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DEVELOPING A FIELD TEST FOR MEASURING UNCONFINED COMPRESSIVE STRENGTH OF INDURATED MATERIALS

by

Bradley J. Cook

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Developing a Field Test for Measuring Unconfined Compressive Strength of Indurated Materials (38 pp.)

Director: Thomas J. Nimlos TJN

This paper presents field techniques for cutting, forming, and strength testing of indurated materials. Measuring unconfined compressive strength of blocks ~~of~~ is the standard strength test of indurated materials. However, field techniques for obtaining quantified measurements of unconfined compressive strength have never been described. These techniques for cutting and forming blocks apply equally to either laboratory or field situations. Testing indurated volcanic-ash blocks, at various moisture contents, has important ties to reclamation where this induration is exposed. A modified hydraulic jack was used to obtain quantified measurements of unconfined compressive strength of ash-flow tuff (tepetate), fine sandstone, coarse sandstone, and chalk in the field. The techniques described in this paper are inexpensive, precise, and testing shows them to have a nearly perfect linear relationship to standard laboratory techniques.

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INTRODUCTION

Indurated volcanic-ash materials are common wherever volcanism has occurred; they are ash-flow tuffs, air-fall ash or reworked ash (Vera and Lopez, 1986 and Nimlos, 1991). Pedocementation by silica, carbonates and iron oxides, especially at the surface of the materials, has augmented their induration.

The nomenclature of indurated volcanic-ash materials is vague and confusing for two reasons. In the first place, at least one local name, usually of indigenous dialect, has been applied to these materials in each country (Nimlos, 1987). Moreover, the nomenclature is obscure because the lower limit of pedologic development is difficult to identify, so it is not clear whether these materials are soil or rock.

Indurated volcanic-ash materials are widespread throughout the Pacific Rim portion of Latin America. In many areas, the porous overlying soil has been completely eroded leaving the indurated material exposed. Two-thirds of the land area in some watersheds in the Valley of Mexico, the basin that contains Mexico City, have had all soil eroded and the induration (locally called *tepetate*) exposed (Nimlos and Ortiz., 1987). Near Quito, Ecuador, exposure of indurated material (locally called *cangahua*) is so extensive that one can walk for two miles without touching soil.

Reclaiming these lands is necessary if the countries of Latin America are to meet their agricultural production needs. Historically, *campesinos* (farmers) have reclaimed indurated materials by breaking chunks of the material loose from the matrix and building some type of structure; usually terraces with them. The most famous complex of terraces are those built by the Incas at Machu Picchu.

Reclamation programs have been instituted more recently in Mexico (Nimlos and Ortiz, 1987) and Ecuador (Nimlos and Savage, 1991 and Nimlos, 1991). The type of reclamation procedure depends on the indurations' strength. In some areas, the strength is low and terraces are built manually (Nimlos, 1991). More commonly large crawler tractors are used to rip the induration.

Unconfined compressive strength has been measured in the laboratory on a number of samples from Mexico and Ecuador (Nimlos, 1989 and Nimlos and Hillery, 1990). The resulting data show that strength declines rapidly with increasing moisture content and is higher in samples cemented pedogenetically with carbonates. Strength varies from 0 psi in some saturated samples that slake in water to 650 psi (4.485×10^6 Pa) in oven-dry samples with dispersed carbonates.

This study began in search of a quantitative field method for determining the unconfined compressive strength of indurated volcanic-ash materials. However, shortly after starting, I realized that this work can be applied to all indurated materials. Subsequently, the methods described within are not limited to volcanic-ash materials. The techniques developed here are valuable because they can provide accurate quantitative data in the field and are very inexpensive compared to standard laboratory techniques.

This thesis presents the development of a field method in four distinct parts : 1) the techniques for cutting, forming, and moisture adjustment of sampling materials (i.e. blocks); 2) strength tests and the development and calibration of our modified hydraulic jack; 3) the application and results of field testing the Modified Jack; and 4) conclusions.

PART ONE:
TECHNIQUES OF CUTTING, FORMING, AND MOISTURE ADJUSTMENT OF SAMPLING MATERIALS

Unconfined Compressive Strength and Blocks

Unconfined compressive strength is the standard strength test for soil materials; the comparable test used by geologists for rock is tensile strength. Since the surface of indurated volcanic-ash materials is in the gray zone between rock and soil, the choice of strength tests is subject to question. Ripping is the most common method of reclamation and entails both compressive and tensile strength; the indurated material is compressed as the ripper enters, and the ease of pulling the bar through the material is a function of the tensile strength. Compressive strength is a more common test; there are more data for comparisons, sample preparation is much easier, and measuring tensile strength in the field would be extremely difficult. Further, Farrell et al. (1967) have shown a very close correlation between the two parameters on soil samples with moisture contents between 2% and 14%. Most tepetate have a field moisture content within this range.

Procedures for testing unconfined compressive strength are established by AASHTO (American Association of State Highway and Transportation Officials, 1984). These procedures call for the measurement of the pressure required to crush blocks of the indurated material; blocks are shaped as right parallelepipeds (i.e. a six-sided right angled prism with parallelogram faces). Block dimensions can vary, but the long axis of the blocks must measure between two and three times the length of the short axes. (Blocks made from homogeneous substances commonly break at angles 30° to the long axis plane. Blocks having shorter long axis measurements can have higher strength readings.) Most of the blocks tested were about 1x1x2.5 in (2.5x2.5x6.25 cm).

Block Cutting

Cutting blocks out of the matrix is very rapid in some samples but time-consuming and frustrating in others. Samples of low strength (less than 15 psi or $10.35x10^4$ Pa) often break while being cut, and samples of high strength (more than 150 psi or $10.35x10^5$ Pa) are so hard they cut slowly by hand. Samples with carbonate lamellae are especially vexing because the interface between the lamellae and matrix is a natural plane of weakness. These samples frequently crumble while being cut. Cutting is easiest in massive materials without carbonate lamellae.

At least three types of saws can be used to cut rough blocks from the matrix:

1) Quick saw. A quick saw is a gas-powered, 2-cycle saw that resembles a chain saw with the tung and chain replaced with a 12- or 14-inch cutting disc (See Photo 1.). The discs or blades employ cutting teeth for use on wood or an abrasive for use on masonry or metal. I used a Stihl TS360 with a 12-inch masonry blade; I found the metallic blade to be less effective. Cutting through four inches of indurated material is quick and easy. The saw's power is more than adequate and the time spent cutting is reduced exponentially when compared with manual methods of cutting. Parallel cuts are made in the material to form the planes of the long axis. Then cuts are made at right angles and the blocks are gently broken from the matrix. All cuts are made slightly over the desired dimensions so that the blocks can be formed to specific size later. However, cutting blocks too large requires excessive time forming them later.

One disadvantage of this saw and the chop saw is that they create clouds of dust. Cutting outside with a strong wind is preferred. It is best the user wear a mask and that the saw's air filter be cleaned periodically.

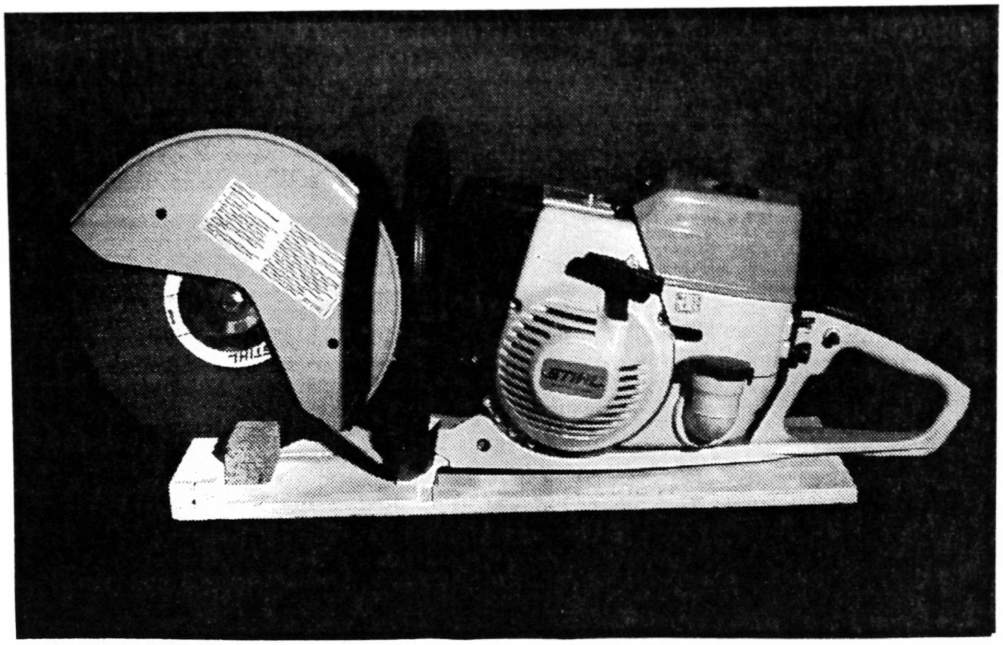

Photo 1. Quick Saw. A gas-powered saw used for cutting and forming samples in the field. Plywood frame with fence beneath the saw is used when forming blocks. Block in photo is in position to be formed; perpendicular to the blade and against the fence.

2) Chop saw. A chop saw is an AC-powered (110 volt) circular saw mounted on its own base and can use the same blades as the quick saw (See Photo 2.). I used a Makita (model No. 2414) with a 14-inch masonry blade which had a cutting platform on the base and a fence along the back to ensure right angle cuts. To use the chop saw, samples of indurated material must be removed from the matrix and cut where electricity is available.

3) Hacksaw. Initially I used a standard hacksaw with cutting blades having 12 teeth per inch. This proved cheap but very slow on samples with high strength and the blades wore out rapidly; it took four hours to cut a block from a sample with strength of 650 psi ($4.485x\ 10^{6}$ Pa). The advantage of this saw lies with cutting samples of low strength; samples break less frequently because the blades are relatively thin and make a narrow cut. To overcome the rapid dulling of the blades I switched to carbide-coated blades. These blades abrade the material rather than cut it, leaving a wider, less precise cut. Although carbide-

coated blades wear out more slowly, they are more apt to cause breakage in low-strength samples.

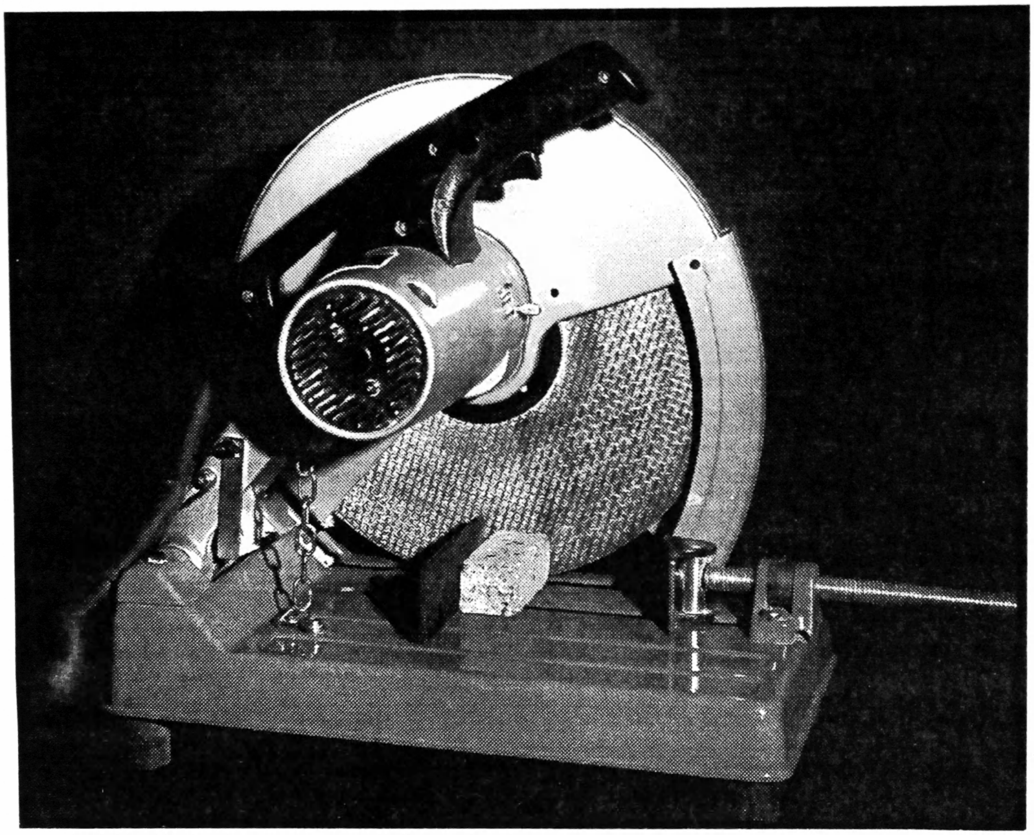

Photo 2. Chop Saw. The chop saw can only be used to cut and form blocks where electricity is available. Access to a portable generator could make this saw a useful piece of field equipment.

Block Forming

Once the blocks are cut they must be formed before testing. The forming method is a two-step process. Initial forming is done in the field along the side of the quick saw disk, much like using a disk-sander. I constructed a plywood frame that holds the quick saw in a rigid position while forming blocks (See Photo 1.). Samples of high strength can be formed to near-perfect dimensions in the field and require little additional effort. Blocks of low strength require much more care when forming; corners can be easily rounded or even break during formation. For the more refined formation I used 50 to 80 grit sandpaper or a mill bastard file. Good blocks can be formed if the sandpaper or file is placed along a square inside corner, such as the inside of a tool box. The corner is used to keep the long and short axis planes of the block perpendicular. Oven drying low-strength samples increases their strength and makes them easier to cut and form. The most important aspect of cutting and forming blocks is to keep the short axis planes both flat and parallel.

Moisture Adjustment

Strength declines with increasing moisture content. Below are the techniques used to establish four moisture levels as a means to obtain measurements throughout the full range of the Modified Jack's pressure gauge (Cook et al., 1992).

Moisture level	Moisture content(%)	Procedure
Oven dried	0	Dry in oven at 110^{o}C for at least 6 hours.
Air dried	1-7	In situ moisture content of samples from the field.
Humid	3-11	Store in humidity chamber for at least 10 days.
Saturated	10-25	Immerse in water for 10 minutes.

Virtually all moisture loss in blocks occurs within the first six hours of oven drying. There is some difference between samples in how long they take to become completely oven dried, but all blocks measured had moisture contents below 1% after six hours.

In order to create a moisture level intermediate between saturated and air-dried, I made a humidity chamber using a covered plastic container with free water in the bottom. Samples were placed on an inverted standard sieve used as a rack inside the container above the water line. I added paper towels, loosely rolled and rising out of the water to wick moisture, increasing the surface area of the water surface and maintaining a saturated atmosphere. Most samples reached a near constant weight in the chamber in less than 10 days. I assume this moisture content corresponds to hygroscopic moisture content. It is not essential that the hygroscopic moisture content be reached, but that the moisture content be at some level above air-dried.

When removing samples from the humidity chamber for testing or weighing, moisture content decreases instantly in dry labs or any atmosphere less than 100% relative humidity.

Samples immersed in water reached saturation in less than 10 minutes. I assume the difference in saturation moisture contents between samples is due to differences in texture, type of cementation and chemical composition. Low-strength samples often slake when saturated, and it is not possible to use this method to determine the unconfined compressive strength of these samples when saturated.

PART TWO:
STRENGTH TESTS AND THE DEVELOPMENT AND CALIBRATION OF A MODIFIED HYDRAULIC JACK

Strength Tests

Strength can be measured in the laboratory with sophisticated, expensive equipment, approximated in the field with simple manual techniques, or measured in the field with the Modified Jack.

Measuring with Laboratory Equipment:

Many commercial testing machines are available. The standard, most sophisticated testing machine is the Tinius Olsen. I used the Super L model. This machine is not too dissimilar to a large hydraulic vise; crushing block samples between two large steel plates (See Photo 3.). The upper steel plate is made to pivot and allows adjustment of the plane of the plate to fit flush against the upper planer surface of the block. One feature that makes the Tinius Olsen so sophisticated is that it applies the desired load evenly at the desired rate (e.g. 6 lbs sec^{-1}). These machines are expensive; usually costing over $40,000.

Proving rings are also commonly used in the laboratory. Proving rings are simply stainless steel rings set into a frame. A dial indicator is mounted to the rings to measure the amount of deformation in the rings as the load increases. Loads are applied using a geared mechanical jack. A correction factor is used to calculate pressure (measured in psi or Pa) from deformation readings (measured in 0.001 in). I used a 1500 pound capacity, double ring type made by Soil Test, Inc. (Evanston, Ill.). The double ring type allows for a greater range of measurements. Commonly, single rings are used for measuring specific ranges of strength. This may require the use of several rings for measuring materials with wide ranging strengths. One consequence of using proving rings is that they too, like the Modified Jack, need to be calibrated. Those I used were calibrated with the Tinius Olsen. Prices vary (between $500 and $700) depending on ring size and sophistication of the dial indicator.

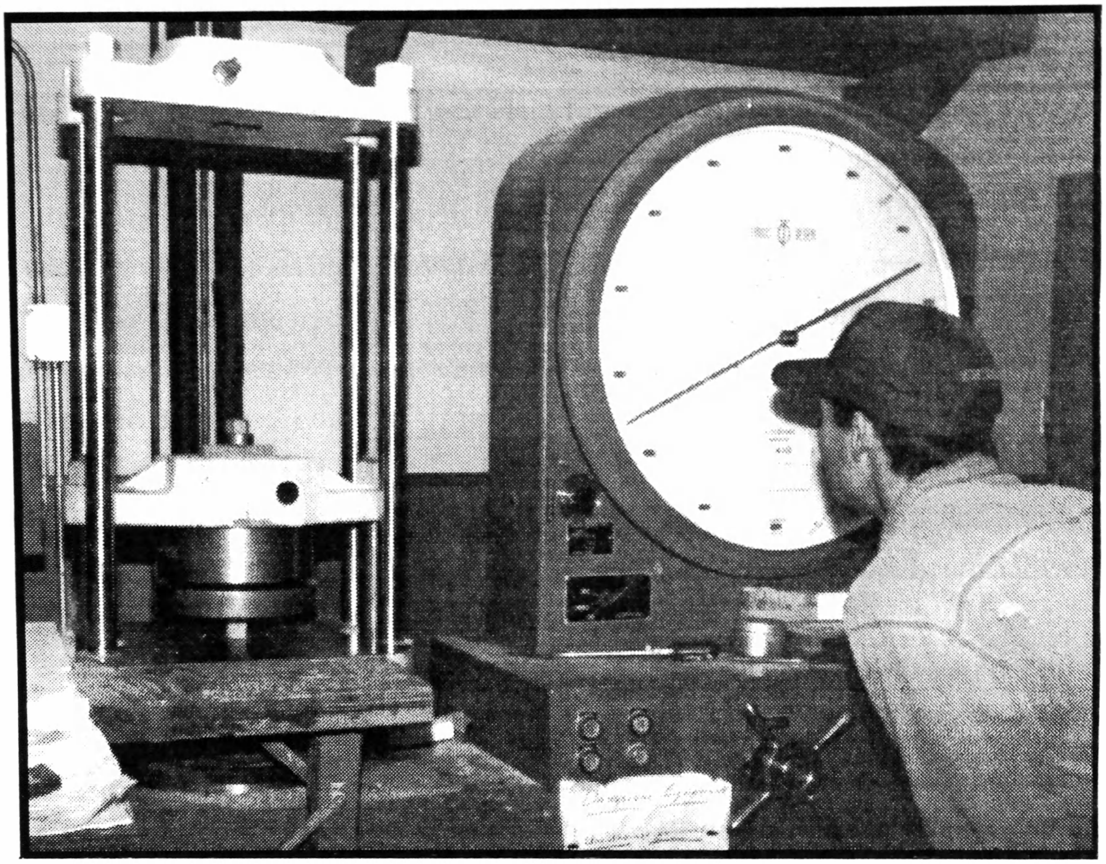

Photo 3. The Tinius Olsen. The laboratory standard for measuring unconfined compressive strength. New machines cost in excess of $40,000.

Measuring with Manual Field Techniques:

The U.S. Soil Conservation Service (Grossman, 1991) has developed a simple procedure that soil mappers can use in the field to measure rupture resistance (strength). A 1-inch (2.54 cm) cube sample, at various moisture contents, is compressed by a series of tests (of increasing pressures) until the sample is crushed: squeezed between the fingers, crushed under one's foot or subjected to a dropped geologic hammer from a given height. I feel this test is inadequate for many reasons; it does not provide quantitative data, it is highly subjective, and the units of force/energy applied to samples differs between techniques. Samples that break between the fingers or under foot are placed in strength classes by measured force in newtons, whereas the energy of a falling hammer is measured in joules. However, this method does have the advantage of a simple field technique that requires very little equipment.

Measuring with the Modified Jack Field Equipment:

We have developed a simple, inexpensive technique for measuring strength in the field. A 1.5-ton hydraulic jack, modified with a 1000 psi pressure gauge and fit into an angle-iron frame, is used to crush blocks (See Figure 1.). Modification of the hydraulic jack with the pressure gauge is simple. A hole is drilled and tapped into the jack's reservoir. A short nipple connects the pressure gauge to the jack. Total cost for materials is less than $50. The pressure gauge makes up 80% of the price and will vary with the range of measurement needed and the incremental accuracy desired. Readings at the extreme low and extreme high ranges of most pressure gauges can be less accurate, especially with lower quality gauges (Calcaterra, 1994).

Blocks are placed on the jack piston and squeezed against the frame by pumping the jack arm. It is of utmost importance that the interface between the sample and the frame or jack be clean and have a flush fit. A poor fit, leaving air space between the sample and frame or jack, will apply pressure to a smaller area of the block and cause premature failing and erroneous measurements. I used a 2x2 inch plate of three-eighths inch steel between the sample and the jack piston to provide this smooth interface. I also modified the steel plate by welding a 1/4 inch ball bearing to the center of the underside. This allows the plate to pivot on top of the jack piston and ensures a flush fit between the block and the frame. Blocks of very high strength may top-out the pressure gauge and are cut proportionally smaller to be tested in the jack. Strength measurements are then corrected to a per unit standard (psi or Pa). To standardize testing with the

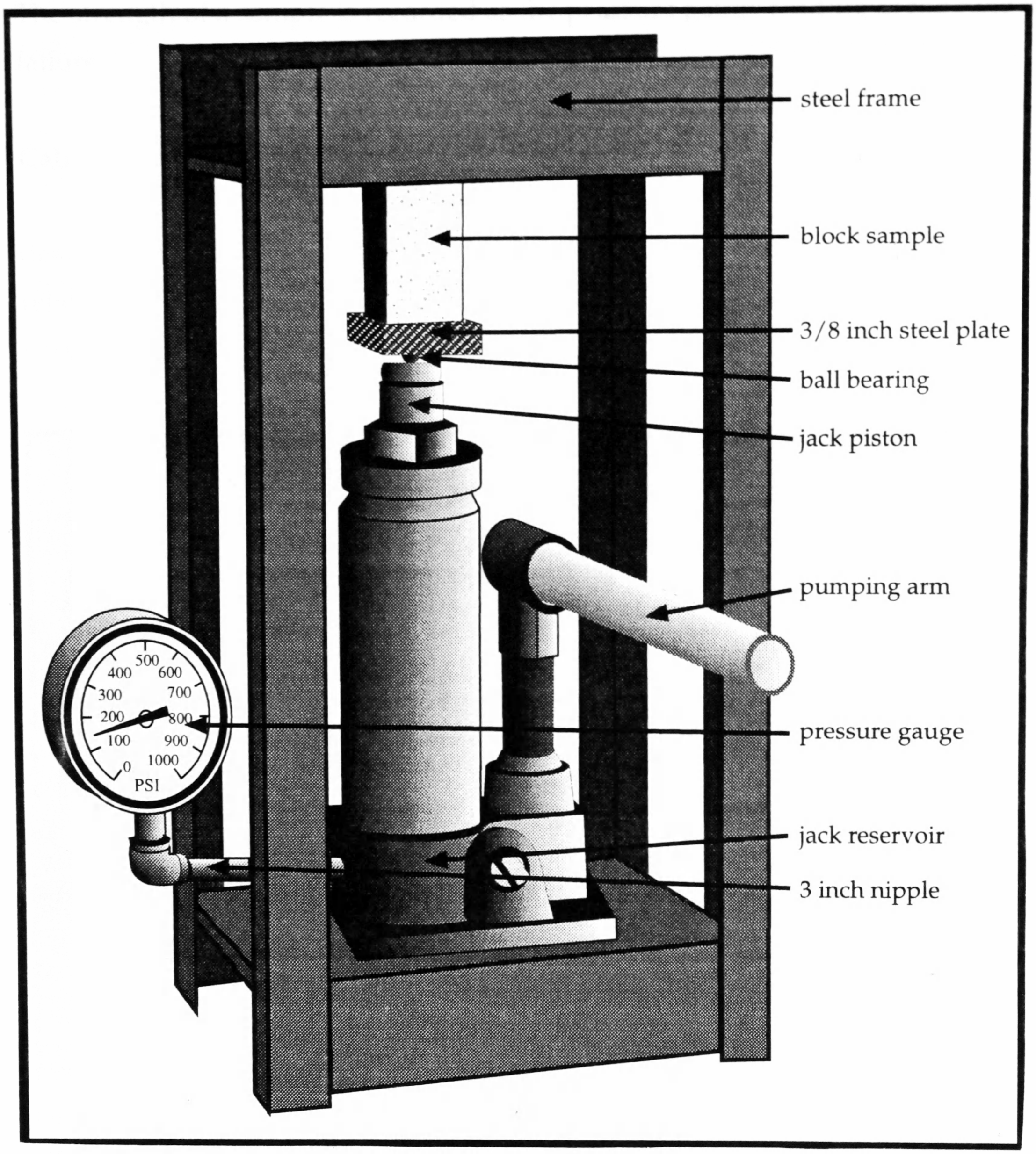

Figure 1. The Modified Jack and steel frame. A 1.5 ton hydraulic jack modified with a 1000 psi pressure gauge. The steel frame is made from light gauge channel and angle iron.

jack, each block is fitted into place as described above, and the jack arm is then raised to the full upright position. Pumping the jack arm increases pressure on the sample; the operator standardizes the application of pressure by coordinating a mental count of five seconds with every increase of 100 psi. Theoretically, a sample tested to have a strength of 200 psi would have taken 10 seconds to fail. The strength of a sample is recorded as the pressure gauge reading at the time of failure.

Calibration of the Modified Jack

I calibrated the Modified Jack with the Tinius Olsen, proving rings, and by dead loading. A calibration curve was developed for each to demonstrate the relative ease of calibration. This also provides options for laboratories with varying technological capabilities.

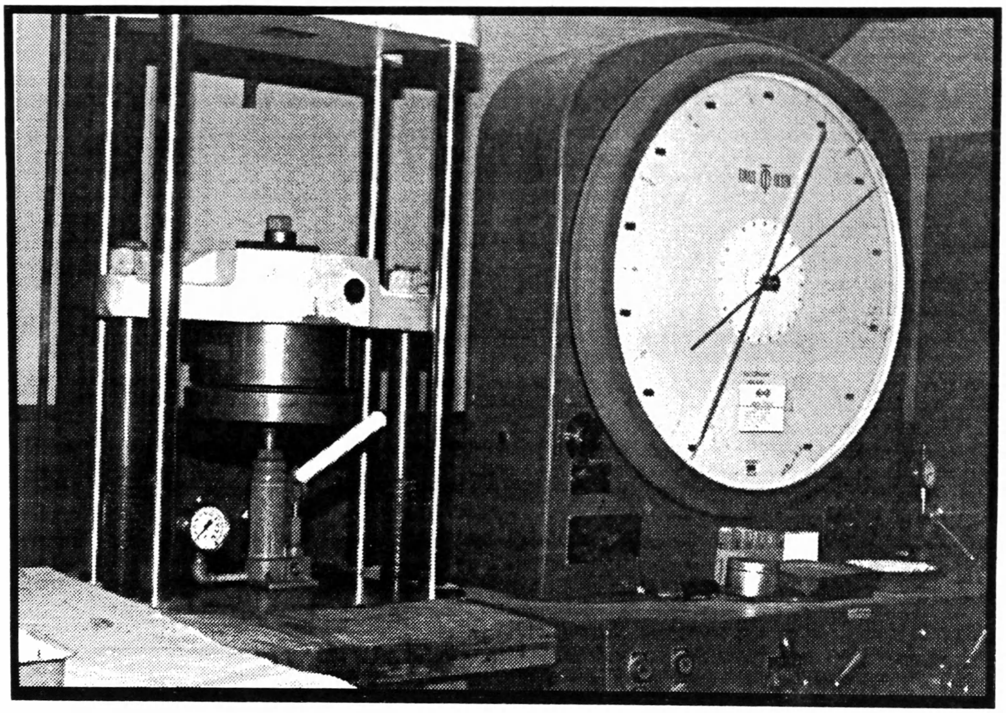

Photo 4. Calibration of the Modified Jack using the Tinius Olsen. Paired direct readings were taken by centering the Modified Jack snugly between the vise-like steel plates of the Tinius Olsen and applying pressure by pumping the jack arm.

Calibration with the Tinius Olsen

Paired direct readings were taken by centering the Modified Jack snugly between the vise-like steel plates of the Tinius Olsen and applying pressure by pumping the jack arm (See Photo 4.). The jack arm was pumped until the jack pressure gauge read 50 psi and a paired reading was taken by reading the Tinius

Olsen pressure gauge. This was repeated at intervals of 50 psi until the Modified Jack's pressure gauge was topped out at 1000 psi. Figure 2 displays the linear relationship between these paired readings. A regression of these data was made with a statistical software program. A R-squared value of 1.0 was computed (See Appendix 1.). Direct paired readings were taken twice more (at 100 psi intervals) to test repeatability of the process. Readings between these tests are nearly identical (See Appendix 2.). This method of applying pressure with the Modified Jack, rather than increasing the load using the Tinius Olsen, was used to simulate field conditions (i.e. those described in the preceding section).

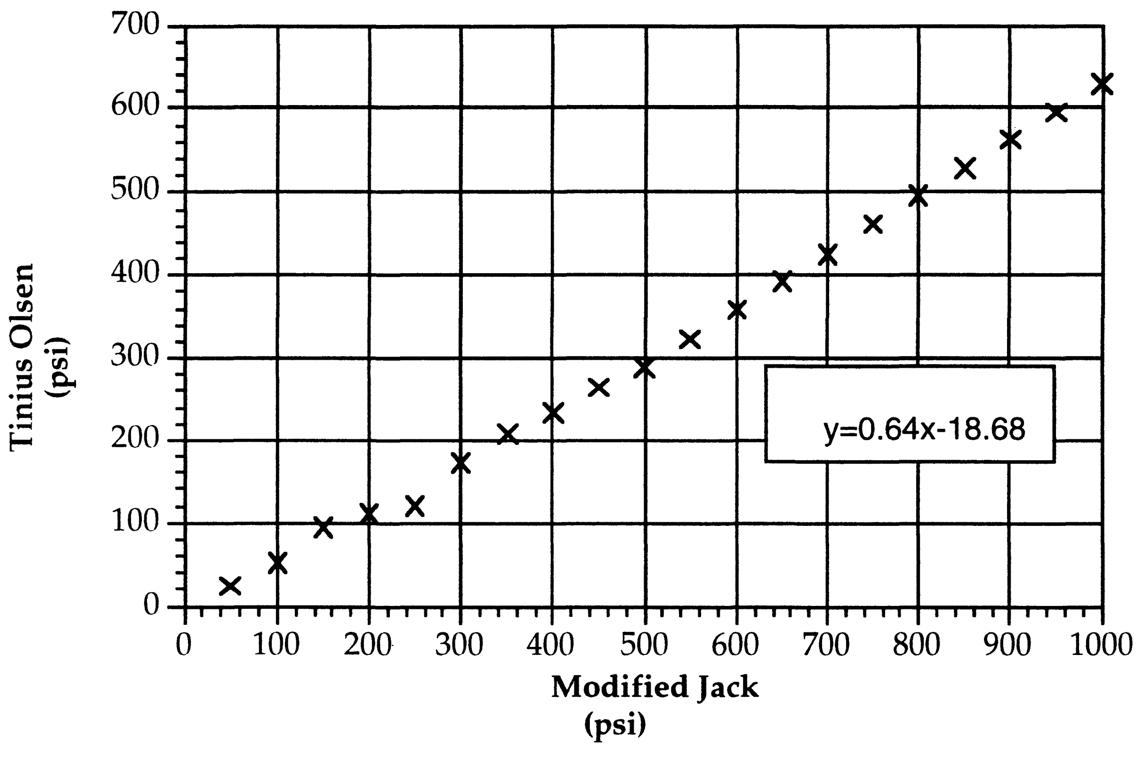

Figure 2. Calibration curve of the Modified Jack using the Tinius Olsen. This graph demonstrates the near perfect linear relationship between direct paired readings (n=20).

Calibration using Proving Rings

Paired direct readings were taken using the same method as that with the calibration using the Tinius Olsen. The proving rings were placed on top of the Modified Jack's piston and both were then centered snugly within the vise-like steel plates of the Tinius Olsen (See Photo 5). The Tinius Olsen was then shut off and used simply as a vise to hold the other equipment. A simple steel frame, similar to that used with the Modified Jack, could be constructed and used here to replace the Tinius Olsen. The remainder of the calibration methodology with regard to readings and repeatability was the same as that used with the Tinius Olsen described in the preceding paragraph (See Appendix 2.).

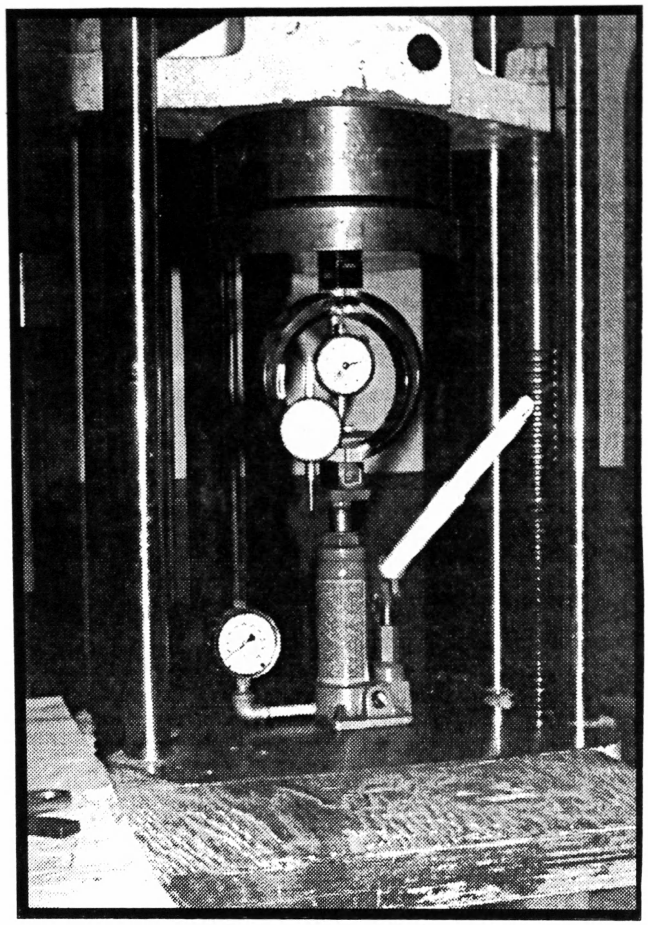

Photo 5. Calibration of the Modified Jack using proving rings. Paired direct readings were taken by centering the proving rings and Modified Jack snugly between the vise-like steel plates of the Tinius Olsen and applying pressure by pumping the jack arm.

Figure 3 is the graphic representation of the linear relationship between these paired readings. A regression of these data was done using a statistical software program; again, a R-squared value of 1.0 was computed (See Appendix 1.).

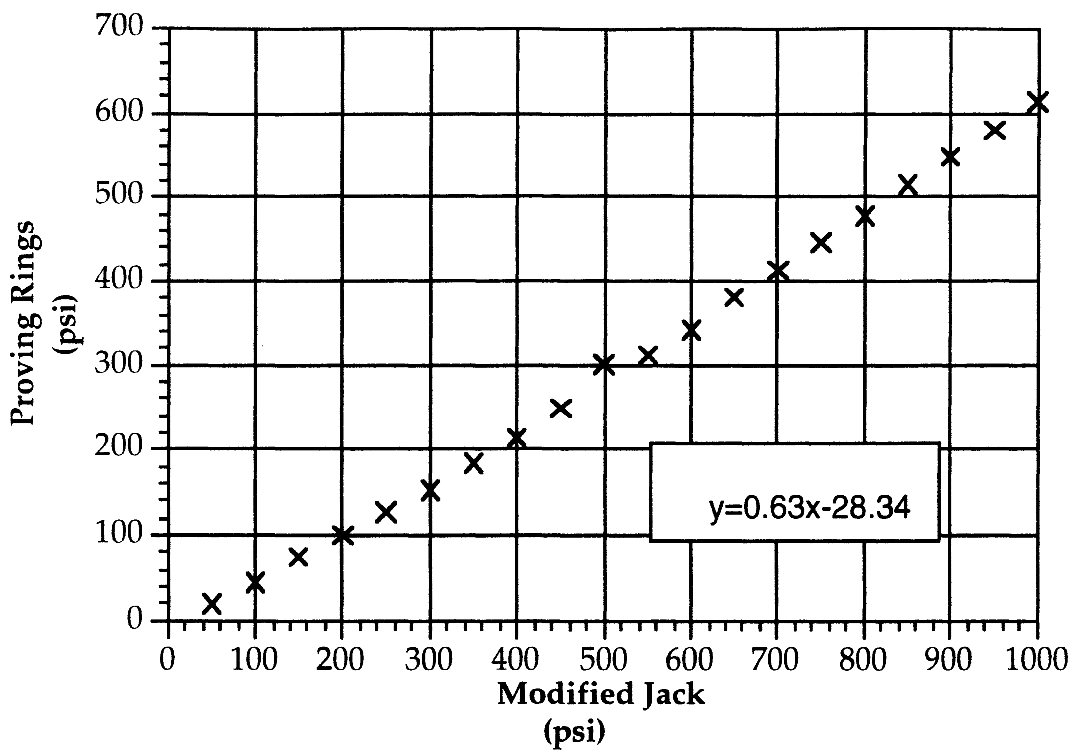

Figure 3. Calibration curve of the Modified Jack using proving rings. This graph demonstrates the near perfect linear relationship between paired direct readings (n=20).

Calibration by Dead Loading

Dead weights were stacked and balanced at 50 lbs increments to establish a calibration curve for the Modified Jack. (All dead weights were first weighed on a Toledo scale for accuracy.) The weights were cribbed to a height just above the height of the jack's piston. Centering the jack beneath the weights for balancing was the most difficult step in the process. The jack was then pumped to a snug fit under the weights and the jack arm was raised to the full upright position. The jack was then pumped until the weights were lifted clear of the cribbing and a reading was made from the jack's pressure gauge. This test was performed only once (See Appendix 2.). Figure 4 demonstrates the linear relationship between these paired readings. The computed R-squared value was again 1.0 (See Appendix 1.).

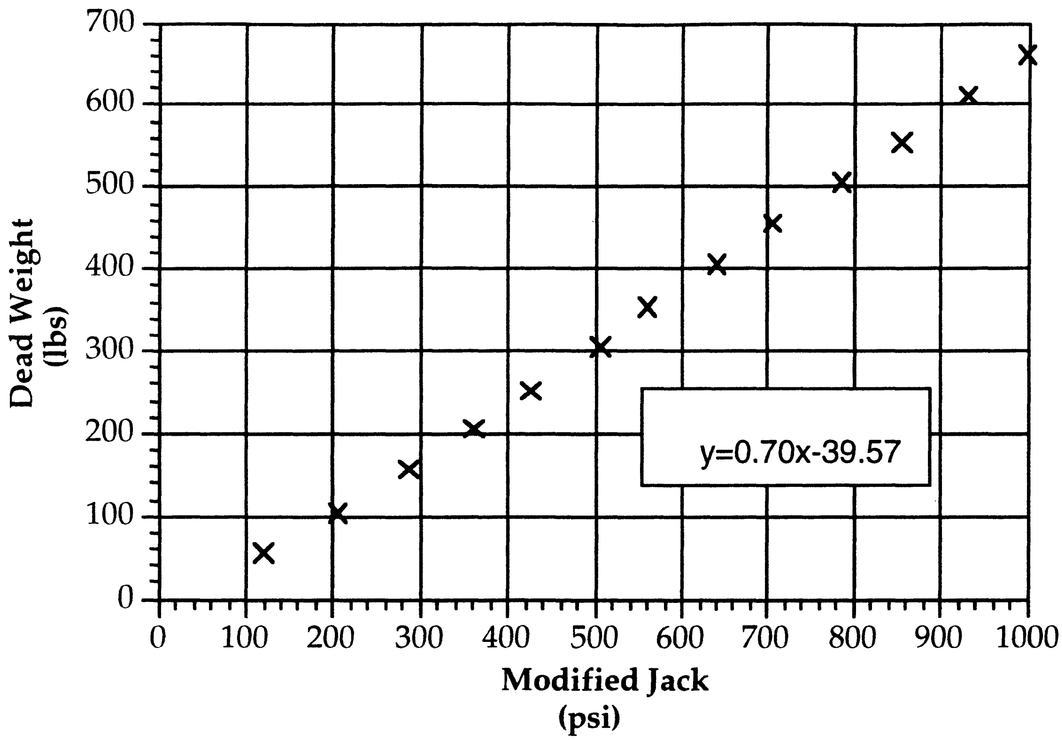

Figure 4. Calibration curve of the Modified Jack using dead weights. This graph demonstrates the near perfect linear relationship between paired direct readings (n=13).

All three calibration methods demonstrate a near perfect linear relationship between the Modified Jack and the respective testing equipment. Each technique is quick, relatively simple, and establishes the Modified Jack as a precise instrument for obtaining quantified measurements in the field.

PART THREE:
APPLICATION AND RESULTS OF FIELD TESTING THE MODIFIED JACK

Field Testing the Modified Jack

Four samples of indurated materials were collected, cut, and shaped following the techniques described in Part One. Indurated volcanic-ash (*tepetate*) was taken from the Valley of Mexico. Two sandstone samples (fine and coarse textured) were then taken locally. The fourth was chalk (magnesium carbonate) purchased at a local athletic equipment retailer. The testing of each will be discussed below.

Tepetate

Eight blocks were cut and formed in the field at each of seven locations. Although very little is known of the spatial distribution of *tepetate* or individual ash flows, there were significant differences in color and bedding patterns to suggest seven different samples. The eight blocks from each location were randomly paired to be tested in the Tinius Olsen and the Modified Jack. To obtain measurements throughout the full range of the jack's pressure gauge, the moisture content of each pair was adjusted using the techniques described in the last section of Part One. Figure 5 is a graph of these data (See Appendix 3.). The Modified Jack readings have been corrected using the calibration equation from Figure 2.

Tepetate was the original focus for testing the jack, but I felt two reasons justified expanding the study to other indurated materials. First, the Modified Jack, like other strength tests, has wider applicability. Second, several of the *tepetate* samples had many natural planes of weakness (i.e. laminar carbonates, bedding planes,vesicles) or were so weak that forming good blocks was difficult.

I thought the heterogeneous *tepetate* blocks would have a high variation that could be reduced using a more homogeneous substance when testing the Modified Jack. Both sandstone samples and the chalk were selected for their homogeneity and varied strengths. I assumed these three samples would individually represent the high, middle, and low testing range of the Modified Jack.

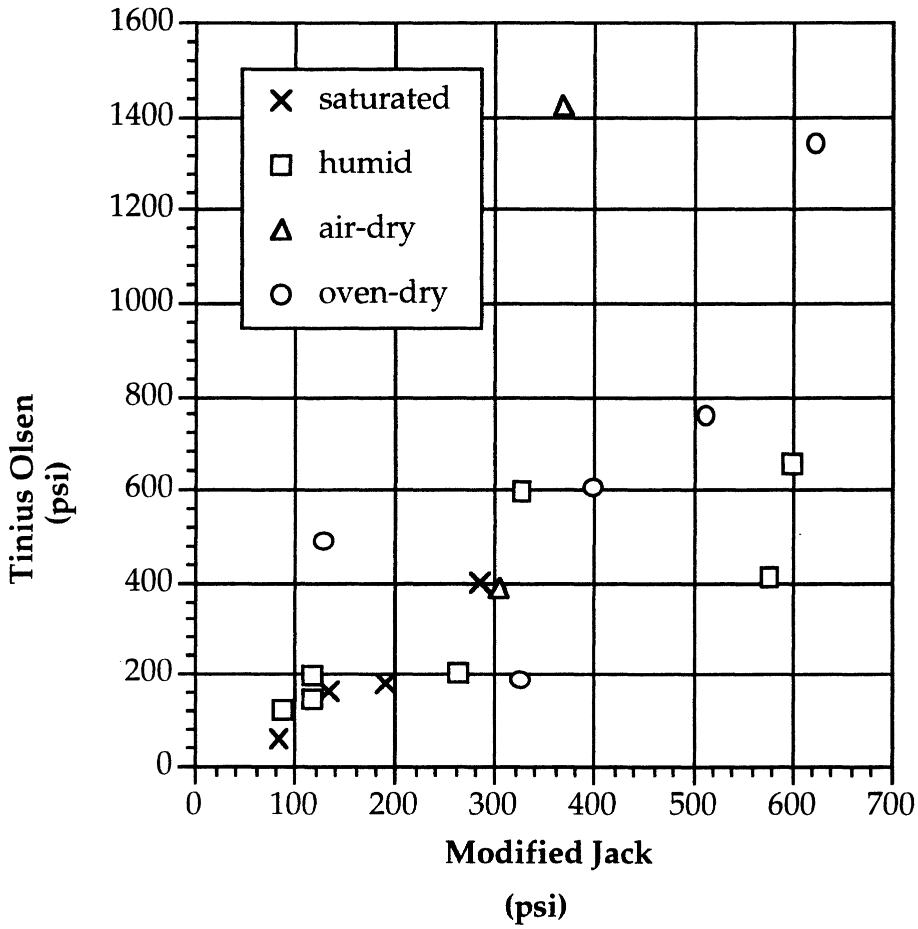

Figure 5. Graph of readings from paired *tepetate* blocks. Paired samples were crushed at four moisture contents to test the Modified Jack at a full range of scale. Note the y-axis scale is twice that of the x-axis.

Fine Sandstone

Twelve, fine textured, sandstone blocks were cut and formed using the field methods described in Part One. Bedding plains were common in each, but blocks formed easily. Bedding planes were a change in color, not texture, and did not show any sign of being a natural plane of weakness.

The fine sandstone was selected to test the high range of the Modified Jack. Preliminary testing of 1x1x2.5 in (2.5x2.5x6.25 cm) blocks showed the fine sandstone to have very high strength (the pressure gauge on the jack was topped out). Each block was resized several times, eventually to approximately 0.5x0.5x1.5 in (1.25x1.25x3.8cm). Each block was measured along its three axes (x,y, and z; z being the long axis). Blocks having equal or most similar xy values were then paired and tested in either the Tinius Olsen or the Modified Jack (See Appendix 3.).

Coarse Sandstone

Fourteen, coarse textured, sandstone blocks were cut, formed, and paired using the same methods described for the fine sandstone. No difficulties were encountered cutting and forming blocks. Bedding planes were originally observed in the coarse sandstone but were uncommon in blocks. The coarse sandstone was selected to test the mid-range of the Modified Jack (See Appendix 3.).

Chalk

Chalk (magnesium carbonate of this type is used by gymnasts to increase their grip) was selected to test the low range of the Modified Jack and for its greater homogeneity than the sandstones. It was purchased in factory-made blocks approximately 1.75x3.5x3.5 in (4.5x9x9 cm). Seven blocks were cut in half to approximately 1.75x1.75x3.5 in (4.5x4.5x9 cm). Blocks easily crumbled when cut; hence the large size. Each pair of halves was considered a matched pair and tested in either the Tinius Olsen or the Modified Jack (See Appendix 3.).

Figure 6 is a graph of the data obtained from testing the paired blocks made from the fine sandstone, coarse sandstone, and chalk. The Modified Jack readings have been corrected using the calibration equation from Figure 2.

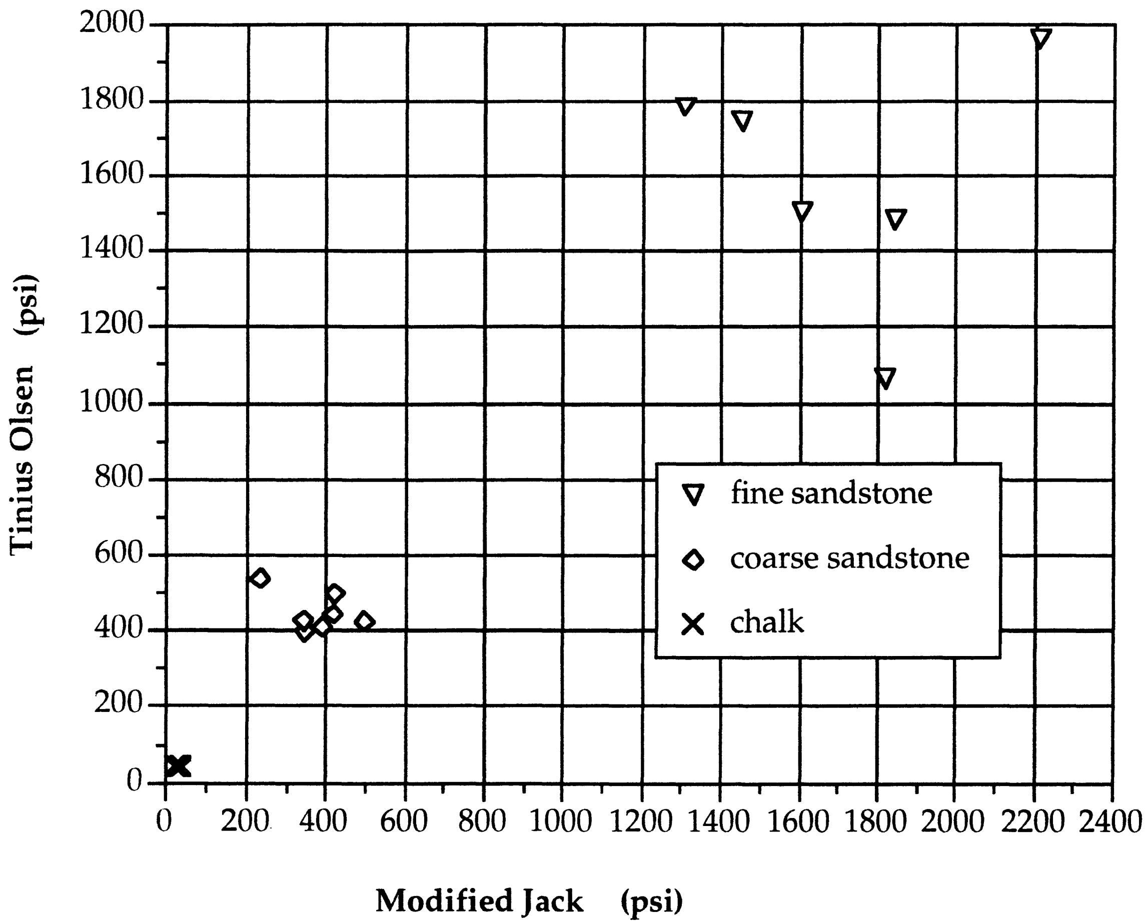

Figure 6. Graph of readings from paired blocks made from fine sandstone, coarse sandstone, and chalk. This graph shows the relative distribution of each material at the high, middle, and low range of the Modified Jack's testing range.

The fine sandstone, coarse sandstone, and chalk samples effectively tested the high, middle, and low ranges of the Modified Jack (See Figure 6.). Figure 6 also provides some insight to the variation within each sample. The chalk data points are nearly on top of each other; the fine sandstone are widely scattered; and the coarse sandstone spread falls somewhere between the other two. At this scale, the graph suggests an increasing variation among samples as sample strength increases. The standard deviation is a measure of the degree of variability within a sample. However, it is of limited value when comparing the variability of samples whose means are appreciably different. In this instance the coefficient of variation, a ratio of the standard deviation to the mean, is used to compare variability in samples from populations having different means. Below are the mean and coefficient of variation values for each sample.

Sample	Mean	Coefficient of Variation
chalk	36	6.25
coarse sandstone	414	10.91
fine sandstone	1648	22.10

Each sample has a different mean by an order of magnitude, thus establishing the coefficient of variation as the appropriate statistic to compare variability. Coefficient of variation values are also different for each sample; therefore the relative variability of each sample is different. The source of this variation is now the question at hand.

Variation in block readings may come from imperfectly formed blocks, from malfunctions of the Modified Jack, and/or as natural variation within the indurated material. Block samples tested in both the Tinius Olsen and the Modified Jack were cut and formed using the same technique. Samples were paired by having nearly identical dimensions, and then selected at random to be tested in either the Tinius Olsen or the Modified Jack. Any variation that may come from imperfectly formed blocks will be equal between samples and is not the cause for the differences in coefficient of variation values.

The Modified Jack is not a likely source of variation in block readings. In Part Two, I established three calibration curves using three different techniques (and tested these techniques three times with two of them); each demonstrated a nearly perfect linear relationship throughout the full range of the Modified Jack. If these had not been linear relationships or if there had been variation among readings when the tests were repeated, the Modified Jack would then be suspect. These situations were not present. Therefore the Modified Jack is not a source of significant variation. However, the pressure gauge on the Modified Jack is graduated at increments of 10 psi and that of the Tinius Olsen at increments of 2 psi. Readings can only be roughly estimated between the values of ten. I assume this "reader error" to be a real but minor source of variation. Since it will be most significant for low strength readings, "reader error" may be minimized by cutting blocks large enough to utilize the middle range of the pressure gauge. Using a more sophisticated pressure gauge would also reduce "reader error".

Eliminating the blocks and the Modified Jack as significant sources of variation, leads to the conclusion that the source to the variation must lie in the natural variation of the indurated materials. This is consistent with my observations above regarding the homogeneity and bedding planes for each sample.

PART FOUR:
CONCLUSIONS

The following conclusions are presented in three sections. Each section concludes the information presented in the previous three parts of this thesis.

Techniques for Cutting, Forming, and Moisture Adjustment of Materials

The techniques for cutting and forming indurated materials, described in Part One, enabled me to produce the blocks needed for testing all four indurated materials (tepetate, fine sandstone, coarse sandstone, and chalk). Each material tested, presented unique features (i.e. differences in strength, bedding planes) that required preliminary testing and experimenting with different saws, files or, sandpaper until the desired block was formed. I assume this will be required for any and all materials to be tested.

In Part One I stated, "The most important aspect of cutting and forming blocks is to keep the short axis planes both flat and parallel." Testing imperfectly formed blocks can introduce error in measurements or increase variation within a population sample. However, techniques for cutting and forming laboratory samples have not been described. I feel my field techniques have equal application for field and laboratory use. I assume the conscientious person will form the best blocks possible and any error or variation introduced to either the laboratory or field tests (paired samples) would be equal.

The techniques describing the moisture adjustment of materials have already been established (Cook et al., 1992) and were effective for testing a wider range of strength in *tepetate* samples. However, this sample set provides only two replicates for each *tepetate* sample at each moisture content and prevents me from making any other inferences with regard to these data. However, these techniques may also be helpful in coordinating reclamation with moisture content.

Strength Tests and the Development and Calibration of the Modified Jack

The Tinius Olsen and proving rings are the established laboratory standards for determining unconfined compressive strength. The Tinius Olsen is the most sophisticated and most expensive. Proving rings are considerably less expensive, but require some means of calibration and various rings are needed for measuring a wide range of strengths. The manual field techniques developed by the Soil Conservation Service do not provide quantitative data and are highly subjective. Moreover the units of force/energy applied to samples differ between techniques.

The Modified Jack is inexpensive, provides quantified data, and is easily carried into the field. The pressure gauge is the most expensive item to purchase, and cost is a function of the range of measurement needed and the incremental accuracy desired.

Calibration curves were developed by making direct paired readings using three techniques of varying degrees of sophistication (i.e. by using the Tinius Olsen, proving rings, and dead weight). Paired direct readings were taken three times, using the Tinius Olsen and proving rings, to ensure repeatability and to exclude the possibility of equipment malfunction. All three techniques and each replicate produced a near perfect linear correlation between the Modified Jack and the calibration equipment. Regressions were done on data taken from each technique, and R-squared values of 1.0 were computed for each.

The nearly perfect linear relationship between the Modified Jack and the calibration equipment establishes the jack as a means of obtaining quantified data on unconfined compressive strength in the field.

Application and Results of Field Testing the Modified Jack

Four samples of indurated materials were tested (*tepetate*, fine sandstone, coarse sandstone, and chalk). As stated above, in Part Four, the small number of *tepetate* replicates prevents any further inferences from those data. In retrospect, it would have been best to test only three or four *tepetate* samples in the same way I did the sandstones and chalk. To utilize the seven samples in hand, I could have run preliminary tests to determine the relative strengths of all seven samples. If more than one sample had similar strengths, I could adjust all the blocks of one sample to a different moisture content (higher or lower), using the same techniques, and fill any gap throughout the pressure range of the Modified Jack.

The chalk, coarse sandstone, and fine sandstone samples effectively tested the low, middle, and high ranges of the Modified Jack. Coefficient of variation values were different for each sample, thus, indicating the relative variability of each sample was different. I eliminated the blocks and the Modified Jack as significant sources of variation, and concluded that the source to the variation must lie in the natural variation of the indurated materials. Variations in jack readings due to equipment and reader error are most likely to occur at the extreme low range of the pressure gauge, but can be minimized with a more sophisticated gauge.

The determination of strength of indurated volcanic-ash materials is prerequisite to reclamation. While several methods for determining strength are available, most are either too expensive or do not provide the reliable quantitative data needed in the field. My study shows that the Modified Jack is an inexpensive, precise instrument for determining unconfined compressive strength in the field and that the associated field techniques (cutting, forming, and moisture adjustment) have wide applicability for use with indurated materials.

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Appendix 1. Regression of Paired Direct Readings from Tinius Olsen and the Modified Jack

Tinius Olsen	**Modified Jack**			
24	50		**units= psi**	
53	100		**(n=20)**	
94	150			
111	200			
121	250			
172	300			
207	350			
234	400			
265	450			
289	500			
323	550			
358	600			
393	650			
425	700			
462	750			
496	800			
529	850			
562	900			
595	950			
629	1000			

REGRESSION

Dependent Variable:	Tinius Olsen			
		Parameter	Standard	T for H0:
Variable	Mean	Estimate	Error	parameter=0
Intercept		-18.68	4.07	-4.59
Modified Jack	525.00	0.64	0.01	94.06
		Sum of	Mean	
Source	DF	Squares	Square	F-Value
Model	1.00	680064.29	680064.29	8847.93
Error	18.00	1383.51	76.86	
Total	19.00	681447.80		
Dependent Mean	317.10			
Root Mean Square Error	8.77			
Coefficient of Variation	2.76			
R-Square	**1.00**		**not rounded R-Square 0.9979697**	
Adjusted R-Square	1.00			

Appendix 1. Regression of Paired Direct Readings from Proving Rings and the Modified Jack

Proving Rings	Modified Jack			
19	50		units=psi	
45	100		(n=20)	
74	150			
100	200			
126	250			
152	300			
184	350			
213	400			
248	450			
300	500			
312	550			
342	600			
381	650			
413	700			
446	750			
478	800			
515	850			
548	900			
580	950			
614	1000			

REGRESSION

Dependent Variable:	Proving Rings			
		Parameter	Standard	T for H0:
Variable	Mean	Estimate	Error	parameter=0
Intercept		-28.34	3.96	-7.15
Modified Jack	525.00	0.63	0.01	95.86
		Sum of	Mean	
Source	DF	Squares	Square	F-Value
Model	1.00	668220.15	668220.15	9189.72
Error	18.00	1308.85	72.71	
Total	19.00	669529.00		
Dependent Mean	304.50			
Root Mean Square Error	8.53			
Coefficient of Variation	2.80			
R-Square	**1.00**		**not rounded R-Square 0.9980451**	
Adjusted R-Square	1.00			

Appendix 1. Regression of Paired Direct Readings from Dead Loading and the Modified Jack

Dead Weight (lbs)	**Modified Jack (psi)**			
55.1	120			
104.4	205		**(n=13)**	
157	287			
206.3	360			
252.1	425			
304.7	505			
354	560			
406.1	640			
455.4	705			
505.6	785			
554.3	855			
610.7	930			
660.9	998			
		REGRESSION		
Dependent Variable:	Dead Weight (lbs)			
		Parameter	Standard	T for H0:
Variable	Mean	Estimate	Error	parameter=0
Intercept		-39.57	3.37	-11.74
Modified Jack	567.31	0.70	0.01	129.95
		Sum of	Mean	
Source	DF	Squares	Square	F-Value
Model	1.00	460914.47	460914.47	16885.79
Error	11.00	300.26	27.30	
Total	12.00	461214.73		
Dependent Mean	355.89			
Root Mean Square Error	5.22			
Coefficient of Variation	1.47			
R-Square	**1.00**		**not rounded R-Square 0.9993489**	
Adjusted R-Square	1.00			

Appendix 2. Paired Direct Readings

Modified Jack v. Tinius Olsen - Test A (n=20)

Modified Jack (psi)	Tinius Olsen (psi)	converted (Pa)		
50	24	165600		
100	53	365700		
150	94	648600		
200	111	765900		
250	121	834900		
300	172	1186800		
350	207	1428300		
400	234	1614600		
450	265	1828500		
500	289	1994100		
550	323	2228700		
600	358	2470200		
650	393	2711700		
700	425	2932500		
750	462	3187800		
800	496	3422400		
850	529	3650100		
900	562	3877800		
950	595	4105500		
1000	629	4340100		

Modified Jack v. Tinius Olsen - Test B (n=10)

Modified Jack (psi)	Tinius Olsen (psi)	converted (Pa)		
100	53	365700		
200	111	765900		
300	173	1193700		
400	237	1635300		
500	291	2007900		
600	356	2456400		
700	424	2925600		
800	492	3394800		
900	562	3877800		
1000	630	4347000		

Modified Jack v. Tinius Olsen - Test C (n=10)

Modified Jack (psi)	Tinius Olsen (psi)	converted (Pa)		
100	54	372600		
200	114	786600		
300	172	1186800		
400	242	1669800		
500	294	2028600		
600	360	2484000		
700	428	2953200		
800	492	3394800		
900	564	3891600		
1000	630	4347000		

Appendix 2. Paired Direct Readings

Modified Jack v. Proving Rings - Test A (n=20)

Modified Jack (psi)	units=0.0001 in	corrected (psi)	converted (Pa)
50	21	19	131100
100	49	45	310500
150	79	74	510600
200	107	100	690000
250	136	126	869400
300	164	152	1048800
350	199	184	1269600
400	229	213	1469700
450	266	248	1711200
500	299	300	2070000
550	336	312	2152800
600	369	342	2359800
650	410	381	2628900
700	445	413	2849700
750	481	446	3077400
800	517	478	3298200
850	555	515	3553500
900	592	548	3781200
950	630	580	4002000
1000	667	614	4236600

Modified Jack v. Proving Rings - Test B (n=10)

Modified Jack (psi)	units=0.0001 in	corrected (psi)	converted (Pa)
100	52	48	331200
200	113	105	724500
300	177	164	1131600
400	240	224	1545600
500	303	283	1952700
600	373	346	2387400
700	446	414	2856600
800	520	482	3325800
900	592	548	3781200
1000	668	615	4243500

Modified Jack v. Proving Rings - Test C (n=10)

Modified Jack (psi)	units=0.0001 in	corrected (psi)	converted (Pa)
100	51	47	324300
200	112	104	717600
300	178	165	1138500
400	249	233	1607700
500	325	302	2083800
600	394	366	2525400
700	472	437	3015300
800	549	509	3512100
900	628	578	3988200
1000	687	637	4395300

Appendix 2. Paired Direct Readings

Modified Jack v. Dead Loading - Test A (n=13)

Modified Jack (psi)	Dead Weight (lbs)		Calibrated Jack(psi)
120	55.1		44.4
205	104.4		103.9
287	157		161.3
360	206.3		212.4
425	252.1		257.9
505	304.7		313.9
560	354		352.4
640	406.1		408.4
705	455.4		453.9
785	505.6		509.9
855	554.3		558.9
930	610.7		611.4
998	660.9		659.0

Appendix 3. Tepetate Block Dimensions and Strength Measurements						
Tinius Olsen Samples						
Paired Tepetate Samples at Various Moisture Contents						
	block dimensions (in)				**uncorrected**	**corrected**
	X	**Y**	**Z**	**XY**	**reading (psi)**	**reading (psi)**
saturated 1	0.94	0.89	2.23	0.83	334	400
saturated 2	0.88	0.86	2.53	0.75	137	181
saturated 3	0.97	1.21	2.91	1.18	434	369
saturated 4	*	*	*	*	not available	
saturated 5	1.00	1.08	2.43	1.08	64	59
saturated 6	0.90	1.15	2.20	1.04	170	164
saturated 7	0.84	0.93	2.22	0.78	crumbled when saturated	
humid 1	0.76	1.06	2.18	0.81	528	655
humid 2	1.02	1.02	2.20	1.04	430	413
humid 3	0.86	1.10	2.00	0.95	564	596
humid 4	1.16	1.01	2.47	1.17	170	145
humid 5	1.14	1.18	2.76	1.34	268	200
humid 6	0.91	0.91	2.16	0.83	170	205
humid 7	1.21	1.24	2.51	1.50	187	125
air-dry 1	0.80	1.07	1.99	0.86	1226	1425
air-dry 2	*	*	*	*	not available	
air-dry 3	1.04	1.07	2.58	1.11	826	742
air-dry 4	1.01	1.15	2.40	1.16	452	389
air-dry 5	1.00	1.05	1.96	1.05	inherent fracture	
air-dry 6	0.97	1.16	2.41	1.13	452	400
air-dry 7	*	*	*	*	not available	
oven-dry 1	0.89	1.08	2.12	0.96	1292	1344
oven-dry 2	0.93	0.94	2.46	0.88	668	759
oven-dry 3	0.99	1.00	2.52	0.99	600	606
oven-dry 4	1.00	0.95	2.89	0.95	466	492
oven-dry 5	0.88	1.05	2.28	0.92	174	189
oven-dry 6	0.89	1.01	2.33	0.90	378	419
oven-dry 7	0.95	0.91	1.89	0.86	inherent fracture	

Appendix 3. Tepetate Block Dimensions and Strength Measurements							
Modified Jack Samples							
Paired Tepetate Samples at Various Moisture Contents							
	block dimensions (in)				**uncorrected**	**corrected**	
	X	**Y**	**Z**	**XY**	**reading (psi)**	**reading (psi)**	
saturated 1	0.91	1.00	2.23	0.91	430	473	
saturated 2	0.94	0.92	2.50	0.86	280	324	
saturated 3	*	*	*	*	not available		
saturated 4	1.00	0.98	2.47	0.98	120	122	
saturated 5	0.98	0.96	1.93	0.94	150	159	
saturated 6	1.00	1.18	2.28	1.18	280	237	
saturated 7	0.80	0.73	2.34	0.58	crumbled when saturated		
humid 1	0.85	0.95	2.30	0.81	780	966	
humid 2	0.96	1.04	2.44	1.00	930	931	
humid 3	0.92	1.07	2.21	0.98	530	538	
humid 4	0.95	1.00	2.87	0.95	200	211	
humid 5	0.93	0.96	2.10	0.90	190	212	
humid 6	1.00	1.00	2.25	1.00	440	440	
humid 7	0.83	0.73	2.15	0.61	100	165	
air-dry 1	0.91	1.06	2.03	0.96	topped-out gauge		
air-dry 2	0.86	0.97	2.45	0.83	topped-out gauge		
air-dry 3	0.93	1.08	2.69	1.00	topped-out gauge		
air-dry 4	0.79	1.03	2.10	0.81	490	602	
air-dry 5	1.03	1.03	2.09	1.06	670	632	
air-dry 6	1.04	0.92	2.24	0.96	480	502	
air-dry 7	0.90	0.86	2.20	0.77	280	362	
oven-dry 1	0.92	1.05	1.90	0.97	topped-out gauge		
oven-dry 2	1.03	0.94	2.53	0.97	970	1002	
oven-dry 3	1.00	1.05	2.58	1.05	870	829	
oven-dry 4	0.90	0.94	2.18	0.85	550	650	
oven-dry 5	0.92	1.10	2.50	1.01	230	227	
oven-dry 6	1.17	1.05	2.25	1.23	660	537	
oven-dry 7	0.79	0.87	1.78	0.69	210	306	

Appendix 3. Coarse and Fine Sandstone Block Dimensions and Strength Measurements							
Jack Testing		TO=Tinius Olsen			MJ= Modified Jack		
					uncorrecte	corrected	calibrated
coarse sandstone	block dimensions (in)				reading	reading	reading
paired samples	X	Y	Z	XY	psi	psi	psi
A-TO	0.855	0.879	1.671	0.752	320	426	
A-MJ	0.827	0.910	1.647	0.753	605	804	496
B-TO	0.827	0.879	1.643	0.727	323	444	
B-MJ	0.812	0.890	1.592	0.723	491	679	416
C-TO	0.922	0.926	1.832	0.854	350	410	
C-MJ	0.910	0.930	1.785	0.846	540	638	390
D-TO	0.965	0.985	1.848	0.951	512	539	
D-MJ	0.957	1.005	1.808	0.962	380	395	234
E-TO	0.894	0.926	1.757	0.828	414	500	
E-MJ	0.938	0.957	1.808	0.898	615	685	420
F-TO	0.855	0.898	1.738	0.768	308	401	
F-MJ	0.859	0.902	1.548	0.775	442	570	346
G-TO	0.760	0.772	1.485	0.587	251	428	
G-MJ	0.729	0.733	1.407	0.534	300	561	341
					uncorrecte	corrected	calibrated
fine sandstone	block dimensions (in)				reading	reading	reading
paired samples	X	Y	Z	XY	psi	psi	psi
A-TO	0.494	0.513	1.442	0.253	270	1065	
A-MJ	0.493	0.516	1.417	0.254	730	2870	1818
B-TO	0.488	0.5	1.392	0.244	435	1783	
B-MJ	0.492	0.501	1.479	0.246	510	2069	1306
C-TO	0.504	0.514	1.438	0.259	508	1961	
C-MJ	0.493	0.518	1.479	0.255	890	3485	2212
D-TO	0.499	0.5	1.407	0.250	435	1743	
D-MJ	0.459	0.493	1.45	0.226	520	2298	1452
E-TO	0.512	0.522	1.472	0.267	396	1482	
E-MJ	0.514	0.522	1.451	0.268	780	2907	1842
F-TO	0.461	0.474	1.42	0.219	328	1501	
F-MJ	0.426	0.481	1.437	0.205	520	2538	1605

Appendix 3. Chalk Block Dimensions and Strength Measurements							
Jack Testing		TO=Tinius Olsen			MJ=Modified Jack		
					uncorrected	**corrected**	**calibrated**
chalk	**block dimensions (in)**				**reading**	**reading**	**reading**
paired samples	**X**	**Y**	**Z**	**XY**	**psi**	**psi**	**psi**
A-TO	1.74	1.74	3.46	3.03	131	43	
A-MJ	1.73	1.74	3.46	3.01	175	58	19
B-TO	1.71	1.75	3.46	2.99	116	39	
B-MJ	1.72	1.72	3.46	2.96	242	82	34
C-TO	1.48	1.72	3.45	2.55	114	45	
C-MJ	1.46	1.73	3.45	2.53	200	79	32
D-TO	1.66	1.8	3.46	2.99	128	43	
D-MJ	1.56	1.66	3.46	2.59	220	85	36
E-TO	1.64	1.72	3.47	2.82	113	40	
E-MJ	1.72	1.75	3.47	3.01	255	85	36
F-TO	1.72	1.72	3.47	2.96	119	40	
F-MJ	1.71	1.75	3.47	2.99	232	78	31
G-TO	1.65	1.69	3.47	2.79	109	39	
G-MJ	1.71	1.72	3.46	2.94	220	75	29