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PNNL-18479

Shear Strength Measurement Benchmarking Tests for K Basin Sludge Simulants

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June 2009

Pacific Northwest
NATIONAL LABORATORY

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Summary

Equipment development and demonstration testing for sludge retrieval is being conducted by the K Basin Sludge Treatment Project (STP) at the MASF (Maintenance and Storage Facility) using sludge simulants. For this testing, the STP has identified that simulant shear strength is a key parameter that must be bounded to verify the operability and performance of retrieval systems. K Basin sludge material contains both fine and larger grain particles, and the shear strength measurements show that frictional forces are a very significant contributor. Consequently, large volumes of simulant loaded into prototypical vessels at depths of 1 to several feet are expected to exhibit higher shear strength than laboratory samples in small containers. To confirm this assumption, STP has procured a portable torque/vane system (Humboldt Geovane hand held, manually-operated, soil shear strength tester Model H-4221) that can be used to obtain *in situ* shear strength measurements in prototype systems.

In testing performed at the Pacific Northwest National Laboratory (under contract with the CH2M Hill Plateau Remediation Company), the performance of the Geovane instrument was successfully benchmarked against the M5 Haake rheometer using a series of simulants with shear strengths (τ) ranging from about 700 to 22,000 Pa (shaft corrected). Data obtained for the settler simulant have been excluded from the calculation of the correlation factor reported here. The M5 unit used for this testing is equivalent to similar systems previously used for measurements on actual sludge samples and simulants. It has been demonstrated that the Geovane gives similar shear strength values compared to the M5 Haake rheometer. Analysis of the data obtained from the hand held device has enabled the device to be scaled to the M5. An average correlation factor of 0.96 (i.e., τ_M/τ_H) has been determined for the hand held Geovane device for the data obtained in this investigation. The bounding scaling factors are 0.68 and 1.23 based on lower and upper 95% confidence limits for exceedance, respectively.

The minimum shear strength required from the Geovane to make certain that a true shear strength of 12.2 kPa is measured, where true shear strength is defined here as the best estimate based on the analysis of the M5 shear strength readings, can be calculated with the lower bounding scaling factor.

$$\tau_S = 0.68 \times \tau_H \tag{S.1}$$

Hence, a minimum Geovane reading of 17.9 kPa would confirm that simulant loaded into large-scale test systems exhibits shear strengths equivalent to or in excess of 12.2 kPa (i.e., the STP established bounding target.[a]

Operating steps for obtaining consistent shear strength measurements with the Geovane instrument during the benchmark testing were refined and documented.

(a) GA Leshikar. 2009. *Settler Tank Retrieval Equipment Qualification Testing Strategy*. White Paper, A21C-STP-TI-0006, Rev. 0.

Acronyms

APEL	Applied Process and Engineering Laboratory
CHPRC	CH2M Hill Plateau Remediation Company
HH	Hand Held, Geovane
M5	M5 Haake Rheometer
MASF	Maintenance and Storage Facility
PNNL	Pacific Northwest National Laboratory
STP	Sludge Treatment Plant
UCL	Upper Confidence Limit
LCL	Lower Confidence Limit

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1.0 Introduction

This report describes the head-to-head testing conducted at Pacific Northwest National Laboratory (PNNL) the week of May 18, 2009, to benchmark the Humboldt Geovane hand held (HH), manually operated, soil shear strength tester (Model H-4221) against the M5 Haake rheometer. The M5 unit used was equivalent to similar systems previously used for measurements on actual sludge samples and simulants. The M5 Haake rheometer was performance checked with a certified viscosity standard.

Shear strength measurements were taken with both instruments in three homogenous cohesive simulants, a dry granular simulant, and a K-Basin Settler simulant as described in Section 2.3. The K Basin Settler simulant exhibited vertical stratification during transfer to the test containers. Due to the difference in shear vane size (i.e., overall height for which measurement is taken), the stratification increases the complexity in comparing the measurements. Therefore, the comparison between the two instruments was evaluated, excluding the measurements for the K-Basin simulant. However, the comparison of the measurements in the K-Basin Settler simulant is discussed in the report.

The objectives of the tests and background as to the need for the testing are provided in the following subsections. The test setup, instruments, and simulant are presented in Section 2. The test approach and methodology are discussed in Section 3. The test measurements and data reduction are provided in Section 4, and an assessment of the comparison and conclusions is provided in Section 5.

1.1 Objective/Purpose

The objectives for this task defined by the test approach and corresponding response to the objective are listed below.

- Identify at least three simulants/materials that could be used for head-to-head testing of shear strength measurements with the M5 Haake rheometer and the Humboldt Geovane shear strength tester. The selected simulants were to provide a comparison between the two instruments for the approximate range of 0.5 kPa to 12 kPa. A suite of simulants was identified consisting of both granular and cohesive materials. Scoping tests indicated that the cohesive materials provided better repeatability. The granular materials tended to be sensitive to the amount of packing to which the material was subjected. The simulants identified provided a shear strength range of approximately 700 Pa to 22 kPa.
- Define recommended operating steps for the two instruments during head-to-head tests that will minimize variability in the test results. Operating steps were generated and modified as a result of scoping tests. The operating steps provided with this report document what steps were actually performed and differ from those presented in the test approach.
- Obtain shear strength measurements for the two instruments during head-to-head testing. Shear strength measurements were obtained in five simulants during head-to-head testing of the two instruments.
- Provide a comparison of the shear strength measurements over the range of testing in a letter report. - The measurements and comparison are provided in this report.

1.2 Background

Equipment development and demonstration testing for sludge retrieval are being conducted by Sludge Treatment Project (STP) staff at the Maintenance and Storage Facility (MASF) using two base simulant formulations: Settler Tank Simulant, and KW Container Sludge Simulant. For this testing, STP has identified the simulant shear strength to be a key parameter that must be bounded to verify the operability and performance of retrieval systems.

Shear strength targets were not established during the development of the simulants; however, data on actual sludge samples obtained using a bench top vane system (Plys and Schmidt 2004) indicate:

- Shear strength in size segregated samples (containing only particles less than 250 μm) range from about 200 to 400 Pa.
- Size fractionated samples containing only particles between 250 and 6350 μm exhibited shear strengths up to about 3 kPa.
- One KE canister sludge sample (KC-2/3) containing particles spanning the entire particle size range of sludge (< 6350 μm) exhibited shear strength of up to 8.2 ± 4 kPa.

Based on this data, the STP would like to confirm that simulant loaded into large-scale test systems exhibits shear strengths up to or in excess of 12.2 kPa.

The Settler Sludge Simulant contains both fine and larger grain materials and when loaded into the prototype setter tank (horizontal tank, 20 in. diameter, 16 feet long) at nominal flow rates, is expected to segregate vertically and horizontally, in a manner similar to that of the actual sludge in the settler tanks. The large and dense components will concentrate near the entrance of the settler tank, and will likely exhibit very high shear strengths relative to a homogeneous sample. To confirm this assumption, STP has procured a portable torque/vane system that can be used to obtain in situ shear strength measurements during prototype testing.

Under contract to CH2M Hill Plateau Remediation Company (CHPRC), PNNL and CHPRC performed side by side shear strength measurement testing to evaluate the comparability of data obtained from the portable system with the more sophisticated bench top unit. After comparability is established, the portable unit will be used by STP to collect in situ shear strength data in larger scale mock-up testing.

2.0 Test Setup

The testing was conducted in PNNL's Applied Process and Engineering Laboratory (APEL), Room 112. The setup consisted of two shear vane testers (refer to Section 2.1) and simulants (refer to Section 2.2).

Calibrated 6-inch dial calipers were used to measure the dimensions of the shear vanes used.

A hand-operated stopwatch was used to time the rotation speed of the Geovane unit.

2.1 Shear Vane Units

The M5 Haake viscometer was provided by PNNL, and CHPRC supplied the HH unit with a trained operator, Ryan Lokken, who is expected to operate the instrument during the K-Basin Settler Tube Tests. A brief description of the M5 unit and shear vanes used during testing is provided in Section 2.1.1. The HH unit and the corresponding shear vanes are described in Section 2.1.2.

The M5 Haake viscometer and controller were setup on the floor of the laboratory. This was done to limit the handling of the simulants and provide the operator of the Geovane unit with a preferred position for operation that is similar to that available during the settler tube tests.

The simulant containers were placed on a laboratory jack that was raised and lowered to insert and extract the M5 shear vanes from the simulant. The M5 measurement head was pushed to one side to provide the Geovane operator access to the simulant containers, this is readily achieved without disturbing the simulant container. The Geovane shear vanes were inserted and extracted manually. The simulant container was gently rotated (manually) after each set of measurements to the next test position.

2.1.1 M5 Haake

The Haake M5 viscometer is a bench top unit with a computer based interface. The viscometer is capable of evaluating fluid rheological properties using Couette flow devices or shear strength using shear vanes. The viscometer is stationed in APEL, Room 112. Figure 2.1 contains a photo of the M5 measurement head used.

A shear strength measurement is actually a measurement of the yield stress in shear. The shear strength is obtained by rotating a shear vane of known geometry at a constant rate (0.3 rpm was used in the current study) to obtain a resulting torque versus time profile. The rotational speed of the shear vane is controlled by the Haake control system.

The peak torque measured and the shear vane geometry are used to calculate the shear strength. The calculation used to obtain the shear strength is summarized in Section 3. The M5 instrument uses an operator defined job description, which includes the vane dimensions, to automatically calculate the shear strength. The shear vanes used are referred to as paddle wheel vanes. The rectangular vanes are attached to a round shaft such that the vanes are parallel to the axis of the shaft and extend radially from the shaft. The vanes are distributed uniformly about the circumference of the shaft. The bottom of each vane is aligned with the bottom of the shaft. Table 2.1 provides the dimensions of the Haake shear vanes used during the head-to-head tests.

Figure 2.1. Haake M5 Measurement Head and Associated Controller Unit

Table 2.1. Shear Vanes Used with the Haake M5 Viscometer

Nominal Shear Vane Indication (dia × ht)	No. of Vanes Used to Form Paddle Wheel Shear Vane	Measured Shear Vane Overall Diameter mm (inches)	Measured Vane Height mm (inches)	Measured Shaft Diameter mm (inches)
8 mm × 16 mm	4	8.03 (0.316)	15.98 (0.629)	3.23 (0.127)
16 mm × 16 mm	4	15.98 (0.629)	16.00 (0.630)	6.02 (0.237)
16 mm × 4 mm[(a)]	4	16.00 (0.630)	4.23 (0.167)	5.99 (0.236)
6 mm × 6 mm	4	3.17 (0.125)	6.48 (0.255)	6.405 (0.252)

(a) Vane dimensions do not satisfy requirements of RPL-COLLOID-02. This vane was selected and used to assess vertical material heterogeneity because it was capable of achieving immersion depths similar to the maximum immersion achieved by the Geovane.

2.1.1.1 Performance Check of Haake M5

The rheometer performance was verified before and after the shear vane tests with a 48.0-cP standard, Brookfield (Lot # 062408, expiration date 5/4/10). The standard flow curves were obtained on both M5 RV20 and Haake RS 600 rheometers using standard-size concentric-cylinder geometry. The performance check of the rheometer was performed according to PNNL technical procedure, RPL-COLLOID-02 (Daniel 2007).

The viscosity standard should be performed at 25ºC because of its temperature sensitivity; thus, a temperature lower than 25ºC may result in an increase in viscosity. The Haake RS 600 has temperature control capabilities, whereas the M5 RV20 Rheometer does not. As a result, the standard was run using both instruments. The standard was performed on the Haake RS 600 at 25ºC and at the current room temperature of 19ºC. The standard was also performed on the M5 RV20 at the current room temperature of 19ºC and then compared to the results of the Haake RS 600. The viscosity of the standard was within 10% of the reported value when performed on the Haake RS 600 at 25ºC. Viscosity values of the standard obtained at 19ºC were also within 10% when performed on both instruments.

While these tests do not directly test the vane geometry, they confirm that the torque measurement system is operating properly.

2.1.2 Geovane Unit

The Geovane soil shear strength tester, Model H-4221, manufactured by Humboldt, is an HH instrument used to obtain soil shear strength measurements. The unit can be operated with different size shear vanes. Table 2.2 provides the dimensions of the Geovane shear vanes used during the head-to-head tests.

The unit is marked with 0 to 140, an arbitrary scale in increments of two. When the device is rotated manually, a maximum scale (dial) indicator captures the peak scale reading, which corresponds to the maximum torque applied to the unit. A conversion table, specific to the vane size installed, is used to convert the maximum scale reading to a shear strength in units of kPa. The recommended rotational speed for the unit was approximately 1 rpm. The operator attempted to rotate the device manually at a constant rate until the scale reading associated with maximum scale indicator no longer increased. Figure 2.2 contains a photo of the Geovane device with the 19-mm shear vane installed.

The Geovane unit coupled with the shear vane sizes available had a maximum capacity of 200 kPa.

Figure 2.2. Geovane HH, Manually Operated, Soil Shear Strength Tester Manufactured by Humbolt (Model H-4221) with the 19-mm Shear Vane Installed

Table 2.2. Shear Vanes Used with the Humbolt Geovane HH Unit

Nominal Shear Vane Indication	No. of Vanes Used to Form Paddle Wheel Shear Vane	Shear Vane Measured Diameter mm (inches)	Shear Vane Measured Height mm (inches)	Shear Vane Measured Shaft Diameter mm (inches)
G-small (19 mm)	4	19.13 (0.753)	29.24 (1.151)	6.35 (0.250)
G-Large (33 mm)	4	33.83 (1.332)	51.87 (2.042)	6.35 (0.250)

2.2 Simulant Descriptions

2.2.1 K-Basin Settler Simulant-

The settler simulant used in this testing was prepared by STP staff at MASF (Maintenance and Storage Facility) and shipped to PNNL in a 5-gallon bucket as a wet slurry with an excess of water. At PNNL, the simulant was mobilized with an electric mixer and then split into two additional containers for shear strength testing. The simulant was transferred into two cut-off 5-gallon buckets for the shear strength testing (28 cm diameter, simulant depth 9.5 cm). No special measures were taken by PNNL staff to verify that the contents of each container were equally split. In fact, initial scoping tests indicated that settler simulant in one container exhibited a greater strength. The first container was filled with simulant, and then the original bucket was mixed again to try and mobilize the remaining settler simulant that had settled to the bottom that had not mobilized before transferring it to the second container. Because of stratification of settler simulant in the original container, the simulant fraction added to the second container was much thicker and paste-like when compared to the material added to the first container. It was noted that after the simulant was split into the two test containers, residual simulant material was present in the bottom of the original container as very dry paste, suggesting that the original container may not have been adequately mixed. The residual mixture was cream/white in color with dark-colored granular material visibly present, suggesting that the cerium oxide was not completely dispersed throughout the bucket; the granular material was most probably a mixture of the tungsten, steel grit, and flyash used to make up the simulant. It was also observed during testing that a soft, fluffy layer of particles had separated out of the settler simulant during dewatering and was easily disturbed when dewatering the simulant just before testing. Because of the large range in particle sizes (600 micron to sub-micron) and densities (2.5 to 19 g/cm^3) of the individual sludge components, dispersions of these materials may be subject to significant size and density segregation. Dilute suspensions of the slurry are likely to yield stratification of simulant components based on the overall particle/aggregate settling velocities. However, well-mixed thickened sludge simulant has sufficient shear strength to uniformly suspend dense particles and concentration-hindered particle settling also limits the degree of component segregation. The simulant must be carefully dewatered and mixed several times to confirm that a well-mixed thickened sludge is obtained; this was not done for the settler simulant used for this test.

The simulant was allowed to settle for 5 days with excess water periodically removed. Excess supernatant was removed just before testing.

The general composition of the setter simulant is provided in Table 2.3. A detailed description of the technical basis for the settler tank simulant is provided in Schmidt and Zacher (2007). Additional details of the composition and characteristics of this simulant are given in Burns et al. (2009).

Table 2.3. Settler Simulant Composition

Component Used	Wt% (Dry Basis)
Tungsten particles	6
Steel grit	14
Cerium oxide	68
Flyash	11
Iron hydroxide (added as a slurry)	1

2.2.2 Bentonite Clay

A mixture of water and 20% by weight bentonite was made and placed into the airtight test container, (15.3-cm diameter round container, 15.3-cm simulant depth) and kept quiescent for 5 days at room temperature.

2.2.3 Play Dough

Play dough was made by adding 1 liter of flour, 500 mL of salt, ~200 g of cream of tartar, 60 mL of vegetable oil, and 1 liter of water together with 5 mL of yellow food dye. The mixture was stirred over a heat source for 5 minutes until the mixture congealed. The dough was allowed to cool and kneaded to form a dough. The play dough was kept in an airtight round container (15.3-cm diameter round container, 11.4-cm simulant depth) at room temperature until testing.

2.2.4 Modeling Clay

Store bought colored modeling clay (EZ Shape®) was formed into a 12.1-cm-diameter by 9.7-cm-high disk and allowed to equilibrate to room temperature before testing.

2.2.5 Glass Beads

Potters Mill 9 glass beads, Potters Industries, were used as a granular simulant demonstrating a low shear strength. The particle size range of these beads as per the manufacturer's specifications is 125 to 180 μ with a minimum roundness of 80%. The glass beads were poured into the test container, (8.9 cm × 8.9 cm, rounded square food storage container, simulant depth 10.2 cm) and mixed by inverting and rolling the container just before testing.

3.0 Test Approach

To benchmark the Geovane manually operated unit, head-to head tests were conducted with both the Geovane and the Haake M5 laboratory benchtop rheometers. The shear vane measurements from the manual device where compared to those obtained with a bench-top unit whose operation can be performance checked against traceable standards. For the purpose of this approach, the term "shear strength" will refer to a "yield stress obtained in shear."

Because no standards exist for shear strength, the M5 unit is performance checked using a certified viscosity standard both before and after the tests are conducted as described in Section 2.1.1.1. While this does not directly test the shear vane geometry, it verifies that the torque measurement system of the Haake M5 is operating properly.

To collect shear vane measurements, the testing used the actual manually operated shear vane instrument and corresponding CHPRC operator designated for conducting the settler simulant tests at MASF. By using the actual (single) operator and device to conduct the tests, the operator-to-operator and any device-to-device variations associated with operating the manual device were eliminated from the comparison.

Due to the variation in shear strength exhibited by various batches of simulant and because of factors such as age, handling, original make-up process, container geometry, chemistry, etc., the measurements with the two instruments were made essentially at the same time in the same container of simulant. When possible, the measurements for the two devices were obtained in an alternating sequence. However, due to the size difference in shear vanes used by the two devices, the extraction of the Geovane vane from the simulant container could be disruptive to the region around the measurement location. Therefore, for some simulants, the M5 measurements, which utilized a much smaller vane, were taken. This provided room between the measurement locations for the Geovane measurements to be taken. The objective was for the measurements with both devices to be made in the same container at an undisturbed geometrically similar location. The test approach required taking a minimum of three measurements with each device in each simulant container.

3.1 Shear Strength Measurement

The shear strength is a semi-quantitative measurement of the stress required to yield a sample in shear such that it ceases to deform like a solid but instead flows like a truly viscous material with a finite viscosity. The shear strength of a sample may be dependent on sample history. The shear strength can be obtained by directly measuring resulting torque as a function of time when an immersed vane is slowly rotated in the sample material. The measured torque is converted to a shear stress by equations 3.1 and 3.2 (Nguyen and Boger 1985).

$$\tau = \frac{T}{K} \tag{3.1}$$

where

$$K = \frac{\pi D^3}{2}\left(\frac{H}{D} + \frac{1}{3}\right) \tag{3.2}$$

where τ = calculated shear stress in Pascal
T = measured torque in Newton-meters
K = shear vane constant in cubic meters
D = shear vane diameter in meters
H = shear vane height in meters.

This equation is based on the premise that the diameter of the vane shaft is much smaller than the diameter of the vane itself. A typical stress/time profile is shown in Figure 3.1. The profile shows an initial linear region (τ_y) followed by a nonlinear region, a stress maximum (τ_s), and a stress decay region. The stress maximum is the transition between the visco-elastic and fully viscous flow. The shear strength is defined as the transition between these two flows and is measured at the stress maximum. The actual shear strength of the material is equal to τ_S.

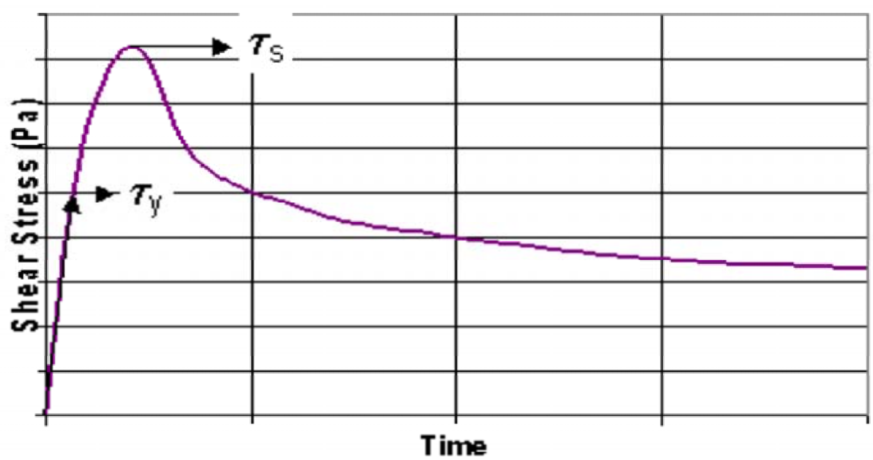


Figure 3.1. Typical Stress-Versus-Time Profile for a Shear Vane at Constant Shear Rate

In cases where the shaft diameter (D_s) approaches that of the vane or for very deep vane immersion depths, shaft torque contributions may become significant relative to vane torque contributions. In this case, corrections for shaft contributions can be roughly approximated (assuming no slip of material around the shaft) by using the revised shear vane constant K_{shaft}:

$$K_{shaft} = \left[\frac{\pi D_s^3}{2}\left(\frac{h}{D_s} - \frac{1}{6}\right) + \frac{\pi D^3}{2}\left(\frac{H}{D} + \frac{1}{3}\right)\right] \tag{3.3}$$

Here, *h* is the immersion depth of the vane (as measured by the vertical distance from the height of the solids bed to the top surface of vane rotation). This equation is premised on the fact that failure of material around the shaft is characterized by 1) a stress that is equivalent to the shear strength of the material and 2) a cylindrical slip plane with a diameter equal to that of the vane shaft.

Shaft corrections made using the above equation are approximate at best. First, the failure stress associated with shaft movements may not necessarily be equal to the shear strength. If failure occurs as a result of slip between the vane tool shaft and test material, then the stress may be adhesive or frictional (for granular materials) in nature. This situation likely occurs when adhesive or frictional forces are weak relative to the material shear strength or when a lubrication layer (such as a thin water layer) forms next to the shaft. Should these failure mechanisms be present, the equation for shaft-corrected shear strength would tend to underestimate shear strength.

On the other hand, if adhesion and/or friction between the test material and the shaft are strong, then material failure is likely. The failure stress of the material would be equivalent to the shear strength; however, the slip plane would be located some finite distance away from the shaft such that the diameter of shear is larger than the shaft diameter. Should this failure mechanism be present, the equation for shaft-corrected shear strength would tend to overestimate shear strength.

Unfortunately, it is difficult to accurately assess shaft torque contributions without performing parallel studies using shaft tools (i.e., a tool without vanes) of varying diameter. Such studies were beyond the scope of the current report. As such, the need to shaft-correct results will be based on observable (and persistent) increases in the measured shear strength with increasing vane insertion depth. If persistent depth dependence is observed, then shaft contributions will be approximated using the equation above. The derivation of the shear vane constant, K_{shaft} has been included in Appendix A.

It should be noted that for the current study, shaft corrections are applied to M5 results alone. The corrected shear strengths are always lower than their corresponding uncorrected values. As a result, the correction of M5 data makes the correlation of M5 data to the HH device conservative relative to correlations based on uncorrected data. That is, the consequence of shaft correcting M5 data is a higher target shear strength value for the HH (Geovane) device to satisfy the 12.2-kPa validation target.

In general, the test material should be saturated, fine grained (relative to the vane diameter), and homogeneous to provide reliable/consistent results from the shear vane test system. There are two primary force contributions to the torque measurement with the shear vane technique: 1) colloidal forces and 2) frictional forces. The colloidal forces will be dominant for slurries with smaller particles (generally under 1 to 10 µm). Frictional forces become important for slurries with large particles (generally greater than 50 microns). The friction will vary with the depth of the slurry and the test geometry of the sample container. The K Basin simulants and sludge contain both fine and larger grain materials, and frictional forces are expected to be a significant contributor to the shear strength measurements. The STP base simulant compositions (particle-size distribution and density) are designed to represent three primary K Basin sludge streams and are documented in a memorandum.[a]

The shear strength may not be constant throughout the material if the solid concentration or particle-size distribution is not uniform with depth. The equations presented assume a uniform shear stress over the depth of the device. Therefore, the calculated shear stress is actually an averaged shear stress that

(a) GT MacLean. 2008. *K Basin Sludge Simulants,* Letter Report, From GT MacLean (Fluor Government Group) to R Lokken, August 7, 2008, Fluor Government Group, Richland, Washington.

may be dependent on the size of the shear vane used if gradients on the scale of the shear vane exist. This can result in shear vanes of different sizes yielding different values.

3.2 Operating Steps

The measurements with the two devices were taken in the simulant containers described in Section 2.2. Testing was conducted via the operating steps for each device given in Appendices B and C.

The operating steps presented in the test approach were modified slightly to address the normal forces applied to the M5 shear vane during the insertion of the shear vane into the simulant. It was possible to load the M5 head such that the ability to rotate the device during testing at 0.3 rpm was disrupted. Therefore, in some cases, the laboratory jack was lowered slightly (on the order of 1 mm or less) after vane insertion to reduce the normal forces on the shear vane. Two criteria were used to determine if the laboratory jack needed to be lowered.

- Based on visual observation, was the M5 head tilted or raised during the vane insertion process? The jack was to be lowered until the M5 head alignment was vertical.
- Under static initial conditions, the indicated torque on the controller was greater than 1%. The laboratory jack was to be lowered until the indicated torque was less than 1%.

After conducting the test, the data file was reviewed to confirm that the rotational speed of the unit was acceptable.

The depth of the measurements is defined as the distance between the top of the simulant (surface of material) and the midpoint of the shear vane. The bulk of the measurements were taken with the depth for both devices being the same. This resulted in the bottom of the larger vanes of the Geovane manual tester being inserted farther into the simulant. To address the observed stratification in the K Basin settler simulant, measurements were taken at two depths with the M5 device. The shallow measurement was taken first, and then the M5 vane was lowered, without changing position, to a greater depth and the measurement repeated.

For testing with the glass beads, refer to Section 2.2.5. The simulant was reloaded before each measurement, and the measurements were taken in the centre of the container with both devices.

4.0 Test Results

4.1 Measurements

Rheograms obtained for the test simulants used are provided in Appendix D. A summary of the averaged data obtained for both the HH, Geovane unit, and the M5 Rheometer is given in Table 4.1. The test conditions for the individual measurements used to obtain the data presented in Table 4.1, i.e., measurement depth, vane size, and device, are given in Tables E.2 and E.3 of Appendix E. Shear strength radial variations within the test container are shown in Table 4.2 with comparison plots given in Appendix F. Measurements were taken from an arbitrary zero point around the circumference of the test container, expressed in degrees, whereby the first M5 measurement (not necessarily the first measurement) was demoted as 0 degrees (see Data sheet III in Appendix B).

It should be noted that the 0 degree shear strength values obtained for the settler simulant using the M5 are considerably lower than all the other values obtained. The Geovane unit was used first at 45 degrees to obtain an initial shear strength value of the settled settler material to facilitate the choice of vane for the M5 instrument. The 0 degree measurement was most likely affected by removing the Geovane from the simulant (due to the nature of the simulant, it was very difficult to remove the large vane used with the Geovane without disrupting the surrounding simulant). This measurement was discarded in calculating the average value.

The test 1 and test 2 values reported in Table 4.2 for the M5 are measurements taken at different depths at the same angle, where test 1 is the first measurement taken at a shallower depth.

Table 4.1. Summary of Average Shear Strength Values Obtained

Material	PNNL M5 Rheometer with Shear Vane								HH Tester				Scaling
	Standard Shear Strength				Shaft Corrected Shear Strength				Standard Shear Strength				Ratio M5 shaft corrected-to-HH
	Value [Pa]	Count[a]	Error[b] [Pa]	95% CL[c] [Pa]	Value [Pa]	Count[a]	Error[b] [Pa]	95% CL[c] [Pa]	Value [Pa]	Count[a]	Error[b] [Pa]	95% CL[c] [Pa]	
Settler Simulant	7571	6	311	800	4319	6	183	470	9705	4	825	2622	0.445
Bentonite (20-wt%)	4251	6	119	306	2961	6	151	388	2730	3	0	0	1.084
Play Dough	7777	4	478	1329	4420	4	158	438	5833	3	363	1562	0.758
Modeling Clay	33864	7	1669	3940	21534	6	1269	2994	28350	5	865	2404	0.760
Potters Mil 9	931	2	8	33	672	2	6	24	550	1	n/a	n/a	1.221

(a) Number of measurements included in average value reported above.
(b) Standard error of the mean.
(c) 95% confidence limit about the mean, t-values for 95% similarity.

Table 4.2. Shear Strength Radial Variation

Settler Simulant

Test Angle	Shear Strength [Pa]					
	M5 Rheometer				Geovane	
	uncorrected		Shaft corrected			
	Test 1	Test 2	Test 1	Test 2	uncorrected	shaft corrected
Center						
0 degrees	2446	2288	2108	1749		
45 degrees					9840	9715
90 degrees	6161	8070	3852	4201		
135 degrees					7380	7306
180 degrees	7938	8288	4963	4314		
225 degrees					11210	11098
270 degrees	7539	7432	4713	3869		
315 degrees					10390	10286

Bentonite (20-wt%)

Test Angle	Shear Strength [Pa]					
	M5 Rheometer				Hand-Held Tester	
	uncorrected		Shaft corrected			
	Test 1	Test 2	Test 1	Test 2	uncorrected	shaft corrected
Center					2730	2703
0 degrees	4103	4402	3318	3177		
45 degrees	4050	4127	3274	2978		
90 degrees						
135 degrees						
180 degrees	4044	4781	2528	2489		
225 degrees						
270 degrees					2730	2703
315 degrees					2730	2703

Play Dough

Test Angle	Shear Strength [Pa]					
	M5 Rheometer				Hand-Held Tester	
	uncorrected		Shaft corrected			
	Test 1	Test 2	Test 1	Test 2	uncorrected	shaft corrected
Center						
0 degrees	7551	8957	4721	4663	6560	6459
45 degrees						
90 degrees						
135 degrees					5470	5415
180 degrees	6651	7948	4158	4137		
225 degrees						
270 degrees						
315 degrees					5470	5415

Modeling Clay

Test Angle	Shear Strength [Pa]					
	M5 Rheometer				Hand-Held Tester	
	uncorrected		Shaft corrected			
	Test 1	Test 2	Test 1	Test 2	uncorrected	shaft corrected
Center					28750	28463
0 degrees			18228			
45 degrees					29000	26971
90 degrees	34081	37719	26850	19326		
135 degrees					30000	27901
180 degrees	28010	38386	22067	19668		
225 degrees					29000	26971
270 degrees	29019	35972	22862	18431		
315 degrees					25000	23251

4.2 Correlation of Results

The ultimate goal of the current assessment is to be able to compare HH shear strength measurements to M5 shear strength measurements. The basic premise is that the M5 measurement provides a representative measure of the material's "true" shear strength. Because HH and M5 devices provide different measures of shear strength, a direct comparison between methods is difficult.

As shown in Figure 4.1, shear strength measurements made by the HH device typically fall around that measured by the M5 measuring device. Three of the simulants tested are cohesive simulants and are expected to show minimal material heterogeneity. The fourth is a well-defined (uniform) granular solid and is expected to show increasing lithostatic load with depth. For granular materials, the consequence of increased lithostatic load with depth is an increase in the material shear strength at deeper depths. This increase results from a corresponding increase in interparticle friction because of higher normal force (lithostatic load) between particles.

Comparison of K-Basin settler similar shear strength measurements on the HH and M5 devices was further complicated by significant disruption of the test material that occurred when removing the Geovane test device from the slurry. This disruption spanned several Geovane vane diameters, affecting all M5 test locations. The impact of such disruption would be a lowering of the shear strength in regions where M5 testing occurred. It appears as if this lowering occurs, as out of all materials tested, the uncorrected M5 shear strengths for the K-Basin simulant were the only measurements to routinely fall below those measured by the HH device. Due to the difference in shear vane size (i.e., overall height for which measurement is taken) between the two devices used, the stratification increases the complexity in comparing the measurements. Therefore, further comparisons between the two instruments presented in the main body of this report exclude the measurements obtained for the K-Basin settler simulant.

To determine if the deviation between M5 and HH measurements presented in Figure 4.1 is significant, a standard significance test is applied to the results (Shoemaker et al. 1996). First, the difference (Δ) between the average shear strengths measured by the M5 and HH devices is determined. For a test material *i*, this is:

$$\Delta_i = \left| \tau_{M,i} - \tau_{H,i} \right| \tag{4.1}$$

where $\tau_{M,i}$ and $\tau_{H,i}$ are the M5 and HH measured shear strengths for material, *i*, respectively. Next, the pooled deviation ($S_{P,i}$) of M5 and HH shear strength measurements is calculated using:

$$S_{P,i} = \left[\frac{\left(N_{M,i} - 1\right) S_{M,i}^2 + \left(N_{H,i} - 1\right) S_{H,i}^2}{N_{M,i} + N_{H,i} - 2} \right]^{1/2} \tag{4.2}$$

where $N_{M,i}$ = number of M5 shear strength measurements for test material *i*
$N_{H,i}$ = number of HH shear strength measurements for test material *i*
$S_{M,i}$ = standard deviation of M5 shear strength measurements for test material *i*
$S_{H,i}$ = standard deviation of HH shear strength measurements for test material *i*.

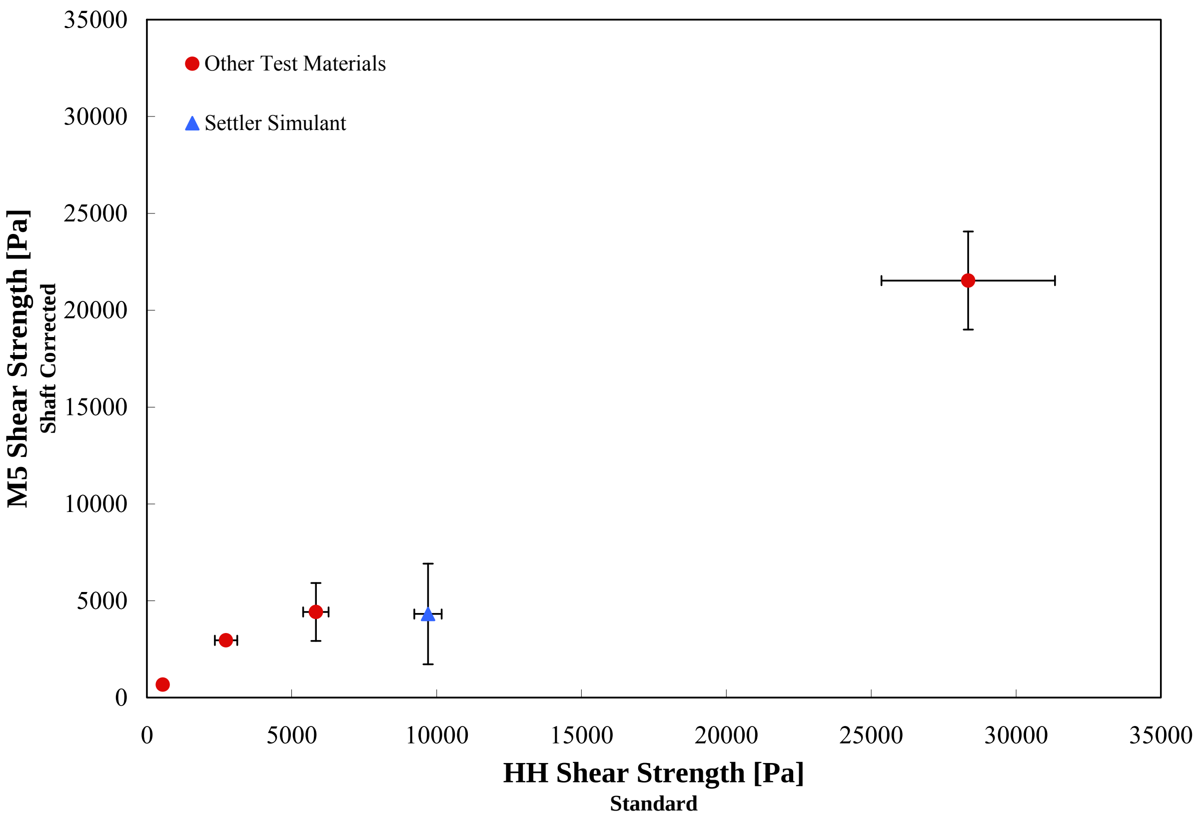


Figure 4.1. Comparison of Shear Strength Obtained from the M5 Instrument and the HH, Geovane. The error bars on each data point are 95% confidence limits for similarity.

The standard deviation in the difference between the two shear strength averages (τ_M and τ_H) can be calculated using:

$$s_i = S_{P,i}\left(\frac{1}{N_{M,i}} + \frac{1}{N_{H,i}}\right)^{1/2} \tag{4.3}$$

It should be noted that this equation treats the standard deviations for all measurements for material *i* as being equivalent to the pooled deviation. This allows estimation of the standard errors in the difference when limited repeat measurements are available (such as for the Geovane measurements of the Potters Mil 9 glass bead power).

Next, the allowable range of difference for test material *i* (δ_i) is calculated by applying 95% confidence limit intervals such that:

$$\delta_i = ts_i \tag{4.4}$$

Here, *t* is taken from Table 4.3 and depends on the degrees of freedom ν_i which, for the comparison of M5 and HH results, is defined as:

$$\nu = N_{M,i} + N_{H,i} - 2 \tag{4.5}$$

If Δ_i is greater than δ_i, then the difference between M5 and HH shear strength measurements for test material *i* is significant. On the other hand, if Δ_i is less than δ_i, then the M5 and HH shear strength measurements are statistically similar.

Table 4.3. Critical Values of t (adapted from Shoemaker et al. 1996)

Degrees of freedom (ν)	Value of *t* for Exceedance Test[(a)] (95% confidence limit)	Value of *t* for Similarity Test[(b)] (95% confidence limit)
1	6.31	12.7
2	2.92	4.30
3	2.35	3.18
4	2.13	2.78
5	2.02	2.57
6	1.94	2.45
7	1.89	2.36
8	1.86	2.31
9	1.83	2.26
10	1.81	2.13
∞	1.61	1.96

(a) Used to calculate confidence limits to determine if a given mean exceeds a specified value.
(b) Used to calculate confidence limits to determine if a given mean is similar to a specified value.

Table 4.4 shows the results of significance analysis for the five different test materials. For four out of the five test materials, the difference between the HH and M5 measured shear strengths is significant. It should be noted that the standard variance of the Geovane (i.e., S_H^2 in Equation 4.2) is assumed zero for Potters Mil 9.

From the current set of test data, it is not possible to determine the root cause of differences in M5 and HH shear strength. However, it can be speculated that the differences result from 1) overestimation of shaft contributions for the M5 results and 2) possible disruption and weakening of material by insertion and removal of the Geovane.

Table 4.4. Significance Test for HH and M5 Measured Shear Strengths.

Test Material	δ_i [Pa]	Δ_i [Pa]	Confidence Limit (95%) Significance
Settler Simulant	1600	5400	Different (HH Significantly Higher)
Bentonite (20-wt%)	510	230	Similar
Play Dough	920	1400	Different (HH Significantly Lower)
Modeling Clay	3600	6800	Different (HH Significantly Lower)
Potters Mil 9	121[(a)]	122	Different (HH Slightly Lower)

(a) Calculation of δ_i for Potters Mil 9 treats the standard deviation for the Geovane measurement as equal to the M5 standard deviation for this material.

To facilitate comparison of HH and M5 devices, a scaling factor is defined to allow conversion of an HH measured shear strength to an M5 (i.e., "true") shear strength measurement. The scaling factor is defined as the ratio of M5 shear strength to HH shear strength. For a test material *i*, the scaling factor (F_i) is:

$$F_i = \frac{\tau_{M,i}}{\tau_{H,i}} \tag{4.6}$$

For perfect agreement between M5 and HH values, *F* would be 1.0.

Table 4.5 shows the scaling factors for the current test measurements. The settler simulant shows a scaling factor of 0.45, indicating that the HH device significantly over-predicts that given by the M5. This result is excluded from further consideration because of concerns that Geovane testing disrupted the material in regions used by the M5, substantially impacting M5-measured shear strength as a result. The average scaling factor (excluding the settler simulant) is 0.96 ± 0.12. The reported uncertainty is the standard error of the mean.

The average scaling factor can be used to determine the "true" shear strength (τ_S) from a HH measurement via:

$$\tau_S = F_{ave}\tau_H \tag{4.7}$$

where τ_H is the measured HH shear strength, and F_{ave} is the average scaling factor (0.96). Applying a 95% confidence analysis yields lower and upper scaling-factor bounds of 0.68 and 1.23, respectively. For example, a measurement of 12.2 kPa on the HH device translates to a "true" shear strength in the range of 8.3 kPa to 15.0 kPa (based on 95% CL for exceedance). Conversely, an HH reading of 17.9 kPa would validate the STP target shear strength value of 12.2-kPa true shear strength. Figure 4.1 shows the shear strength correlation results for accepted test materials (i.e., all except the settler simulant) and the M5-HH stress correlation curves corresponding to the following:

1. perfect correlation scaling factor ($F = 1.0$)
2. the average test simulant scaling factor derived from the current study ($F_{ave} = 0.96$)
3. the scaling factor 95% upper confidence limit (UCL) ($F = 1.23$)
4. the scaling factor 95% UCL ($F = 0.68$).

It should be noted that the current scaling factor results presented are weighted heavily by the three test simulants with shear strengths below ~7 kPa (i.e., bentonite, play dough, and Potters Mil 9). Correlation to strengths beyond 7 kPa is limited to the single test with modeling clay. As such, caution should be taken when applying the current test results to shear strengths beyond those studied herein. It would also be helpful to find additional simulants in the 7 to 30 kPa test range to provide additional certainty to the confidence bands.

As stated previously, the scaling factor analysis presented above excludes the settler simulant result. However, a similar analysis of the data, which includes settler simulant measurements, is given in Appendix G. It is not recommended that the scaling factor values in Appendix G be used; however, they have been included in Appendix G for completeness.

Table 4.5. Summary of M5-to-HH Shear Strength Scaling Factors

Test Material	M5(shaft corrected)-to-HH Scaling Factor (F_i)
Settler Simulant	0.45
Bentonite (20-wt%)	1.08
Play Dough	0.76
Modeling Clay	0.76
Potters Mil 9	1.22
Average[a]	0.96
Standard Error of the Mean[a]	0.12

(a) Average and standard error exclude the settler simulant.

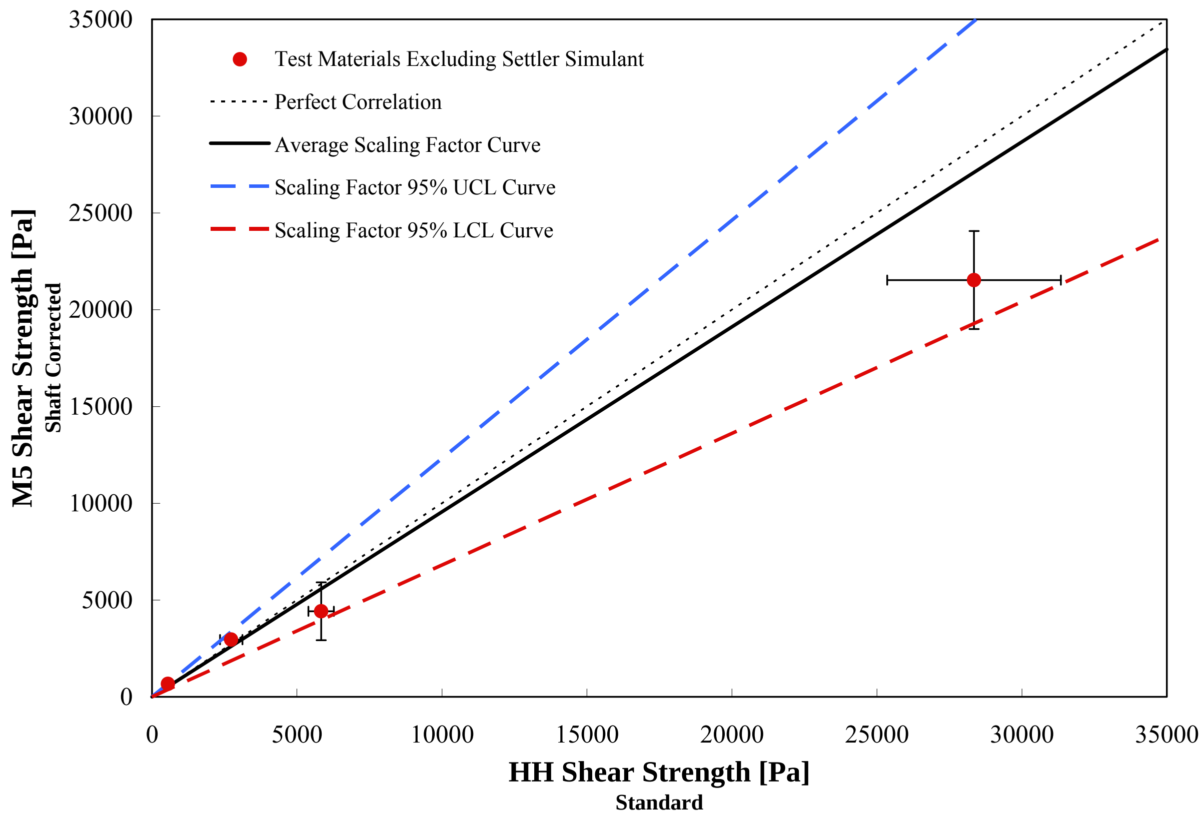


Figure 4.2. Correlation Between Shear Strength Obtained from the M5 Instrument and the HH, Geovane. The error bars on each data point are 95% confidence limits for similarity. The average scaling factor correlation ($F_{ave} = 0.96$, solid line) is shown versus that for perfect correlation ($F = 1.0$, short dashed line). The curves associated with the 95% UCLs and lower confidence limits (LCLs) for the scaling factor are shown (long dashed lines).

5.0 Conclusions

We have successfully benchmarked the Humboldt Geovane HH, manually-operated, soil shear strength tester (Model H-4221) against the M5 Haake rheometer. It has been demonstrated that the Geovane measures similar values for shear strength compared to the shaft-corrected values obtained on the M5 Haake rheometer. Analysis of the data obtained from the HH device has enabled the device to be scaled to the M5. An average correlation factor of 0.96 has been determined for the Geovane for the data obtained in this investigation based on a 95% confidence limit. The bounding scaling factors are 0.68 and 1.23. Hence, a Geovane reading of 17.9 kPa or greater is required to validate (i.e., exceed based on statistical confidence limits) the STP target of a 12.2-kPa true shear strength.

6.0 References

Burns CA, M Luna, and AJ Schmidt. 2009. *Characterization of Settler Tank and KW Container Sludge Simulants*. PNNL-18408, Pacific Northwest National Laboratory, Richland, Washington.

Daniel RC. 2007. PNNL Technical Procedure, "Measurement of Physical and Rheological Properties of Solutions, Slurries and Sludges." RPL-Colloid-02 Rev. 1, Pacific Northwest National Laboratory, Richland, Washington.

Nguyen QD and DV Boger. 1985. "Direct Yield Stress Measurement with the Vane Method." *Journal of Rheology* 29(3):335–347.

Schmidt AJ and AH Zacker. 2007. *Composition and Technical Basis for K Basin Settler Sludge Simulant for Inspection, Retrieval and Pump Testing*. PNNL-16619, Rev 1., Pacific Northwest National Laboratory, Richland, Washington.

Shoemaker DP, CW Garland, and JW Nibler. 1996. *Experiments in Physical Chemistry.* 6th Edition. The McGraw-Hill Companies, Inc., San Francisco, California.

Appendix A

Derivation of Shear Vane Constant

Appendix A: Derivation of Shear Vane Constant

The torque M required to rotate a differential surface element (*dA*) at a radial distance *r* from the axis of rotation in a fluid with constant shear strength of τ_m is given by:

$$dM = r\tau_m dA \tag{A.1}$$

For shear vane experiments, there are two surface orientations: 1) radial and 2) axial. Radial surfaces include the cylinder of rotation formed by rotation of the sides of the vane and by the vane shaft. Axial surface elements correspond to the disks of rotation formed by rotation of the top and bottom surface of the vane.

For radial surfaces, the differential area of the surface element is

$$dA = 2\pi r\,dz \tag{A.2}$$

where *z* is the vertical distance from the top of the solids surface. Substituting Equation A.2 into A.1 yields a radial surface specific torque equation

$$dM = 2\pi r^2 \tau_m dz \tag{A.3}$$

Thus, the shaft torque (M_s) acting on a shaft of radius R_s is:

$$M_s = 2\pi R_s^2 h\tau_m \tag{A.4}$$

where *h* is the immersion depth of the vane tool relative to the top of the vanes. The radial vane torque (M_r) for a vane of radius *R* and height *H* is given by:

$$M_r = 2\pi R^2 H\tau_m \tag{A.5}$$

For axial surfaces, the differential area of the surface element is:

$$dA = 2\pi r\,dr \tag{A.6}$$

Thus, the torque relationship (i.e., Equation A.1) becomes:

$$dM = 2\pi r^2 \tau_m dr \tag{A.7}$$

Integration of this equation yields an upper vane surface torque contribution (M_u) of:

$$M_u = \frac{2}{3}\pi\left(R^3 - R_s^3\right)\tau_m \tag{A.8}$$

and a lower vane surface torque contribution of (M_l) of

$$M_l = \frac{2}{3}\pi R^3 \tau_m \tag{A.9}$$

The total torque (M) acting on the vane tool is the sum of the individual components such that:

$$M = M_s + M_r + M_u + M_l \tag{A.10}$$

Thus,

$$M = \left(2\pi R_s^2 h + 2\pi R^2 H + \frac{4}{3}\pi R^3 - \frac{2}{3}\pi R_s^3 \right)\tau_m \tag{A.11}$$

$$M = \left[2\pi R_s^3 \left(\frac{h}{R_s} - \frac{1}{3} \right) + 2\pi R^3 \left(\frac{H}{R} + \frac{2}{3} \right) \right]\tau_m \tag{A.12}$$

Expressing the shaft and vane radius in terms of diameter, we get:

$$M = \left[\frac{1}{4}\pi D_s^3 \left(\frac{2h}{D_s} - \frac{1}{3} \right) + \frac{1}{4}\pi D^3 \left(\frac{2H}{D} + \frac{2}{3} \right) \right]\tau_m \tag{A.13}$$

$$M = \left[\frac{\pi D_s^3}{2} \left(\frac{h}{D_s} - \frac{1}{6} \right) + \frac{\pi D^3}{2} \left(\frac{H}{D} + \frac{1}{3} \right) \right]\tau_m \tag{A.14}$$

And solving for τ_m,

$$\tau_m = \frac{M}{\left[\frac{\pi D_s^3}{2} \left(\frac{h}{D_s} - \frac{1}{6} \right) + \frac{\pi D^3}{2} \left(\frac{H}{D} + \frac{1}{3} \right) \right]} \tag{A.15}$$

We define the shear vane constant, K_{shaft}, that corrects for shaft contributions such that:

$$\tau_m = \frac{M}{K_{shaft}} \tag{A.16}$$

where

$$K_{shaft} = \left[\frac{\pi D_s^3}{2} \left(\frac{h}{D_s} - \frac{1}{6} \right) + \frac{\pi D^3}{2} \left(\frac{H}{D} + \frac{1}{3} \right) \right] \tag{A.17}$$

For $D >> D_s$ *or* $h \sim H$, this relationship simplifies to the standard shear vane constant

$$K = \left[\frac{\pi D^3}{2} \left(\frac{H}{D} + \frac{1}{3} \right) \right] \tag{A.18}$$

Appendix B

Operating Steps for the Haake M5 Rheometer

Appendix B: Operating Steps for the Haake M5 Rheometer

The following operating steps refer to Example Data Sheet I for recording measurements. These operating steps assume the pre-test performance check of the M5 Haake rheometer has been completed per RPL-COLLOIDS-02.

1. Enter a description of the specific testing to be conducted in the project specified LRB (e.g., date, time, simulant, simulant container/batch designation/description)
2. Select the appropriate shear vane to be used with the simulant being tested based on recommendations generated from scoping tests. If not already provided, enter a description of the shear vane in the LRB and provide the instrument description name entered into the instrument. The description should include the number of vanes and the height and diameter of the shear vane measured with calibrated calipers to a tolerance of ±0.004 inches (±0.1 mm).
3. Mark the target depth of insertion on the selected shear vane. Provide some scale markings above and below the target mark in case the target depth is not achieved. Note: The positioning of the shear vane should be performed with a continual slow insertion. The vane should not be moved up or down if the target depth is missed. Record the actual depth of the vane using the scale markings on the vane.
4. Complete the pretest information on Data Sheet I
5. Use a copy of the plan view (Data Sheet III) for the simulant container to identify measurement locations.
6. With minimal disturbance to the simulant, mark the surface of a cohesive simulant as to where the shear vane measurements are to be made. For granular materials, it may be determined that the container will be reloaded for each test run, and the measurements will be taken in the center of the container. The reloading will be repeated to obtain a minimum of three measurements with each device.
7. Set up the instrument for shear strength measurements per procedure RPL-COLLOID-02.
8. Install the shear vane per the manufacturer's operating instructions. Verify that the vane is securely installed with no vertical or rotational slip.
9. Verify the instrument settings on the RV20 control unit (property No. WD00286).
   - Rate controller knobs set to 100 and 10
   - Maximum torque dial set to 100
   - Filter dial set to 0
10. Use the zero adjust dial to achieve an indicated torque of 0% on the digital display.
11. Complete the setup file for the instrument, including description of test and filename. Verify that the device settings and the name of the output file to be generated are indicated on Data Sheet I.
12. Position the simulant container on the lab jack and raise the container until the simulant surface is just below (several mm) the bottom of the vane. Adjust the position of the container so the shear vane is directly above an indicated measurement location. **Note:** If previous measurements have been taken in the container, it is recommended the measurement location be adjacent to an already used measurement location. However, the larger size Geovane vanes may result in the surrounding region of some simulants being disrupted when the vane is extracted. If this is the case, the M5

measurements will have to be taken first. The M5 measurements are to be taken at locations that allow for Geovane measurements to be made in between the M5 measurement locations.

13. Record the measurement designation on Data Sheet I and on the plan view of the simulant container.
14. Raise the simulant container slowly with the lab jack. Visually observe the M5 head to monitor for any tilt or slip resulting from normal forces on the shear vane generated during the loading process.
15. Insert the shear vane to the target depth by positioning the target depth mark on the shear vane shaft even with the simulant surface.
16. After inserting the shear vane, the lab jack will be lowered slightly to relieve any tilt in the M5 head observed during Step 14. The lab jack is also lowered slightly if necessary to reduce the indicated torque on the controller digital display to less than 1%. **Note:** do not attempt to adjust the torque with the controller after inserting the shear vane.
17. Record the final measurement depth on Data Sheet I
18. Obtain the rheogram by measuring the torque as a function of time with a vane rotational rate of approximately 0.3 rpm. Refer to the manufacturer's operating instructions and procedure RPL-COLLOID-02 for the operation of the rheometer. If the material possesses a yield stress, the rheogram will show a peak torque at the beginning. Then it will level-off with time and finally drop-off to a lower value. Record the peak torque, shear strength, and the test time at which the peak torque occurred on Data Sheet I and verify that the units of the measurement are labeled correctly at the head of each column.
19. Verify that the rotational speed was approximately 0.3 rpm during the measurement.
20. Lower the lab jack to extract the shear vane with minimal disturbance to the adjacent material.
21. If this is the first or last measurement being taken in the simulant container or if the temperature has not been recorded in the last 30 minutes, then take a simulant temperature reading. The temperature device should be inserted into the location where a shear vane measurement was last taken. Record the temperature on Data Sheet I.
22. Remove the simulant container form the lab jack to allow the HH device measurement to be taken per the corresponding operating steps.
23. Clean the shear vane in preparation for the next measurement.
24. Repeat Steps 9 through 23 as needed.

Note: A new data sheet is to be started for each simulant container tested. The measurement designations for both devices are to be entered on the same plan view of the simulant container.

Inserted in LRB No. ______________ on pg: _________

Data Sheet I for Device Comparison Shear Strength Measurements (M5 unit)

Date: _____________ Related LRB entries on pg: _______________________________

Test Personnel: ____

Device & shear vane designation: ____

LRB entry for Shear Vane designation/description: ___________________________________

Device Operator: ____________________________

Simulant: ____

Location of Simulant Description: ____

Specify instrument job name and location of LRB description: _____________________________

____

Device settings: ____

Data table for shear strength measurements

Time[1] (hr:min)	Measurement Designation[2] (device-sequence)	Meas. Depth[3] (mm)	Test time for Indication of peak torque/stress (min:sec)	Peak Torque (N-cm)	Instrument Calculated τ_{ss} (Pa)	Electronic File Name for Stress vs Time Data	Temperature[4] of Simulant (deg C)

1 Recorded as 24-hour clock format

2 Provides the designation for the device and the sequence the measurement was taken. Example: M5-3. Measurement acquired with Haake M5 rheometer and the third measurement taken in simulant batch.

3 Depth from simulant surface to center of shear vane.

4 Temperature to be taken after shear vane measurement and does not need to be taken each time. Should be taken a minimum of two times during test run (beginning and end) and every 30 minutes in cases where longer durations exist between individual measurements.

Data Sheet completed by: ____date: _________

Data Sheet reviewed by: ____date: __________

LRB No. BNW 60345 p.

Data Sheet III for Shear Vane Comparison Tests, ~~6 1/2 Inch Container~~ RCD 5/19/09 No container - freestanding

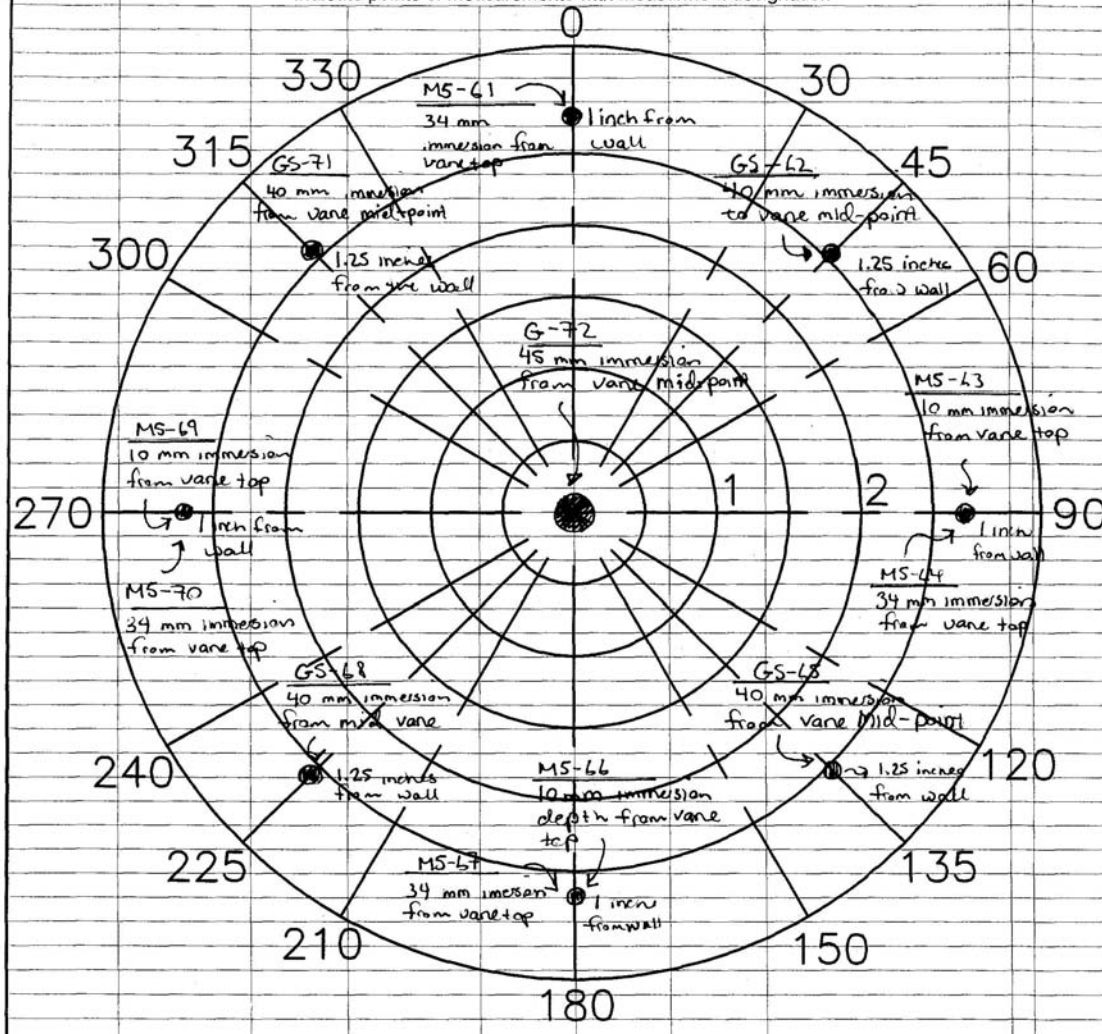
Date of Measurements: 5-19-09

Simulan ID: Modeling Clay (Free standing - No container) - See BNW 60346 p40 for dimensions

Time of First Meas.: 12:44

Time of Last Meas.: 13:22

Indicate points of measurements with measurment designation



6 1/2 Inch Paint Can
(Full Scale)

Data Sheet Completed by: [signature]

Date Completed: 5/19/09

Data Sheet Reviewed by: [signature]

Date Reviewed: 6/08/09

Filename: 6 & a Half In Data Sheet.xls

Appendix C

Operating Steps for Geovane

Appendix C: Operating Steps for Geovane

The following operating steps refer to Data Sheet II for recording measurements (Note: Data Sheet I is included in the M5 rheometer operating steps).

1. Enter a description of the specific testing to be conducted in the project specified LRB (e.g., date, time, simulant, simulant container/batch designation/description).
2. Select the appropriate shear vane to be used with the simulant being tested based on anticipated shear strengths obtained from scoping tests with the M5 unit.
3. If not already done, provide a shear vane designation/name and accompanying description in the LRB. The description should include the number of vanes and the height and diameter of the shear vane. The height and diameter of the shear vane should be obtained with calibrated calipers to a tolerance of ±0.004 inches (±0.1 mm).
4. Mark the target depth of insertion on the selected shear vane. Provide some scale markings above and below the target mark in case the target depth is not achieved. **Note:** The positioning of the shear vane should be performed with a continual slow insertion. The vane should not be moved up if the target depth is missed.
5. On the circumference of the instrument, verify that reference points or marks of some kind exist at increments of 45º that can be used by a second person to time the rotational speed. Note: The target speed for manual turning is approximately 1 rpm.
6. Complete the pretest information on Data Sheet II.
7. Use a copy of the plan view for the simulant container to identify measurement locations using the measurement designation. The measurement designation provides the device and the sequence the measurement was taken for a given simulant. Example: M5-3 is the third measurement taken within the simulant container and was acquired with the Haake M5 rheometer. Note: The same container plan view will be used for marking the measurement locations for both the Geovane and the M5 unit. The sequencing can be universal throughout the test campaign or started over for each simulant.
8. With minimal disturbance to the simulant, mark the surface of a cohesive simulant as to where the shear vane measurements are to be made. For granular materials, it may be determined that the container will be reloaded for each test run, and the measurements will be taken in the center of the container. In such a case, the reloading will be repeated to obtain a minimum of three measurements with each device.
9. Install the shear vane into the device per the manufacturer operating instructions. Verify that the vane is securely installed with no vertical or rotational slip.
10. Record the measurement designation on Data Sheet II and on the plan view of the simulant container. **Note:** If previous measurements have been taken in the container, the measurement location should be adjacent to an already used measurement location.
11. Insert the shear vane to the target depth by positioning the target depth mark on the shear vane shaft even with the simulant surface. Insert the vane into the simulant in a slow continuous process maintaining a vertical orientation. Do not twist the vane during the loading process and attempt to minimize any rocking or "wiggle." Record the measurement depth on Data Sheet II.
12. Have a stop watch and separate operator ready to record the time required to measure one-eighth rotation of the device. The stop-watch operator will align himself/herself with one of the 45º incremented markings on the circumference of the device. The timing will start when the device

operator says go and will be stopped when the next 45º scale marks reach approximately the same location as the original index mark.

13. Initiate the manual rotation of the Geovane by saying "go" for the time operator. The rotation is to be performed at approximately 1 rpm. The objective is to maintain the device in a constant vertical orientation until a peak scale indication is reached, and the scale indicator begins to decrease in value. A maximum scale marker will capture the greatest value obtained.
14. Extract the shear vane from the simulant with minimal disturbance.
15. Record the maximum scale reading and measured time for 45º rotation on Data Sheet II. **Note:** temperature readings will be recorded on Data Sheet I as part of the M5 operating steps.
16. Clean the shear vane in preparation for the next measurement.
17. Record the shear strength for the corresponding peak scale reading on Data Sheet II using the manufacturer-provided table.
18. Calculate the rotational speed in rpm from the measured time. $rot\_speed = \frac{7.5}{t}$ where t is the measured time in seconds per 45^0 of rotation, and 7.5 is the conversion factor (rot s/min)
19. Repeat Steps 9 through 18 as needed.

Note: A new data sheet is to be started for each simulant tested. The measurement designations for both devices are to be entered on the same plan view of the simulant container

Inserted in LRB No. ______________ on pg: _________

Data Sheet II for Device Comparison Shear Strength Measurements (Geovane unit)

Date: _____________ Related LRB entries on pg: _______________________________

Test Personnel: ____

Device & shear vane designation: ____

LRB entry for Shear Vane designation/description: ___________________________________

Device Operator: ____________________________

Simulant: ____

Location of Simulant Description: ____

Data table for shear strength measurements

Time[1] (hr:min)	Measurement Designation[2] (device-sequence)	Meas. Depth[3] (mm)	Time Measured for First 45º Rotation (sec)	Approximate Rotational speed Based on Time for 45º Rotation (rpm)	Peak Scale Reading (0 to 140)	Corresponding Manufacturer Table Provided τ_{ss} (kPa)

[1] Recorded as 24-hour clock format
[2] Provides the designation for the device and the sequence the measurement was taken. Example: M5-3. Measurement acquired with Haake M5 rheometer and the third measurement taken in simulant batch.
[3] Depth from simulant surface to center of shear vane.

Data Sheet completed by: ____date: ________

Data Sheet reviewed by: ____date: ________

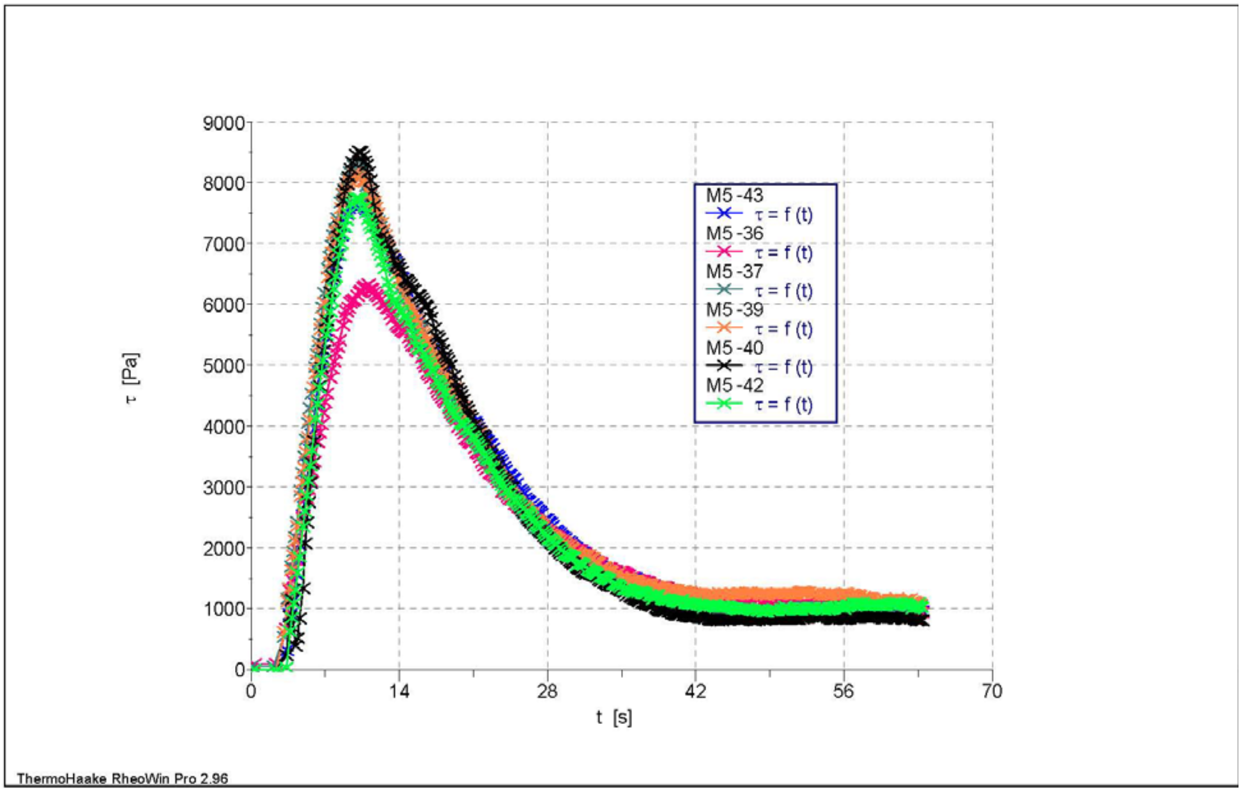
Appendix D

Rheograms Obtained for Test Materials Using the Haake M5 Rheometer

Appendix D: Rheograms Obtained for Test Materials Using the Haake M5 Rheometer

Settler

ThermoHaake RheoWin 5/26/2009 / 11:29 AM



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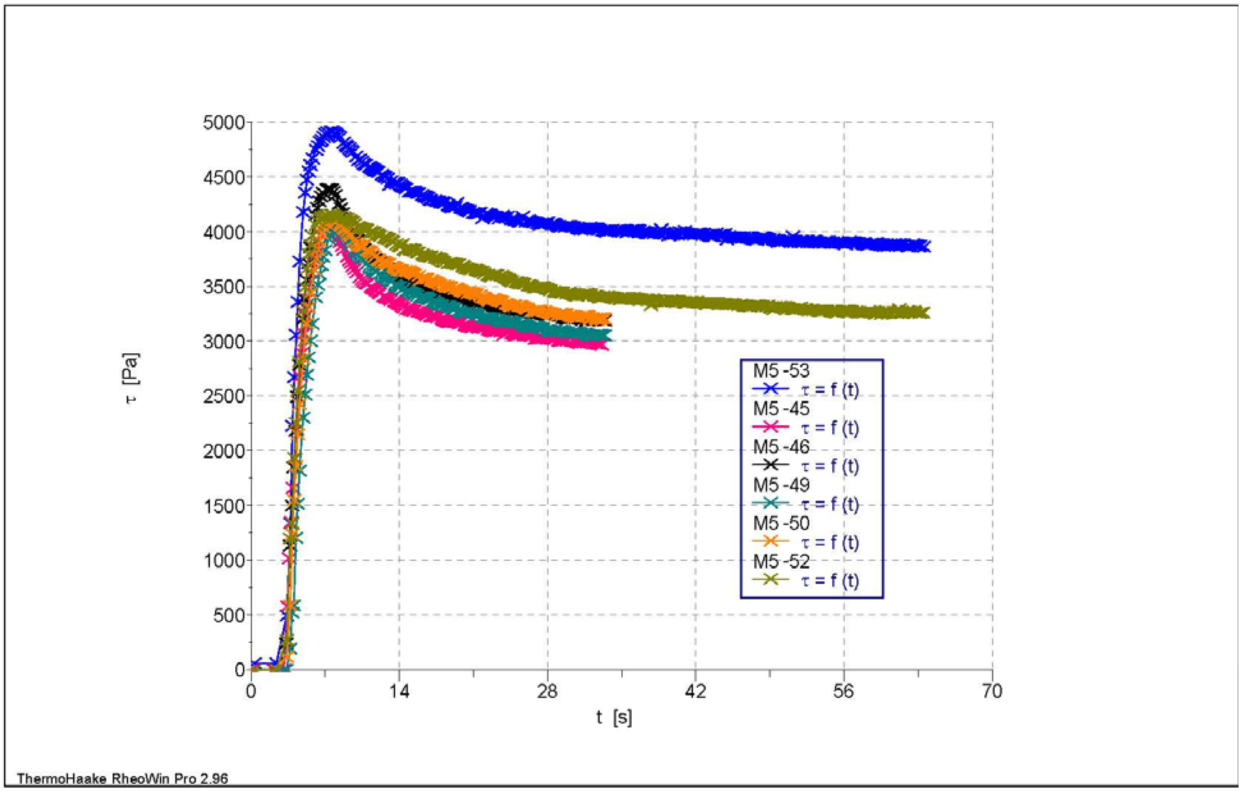
Company / Operator: PNNL / Richard Daniel
Date / Time / Version: 19.05.2009 / 11:04:15 AM / RheoWin Pro 296
Substance / Sample no: M5-43 / M5-43
2: C:\Documents and Settings\d3m966\Desktop\K-Basin2\Shear Strength (Vane M5)\090519\M5-36.rwd
Company / Operator: PNNL / Richard Daniel
Date / Time / Version: 19.05.2009 / 10:40:29 AM / RheoWin Pro 296
Substance / Sample no: M5-36 / M5-36
3: C:\Documents and Settings\d3m966\Desktop\K-Basin2\Shear Strength (Vane M5)\090519\M5-37.rwd
Company / Operator: PNNL / Richard Daniel
Date / Time / Version: 19.05.2009 / 10:44:01 AM / RheoWin Pro 296
Substance / Sample no: M5-37 / M5-37
4: C:\Documents and Settings\d3m966\Desktop\K-Basin2\Shear Strength (Vane M5)\090519\M5-39.rwd
Company / Operator: PNNL / Richard Daniel
Date / Time / Version: 19.05.2009 / 10:51:02 AM / RheoWin Pro 296
Substance / Sample no: M5-39 / M5-39
5: C:\Documents and Settings\d3m966\Desktop\K-Basin2\Shear Strength (Vane M5)\090519\M5-40.rwd
Company / Operator: PNNL / Richard Daniel
Date / Time / Version: 19.05.2009 / 10:53:47 AM / RheoWin Pro 296
Substance / Sample no: M5-40 / M5-40
6: C:\Documents and Settings\d3m966\Desktop\K-Basin2\Shear Strength (Vane M5)\090519\M5-42.rwd
Company / Operator: PNNL / Richard Daniel
Date / Time / Version: 19.05.2009 / 11:02:28 AM / RheoWin Pro 296
Substance / Sample no: M5-42 / M5-42

Bentonite

ThermoHaake RheoWin   5/26/2009 / 10:49 AM



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Substance / Sample no: M5 -53 / M5 -53
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Company / Operator: PNNL / Maria Luna
Date / Time / Version: 19.05.2009 / 11:20:35 AM / RheoWin Pro 296
Substance / Sample no: M5 -45 / M5 -45
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Company / Operator: PNNL / Maria Luna
Date / Time / Version: 19.05.2009 / 11:28:42 AM / RheoWin Pro 296
Substance / Sample no: M5 -46 / M5 -46
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Company / Operator: PNNL / Maria Luna
Date / Time / Version: 19.05.2009 / 11:41:46 AM / RheoWin Pro 296
Substance / Sample no: M5 -49 / M5 -49
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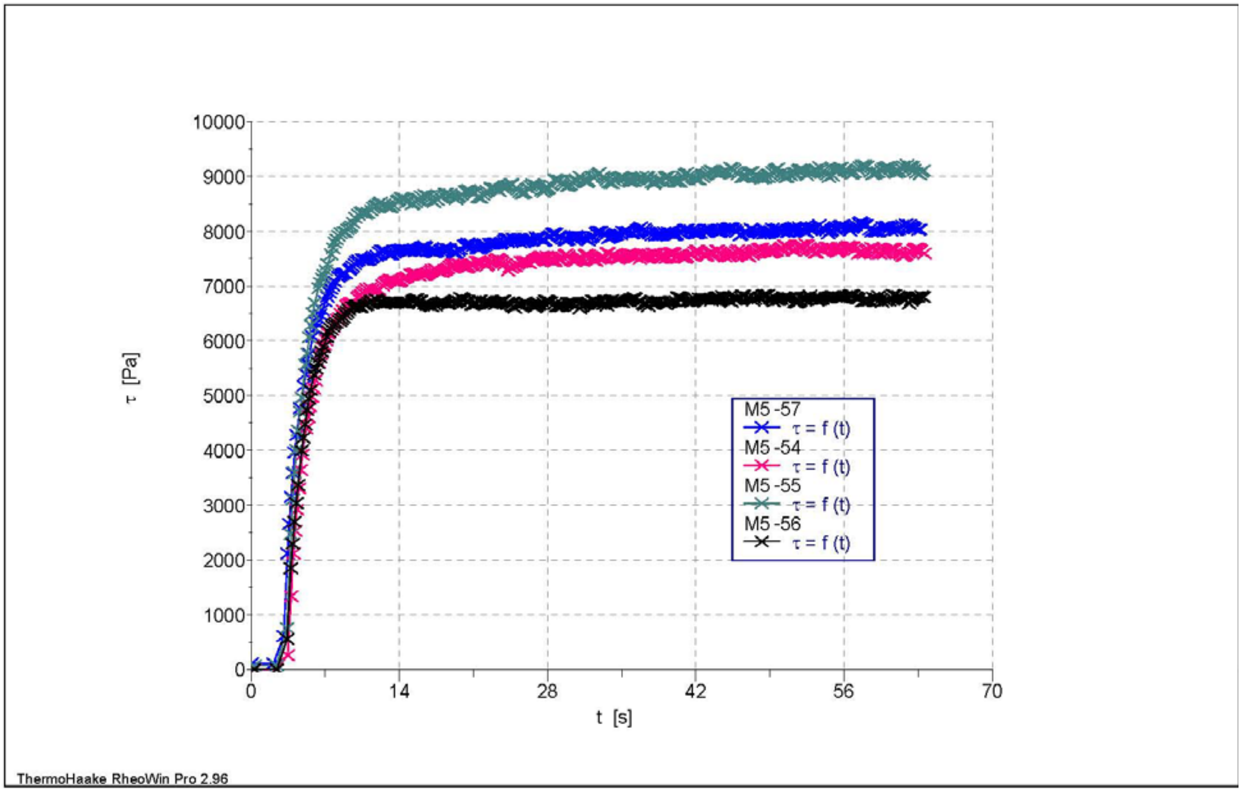
Company / Operator: PNNL / Maria Luna
Date / Time / Version: 19.05.2009 / 11:46:32 AM / RheoWin Pro 296
Substance / Sample no: M5 -50 / M5 -50
6: C:\Documents and Settings\d3m966\Desktop\K -Basin2\Shear Strength (Vane M5)\090519\M5 -52.rwd
Company / Operator: PNNL / Richard Daniel
Date / Time / Version: 19.05.2009 / 11:56:23 AM / RheoWin Pro 296
Substance / Sample no: M5 -52 / M5 -52

Play Dough

ThermoHaake RheoWin 5/26/2009 / 10:58 AM



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Date / Time / Version: 19.05.2009 / 12:16:53 PM / RheoWin Pro 296
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Date / Time / Version: 19.05.2009 / 12:08:24 PM / RheoWin Pro 296
Substance / Sample no: M5 -54 / M5 -54
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Substance / Sample no: M5 -55 / M5 -55
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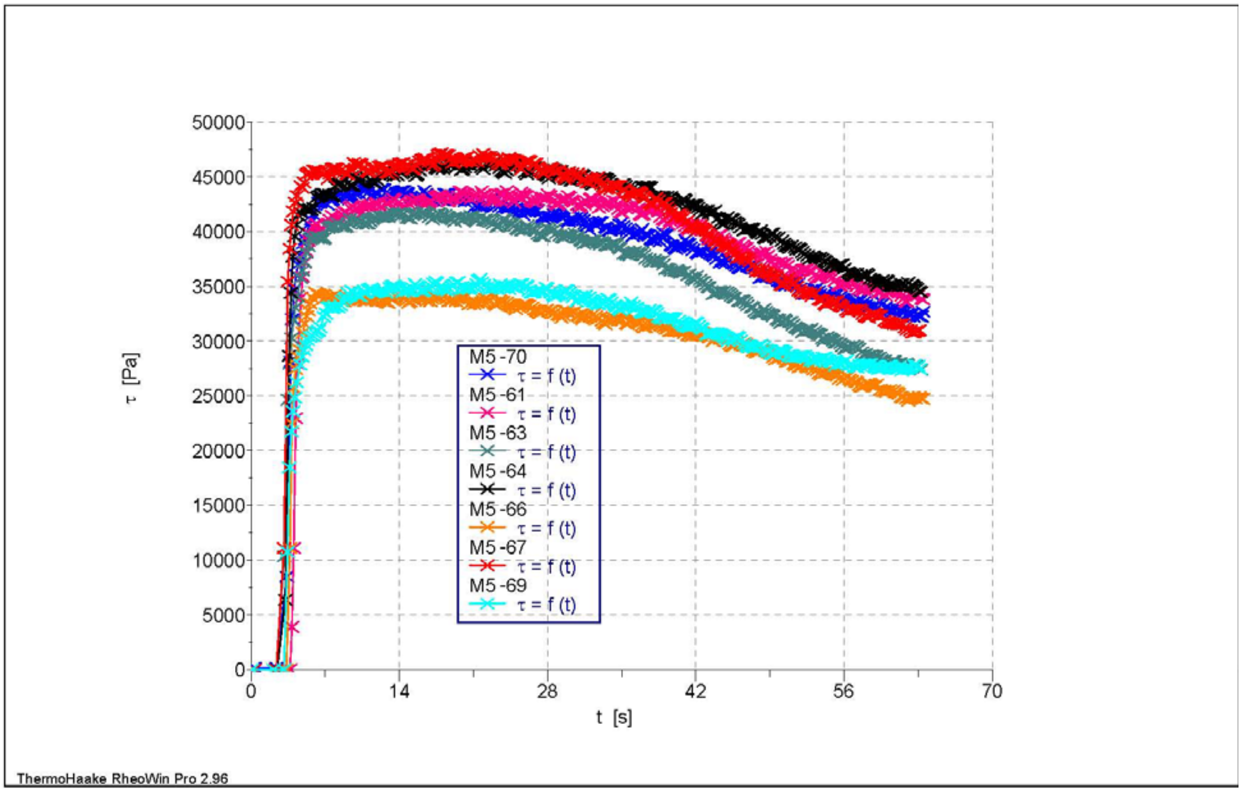
Company / Operator: PNNL / Richard Daniel
Date / Time / Version: 19.05.2009 / 12:14:56 PM / RheoWin Pro 296
Substance / Sample no: M5 -56 / M5 -56

Modeling Clay

ThermoHaake RheoWin 5/26/2009 / 11:04 AM



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Date / Time / Version: 19.05.2009 / 13:16:55 PM / RheoWin Pro 296
Substance / Sample no: M5 -70 / M5 -70
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Company / Operator: PNNL / Richard Daniel
Date / Time / Version: 19.05.2009 / 12:36:38 PM / RheoWin Pro 296
Substance / Sample no: M5 -61 / M5 -61
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Company / Operator: PNNL / Richard Daniel
Date / Time / Version: 19.05.2009 / 12:58:40 PM / RheoWin Pro 296
Substance / Sample no: M5 -63 / M5 -63
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Company / Operator: PNNL / Richard Daniel
Date / Time / Version: 19.05.2009 / 13:00:58 PM / RheoWin Pro 296
Substance / Sample no: M5 -64 / M5 -64
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Company / Operator: PNNL / Richard Daniel
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Substance / Sample no: M5 -66 / M5 -66
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Company / Operator: PNNL / Richard Daniel
Date / Time / Version: 19.05.2009 / 13:10:38 PM / RheoWin Pro 296
Substance / Sample no: M5 -67 / M5 -67
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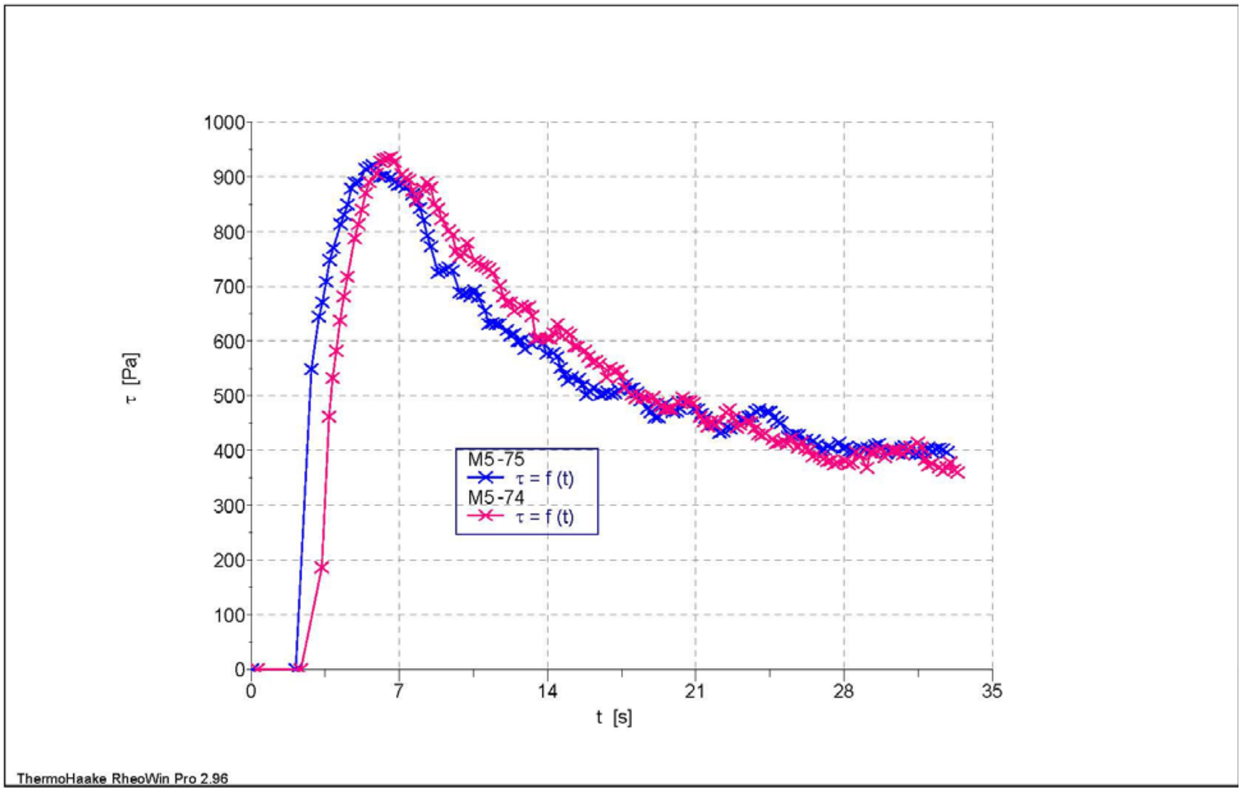
Company / Operator: PNNL / Richard Daniel
Date / Time / Version: 19.05.2009 / 13:14:25 PM / RheoWin Pro 296
Substance / Sample no: M5 -69 / M5 -69

Glass Beads

ThermoHaake RheoWin   5/26/2009 / 11:22 AM



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Date / Time / Version: 19.05.2009 / 13:47:14 PM / RheoWin Pro 296
Substance / Sample no: M5-75 / M5-75
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Company / Operator: PNNL / Maria Luna
Date / Time / Version: 19.05.2009 / 13:44:16 PM / RheoWin Pro 296
Substance / Sample no: M5-74 / M5-74

Appendix E

Shear Strength Summary Tables

Appendix E: Shear Strength Summary Tables

Table E.1. Summary of Average Shear Strength Values

Material	PNNL M5 Rheometer with Shear Vane								HH Tester				Scaling
	Standard Shear Strength				Shaft Corrected Shear Strength				Standard Shear Strength				Ratio M5 shaft corrected-to-HH
	Value [Pa]	Count[a]	Error[b] [Pa]	95% CL[c] [Pa]	Value [Pa]	Count[a]	Error[b] [Pa]	95% CL[c] [Pa]	Value [Pa]	Count[a]	Error[b] [Pa]	95% CL[c] [Pa]	
Settler Simulant	7571	6	311	800	4319	6	183	470	9705	4	825	2622	0.445
Bentonite (20-wt%)	4251	6	119	306	2961	6	151	388	2730	3	0	0	1.084
Play Dough	7777	4	478	1329	4420	4	158	438	5833	3	363	1562	0.758
Modeling Clay	33864	7	1669	3940	21534	6	1269	2994	28350	5	865	2404	0.760
Potters Mil 9	931	2	8	33	672	2	6	24	550	1	n/a	n/a	1.221

(a) Number of measurements included in average value reported above.

(b) Standard error of the mean.

(c) 95% confidence limit about the mean, t-values for 95% similarity.

Table E.2. Hand-Held Shear Strength Results in Detail

Test	Material	Time	Sensor	Time for 45°	Approx. Rate	HH Reading	Maximum Stress	Test Depth h	Standard Immersion Depth	Vane D	Vane H	Shaft D	Test Angle	Distance from wall	Standard A	Shaft-Corrected A	Shaft Corrected Stress	Max Immersion Depth
		[dd.mm.yyyy/hh:mm AM/PM]		[s]	[RPM]	[divisions]	[Pa]	[mm]	(mark top of vane)	[mm]	[mm]	[mm]	[deg]	[inches]	[Pa/N·m]	[Pa/N·m]	[Pa]	[mm]
G-31	Settler #1	19.05.2009/09:56 AM	Large vane	8.4	0.89	36	9840	50	24.065	33.8	51.87	6.35	45	2.5	8826	8714	9715	76
G-35	Settler #1	19.05.2009/10:29 AM	Large vane	9.0	0.83	27	7380	45	19.065	33.8	51.87	6.35	135	2.5	8826	8738	7306	71
G-38	Settler #1	19.05.2009/10:48 AM	Large vane	6.9	1.09	41	11210	45	19.065	33.8	51.87	6.35	225	2.5	8826	8738	11098	71
G-41	Settler #1	19.05.2009/10:58 AM	Large vane	6.3	1.19	38	10390	45	19.065	33.8	51.87	6.35	315	2.5	8826	8738	10286	71
	Settler Sim Average						**9705**										**9602**	
	Settler Sim Deviation						**1649**										**1632**	
	Settler Sim Count						**4**										**4**	
	Settler Sim SE						**825**										**816**	
G-44	20-wt% Bentonite	19.05.2009/11:13 AM	Large vane	8.35	0.898	10	2730	45	19.065	33.8	51.87	6.35	n/a	center	8826	8738	2703	71
G-48	20-wt% Bentonite	19.05.2009/11:38 AM	Large vane	8.15	0.920	10	2730	45	19.065	33.8	51.87	6.35	270	1.5	8826	8738	2703	71
G-51	20-wt% Bentonite	19.05.2009/11:50 AM	Large vane	7.84	0.957	10	2730	45	19.065	33.8	51.87	6.35	315	1.5	8826	8738	2703	71
	Bentonite Average						**2730**										**2703**	
	Bentonite Deviation						**0**										**0**	
	Bentonite Count						**3**										**3**	
	Bentonite SE						**0**										**0**	
G-58	Play Dough	19.05.2009/12:19 PM	Large vane	7.37	1.018	20	5470	45	19.065	33.8	51.87	6.35	315	1.5	8826	8738	5415	71
G-59	Play Dough	19.05.2009/12:21 PM	Large vane	6.78	1.106	24	6560	55	29.065	33.8	51.87	6.35	45	1.5	8826	8690	6459	81
G-60	Play Dough	19.05.2009/12:28 PM	Large vane	7.47	1.004	20	5470	45	19.065	33.8	51.87	6.35	135	1.5	8826	8738	5415	71
	Play Dough Average						**5833**										**5763**	
	Play Dough Deviation						**629**										**602**	
	Play Dough Count						**3**										**3**	
	Play Dough SE						**363**										**348**	
G-62	Modeling Clay	19.05.2009/12:54 PM	Small vane	6.84	1.096	20	29000	40	25.38	19.13	29.24	6.35	45	1.3	48842	45425	26971	55
G-65	Modeling Clay	19.05.2009/13:03 PM	Small vane	n/a	n/a	21	30000	40	25.38	19.13	29.24	6.35	135	1.3	48842	45425	27901	55
G-68	Modeling Clay	19.05.2009/13:12 PM	Small vane	n/a	n/a	20	29000	40	25.38	19.13	29.24	6.35	225	1.3	48842	45425	26971	55
G-71	Modeling Clay	19.05.2009/13:19 PM	Small vane	9.13	0.821	17	25000	40	25.38	19.13	29.24	6.35	315	1.3	48842	45425	23251	55
G-72	Modeling Clay	19.05.2009/13:22 PM	Large vane	7.53	0.996	105	28750	45	19.065	33.8	51.87	6.35	n/a	center	8826	8738	28463	71
	Modeling Clay Average						**28350**										**26711**	
	Modeling Clay Deviation						**1933**										**2037**	
	Modeling Clay Count						**5**										**5**	
	Modeling Clay SE						**865**										**911**	
G-73	Potters Mil 9	19.05.2009/13:38 PM	Large vane	6.53	1.149	2	550	45	19.065	33.8	51.87	6.35	n/a	center	8826	8738	545	71
	Potters Mil 9 Average						**550**										**545**	
	Potters Mil 9 Deviation						**n/a**										**n/a**	
	Potters Mil 9 Count						**1**										**1**	
	Potters Mil 9 SE						**n/a**										**n/a**	

Table E.3. PNNL Shear Strength Results in Detail

Test	Material	Time	Sensor	A-Factor	Test Duration	Average Rate	Maximum Torque	Maximum Stress	Test Depth h	Vane D	Vane H	Shaft D	Test Angle	Distance from wall	Standard A	Shaft-Corr A	Standard Shr Str	Shaft Corr Shr Str	Max Immersion Depth
		[dd.mm.yyyy/hh:mm:ss AM/PM]		[Pa/N·m]	[s]	[RPM]	[uN·m]	[Pa]	[mm]	[mm]	[mm]	[mm]	[deg]	[inches]	[Pa/N·m]	[Pa/N·m]	[Pa]	[Pa]	[mm]
M5-32	Settler #1	19.05.2009/10:12:28 AM	8×16 mm vane	532885	60	0.343	4617	2460	19	8.026	15.976	3.23	0	1.5	529873	456664	2446	2108	35
M5-33	Settler #1	19.05.2009/10:16:17 AM	8×16 mm vane	532885	60	0.343	4318	2301	36	8.026	15.976	3.23	0	1.5	529873	405123	2288	1749	52
M5-36	Settler #1	19.05.2009/10:40:29 AM	16×4 mm vane	266442	60	0.344	23750	6327	42	16.015	4.23	5.99	90	1.5	259412	162187	6161	3852	46
M5-37	Settler #1	19.05.2009/10:44:01 AM	16×4 mm vane	266442	60	0.343	31110	8289	64	16.015	4.23	5.99	90	1.5	259412	135032	8070	4201	68
M5-39	Settler #1	19.05.2009/10:51:02 AM	16×4 mm vane	266442	60	0.344	30600	8154	42	16.015	4.23	5.99	180	1.5	259412	162187	7938	4963	46
M5-40	Settler #1	19.05.2009/10:53:47 AM	16×4 mm vane	266442	60	0.343	31950	8512	64	16.015	4.23	5.99	180	1.5	259412	135032	8288	4314	68
M5-42	Settler #1	19.05.2009/11:02:28 AM	16×4 mm vane	266442	60	0.343	29060	7744	42	16.015	4.23	5.99	270	1.5	259412	162187	7539	4713	46
M5-43	Settler #1	19.05.2009/11:04:15 AM	16×4 mm vane	266442	60	0.343	28650	7633	64	16.015	4.23	5.99	270	1.5	259412	135032	7432	3869	68
	Settler Sim Average																**7571**	**4319**	
	Settler Sim Deviation																**762**	**448**	
	Settler Sim Count																**6**	**6**	
	Settler Sim SE																**311**	**183**	
M5-45	20-wt% Bentonite	19.05.2009/11:20:35 AM	16×16 mm vane	116569	30	0.337	35090	4091	36	15.9766	16.002	6.07	0	1.5	116942	94552	4103	3318	
M5-46	20-wt% Bentonite	19.05.2009/11:28:42 AM	16×16 mm vane	116569	30	0.335	37640	4388	58	15.9766	16.002	6.07	0	1.5	116942	84392	4402	3177	
M5-49	20-wt% Bentonite	19.05.2009/11:41:46 AM	16×16 mm vane	116569	30	0.336	34630	4037	36	15.9766	16.002	6.07	45	1.5	116942	94552	4050	3274	
M5-50	20-wt% Bentonite	19.05.2009/11:46:32 AM	16×16 mm vane	116569	30	0.336	35290	4114	58	15.9766	16.002	6.07	45	1.5	116942	84392	4127	2978	
M5-52	20-wt% Bentonite	19.05.2009/11:56:23 AM	16×4 mm vane	266442	60	0.342	15590	4154	42	16.015	4.23	5.99	180	1.5	259412	162187	4044	2528	
M5-53	20-wt% Bentonite	19.05.2009/11:58:20 AM	16×4 mm vane	266442	60	0.343	18430	4912	64	16.015	4.23	5.99	180	1.5	259412	135032	4781	2489	
	Bentonite Average																**4251**	**2961**	
	Bentonite Deviation																**291**	**369**	
	Bentonite Count																**6**	**6**	
	Bentonite SE																**119**	**151**	
M5-54	Play Dough	19.05.2009/12:08:24 PM	16×4 mm vane	266442	60	0.336	29110	7757	42	16.015	4.23	5.99	0	1.5	259412	162187	7551	4721	
M5-55	Play Dough	19.05.2009/12:12:05 PM	16×4 mm vane	266442	60	0.336	34530	9200	64	16.015	4.23	5.99	0	1.5	259412	135032	8957	4663	
M5-56	Play Dough	19.05.2009/12:14:56 PM	16×4 mm vane	266442	60	0.339	25640	6833	42	16.015	4.23	5.99	180	1.5	259412	162187	6651	4158	
M5-57	Play Dough	19.05.2009/12:16:53 PM	16×4 mm vane	266442	60	0.338	30640	8163	64	16.015	4.23	5.99	180	1.5	259412	135032	7948	4137	
	Play Dough Average																**7777**	**4420**	
	Play Dough Deviation																**956**	**315**	
	Play Dough Count																**4**	**4**	
	Play Dough SE																**478**	**158**	
M5-63	Modeling Clay	19.05.2009/12:58:40 PM	6×6 mm vane	2210485	60	0.342	18920	41830	10	6.405	6.48	3.17	90	1.0	1801302	1419120	34081	26850	
M5-64	Modeling Clay	19.05.2009/13:00:58 PM	6×6 mm vane	2210485	60	0.341	20940	46280	34	6.405	6.48	3.17	90	1.0	1801302	922938	37719	19326	
M5-66	Modeling Clay	19.05.2009/13:08:17 PM	6×6 mm vane	2210485	60	0.343	15550	34370	10	6.405	6.48	3.17	180	1.0	1801302	1419120	28010	22067	
M5-67	Modeling Clay	19.05.2009/13:10:38 PM	6×6 mm vane	2210485	60	0.341	21310	47110	34	6.405	6.48	3.17	180	1.0	1801302	922938	38386	19668	
M5-69	Modeling Clay	19.05.2009/13:14:25 PM	6×6 mm vane	2210485	60	0.343	16110	35620	10	6.405	6.48	3.17	270	1.0	1801302	1419120	29019	22862	
M5-70	Modeling Clay	19.05.2009/13:16:55 PM	6×6 mm vane	2210485	60	0.341	19970	44150	34	6.405	6.48	3.17	270	1.0	1801302	922938	35972	18431	
	Modeling Clay Average																**33864**	**21534**	
	Modeling Clay Deviation																**4417**	**3108**	
	Modeling Clay Count																**7**	**6**	
	Modeling Clay SE																**1669**	**1269**	
M5-74	Potters Mil 9	19.05.2009/13:44:16 PM	16×16 mm vane	116569	30	0.345	8024	935	58	15.9766	16.002	6.07	n/a	center	116942	84392	938	677	
M5-75	Potters Mil 9	19.05.2009/13:47:14 PM	16×16 mm vane	116569	30	0.344	7893	920	58	15.9766	16.002	6.07	n/a	center	116942	84392	923	666	
	Potters Mil 9 Average																**931**	**672**	
	Potters Mil 9 Deviation																**11**	**8**	
	Potters Mil 9 Count																**2**	**2**	
	Potters Mil 9 SE																**8**	**6**	

Appendix F

Radial Variation in Shear Strength

Appendix F: Radial Variation in Shear Strength

Settler Simulant

Test Angle	Shear Strength [Pa]					
	M5 Rheometer				Geovane	
	uncorrected		Shaft corrected			
	Test 1	Test 2	Test 1	Test 2	uncorrected	shaft corrected
Center						
0 degrees	2446	2288	2108	1749		
45 degrees					9840	9715
90 degrees	6161	8070	3852	4201		
135 degrees					7380	7306
180 degrees	7938	8288	4963	4314		
225 degrees					11210	11098
270 degrees	7539	7432	4713	3869		
315 degrees					10390	10286

Bentonite (20-wt%)

Test Angle	Shear Strength [Pa]					
	M5 Rheometer				Hand-Held Tester	
	uncorrected		Shaft corrected			
	Test 1	Test 2	Test 1	Test 2	uncorrected	shaft corrected
Center					2730	2703
0 degrees	4103	4402	3318	3177		
45 degrees	4050	4127	3274	2978		
90 degrees						
135 degrees						
180 degrees	4044	4781	2528	2489		
225 degrees						
270 degrees					2730	2703
315 degrees					2730	2703

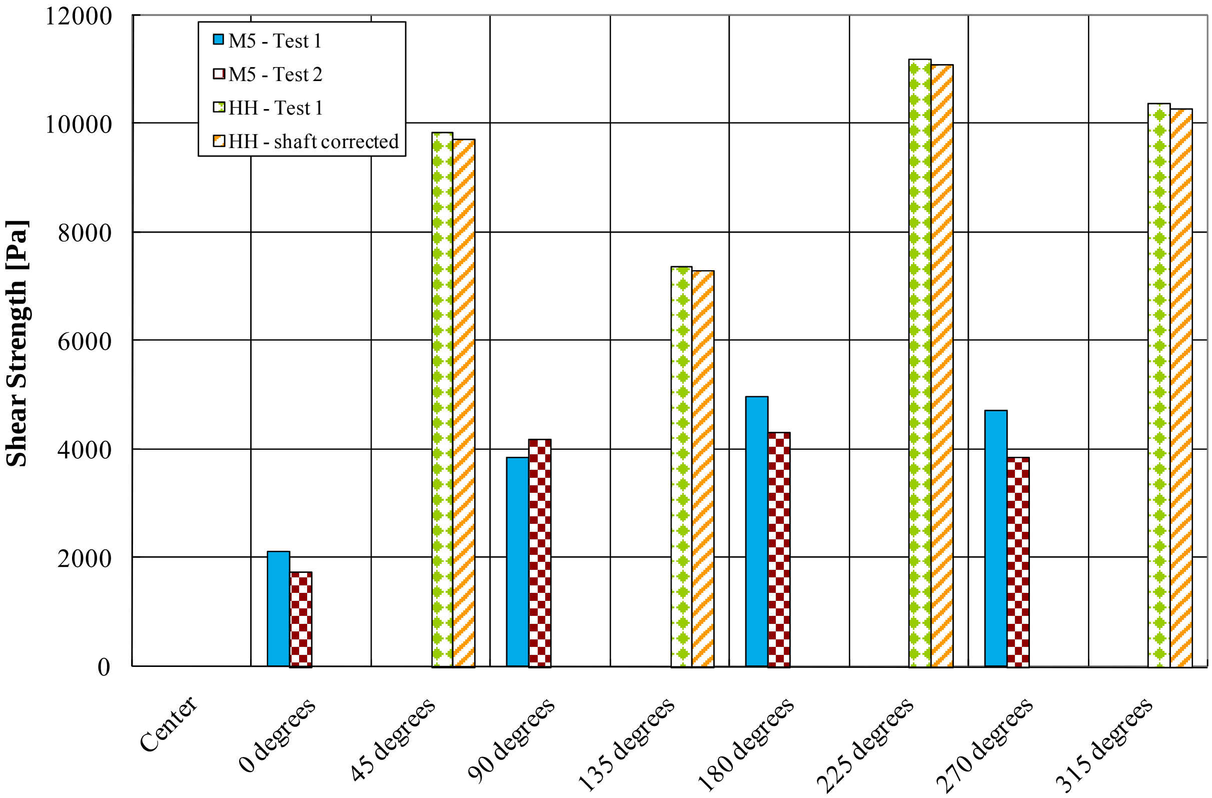
Play Dough

Test Angle	Shear Strength [Pa]					
	M5 Rheometer				Hand-Held Tester	
	uncorrected		Shaft corrected			
	Test 1	Test 2	Test 1	Test 2	uncorrected	shaft corrected
Center						
0 degrees	7551	8957	4721	4663	6560	6459
45 degrees						
90 degrees						
135 degrees					5470	5415
180 degrees	6651	7948	4158	4137		
225 degrees						
270 degrees						
315 degrees					5470	5415

Modeling Clay

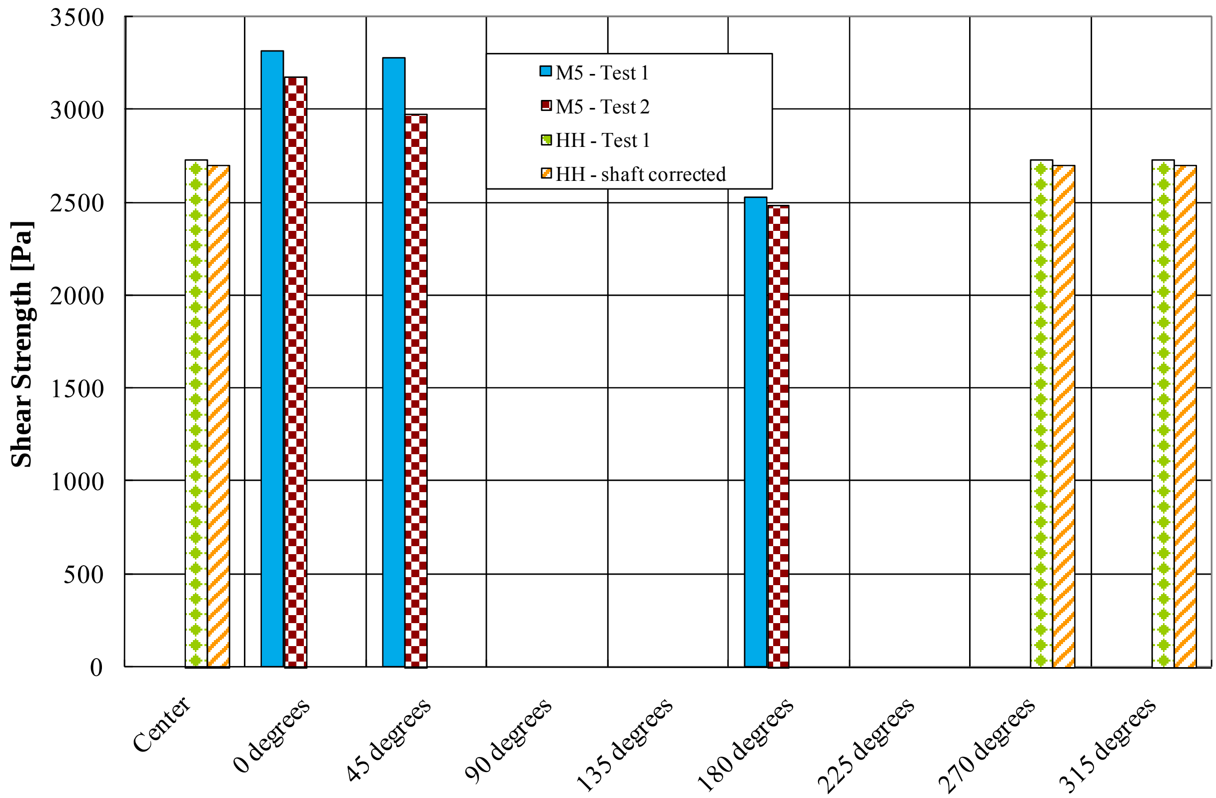
Test Angle	Shear Strength [Pa]					
	M5 Rheometer				Hand-Held Tester	
	uncorrected		Shaft corrected			
	Test 1	Test 2	Test 1	Test 2	uncorrected	shaft corrected
Center					28750	28463
0 degrees			18228			
45 degrees					29000	26971
90 degrees	34081	37719	26850	19326		
135 degrees					30000	27901
180 degrees	28010	38386	22067	19668		
225 degrees					29000	26971
270 degrees	29019	35972	22862	18431		
315 degrees					25000	23251

RV Settler

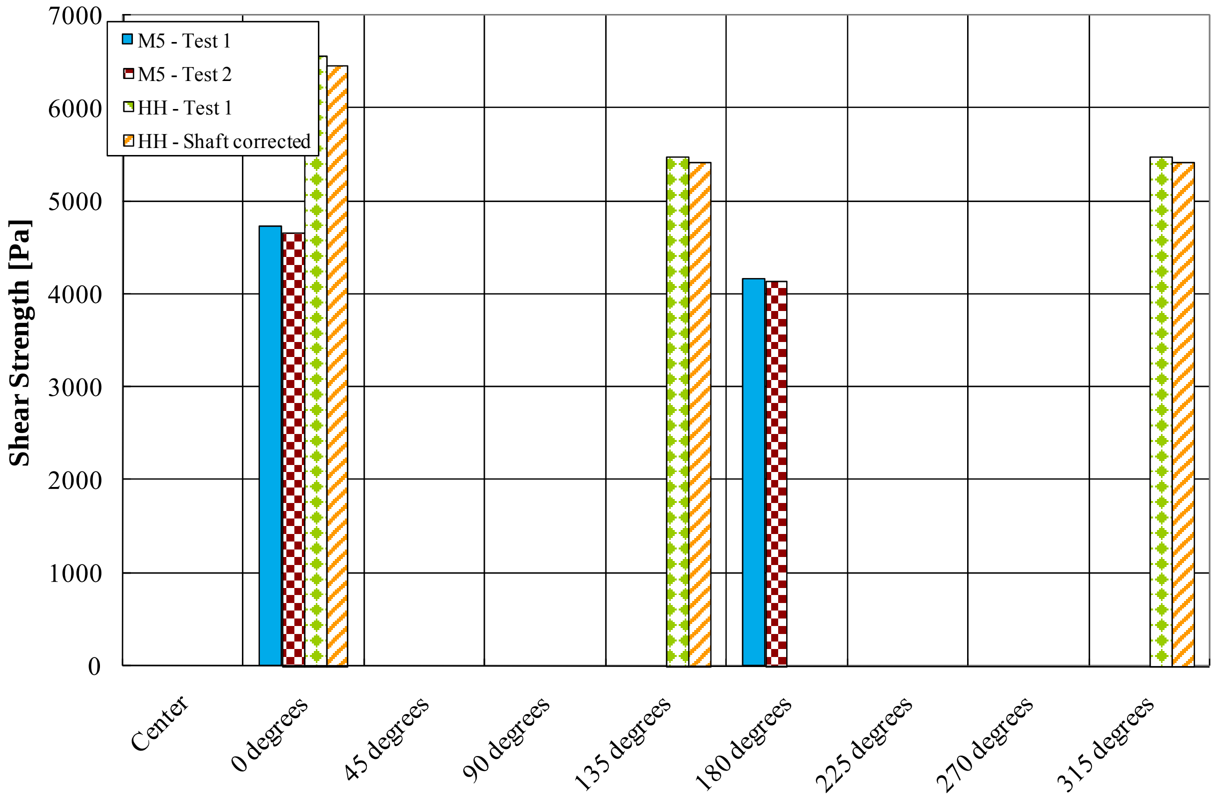


M5 - Test 1
M5 - Test 2
HH - Test 1
HH - shaft corrected
Shear Strength [Pa]
0
2000
4000
6000
8000
10000
12000
Center
0 degrees
45 degrees
90 degrees
135 degrees
180 degrees
225 degrees
270 degrees
315 degrees

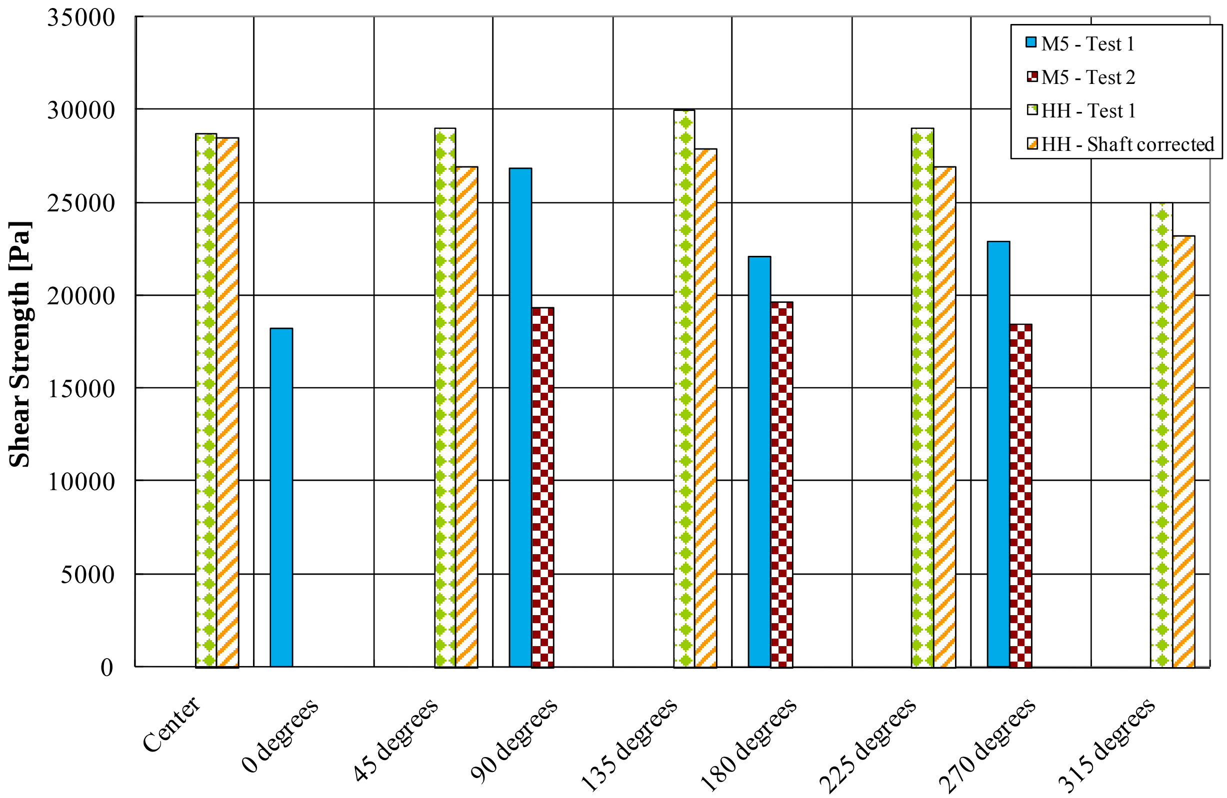
RV Bentonite



RV Play Dough



RV Modeling Clay



Appendix G

Effects of Settler Simulant on Scaling Factor

Appendix G: Effects of Settler Simulant on Scaling Factor

For completeness, the settler simulant has been included in calculating the scaling factor for the shear strength measurements made by the hand held (HH) and the M5 measuring device. The 95 % upper and lower confidence limits for the mean of each measurement (based on similarity arguments) are shown on Figure G.1. The average scaling factor with the settler simulant would be 0.85 ± 0.14 shown in Table G.1. The reported uncertainty is the standard error of the mean.

Applying a 95% confidence analysis yields lower and upper scaling-factor bounds of 0.56 and 1.14, respectively. This would result in a measurement of 12.2 kPa on the HH device, which translates to a "true" shear strength in the range of 10.7 kPa to 21.7 kPa (based on 95% CL for exceedance). Conversely, an HH reading of 21.7 kPa would validate the design basis of a 12.2-kPa true shear strength if the settler simulant is included in the analysis.

Table G.1. Summary of M5-to-HH Shear Strength Scaling Factors

Test Material	M5(shaft corrected)-to-HH Scaling Factor (F_i)
Settler Simulant	0.45
Bentonite (20-wt%)	1.08
Play Dough	0.76
Modeling Clay	0.76
Potters Mil 9	1.22
Average	0.85
Standard Error of the Mean	0.14

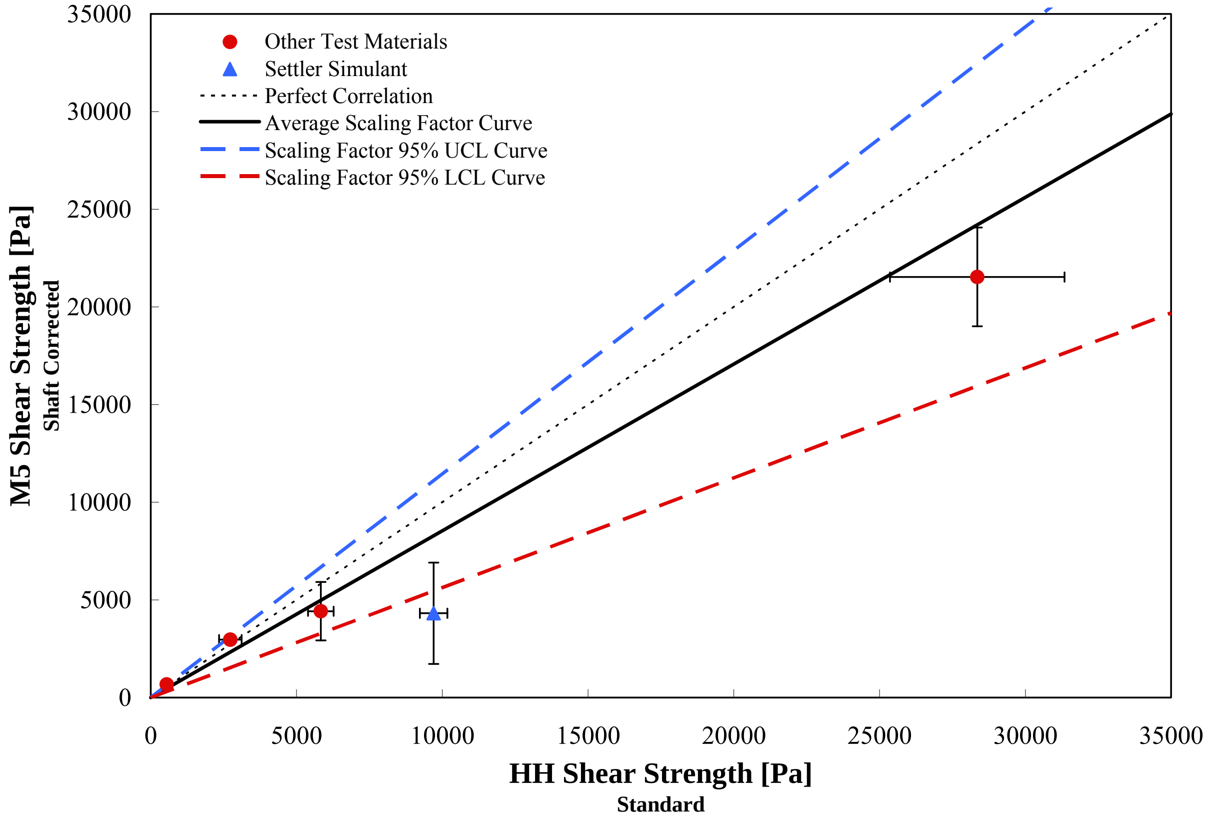


Figure G.1. Comparison of Shear Strength Obtained from the M5 Instrument and the Hand Held Geovane, Settler Simulant Data Included in Confidence Limit Determination