load Tester.

The International Society of Rock Mechanics (ISRM, 1985) has established the basic procedures for testing and calculation of the point load strength index. There are three basic types of point load tests: axial, diametral, and block or lump. The axial and diametral tests are conducted on rock core samples. In the axial test, the core is loaded parallel to the longitudinal axis of the core, and this test is most comparable to a UCS test.

The point load test allows the determination of the uncorrected point load strength index (Is). It must be corrected to the standard equivalent diameter (De) of 50 mm. If the core being tested is "near" 50 mm in diameter (like NX core), the correction is not necessary. The procedure for size correction can be obtained graphically or mathematically as outlined by the ISRM procedures. The value for the Is_{50} (in psi) is determined by the following equation.

$$Is_{50} = P/De^2 \quad (1)$$

P = Failure Load in lbf (pressure x piston area).
De = Equivalent core diameter (in).

As Hoek (1977) pointed out, the mechanics of the PLT actually causes the rock to fail in tension. The PLT's accuracy in predicting the UCS therefore depends on the ratio between the UCS and the tensile strength. For most brittle rocks, the ratio is approximately 10. For soft mudstones and claystones, however, the ratio may be closer to 5. This implies that PLT results might have to be interpreted differently for the weakest rocks.

Early studies (Bieniawski, 1975; Broch and Franklin, 1972) were conducted on hard, strong rocks, and found that relationship between UCS and the point load strength could be expressed as:

$$UCS = (K)\ Is_{50} = 24\ Is_{50} \quad (2)$$

Where K is the "conversion factor." Subsequent studies found that K=24 was not as universal as had been hoped, and that instead there appeared to be a broad range of conversion factors. Table 1 summarizes published results obtained for sedimentary rocks. Most of the estimates place the conversion in a range between 16 and 24, with even lower values for some shales and mudstones.

In studies comparing the PLT with the UCS, it is generally assumed the UCS test is the standard. In reality, however, UCS tests provide an estimate of the "true" UCS of the rock. The accuracy of the estimate depends on the natural scatter in the UCS test results (indicated by the standard deviation (SD)) and the number of tests conducted (n). This relationship is captured by the concept of the "Confidence Interval" (CI). For normally distributed data, the 95% CI of the mean is expressed as:

$$CI_{95\%} = 1.96\ \frac{SD}{\sqrt{n}} \quad (3)$$

Table 1. Published comparisons between the point load and uniaxial compressive strength tests for sedimentary rock.

Reference	Rock Type	Location	Number of tests	Conversion Factor	Comments
Das, 1995	Siltstone	Western Canada, bituminous coalfields	NG[1]	14.7	lumps, fresh core, old core
	Sandstone/siltstone		NG	18	
	Shale/mudstone		NG	12.6	
Vallejo et al, 1989	Sandstone	Eastern KY, VA, WV	420 PLT, 21 UCS	17.4	Freshly blasted rock, irregular lump samples
	Shale	surface coal mines	1,100 PLT, 55 UCS	12.6	
Smith, 1997	Dredge material	various harbors	NG	8	UCS<1000 psi
	Dredge material	various harbors	NG	15	UCS<3500 psi
	sandstone/limestone	unk	NG	24	UCS>6000 psi
Broch and Franklin, 1972	Various	UK (?)	NG	23.7	11 rock types
Carter and Sneddon, 1977	Coal measure	UK	1,000 PLT, 68 UCS	21-22	3 units tested
O'Rourke, 1988	Sedimentary	Paradox Basin, US	66	30	samples from one borehole
Hassani et al., 1980	Sedimentary	UK	1,000	29	
Singh and Singh, 1993	Quartzite	India, copper pit	65	23.4	
Read et al, 1980	Sedimentary rocks	Melbourne, Australia	NG	20	Reference in Choi and Hong, 1998
Bieniawski, 1975	Sandstone	South Africa	160	23.9	
Rusnak, 1998	Coal measure	Southern WV	386	20	Subset of current data
Jermy and Bell, 1991	Coal measure	South Africa	NG	14.1	Mainly sandstones

[1]NG=Not given in reference

In general, the variability in the PLT-UCS relationship can be attributed to three sources:

1. Inaccuracy in the estimate of the true UCS obtained from UCS tests.
2. Inaccuracy in the estimate of the true PLT obtained from PLT tests.
3. Real differences between the two tests.

Many of the studies summarized in Table 1 compared a suite of point load tests to a single UCS test. With such an experimental design, much of the scatter in the results might actually be attributable to the inaccuracy of the UCS tests.

PEABODY ROCK MECHANICS DATA

Peabody established an in house rock mechanics testing facility in the fall of 1986. This facility is located in Freeburg, IL. A full range of equipment was purchased to perform tests including uniaxial compressive strength, indirect tensile strength, point load index, triaxial compressive strength, flexural strength, direct shear strength, long term creep, roof bolt anchorage capacity, slake durability, ultrasonic velocity, swelling strain and Atterberg limits. The diametral point load (DPL) was not initiated until 1996, which resulted from an interest in utilizing of the Coal Mine Roof Rating (CMRR). ASTM and ISRM procedures are followed for all rock mechanics testing.

This testing has been done primarily on core samples obtained from exploration drilling to provide data for mine planning and design. The Freeburg facility was eventually sold to Standard Laboratories in 1991 who continue to operate it. The majority of the data analyzed in this paper was from the testing done at Freeburg. After 1997, all West Virginia testing has been carried out at Commerical Testing and Engineering's facility in Beckley, WV. Currently, the data base contains rock mechanics test results from 914 drill holes from the states of

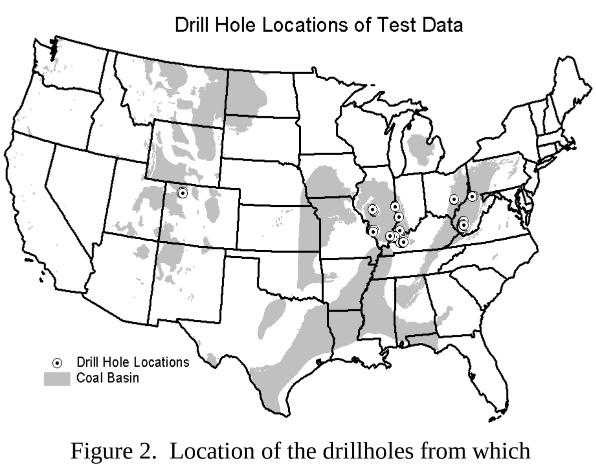

Figure 2. Location of the drillholes from which the samples were obtained.

WV, IL, KY, IN, CO, and OH. Most of the core was NX-size with some 75-mm (3-in) diameter. A map showing the distribution of the drilling is shown below (figure 2).

THE UCS AND PLT DATA BASE – DESCRIPTIVE STATISTICS

The methodology used in the selection of core samples for testing was as follows:

1. Within each hole, rock units were identified where a sequence of tests had been performed with an identical geologic description and no major gaps in elevation.
2. Rock units with at least 3 UCS and 3 PLT results were selected for inclusion in the data base.
3. The mean UCS, mean Is_{50}, the standard deviations, and the CI_{95} were calculated for each rock unit.

The samples were also categorized into rock type based on the geologic description. These rock types correspond to the Ferm Classification numbers. Ferm and Weisenfluh (1981) developed a number system classification for coal measure rock types using color photographs of rock core in an index guide. It as been widely accepted as a means for consistent rock identification and for use in computer data bases of drilling information.

The categories of rock types and their Ferm classification numbers used in this data analysis are as follows:

Rock Type	Ferm Series
Shale and Claystone	100 - 200
Silty or Sandy Shale	300 - 400
Sandstone	500 - 700

Of the original 36,000 tests, more than 10,000 from 908 rock units were retained for the analysis. The distribution of the units and representative values are reported in Table 2. The median of the means is reported, rather than the mean of the means, to reduce the influence of outliers. All the statistical analysis was performed using SPSS version 10.

Figure 3 compares UCS determined for different rock types in different regions. One striking observation is that the rocks from the Midwest (IN, IL, and western KY) are significantly weaker than their counterparts from WV (a fact confirmed by ANOVA).

Figure 4a shows the range of standard deviations for the UCS tests, expressed as a fraction of the mean UCS. The standard deviations are greatest for limestones and shales, with the median SD about 35% of the mean. The median standard deviations for siltstones and sandstones are about 19% of the mean.

Table 2 also reports the median Is_{50} and SD of $Is_{50.}$ Expressed as a percent of the mean, the median standard deviation for the Is_{50} ranges from 20% for sandstone to 35% for shale. As figure 4b confirms, the variability of the PLT is similar to that of the UCS test, as has been reported elsewhere (ISRM, 1985).

Table 2. Summary of the data used in this study.

Rock type	Location	N units	N UCS tests	Median UCS	Median SD of UCS	N PLT tests	Median Is_{50}	Median SD of Is_{50}
Shale	All states	289	1,541	529	1,664	1,719	269	94
	Midwest	209	1,072	4,367	1,314	1,246	175	73
	West Virginia	68	389	10,752	2,680	431	488	149
Siltstone	All states	296	1,557	6,286	1,166	1,518	296	77
	Midwest	236	1,275	5,931	1,027	1,258	261	69
	West Virginia	51	226	13,332	2,699	224	611	146
Sandstone	All states	228	1,591	10,931	2,096	1,459	446	87
	Midwest	99	586	6,773	1,601	546	291	77
	West Virginia	113	833	14,574	2,450	832	591	87
Limestone	Midwest	95	450	18,752	6,614	407	730	241
All states	All states	908	5,139	7,040	1,796	5,103	322	92

N - Number of tests.
UCS - Unconfined compressive strength (psi).
SD - Standard deviation (psi)
Is_{50} - Point Load Index.

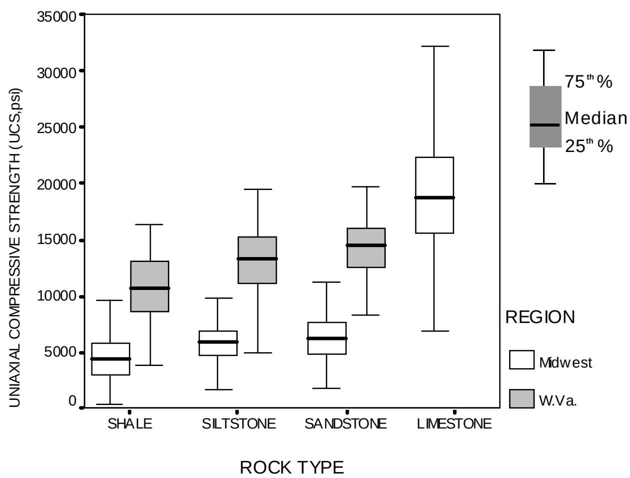

Figure 3. Range of uniaxxial compressive strengths found in the data base.

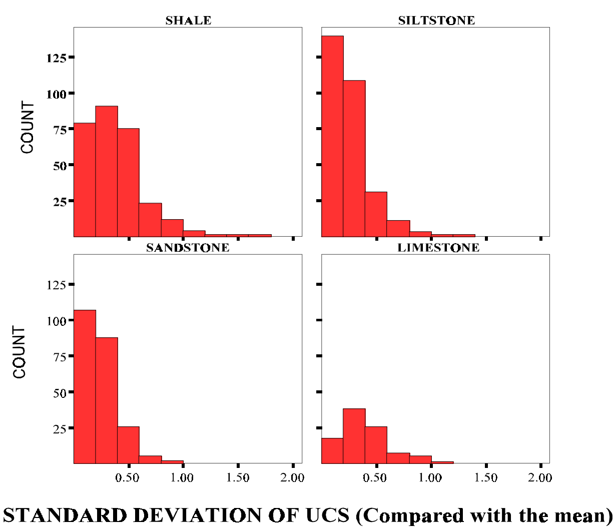

Figure 4a. Histograms of standard deviations, Uniaxial Compressive Strength.

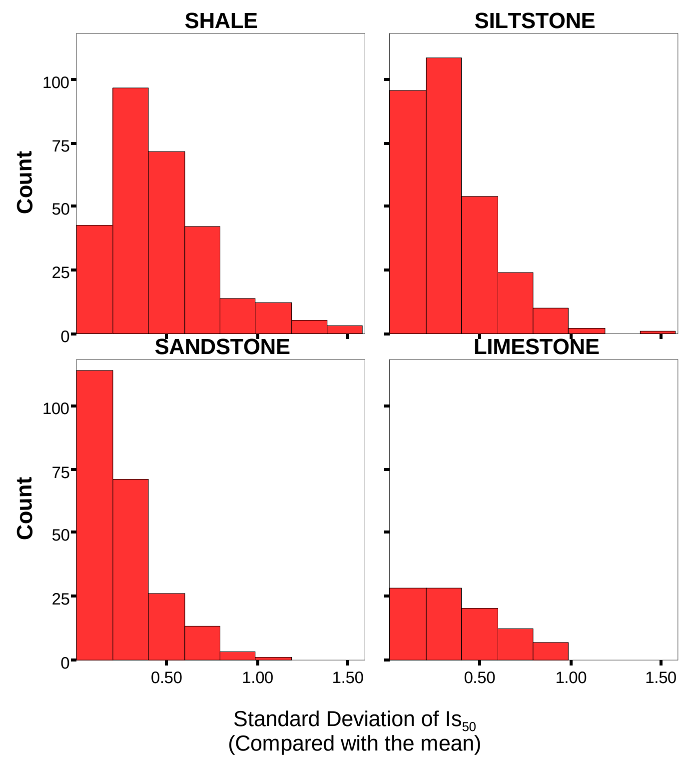

Figure 4b. Histograms of standard deviations, Point Load Test.

The Is_{50} values obtained from this study are compared with data reported by Molinda and Mark (1996) in table 3. Molinda and Mark's data was obtained from throughout the US and includes a high percentage of tests from southern WV. Table 3 reports means of the mean Is_{50} values to make the results comparable. It can be seen that the two studies found similar results.

Table 3. Comparison between PLT data from this study and that presented by Molinda and Mark (1996).

Rock Type	Is(50) (psi)			
	Average, this study	Midwest, this study	WV, this study	Molinda & Mark
Shale	268	193	510	420
Sandy Shale	473	275	610	515
Sandstone	476	313	646	600

SUMMARY OF THE REGRESSION ANALYSIS

A linear regression between the mean Is_{50} and mean UCS values determined for all 908 units yielded the following equation:

$$UCS = 1970 + 17.6\ Is_{50} \qquad (4)$$

The correlation coefficient (r^2) obtained for equation 4 is 0.68, which is not bad for rock mechanics. The regression equation simply uses the pairs of means, without regard to the associated standard deviations. Therefore, the r^2 for equation 4 implies that the point load test explains two-thirds of the variability in the UCS, with one-third attributable to the three potential sources of scatter listed earlier.

Equation 4 contains an intercept, however, unlike the traditional form of the UCS-PLT relationship (equation 3). Unfortunately, the r^2 obtained from a zero-intercept regression is not comparable to the standard r^2. Therefore a different measure of the validity of the result must be used.

For this study, the validity measure was defined as *the percent of mean Is_{50} values that fall within the 95% CI of the corresponding UCS*. In addition, the percent of mean Is_{50} values falling 10 and 20 MPa (1,500 and 3,000 psi) from the 95% CI of the mean UCS were also calculated.

The zero-intercept regression equation obtained from the entire data set is:

$$UCS = 21.0\ Is_{50} \qquad (5)$$

With this equation, 50.4% of the predicted UCS values fall within the 95% CI of the measured UCS. Only 8.5% of the predicted values are more than 20 MPa away from the 95% CI (figure 5). For equation 4, the regression equation with an intercept, 49.0% of the predicted values were within the 95% CI and 7.6% were more than 20 MPa away. It seems that the zero-intercept equation is just as accurate as the standard regression equation that includes an intercept.

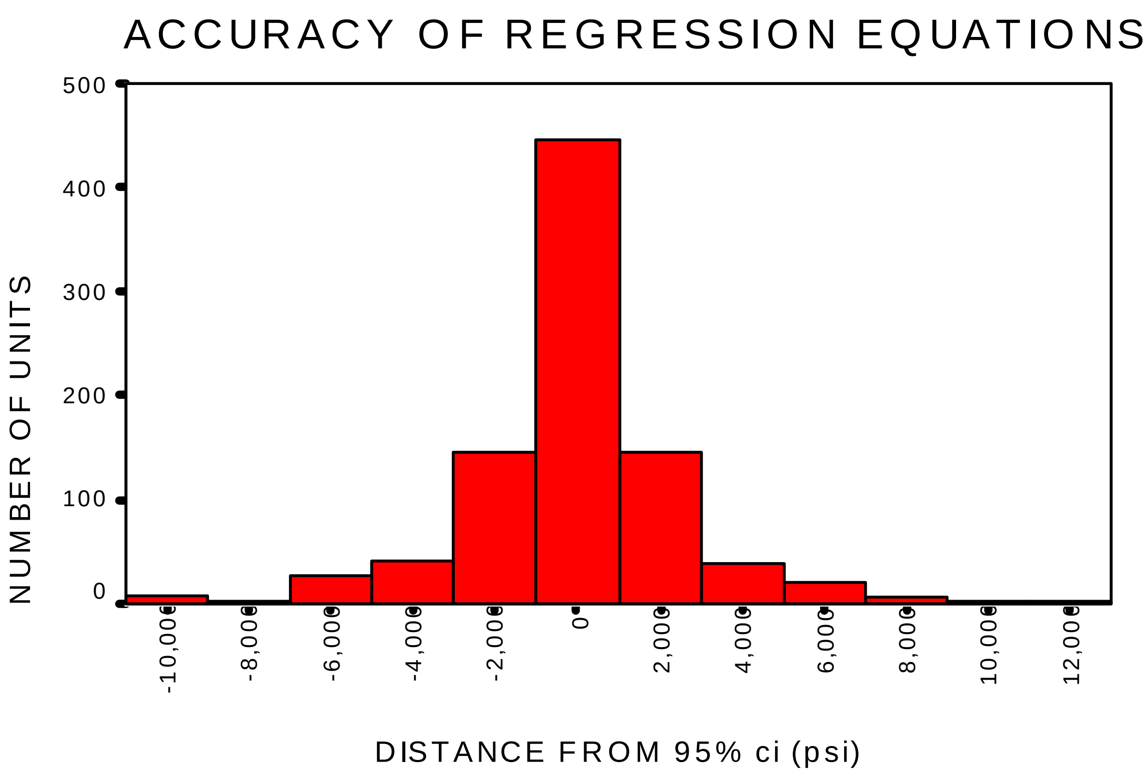

Figure 5. Histogram showing hte difference between UCS predicted by the PLT using equation 5, and the 95% confidence interval of the measured UCS. The zero bar includes all cases that fell withing the 95% CI.

Table 4 shows the conversion factors (K) obtained from zero-intercept regression analyses on various subsets of the data. Nearly all the K values lie between 20 and 22, regardless of rock type or geographic origin. Figures 6a-6e shows the regression equation (equation 5) mapped on the different data subsets.

Table 4. Conversion factors (K) obtained from zero-intercept regression analysis.

Rock type	Location	K
Shale	All states	21.8
	Midwest	22.4
	West Virginia	20.2
Siltstone	All states	20.2
	Midwest	19.6
	West Virginia	20.8
Sandstone	All states	20.6
	Midwest	20.2
	West Virginia	20.4
Limestone	Midwest	21.9
All states	All states	21.0

Finally, the relationship between rock strength and K was explored. There was a slight tendency for the UCS/Is_{50} ratio (K_i) to decrease for low UCS rocks. The median K_i for the entire data set was 22.7, but that decreased to 16.9 for the subset of rocks whose UCS was less than 20 MPa (3,000 psi). Unfortunately, a similar trend was not evident in the PLT data, so efforts to adjust K for low Is_{50} rocks did not improve overall accuracy.

DISCUSSION

Several factors are relevant in comparing this study with previous ones. First, the present study involves the largest number of tests, nearly 10 times as many as the next largest study. It also includes a wide variety of rock types from several mining regions, and it explicitly addresses the variability associated with the UCS tests. One disadvantage of the study was that the number of PLT tests averages about 5 per unit. Therefore it was not possible to follow the ISRM (1985) suggested method for determining the mean value, which involves deleting the two highest and two lowest Is_{50} values from a suite of at least 10 tests. Finally, it should be noted that in these tests the average moisture content varied from 0.79% for the shale to 0.49% for the sandstone. Vallejo et al. (1989) found that K values were greater when the samples were saturated.

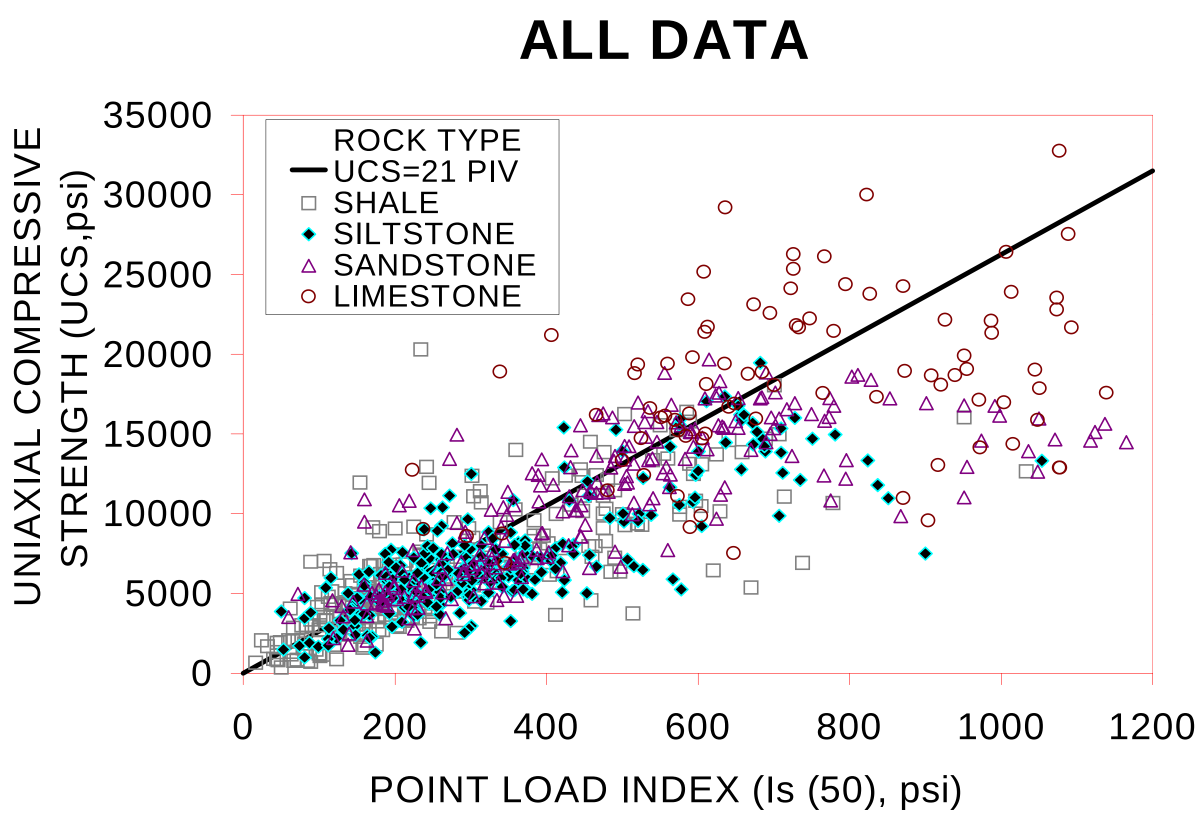

Figure 6a. Regression between uniaxial compressive strength and point load index. All rock types (a random selection of 40% of the data points is shown).

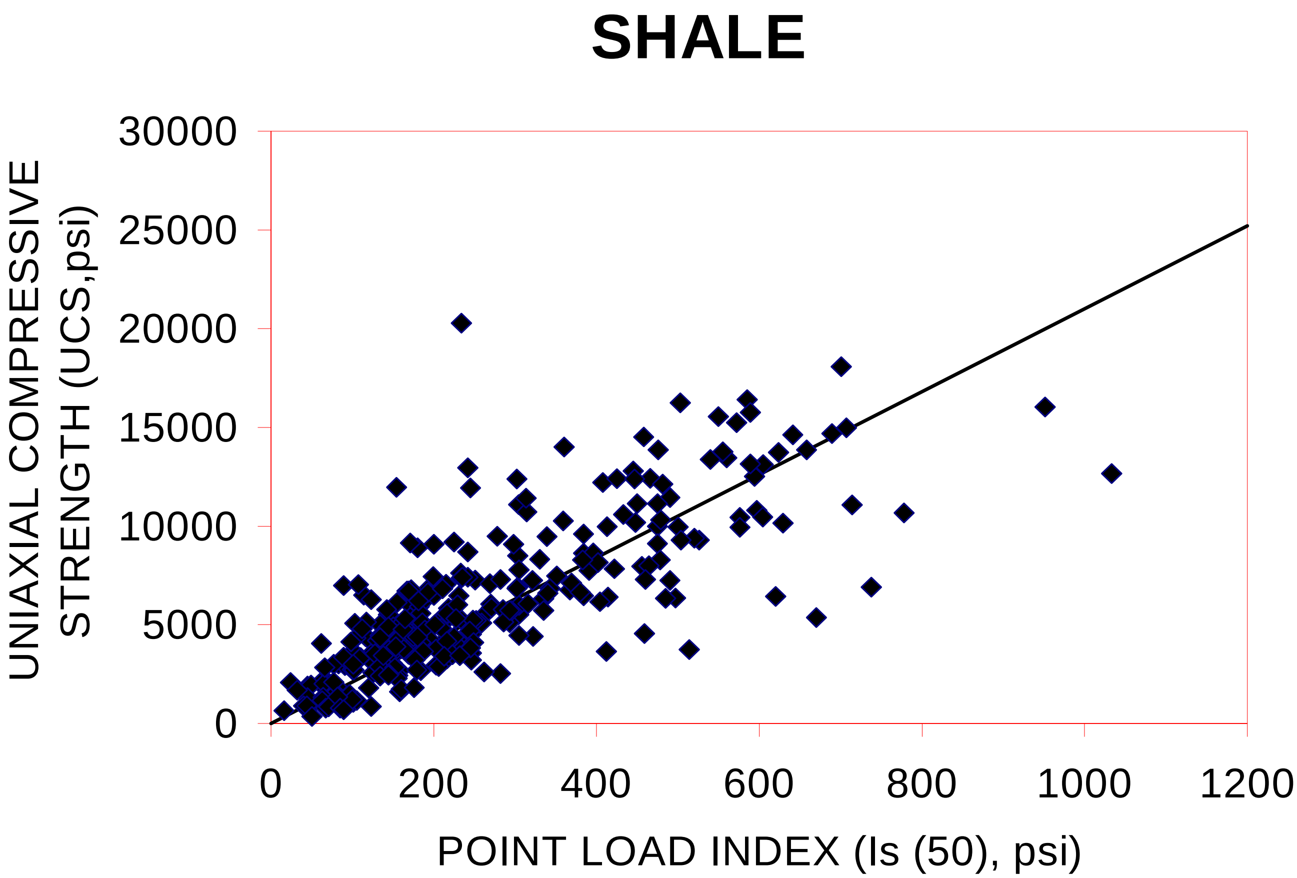

Figure 6b. Regression between uniaxial compressive strength and point load index. SHale.

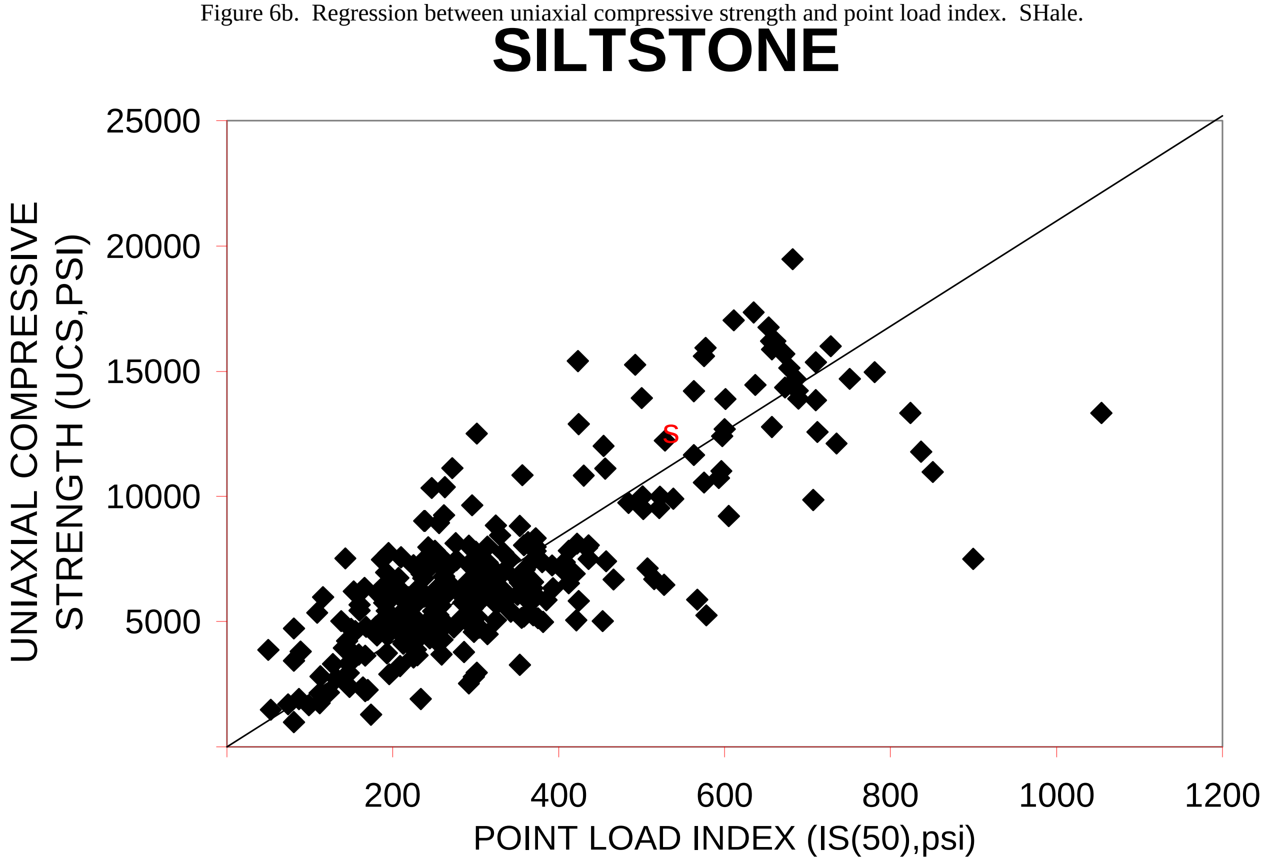

Figure 6c. Regression between uniaxial compressive strength and point load index. Siltstone.

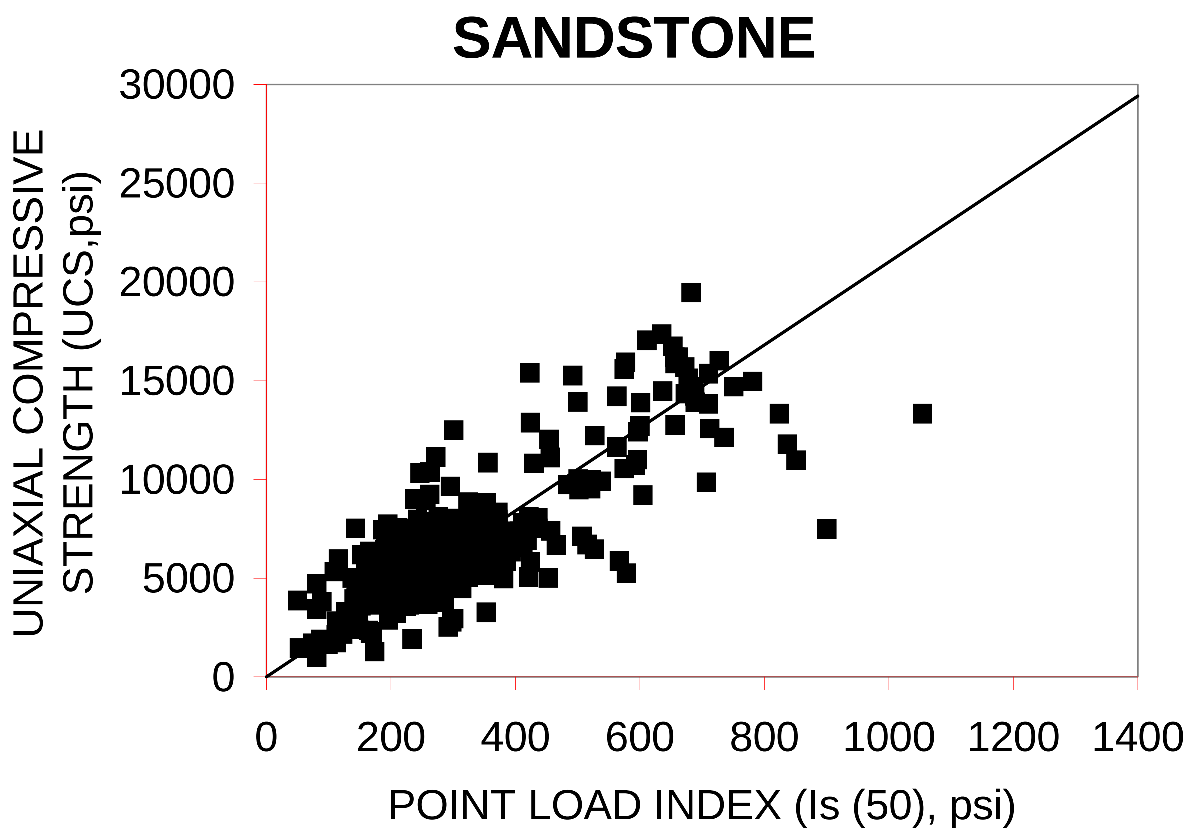

Figure 6d. Regression between uniaxial compressive strength and point load index. Sandstone.

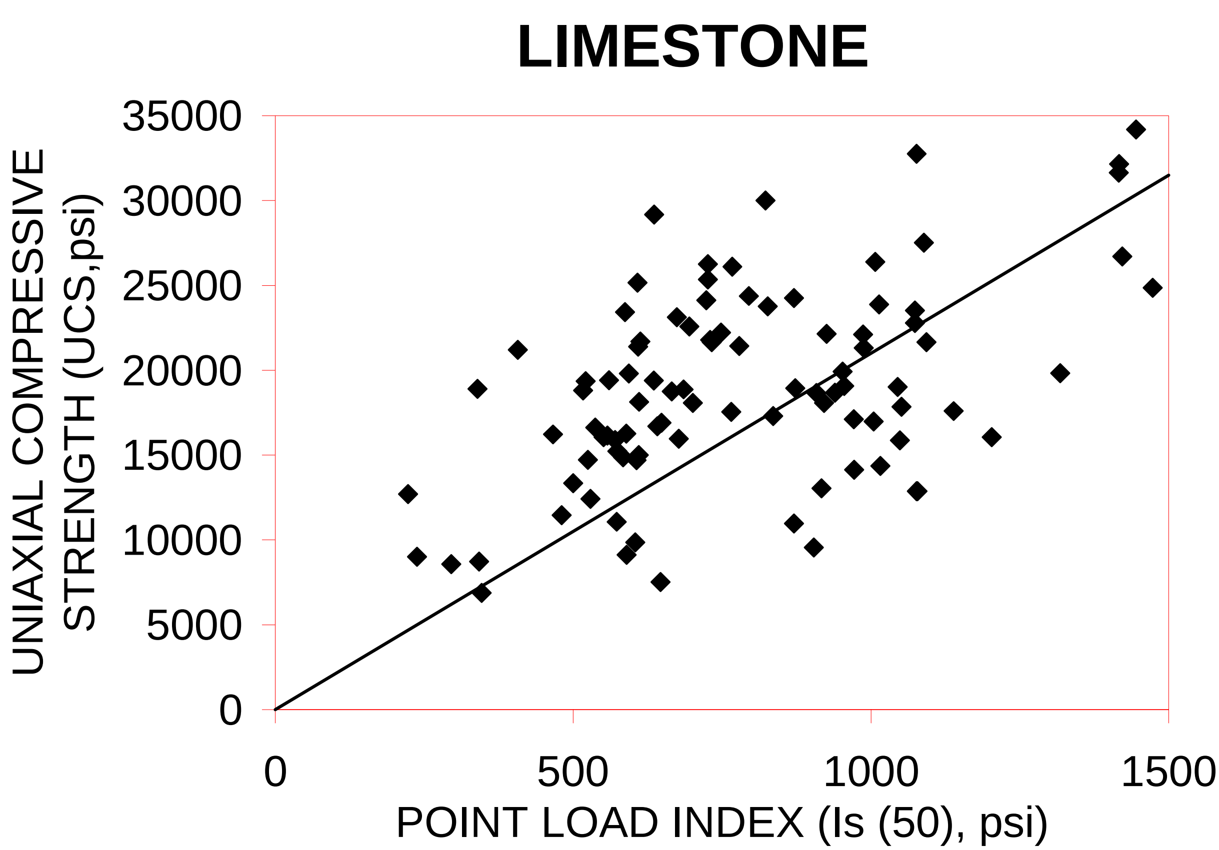

Figure 6e. Regression between uniaxial compressive strength and point load index. Limestone.

he conversion factors (K) determined in this study fall in the middle of the range of the studies reported in table 1. They are somewhat greater than the K factors currently used in the CMRR (Mark and Molinda, 1996). Those values, 12.5 for shales and 17.4 for sandstones, were originally proposed by Vallejo et al. (1989). Many of the samples that Vallejo tested came from the same geologic formations included in this study. However, Vallejo tested lump samples rather than the core samples used here, and he compared the results from single UCS tests with suites of PLT tests.

Like some other researchers, Vallejo et al. (1989) concluded that K should be smaller for shales than for sandstones. While the current study found some evidence that K was less for the weakest rocks (not just shales), it was difficult to identify those rocks from the PLT measurements alone. Therefore, using different K values may not be justified for axial PLT tests. However, diametral tests often give Is_{50} values that are much lower than those from axial tests. Converting diametral test results using the same K value is likely to be inaccurate. It is also unnecessary, because diametral tests are used as an indirect measure of bedding plane cohesion, not rock strength (Mark and Molinda, 1996). It is probably more sensible to report Is_{50} from diametral tests directly.

CONCLUSION

The PLT is an efficient method to determine intact rock strength properties from drill core samples. It has become an accepted test in geotechnical evaluations.

This study found that a conversion factor K=21 worked well for a variety of rock types and geographic regions. The variability of the PLT, as measured by the standard deviation, was no greater than that of the UCS test. There is some indication that K decreases for lower strength rocks, but the tendency was not very pronounced. Geologic and engineering judgment should be used when converting PLT results to UCS. It must be remembered that both tests can only be used to estimate *intact* rock strength and not rock *mass* strength.

The point load test provides for full utilization of data that can be gained from exploration drilling programs. Intact rock strength information can be acquired for use in geotechnical evaluation and design work through numerical modeling and rock mass classification systems. The cost of point load testing is minimal when compared to the overall exploration expense. Point load testing of roof and floor rock core of coal seams that are to be mined by underground methods should be standard procedure in any exploration program.

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