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Evaluating Properties of Weak Shales in Western Missouri

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ABSTRACT: Evaluation of the geomechanical properties of shales, especially weak ones is always problematic. The Missouri Department of Transportation (MODOT) recently undertook a major research initiative to achieve significant and recurring cost savings for MODOT by developing improved, technically sound design specifications. Test drilling in shale was conducted; Boreholes were typically drilled in pairs, side-by-side, with one boring being used for core sampling, and the other being used for in situ penetration testing.

Coring methods were modified to provide better quality samples. Testing was conducted on or as near the site immediately after recovery. On site point load testing was introduced and used along with slake durability testing to rank the shale in the Franklin Shale Rating System. Samples of shale too weak for point load testing were tested for plasticity index, which is also part of the Franklin Shale rating system. In the penetration boreholes, alternating split-barrel sampler penetration and Texas cone penetration tests were conducted at 2.5 foot intervals using a standard automatic safety hammer. Between tests, the borehole was cleaned and drilled to the next testing level using a tri-cone roller bit.

1. INTRODUCTION.

Evaluation of the geomechanical properties of shales, especially weak ones, is always problematic. Many shales are significantly weaker and less durable than other types of rock but tend to be significantly stronger than soil. As such, drilling and testing techniques designed for soil are often inadequate for shales while drilling techniques designed for rock often simply overpower the shales. Issues that come up are poor core recovery, mechanically damaged core, and deterioration of samples. As a result there is often a sampling bias in selecting samples large and robust enough for testing, and testing results are highly variable (Figure 1).

Figure 1: Shale core from Grandview Missouri (bottom row). Pieces are in general too small and fragile for uniaxial compression testing.

2. CHARACTERIZING SHALE

2.1. Drilling in Shale

Drilling in shale needs to be performed carefully using, at a minimum a double tube coring system with preferably a split inner core barrel (which eliminates the need to mechanically extrude the sample). Triple tube coring is even better, as it results in even less damage to the core. Using shale bits rather than diamond surface set bits allows faster advance and less water to avoid gumming up the bit. Less water results in less washing away of the shale core. Thrust and rotation speeds need to optimized to avoid excessive vibrations and other conditions that could damage the core. Wireline drilling is used to further reduce core damage, even in shallow holes. Once the core barrel is pulled out of the hole the core needs to be carefully extracted to avoid further breakage.

Once in the core box the core should be examined and logged and samples selected immediately. If RQD (Rock Quality Designation) is measured, it needs to done quickly as in some cases the shale core will spontaneously break into smaller pieces as a result of stress release. Samples need to be tested as soon as possible, and protected from deterioration due to desiccation by sealing them with wax, cellophane, and/or aluminum foil.

2.2. Testing of Shale

Various lab and field tests can be used or have been specifically designed for testing the geomechanical properties of shales. These can be divided into strength, strength index, and durability tests.

There are several examples of durability tests including the slake test, jar slake test, free swell test [1], and slake durability test [2] (ASTM D4644-04). The slake durability test is probably the most common and useful test that takes 10 lumps (approx. 500 g) of material and measures the % loss of material (by dry weight) after two cycles of being mechanically agitated in a partially submerged wire mesh drum (Figure 2), and then dried.

Strength and strength index tests include both in-situ penetration tests and lab strength tests.

Penetration tests are performed by driving split spoons or steel cones (Figure 3) into the shale and counting the number of blow required to penetrate a given distance. Typically, when a split spoon is hammered into shale, it is the blow count that is of interest; there is typically very little if any sample. For the split spoon or Texas cone [3] (TexDOT Designation TEX-132E) there is often very little penetration, and results are recorded not as blows per foot but rather as penetration per 100 blows [4]. An expendable tip cone can be used as well, but can possibly only work in very soft shale because it needs to be continuously driven, not incrementally as with the Texas cone or split spoon.

Lab tests include of uniaxial or triaxial compression tests as well as point load testing [5] (ASTM D5731-07). Point load testing (Figure 4) is quick and easy and can readily be done in the field. Point load index testing can be correlated to uniaxial or unconfined compressive strength (UCS) test results using a straight line best fit. Rasnak and Mark [6] report two different studies in shale of which both result in a conversion of UCS=12.6 * pointload strength.

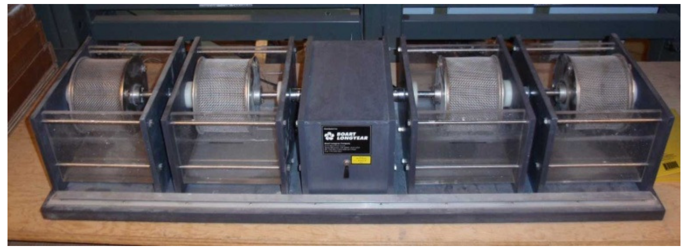

Figure 2: Shale durability testing apparatus.

Figure 3: Driven tools. Right: split spoon. Center: Texas Cone. Left: Expendable tip cone.

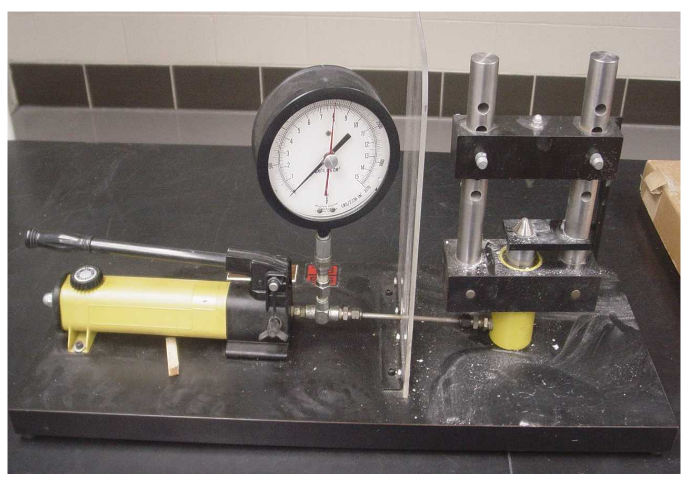

Figure 4: Point load testing apparatus.

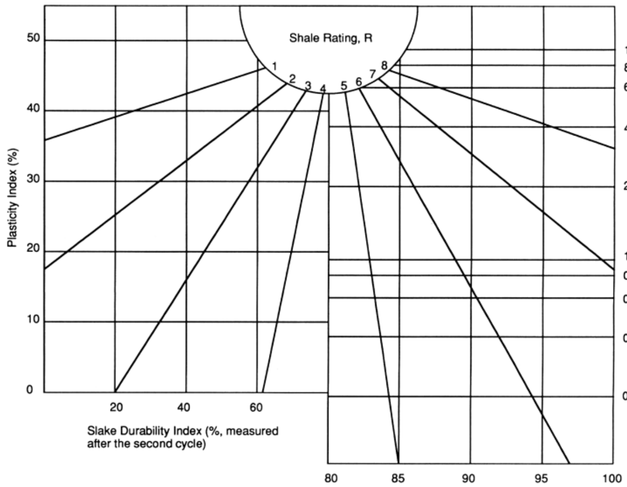

Figure 5: Franklin's shale rating system [1].

Additional testing to be considered for very weak shale is Atterberg limits (ASTM D 4318-05).

2.3. Classification and Empirical Design

Classification and empirical design methods abound in rock engineering. Santi [7] describes methods for field characterization of weak rock. Bienwaski's Rock Mass Rating (RMR) system has long been used for design of underground openings [8]. Barton's Q-system is used to design support in underground openings [9]. Numerous other classification systems include empirically derived design guidelines based on the specially designed classifications [10].

For shales, Franklin suggested a similar classification system called the Shale Rating (R) system [11, 12]. The system can be used for design purposes when both strength and durability are issues, and is comprised of three parameters (Figure 5). The horizontal axis is slake durability index (Id_2), while the vertical axis it point load strength (Is_{50}) (for Id_2 > 80%) or plasticity index (for Id_2 < 80%) Franklin [11] proposed various design criteria based on the shale rating system, including lift thickness for embankments (Figure 6), embankment slope angles and heights (Figure 7), and cut slope angles in shales (Figure 8).

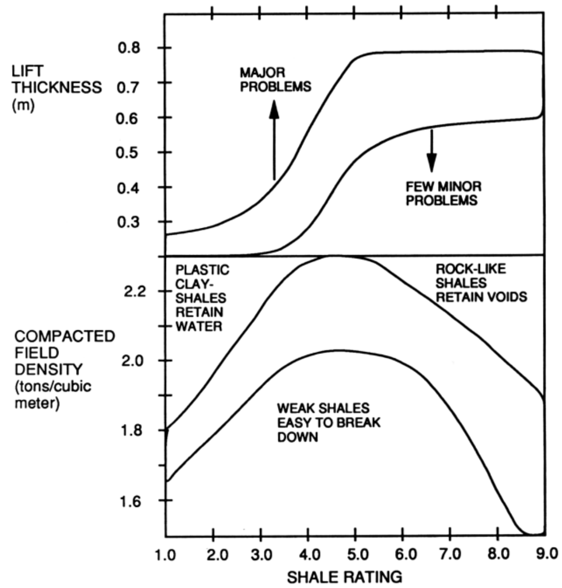

Figure 6: Franklin's design lift thickness and compacted field density as a function of shale rating [1].

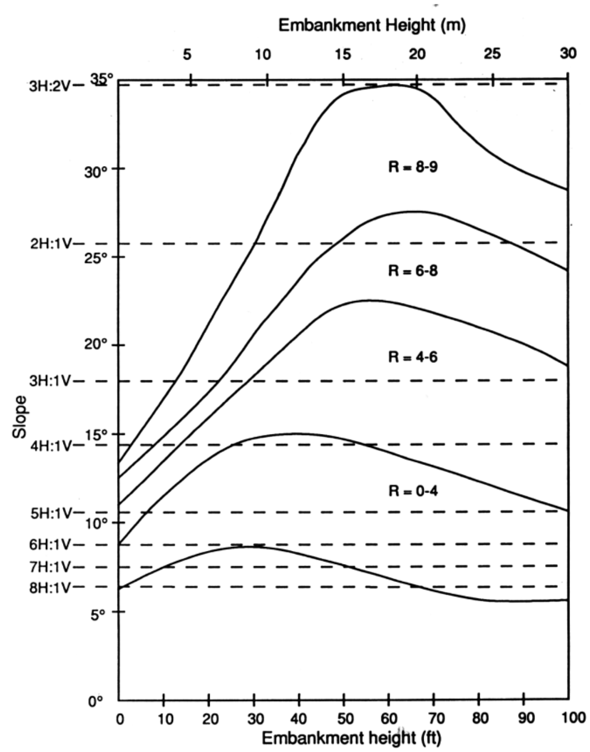

Figure 7: Franklin's design chart for embankment height and slope angle as a function of shale rating [1].

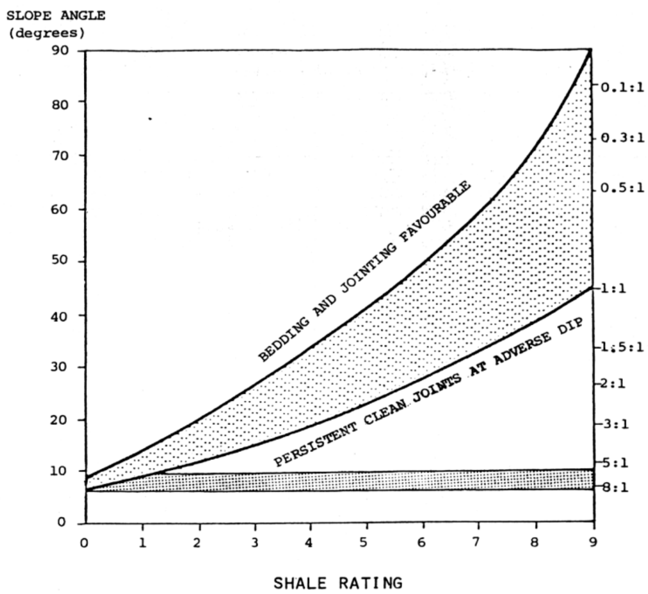

Figure 8: Franklin's design chart for cut slope angles as a function of shale rating [11].

2.4. *Shale Foundations*

When considering allowable bearing pressures on shale, especially for deep foundations, durability is typically not considered, and designs are based primarily on measured strengths. It is not that weathering of the shale has not occurred at depth (that will be reflected by lower strengths in more highly weathered sections) but rather by the assumption that no additional deterioration of the shale will be expected during the engineering lifespan of the structure being supported.

3. MISSOURI SHALE INVESTIGATIONS

3.1. *Major Missouri DOT Initiative*

The Missouri Department of Transportation (MODOT) in 2009 undertook a major research initiative along with Missouri University of Science and Technology (MS&T) and University of Missouri-Columbia (MU) to "achieve significant and recurring cost savings for MODOT by developing improved, technically sound design specifications". Part of the research effort is intended to evaluate common site characterization practices to quantify the variability in parameters used for Load and Resistance Factor Design (LRFD). The expectation is that, by quantifying variability, the benefits of improved practices will become apparent. MODOT has had issues with reliability and confidence in applying shale testing results to designs of deep foundations and retaining walls. The problems in general were poor or damaged core recovery and highly variable unconfined compressive tests.

3.2. *Shales in Western MO*

The shale formations investigated in western Missouri are Pennsylvanian in age. These are part of predominantly clastic sediments, with some limestone and coal beds [13]. An example of a stratigraphic sequence very similar to the one in encountered in the Grandview Site is shown in Figure 9 [14]. Shales are in general gray, silty, and slightly commonly calcareous and fissile [14]. In some places thin coal beds are encountered.

The shales are variably weathered. In some places the shales could be more aptly characterized as clays. The highly weathered shales are not only seen near the ground surface or top of the succession, but rather are distributed throughout the succession.

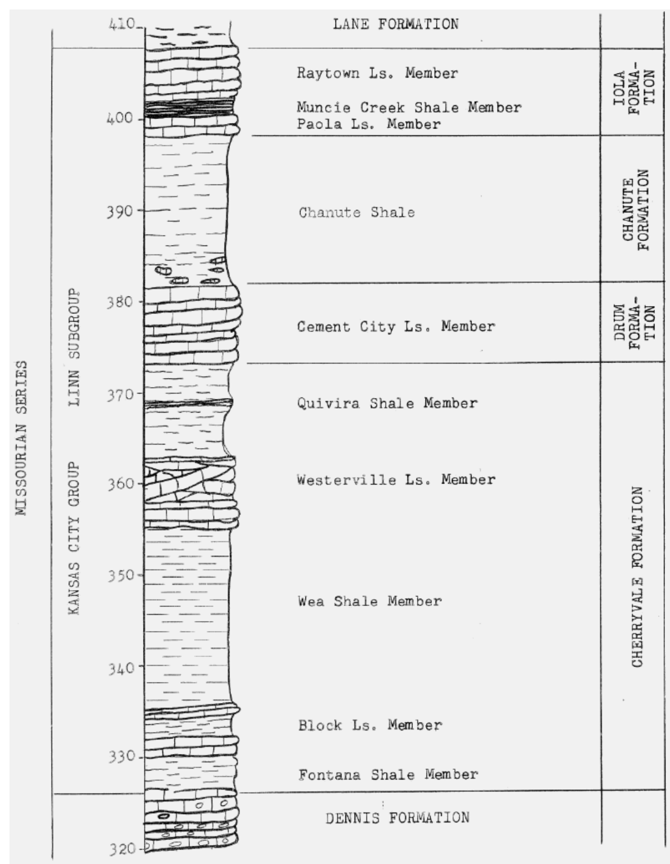

Figure 9: Stratigraphic section representative of the Kansas City location.

3.3. Testing Sites and Geology

During the phase of the MODOT program that related to shale investigations, MODOT conducted drilling at five different sites; results from four of which are reported here. At all the shale sites, field load testing (Osterberg Cell) has been or will be completed on full-scale drilled shaft foundations. In all, twelve borings were drilled for the purpose of this. Boreholes were typically drilled in side-by-side pairs, with one boring being used for core sampling, and the other hole being used for penetration testing. Test site locations are shown in Figure 10.

Figure 10. Drilling test site locations in western Missouri. Clockwise from top left: Kansas City, Lexington, Warrensburg, and Grandview.

3.4. Drilling and Testing

Several new investigative approaches were used. Coring methods were modified to provide better quality samples. Core runs were carefully extruded, logged and photographed (Figure 11).

Shear strength testing was conducted on or near the site via Unconsolidated-Undrained (UU) and Unconfined Compression (UC) procedures according to ASTM D2850 and D2166, respectively. Specimens for strength testing were cut to length from individual core pieces that were at least 150 mm (~6”) long. Samples were sealed with plastic wrap and aluminum foil in the field (Figure 10), transported to an on-site laboratory, and trimmed to specimen lengths averaging approximately 100 mm (4”) using a rock saw. Specimens were not trimmed along the diameter, which averaged approximately 50 mm (~2”). Unconsolidated-Undrained (UU) triaxial compression tests were conducted by encasing the specimens in a latex membrane and applying isotropic confining pressure without allowing drainage. Isotropic confining pressure (σ_3) was applied with a magnitude approximately equal to the in-situ confining stress which was assumed to be 0.75z (in psf), where z was the sampling depth in units of feet. All specimens were loaded to failure under strain-controlled axial loading using an axial strain rate of 1%/min. The peak deviator stress ($\sigma1 – \sigma3$) was used to calculate undrained shear strength [s_u (UU)] and compressive strength [UCS (UU)]. Additional specimens were tested under unconfined compression (UC) to determine undrained shear strength and compressive strength [UCS (UC)] [s_u (UC) = $q_u/2$] [15]. These results were used for comparison with the UU test results and to assess any variably and bias between this testing protocol and conventional MoDOT practice. All UU and UC testing was conducted where possible the same day (and generally within 5 hours of sampling) to minimize stress release and other deteriorating effects by bringing the testing apparatus to a nearby MODOT field office (Figure 12).

Figure 11. Shale core samples for on-site triaxial strength testing. Samples were wrapped in plastic wrap and foil and transported to an on-site laboratory within five hours of sampling. (Photo: Dory Colbert)

Figure 12: Triaxial testing in MODOT field office. (Photo: Dory Colbert)

On site pointload testing was conducted (Figure 13) and correlated with unconfined compressive strength, and used along with slake durability testing to rank the shale in the Franklin Shale Rating System. Because diametral testing of the horizontally bedded shale makes no sense axial testing was performed using approx 25 mm lengths of core cut with a tile saw (Figure 14).

Samples of shale too weak for point load testing were tested for plasticity index, which is also part of the Franklin Shale rating system.

Weak shales were also tested with a specially adapted pocket penetrometer with an indentation cross sectional area that was one half of the standard size (Figure 12), a tool and method currently used by MODOT.

In penetration sampling boreholes, alternating, split-barrel sampler, and Texas cone penetration test were conducted at 2.5 foot intervals a standard automatic safety hammer (Figure 3). Between tests the borehole hole was cleaned and drilled to the next testing level using a tri-cone roller bit.

Figure 13: Point load test machine in the field showing axial testing.

Figure 14: Point load testing in the field. Because axial testing was deemed necessary, a tile saw was used in the field to prepare samples.

Figure 15: Specially modified pocket penetrometer. With indentation cross section one half of the standard size.

4. RESULTS

4.1. *Pocket Penetrometer Testing*

Pocket penetrometer testing was conducted on extruded shale core sample with the modified pocket penetrometer (Figure 15). In all cases the limit of the device (9 tons per square foot) was exceeded.

Although this method was not adequate here the concept remains viable. It may be feasible to modify the pocket penetrometer with even a smaller tip.

4.2. *Penetration Testing*

Penetration testing was conducted on all four testing sites with five boreholes in total. Alternating split spoon and Texas cone tests were performed at 5 foot intervals. In most/all cases a parallel core hole was drilled beside the penetration hole. Because MODOT does not use the 170 lb hammer falling 24 inches that the Texas cone calls for, a 140 lb hammer falling 30 inches was used instead. This results in a nominal hammer energy of 350 ft-lbs per blow rather than the prescribed 340 ft-lbs per blow.

Test results were recorded in inches per 50 blows for the split spoon and inches per 100 blows for the Texas cone

Test results show that in both cases a very weak correlation was determined using a power law (Figures 16, 17).

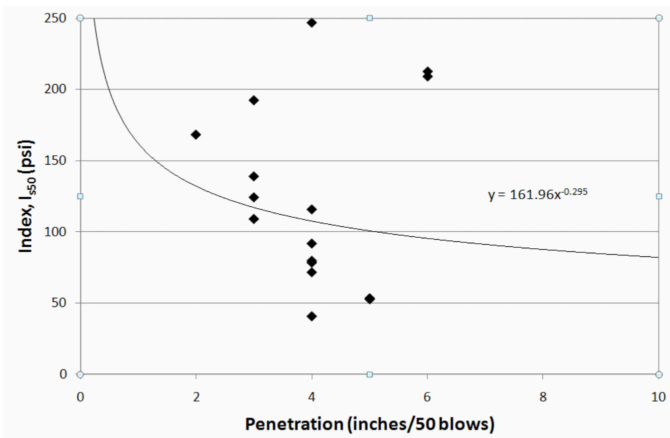

Figure 16: Split spoon penetration tests vs. point load index tests, all sites.

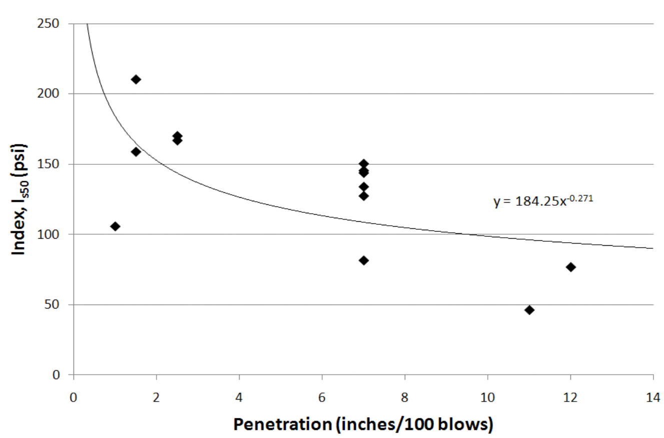

Figure 17: Texas cone penetration tests vs. point load index tests, all sites.

4.3. Triaxial Strength Testing

Triaxial strength tests were conducted for shale specimens trimmed from samples obtained at the Kansas City, Lexington, Warrensburg, and Grandview test sites. Figures 18-21 show compressive strength determined from unconsolidated-undrained (UU) and unconfined compression tests (UC) plotted with sampling depth at each site.

Figure 22 is a comparison of variability in shale strength determined using three sampling and testing protocols for the Kansas City site. Closed circles are undrained shear strength determined from on-site UU testing; open circles are undrained shear strength determined from on-site UC testing; crosses are undrained shear strength obtained from shale sampled at a nearby borehole (denoted BH-8) following a conventional off-site UC sampling and testing protocol. Average strength (μ) and standard deviation (σ) values were calculated to determine corresponding coefficients of variation (COV = μ/σ) in strength measurements following each protocol. Results from this site suggest that a reduction in the degree of variability of strength measurements may be achieved following an on-site laboratory testing protocol. Average UCS obtained for shale sampled at depths ranging from 90 feet to 150 feet is 589 psi following conventional protocol is 589 psi, with a COV about this average of 0.32 (Table 1). Average compressive strength determined using on-site UC testing is 862 psi with COV of 0.16. Average compressive strength determined using on-site UU testing is 900 psi with COV of 0.23.

Table 1: Coefficient of variation Su from UU, CU, and onsite UU testing.

Test	Coefficient of variation Su
On site UU	0.23
On site UC	0.16
Off site UC	0.32

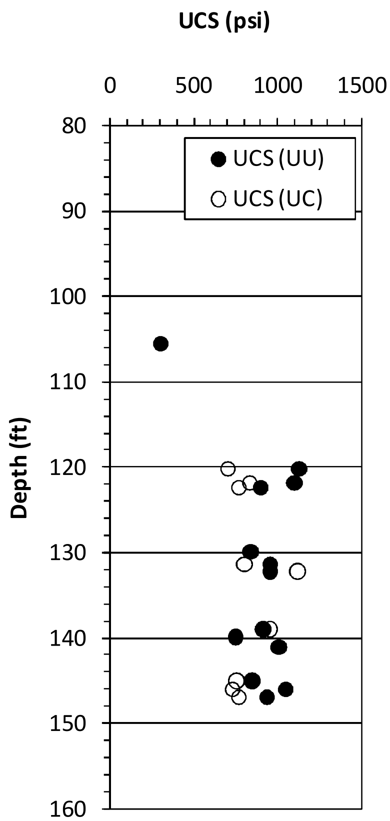

Figure 18: Results from on-site triaxial strength tests – Kansas City site.

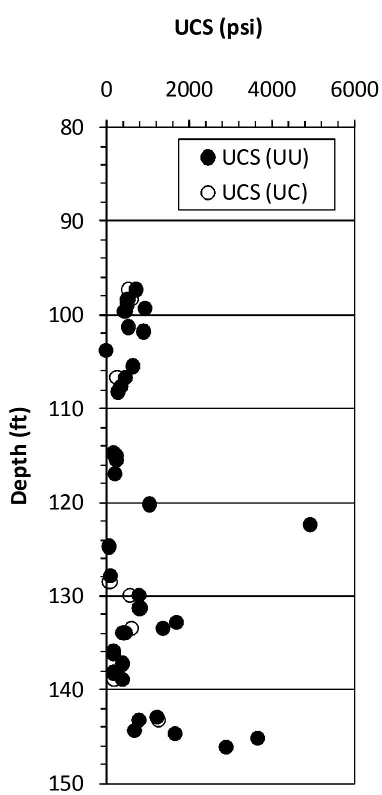

Figure 19: Results from on-site triaxial strength tests – Lexington site.

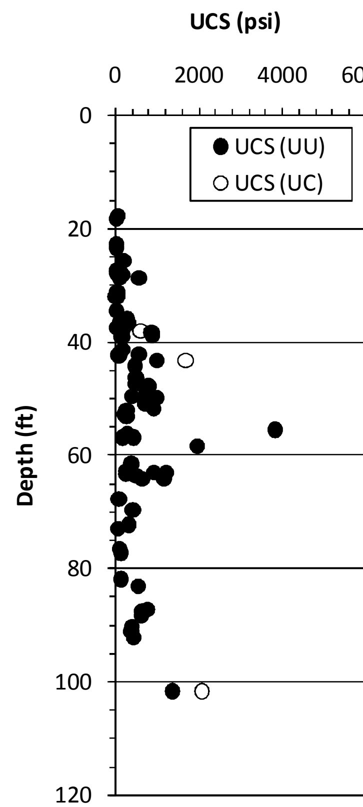

Figure 20: Results from on-site triaxial strength tests – Warrensburg site.

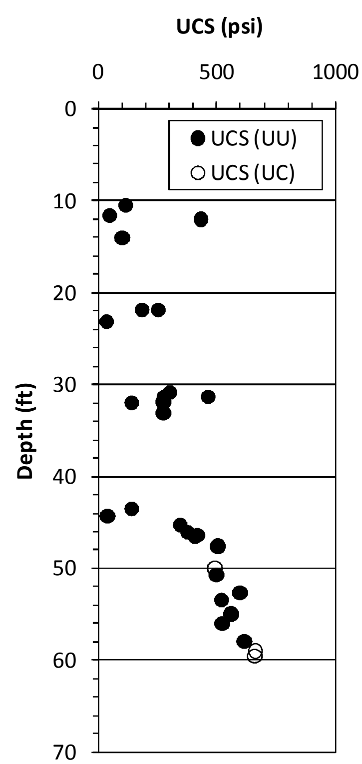

Figure 21: Results from on-site triaxial strength tests – Grandview site.

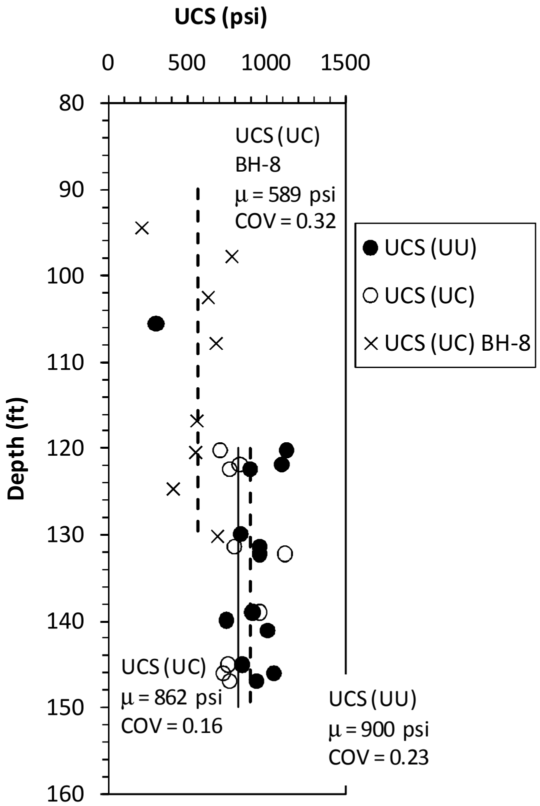

Figure 22: Variability in shale strength determined from three testing protocols – Kansas City site.

4.4. Point Load and Compressive Testing

In comparing point load and compressive testing results for the four sites, data pairs of (Q_u and $I_{s(50)}$) were selected where the two samples were no more than 50 mm (2 inches) apart vertically in the recovered core.

Q_u (Unconfined compressive strength) values were taken to be the maximum axial load from unconfined compression tests, or the maximum principal stress difference from UU compression test results. While results from UU type triaxial tests do not strictly provide unconfined compressive strength, results shown in Figures 19 to 22 illustrate the general correspondence of these values. UU tests are considered appropriate for deep foundations in shale because they depict the conditions found in deeper foundations in shale.

$I_{s(50)}$ (corrected point load index) values were obtained using axial tests on cores pieces with square ends. The usual method of using diametral tests was deemed to be unreliable, as the break would always follow through weak fissile planes in the horizontally bedded vertically drilled samples.

Figures 23-26 show the results of correlations between Q_u and $I_{s(50)}$.

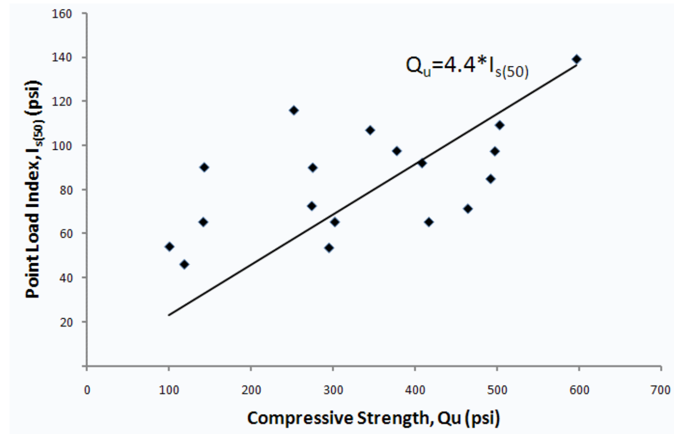

Figure 23: Correlation between Q_u and $I_{s(50)}$, Grandview site.

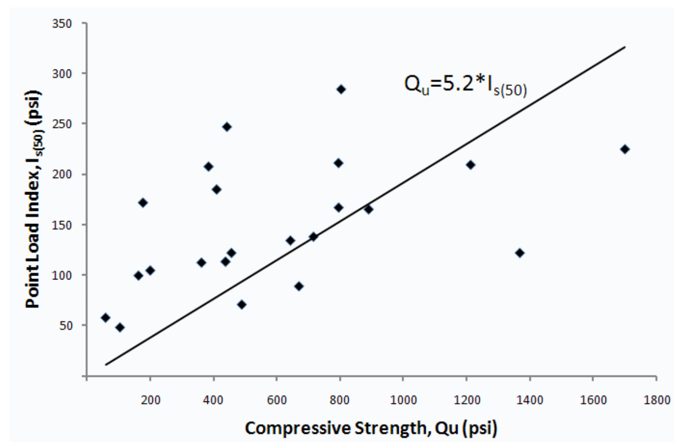

Figure 24: Correlation between Q_u and $I_{s(50)}$, Lexington site.

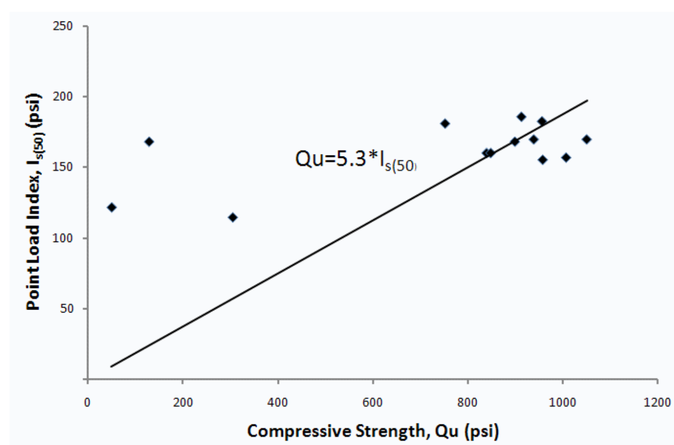

Figure 25: Correlation between Q_u and $I_{s(50)}$, Kansas City site.

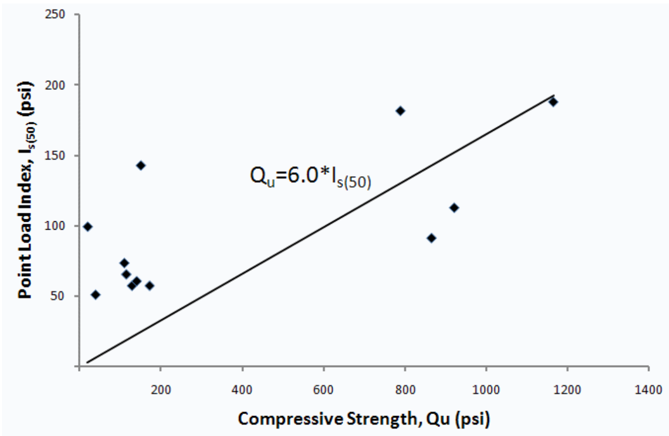

Figure 26: Correlation between Q_u and $Is_{(50)}$, Warrensburg site.

Table 2: Coefficient of variation for point load and compressive testing at the different sites.

Site	Coefficient of variation $I_{s(50)}$	Coefficient of variation Q_u
Grandview	0.29	0.44
Lexington	0.42	0.69
Kansas City	0.13	0.46
Warrensburg	0.49	0.69

The testing results show despite a high degree of scatter in the data, there is fairly consistent relationship between point load and compressive testing. The coefficient of the relationship between Q_u and $I_{s(50)}$ is lower than might be expected from the literature, and may be in part because of the nature of weak shale of the behavior of testing on low strength materials. The fact that axial testing was used, resulting in stronger point load values than diametral testing, may also be in part responsible.

To determine which is more variable, load testing or compressive testing, the coefficient of variation was calculated and is presented in Table 2. The coefficient of variation or relative standard deviation, calculated by dividing the standard deviation by the mean, allows comparing the variability of measurements of different units or different ranges of the same units. The results from these site tests indicate that there is less variability in the point load measurements than in the compressive testing measurements, although that may not correlated strength estimates are less variable

4.5. Shale Rating System

In this investigation, the shale rating system was used to characterize the rock encountered during drilling (Figures 27-29).

Samples not used for compression testing were used for point load tests if durable enough to produce valid point load results. If not, samples were set aside for determination of plasticity index. In either case samples were set aside for slake durability testing.

Two shortcomings of the shale rating system became evident during this investigation.

First, because of the way the system is set up, a-priori knowledge of the slake durability index is required to select the secondary test; for $I_{d2} < 80\%$ Atterberg limits are required; for $I_{d2} > 80\%$ point load tests are required. In the field, determination of whether to collect samples for Atterberg limits cannot simply be made because samples are too weak for point load testing.

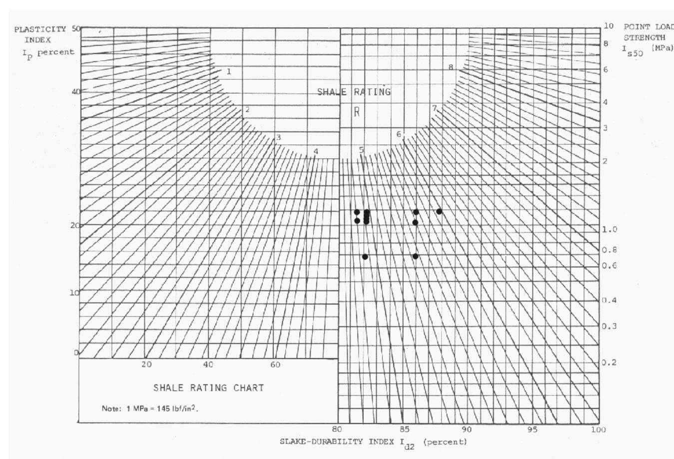

Figure 27: Shale rating of Kansas City site.

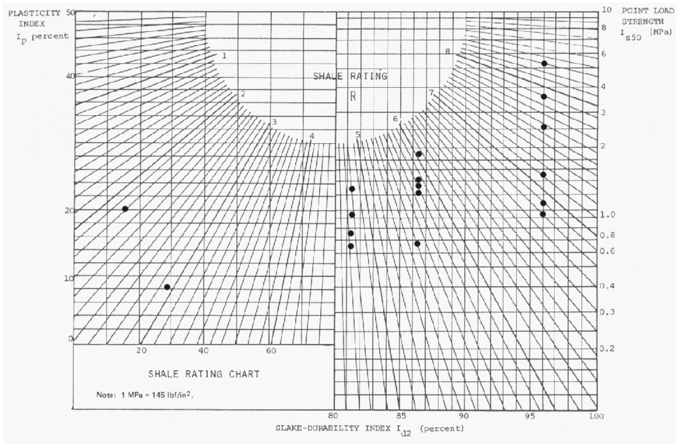

Figure 28: Shale rating of Warrensburg site.

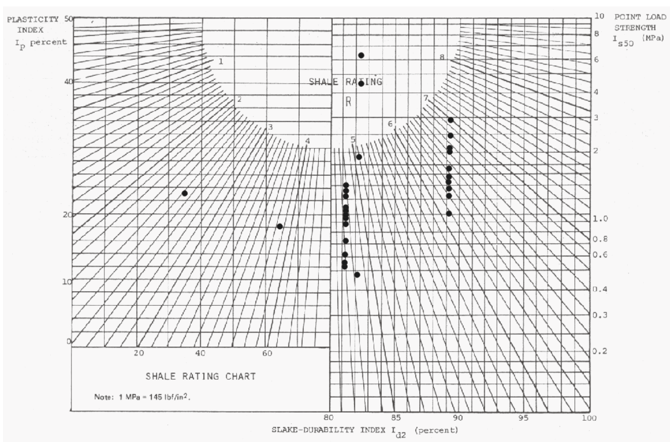

Figure 29: Shale rating of Lexington site.

As a result there were an overabundance of point load test that did not plot on the chart because I_{d2} < 80%, while there were not enough plasticity index tests.

A second shortcoming of the shale rating system is that from the Lexington site two samples with low point load values and I_{d2} > 80% plot in a part of the graph that should have no data points in it (Figure z3). Additionally, if the point load value had been a little lower, and a plasticity index calculated, the data point would have plotted on a completely different part of the graph.

Of particular interest is the bimodal distribution of slake durability measurements (Figure 30).

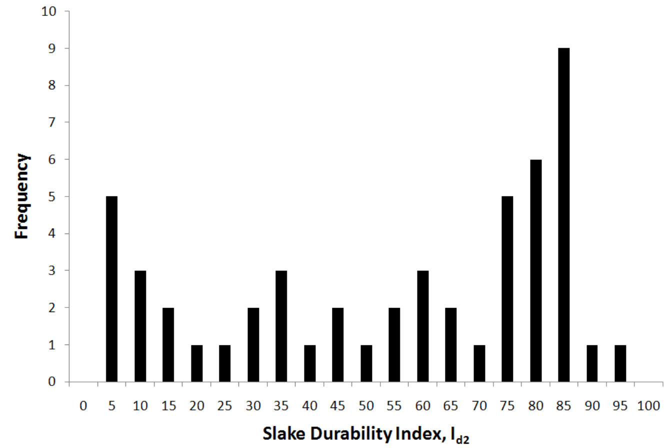

Figure 29: Distribution of slake durability index values from all four sites.

5. SUMARY AND CONCLUSIONS

The results of these investigations show that characterizing shales is difficult. Careful drilling and better core recovery were achieved during this project.

The standard testing method in shales is compression strength testing. Initial indications are that testing samples immediately after drilling may result in lower variability.

Weak correlations were found between compression test results and point load tests. The relationship was found to be consistent between sites, but unexpectedly much lower than the few published results for shale. Also unexpectedly, the point load tests show lower variability than the compression test; unexpected because it is universally assumed that index tests (like point load tests) have higher variability than design tests (like compression tests).

A weak relationship was also found between point load test results (as a proxy for compressive testing) and penetration testing.

The Franklin Shale Rating System was used to incorporate both strength and durability as measured by the slake durability test. This system has a tentative proposed design methodology attached to it for embankments and cut slopes. The rating system was tried during this project.

6. AKNOWLEDGEMENTS

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