A Proposed Best Practice Method of Defining a Standard of Care for Stabilized Compressed Earthen Block Production

by

Adam Davis Krosnowski

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Written by Adam Krosnowski
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Bernard Amadei

Abbie Liel

John McCartney

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Krosnowski, Adam Davis (M.S., Department of Civil, Environmental, and Architectural Engineering)

A Proposed Best Practice Method of Defining a Standard of Care for Stabilized Compressed Earthen Block Production.

Thesis directed by Professor Bernard Amadei

Abstract

Earthen building has evolved with mankind and creates housing opportunities world-wide. Building with stabilized compressed earthen blocks (SCEBs) is becoming more popular due to the low cost, relative abundance of materials, and quality product performance. The need for a standardized method of soil selection, SCEB production procedure, and subsequent quality control is apparent. This thesis serves multiple purposes by: (i) contributing to the growing field of alternative building design; (ii) motivating the need for a standardized framework of production methods with associated quality standards; (iii) proposing a formal testing methodology or matrix for establishing a successful earthen block project; and (iv) introducing special topics that the author believes deserve additional attention. The proposed testing matrix is applied to soil samples provided by two Native American communities (Crow and Ute Mountain Ute Tribes). Developing a systematic design approach and testing regime validates earthen building technology as a reliable option for providing low-cost housing.

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1. Introduction

The demand for sustainable building materials at low cost is growing as social, economic, and environmental issues evolve in today's society. Stabilized compressed earthen block (SCEB) technology offers an alternative to traditional building practices that is relatively inexpensive, uses local resources, and in some cases, has been found to last several millennia (ASTM E2392). Although earthen building is not a new concept, the documentation regarding best practices for SCEB production is limited or inconsistent. Often soils used in SCEB production are conveniently mined in proximity to the project site lending to a wide variety of soil types and properties from project to project. The uncertainty behind selecting a suitable soil for SCEB production presents the need for a systematic approach to implementing and guaranteeing a successful project. This report emphasizes the importance of standardization by: (i) providing a suggested best practice procedure for selecting suitable soils; (ii) developing a suite of material quality tests; and (iii) introducing adapted field testing procedures.

Throughout this report, SCEBs refer to blocks that are comprised of a mixture of angular sand aggregate (40-70%), clayey soil (30-60%), water (~10%), and Portland cement (5-6%). This predetermined soil mix is added to a block mold and pressed, either manually or hydraulically, to form a block. Due to the geographic locations of the case studies presented (Southern CO and Southern MT), Portland cement was added to stabilize the blocks which were used as samples for this report. The addition of cement is intended to minimize any swelling characteristics of the clayey soil and to reduce the amount of moisture that the blocks can retain, therefore reducing the effects of freeze/thaw cycles experienced in cold climates.

The testing methodology proposed in this report is intended to provide a systematic process of evaluating potential soils, by applying both geotechnical and structural engineering principles. Given the availability of a suitable soil, following the suggested guidelines and criteria will ultimately lead to a satisfactory SCEB. This report and included testing methodologies are intended to form the foundation on which a robust best practice standard can be developed. The author does not intend to suggest that all issues concerning earthen building are addressed directly or that the results achieved from the provided case studies can be directly extended to any soil other than the specified soils in the study. However, many of the fundamental concepts and procedures can be applied more broadly. Currently, the technical level of understanding is limited to the assumption that regardless of the exact soil composition of the mix in question, if the mix produces a high quality product then it is suitable given proper testing. The testing matrix proposed herein attempts to further define acceptance criteria and streamline the process required to initiate a SCEB building project.

Identifying the availability of a suitable soil or soil mix for use in SCEB production is the first step to starting a successful project. While many options are possible, the soils of interest in this report are referred to as clayey soils and well-graded sands. The soils are formally classified as per the United Soil Classification System (USCS). Documenting the soil classification in relation to its performance in SCEB production will hopefully lead to better understanding of this relationship. Current building codes offer no suggestions or guidelines for selecting a suitable soil based on classification. Identifying the optimal soil mix or recipe based on a selection of different soils must be defined to standardized building codes. Several factors are important; material availability, soil gradation, particle size/shape/angularity, optimal moisture content, presence of cohesive forces, and the ultimate performance of the block produced. Due to high regional variability, any combination of these factors will be encountered when investigating a potential soil mix. This variability is partly what motivates this thesis and the proposed SCEB material testing methodology.

The original intent of this thesis was to develop a step-by-step procedure for building with earth, but the need for a more dynamic, iterative approach was quickly realized. Through experience with different soils and a review of the available literature, the author anticipates that comprehensive studies and collaborative research in different locales will lead to a framework for standardizing earthen building technology.

Several Native American nations in the western United States have begun looking at compressed earth building technology as a sustainable technology with increased interest. Projects initiated by the Crow Tribe in Montana and the Ute Mountain Ute Tribe in Colorado have received funding from the Bureau of Indian Affairs (BIA) within the Division of Energy and Minerals Development (DEMD), and coordinated with research programs at the University of Colorado, Boulder. The Tribes are able to take advantage of the resources mined locally on their reservation, implement a successful building project, and provide housing and jobs for members of their community. In addition to the added housing brought in by these programs, the projects have the potential to stimulate the economic growth within the Tribes.

Earthen building techniques offer more than just a proven construction material. Because of their relatively low production cost, earthen block production can offer a variety of secondary benefits such as: (i) stimulating economic growth and create jobs in the local community; (ii) taking advantage of available renewable resources such as passive solar heating and geo-thermal heating; (iii) regulating indoor conditions such as humidity and air quality; and (iv) producing quality structures of which the builders and owners are proud. Changing demands regarding energy use, growing populations, and resource depletion will ultimately bring more attention to applying earthen building techniques in “modern society”. However, the process of implementing a successful, earthen building plan involves multiple disciplines including human resources, geologic constraints, mining, resource delivery and processing, access to a skilled labor force, quality control testing, approved building plans, etc. These and numerous other factors are an inherent challenge when applying earthen building technology.

Perhaps the most concerning issue regarding SCEB technology may be public acceptance in regions where earthen building is seen as inferior to more contemporary building materials, such as timber, concrete and steel. While several exceptions exist, earthen building techniques are typically limited to one story structures. In large cities, where often the most cost effective option is to build vertically, earthen building technology is highly restricted. Additionally, the percentages of the population living in earthen homes today tend to be among the poorest. Because of this, there exists a social stigma around living in an earthen structure in many developed communities. Earthen structures are viewed as being primitive, rodent infested, cold and damp (Minke, 2006). While these are just stereotypes, the building market strives to meet market demands dictated by the consumer. In this way, earthen building can be restrictive. As trends move more towards sustainable "green" technology, however, the interest in earthen building techniques will surely increase.

This thesis is intended to serve multiple purposes. First and foremost, it contributes to the current understanding of various key components related to earthen building technology. Test results reported by the author are made available to the research community for future examination, enhancing the industry's understanding of the SCEB material properties. Next, current soil testing and production methods are introduced and reviewed. The author supplies support for tests included in the proposed methodology and offers a critique of commonly misinterpreted test results. The author then proposes a methodology for testing soil properties identifying suitable soil mix ratios, manufacturing blocks, and subsequent standardization of material property tests. Detailed explanations of the various steps and evaluation criteria are presented in the form of a flow chart. Suggestions for efficient, on-site quality control tests are offered, including examples of experimental results. Soils from the Crow and Ute Mountain Ute Tribes were subjected to the author's evaluation, providing results and conclusions for material recommendations. Topics such as optimal water content, correlation analysis, aspect ratio effects, freeze/thaw durability testing, swelling properties, mortar joint properties, full-scale testing and on-site testing are highlighted.

2. Literature Review

Earthen building techniques are not new concepts and their application has been known for over 9,000 years (Keefe, 2005; Minke, 2006; ASTM E2392). Earthen structures throughout history are evident around the world. Several traditional options include: rammed earth, fired clay/mud, earthen blocks, adobe, etc. Structures including the Great Wall of China, the Temple of Ramses in Egypt, and the Sun Pyramid in Mexico are all founded on earthen building technology (Minke, 2006). Approximately 30-40% of the world's population currently resides in earthen structures and 25% does not have access to decent housing (Keefe, 2005; Auroville Earth Institute, [no date]). *Figure 2.*1 illustrates the regions of the world where earthen construction technology is utilized. Using soil as a building material is a practical alternative because it is: economical, proven to work when implemented correctly, more sustainable than many modern options, and often readily available when other materials are not.

Figure 2.1: World map showing zones where earthen construction is applied. Courtesy of Matthew Jelacic

2.1. SCEB Technology Advantages

The motivation of this thesis is the standardization of earth as an alternative building material. Concrete has grown into the most important building material over the last century and in industrialized nations the annual production amounts to 1.5-3 tons per capita (Glivand, Mathisen, Nielsen; 2005). The use of cement in the production of concrete contributes vastly to the construction industry's carbon footprint.

Cement production is responsible for 10% of global CO_2 emissions (Keefe, 2005). Aggregate is often created by mining, and crushing rock to the desired specifications. Building sites are rarely located within proximity to the mining sites, necessitating additional energy requirements to transport the materials. This process requires a huge amount of "embodied energy". Embodied energy is the sum of all the various processes involved to implement a material into production. Keefe (2005) offers an embodied energy consumption value for various building materials. "Concrete block" registers 600-800 kWh/m^3 and "Earth" registers 5-10 kWh/m^3, clearly indicating an advantage to earth building. The addition of cement triggers a chemical reaction which emits noticeable amounts of carbon dioxide into the atmosphere. One mass unit of cement generates approximately an equivalent mass unit of CO_2 emissions (Glivand, Mathisen, Nielsen; 2005).

To investigate additional advantages of SCEBs, current research is investigating the indoor climate regulating effects of structures built from earthen blocks. Minke (2006) presents data showing that earthen construction materials are able to absorb and desorb moisture more efficiently than any other building material, allowing them to regulate indoor climate. He suggests a range of 40-70% relative humidity as ideal for indoor environments and explains in detail how both high and low levels of relative humidity can lead to health related issues. Minke mentions a case study in Germany in which an earthen structure maintained an indoor humidity range of 45-55% for a five year period.

Morony (2004, 2005, and 2007) performed a series of experiments to support the hypothesis that earthen building techniques create structures which are warmer in the winter and cooler in the summer. Two modules of identical dimensions were constructed, one with earthen blocks (adobes) and one with cinderblocks (concrete masonry units). The flooring and roofs were of the same material. Temperature readings were recorded to investigate the thermal properties of the two materials. On a hot summer day in Del Rio, Texas the outdoor temperature was 98° F (no relative humidity data available). The temperature was 90° F in the earthen block module and 103° F in the cinderblock module. Not only did the earthen block module register an interior temperature below the ambient temperature, it also remained a dramatic 13° F cooler than the cinderblock module.

In his discussion, Morony (2004) classifies earthen blocks as a *Phase Change Material* – PCM, which takes advantage of moisture differentials and latent heat phenomena. Latent heat of condensation results in heat storage in a PCM when relative humidity is high. Excess water vapor is absorbed into the material and stored in the liquid phase, an endothermic reaction. Latent heat of vaporization results in heat being released from a PCM when relative humidity is low. Water stored in the material in the liquid phase is released as a vapor, an exothermic reaction. Morony explains that it is through this mechanism that the earthen block module was able to “lose” 8° F by way of latent heat of vaporization. The effect of a moisture differential prevents the traditional assignment of an R-value to earthen blocks in order to quantify their thermal properties.

2.2. SCEB Technology Disadvantages

A major disadvantage to earthen block technology is that soil is not a standardized building material. Strict material and building codes specify requirements for numerous building materials. Such codes are very limited in scope for earthen block construction. Natural geologic variability ensures that soil properties vary from site to site, requiring the preparation of the correct mix to also differ (Minke, 2006). This creates a difficult issue and supports the need to develop a systematic approach that addresses the various concerns related to earthen building.

The opportunity for material shrinkage and/or cracking is another disadvantage of SCEB technology. Understanding this behavior is crucially important and may indicate the need for soil amendments (Keefe, 2005). During its initial curing process, the block loses some of its initial moisture creating extra void space. The material may settle to eliminate the open spaces, which can often cause cracking. In addition, uncertainty exists regarding soil behavior when exposed to moisture and/or extreme temperatures throughout its lifetime. This is complicated by the fact that the moisture content of even a cured earthen block fluctuates with ambient conditions.

A definitive method for delineating between clay and silt particles, based on grain size, remains an area of debate in the geotechnical field. Defined as fine-grained soils, clay and silt are classified by their ability to pass a #200 sieve (0.075 mm mesh opening). Results from a hydrometer test, discussed in Chapter 3, are used by some systems to define the particle size range of 0.002 to 0.005 mm as the lower limit for silt and upper limit for clay (Craig, 2005; ASTM D422). However, as nearly every source cited acknowledges, clay particles are more correctly identified by their physical and chemical structure. Methods for accurately identifying the chemical composition of fine-grained soils involve highly sophisticated and expensive techniques, such as electron microscope or X-ray diffraction analysis (Coduto, 1999).

Determining the exact proportions of clay and silt in a soil sample may be of less importance than the behavior of the soil in response to changes in moisture content or the *plasticity* of the soil. Swedish scientist Albert Atterberg (1846-1916), developed a series of tests that were refined by Karl Terzaghi and Arthur Casagrande in the 1930s. The tests were designed to evaluate the relationship between a soil's moisture content and its consistency. Common in geotechnical engineering applications, these tests are known today as the Atterberg limits test. They define a soil's liquid and plastic limits. Explained in further detail in Chapter 3, the results from the Atterberg limit test provide information regarding a soil's plasticity and therefore knowledge of the clay content present. Unlike soils derived from silt, sand, or gravel, clay has experienced extensive chemical weathering and therefore its engineering properties and behavior are also both different from other soils (Coduto, 1999).

2.3. Standardization of Methods and Techniques

Many methods and techniques have been proposed in the literature for identifying suitable soils for SCEB production. A good portion of these methods are intended to be quick with easy field tests but require some experience and knowledge of similar soil materials. Several authors (Minke, 2006; Hallock, [no date]) suggest as preliminary investigation the following tests: the smell test, nibble test, wash test, cutting test, sedimentation (jar) test, ball drop test, cohesion (ribbon) test, etc. The results from these tests need to be interpreted carefully and are often difficult to quantify. The most efficient way to determine the suitability of a soil for blocks is to make and evaluate several sample blocks from an available source (McHenry, 1984). It is for this reason that the author has chosen to only mention these soil evaluation methods and not devote significant research time to verifying their legitimacy.

In particular, the "jar" test is often suggested to provide the proportions of sand, silt, and clay. While the test may be accurate for certain soils, it is not always correct to interpret the results directly. Statistical analysis performed at Texas A&M has shown wide variability in "jar" test results suggesting that many tests may be needed to be performed before a high level of confidence can be achieved (Graham and Burt, 2001). The interpretation of the jar "test" assumes that the strata layer heights correspond to the proportions of the soil's constituents. This assumption is not exact, as one can only distinguish between successive strata at sudden changes of grain-size distribution, which may not coincide with the actual defined limits between sand, silt and clay (Minke, 2006).

A proposed standard of care must involve a rigorous understanding of the mechanical properties of the construction materials intended for structural design (Craig, 2000). Material properties such as strength, stiffness, and ductility assist with design decisions determining load capacity, settlement, and deformation. An earthen block's primary function in a building application is to provide structural support for the walls themselves, as well as any expected dead and live loads. The block's strength in compression is of particular interest. Mechanically compacted cement-stabilized earthen blocks often achieve compressive strengths comparable to ordinary concrete (ASTM E2392).

Precaution should be taken when comparing testing methods for concrete versus compressed earth as a building material. Standards for testing concrete specify the specimens to be cylinders with a height to diameter ratio of 2:1 (ASTM C39). The author has found no code specifying the actual dimensions of a typical or ideal SCEB test specimen. The New Mexico Earthen Building Materials Code specifies that compressive testing is performed on a block in its flat position with the length measuring a minimum of twice the width (NMAC, 2009). The minimum compressive strength defined by this code is 300 psi. A major issue preventing the adaptation of the ASTM defined cylinder test is the preparation method of the cylinder itself. ASTM C192 specifies two methods for material consolidation (air removal) while preparing concrete test specimens: rodding and vibration. These two methods are not intended to compact the concrete. In the context of this report, soils used in SCEB production undergo high levels of compaction by means of a hydraulic press and ram. Variations in the preparation of test specimens negate any direct correlation between results achieved from concrete versus compressed earth.

The durability properties of stabilized compressed earthen blocks remain relatively un-documented and yet play an important role in the life-time analysis of the applied technology. The porous nature of earthen blocks allows them to “breathe”, or absorb and desorb moisture cyclically. While this behavior is beneficial for regulating indoor humidity levels, it can lead to degrading effects on the blocks themselves. The hygroscopic nature and high relative specific surface of clay particles present numerous opportunities for water to alter the physical characteristics of an earthen block. Typically, as clay absorbs water, the internal void spaces are inundated and the material swells or expands. Subsequently, as the material releases moisture, internal void spaces are created causing material consolidation or shrinkage. Numerous repetitions of this process can eventually lead to cracking and fracturing of the material. In climates where freezing temperatures are common, earthen blocks are even more susceptible to a decrease in performance. ASTM standards C666 and D560 have been proposed to standardize freeze/thaw durability testing procedures.

3. Testing Methodology

3.1. Introduction

This chapter outlines the author's proposed testing methodology for selecting a suitable soil, optimizing the soil mix, producing test blocks, and evaluating strength, deformability, and durability properties of the blocks. The methodology is a systematic series of procedures evaluating potential soils at every phase of production. Readily available potential soils are classified and then methodically evaluated through the sequence of tests illustrated in *Figure 3.1*. If, at any point during the process, the proposed soil or soil mixture does not satisfactorily satisfy the requirements, a step back is taken to reconsider further action through selection of a new soil or soil amendments.

3.2. Testing Methodology Flow Chart

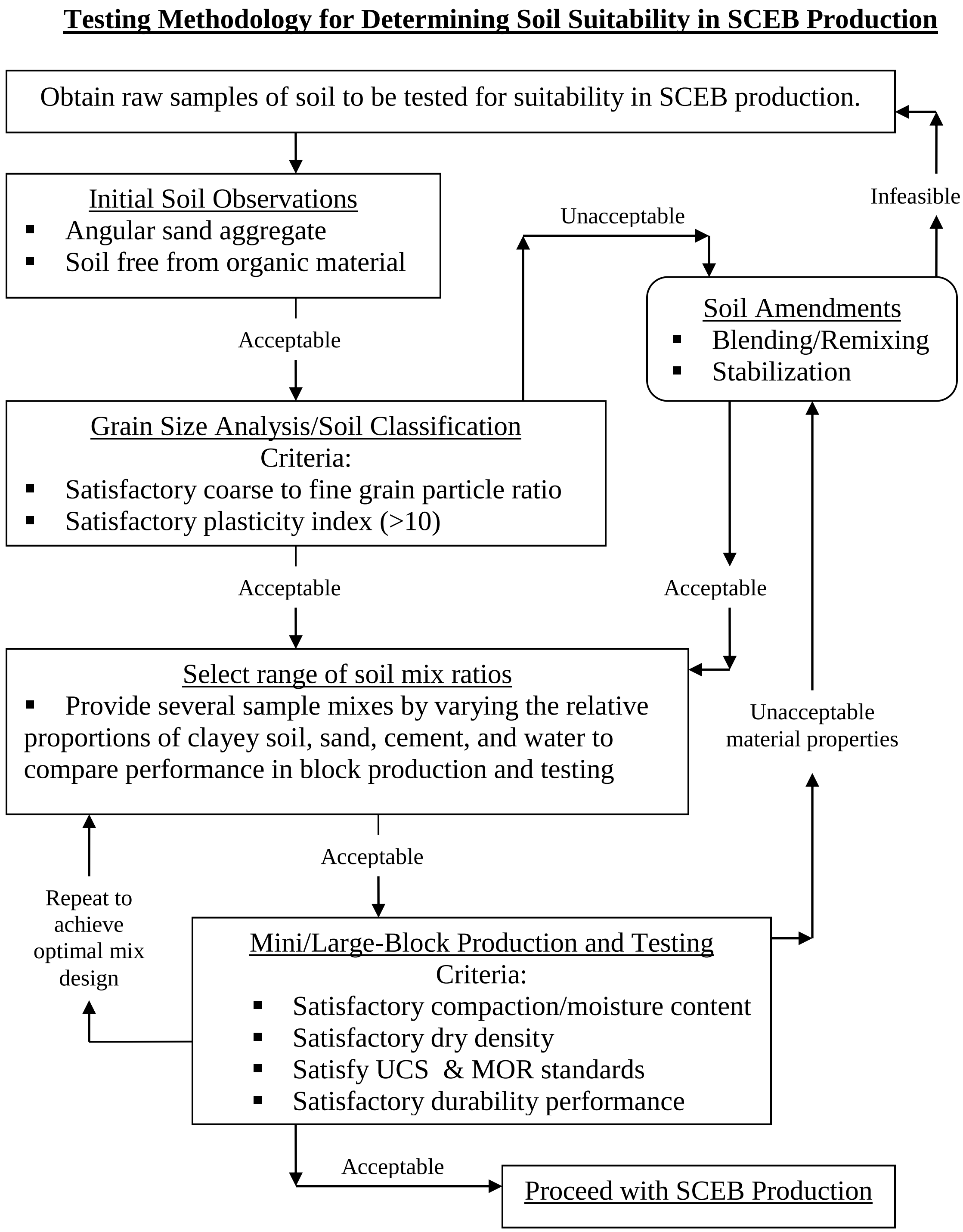

Figure 3.1: SCEB Testing Methodology

3.3. Initial Soil Observations

New soil samples undergo an initial visual inspection when received in the laboratory. The amount of organic material in the sample is observed and noted. The shape and angularity of the soil particles in the sample is observed and noted. The sample's in-situ moisture content is determined. Any irregularities or inconsistencies in the sample are also noted.

Presence of organic material should be of high concern when detected. Section 14.7.4.23 of the 2009 New Mexico Earthen Building Code addresses SCEB production directly (NMAC, 2009). In Section G, a mineral soil is specified, suggesting a material free from any organic constituent. Due to weaker strength and higher compressibility, organic soils containing roots, moss, sticks, leaves, etc. are not suitable for SCEB production (Coduto 1999). As the organic material breaks down, it is possible that it creates additional void space within the block, allowing for water seepage and augmenting freeze/thaw effects. Excessive organic material content may be the result of improper mining techniques, such as not removing enough of the top-layer of earth on-site.

The shape and angularity of the aggregate material (silt, sand and gravel) can vary from very angular to well-rounded. The more angular particles are, the more difficult it is for particles to move past each other when loaded. This effect creates a matrix of particles capable of increased shear strength and therefore better performance when subjected to loads (Coduto 1999).

The initial moisture content of the soil is determined. The moisture content is the ratio of water mass to solid (dry soil) mass. Samples are generally collected and transported sealed in airtight five gallon buckets to prevent moisture loss during transport. Samples that contain too much or too little natural water content will need to be amended before use in SCEB production.

3.4. Soil Classification

A grain size analysis is required to classify a soil. A proper classification will correctly identify a soil, thus providing insight to the soil's properties. Soils are tested and classified as per the Unified Soil Classification System – USCS (ASTM D2487). Clay and silt are commonly referred to as fine grained soils, while sand and clay are referred to as coarse grained soils. A sieve test (ASTM D422) is performed to determine the soil grain size distribution. For fine grained soils, a Liquid and Plastic limit tests (ASTM D4318) is carried out (also known as the Atterberg limit test). The Atterberg limit test provides a method for quantifying a soil's plasticity, providing information regarding the amount of clay present. Using the information obtained from the grain size distribution and Atterberg limit tests a soil classification is determined using the process provided by the USCS. Any soil found to contain organic material is unacceptable. The sand used for aggregate must have angular particle characteristics and its gradation must be compatible with that of the clayey soil to be used.

Current literature and applicable building codes do not offer guidelines for selecting an optimal soil for earthen construction based on the soil's USCS classification. The case studies presented in Chapter 4, offer some goals for optimal soil classifications. The sand aggregate used is ideally well-graded with a USCS classification of SW. The clayey soil used contains a significant amount of clay minerals with a USCS classification of CL. In addition, the clayey soil should achieve a plasticity index which is greater than 10. The definition of plasticity index is explained in Section 3.4.3. The author offers these guidelines based solely on the soils explored in the case studies herein. Sand aggregate and clayey soil that is not classified as SW and CL, respectively, can often be amended to achieve optimal characteristics.

3.4.1. Dry Soil Grain Size Analysis

For coarse grained soils, a grain size analysis is performed by shaking a raw soil sample in a Gilson Testing Screen Model TS-1 shown in *Figure 3.2*. Samples are first air-dried for several days to achieve maximum separation during sieving. The dry sieve analysis passes a dry soil through sieves of decreasing opening sizes and measures the gravitational amounts passing each sieve size. The amount passing each sieve is plotted against the sieve opening size and a best-fit grain size distribution curve is constructed. Samples are shaken for a minimum of 30 minutes or until desired separation has been achieved. The grain size analysis provides a way to classify the soils using a standard procedure (ASTM D 422 and ASTM D 2487). For SCEB application, fine grained soils are also tested in this manner in order to provide an understanding of the gradation of the coarse-grained particles present in the soil and also to provide information regarding the effort that would be needed to prepare the soil for SCEB production.

Figure 3.2: Gilson Testing Screen Model TS-1

3.4.2. Wet Sieve Analysis for Fines Content

Based on grain size, the USCS delineates the division between fine and coarse grained soils by determining the amount of soil that passes through a #200 sieve (particle diameter of 0.075 mm). For instance, if more than 50% of a soil sample passes through a #200 sieve, then the soil is referred to as fine grained. Due to the high levels of cohesion often present in clayey soils, it is difficult to accurately determine this information with the Gilson model soil shaker. A wet sieve procedure is performed on the soil sample to make this determination. Water is used to expedite the sieving process and the retained soil is dried and weighed to complete the test. It should be noted that this process does not give any information regarding the specific amount of clay or silt content in the soil. This process is illustrated in *Figures 3.3-3.6*.

Figure 3.3: #200 Sieve; Original Sample

Figure 3.4: #200 Sieve; Mixing with water

Figure 3.5: #200 Sieve; And more mixing

Figure 3.6: #200 Sieve; Retained soil

3.4.3. Atterberg Limit Tests

Silts and clay are similar in size, but are very different in their reaction to water. When water is added to clay, it exhibits plasticity by changing from a hard and rigid material to a soft and pliable one. On the other hand, silt is only slightly plastic and its properties are less dependent on the water content (Coduto, 1999). To aid in the classification of the soil samples, the Atterberg Limits test is used to determine the plastic limit, liquid limit, and the plasticity index of the soil (ASTM D4318).

Plasticity characterizes the ability of a soil to undergo unrecoverable deformation without cracking or crumbling (Craig 2005). The Plasticity Index, calculated as the difference between a soil sample's Liquid and Plastic limits, defines the range of moisture contents that a soil can remain in the plastic state and can therefore be used to infer the clay content. *Figure 3.7* compares a soil's plasticity index to its relative dry strength, visual-manual strength, and clay content.

CHARACTERISTICS OF SOILS WITH DIFFERENT PLASTICITY INDICES (Sowers, 1979)

Plasticity Index	Classification	Dry Strength	Visual-Manual ID of Dry Sample	
0-3	Nonplastic	Very Low	Falls apart easily	Increasing clay content --------->
3-15	Slightly Plastic	Slight	Easily crushed with fingers	
15-30	Medium Plastic	Medium	Difficult to crush with fingers	
>30	Highly Plastic	High	Impossible to crush with fingers	

Figure 3.7: Plasticity chart

3.4.4. Hydrometer Test

The Hydrometer test (ASTM D422) is used to determine the grain size distribution in soils containing particles sizes less than 75 μm (0.075 mm). The test takes advantage of Stoke's Law, which relates particle size to the rate at which particles settle in solution. A dispersing agent is used during the test to reduce particle interaction. The test can be used to approximate the ratio of silt to clay in a fine-grained soil sample. The range of particles from 0.06 mm to 0.002 mm is commonly classified as silt, while particles that are 0.002 mm and smaller are classified as clay (Coduto, 1999).

A dry soil sample is first sieved through a #200 sieve to obtain particles 0.075 mm and smaller. The sample is then mixed well with 40 g/L of sodium hexametaphosphate and then stored for 24 hours to achieve maximum particle dispersion. The hydrometer used is carefully calibrated to the sedimentation cylinder. The test is performed following ASTM-D422 as closely as possible and readings are taken after 1 min, 2 min, 4 min, 8 min, 16 min, 32 min, 60 min, 1 hr, 2 hrs, 4 hrs, 8 hrs, and 18 hrs. The percentage of the sample passing the 0.002 mm particle size criterion is interpolated using the provided test data.

3.5. Selection of Soil Mix Ratios

The soils to be used for SCEB production contain primarily angular sand, clay and silt. Larger aggregate particles such as gravel and rocks may also be present in the mined soil and are typically removed by screening. Soil samples vary widely from region to region and the composition of the samples from one site may also vary. This makes the selection of a proper soil mix a "trial by error" process. Ratios for SCEB production typically range from 20% to 40% clayey soil and 60% to 80% sand aggregate, but ratios outside of this range can also produce quality blocks.

The clay component provides the cohesion or binding forces necessary to hold the particles comprising the block together. Silt, sand and gravel particles supply the structural strength by combining to create a compact matrix with little void space. Unfortunately, the wet sieve test mentioned in Section 3.4.2 does not define the specific amount of both clay and silt present in a sample. The plasticity of the clayey soil in question can be approximated using the Atterberg Limits Test mentioned in Section 3.4.3, but these results are found to be highly variable. Therefore, it is necessary to test a wide range of soil mix proportions using the process suggested in this Testing Matrix. Suggested clayey soil to sand aggregate ratios include 1:4, 1:3.5, 1:3, 1:2.5, and 1:2.

A clayey soil is often mined and transported to the project site, where it is then processed and amended before block production. This process contributes significantly to project costs. Therefore, minimizing the amount of clayey soil needed has a high potential for minimizing costs. Determining an optimal soil mixture requires methodical specimen production and testing procedures, such as described in this thesis.

3.6. Mini-Block Production and Evaluation:

An Advanced Earthen Construction Technologies, Inc. (AECT) Small Block Press was purchased to perform testing on quarter-size (approximately 2.5” x 3.5” x 1”) compressed earth blocks (see *Figure 3.8 & 3.9*). AECT provided a document outlining a recommended method to produce quarter-size blocks for testing purposes with the purchase of the Small Block Press. In summary, a block mold is loosely filled with soil particles passing a #8 sieve. A hand operated hydraulic pump, connected to the mold frame through a hydraulic hose and cylinder, is used to gradually pressurize the cylinder to which in turn applies pressure to the soil in the mold. After the pressure is applied for a few seconds, it is released and the compressed earth block is extruded by exchanging the mold base for an ejection base.

During mini-block production a pressure of 1,200 psi was applied to the soil. This pressure is used to correspond with the applied pressure of the full-scale production machine.

Immediately after each mini-block is ejected from the Small Block Press, it is weighed and its height, length and width dimensions are measured. The bulk unit weight of each mini-block is calculated before and after the curing period to determine if a satisfactory level of compaction has been achieved. The blocks are carefully placed in a controlled environment at 75º F and 92.5% humidity and any shrinkage or cracking effects are noted before testing. Based on visual inspection of the mini-block specimens immediately after production and interpretation of the material tests mentioned in the following Sections 3.8, 3.9, & 3.10, an experienced evaluation of the soil mix's suitability can be made.

Figure 3.8: Loading small-block press with soil mixture

Figure 3.9: Soil block ejected from press

3.7. Large-Block Production and Evaluation

An Advanced Earthen Construction Technologies, Inc. (AECT) Compressed Earth Block Machine, Impact 2001A, was used to perform testing on full-size (approximately 6" x 12" x 3-4") compressed earth blocks (see *Figure 3.10 & 3.11*). In summary, a soil mixture is created with materials which pass a #4 sieve. An automated hydraulic pump, connected to a mold frame through a hydraulic hose and cylinder, is used to gradually pressurize the cylinder to which in turn applies pressure to the soil in the mold. After the pressure is applied for a few seconds, it is released and the SCEB is extruded by the machine to a conveyor belt for transfer to storage. During block production, the hydraulic cylinder in the Earth Block Machine is pressurized to 1,200 psi to 1,400 psi.

Immediately after each SCEB is ejected from the Earth Block Machine, it is weighed and its height, length and width dimensions are measured. This data is used to calculate bulk unit weights of the SCEBs, and thus immediately evaluate consistency. The blocks are carefully placed in a controlled environment at 75° F and 92.5% humidity and any shrinkage or cracking effects are noted before testing.

Figure 3.10: AECT Impact 2001A Machine

Figure 3.*11*: Soil blocks ejected from press

3.8. Unconfined Compressive Strength (UCS) Tests:

The purpose of a SCEB as a construction material is to provide the structural support required by the design loads anticipated on the building. These loads are created from the weight of the walls themselves, the weight of the roof structure and any other design loads (i.e. wind and snow). The compressive strength of the SCEBs used is the controlling parameter defining the allowable load capacity of the building walls, validating the proposed use of the UCS test.

A MTS machine at the University of Colorado at Boulder Structures Laboratory, equipped with either a 110 kip or a 1,000 kip load cell, was used to measure the unconfined compressive strength of the SCEBs. The testing standards specified in the New Mexico Earthen Building Materials Code Section J of 14.7.4.23 were followed as closely as possible. The strain rate used did not allow for the stress rate to surpass the rate given by the followed code.

Several building codes have established or adopted standards to define the minimum strengths that must be met by earthen masonry units intended for structural purposes. Section J of the New Mexico Earthen Building Materials Code defines an allowable compressed earthen block as one which exhibits a minimum unconfined compressive strength (UCS) value of 300 pounds per square inch (psi) when saturated and tested under certain procedures. Blocks that do not meet this requirement are unacceptable and the soil mix used during production should be amended or deemed infeasible as shown in the author's proposed testing methodology.

To calculate UCS:

$$UCS\,[psi] = \frac{P_f}{A}$$

$$P_f = Force\ at\ failure\ [lbs]$$
$$A = Cross-\mathrm{sec}tional\ area\ of\ top\ face\ of\ block\,[in^2]$$

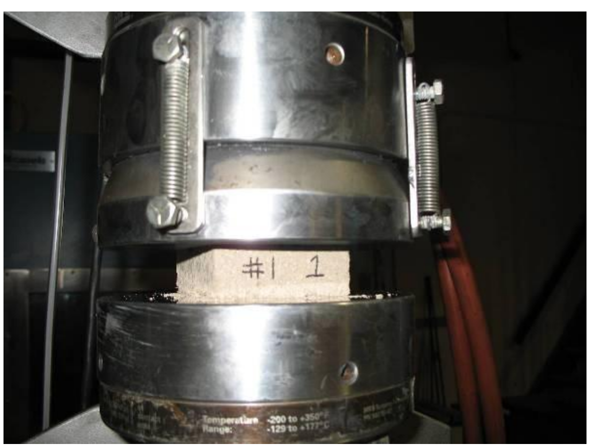

Figure 3.12: UCS Test Set-up

Figure 3.13: Block after UCS test

3.9. Modulus of Rupture: Three-Point Bending Test

SCEBs must be able to resist a certain amount of bending or flexural stress. Induced bending stresses could result from differential settlement of the foundation, point loads in the mortar, or other sources. The modulus of rupture (MOR) quantifies a SCEB's ability to resist bending stress. A modulus of rupture test is specified in Section K 14.7.4.23 of the New Mexico Earthen Building Materials Code which specifies a minimum strength of 50 psi. The procedure outlined in Section K was followed as closely as possible.

To determine flexural stress (σ_f):

$$MOR[psi] = \frac{3 \cdot P_f \cdot L}{2 \cdot b \cdot t^2}$$

P_f = *Force at failure* [*lbs*]
L = *Length of support span* [*in*]
b = *Width* [*in*]
t = *Thickness* [*in*]

Figure 3.14: 110-kip MTS Machine

Figure 3.15: MOR test set-up

3.10. Durability Testing

The durability of the blocks has been assessed at the University of Colorado by determining the effect of repeated wetting and drying on their unconfined compressive strength values. Repeated wetting and drying of the blocks can alter the soil structure and create concentrated weaknesses through cracking and the infiltration of water.

Typically, at least six blocks are tested for durability. A curing period of 28 days is allowed before testing. SCEBs are cured in a controlled environment (~92.5% relative humidity, ~72° F). The blocks are submerged in water for approximately 24 hours immediately prior to UCS testing. The procedure involves saturating all of the blocks, and subjecting a desired number of them to UCS testing. The remaining blocks are then allowed to lose moisture content over a minimum of two days. The saturation process is repeated for all of the blocks and the next set of blocks is subjected to UCS testing. This process is repeated for the remaining blocks. A minimum value of 300 psi block's UCS is required. During the saturation and drying cycles, each block is carefully examined for any observable cracking or degradation effects. *Figure 3.16* shows mini-blocks soaking in water and *Figure 3.17* shows the detrimental effects of several saturation cycles. Despite the fact that Section I 14.7.4.23 of the New Mexico Earthen Building Materials Code allows for shrinkage cracks provided that "these cracks do not jeopardize the structural integrity of the blocks", any observable cracking at this level of testing should cause concern and warrant amending the soil mixture used.

Figure 3.16: SCEBs soaking in water

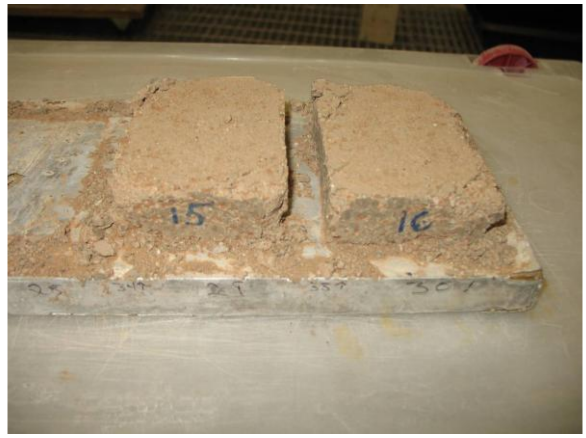

Figure 3.17: SCEBs after several saturation cycles

4. Case Studies

4.1. Crow Nation

4.1.1. Introduction

From April 18 to June 5, 2009, tests were performed on raw soil materials from the Crow Indian Reservation to evaluate their suitability and durability as stabilized compressed earth blocks (SCEBs). The soil samples originated from locations identified as the Amsden Formation and Dead Man's Curve (01 & 02). The purpose was to provide the Crow Nation with a recommended range of soil mixtures for block production. Raw soil materials were collected by Lynn Carpenter, Geologist, of the Division of Energy and Minerals Development (DEMD).

The goal of this testing was to classify the soils using the USCS classification system, produce test blocks, and evaluate their strength, deformability, and durability properties. The durability evaluation of the soil-cement mixes was performed by subjecting sample SCEBs to cumulative wetting and drying cycles and measuring their respective UCS values.

4.1.2. Testing Method

4.1.2.1. Soil Description

Three soil mixes from the Crow Indian Reservation were tested. For classification purposes, the clay samples were wet sieved through a #200 sieve (ASTM D422), subjected to an Atterberg Limit test (ASTM D4318) and a Hydrometer Test (ASTM D422). According to the Unified Soil Classification System (USCS), the Amsden Formation sample (Amsden) can be classified as a Clayey Sand (SC) and both samples from the Dead Man's Curve (DMC-01 & DMC-02) site can be classified as Sandy Lean Clays (CL). A small amount of root material was present in each sample.

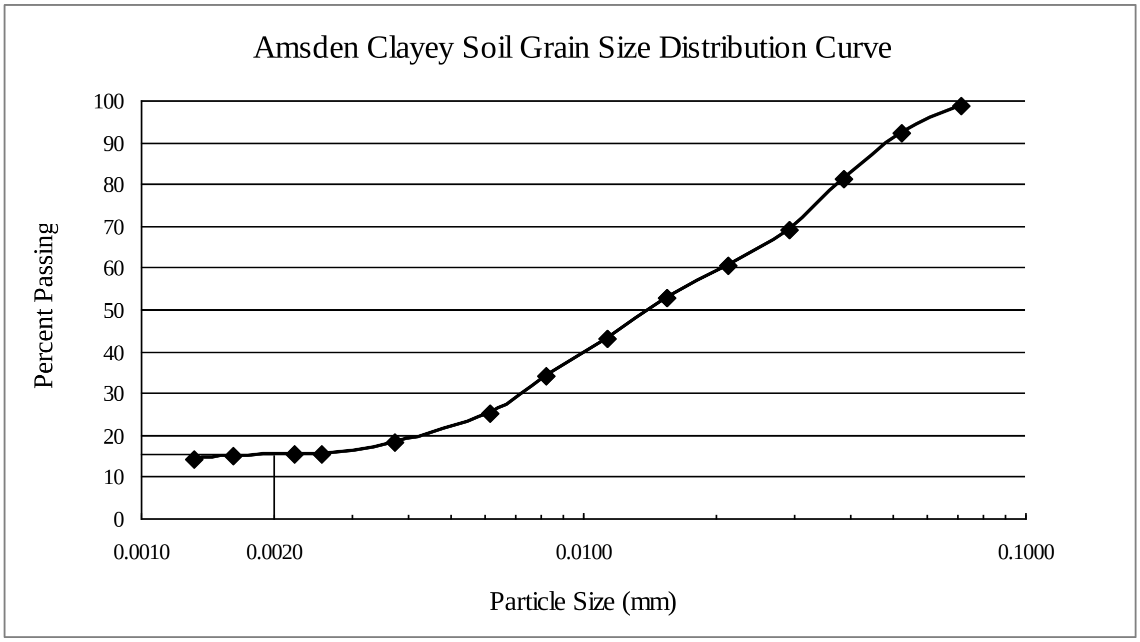

Figure 4.1: Amsden Soil Grain Size Distribution Curve

% Silt in Fine Fraction of Sample	84%
% Clay in Fine Fraction of Sample	16%

Table 4.1:

Soil properties and classification:

AMSDEN	
Percent Fines	41%
Plastic Limit	16
Liquid Limit	22
Plastictity Index	6
Liquidity Index	0.1
Classification Clayey sand (SC)	

DMC 01	
Percent Fines	55%
Plastic Limit	24
Liquid Limit	28
Plastictity Index	4
Liquidity Index	0.1
Classification Sandy lean clay (CL)	

DMC 02	
Percent Fines	76%
Plastic Limit	23
Liquid Limit	30
Plastictity Index	7
Liquidity Index	0.1
Classification Sandy lean clay (CL)	

Table 4.2: Clayey Soil Properties

The sand used in the soil mixes was material from Sand Pit 3, which was collected by Carpenter in July 2008. A dry sieve analysis, ranging from sieve #4 to #200, was performed on Sand Pit 3, as per ASTM Standard D422. The grain size distribution for Pit 3 is shown in *Figure 4.2*. From this analysis, the material in Pit 3 can be classified according to the USCS as poorly-graded sand with gravel (SP). The majority of the sand particles ranged in shape from sub-angular to sub-rounded while the gravel particles tended to exhibit mostly rounded to sub-rounded shapes, with a maximum particle diameter of approximately one inch. The fines in Sand Pit 3 consisted mostly of loose silt. The material in Sand Pit 3 appeared to be free of roots, rootlets, and other deleterious materials (Grunert 2009).

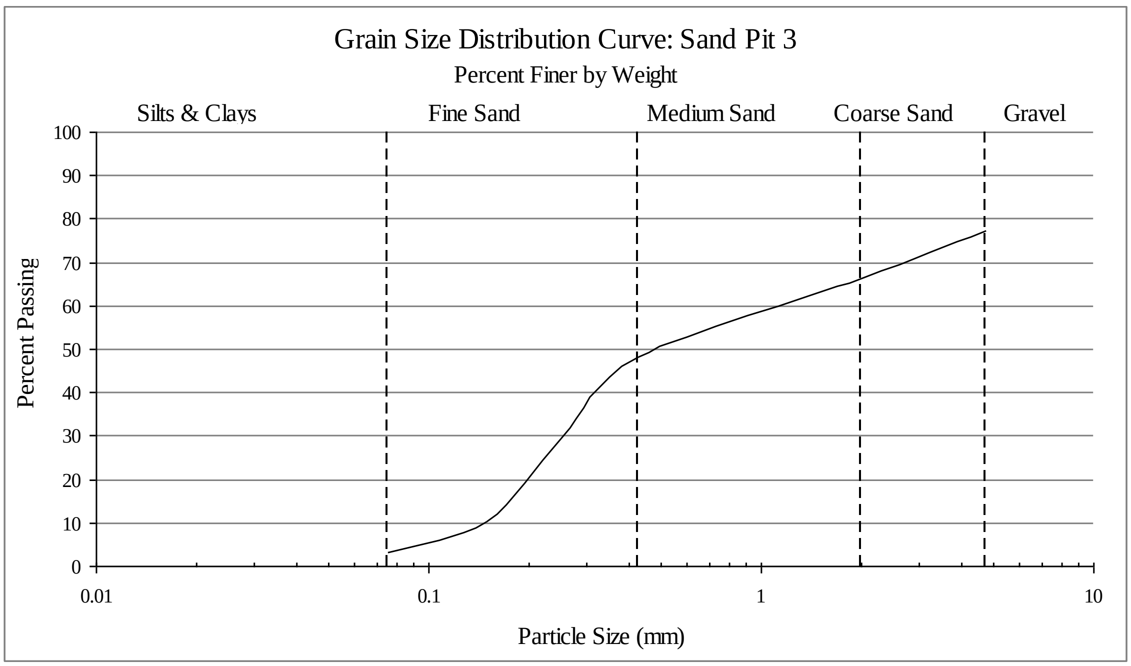

Figure 4.2: Sand Pit 3 Grain Size Distribution Curve

4.1.2.2. Preparation of Soil Mixtures

For each of the clayey soils being tested, two different mixes were used in order to compare the results. All root material was removed by hand. The sand used was taken from Sand Pit 3 and only particles finer than 1/8" were included. To be considered fully stabilized by New Mexico Code standards, 6% Portland Cement Type I/II, by weight, was used in each mix. Suitable water contents were estimated for each mix based on previous experience, visual inspection, and soil workability. The dry material from Sand Pit 3 was screened through a #8 sieve as per specifications for the Advanced Earthen Construction Technologies Small Block Press (AECT).

Table 4.3 summarizes the soil-cement mixes used in this study (by mass and volume). In the table below and throughout the study, the following labeling system is used: 'Amsden 25%' means that the mix contained, gravimetrically, 25% dry Amsden soil and 75% dry sand. Similarly, 'DMC 02 40%' means that the mix contained, gravimetrically, 40% dry Dead Man's Curve Sample 02 soil and 60% dry sand. In *Table 4.3*, the cement and water contents are with respect to the dry soil mass, and the combined wet clay and dry sand volume.

Mass						
Clay Sample	Dry Clay	In-situ Clay	Dry Sand	Cement	Added Water	Total Water
Amsden 25%	25%	28%	75%	6%	4%	7%
Amsden 35%	35%	38%	65%	6%	4%	7%
DMC 01 30%	30%	34%	70%	6%	4%	8%
DMC 01 40%	40%	44%	60%	6%	2%	6%
DMC 02 25%	25%	29%	75%	6%	4%	8%
DMC 02 40%	40%	45%	60%	6%	2%	7%
Volume						
Clay Sample	Dry Clay	In-situ Clay	Dry Sand	Cement	Added Water	Total Water
Amsden 25%	N/A	32%	68%	6%	5%	N/A
Amsden 35%	N/A	44%	56%	6%	5%	N/A
DMC 01 30%	N/A	40%	60%	4%	5%	N/A
DMC 01 40%	N/A	51%	49%	4%	2%	N/A
DMC 02 25%	N/A	35%	65%	6%	5%	N/A
DMC 02 40%	N/A	51%	49%	4%	2%	N/A

Table 4.3: Soil Mixtures Used by Mass and Volume

4.1.2.3. Test Block Production

Immediately after each SCEB specimen was ejected from the Small Block Press, its mass and dimensions were measured. The data were recorded and used to calculate each specimen's bulk unit weight. Typical unit weights of the SCEBs were measured to be approximately 127 pounds per cubic foot (pcf), with a minimum value of 125.8 pcf and a maximum of 127.6 pcf. This corresponds to a full size block weighing approximately 40 to 45 pounds. A full listing of bulk unit weights and other block specifications can be found in Appendix 8.2.1.

For each ratio, ten SCEBs were produced. None of the SCEBs appeared to exhibit significant imperfections after ejection from the Small Block Press. Four were tested during the 28 day curing period at weekly intervals, leaving six blocks available for the durability tests. The compression tests were performed over a 6 week period (4 weeks of curing and 2 weeks for the durability tests).

4.1.2.4. UCS Testing

An Instron materials testing machine available in the Integrated Teaching and Learning Laboratory at CU Boulder and equipped with a 50 kN (11.2 kips) load cell, was used to measure the unconfined compressive strength of the SCEBs. The New Mexico Earthen Building Materials Code testing standards were followed as closely as possible. The dimensions given for full-size SCEBs were adjusted to accommodate the quarter-size blocks. A controlled strain rate of 0.0003 in/sec was used rather than a controlled stress rate. The strain rate used did not allow for the stress rate to surpass the rate given by the followed code.

The SCEBs tested for durability were allowed to cure in a controlled environment (~92.5% relative humidity, ~72^{o} F) for 28 days before any durability strength testing began. This was to allow the cement strength to fully develop thus allowing measured strength values to be independent of cement strength changes. Tests were performed at one week intervals during the initial 28 days to determine any variation in strength. The blocks used for the durability tests were also kept in the controlled environment throughout the process.

The New Mexico Code requires SCEBs to be tested for unconfined compressive strength immediately after becoming completely saturated; the code defines complete saturation as a full-size block being fully submerged in water for 4 hours. Because of the smaller size of the test blocks, the SCEBs were submerged for 1.5 hours immediately before testing. Because the aim of the study was to assess both suitability and durability, SCEBs from each group were exposed to various numbers of saturations; four SCEBs from each mixture were saturated only once, at approximately 7, 14, 21, and 28 days following manufacture, while each of the remaining six SCEBs was saturated between one and six times. For example, the tenth SCEB of each soil mix ratio experienced six saturations; these specimens were allowed to cure in the controlled environment for 28 days. On the 29th day, they were each saturated for the first time. After the first saturation, the specimens were removed from the water and returned to the controlled environment for a minimum of two days, when the second saturation took place (i.e. the 31st day). This pattern continued for five saturations; after the sixth saturation, the specimens were immediately tested for unconfined compressive strength. A similar cycle, with varying numbers of saturations, was experienced by all of the durability-tested specimens.

For the unconfined compression tests, each SCEB was placed between two approximately 6-inch diameter metal plates in the flat position. The upper plate underwent a controlled downward displacement at a rate of 0.015 millimeters per second.

This rate was maintained until failure occurred, as evidenced by the stress-strain curve output from the Instron machine. Failure was defined as the ultimate stress achieved by compressed earth blocks behaving in a brittle manner.

4.1.3. Results

Displayed below are the results of the Unconfined Compression Strength durability tests. *Figures 4.3 - 4.5* show the UCS values of the blocks taken at one week intervals during the initial four week curing phase. One can see that after seven days the SCEBs have reached nearly full strength. *Figures 4.6 – 4.8* show the UCS values of the blocks after each saturation cycle. These results did not show an obvious trend of decreasing strength with repeated saturation cycles. To address the issue of scale effects, a corrected unconfined compressive strength was calculated based on the analysis performed in Chapter 5, Section 5.2.2.1. The mini-blocks tested had an aspect ratio of approximately 0.4. The UCS values are corrected for a specimen with an aspect ratio of 2. In nearly every case, the soil mix with a higher proportion of clayey soil was superior. *Figure 4.9* shows a typical example of deterioration of a SCEB made from 25% Amsden clay by mass after five wetting/drying cycles.

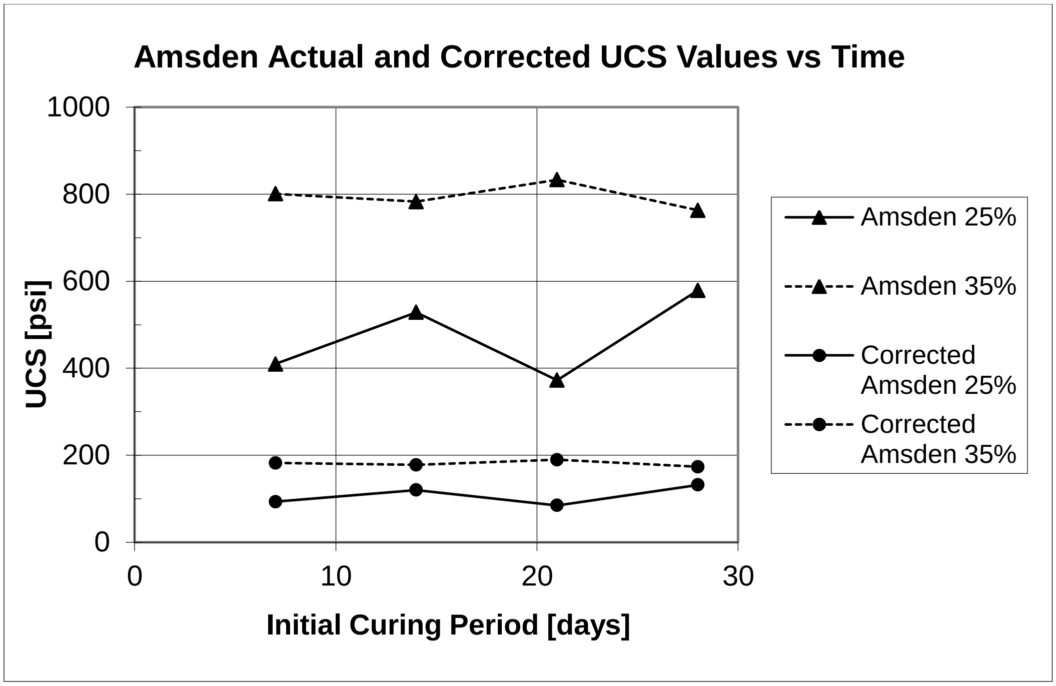

Figure 4.3: Amsden UCS values during curing phase

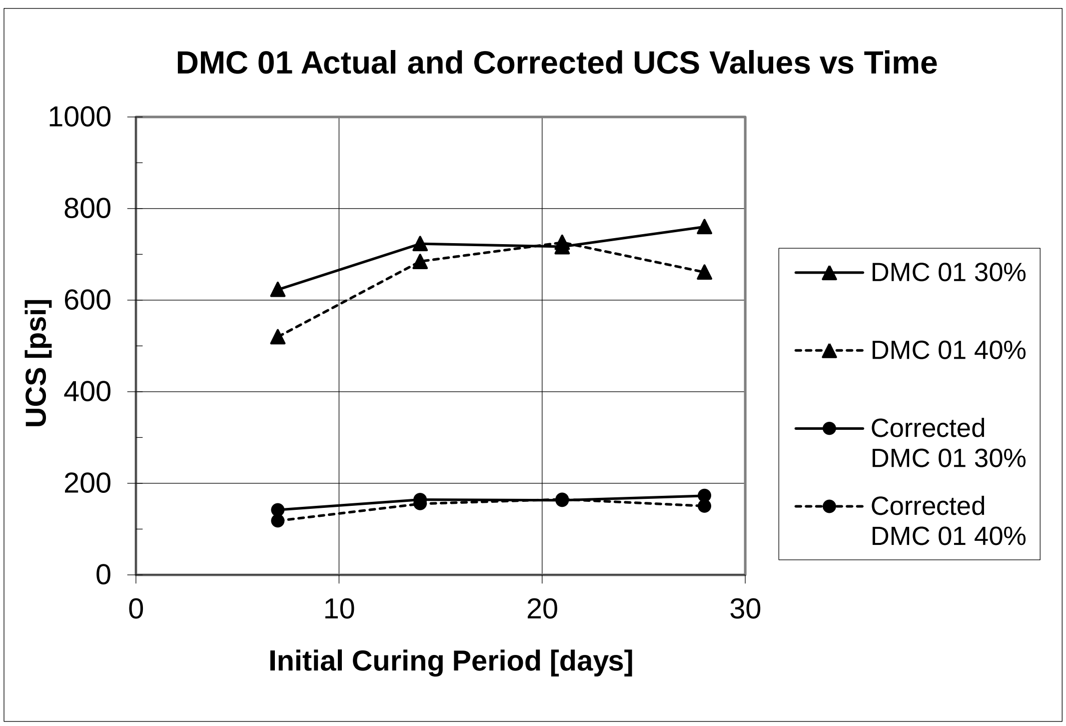

Figure 4.4: DMC 01 UCS values during curing phase

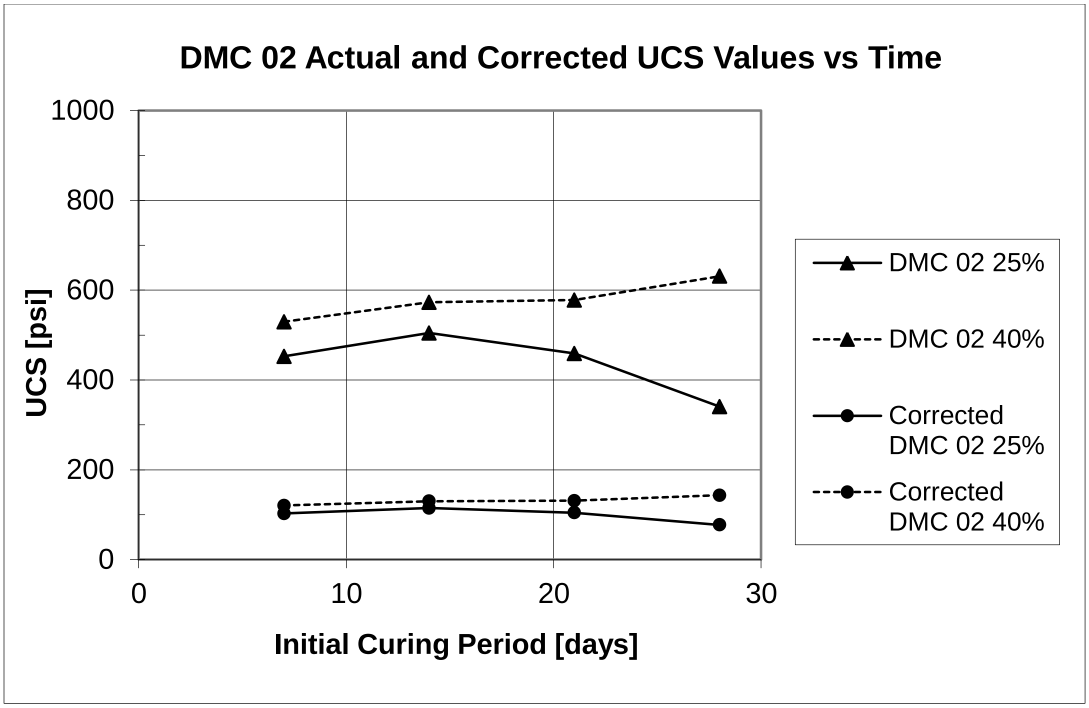

Figure 4.5: DMC 02 UCS values during curing phase

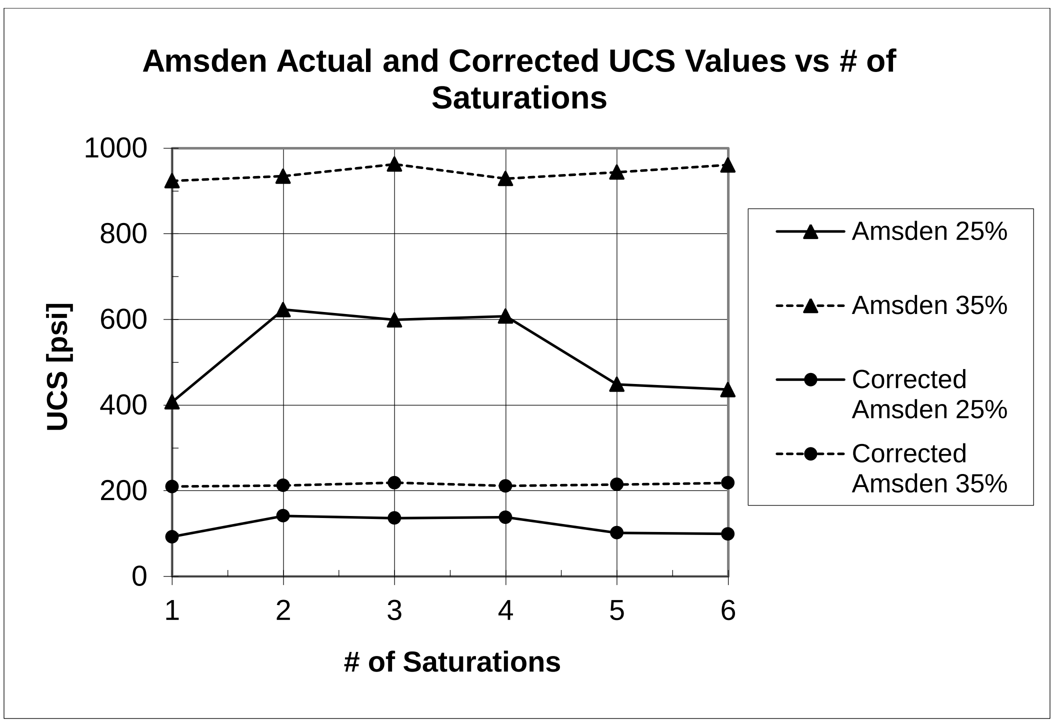

Figure 4.6: Amsden UCS values after saturation cycles

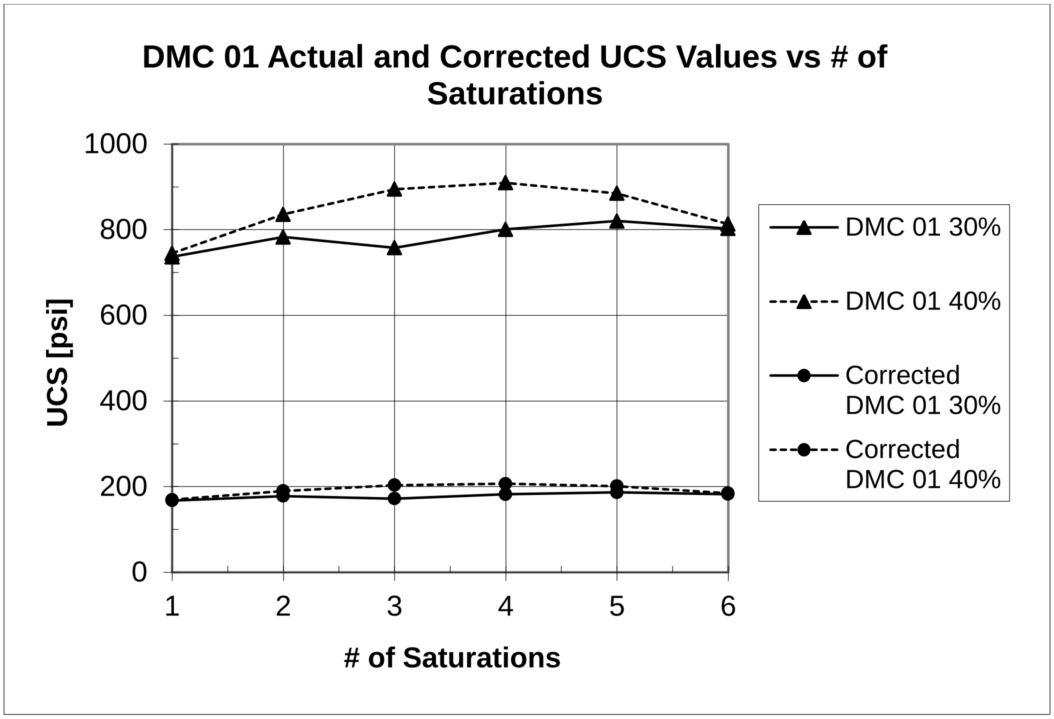

Figure 4.7: DMC 01 UCS values after saturation cycles

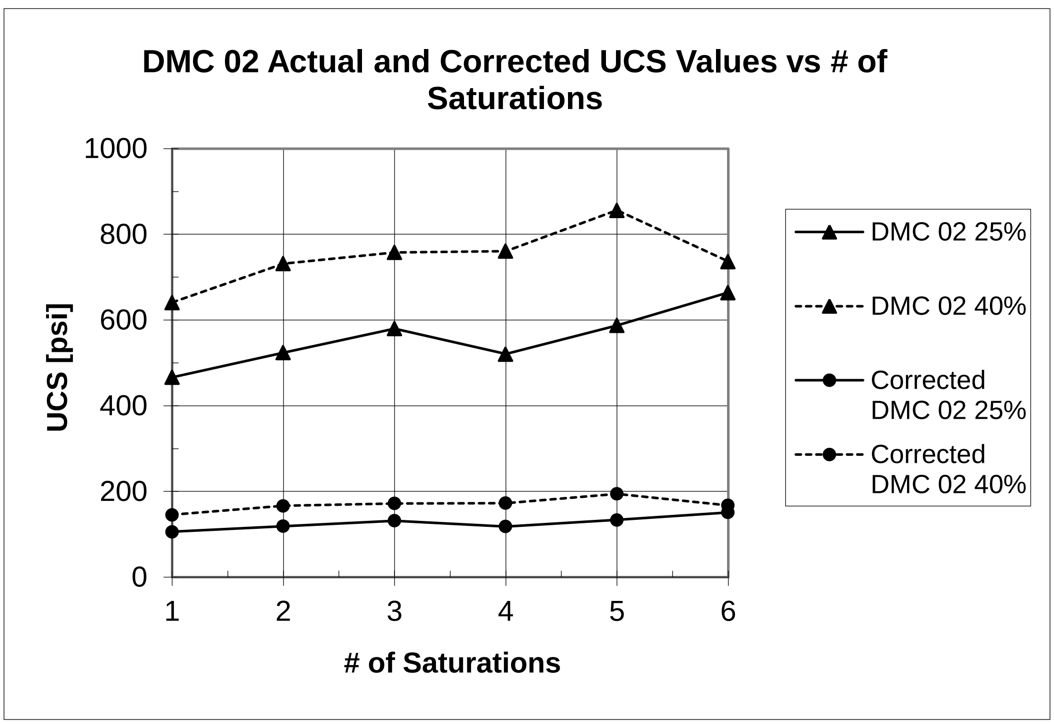

Figure 4.8: DMC 02 UCS values after saturation cycles

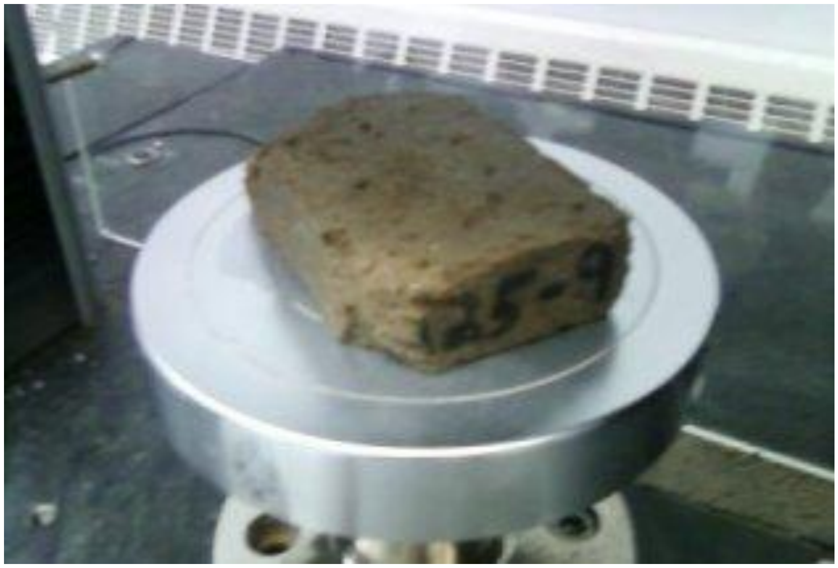

Figure 4.9: Deterioration of an ‘Amsden 25%’ SCEB after five saturations

4.1.4. Discussion of Test Results

Based on the aforementioned results, all three soil samples (Amsden, DMC 01, and DMC 02), were found to be suitable for the production of SCEBs. All of the SCEB’s UCS results were satisfactory for both strength and durability when compared to the New Mexico Building Materials Code recommended value of 300 psi. The results indicate that the Amsden soil performed the best despite containing a slightly lower percentage of fine grained material. It is likely that the Amsden soil contains less silt relative to the other samples. After five saturations, however, UCS values for Amsden 35%, DMC 01 40% and DMC 02 40% differed by less than 100 psi, thus making any of these soil mixtures suitable. Each soil mixture exhibited a higher UCS when a larger amount of fine grained material was used in the mix; therefore, it is recommended that at least 40% of the dry soil weight be comprised of the Amsden, DMC 01, or DMC 02 soils.

It is recommended that the following soil mix ratios (by volume) be used:

<u>Amsden Formation</u>:

Upper Limit: 1 part cement, 2 parts water, 10 parts clay, 10 parts sand

Lower Limit: 1 part cement, 1 part water, 20 parts clay, 20 parts sand

Dead Man's Curve (Samples 01 & 02):

Upper Limit: 1 part cement, 1 parts water, 10 parts clay, 10 parts sand

Lower Limit: 1 part cement, 1 part water, 20 parts clay, 20 parts sand

These ratios assume that the clay used is highly disturbed and moist. Additional water may need to be added if the clay is dry, as compared to the water contents listed in *Table 4.3*. If the cement to be used is relatively loose, rather than densely packed into a bag (i.e. as purchased at a local hardware store), it is imperative that the cement content be either doubled or tripled from the ratios recommended above. As always, organic material, such as roots, should be removed prior to the manufacturing of SCEBs.

4.2. Ute Mountain Ute Tribe

4.2.1. Introduction

The purpose of the tests was to evaluate the suitability and durability of the soil materials in question for use in stabilized compressed earthen block (SCEB) production. The New Mexico Earthen Building Materials Code and ASTM Codes were followed as closely as possible when applicable. The results from wet sieve analysis, Atterberg limit tests, and Hydrometer tests were used to determine the USCS soil classification for each soil sample. Model-sized blocks were made using each soil sample and tested in compression to determine their unconfined compressive strength (UCS). The durability behavior of the model-sized blocks was assessed by testing under uniaxial compression blocks subjected to a series of saturation/drying cycles. Full-scale SCEB blocks were produced and tested to determine their physical, deformability, and strength properties. Portland cement was used to stabilize all blocks. The addition of cement was intended to reduce the amount of moisture that the blocks could retain and subsequently reduce the effects of freeze/thaw cycles.

4.2.2. Test Method

4.2.2.1. Soil Description

Samples #11 & #15 were received at the University of Colorado with an initial moisture content of 8-10% and 10-12%, respectively. Both samples contained very little detritus such as roots or other organic material. After passing a substantial amount of each soil through a #4 sieve, the results revealed that both soil samples contained less than 10% gravel. It was observed that the largest particle size in the soil samples was no more than one inch. The small amount of waste material present in the soil is beneficial and will reduce processing costs.

The results from a wet sieve analyses, Atterberg limit tests, and Hydrometer tests are shown in *Table 4.4* through *Table 4.9* and *Figures 4.10 - 4.12*.

Soil #11:

Wet Sieve Analysis Results:

Soil #11: #200 Wet Sieve Results

Total sample dry weight [g]	Amt. of sample retained by #200 [g]	Amt. of sample passing #200 [g]	% passing #200
875.55	177.08	698.47	79.8%

Table 4.4

Atterberg Limits Results:

Sample #11 Atterberg Limits Results

Plastic Limit	15
Liquid Limit	30
Plasticity Index = LL – PL	15

Table 4.5

Hydrometer Analysis Results:

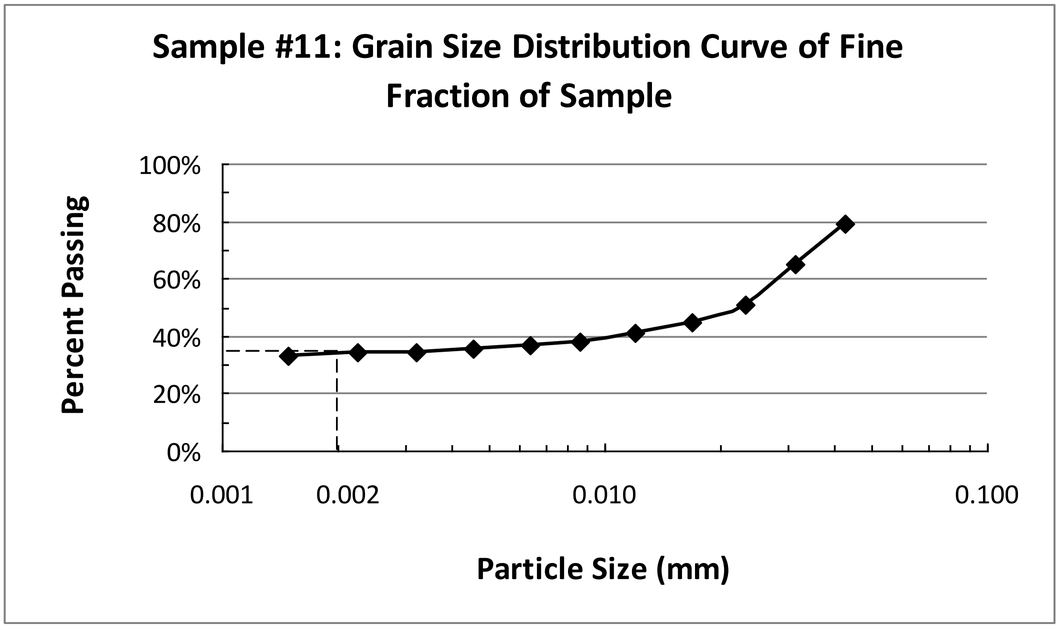

Figure 4.10: Sample #11 Grain Size Distribution Curve

Sample #11: Hydrometer Results

% Silt in Fine Fraction of Sample	66%
% Clay in Fine Fraction of Sample	34%

Table 4.6

Soil #15:

Wet Sieve Analysis Results:

Soil #15: #200 Wet Sieve Results

Total sample dry weight [g]	Amt. of sample retained by #200 [g]	Amt. of sample passing #200 [g]	% passing #200
803.93	174.39	629.54	78.3%

Table 4.7

Atterberg Limits Results:

Sample #15 Atterberg Limits Results

Plastic Limit	14
Liquid Limit	27
Plasticity Index = LL – PL	13

Table 4.8

Hydrometer Analysis Results:

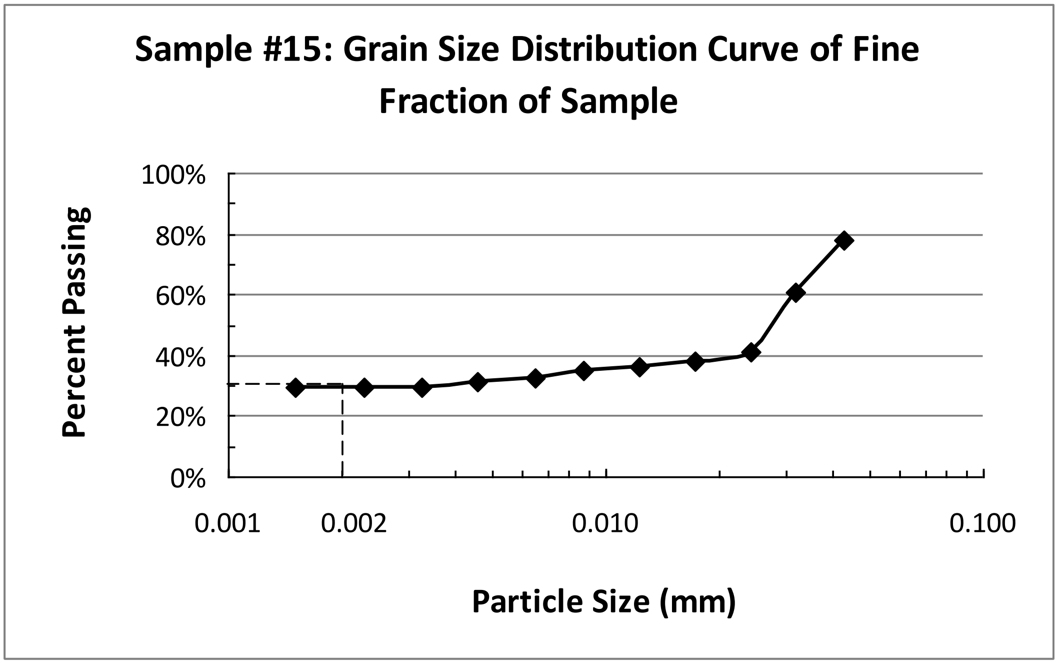

Figure 4.11: Sample #15 Grain Size Distribution Curve

Sample #15: Hydrometer Results

% Silt in Fine Fraction of Sample	70%
% Clay in Fine Fraction of Sample	30%

Table 4.9

Based on the results from the wet sieve analysis and Atterberg limit tests, both soil Samples #11 & #15 can be classified as CL (lean clay with low plasticity) using the USCS method adapted from ASTM D2487 (see Appendix 8.1 for applicable charts). Samples #11 & #15 were found to have plasticity indices of 15 and 13, respectively. *Figure 3.7* suggests that these samples range from slightly plastic to medium plastic indicating a low to medium clay content.

The Hydrometer test results show that the fine grained portion (amount of soil to pass a #200 sieve) of Samples #11 & #15 contain 34% and 30% of clay, respectively. It is noteworthy that this test only measures the silt/clay ratio for the fine grained portion of the sample and not the entire soil sample itself. The cohesive nature of clay supplies the binding forces between particles in the soil mix matrix. While a higher percentage of clay would imply more cohesion and therefore a stronger SCEB, the silt portion also contributes to the range of particle sizes in the soil mix. The silt particles may increase the overall density of the SCEB, enhancing its performance. This topic needs to be researched further, before a definitive conclusion can be made regarding an ideal silt/clay ratio for a suitable soil in SCEB production.

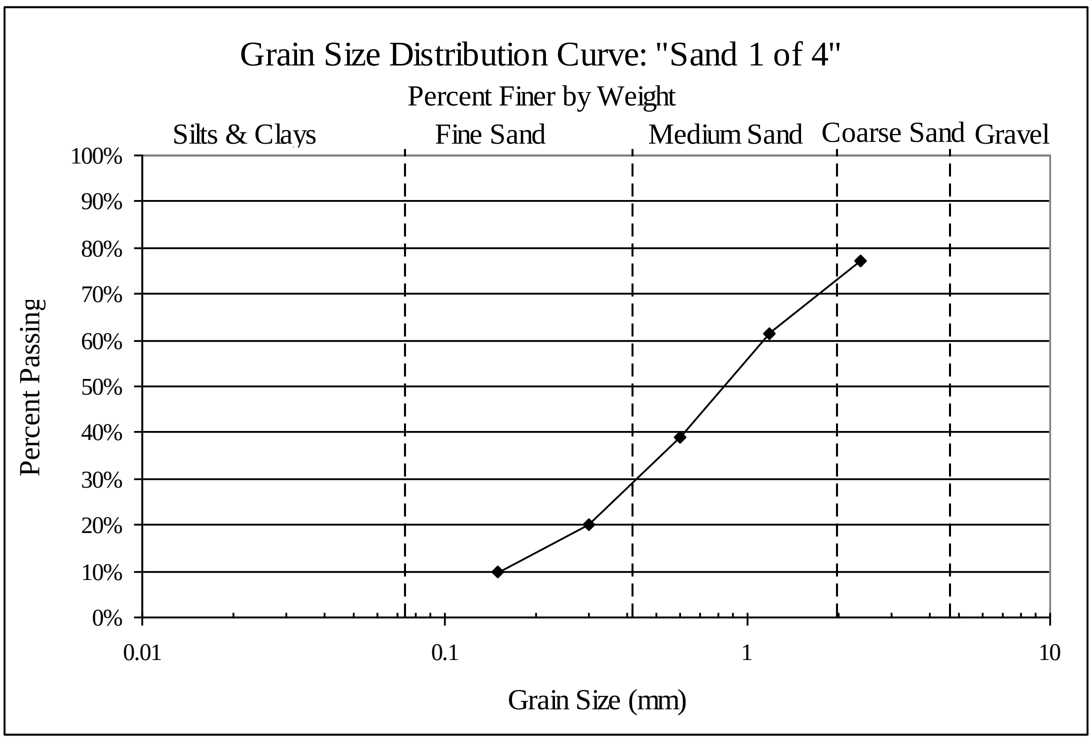

Figure 4.12: “Sand 1 of 4” Grain Size Distribution Curve

4.2.2.2. Preparation of Soil Mixtures

To illustrate the effects of varying the soil mix ratio on unconfined compressive strength, model-size (2.5” x 3.5” x 1”) SCEBs were produced. UMU soil Sample #11 was used to produce mini-blocks in accordance with the procedure described in Section 3.6. Four soil mixes with clayey soil to sand ratios varying from 1:2.5 to 1:4, were used to produce the mini-blocks tested for this analysis. The exact proportions are displayed in *Table 4.10*.

Soil Mix Ratio 1:2.5

Material	Mass	% Mass
Sand [g]	2,000.2	67.4%
Clay [g]	800	26.9%
Cement [g]	168.6	5.7%
Water [g]	273.7	8.4%

Soil Mix Ratio 1:3

Material	Mass	% Mass
Sand [g]	2,100.9	70.8%
Clay [g]	700.6	23.6%
Cement [g]	168.7	5.7%
Water [g]	274.5	8.5%

Soil Mix Ratio 1:3.5

Material	Mass	% Mass
Sand [g]	2,177.1	73.3%
Clay [g]	622.8	21.0%
Cement [g]	168.4	5.7%
Water [g]	274.1	8.5%

Soil Mix Ratio 1:4

Material	Mass	% Mass
Sand [g]	2,240.0	75.5%
Clay [g]	560.0	18.9%
Cement [g]	168.4	5.7%
Water [g]	274.2	8.5%

Table 4.10

Mini-blocks were produced in accordance with the detailed description in Section 3.6 for durability testing. The exact composition of the soil mixes used in mini-block production is shown in *Tables 4.11 & 4.12*.

Soil #11:

Soil mix used for mini-block production:

Soil #11Mini-Block Composition

Material	Mass	% Mass
Sand [g]	4201	64.6%
Clay [g]	1400.7	21.5%
Cement [g]	336.6	5.2%
Water [g]	569.1	8.7%

Table 4.11

Soil #15:

Soil mix used for mini-block production:

Soil #15 Mini-Block Composition

Material	Mass	% Mass
Sand [g]	4200.2	64.2%
Clay [g]	1400.0	21.4%
Cement [g]	336.0	5.1%
Water [g]	606.7	9.3%

Table 4.12

Large blocks were produced from two soil mixtures to compare their compressive and flexural strengths. The soil mixes were amended with approximately 6% Portland cement for stabilization. Exact material quantities are reported in *Tables 4.13 & 4.14*. The "% Mass of Total Dry Soil Mix" was calculated to show the amount of each individual material in relation to the total mass of the dry soil mixture. After the dry materials were thoroughly mixed, water was added to reach a target range of 10-12% water content. A sample from each soil mixture was taken during block production to determine the actual water content which is reported in *Tables 4.13 & 4.14*.

Soil #11: 1:3 Large-Block Composition

Material	Dry Mass [lb]	% Mass of Total Dry Soil Mix
Sand	383.1	70.8%
Clayey Soil	127.7	23.6%
Cement	30.6	5.7%
Water Content		11.3%

Soil #15: 1:3 Large-Block Composition

Material	Dry Mass [lb]	% Mass of Total Dry Soil Mix
Sand	279.0	70.8%
Clayey Soil	93.0	23.6%
Cement	22.3	5.7%
Water Content		10.0%

Table 4.13

Soil #11: 1:1 Large-Block Composition

Material	Dry Mass [lb]	% Mass of Total Dry Soil Mix
Sand	187.1	47.2%
Clayey Soil	187.1	47.2%
Cement	22.5	5.7%
Water Content		12.8%

Soil #15: 1:1 Large-Block Composition

Material	Dry Mass [lb]	% Mass of Total Dry Soil Mix
Sand	172.7	47.2%
Clayey Soil	172.7	47.2%
Cement	20.7	5.7%
Water Content		12.5%

Table 4.14

4.2.2.3. Test Block Production

The mini-blocks made from the soil mixes displayed in *Table 4.11 & 4.12* ejected cleanly from the AECT Small Block Press and were immediately placed in a controlled environment after recording their initial weight and dimensions. The mini-blocks were observed 2-3 times per week during the initial 4 week curing period. No effects due to shrinking/swelling, such as cracking, were observed. Dry densities of the mini-blocks ranged from 120-125 pcf, which is satisfactory. Additional observations related to the mini-block's initial production, such as smooth sides and strong corner integrity, reinforced the author's confidence in the quality of the mini-blocks.

The following series of photos displayed in *Figure 4.13 & 4.14* were taken of the mini-blocks after production.

Figure 4.13: UMU Mini-Blocks

Figure 4.14: UMU Mini-Blocks

An Advanced Earthen Construction Technologies, Inc. (AECT) Compressed Earth Block Machine, Impact 2001A, was used to produce full-size (6" x 12" x ~3.5") compressed earth blocks. In summary, a soil mixture consisting of materials, which pass a #4 sieve, is loaded into the machine. An automated hydraulic pump, connected to a mold frame through a hydraulic hose and cylinder, is used to gradually pressurize the cylinder to which in turn applies pressure to the soil in the mold. After the pressure is applied for a few seconds, it is released and a SCEB block is extruded by the machine to a conveyor belt for transfer to storage. During block production, the hydraulic cylinder in the Earth Block Machine is pressurized to 1,200-1,400 psi.

The large blocks produced were kept undisturbed in a controlled environment during the curing phase. The blocks were observed 2-3 times per week during this time. No detrimental effects due to shrinking/swelling, such as cracking, were observed. The following photos displayed in *Figures 4.15 & 4.16* were taken of the blocks made from Soil #11 after production.

Figure 4.15: UMU Large Blocks

Figure 4.16: UMU Large Blocks

4.2.2.4. UCS and MOR Testing

The large blocks were tested after a 28-day minimum curing period. A 110 kip capacity MTS load frame was used to perform the necessary compression and three-point bending tests. The test set-up used for each test is displayed in Section 3.9 (*Figures 3.13 & 3.14*). The load applied at the block's yield point was recorded as the force at failure. The force and displacement data recorded by the MTS machine were used to develop stress-strain curves (see *Figure 4.17* as an example). Given the fundamental assumptions of traditional mechanical properties of materials theory (i.e. the sampled material is a homogenous, isotropic, linearly elastic material), the slope of the linear portion of each stress-strain curve represents the block's Young's Modulus – E (Modulus of Elasticity). The Young's Modulus is often used in design calculations to estimate a wall unit's expected deflections or the unit's deformability. The average dry density (ambient conditions), UCS, MOR, and Young's Modulus values for all the tests performed are reported in Appendix 8.3.2.

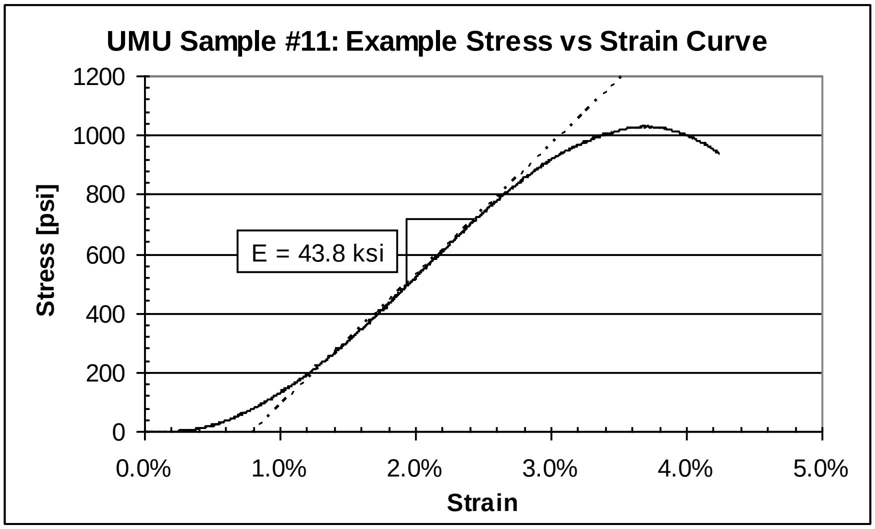

Figure 4.17: Example Stress vs. Strain Curve

4.2.3. Results

4.2.3.1. Durability Results

The procedure outlined in Section 3.10 was followed to determine the durability characteristics of the mini-blocks produced. To summarize, mini-block specimens were submerged in water for 24 hours and then tested in compression. The remaining specimens were allowed to dry for a minimum of 48 hours before being submerged again. The expected decrease in the UCS values with the number of saturation cycles is clearly observed over the series of six saturation cycles performed for both soil Samples #11 & #15. However, the rate at which the UCS decreases also appears to decrease as the number of saturation cycles increases. In other words, the trends illustrated in *Figures 4.18 & 4.19* suggest that the UCS values may be approaching a minimum value asymptotically. The mini-blocks remained almost entirely intact while their UCS values decreased by 23-25% over the course of 6 cycles. Each specimen tested exceeded the New Mexico Earthen Building Materials Code of 300 psi.

Soil #11:

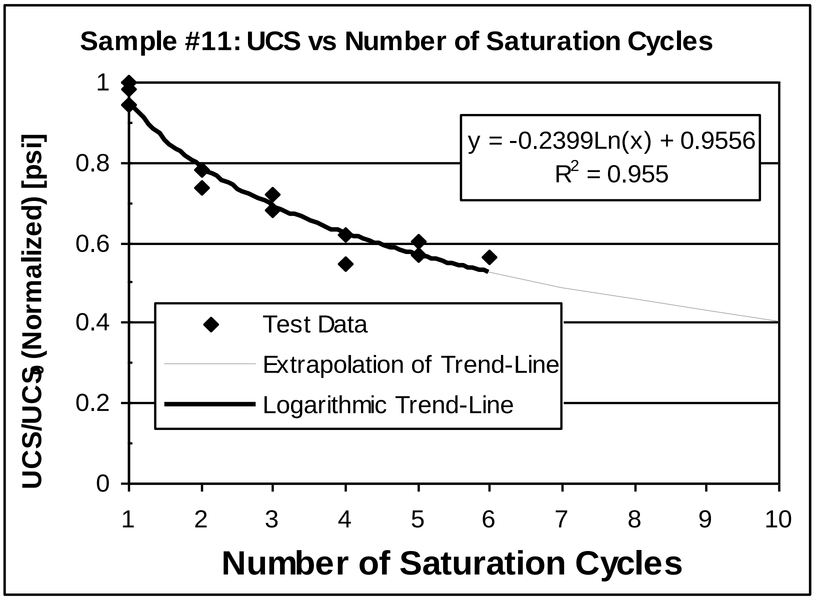

Figure 4.18: Durability Test Effects on UCS

Soil #15:

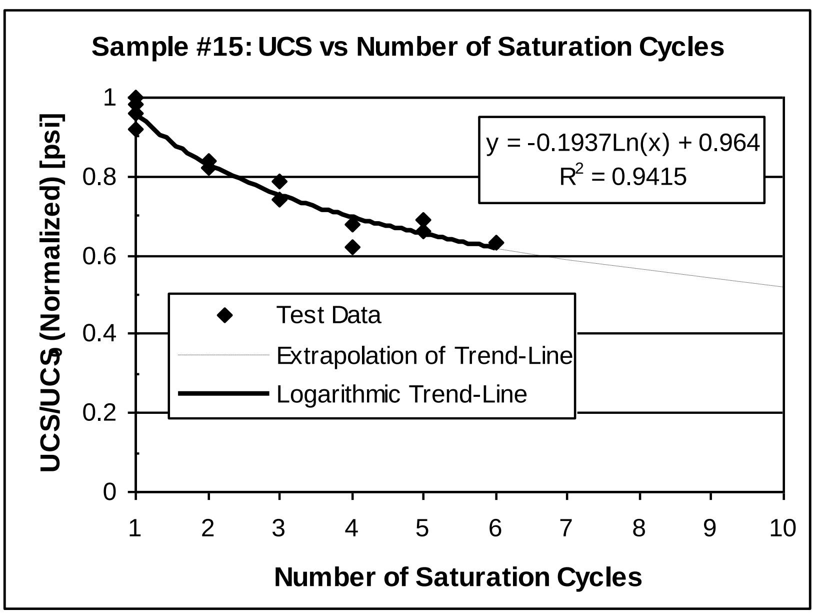

Figure 4.19: Durability Test Effects on UCS

The visually observable effects of the durability testing are shown in *Figures 4.20 - 4.24*.

Figure 4.20: UMU Mini-Blocks; One Saturation Cycle

Figure 4.21: UMU Mini-Blocks; Two Saturation Cycles

Three saturation cycles: N/A

Figure 4.22: UMU Mini-Blocks; Four Saturation Cycles

Figure 4.23: UMU Mini-Blocks; Five Saturation Cycles

Figure 4.24: UMU Mini-Blocks; Six Saturation Cycles

No significant detrimental effects on SCEB integrity can be observed in *Figures 4.20 - 4.24*. The UCS results from the durability tests are displayed in tabular format in Appendix 8.3.3.

4.2.3.2. Mini-Block Optimal Soil Mix Results

The average dry density, UCS, and Young's Modulus of the blocks described in Section 4.2.2.2 are reported in *Table 4.15*. Displayed in *Figure 4.26*, the results show an obvious trend over the range of ratios tested. For soil mix ratios of 1:2.5 to 1:3.5, as the relative amount of sand aggregate increases in the mix, the average compressive strength of the specimens tested also increases. The results from the 1:4 soil mix ratio clearly indicate that no significant strength benefits are achieved by the continued addition of sand to the mix. In fact, the average UCS for the 1:4 soil mixes was slightly less than the average UCS for the 1:3.5 soil mixes. The author suggests that based on the observed trend, a clay to sand soil mix ratio ranging from 1:3 to 1:4 is optimal for further investigation with large block testing.

Special care was taken to prepare the specimens at the same water content to minimize the number of factors affecting the results. Soil samples taken from each mix, at the time of production, indicated a water content range of 11-12%. All specimens were produced with the same applied pressure and cured for the same amount of time.

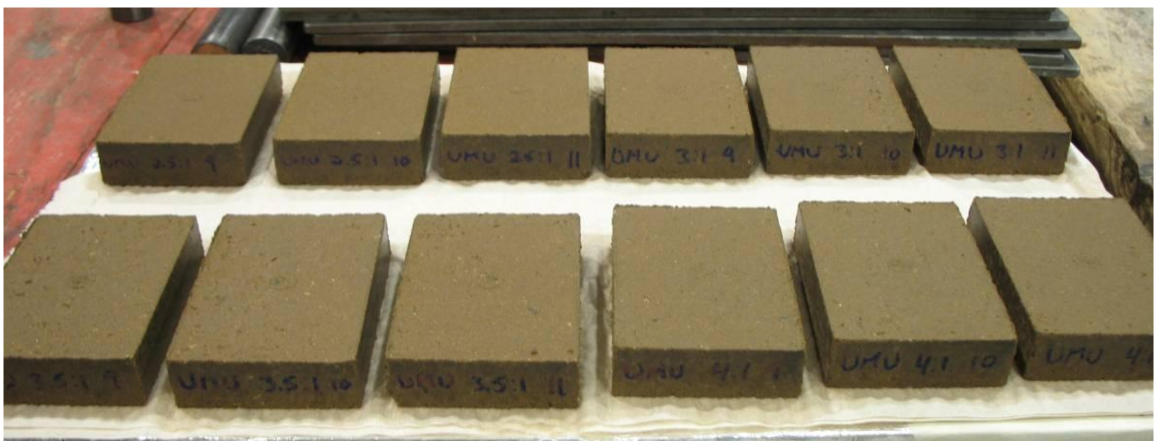

Figure 4.25: UMU Mini-Blocks; Varied Soil Mix Ratios

UMU Soil #11 Mix Ratio Test Results

Soil Mix Ratio	Average Dry Density [pcf]	Average UCS [psi]	Average E [ksi]
1:2.5	136.5	1,346.7	37.4
1:3	136.2	1,741.7	42.7
1:3.5	132.3	1,887.0	43.0
1:4	132.3	1,870.9	42.2

Table 4.15

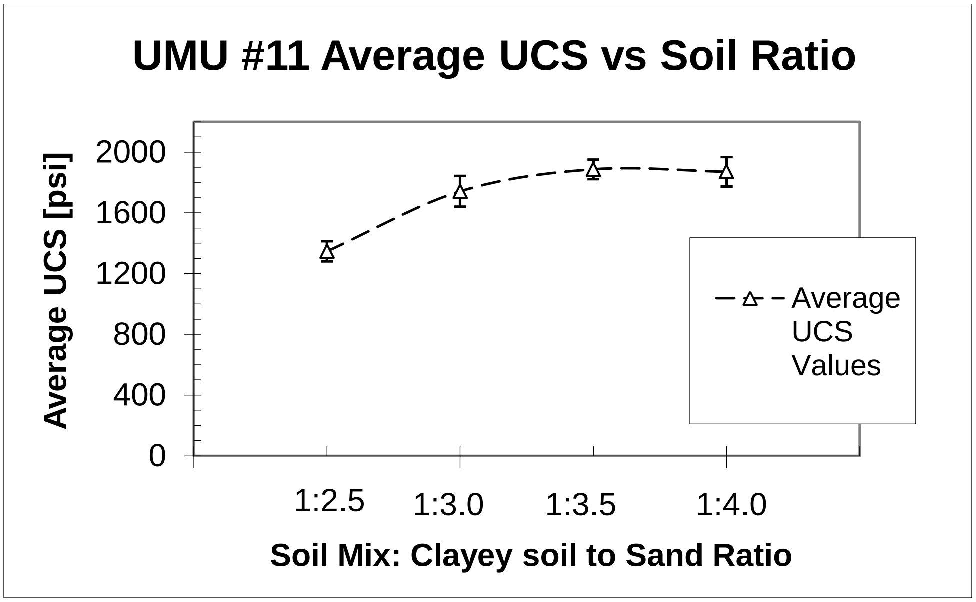

Figure 4.26: Average UCS results over the range of soil mix ratios with error bars

4.2.3.3. Large Block Test Results

Soil mixes containing a 1:1 and a 1:3, clayey soil to sand aggregate ratio, were examined (*Tables 4.14 & 4.15*). Test results indicate that increasing the relative amount of clayey soil, causes a significant decrease in the strength properties measured (*Tables 4.16 & 4.17*). This behavior can be explained by considering the structural matrix formed by the soil particles in the block. While the clay particles provide binding and cohesive forces, the sand particles interlock and provide much of the desired structural strength. An optimal mix design contains enough clayey soil to achieve satisfactory cohesion without negatively affecting the strength properties. Please see Section 3.5 for more discussion regarding this topic.

Soil #11 achieved an average UCS value of 1,141 psi and an average MOR value of 135 psi. Based on the number of blocks tested, the standard deviation (measurement of variation in data) for UCS and MOR was 81 psi and 32 psi, respectively. Soil #15 achieved an average UCS value of 1,278 psi and an average MOR value of 153 psi. The standard deviation for UCS and MOR was 90 psi and 26 psi, respectively.

Soil Mix Ratio 1:3

Soil Sample ID	# of Blocks Produced	Average Dry Density [pcf]	Average UCS [psi]	Average E [ksi]	Average MOR [psi]
Soil #11	22	128.0	1,140.7	48.0	134.8
Soil #15	18	133.0	1,278.0	51.2	153.4

Table 4.16: Soil Mix 1:3 Material Test Results

Soil #11 achieved an average UCS value of 647 psi and an average MOR value of 74 psi. Based on the number of blocks tested, the standard deviation for UCS and MOR was 49 psi and 12 psi, respectively. Soil #15 achieved an average UCS value of 688 psi and an average MOR value of 67 psi. The standard deviation for UCS and MOR was 108 psi and 30 psi, respectively.

Soil Mix Ratio 1:1

Soil Sample ID	# of Blocks Produced	Average Dry Density [pcf]	Average UCS [psi]	Average E [ksi]	Average MOR [psi]
Soil #11	19	123.6	647.0	31.5	73.6
Soil #15	19	125.2	688.3	32.4	67.0

Table 4.17: Soil Mix 1:1 Material Test Results

4.2.4. Discussion of Test Results

Varying the soil mix ratio affects the material properties of the SCEB blocks produced. This behavior is illustrated using both full-scale and model-sized blocks. The large blocks produced from a 1:3 soil mix ratio showed no adverse effects, such as cracking, during the curing phase and achieved satisfactory dry density, UCS, and MOR values. The large blocks produced from a 1:1 soil mix ratio showed no signs of cracking and achieved a satisfactory dry density, but suffered significant reductions in UCS and MOR, making this specific soil mixture not optimal.

Clayey soil is often mined and transported to the project site, where it is then processed and amended before block production. This process contributes significantly to project costs. Therefore, minimizing the amount of clayey soil needed has a high potential for minimizing costs. Determining an optimal soil mixture requires methodical specimen production and testing procedures, such as described in this report.

The various test results bring the author to the conclusion that both Soils #11 and #15 are suitable for SCEB production. A range of suggested target soil mixtures is 1:3 to 1:4 with a water content of approximately 10%.

5. Additional Testing

5.1. Correlation Testing

5.1.1. Unconfined Compressive Strength (UCS) vs. Modulus of Rupture (MOR) Correlation

The MOR test is required by most applicable building codes and requires far less force than the force required for a compressive strength test. A direct correlation between the MOR and UCS would allow for simple on-site material testing taking advantage of the three-point bending test.

Two batches of large blocks were made from UMU Soil Samples #11 & #15 using a 1:1 and 1:3, clayey soil to sand, mix ratio. Blocks were taken from each batch and set aside to study the relationship between UCS and MOR. Each fully saturated block was tested for MOR using a three point bending test. Following the test, the newly created two halves were cut to the same dimensions using a wet circular saw. Each pair was then tested in compression and their UCS values were averaged. The steps taken during this testing process are illustrated in *Figures 5.1 - 5.4*. Average UCS values and average MOR values for each batch of blocks are shown in *Figures 5.5 & 5.6*. The complete set of results can be found in Appendix 8.3.2. Linear correlation analyses were conducted.

Figure 5.1: Full Block in 3-Point Bending Test Set-up

Figure 5.2: Block half after 3-Pt. Test

Figure 5.3: Block half after being cut

Figure 5.4: Block half being tested in compression

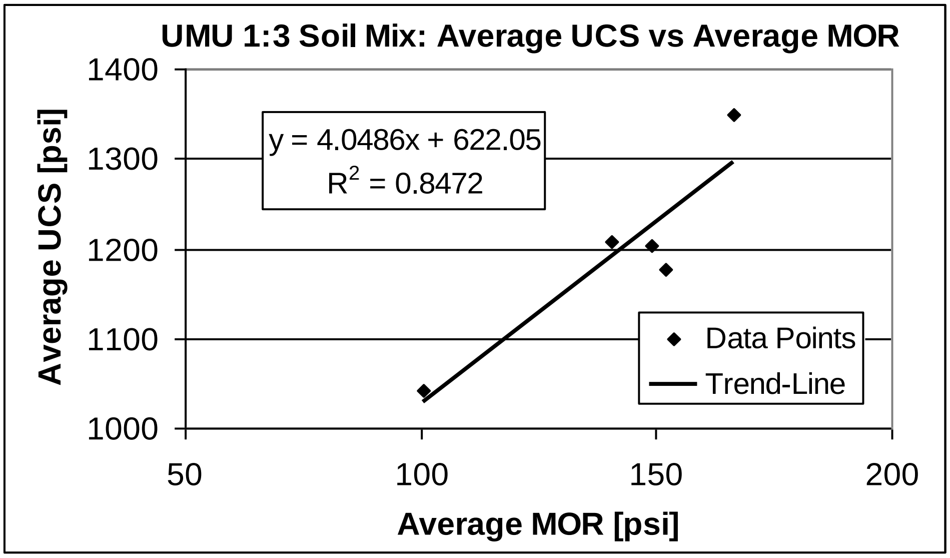

Figure 5.5: UMU 1:3 Soil Mix; UCS/MOR Correlation

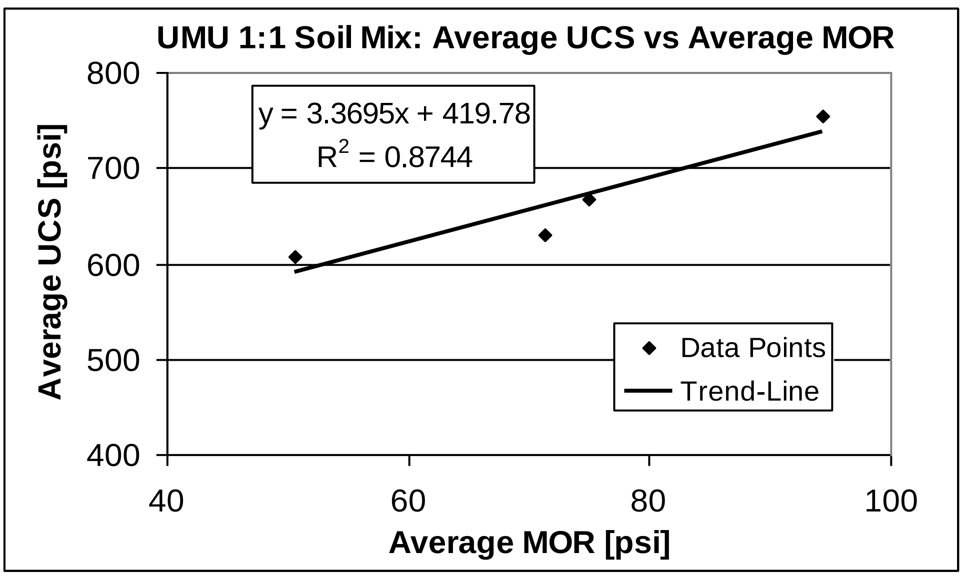

Figure 5.6: UMU 1:1 Soil Mix; UCS/MOR Correlation

A strong correlation between UCS and MOR implies that the results from the relatively inexpensive three-point bending test can be used to infer compressive strength characteristics, which are more costly to determine. The analyses results shown in *Figures 5.5 & 5.6* suggest that the relationship between SCEB UCS and MOR values can be correlated. Linear regression analyses resulted in relatively high R^2 values (goodness of fit measure) of 0.85 and 0.87 for the two soil mixes tested. Additional testing of this nature will increase the level of confidence associated with this correlation. Correlation between UCS and MOR values should not be extended beyond certain soil types and mixtures.

5.1.2. UCS vs. Schmidt Hammer Correlation

A Schmidt Hammer, displayed in *Figures 5.7 & 5.8*, provides a non-destructive testing method that can be closely correlated to a material's unconfined compressive strength (UCS). Such correlations are commonly used on concrete (ASTM C805) and soft rocks (ASTM D5873). The spring-loaded device measures and records the rebound when applied to a surface. The rebound "R" is converted to compressive strength by using a conversion chart supplied by the hammer's manufacturer. A block's Schmidt Hammer compressive strength can then be compared to the actual compressive strength when tested in a lab to determine any correlation. This application provides a simple inexpensive method for quality assurance.

Figure 5.7: Schmidt Hammer

Figure 5.8: Test set-up

The author performed a series of Schmidt Hammer (Model L/LR) tests on eight 7" x 14" x 3 3/4" full-sized blocks made with a 3 to 1 clayey soil to sand ratio and 5%

Portland cement. The blocks originated from the Crow Tribe. The blocks were tested in the flat position and completely dry. The Schmidt Hammer rebound value (R) was recorded at the center of each block. Twelve rebound tests were performed on each block and the results are presented in Appendix 8.2.2. The eight blocks were then immediately tested in compression using the 1,000 kip MTS Machine in the Structures Lab provided by the University of Colorado.

The recorded UCS values were plotted versus the corresponding R values (*Figure 5.9*). A linear regression analysis was carried out to determine the trend between the two parameters. This trend can then be used to predict the unconfined compressive strength of CEB blocks from R measurements conducted in the lab or in the field. It should be noted that this trend is unique for specific CEB mixtures.

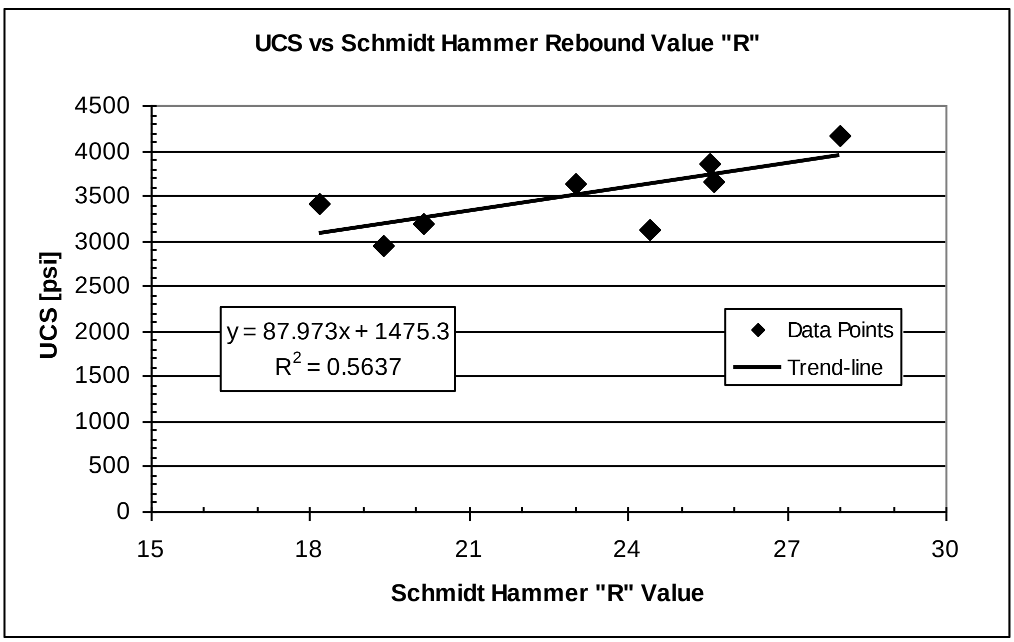

Figure 5.9: UCS Value vs. Schmidt Hammer Rebound Value

The linear regression analysis offers a relatively low R^2 value of 0.56. Although a trend between the two values can be recognized, the results are not sufficiently correlated to suggest a strong relationship between Schmidt Hammer rebound and UCS values at this point of testing. The testing described in this section should continue to further investigate the relationship between rebound and UCS values, paying special attention to the water content of the SCEB during sampling. Also, the Schmidt Hammer used for this analysis is intended to test hard concrete surfaces. It is likely that a more sensitive Schmidt Hammer would produce better results.

5.1.3. Cylinder Tests

During the production of the UMU large blocks described in Sections 4.2.2.2 and 4.2.2.3, the author set aside a portion of each of the soil mixes to prepare cylindrical specimens (pictured in *Figures 5.10 & 5.11*). The soil was compacted into plastic molds in a similar method to the specifications for a Proctor Test (ASTM D698 or D1557). This process involves adding a layer of soil to the mold and using a metal rod as a ram to manually compact the soil. This process was repeated adding layer after layer of soil until the mold was full. The specimens were cured with the large blocks in the same environmental conditions for the same amount of time. Following curing, the specimens were tested under uniaxial compression. *Figure 5.12* shows the relationship between the large block UCS and the corresponding cylinder UCS.

Figure 5.10: UMU Sample #11; 1:1 Soil Mix Cylinders

Figure 5.11: Soil Cylinders; Before and During Testing

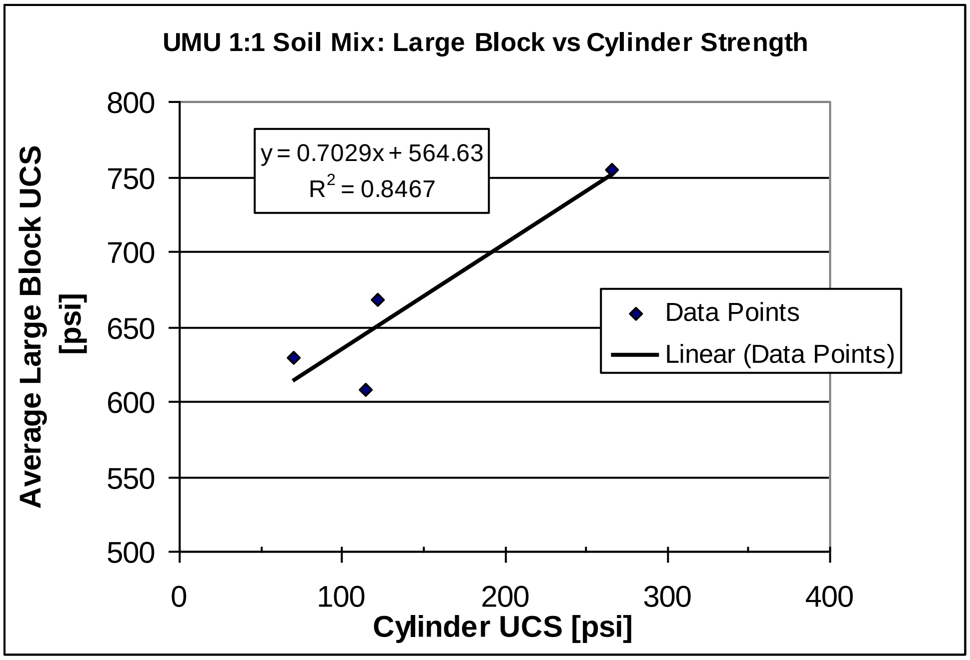

Figure 5.12: UMU 1:1 Soil Mix; Large Block vs Cylinder UCS

Performing a linear regression analysis resulted in a relatively high R^2 value of 0.85. However, due to the limited number of tests performed, the results from the regression analysis are highly uncertain at this phase of testing. The author proposes that continuing the testing described in this section, using an adopted standard procedure for producing and testing stabilized soil cylinders, can lead to a strong correlation between cylinder and block strength properties.

The average force at failure of the four tests performed was 1,300 pounds. The shop press described in Section 5.3.1 is easily capable of supplying the necessary failure load making the cylinder test an excellent candidate for on-site quality control evaluation. The ability to test soil cylinders at a low cost using a simple shop press load frame and confidently infer the actual compressive strength of the material has important implications to SCEB material evaluation

5.2. Scale Effects

The effect of the block aspect ratio on its unconfined compressive strength must be accounted for. The aspect ratio is defined as the height of the specimen divided by its minimum width. An aspect ratio of 2.0 (2H : 1W) or greater is typically accepted as standard for representing the strength of a material (ASTM C39, C42, and C1314). This analysis evaluates UCS and E values of various SCEB prisms to investigate aspect ratio effects. These effects are important for understanding how laboratory UCS results of single blocks compare to full-scale wall sections loaded in the field.

5.2.1. Crow Tribe Large Blocks

Prisms ranging from 1 to 4 or 5 stacked blocks provided by the Crow Tribe (aspect ratio ranging from 0.5 to 2.6) were tested to develop an understanding of the effect of the aspect ratio on the unconfined compressive strength and Young's Modulus (E) (see *Figures 5.13-5.17*). The blocks were produced using a 4:1, clayey soil to sand ratio, soil mixture including ~4% Portland cement.

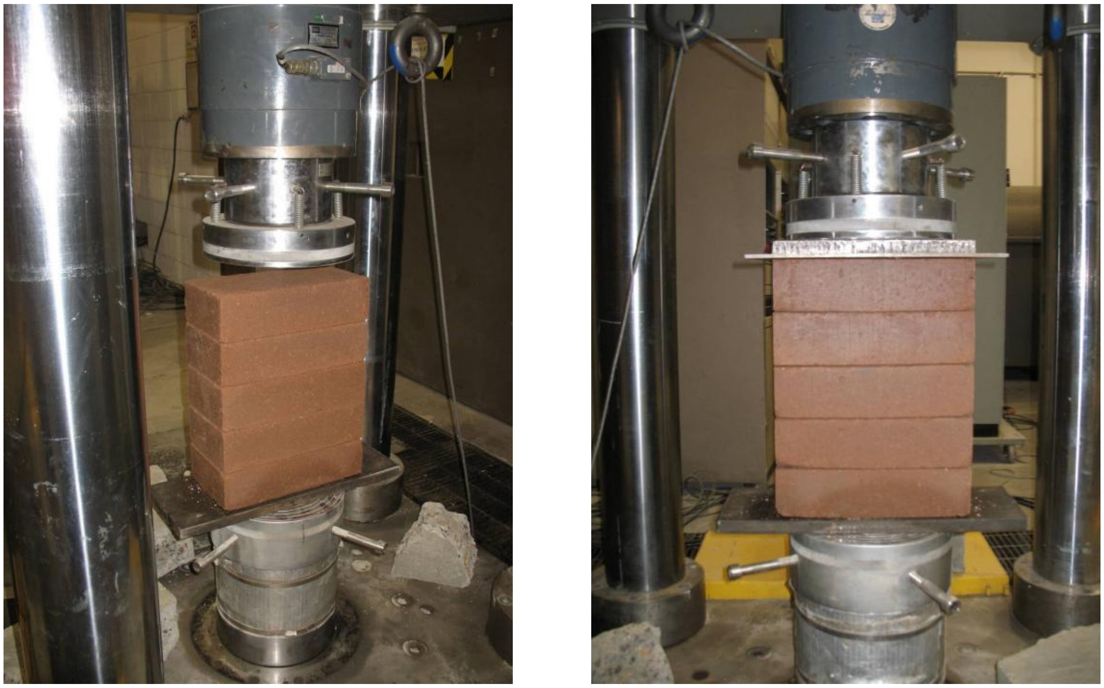

Figure 5.13: Aspect Ratio Test, Five block prism

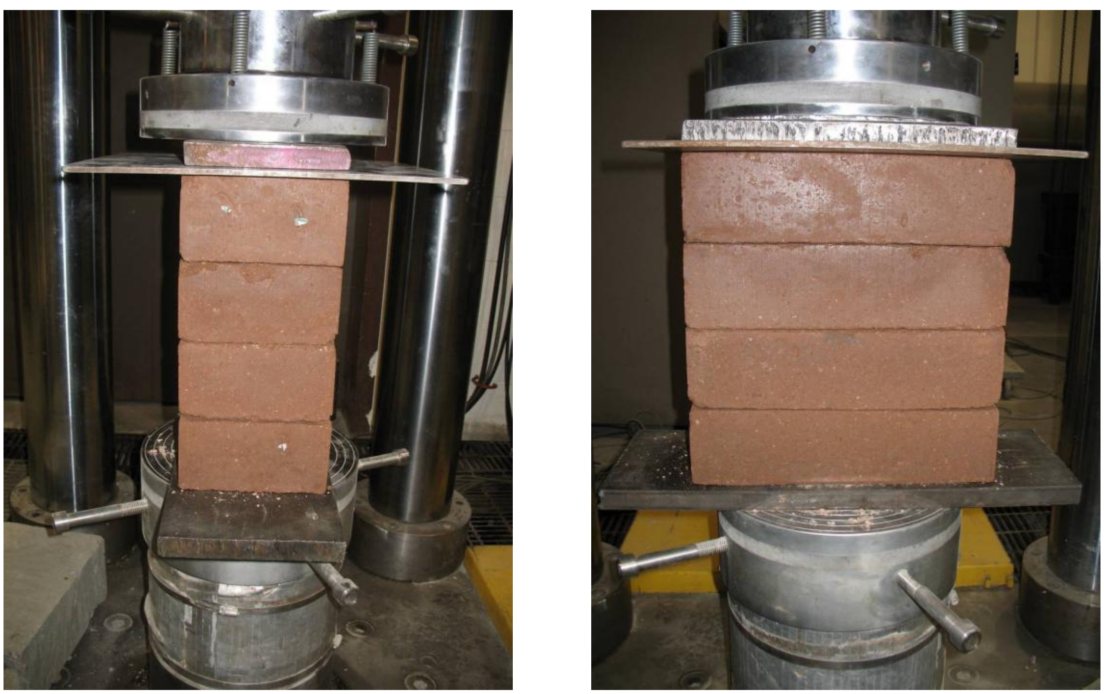

Figure 5.14: Aspect Ratio Test, Four Block Prism

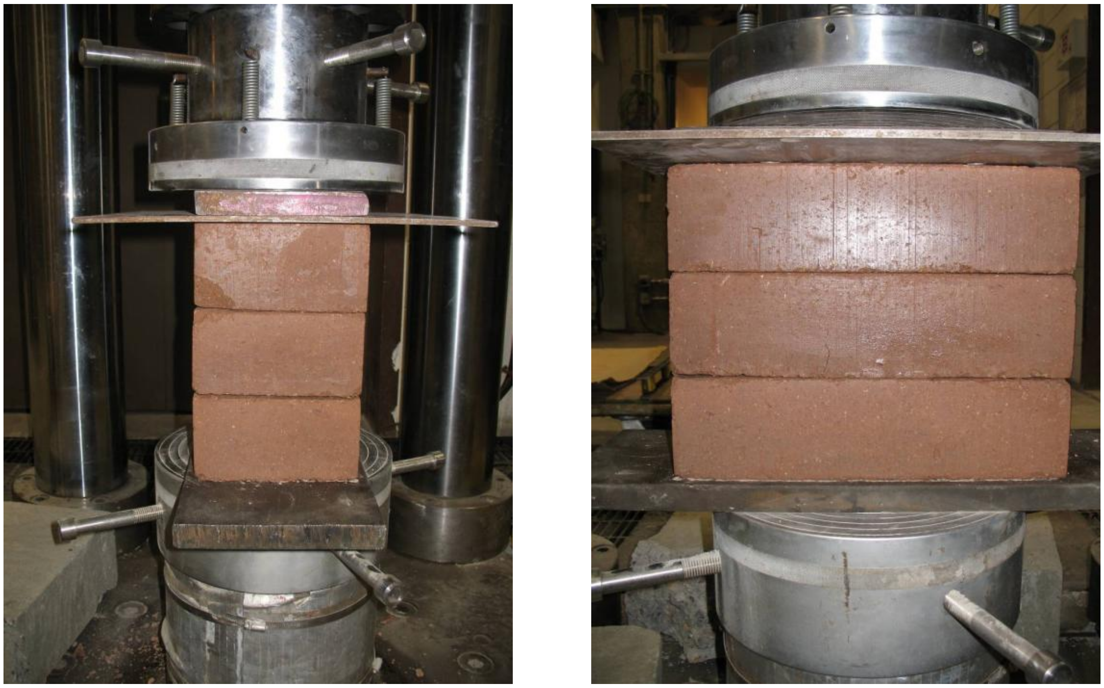

Figure 5.15: Aspect Ratio Test, Three Block Prism

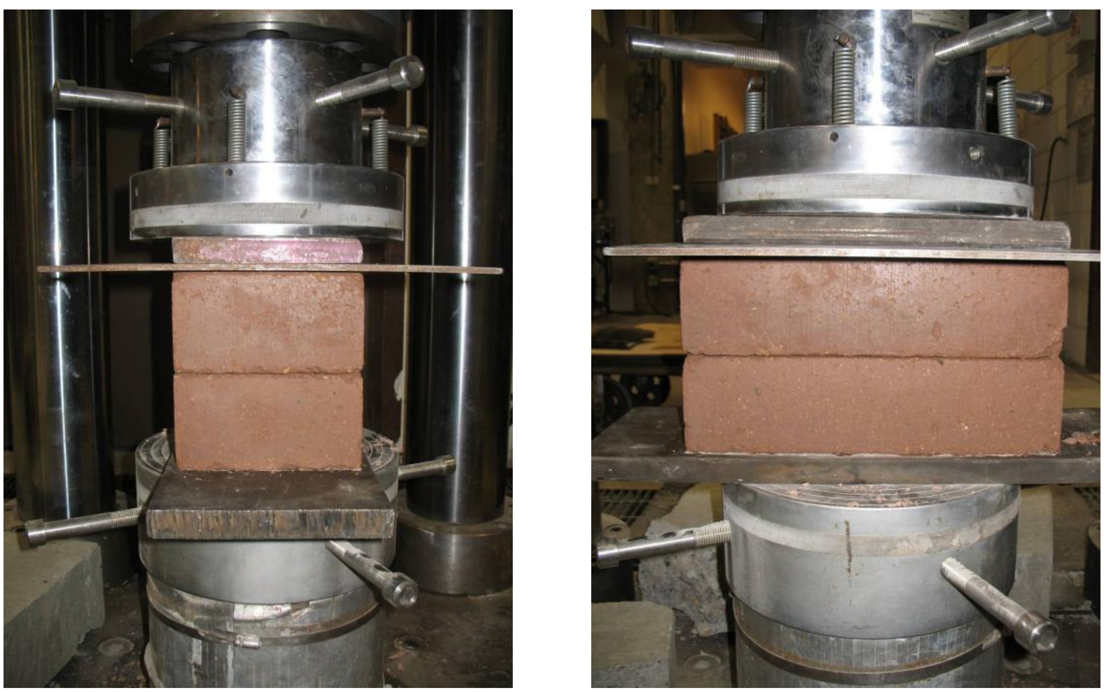

Figure 5.16: Aspect Ratio Test, Two Block prism

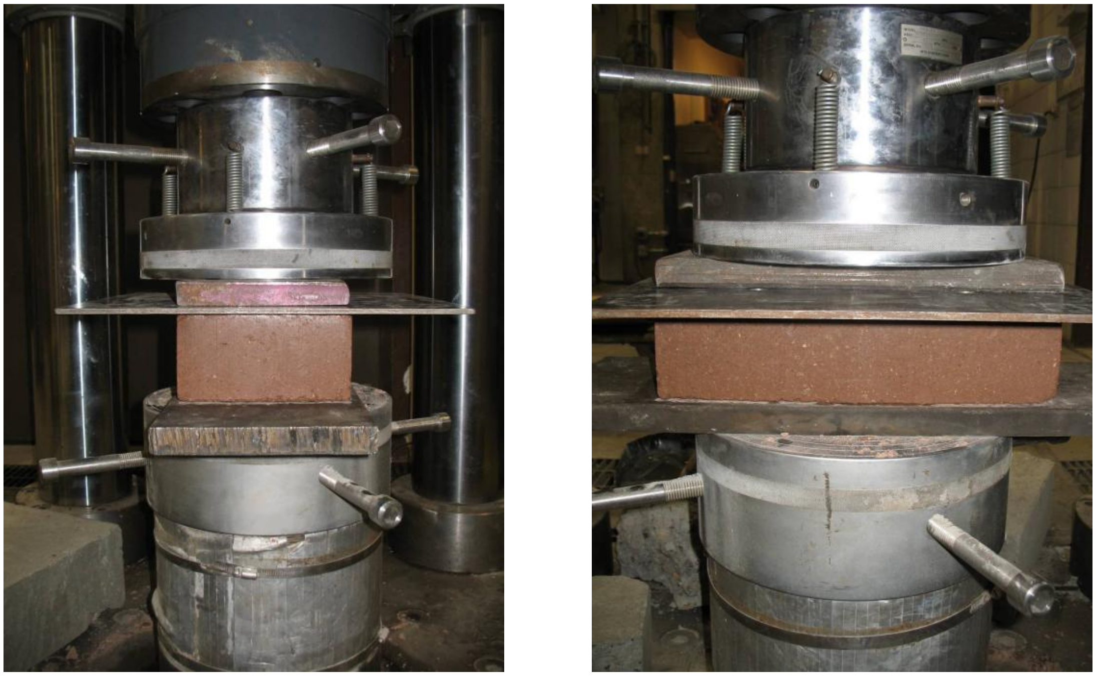

Figure 5.17: Aspect Ratio Test, One Block

5.2.1.1. UCS vs. Aspect Ratio

The test results are presented in *Table 5.1* and shown in *Figure 5.18*. It is clear that the prism's UCS decreases as its aspect ratio increases. To achieve the best fit or model of the data a non-linear trend-line was applied to the test results for analysis.

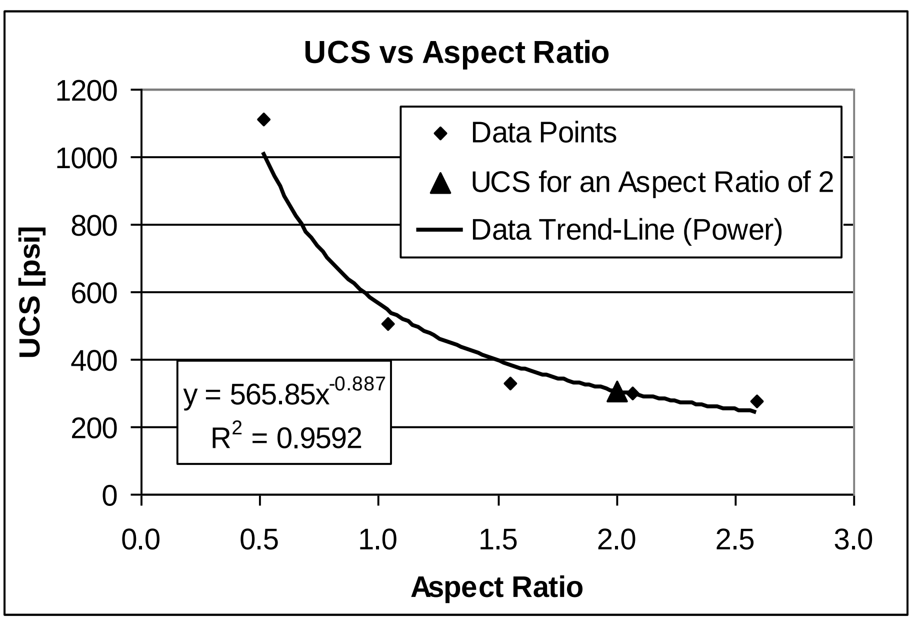

Figure 5.18: Variation of prism UCS with the aspect ratio.

The equation of the trend-line was used to calculate the strength for a prism with an aspect ratio of 2 as follows:

$$y = 565.85 \cdot x^{-0.887} = 565.85 \cdot (2)^{-0.887} = 306.0\ psi$$

# of Stacked Blocks in Prism (height = 3.625 in)	Aspect Ratio	Test Data UCS [psi]	Calculated UCS from Trend-line [psi]	Prism UCS value/ UCS value for an aspect ratio of 2
1	0.5	1112.0	1014.4	3.3
2	1.0	506.4	548.5	1.8
3	1.6	328.9	382.8	1.3
4	2.1	300.5	296.6	1.0
5	2.6	276.2	243.3	0.8

Table 5.1: Aspect Ratio Results on UCS

The last column in *Table 5.1* gives the values of the ratio between each prism's UCS and the UCS of a prism with an aspect ratio of 2.0. These factors can be used to infer the UCS of a SCEB unit in the field from testing a single block in the laboratory.

5.2.1.2. Young's Modulus (E) vs. Aspect Ratio

A similar analysis was performed to analyze the effect of the aspect ratio on the prism's Young Modulus (E). The results presented in *Table 5.2* and *Figure 5.19* show a reduction in the prism's E value as the aspect ratio increases. Again, a non-linear trend-line was applied to the test results.

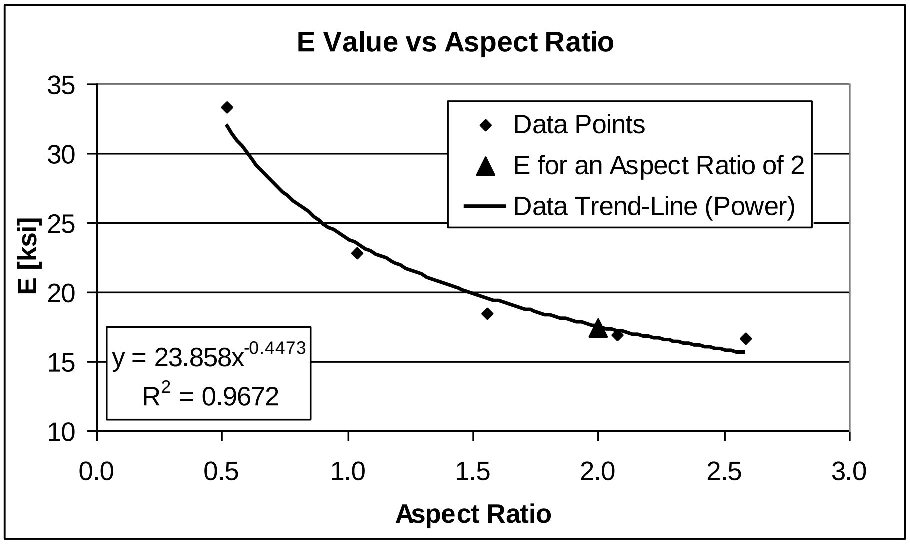

Figure 5.19: Variation of prism E value with the aspect ratio.

The equation of the trend-line was used to calculate the E value for a prism with an aspect ratio of 2 as follows:

$$y = 23.858 \cdot x^{-0.4473} = 23.858 \cdot (2)^{-0.4473} = 17.5\,psi$$

# of Stacked Blocks in Prism (height = 3.625 in)	Aspect Ratio	Test Data E [ksi]	Calculated E from Trend-line [psi]	Prism E value/ E value for an aspect ratio of 2
1	0.5	33.3	32.0	1.8
2	1.0	22.8	23.5	1.3
3	1.6	18.5	19.6	1.1
4	2.1	16.9	17.2	1.0
5	2.6	16.7	15.6	0.9

Table 5.2: Aspect Ratio Effects on E

The last column in *Table 5.2* gives the values of the ratio between each prism's E value and the E value of a prism with an aspect ratio of 2.0. These factors can be used to infer the E value of a SCEB unit in the field from testing a single block in the laboratory.

5.2.2. UMU Tribe Mini Blocks

The same analysis was applied to a series of mini-sized blocks from Soil Sample #15 supplied by the Ute Mountain Ute Tribe. The mini-blocks were produced using a

1:3, clayey soil to sand aggregate ratio, ~5% Portland cement and ~11% water content. A more detailed description of the block composition can be found in Section 4.2.2.2.

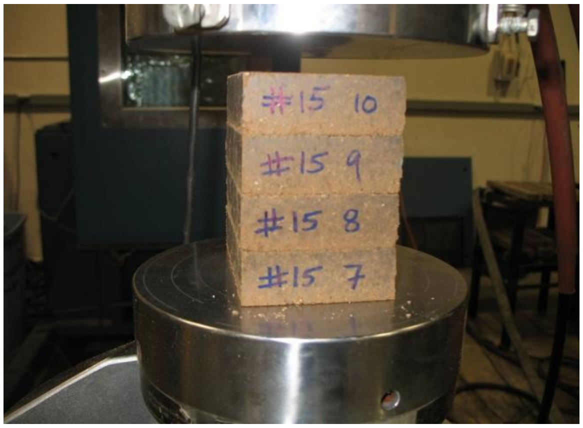

Figure 5.20: Prism Consisting of Four Stacked Mini-Blocks

5.2.2.1. UCS vs. Aspect Ratio

It is clear from the results presented in *Table 5.3* and *Figure 5.21* that the prism's UCS decreases as its aspect ratio increases. A non-linear trend-line was applied to the test results for analysis.

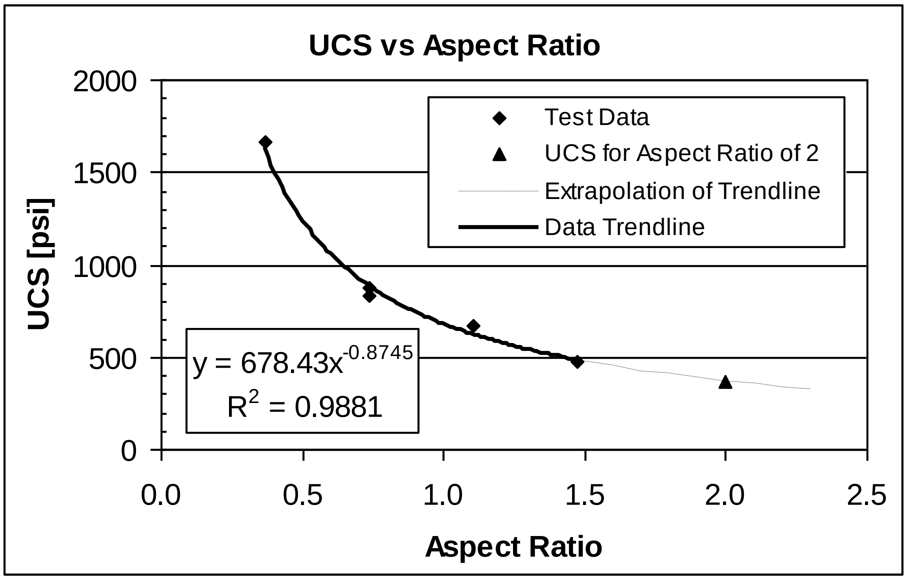

Figure 5.21: Variation of prism UCS with the aspect ratio.

The equation of the trend-line was used to calculate the "strength" for a prism with an aspect ratio of 2 as follows:

$$y = 678.43 \cdot x^{-0.8745} = 678.43 \cdot (2.0)^{-0.8745} = 370.0 \; psi$$

# of Stacked Blocks in Prism (height = 0.9375)	Aspect Ratio	Test Data UCS [psi]	Calculated UCS from Trend-line [psi]	Prism UCS value/ UCS value for an aspect ratio of 2
1	0.37	1667.3	1627.6	4.40
2	0.74	854.4	887.7	2.40
3	1.10	667.9	622.7	1.68
4	1.47	476.1	484.2	1.31

Table 5.3:

The last column in *Table 5.3* gives the values of the ratio between each prism's UCS and the UCS of a prism with an aspect ratio of 2.0.

5.2.2.2. Young's Modulus (E) vs. Aspect Ratio

A similar analysis was performed to analyze the effect of the aspect ratio on the prism's Young Modulus (E). *Table 5.4* and *Figure 5.22* show a reduction of the prism's E value as the aspect ratio increases. Again, a non-linear trend-line was applied to the test results.

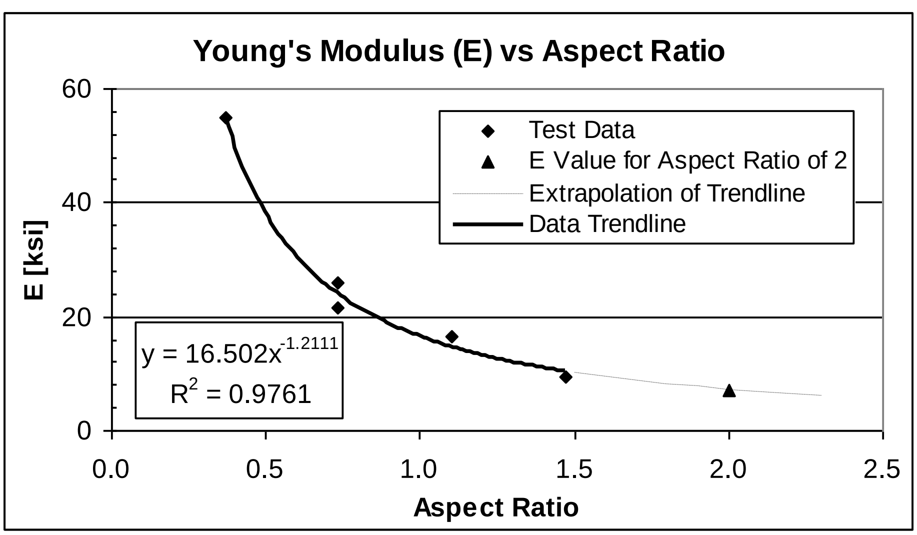

Figure 5.22: Variation of prism E value with the aspect ratio.

The equation of the trend-line was used to calculate the E value for a prism with an aspect ratio of 2 as follows:

$$y = 16.502 \cdot x^{-1.2111} = 16.502 \cdot (2.0)^{-1.2111} = 7.1\,ksi$$

# of Stacked Blocks in Prism (height = 0.9375)	Aspect Ratio	Test Data E [ksi]	Calculated E from Trend-line [psi]	Prism E value/ E value for an aspect ratio of 2
1	0.37	54.9	55.4	7.78
2	0.74	23.7	23.9	3.36
3	1.10	16.5	14.7	2.06
4	1.47	9.6	10.3	1.45

Table 5.4:

The last column in *Table 5.4* gives the values of the ratio between each prism's E value and the E value of a prism with an aspect ratio of 2.0.

5.3. On-site Testing

5.3.1. Shop Press

A simple set-up that can be used for on-site modulus of rupture (MOR) testing is shown in *Figure 5.23.* It consists of a 10-ton shop press ($300 value in the U.S.) fitted with a pressure gauge to record the applied pressure at failure. After loading the block into the frame a hydraulic pump is used to steadily apply force until failure. The recorded pressure at failure is converted to a force, which is used in the calculation of the specimen's MOR (Section 3.9). As mentioned in Section 5.1.3, the shop press pictured is also able to apply the force required to test the stabilized compressed earth cylinders.

The ability to perform on-site quality control tests allows for more frequent testing of block specimens without drastically increasing project costs. Testing earthen blocks in a laboratory facility can be expensive due to transportation costs, laboratory fees, and time lost waiting for results. On-site testing is also beneficial during the process of optimizing a soil mix design. Often, many soil mixes are explored resulting in numerous test specimens being produced. Performing all the material tests in a laboratory could potentially be very expensive.

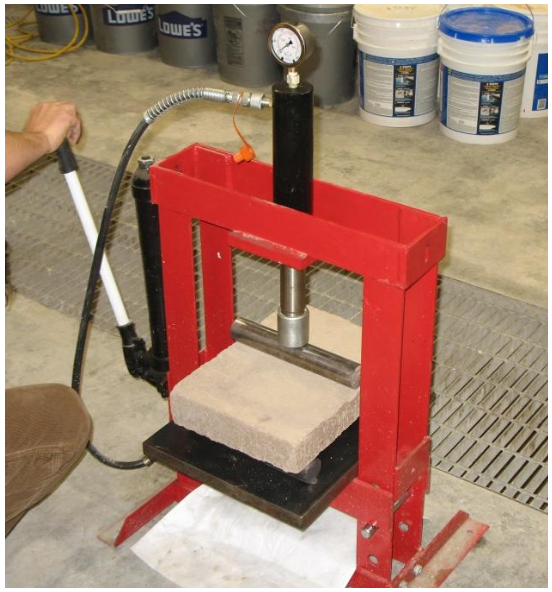

Figure 5.23: MOR test performed in shop press

5.3.2. Schmidt Hammer

The Schmidt Hammer discussed in Section 5.1.2 is an extremely simple and non-destructive tool for testing material hardness properties. It can be transported virtually anywhere and is relatively inexpensive. Once a strong correlation between rebound value "R" and UCS is determined, the Schmidt Hammer can be used to estimate UCS directly in the field.

6. Conclusions

6.1. Summary

Standardizing soil as an alternative building material is critical to developing technology which can be adopted and implemented wherever affordable housing is needed. Earthen building has proven itself to be widely available, reliable, and economical. This thesis provides a foundation for developing an appropriate standard of care applied to SCEB technology. It outlines the current industry understanding, available uses, key components, as well as the strengths and weaknesses related to modern earthen building techniques. The proposed testing methodology was applied to soil samples provided by the Crow and Ute Mountain Ute tribes through funding provided by the DEMD. The findings and conclusions of this thesis are specific to the soils tested as indicated and may not apply to all potential earthen building materials.

The author wishes to highlight the current deficiencies contained in the limited number of codes intended for earthen building regulation. Most building codes are limited to specifying strength property requirements only. However, SCEB behavior related to durability and deformability is highly important and relatively unknown or quantified. The effects of wetting/drying and freezing/thawing are inherent risks when applying SCEB technology in cold and wet climates. These durability effects are not addressed by current codes. Important scaling issues directly affecting material properties, such as compressive strength, are also not addressed. In addition, current building codes do not specify allowable limits regarding soil particle size distribution or plasticity. They also do not offer guidelines regarding suitable soils based on their USCS classification.

The proposed testing methodology by the author lays out a framework of procedures and evaluations for identifying suitable soils and optimizing the overall performance of the blocks produced from the soil. The varying nature of suitable soils requires the framework to accommodate a wide range of potential materials. As research continues and the proposed methodology is followed with various soils, the information collected will contribute to an extensive database. As the database expands, a standard of care including specifications related to particle size distribution, cohesion, plasticity, swelling index, water content, etc. may be defined. Cooperation between researchers applying systematic testing methods will lead to an established industry standard of care code. The overarching goal of this thesis was met by defining the scope of a standard of care for evaluating suitable soils in SCEB production and contributing valuable test results to the community of earthen builders.

The Case Studies presented in Chapter 4 illustrate the author's proposed testing methodology detailed in Chapter 3. The soils provided by the Crow and Ute Mountain Ute Tribes were classified using the Unified Soil Classification System (USCS). Various soil mixes were investigated through a system of material testing and evaluation in order to provide suggestions to the Tribes regarding soil suitability and optimal soil mix design. Recommendations for on-site quality control testing were supplied in order to enable the Tribes to reduce project costs and improve material performance.

Several issues regarding SCEB technology are not yet fully understood. Issues that must be analyzed and addressed by the earthen building community and construction industry include: soil stabilization, expansive soils, clayey soil mineral composition, optimal water content, long-term block durability, and wall unit insulation properties.

6.2. Suggestions for Future Research

Several important areas of SCEB technology remain to be fully investigated and/or understood satisfactorily by the engineering community. A unified system of SCEB production has yet to be defined due to the unlimited number of: (i) potential suitable soils; (ii) variables affecting soil properties; (iii) building techniques.

6.2.1. Optimal Water Content Determination

Testing that efficiently identifies a soil mixture's optimal water content during production is of the utmost importance. The author suggests an adaptation of the modern Proctor Test (ASTM D698 or D1557), which relates water content to maximum dry density of soils. In summary, a predetermined soil mix is divided into several batches which are mixed at different levels of water content. Compressed earth blocks are produced and allowed to properly cure. The blocks are then tested to determine their respective UCS and MOR values. The UCS and MOR results are plotted against the corresponding water contents. A peak in the plot identifies the maximum UCS and MOR values and related water content.

6.2.2. Aspect Ratio Issues

The author suggests further development to define a standard procedure for compression test specimen preparation. SCEB dimensions depend directly on the mold used to press the soil into, which varies widely in practice. Compressive strength is calculated directly using the surface area of the unit tested. Therefore, the dimensions of the SCEB strongly influence its compressive strength as shown in this thesis. The New Mexico Earthen Building Code simply states that, "*The length of the unit must be a minimum of twice the width*." As discussed in Section 5.2., the aspect ratio (defined as the height divided by the width or diameter) of a compression test specimen must be accounted for. Several procedures are offered here by the author to address the aspect ratio issue:

1. Bore a cylindrical specimen from a fully cured SCEB and determine its UCS. The specimen should be bored with a diameter to achieve an aspect ratio of two.
2. Prepare a cylindrical specimen in a mold using a portion of soil taken directly from the mix used in large block production. The soil is compacted into the mold in layers, using a standard procedure easily adapted from an ASTM code or similar test, such as the Proctor Test.
3. Machine a mold that can be passed through the hydraulic block press machine during block production. As the block is extruded from the machine, the excess soil surrounding the mold is removed keeping the cylindrical specimen intact.

Each of these options will have advantages and disadvantages, but ultimately offer a solution for addressing aspect ratio issues. Testing methods similar to Sections 5.2.1 & 5.2.2 should be continued to further understand the effect of the aspect ratio on strength.

6.2.3. Stabilized Compressed Earth Cylinders (SCEC)

Producing and testing cylindrical test specimens presents another option for further research. Section 6.2.2 lists possible options for producing specimens. Establishing a standard practice for producing and strength testing stabilized compressed earth cylinders (SCEC) provides a consistent method for comparing strength characteristics to full-sized blocks. Recognizing a strong correlation between the compressive strength properties of SCEC and SCEB specimens would be useful for designing a soil mixture and quality control testing.

6.2.4. Freeze/Thaw Durability Testing

The geographic location of the two project sites which provided soils for the testing included in this report demand that the durability effects related to freeze/thaw cycles is investigated. The Crow Tribe and the Ute Mountain Ute Tribe located in southern Montana and southwest Colorado, respectively, can experience annual minimum temperatures well below 0° F. The natural ability of the blocks to retain moisture presents an inherent danger of material expansion and contraction during freeze/thaw cycles. The performance of stabilized compressed earthen blocks must be proven to be satisfactory under these extreme conditions.

Although the author was not able to incorporate this phase of testing into this thesis, testing to address this area of concern is currently being initiated at the University of Colorado. Specimens will be fashioned from large blocks to accommodate the container size dimension in a freeze chamber. Mortared block prisms will also be tested to determine effects on bond joints. An additional set of specimens will be prepared and set aside to be used for a comparison analysis. The procedure detailed in ASTM C666 will be followed which involves multiple cycles of specimen submersion, freezing and then thawing. Data including specimen mass and dimensions will be collected to determine any loss of material. After the specified number of freeze/thaw cycles, the specimens will be tested for compressive strength and compared to results obtained from specimens set aside.

The results from this type of testing can ultimately be used to optimize the soil mix used in the block production. Portland cement is expensive and is added primarily to reduce the amount of moisture absorbed by the block, therefore minimizing effects from water expansion/contraction during freeze/thaw cycles. Determining the minimum amount of cement needed to ensure satisfactory block stabilization would greatly reduce the project cost. Minimizing the amount of cement in the soil mix also increases the natural ability of the material to "breath", regulating indoor climate. The overall sustainability of the project is enhanced with reduction of the amount of cement used.

6.2.5. Swelling/Expansive Soil Analysis

The swelling potential of a clayey soil is a topic of debate in the geotechnical engineering community. ASTM standard D4829 specifies a procedure for determining a soil's Expansion Index (EI). The Expansion Index is defined as 1000 times the final minus the initial height divided by the initial height. A classification of a soil's potential expansion related to its Expansion Index is given in the ASTM standard. Relating a soil's performance in SCEB production to its Expansion Index would be extremely helpful in the suitable soil selection process.

6.2.6. Mortar Joint Property Tests

The interaction between the block and the mortar used to form joints in a SCEB wall unit needs to be analyzed to determine the strength and deformation properties of the structure being constructed. Designing a SCEB structure requires specific knowledge regarding the compressive, tensile, shear, and bond strength properties of the mortar used in construction.

The purpose of the Mortar Bond Strength test is to determine the bonding properties between a mortar mix and set of blocks. Test prisms are constructed by bonding two blocks with the top block oriented 90 degrees to the bottom block. The mortar's Bond Strength is determined by loading the block prism into a load frame and testing to failure as per ASTM C 952-02. The mortar's tensile bond strength is calculated with the following equation.

$$\tau\,[psi] = \frac{P_f}{A}$$

$$P_f = force\ at\ failure\ [lbs]$$

$$A = Area\ of\ mortar\,[in^2]$$

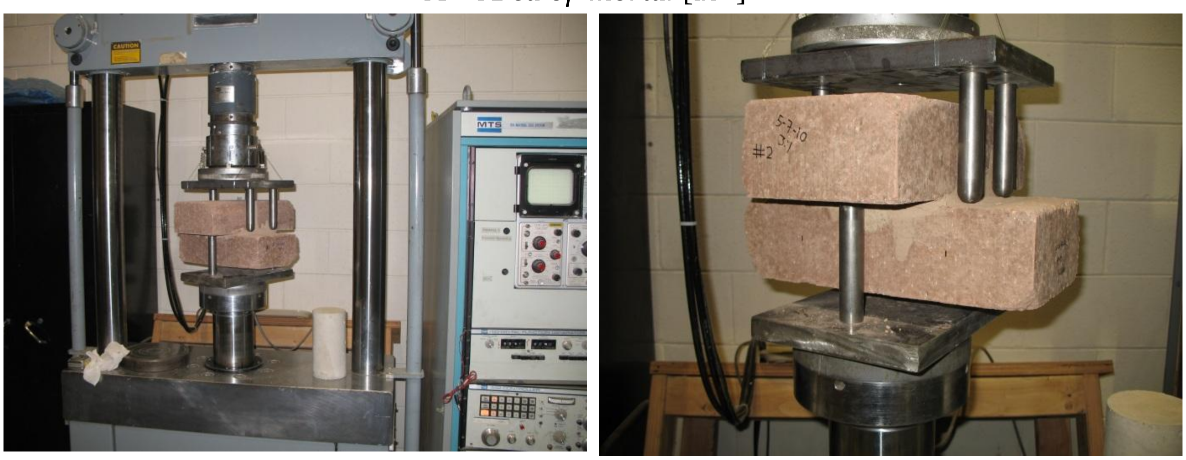

Figure 6.1: Mortar Bond Strength Test Set-up

The purpose of the Mortar Shear Strength test is to determine the bonding properties between a mortar mix and set of blocks when tested in shear. A test prism is constructed (horizontal orientation: *Figure 6.2.a*) with the middle block offset by 2". After being allowed to cure, the prism is placed into a load frame (vertical orientation: *Figure 6.2.b*) and tested to failure. To determine the mortar's shear strength, the following equation is used:

$$\tau\,[psi] = \frac{P_f}{2 \cdot A}$$

$$P_f = force\ at\ failure\ [lbs]$$

$$A = Area\ of\ mortar\,[in^2]$$

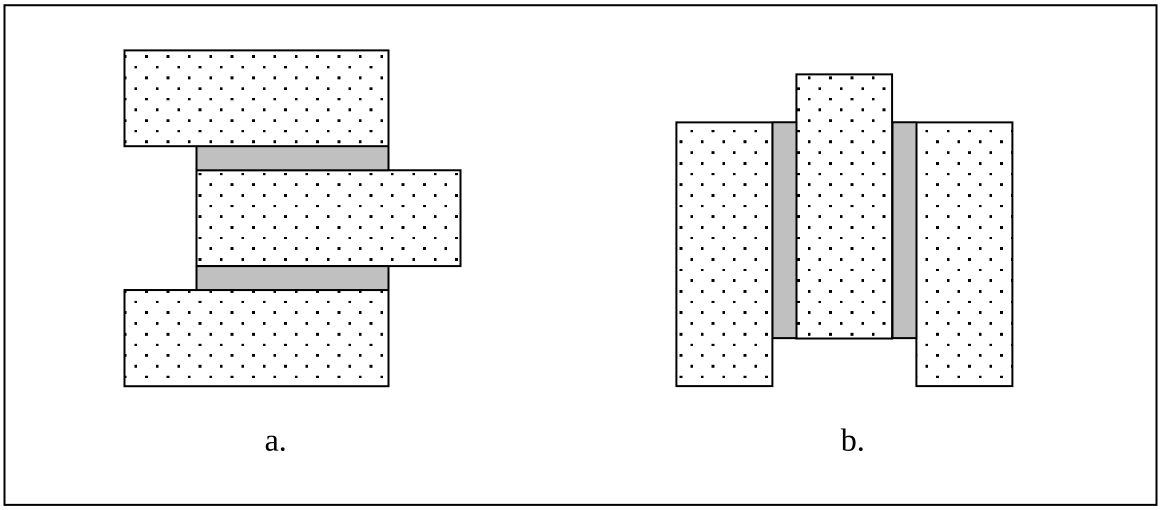

Figure 6.2: Mortar Shear Strength Test Set-up

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8. Appendix

8.1. Soil Classification Charts

D2487 – 10

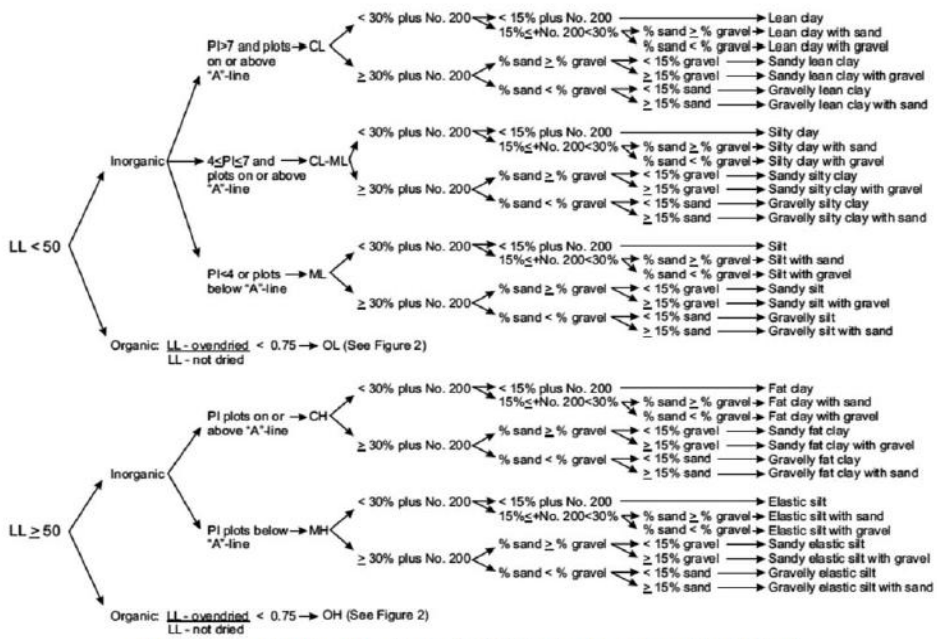

FIG. 1 Flow Chart for Classifying Fine-Grained Soil (50 % or More Passes No. 200 Sieve)

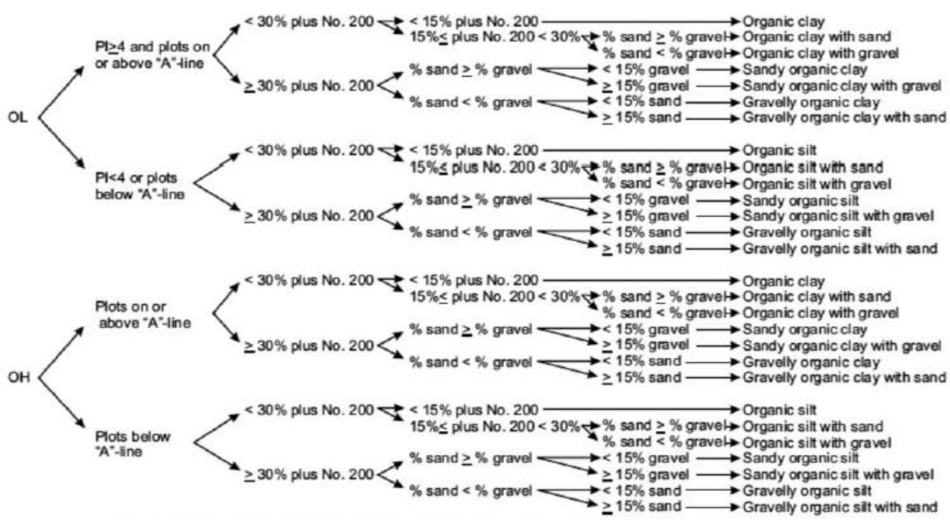

FIG. 2 Flow Chart for Classifying Organic Fine-Grained Soil (50 % or More Passes No. 200 Sieve)

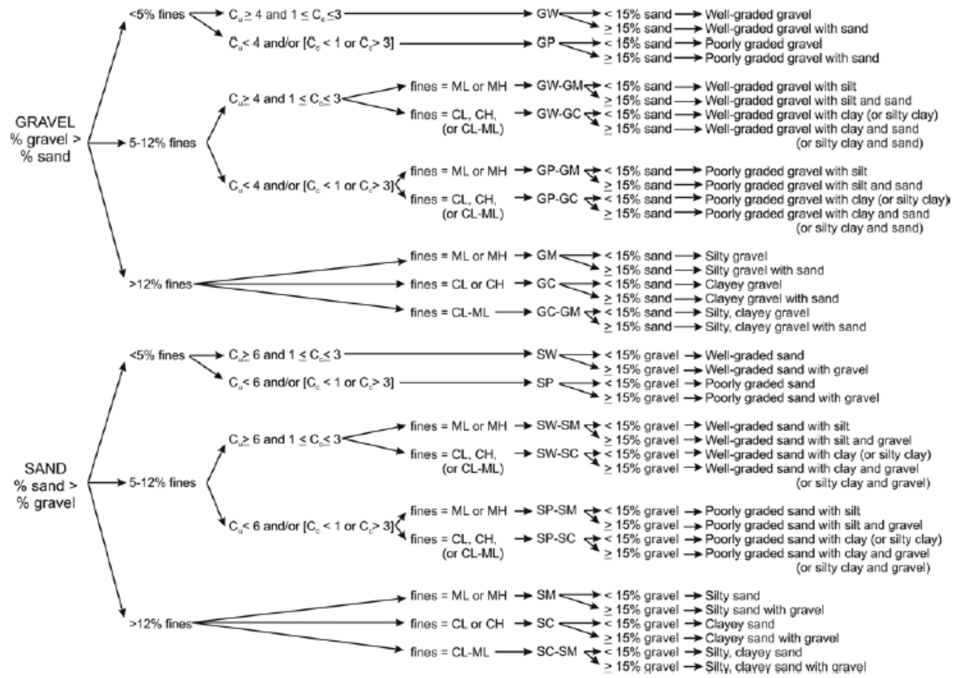

FIG. 3 Flow Chart for Classifying Coarse-Grained Soils (More Than 50 % Retained on No. 200 Sieve)

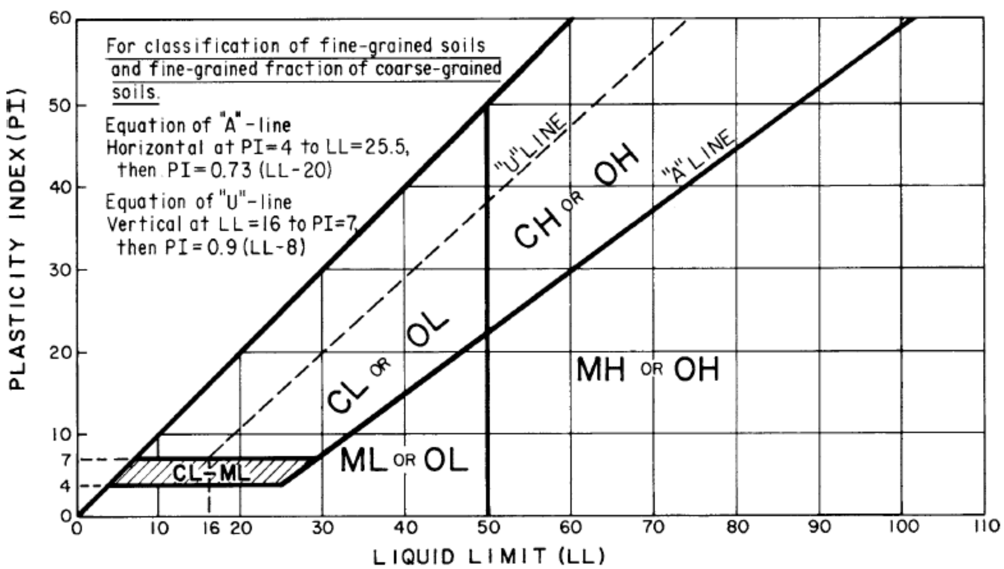

FIG. 4 Plasticity Chart

8.2. Crow Tribe Case Study Test Data

8.2.1. Mini-Block Test Data

25% Amsden										
Sample ID	A25-1	A25-2	A25-3	A25-4	A25-5	A25-6	A25-7	A25-8	A25-9	A25-10
Height (in)	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938
Area (sq in)	8.925	8.925	8.925	8.925	8.925	8.925	8.925	8.925	8.925	8.925
Mass (g)	277.9	278.3	279.1	278.2	279.3	276.6	278.6	278.8	278.9	278.8
Weight (lbs)	0.613	0.614	0.615	0.613	0.616	0.610	0.614	0.615	0.615	0.615
Density (pcf)	126.5	126.7	127.1	126.7	127.2	126.0	126.9	126.9	127.0	126.9
UCS (psi)	410	529	372	579	407	623	599	608	449	436
% Strain	4.9	7.7	5.6	6.9	6.1	6.1	6.1	6.2	7.8	5.1
E (psi)	12250	16000	12200	16200	12900	16650	15350	16250	11900	12700
Date Made	4/18	4/18	4/18	4/18	4/18	4/18	4/18	4/18	4/18	4/18
Date Tested	4/27	5/4	5/13	5/19	5/21	5/26	5/29	6/1	6/3	6/5
# Saturations	1	1	1	1	1	2	3	4	5	6

35% Amsden										
Sample ID	A35-1	A35-2	A35-3	A35-4	A35-5	A35-6	A35-7	A35-8	A35-9	A35-10
Height (in)	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938
Area (sq in)	8.925	8.925	8.925	8.925	8.925	8.925	8.925	8.925	8.925	8.925
Mass (g)	280.2	279.6	278.9	279.5	278.8	280.2	279.9	279.5	278.9	279.0
Weight (lbs)	0.618	0.616	0.615	0.616	0.615	0.618	0.617	0.616	0.615	0.615
Density (pcf)	127.6	127.3	127.0	127.2	126.9	127.6	127.4	127.3	127.0	127.0
UCS (psi)	801	783	833	763	924	935	963	929	944	961
% Strain	5.6	6.3	5.2	7.4	6.6	8.8	6.8	7.1	6.7	5.9
E (psi)	22500	21200	23100	19300	20950	21800	22200	21167	22800	23200
Date Made	4/18	4/18	4/18	4/18	4/18	4/18	4/18	4/18	4/18	4/18
Date Tested	4/27	5/4	5/13	5/19	5/21	5/26	5/29	6/1	6/3	6/5
# Saturations	1	1	1	1	1	2	3	4	5	6

30% Dead Man's Curve 01										
Sample ID	D13-1	D13-2	D13-3	D13-4	D13-5	D13-6	D13-7	D13-8	D13-9	D13-10
Height (in)	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938
Area (sq in)	8.925	8.925	8.925	8.925	8.925	8.925	8.925	8.925	8.925	8.925
Mass (g)	280.2	279.4	279.1	278.3	279.0	279.0	278.3	278.7	278.9	278.9
Weight (lbs)	0.618	0.616	0.615	0.614	0.615	0.615	0.613	0.615	0.615	0.615
Density (pcf)	127.6	127.2	127.1	126.7	127.0	127.0	126.7	126.9	127.0	127.0
UCS (psi)	623	723	717	761	737	783	758	801	820	803
% Strain	5.2	5.3	5.9	6.2	6.3	6.6	6.5	5.4	6.1	6.6
E (psi)	16250	18750	19200	18600	18900	19300	18250	19550	19400	18400
Date Made	4/18	4/18	4/18	4/18	4/18	4/18	4/18	4/18	4/18	4/18
Date Tested	4/27	5/4	5/13	5/19	5/21	5/26	5/29	6/1	6/3	6/5
# Saturations	1	1	1	1	1	2	3	4	5	6

40% Dead Man's Curve 01										
Sample ID	D14-1	D14-2	D14-3	D14-4	D14-5	D14-6	D14-7	D14-8	D14-9	D14-10
Height (in)	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938
Area (sq in)	8.925	8.925	8.925	8.925	8.925	8.925	8.925	8.925	8.925	8.925
Mass (g)	280.0	279.8	279.7	276.2	278.9	279.7	279.2	279.6	278.9	279.1
Weight (lbs)	0.617	0.617	0.617	0.609	0.615	0.617	0.615	0.616	0.615	0.615
Density (pcf)	127.5	127.4	127.3	125.8	127.0	127.4	127.1	127.3	127.0	127.1
UCS (psi)	520	685	726	661	745	836	895	909	885	813
% Strain	5.6	7.0	6.4	6.9	6.2	6.7	7.2	8.1	7.5	6.1
E (psi)	14500	17300	18800	15750	18500	18700	19200	19350	18550	18450
Date Made	4/18	4/18	4/18	4/18	4/18	4/18	4/18	4/18	4/18	4/18
Date Tested	4/27	5/4	5/13	5/19	5/21	5/26	5/29	6/1	6/3	6/5
# Saturations	1	1	1	1	1	2	3	4	5	6

25% Dead Man's Curve 02										
Sample ID	D23-1	D23-2	D23-3	D23-4	D23-5	D23-6	D23-7	D23-8	D23-9	D23-10
Height (in)	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938
Area (sq in)	8.925	8.925	8.925	8.925	8.925	8.925	8.925	8.925	8.925	8.925
Mass (g)	279.4	278.8	278.8	279.5	279.6	278.6	279.1	278.9	278.7	279.5
Weight (lbs)	0.616	0.615	0.615	0.616	0.616	0.614	0.615	0.615	0.615	0.616
Density (pcf)	127.2	126.9	126.9	127.2	127.3	126.9	127.1	127.0	126.9	127.2
UCS (psi)	452	504	459	341	467	524	580	521	587	664
% Strain	5.2	7.3	5.2	7.5	6.9	4.5	5.9	5.5	5.6	5.4
E (psi)	12750	14000	13100	10000	13500	14400	14250	13200	15600	17600
Date Made	4/18	4/18	4/18	4/18	4/18	4/18	4/18	4/18	4/18	4/18
Date Tested	4/27	5/4	5/13	5/19	5/21	5/26	5/29	6/1	6/3	6/5
# Saturations	1	1	1	1	1	2	3	4	5	6

40% Dead Man's Curve 02										
Sample ID	D24-1	D24-2	D24-3	D24-4	D24-5	D24-6	D24-7	D24-8	D24-9	D24-10
Height (in)	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938	0.938
Area (sq in)	8.925	8.925	8.925	8.925	8.925	8.925	8.925	8.925	8.925	8.925
Mass (g)	279.5	279.4	277.8	278.6	278.4	279.1	278.2	278.5	278.2	278.8
Weight (lbs)	0.616	0.616	0.612	0.614	0.614	0.615	0.613	0.614	0.613	0.615
Density (pcf)	127.3	127.2	126.5	126.8	126.8	127.1	126.6	126.8	126.7	127.0
UCS (psi)	529	573	578	631	641	732	758	761	856	737
% Strain	5.4	6.5	5.8	6.6	7.8	7.2	6.5	3.5	8.7	6.0
E (psi)	14000	14350	14800	14900	14750	16250	15750	16050	17800	16400
Date Made	4/18	4/18	4/18	4/18	4/18	4/18	4/18	4/18	4/18	4/18
Date Tested	4/27	5/4	5/13	5/19	5/21	5/26	5/29	6/1	6/3	6/5
# Saturations	1	1	1	1	1	2	3	4	5	6

8.2.2. Schmidt Hammer Test Data

R Values								
	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6	Block 7	Block 8
Test 1	20.5	19.5	20.0	23.5	17.0	24.0	24.0	17.0
Test 2	17.5	24.0	17.5	26.5	15.0	28.5	25.0	22.0
Test 3	17.5	23.5	15.0	24.5	16.5	19.5	20.5	24.0
Test 4	22.0	20.0	26.0	29.0	21.5	27.5	25.0	23.0
Test 5	20.0	26.5	17.5	28.0	21.0	22.5	21.0	24.0
Test 6	20.5	30.0	22.5	29.0	16.0	27.5	26.0	26.5
Test 7	21.0	26.5	21.0	26.0	19.5	28.0	26.0	28.5
Test 8	18.5	26.0	19.0	26.0	15.0	23.5	26.5	20.0
Test 9	17.5	22.0	24.5	34.0	19.5	23.0	29.5	22.0
Test 10	21.0	22.5	23.0	34.0	16.0	30.0	26.0	25.0
Test 11	19.5	25.5	18.5	29.5	18.0	27.5	29.5	20.0
Test 12	17.0	27.0	17.0	26.0	23.0	26.0	27.5	24.0
Average R =	19.4	24.4	20.1	28.0	18.2	25.6	25.5	23.0

Recorded Machine UCS (psi)								
	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6	Block 7	Block 8
Recorded UCS (psi)	2947	3136	3189	4172	3413	3654	3861	3639

8.3. Ute Mountain Ute Tribe Test Data

8.3.1. Soil Classification Data

"Sand 1 of 4"

Sieve No.	Opening (μm)	Opening (mm)	Mass of Sieve (lb)	Mass of Sieve + Soil (lb)	Mass of Soil Retained (lb)	Mass Finer (lb)	Percent Finer
8	2360	2.36	14.10	20.66	6.56	21.98	77.0%
16	1180	1.18	14.10	18.60	4.50	17.48	61.2%
30	600	0.6	14.04	20.36	6.32	11.16	39.1%
50	300	0.3	13.32	18.74	5.42	5.74	20.1%
100	150	0.15	15.30	18.18	2.88	2.86	10.0%
Pan	--	0	12.58	15.44	2.86	0.00	0.0%
Total	--	--	83.44	111.98	28.54		

"Sand 1 of 4"	
$D_{10\%}$ (mm)	0.150
$D_{30\%}$ (mm)	0.456
$D_{60\%}$ (mm)	1.147
Coefficient of Uniformity (C_u)	7.665
Coefficient of Curvature (C_c)	1.212

8.3.2. Large Block Test Data

UMU Sample #11 1:3 (6 x 12 x 3 5/8)								
Sample ID	#11-1	#11-2	#11-3	#11-4	#11-5	#11-6	#11-7	#11-8
Height (in)	3.625	3.625	3.625	3.625	3.625	3.625	3.625	3.625
Area (sq in)	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0
Mass Wet (lbs)	20.1	20.1	19.9	20.3	20.5	19.8	19.8	19.8
Dens. Wet (pcf)	133.1	132.8	131.6	134.1	135.5	130.8	131.2	131.2
Mass Dry (lbs)	19.50	19.40	19.20	19.68	19.80	19.12	19.22	19.24
Dens. Dry (pcf)	129.1	128.4	127.1	130.3	131.1	126.6	127.2	127.4
Moisture Content	3.1%	3.4%	3.5%	2.9%	3.3%	3.3%	3.1%	3.0%
UCS/[MOR]* (psi)	1031	1052	95*	107*	107*	89*	103*	NA**
E (ksi)	44	45	NA	NA	NA	NA	NA	NA**
Date Made	11/16/10	11/16/10	11/16/10	11/16/10	11/16/10	11/16/10	11/16/10	11/16/10
Date Tested	1/12/11	1/12/11	1/12/11	1/12/11	1/12/11	1/12/11	1/12/11	1/12/11

*Specimen was tested for MOR; **Specimen was not tested and used for demonstration purposes

UMU Sample #15 1:3 (6 x 12 x 3 7/16)									
Sample ID	#15-1	#15-2	#15-3	#15-4	#15-5	#15-6	#15-7	#15-8	#15-9
Height (in)	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44
Area (sq in)	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0
Mass Wet (lbs)	19.8	19.8	19.6	19.9	19.6	19.8	19.8	19.8	19.8
Dens. Wet (pcf)	138.2	138.0	137.1	138.9	136.7	138.0	137.9	138.3	138.4
Mass Dry (lbs)	19.20	19.12	19.00	19.28	19.02	19.12	19.20	19.18	19.18
Dens. Dry (pcf)	134.1	133.5	132.7	134.6	132.8	133.5	134.1	133.9	133.9
Moisture Content	3.1%	3.4%	3.4%	3.2%	2.9%	3.4%	2.9%	3.2%	3.3%
UCS/[MOR]* (psi)	1303	1394	182*	194*	158*	182*	152*	185*	108*
E (ksi)	46	44	NA	NA	NA	NA	NA	NA	NA
Date Made	11/23/10	11/23/10	11/23/10	11/23/10	11/23/10	11/23/10	11/23/10	11/23/10	11/23/11
Date Tested	1/24/11	1/24/11	1/24/11	1/24/11	1/24/11	1/24/11	1/24/11	1/24/11	1/24/11

*Specimen was tested for MOR

UMU Sample #11 1:3 (6 x 12 x 3 3/8)									
Sample ID	#11-1	#11-2	#11-3	#11-4	#11-5	#11-6	#11-7	#11-8	#11-9
Height (in)	3.38	3.38	3.38	3.38	3.38	3.38	3.38	3.38	3.38
Area (sq in)	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0
Mass Wet (lbs)	20.1	20.0	19.6	19.9	20.1	19.8	20.3	19.7	20.1
Dens. Wet (pcf)	142.9	142.4	139.5	141.5	142.6	140.6	144.3	139.8	143.2
Mass Dry (lbs)	19.5	19.4	19.0	19.3	19.5	19.2	19.7	19.0	19.6
Dens. Dry (pcf)	138.7	138.1	135.1	137.1	138.5	136.5	139.9	135.4	139.2
Moisture Content	3.1%	3.1%	3.2%	3.2%	2.9%	3.1%	3.1%	3.2%	2.8%
UCS/[MOR]* (psi)	1237	1168	174*	133*	158*	193*	131*	103*	NA**
E (ksi)	52	54	NA	NA	NA	NA	NA	NA	NA**
Date Made	11/24/10	11/24/10	11/24/10	11/24/10	11/24/10	11/24/10	11/24/10	11/24/10	11/24/10
Date Tested	1/26/11	1/26/11	1/26/11	1/26/11	1/26/11	1/26/11	1/26/11	1/26/11	1/26/11

*Specimen was tested for MOR; **Specimen was not tested and used for demonstration purposes

UMU Sample #15 1:3 (6 x 12 x 3 5/8)									
Sample ID	#15-1	#15-2	#15-3	#15-4	#15-5	#15-6	#15-7	#15-8	#15-9
Height (in)	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63	3.63
Area (sq in)	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0
Mass Wet (lbs)	20.2	19.6	19.9	19.8	19.8	19.7	20.1	20.1	19.7
Dens. Wet (pcf)	133.7	130.0	132.0	131.1	131.0	130.3	132.9	133.2	130.7
Mass Dry (lbs)	19.6	19.1	19.3	19.2	19.2	19.1	19.5	19.5	19.1
Dens. Dry (pcf)	129.8	126.2	128.0	127.4	127.1	126.3	129.2	129.2	126.6
Moisture Content	3.0%	3.0%	3.1%	2.9%	3.0%	3.2%	2.9%	3.1%	3.3%
UCS/[MOR]* (psi)	1217	1198	142*	155*	131*	147*	153*	130*	125*
E (ksi)	57	58	NA	NA	NA	NA	NA	NA	NA
Date Made	12/20/10	12/20/10	12/20/10	12/20/10	12/20/10	12/20/10	12/20/10	12/20/10	12/20/10
Date Tested	1/31/11	1/31/11	1/31/11	1/31/11	1/31/11	1/31/11	1/31/11	1/31/11	1/31/11

*Specimen was tested for MOR

UMU Sample #11 1:3 (6 x 12 x 3 3/8)									
Sample ID	#11-1	#11-2	#11-3	#11-4	#11-5	#11-6	#11-7	#11-8	#11-9
Height (in)	3.38	3.38	3.38	3.38	3.38	3.38	3.38	3.38	3.38
Area (sq in)	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0
Mass Wet (lbs)	20.2	19.9	19.9	20.1	20.3	20.3	20.3	20.3	20.2
Dens. Wet (pcf)	143.9	141.7	141.2	142.6	144.0	144.7	144.1	144.6	143.6
Mass Dry (lbs)	19.4	19.5	19.4	19.5	19.2	19.3	19.3	19.4	19.3
Dens. Dry (pcf)	137.9	138.7	138.2	138.4	136.5	137.2	137.2	137.6	137.2
Moisture Content	4.4%	2.2%	2.2%	3.0%	5.6%	5.4%	5.1%	5.1%	4.6%
UCS/[MOR]* (psi)	1189	1167	159*	155*	171*	136*	138*	NA**	NA**
E (ksi)	46	48	NA	NA	NA	NA	NA	NA**	NA**
Date Made	12/21/10	12/21/10	12/21/10	12/21/10	12/21/10	12/21/10	12/21/10	12/21/10	12/21/10
Date Tested	2/1/11	2/1/11	2/1/11	2/1/11	2/1/11	2/1/11	2/1/11	2/1/11	2/1/11

*Specimen was tested for MOR; **Specimen was not tested and used for demonstration purposes

UMU Sample #15 1:1 (6 x 12 x 3 7/16)									
Sample ID	#15-1	#15-2	#15-3	#15-4	#15-5	#15-6	#15-7	#15-8	#15-9
Height (in)	3.31	3.38	3.50	3.38	3.38	3.38	3.38	3.38	3.44
Area (sq in)	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0
Mass Wet (lbs)	18.52	17.76	19.56	18.10	18.64	18.86	17.92	18.26	18.72
Dens. Wet (pcf)	134.2	126.3	134.1	128.7	132.6	134.1	127.4	129.8	130.7
Mass Dry (lbs)	17.82	17.04	18.86	17.40	17.94	18.12	17.20	17.52	17.96
Dens. Dry (pcf)	129.1	121.2	129.3	123.7	127.6	128.9	122.3	124.6	125.4
Moisture Content	3.9%	4.2%	3.7%	4.0%	3.9%	4.1%	4.2%	4.2%	4.2%
UCS/[MOR]* (psi)	850	593	784	62*	104*	117*	719	741	843
E (ksi)	35	35	26	NA	NA	NA	38	37	34
Date Made	1/26/11	1/26/11	1/26/11	1/26/11	1/26/11	1/26/11	1/26/11	1/26/11	1/26/11
Date Tested	2/23/11	2/23/11	2/23/11	2/23/11	2/23/11	2/23/11	2/23/11	2/23/11	2/23/11

*Specimen was tested for MOR

UMU Sample #11 1:1 (6 x 12 x 3 7/16)									
Sample ID	#11-1	#11-2	#11-3	#11-4	#11-5	#11-6	#11-7	#11-8	#11-9
Height (in)	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44
Area (sq in)	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0
Mass Wet (lbs)	18.84	18.70	18.74	18.62	18.38	18.20	18.82	18.14	18.12
Dens. Wet (pcf)	131.5	130.6	130.8	130.0	128.3	127.1	131.4	126.7	126.5
Mass Dry (lbs)	18.20	18.08	18.14	17.92	17.68	17.54	18.16	17.52	17.52
Dens. Dry (pcf)	127.1	126.2	126.7	125.1	123.4	122.5	126.8	122.3	122.3
Moisture Content	3.5%	3.4%	3.3%	3.9%	4.0%	3.8%	3.6%	3.5%	3.4%
UCS/[MOR]* (psi)	614	688	705	616	538	616	72*	69*	72*
E (ksi)	26	35	36	32	30	33	NA	NA	NA
Date Made	1/27/11	1/27/11	1/27/11	1/27/11	1/27/11	1/27/11	1/27/11	1/27/11	1/27/11
Date Tested	2/25/11	2/25/11	2/25/11	2/25/11	2/25/11	2/25/11	2/25/11	2/25/11	2/25/11

*Specimen was tested for MOR

UMU Sample #15 1:1 (6 x 12 x 3 3/8)										
Sample ID	#15-1	#15-2	#15-3	#15-4	#15-5	#15-6	#15-7	#15-8	#15-9	#15-10
Height (in)	3.38	3.38	3.38	3.38	3.38	3.38	3.38	3.38	3.38	3.38
Area (sq in)	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0
Mass Wet (lbs)	18.42	18.32	18.16	18.26	18.04	18.02	18.46	18.32	18.38	18.44
Dens. Wet (pcf)	131.0	130.3	129.1	129.8	128.3	128.1	131.3	130.3	130.7	131.1
Mass Dry (lbs)	17.72	17.62	17.48	17.58	17.24	17.16	17.70	17.54	17.62	17.68
Dens. Dry (pcf)	126.0	125.3	124.3	125.0	122.6	122.0	125.9	124.7	125.3	125.7
Moisture Content	4.0%	4.0%	3.9%	3.9%	4.6%	5.0%	4.3%	4.4%	4.3%	4.3%
UCS/[MOR]* (psi)	627	31*	607	654	514	60*	39*	68*	55*	640
E (ksi)	30	NA	31	32	28	NA	NA	NA	NA	30
Date Made	1/28/11	1/28/11	1/28/11	1/28/11	1/28/11	1/28/11	1/28/11	1/28/11	1/28/11	1/28/12
Date Tested	2/28/11	2/28/11	2/28/11	2/28/11	2/28/11	2/28/11	2/28/11	2/28/11	2/28/11	2/28/11

*Specimen was tested for MOR

UMU Sample #11 1:1 (6 x 12 x 3 3/8)										
Sample ID	#11-1	#11-2	#11-3	#11-4	#11-5	#11-6	#11-7	#11-8	#11-9	#11-10
Height (in)	3.38	3.38	3.38	3.38	3.38	3.38	3.38	3.38	3.38	3.38
Area (sq in)	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0	72.0
Mass Wet (lbs)	17.72	17.68	17.94	18.18	18.46	18.20	18.36	18.72	17.30	18.04
Dens. Wet (pcf)	126.0	125.7	127.6	129.3	131.3	129.4	130.6	133.1	123.0	128.3
Mass Dry (lbs)	17.10	16.92	16.92	17.38	17.58	17.36	17.48	17.90	16.44	17.14
Dens. Dry (pcf)	121.6	120.3	120.3	123.6	125.0	123.4	124.3	127.3	116.9	121.9
Moisture Content	3.6%	4.5%	6.0%	4.6%	5.0%	4.8%	5.0%	4.6%	5.2%	5.3%
UCS/[MOR]* (psi)	695	647	652	683	69*	82*	86*	89*	49*	664
E (ksi)	31	32	31	30	NA	NA	NA	NA	NA	31
Date Made	1/28/11	1/28/11	1/28/11	1/28/11	1/28/11	1/28/11	1/28/11	1/28/11	1/28/11	1/28/12
Date Tested	3-1-11	3/1/11	3-1-11	3-1-11	3/1/11	3-1-11	3-1-11	3/1/11	3-1-11	3-1-11

*Specimen was tested for MOR

8.3.3. Durability Testing

UMU Sample #11: Durability Results									
Sample ID	#11-11	#11-12	#11-13	#11-14	#11-15	#11-16	#11-18	#11-19	#11-20
UCS (psi)	1447	1533	1337	1415	1218	1076	1189	1124	1111
% Strain	5.7%	4.8%	5.1%	5.1%	5.0%	4.8%	5.4%	5.4%	7.1%
E (psi)	40920	46860	39050	47040	27480	25280	27470	25410	30650
Date Made	9/30	9/30	9/30	9/30	9/30	9/30	9/30	9/30	9/30
Date Tested	11/18	11/18	11/23	11/23	11/30	11/30	12/2	12/2	12/7
# Saturations	2	2	3	3	4	4	5	5	6
Corrected UCS (psi)	593	628	548	580	500	441	487	461	455

UMU Sample #15: Durability Results									
Sample ID	#15-11	#15-12	#15-13	#15-14	#15-15	#15-16	#15-18	#15-19	#15-20
UCS (psi)	1422	1384	1333	1249	1148	1045	1162	1116	1070
% Strain	5.3%	4.8%	6.0%	5.1%	5.1%	4.7%	5.5%	5.5%	7.9%
E (psi)	44365	42815	32095	28215	26985	25630	27930	25700	25510
Date Made	9/14	9/14	9/14	9/14	9/14	9/14	9/14	9/14	9/14
Date Tested	11/18	11/18	11/23	11/23	11/30	11/30	12/2	12/2	12/7
# Saturations	2	2	3	3	4	4	5	5	6
Corrected UCS (psi)	583	567	546	512	471	428	476	458	439