Earthen Construction Initiative
www.earthenci.org

AIA Upjohn Research Initiative Grant - 2020

Mix Design Guidance and Testing for Stabilized Compressed Earth Block (SCEB) Units

July 15, 2022
Final Report

PREPARED FOR:
AIA Upjohn Research Initiative Grant - 2020

PREPARED BY:
Earthen Construction Initiative
P.O. Box 18498
San Antonio, Texas 78218

Earthen Construction Initiative
www.earthenci.org

AIA Upjohn Research Initiative Grant - 2020

Mix Design Guidance and Testing for Stabilized Compressed Earth Block (SCEB) Units

Principal Investigators:

Lauran Drown, AIA
Wiss, Janney, Elstner Associates, Inc.

Michael Donoghue, PE
Maritech Engineering, Inc.

Collaborators:

Celia Mendoza, RA
Arquitecta / Project Administrator

Ron Evans
De la Tierra Rammed Earth Structures / Advisor

Jim Hallock
Earth Block Texas / Advisor

July 15, 2022
Final Report

PREPARED FOR:
AIA Upjohn Research Initiative Grant - 2020

PREPARED BY:
Earthen Construction Initiative
San Antonio, Texas 78218

CONTENTS

PREFACE

This study was undertaken by Earthen Construction Initiative (ECI), a 501(c)(3) non-profit educational organization dedicated to the advancement and promotion of earthen construction building technologies. The principal investigators and collaborators involved in this study are all members of ECI. ECI board members, members at-large and other friends of earthen construction not directly named also graciously supported this project by volunteering time to meet, make blocks, and peer review this study.

INTRODUCTION

The future entreats us to find new materials and processes, and to rethink or reimagine old ones that are more in harmony with the environment. This study is about reimagining on of the oldest materials for building – earthen, or unfired soils-based material sources. Earthen building systems, such as adobe, rammed earth, and compressed earth blocks (CEBs), offer an extremely low-carbon, and thermally resilient alternative to conventional building systems.

However, a lack of tested standards for quality assurance and no commercially available mixes specific to earthen construction present barriers to wider adoption of the materials. Individual architects, engineers, contractors, and owners must determine how and where to procure and process materials - adding time, costs and risk to their projects. CEBs are an increasingly popular construction method in Texas and other regions, however, the CEB block-making process is often trial and error, and difficult to replicate.

To address this, ECI seeks to advance the practice of earthen materials selection and design by developing a Mix Design Guide for reliably and repeatedly fabricating stabilized CEBs using commercially available machinery and appropriate testing methods. This Guide will be geared toward streamlining unit fabrication to facilitate wider adoption of earthen construction, in the US and beyond. The research and testing supported by the AIA Upjohn Initiative Research Grant has laid the groundwork for ECI to develop the Guide and is the subject of this report.

CEBs Defined

Compressed earth blocks (CEBs) are a type of load-bearing masonry unit formed by mechanically compressing a specified soil mix containing sand and clay into modular blocks. The blocks are unvitrified (not fired in a kiln). Hydrated lime, ordinary portland cement, or both lime and cement, are typically added to the mix to augment the structural and weatherization properties of the blocks. Such blocks are often called stabilized CEBs or SCEBs. However, the term CEB does not preclude the addition of stabilizer.

Compressed earth blocks are used to build residential and commercial structures, most often one or two stories in height, and most often in areas of low seismic activity. CEBs are used for load-bearing walls, and for the exterior envelope. CEB walls are laid on a concrete stem wall six inches above grade and over a suitable foundation with adequate site grading and drainage. Units are laid in running bond pattern and mortared together using a compatible mortar. The exterior surface of the blocks is recommended to be rendered with lime stucco or mud plaster (cement stucco is not recommended due to its proclivity to trap moisture). CEB walls are recommended to be sheltered by roof overhangs, or by a metal coping at parapet walls. Arches, domes, and vaults are often incorporated into CEB masonry structures and sometimes fired brick is used for these features or incorporated as accents. Interior partitions can be built of CEB units, however, as CEB walls are thicker and heavier than frame walls, wood frame partitions may also be incorporated into CEB structures. Interior surfaces may be rendered with lime plaster, mud plaster, or left exposed. In colder climate zones, exterior insulation may be incorporated into the design of CEB walls.

Exposed surfaces of CEB walls (including those rendered with lime stucco) help to regulate indoor air temperatures through their ability to absorb, store, and radiate heat. Due to their clay content, CEBs also have the ability to absorb and release water vapor further contributing to indoor air quality and occupant comfort by modulating interior humidity fluctuations. The thermal and hygroscopic properties of CEB walls, particularly on buildings that are sited to account for their solar orientation, also contribute to reduced mechanical heating and cooling loads. This, plus the low-embodied energy content of the material makes them particularly suitable to resilient and sustainable applications.

Research Progress Summary

ECI conducted this research with a selected benchmark soil and stabilizer. However, we originally envisioned starting with several different soils, conducting soils analyses, and then choosing two or more ideal soils to compare. In the interest of time, we pre-selected a local soil proven to be appropriate for earthen construction. Soils analyses were performed on a parallel track during block making. The results did not inform our soil selection but rather highlighted the need for further research on earthen materials and further development of soils analyses techniques. This project is divided into the following phases:

- Soils Analyses Tools Development
- Phase I: Materials Selection and Unit Fabrication
- Phase II: Mechanical Testing of SCEBs

Phase I includes discussion of the selected materials for our soils mix the mixing technique as well, equipment, fabrication, curing, and transport. Phase II includes the testing preparation and procedures, testing results and the interpretation of the data.

SOILS ANALYSIS TOOLS DEVELOPMENT

A reliable grasp of materials is required for rational structural design. In construction and in most industries, the first steps of material selection and use are provided in the Quality Assessment (QA) phase. Monitoring, of materials, constructed quality, and conformance to design requirements are carried out under Quality Control (QC). Contemporary model codes build QA/QC protocols directly into the body of the code as exemplified by the International Building Code's (IBC) Chapter 17 Special Inspections and Tests. While included in IBC Section 2109, earthen construction does not have its own corresponding special inspections and testing in Chapter 17.

To advance the state of the craft and technology and realize earthen building's environmental potentials, a credible set of QA/QC tools for assessing, understanding, tracking, and monitoring materials incorporated in earthen construction is needed. This work proposes a prototype set of QA/QC tools to begin to develop a sound basis for characterizing earthen building materials before and during construction. A summary of the protype tools is provided below:

- **Calibrated Jar Series Test (CJT).** The CJT is proposed as an early "size-up" tool to assess basic qualities of an earthen source material and its response to deflocculants, if used. Deflocculants are substances that inhibit the clumping of particles. The CJT is also presented as a practical means of monitoring and recording materials as they are delivered and flow through the manufacturing process.

- **Methylene Blue Test (MBT).** The MBT is for assessing the basic clay types in a soil. Understanding of the clay types is fundamental to assessing the reaction of the materials to water, the type of binders present naturally, their binding power, and the selection and effectiveness of supplementary materials.
- **Mix Design Process (MDP).** The MDP has been a source of continual development and some debate in the concrete industry for more than a hundred years. One idea has emerged: a sound mix is not one thing but the marriage of two: the paste and the aggregate. To emphasize that the mix design is co-dependent, we put the two tests under the one heading: MDP.
  - **The Skeleton** is the stylized description of the compacted force-carrying component of an earthen body – largely constituted by the coarse aggregates in a mix. The Skeleton relies on the traditional use of the coarse grain-size distribution (GSD) of a soil. Having a quantitative grasp of a soil mix's GSD is fundamental to using the material effectively. The Skeleton focuses on optimizing the distribution of particles to create a more effective mixing process and more continuous transmission of forces, through force chains, in the earthen mass.
  - **The Cupcake Test (CCT)** The paste in a mix acts as the binder holding the particles in the skeleton together. The paste is meant not to carry forces directly but to restrain the well-packed coarser materials thus forming the integrated whole. An efficient paste optimizes the amount and type of lubricating, adhering, and space filling medium in the mix as measured by the optimum moisture content and maximum density of a paste/aggregate mixture. The results of the CCT may be helpful in many ways, but primarily it is proposed as a means of developing the targets for optimum density and water-to-binder ratio in a mix.

These tests are in development. We anticipate that future research will include employing these tests on a larger range of soil types.

A further exploration of the tests related to the analysis of soils undertaken for this report (Sieve Analysis, MBT, and CCT) is provided in Appendix A.

PHASE I: MATERIALS SELECTION AND UNIT FABRICATION

The manufacture of CEB units involves soils selection and procurement, materials storage, materials mixing, block making, curing, and storing of the completed units until they are ready to be used in construction or transported to a site. With extremely few full-scale production yards in the US, the process of CEB production typically occurs as a temporary mobilization at or near to the building construction site, or at the soils extraction site. The temporal nature of the process comes with inherent limitations on the efficiency and cost effectiveness of block making, as well on the ability to ensure quality control. A performance-based Mix Design Guide would potentially help to offset some of these factors.

Soils Selection

Stabilized CEB mixes consist of three elements: soil, stabilizing agents, and water. Soil constituents include aggregates, silts, and clays, each with a specific function. Generally, sand and larger aggregates form the "skeleton" of the block with clays and silts filling in the interstitial spaces of the skeleton and binding it together. Clays, in particular, with such tiny particle sizes, serve a unique function as a micro-level hydro-electrostatic binder between the larger particles.

For this study, we selected two soil matrices for unit fabrication:

- Soil A: Screened Red Soil obtained from Freddie Harris Sand and Clay (FH)
- Soil B: 66% Screened Red Soil (FH) and 33% decomposed granite (DG) screened to 3/8-inch minus

Soil A was selected as the baseline soil matrix upon the recommendation of a local earthen contractor involved as a collaborator in the project, Ron Evans of De La Tierra Builders. It is a locally sourced material that is simply mined and screened from a nearby quarry located in Von Ormy, Texas. Choosing a baseline soil that was not a blend imparted consistency to our study and the potential for future replication. The reported clay content of Soil A is approximately 15 to 20%. It is commonly used for baseball infields.

Soil B is a blended variation on Soil A with the addition of coarse aggregate. The coarse aggregate used was decomposed granite screened by our team to 3/8-inch minus, meaning that particle sizes ranged from fines up to just under 3/8 inch. The decision to include coarse aggregate in a range of particle sizes is based on the theory of optimized grain sized distribution.[1] After initially trying a 1:1 ratio of FH to DG (by volume), we decided on a 2:1 ratio, with Soil B consisting of 66% FH and 33% DG. The 2:1 ratio produced more uniform blocks than the 1:1. Due to the addition of aggregate, the expected clay content of soil B is approximately 10 to 13%.

Stabilizer Selection

Cement and lime are the two most common stabilizing agents used to help stabilized CEBs achieve strength and durability. They can be used separately or in combination. Cement stabilization for CEBs works similarly to that of concrete, binding the sand and other aggregate particles together. Lime stabilization works differently in that lime reacts chemically with the clay particles making them bond together.

While lime is generally considered more sustainable for its lower carbon footprint, we ultimately chose to work with ordinary portland cement (OPC) as the stabilizer for several reasons. OPC is more commonly used in stabilized CEBs, more readily available than lime, and is more familiar as a starting point from its use in concrete.

For each soil matrix, we manufactured four series of blocks varying the amount of OPC from 0%, 3%, 5% and 7% by weight, See Table 1 below. These increments were chosen from a desire to optimize the use of stabilizer without compromising defining characteristics of soil blocks, such as water vapor transmission. (Normal concrete, by contrast, typically contains 10 to 15% OPC.)

Water

Water is an important element serving multiple functions. Moisture, always present in soils to some degree, aids the workability by acting as a lubricant between particles so that it can be handled and processed into blocks. When a hydraulic binder is present, water also reacts chemically with the stabilizing agent to harden or cure the unit. Too much water will lower the density and porosity of the mix and may prevent the units from compressing properly. The moisture content of the soil mix in SCEB production is generally recommended to be no greater than 10%. The optimal water content for a given mix will depend on the soil

---

[1] Research out of Oklahoma State University combined particle packing theory for maximum density with grain-size distribution gaps in the mid-sized particle fraction. Their work indicates that allowing any one grain-size to exceed about 20% of the soil profile upsets the mix balance and leads to premature fracture and cascading failure.

type and aggregate size, as well as the ratio of stabilizer used. The optimum water content in our blocks was confirmed by the observation of two experienced builders, project collaborators Mr. Evans, and James Hallock of Earth Block Texas. Potable water was added with a hose after the addition of the soils and OPC in the mixer.

Table 1. Block Series

	Block Series	Screened Red Soil (FH)	Coarse Aggregates (DG)	Inherent Soil Clay Content	Stabilizing Agent (OPC) by weight
Soil A	**A0**	100%	0%	15-20%	None
	A1	100%	0%	15-20%	3%
	A2	100%	0%	15-20%	5%
	A3	100%	0%	15-20%	7%
Soil B	**B0**	66%	33%	10-13%	None
	B1	66%	33%	10-13%	3%
	B2	66%	33%	10-13%	5%
	B3	66%	33%	10-13%	7%

Block Series and Fabrication

Block fabrication for this study took place in Fredericksburg, Texas. The dimensions of units fabricated for this study was 12 inches long by 6 inches wide by approximately 3-5/8 inch (to allow for a 3/8-inch mortar joint). The actual height of the blocks varied based on the series that was being fabricated due to manual control for the machine settings. However, the standard deviation for the blocks within each series was low. See Table 2.

Table 2. Block Series Manufactured for Mechanical Testing

Block Series	Stabilizing Agent (OPC)	Manufacture Date	Average Block Weight (lbs)	Average Block Height (in)	Standard Deviation in Height (in)	No. of Units Produced
A0	None	7/24/2021	16.3	3.73	0.04	16
A1	3%	7/24/2021	16.0	3.42	0.14	18
A2	5%	7/24/2021	16.9	3.61	0.06	20
A3	7%	8/07/2021	17.0	3.61	0.02	20
B0	None	8/07/2021	17.9	3.88	0.11	17
B1	3%	8/07/2021	18.9	3.96	0.07	17
B2	5%	8/28/2021	17.4	3.52	0.07	18
B3	7%	8/28/2021	17.2	3.45	0.05	22

Materials Mixing

Materials mixing is commonly achieved through the use of mechanical equipment, namely of a drum-type concrete mixer or tumbler. With a moisture content of up to 10%, CEB mixes are stiff, low-slump mixes that tend to stick to the walls of a drum mixer causing the particles to be unevenly distributed. While mixing time is important, increased mixing times in this type of mixer do not tend to improve the distribution of particles. For SCEBs, this can result in uneven stabilization of the units and can be evidenced by visible agglomerations of uncured stabilizing agent in fabricated blocks. In an attempt to counter this, manufacturers may add extra stabilizer with or without measure, driving up materials costs while driving down the block's sustainable attributes.

To fabricate units for this study, we used the Imer Mix 360, a vertical shaft mixer with two fixed rotating blades and a planetary arm with 3 counter-rotating paddles. The planetary arm is unique to Imer brand mixers. Conventional paddle mixers lift and drop paddles into the mix, but this mixer's paddles rotate through the mix, increasing mixing speed and efficiency, particularly for low slump materials. The Imer Mix 360 can mix up to 9 ft^3 in less than 5 minutes. The mixer's maximum aggregate size is 3/8 inch minus.


Figure 1. Imer Mix 360.


Figure 2. AECT Impact 2001A.

Block Making

Advanced Earthen Construction Technologies (AECT) produces a number of hydraulic press CEB machines and is based in San Antonio. We used AECT's smallest model, the Impact 2001A, which produces blocks that are 6 inches by 12 inches, with block height adjustable from 2 inches to 4.5 inches. Material from the hopper is gravity fed into the block press chamber and the hydraulic arm of the machine presses the soil mix from below. One seeming advantage of the 2001A is that the blocks are pressed in the same direction that they are intended to be loaded in a wall.

While advertised to produce up to 300 blocks per hour, the 2001A's actual output rate is controlled by the hopper capacity which can hold soil for about 8 to 9 blocks at a time. Unless soil is continually added to the hopper, the last block in a run is usually sacrificial as it will contain less material than required. Soil spillage from the press operation can be recovered via a bucket or tarp for immediate reuse only as delayed reuse of stabilized material can result in hydration reactions occurring before the block has been pressed. Recovery from the bare ground risks contaminating the blocks with organic matter or other foreign material. A good rule of thumb to guide reuse of material is "when in doubt, leave it out."

For each block series, we mixed approximately 4 to 5 cubic feet of material to produce a minimum of 16 blocks with a target height of 3-5/8 inches for testing. This included a 1.4 factor for material waste due to the mixing and manufacturing processes.

For the Impact 2001A, the machine controls include the uncompacted volume of soil permitted to enter the press chamber, and the line pressure of the hydraulic press. Adjusting these settings results in changes to unit height and unit density. It is important to note that the line pressure, measured in pounds per square inch (PSI), is not equivalent to the pressure exerted on the soil in the press chamber, due to loss of mechanical friction. It is also important to note that the pressure exerted on the soil in the chamber to press a block into shape is not the same as the compressive strength of the block. These numbers are sometimes conflated by machine users.

For our operation, the machine's throttle was lowered to reduce the air pressure in the press chamber as the soil mix was compressed. This was based on our theory that if high pressure is established during compression (because of high speed in an enclosed chamber), high pressure will remain in the voids of the block and cause micro- and/or macro-cracking of the block.

Blocks were brushed with a soft-bristle brush as they came out of the machine to remove any excess particles. Blocks were then transported by hand to a nearby plastic pallet and placed in the same orientation as they were pressed. We manufactured a minimum of 16 units for each of the eight series of blocks noted above. Blocks were stacked up to four high on a pallet.

Block Curing, Storage and Transport

Palletized blocks were misted with water from a hose and covered in plastic stretch wrap within one to four hours after fabrication. The pallets were then covered with a black plastic tarp for protection as they remained outside. Condensation was typically visible on the inside of the plastic wrap after two weeks' time (the interval between block-making sessions when volunteers returned to the site). There are varying schools of thought on whether plastic wrapping the blocks is necessary for curing; observation of condensation led us to believe that moisture in the blocks had not evaporated early and that hydration had occurred.

Blocks were transferred by car approximately 100 miles to the materials testing laboratory facility at Wiss, Janney, Elstner Associates (WJE) in Austin, Texas. No blocks were broken or cracked during transport, although a few blocks were accidentally broken or found to have micro cracks during testing. The cured blocks were stored on end on plastic pallets in an insulated, unconditioned metal storage building prior to testing. They were stored this way to provide ease of view and access. Surfaces of the blocks were coated with white spray paint to facilitate labelling with permanent marker for tracking during the testing phase.

Figure 3. Sample SCEB units in WJE's lab storage annex.

Figure 4. Sample SCEBs being viewed outdoors.

Figure 5. A0 (unlabeled) and A1 block runs.

Figure 6. A2 and A3 block runs.

Figure 7. B0 and B2 block runs.

Figure 8. B1 and B3 block runs.

PHASE II: MECHANICAL TESTING OF CEBS

Mechanical Testing Program

Testing of the CEB units took place at WJE's materials testing laboratory between October 2021 and April 2022. Testing was originally intended for early block ages to consider early strength-gain correlations; however, this was infeasible due to project logistics. Spitting tensile and unit compressive strength testing for the eight series of blocks was divided into two rounds. This was partly in consideration of potential late-age strength-gain correlations, and partly for the opportunity to apply lessons learned from the first testing round to the second round if changes or corrections needed to be made. In the end, however, no changes were made between the two rounds of testing.

The testing program was designed to evaluate the compressive strength and splitting tensile strength of eight different block mixes, which included two soil matrices with incremental additions of OPC, and two unstabilized control groups (See Table 1, above). Compressive strength, as measured by standardized cylinders, prisms, or other geometries, is a universally accepted measure by which to specify the quality of masonry units and concrete, as well as a basic parameter required by engineers for rational structural design. Tensile strength is an important indicator of the compressive strength capacity as compression induces indirect tensile stresses.

One of the primary testing goals was to determine the minimum amount of OPC required to stabilize a given soil mix for adequate in-wall structural performance. A secondary goal of testing was to observe the relationships between test-type results. As tensile strength testing requires significantly less applied load than compressive strength testing, it could potentially be developed and used as an indirect indicator for unit compressive strength for quality control testing in the field. Both individual units and constructed prisms were tested for compressive strength in consideration of appropriate aspect ratio correction factors for CEBs.

The 2015 New Mexico Earthen Building Materials Code, and the 2021 International Building Code (IBC) state that the minimum required compressive strength for cured CEB units (including unstabilized) is 300 pounds per square inch (PSI). As a minimum standard, this does not imply that 300 PSI is a useful or safe design strength for any given application, just that it is the lower bound at which the material was tested in developing code provisions. Furthermore, CEB unit sizes vary widely, and this requirement fails to account for the effect that specimen geometry, namely the aspect ratio, has on compressive strength calculations.

To determine unit compressive strength, a load is applied uniformly through two steel platens perpendicular to the bed surface of a single unit and increased at a given rate until failure results. Prior to failure, as the load is applied, the specimen expands laterally between the platens. Due to friction at the interface between the platen and the specimen, the lateral expansion is restrained resulting in an artificial increase in the apparent strength of the unit. This is referred to as the confined compressive strength. For a given specimen width, as the distance between the platens relative to the specimen height increases (aspect ratio), the restraint effect is reduced[2]. To account for this, aspect ratio correction factors must be used. While there are established aspect ratio correction factors for concrete and fired brick materials, these are not necessarily appropriate for CEBs.

---

[2] Jean-Claude Morel, Abalo Pkla, Peter Walker, "Compressive strength testing of compressed earth blocks," *Construction and Building Materials*, Volume 21, Issue 2, 2007.

The compressive strength of individual masonry units can be a useful measure for a relative analysis of block qualities, but cannot necessarily provide or predict the in-wall performance capacity of those units that in a wall would be joined with mortar. The testing of prisms provides a better model for in-wall performance by increasing the slenderness of the specimen relative to its height, thereby reducing the effect of platen restrain, and by including mortar joints to better replicate field conditions. *ASTM C1314: Standard Test Method for Compressive Strength of Masonry Prisms,* written for fired brick masonry, prescribes testing of prisms made of two masonry units mortared together vertically. The RILEM Technical Committee 164: Mechanics of Earth as a Building Material recommends a procedure for CEBs that similarly includes a prism of two units. For our study, we chose prisms constructed of three blocks stacked vertically with two mortar joints to replicate in-wall performance more closely.

The tests performed are listed in Table 3 below. As established testing methodologies for earthen materials do not exist, standard testing procedures for fired brick or concrete are generally adapted.

Table 3. CEB Structural Testing Program

Test Method	**Description / Rationale**	**Modifications**
ASTM C1006: Standard Test Method for Splitting Tensile Strength of Masonry Units	This test produces a line load along the bed surface of the unit to determine the maximum stretching load that a block can support without fracturing. Potentially, it can be used as an indirect measure of compressive strength.	A custom alignment jig was fabricated to accommodate the unit dimensions. Capping compound to adhere the 5/16-inch bearing rod to the unit was omitted after it was found to artificially increase the values.
ASTM C67: Standard Test Method for Sampling and Testing Brick and Structural Clay Tile; Test Method 7: Compressive Strength	To determine unit compressive strength, a load is applied perpendicular to the bed surface of a single unit and increased at a given rate until failure in compression results.	This test was performed on half-block units. The top and bottom of units were capped with plaster of paris to obtain parallel bearing surfaces.
ASTM C1314: Standard Test Method for Compressive Strength of Masonry Prisms	This test method provides a means to evaluate the compressive strength characteristics of in-place masonry units as opposed to individual units.	This test was performed on a prism of three half-block units stacked and mortared vertically. The top and bottom of prisms were capped with plaster of paris to obtain parallel bearing surfaces.

The machine used for the compression testing was Test Mark Industries model number CM-2500-SD. For each block series, splitting tensile tests were performed on whole block units (Figure 9 and Figure 10). Compressive strength tests were then performed on the half-block units obtained after the splitting tensile tests were completed (Figure 13, Figure 14, Figure 19, and Figure 20). The use of half blocks in this manner of testing followed the recommendation of the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM) Technical Committee 164: Mechanics of Earth as a Building Material. Recovery of half blocks provided efficiency in the production, transport, and storage of less blocks, and increased the slenderness ratio for the prism specimens.

For each block series, the test set included twelve splitting tensile tests, six unit compressive strength tests, and four to six prism compressive strength tests (depending on breakage). Mortar used for the prisms consisted of a 1:3 ratio of hydrated lime and the same screened red soil used in the blocks. This mortar was chosen to ensure its compressive strength would be lower than that of any of the stabilized blocks. Mortar joint sizes were approximately 3/8-inch on average. Prisms were tested sixty or more days after being mortared. Mortar cube samples were also tested for compressive strength per ASTM C109.

Mechanical testing was carried out by the laboratory personnel at WJE with some assistance or observation by the primary investigators, Michael Donoghue and Lauran Drown. To control costs, Mr. Donoghue was responsible for capping the samples and mortaring the prisms, with assistance provided by other ECI team members. For convenience, the prisms were constructed off site and transported back to the lab, which resulted in breakage of some samples.

Figure 9. A splitting tensile test set up on an A3 series block prior to loading.

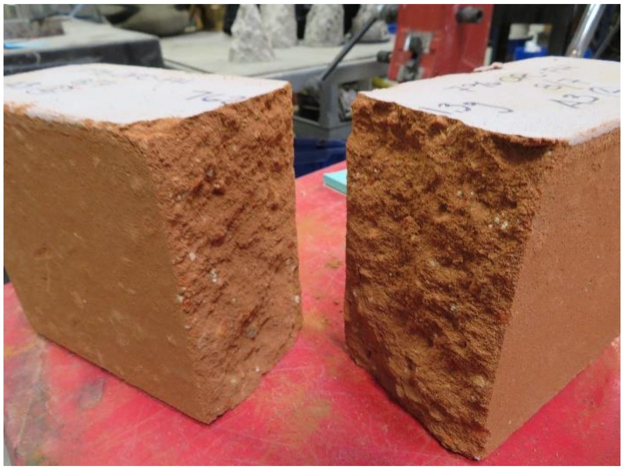


Figure 10. An A3 series block after a splitting tensile test.

Double-click to insert picture

Figure 11. Side view of a B2 series block after a splitting tensile test.

Figure 12. A B2 series block after a splitting tensile test.

Figure 13. An A3 series block during C67 testing.

Figure 14. An A3 series block after loading to failure during C67 testing.

Figure 15. A B2 series block during C67 testing.

Figure 16. A B2 series block after loading to failure during C67 testing.

Figure 17. A2 series prism 6-5-6 prior to C1314 testing.

Figure 18. A2 series prism 6-5-6 after C1314 testing, and being dissected to determine the failure mode. The failure mode was classified as “cone and shear”.

Figure 19. B2 series prism 5-5-6 prior to C1314 testing.

Figure 20. B2 series prism 5-5-6 after C1314 testing, and being dissected to determine the failure mode. The failure mode was classified as “cone and split”.

Mechanical Testing Results

Averages of the results obtained across all block series are shown in Table 3 below. Complete results for each block series are provided in Appendix B. In accordance with the respective ASTM test standard reporting procedures, splitting tensile values are rounded to the nearest 5 PSI and compressive strength values are rounded to the nearest 10 PSI.

The mortar used form prisms consisted of a 1:3 ratio of lime to FH soil. Four mortar cube specimens were tested at a minimum age of 75 days per ASTM C67. The average compressive strength value was 260 PSI.

Table 4. Average Values Across All Block Series - All Test Ages

Block Series	Cement by Weight	Average Density (LBS/ft^3)	Avg. Unit Splitting Tensile Strength (PSI)	Avg. Unit Compressive Strength (PSI)	Avg. Prism Compressive Strength (PSI)
A0	0%	105.0	5	160	60
A1	3%	112.6	15	520	180
A2	5%	112.5	35	730	370
A3	7%	113.0	35	720	410
B0	0%	111.1	5	170	60
B1	3%	114.5	10	410	150
B2	5%	118.9	30	940	380
B3	7%	119.9	30	1060	410

Table 5 below shows the relationships between the values for tensile strength and prism compressive strength, and between the values for unit compressive strength and prism compressive strength given in Table 4. The aspect ratio of units to prisms was 2:1.

Table 5. Relationships Between Values

Block Series	Cement by Weight	Average Density (LBS/ft^3)	Tensile Strength as a Percent of Unit Compressive Strength	Prism Compressive Strength as a Percent of Unit Compressive Strength
A0	0%	105.0	3%	38%
A1	3%	112.6	3%	35%
A2	5%	112.5	5%	51%
A3	7%	113.0	5%	57%
B0	0%	111.1	3%	35%
B1	3%	114.5	3%	37%
B2	5%	118.9	3%	40%
B3	7%	119.9	3%	39%
		Average	**3.5%**	**42%**

Testing for splitting tensile strength and unit compressive strength was performed in two rounds with an average of about three months' time between the two rounds. Table 6 below illustrates the relationship of unit compressive strength values between the earlier and later testing ages. Initial reported values used to calculate the average per age, and the average per age values were both rounded to the nearest 10 PSI.

Table 6. Late-Age Strength Gain Correlations

Block Series	Cement by Weight	Unit Age at Test (Days)	Avg. Unit Compressive Strength (PSI)	Percent Increase in Strength Between Ages	Difference Between Ages (Days)
A0	0%	150	130	38%	71
A0	0%	221	180		
A1	3%	100	470	21%	121
A1	3%	221	570		
A2	5%	100	560	61%	121
A2	5%	221	900		
A3	7%	109	590	42%	98
A3	7%	207	840		
B0	0%	136	140	50%	71
B0	0%	207	210		
B1	3%	109	340	41%	98
B1	3%	207	480		
B2	5%	111	780	41%	75
B2	5%	186	1100		
B3	7%	111	830	53%	75
B3	7%	186	1270		
			Average	**44%**	**91**

Analysis and Discussion

Key observations made from the data include:

- The unstabilized A0 and B0 control groups performed nearly identically in each test category with a virtually negligible strength increase (10 PSI) noted in the B0 blocks for unit compressive strength.
- In general, the B series blocks exhibited higher strengths than the A series blocks for each test and stabilization level, with one anomaly being that the B1 specimens tested lower than their A1 counterparts in all tests. B1 specimens exhibited a coefficient of variation (CoV) of 2 when tested at 109 days, and a CoV of 8 when tested at 207 days, indicating low scatter. These results appear to indicate that for similar high-aggregate mixes with under 15% clay, the ideal OPC stabilizer content would be 5% minimum.
- In general, for both Group A and Group B, the recorded values trended upward with increase in percentage of OPC, with one anomaly being that the A2 specimens slightly outperformed the A3 specimens for unit compressive strength in the later testing age only (see Appendix B). The late-age average unit compressive strength value of the A2 specimens was 900 (tested at 221 days) and of the A3 specimens was 840 (tested at 207 days). These results may indicate that there is limited strength gain

obtained between 5% and 7% additions of OPC stabilizer for similar mixes with low particle size distribution and over 15% clay content.

- The tensile strength values were 5 PSI higher for each OPC-augmented series of the A group than for the B group. For both A and B groups, the tensile strength values did not increase with the increase in OPC content from 5% to 7%. These results appear to indicate that the clay content of the blocks contributes more significantly to their ability to resist tensile stress than does the particle size distribution of the aggregates. For reference, RILEM indicates that usual tensile strength values for tested adobe/CEB units have been observed to be around 0.2 MPa (29 PSI)[3]. (Note that adobes contain significantly more clay than CEBs, and often contain textural binders such as straw.)
- The data set for tensile strength value expressed as a percentage of unit compressive strength ranged averaged at 3.5%. For reference, RILEM indicates that tensile strength values of tested adobe/CEB units have been observed to be around 10% to 20% of the compressive strength for a given specimen type. This difference can likely be attributed to the grouping together of adobes and CEB in the RILEM data.
- At least one prism failure may have been prematurely induced by cracking due to handling, for which the data was discarded. At least two failures were observed to originate along the mortar bed joint (specimens A1: 2 4 4 and A1: 6 7 6), however the strengths achieved were not out of line with other data in the set, which would be expected for compression testing of a prism specimen.
- The mode of failure of the prisms (provided in Appendix B) followed similar failure modes seen in other tests of both concrete and other earthen masonry tests. The most common modes of failure included conical shear (type 1), cone and shear (type 2), and cone and splits (type 3).
- On average for all of the block series, a striking 44% increase in compressive strength values was observed between the earlier and later age of testing. This increase occurred even for the A0 and B0 block series, which did not contain cement. The average change between the two ages of testing was 91 days, about three months. This phenomenon of late-age strength gain does not appear to be associated with continual hydration of cement, but may be due to soil suction effect. The negative pore water pressure created within the block due to the effect of drying causes a suction pressure between the soil particles, which is up to 1000 times greater between clay particles than sands. RILEM has reported that strength reduces as moisture content increases[2]; our results shows that the reverse is also true: strength increases as moisture content decreases.
- Average prism compressive strength values for the A2s and B2s were nearly identical, and average compressive strength values for the A3s and B3s were identical. This was unexpected and it may be that the softer mortar was controlling the upper bounds of the prism strengths.

Code Requirements and Correction Factors

All of the stabilized CEB specimens tested exceeded the minimum 300 PSI required by IBC for individual units. However, this requirement is rather arbitrary since it fails to account for the effect of unit aspect ratio.

The City of San Antonio’s 2018 building code contains local amendments to the IBC concerning Empirical Design of Earthen Wall Systems, Section 2109. These amendments, authored by ECI in 2018, revised the

---

[3] Antonin Fabbri et al. *Testing and Characterization of Earth-based Building Materials and Elements: State of the Art Report of the RILEM TC 274-TCE,* 2022.

article of code relating to the compression strength requirement, and provided a table of correction multipliers for test values to promote consistency between comparative results. The revised article is provided below:

> **2109.2.1 Characteristic compressive strength,** $f`_e$**.** *Earthen construction* units shall have an average characteristic compressive strength as required by design but not less than 150 psi (2068 kPa). Five samples shall be tested in accordance with ASTM C67 and characteristic compressive strength for each unit shall be determined by multiplying the result by the correction multiplier provided in Table 2109.2.1. No individual unit is permitted to have a characteristic compressive strength of less than 125 psi (1724 kPa).
>
> **TABLE 2109.2.1**
>
> **PRISM STRENGTH CORRECTION FOR CHARACTERISTIC COMPRESSIVE STRENGTH,** $f`_e$

Test Unit Height to Least Width Ratio H/W	ASTM C67 Correction Multiplier
<=0.5	0.50
0.70	0.60
1	0.70
1.5	0.75
2	0.77
3	0.95
4	1.00

The average results of the unit compressive strength analysis corrected according to this table are provided in Table 7 below for reference. According to the amended code, all of the stabilized CEB specimens again exceed the minimum requirement, this time of 150 PSI.

Table 7. Average Unit Compressive Strength with Applied Correction Factors

Block Series	Cement by Weight	Avg. Unit Compressive Strength (PSI)	H/W Ratio	Correction Factor	Corrected Value (PSI)
A0	0%	160	0.63	0.6	96
A1	3%	520	0.56	0.6	312
A2	5%	730	0.61	0.6	438
A3	7%	720	0.60	0.6	432
B0	0%	170	0.65	0.6	102
B1	3%	410	0.66	0.6	246
B2	5%	940	0.59	0.6	564
B3	7%	1050	0.58	0.6	630

Correction factors help to evaluate test specimens with more reliability against the accepted required value. However, the accepted value itself needs reconsideration. 300 PSI, or 150 PSI with the above correction factors applied, is seemingly a rather low benchmark for stabilized CEBs as it was exceed by at least of factor of 2 for all OPC levels in this study.

Material durability is another factor that is signaled by the minimum compressive strength value. With low stabilizer ratios, CEBs maintain a measure of friability at the surface and can be vulnerable to erosion when exposed to weather. Durability to repeated wetting and drying, to wind erosion, and to freeze thaw for some climates, is important. Durability testing represents an area of further research we would like to carry out on the remaining block specimens. Measuring the relative durability of our block mixes will help us to establish more rationalized minimum performance standards for tensile strength and compressive strength.

Statistical Resampling

Statistical resampling was used to interrogate the data by block series for each set of test values. Test values were plotted with OPC stabilizer content by weight along the x-axis and compressive strength values along the y-axis. A normal data distribution was assumed, and a 95% confidence interval was computed by calculating the mean and two standard deviations from the mean for each value set. In each graph, the green line represents the mean, and the light green shaded area predicts the bounds within which 95% of the test data for the soil sample would fall into.

Note that for each graph, the mean curve appears to peak around 6% OPC content. Since there is no data in this study for 6% OPC content, the mean curve is based off of data points at 5% and 7% benchmarks only, forcing the peak. Looking beyond the distraction of this curvature, the graph illustrates clearly that the increase in strength between 3% and 5% OPC is notably greater than the increase in strength between 5% and 7% OPC. This visual model is consistent with the observations provided above: for both soil mixes A and B, a 5% OPC content may be optimal in terms of strength, cost, and preservation of other soils characteristics.

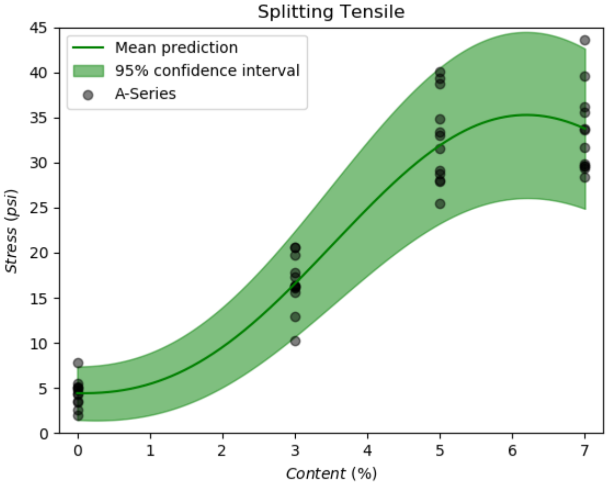


Figure 21. A-Series Tensile Strength Values.

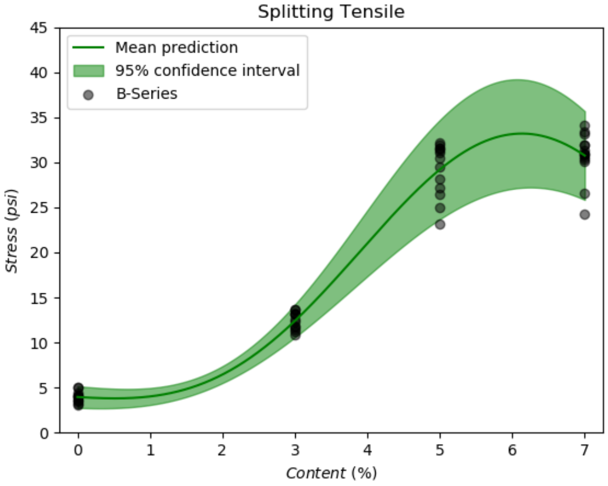


Figure 22. B-Series Tensile Strength Values.

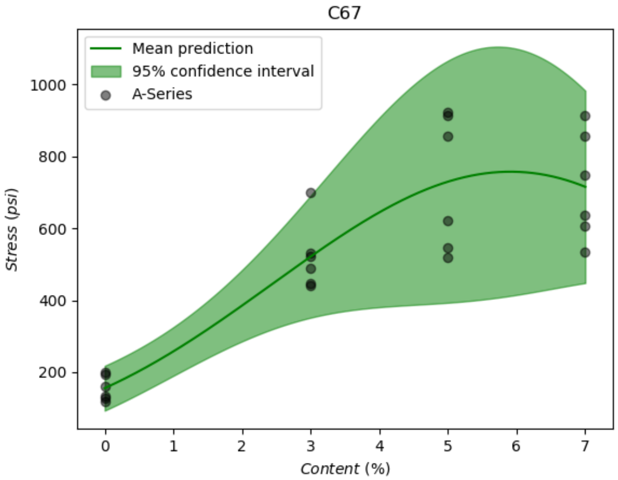


Figure 23. A-Series Unit Compressive Strength Values.

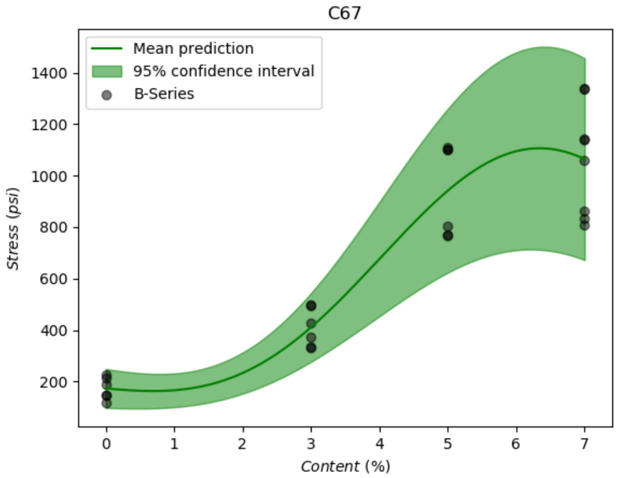


Figure 24. B-Series Unit Compressive Strength Values.

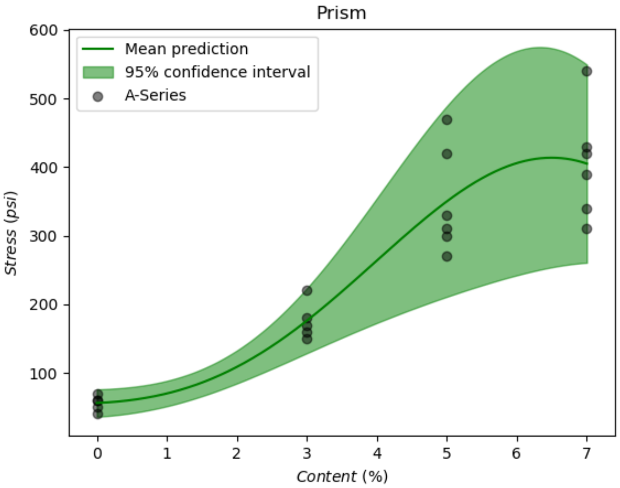


Figure 25. A-Series Prism Compressive Strength Values.

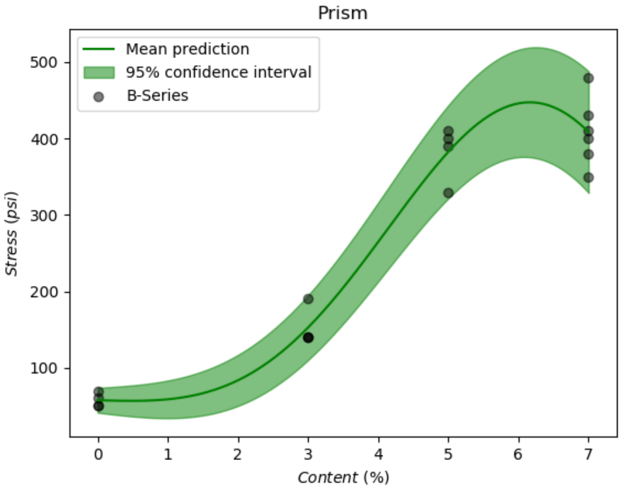


Figure 26. B-Series Prism Compressive Strength Values.

CLOSING

Major findings from this study that potentially can inform CEB mix design are listed below. These findings are preliminary pending durability testing on the remaining specimens for each test series:

- Recommendation for use of a vertical shaft mixer for adequate mixing of stabilized CEB materials (which are low-slump).
- Recommendation to include larger aggregates (up to 3/8-minus) and a gradation of particles sizes for increased strength in OPC-stabilized mixes.
- Recommendation that for high-aggregate mixes with under 15% clay, the ideal OPC stabilizer content would be approximately 5% minimum.
- Recommendation for block mixes with at least 15% clay and low particle-size distribution to maintain the OPC content between 5% and 7%.
- Consideration that a carefully executed (and recorded) mixing process can produce blocks with uniform strengths.

Durability testing should be conducted in the near term on the existing specimens manufactured for this study. Beyond the scope of this study and stemming from its results, some of the future analyses we would like to consider include:

- Manufacture and testing of CEB units with the same soil types used herein, but with varying contents of hydrated lime in lieu of the OPC stabilizer.
- Manufacturer and testing of CEB units with a different base soil type, but with the same increments of OPC stabilizer.
- Use of a harder mortar for masonry prism construction, using blocks of the same profile in this study.
- Study of the effect of mortar strength on prism strength values, for different types of mortar, and different strengths of block.

APPENDIX A - SOILS ANALYSIS RESEARCH

ECI performed several analyses on the benchmark soil. While these are usually performed to help select a soil, ECI undertook these analyses to better understand the characteristics of the clay, binders, water, and additives.

Sieve Analysis (ASTM D6913)

Description: Soil is sieved to separate into particle size ranges from coarse (3/4", or 19mm) to fine aggregate (75 µm), quantifying the soil weight in each sieve. Wet sieving (washing a soil sample with water through nested sieves to collect the clay particles) is required to collect the weight of fines passing the 75 µm sieve. Particle size distribution (PSD) graphs the recorded results and calculations from sieving.

Purpose: To optimize the load bearing capacity and improve the workability of the soil mix. A soil's PSD is a key characteristic of soil that can affect a wide range of soil properties including the aggregate or soil skeleton and the water demand for a mix design.

Execution: Wet sieving: Weigh and record the weight of 200-300 grams of soil. Dry the soil to a constant mass by heating at 210-225°F (100-110°C) for 24 hours or until the weight of the clay changes less than 0.1% from the previously sampled weight. Record the moisture content of the sample, the original sample weight minus the dried sample weight. Gently wash the soil through a set of standard set of graduated sieves. The finest sized sieve is at the bottom, and each layered sieve stacked above is in order of increasing sieve opening size. A bucket below the stack of sieves collects the fines passing through the finest sieve. The material remaining on each sieve is dried to a constant weight and recorded. Once the fines solution in the bucket settles, most of the water is decanted, the fines are dried to constant weight, and the weight is recorded. The percent of total soil sample weight remaining on each sieve or individual percent remaining (IPR), the Cumulative Weight Retained, and the Cumulative Percent Finer than (CPFT) is calculated for the dry material from each sieve and recorded.

Particle Size Distribution (PSD): The IPR is graphed for the full spectrum of particle sizes.

Issues: The main challenge with the sieve analysis is to thoroughly clean each sieve so that the last soil sifted doesn't impact the weight readings of future soils to be analyzed. Accordingly, an ultrasonic bath was added to the sieve cleaning regimen.

Results/Observations: Soil A was sieved several times, each time yielded slightly different results while occasionally showing quite different results. The results varied due to either of the following or a combination thereof: faulty sieving technique, biased sampling from the source, and because materials are not naturally uniform.

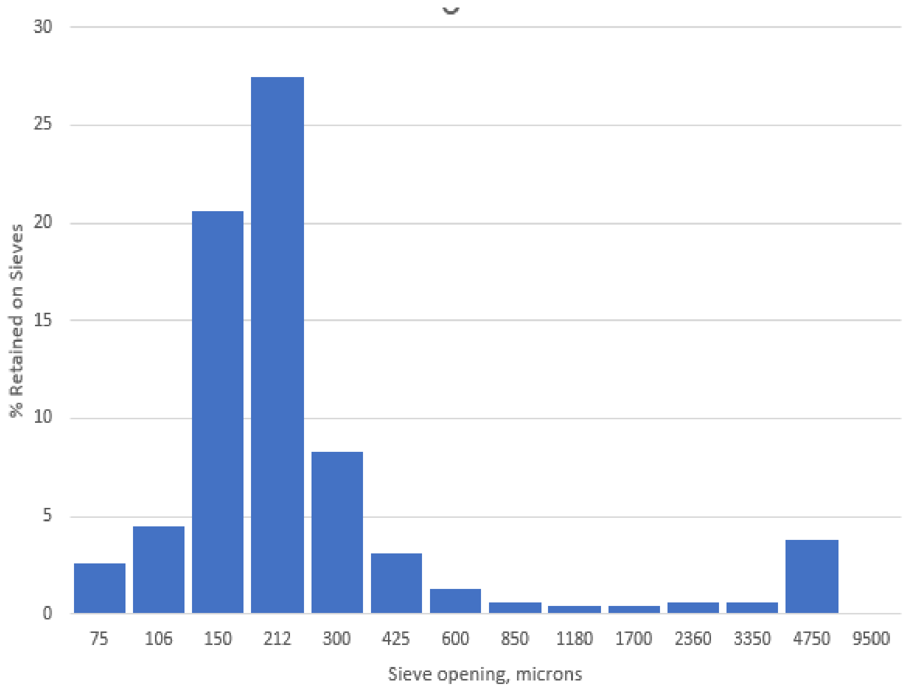


Figure 27. FH Soil Wet Sieving Results

Methylene Blue Test (ASTM C837-09, 2019)

Description: Measures the amount of methylene blue dye adsorbed by the surfaces of clay particles.

Purpose: Identify probable clay types in a soil; calculate the methylene blue index (MBI), which is equivalent to the cation exchange capacity (CEC)[4]. These measure how much water the soil can retain, i.e., the expansive potential of the soil.

Execution: Collect the soil's clay fines by wet sieving[5] a 300 g soil sample with a no. 200 sieve (75 µm mesh). Once the clay solution settles, decant most of the water and dry the clay material to a constant mass by heating at 210-225°F (100-110°C) for 24 hours or until the weight of the clay changes less than 0.1%. from the previously sampled weight. Use a mortar and pestle to break up any clumped particles in the dried clay. A 2 g clay sample is thoroughly mixed with distilled water and brought to a pH between 2.5 and 3.8. Five ml of 0.01M methylene blue solution are added to the slurry, the slurry is thoroughly mixed, and a drop of the slurry is placed on filter paper. This process is repeated until a blue-green or light blue "halo" forms around the slurry drop on the filter paper, indicating that methylene blue has reached the end point or saturation point.

---

[4] MBI and CEC unit of measurement is milliequivalents per 100 grams of sample.

[5] Wet sieving is washing a soil sample with water through nested sieves to collect the clay particles.

Issues: Commonly available methylene blue concentrations are different from ASTM requirements. After initial tests, the methylene blue concentration was corrected to meet ASTM standards.[6]

Halo width must have consistent criteria. Visual acuity varies among technicians, and one person's visual acuity also varies. Magnifying the potential end point spot and measuring with a mm ruler can overcome variations in visual acuity.

Dispersal/agitation of the clay slurry is key for test accuracy. Using a mixer that shears the clay particles prevents agglomeration or clumping – and underestimation – of the clay fraction.

Results Methylene blue tests were conducted on benchmark kaolinite and bentonite clay samples of high purity and on soil clays from three sources.

For kaolinite, the MBIs were 9.5, 9.5, and 10 for an average of 9.7.

For sodium bentonite, the MBIs were 75 and 77.5, for an average of 76.3

For the Fred Harris clay, the MBIs were 29.5, 32.0, 31.0, 32.0, 34.5, and 35.0, for an average of 32.3.

Observations:-Each soil probably has a mixture of kaolinite and montmorillonite and perhaps some illite since their MBIs were all above kaolinite. The Fred Harris appears to be moderately expansive in comparison to sodium bentonite.

Water/Binder Ratio (Cupcake) Test (Derived from the ACI 211 Mix Design Standard)

Description: Increments of soil are added and mixed into a fixed weight amount of water in a cup of fixed size, the 'cupcake.' The mixture is allowed to hydrate briefly, then leveled evenly with the top of the cup, and weighed. The weights are recorded and charted to determine the low point of the fitted line curve – the optimum water/binder ratio.

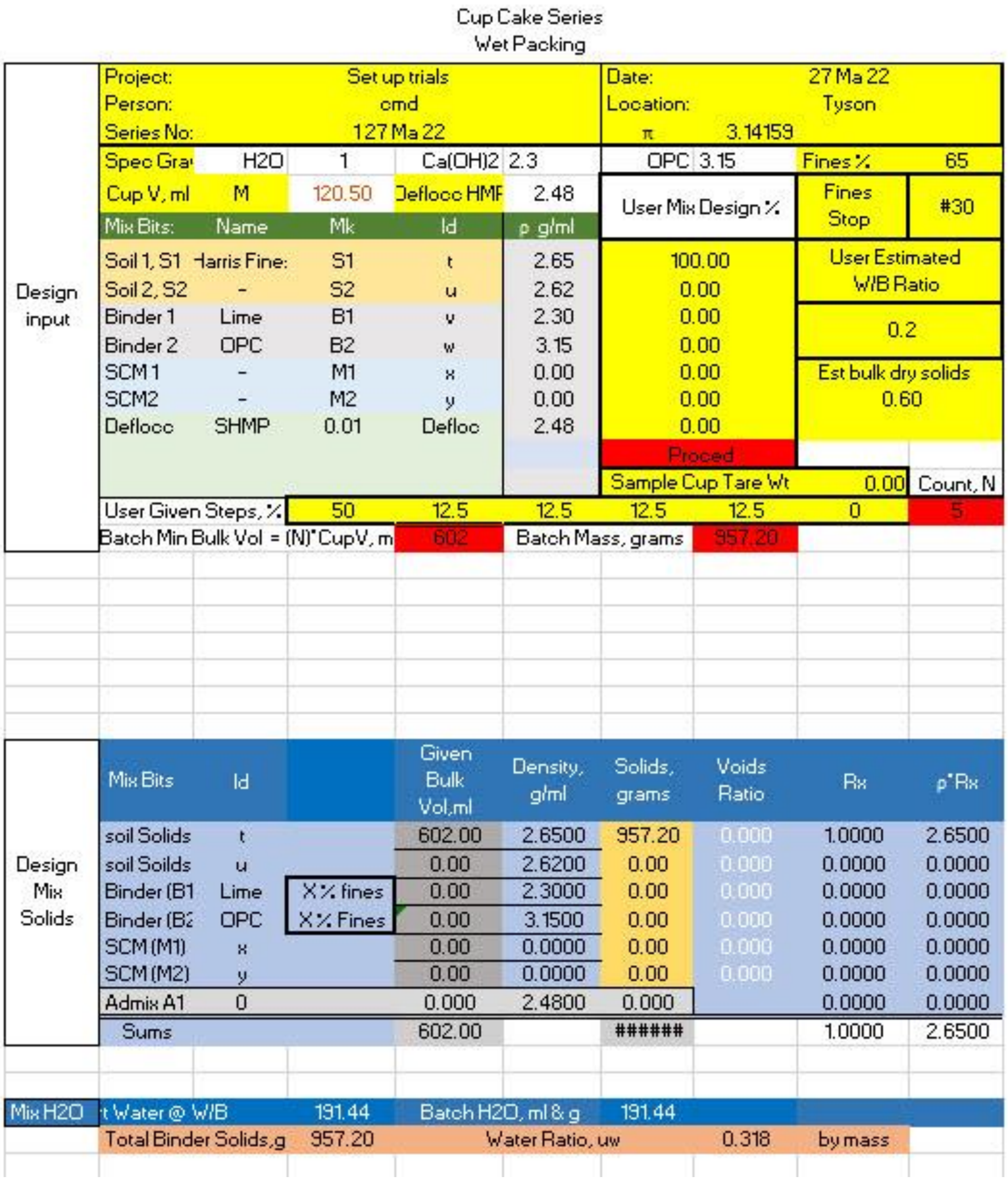
Purpose: To determine the optimum water to binder ratio and maximum packing density for a given soil mix, which enables the standardization of earthen materials production. Knowing the total water required per batch allows for improved batch process control and production Quality Assurance and Quality Control (QA/QC) procedures. A known quantity of water per batch contributes to consistency and streamlining the block manufacturing process. One can begin the mixing process by having started with wet slurry containing the total desired water content and gradually adding the dry soil to it. This expedites and improves the mixing process.

Water's function is two-fold: provide workability acting as a lubricant between particles and, if a chemical binder component is present, hydrate and react with these chemical constituents. Too much water weakens the mix by lowering the density and increasing porosity, allowing air to fill the voids. Assessing the optimum water/binder ratio is an essential part of mix design. ASTM defines optimum moisture content as providing just enough lubrication between particles to allow them to move and rearrange to fill voids under the application of a standard compaction energy but not so much water that the incompressible fluid itself fills voids and impedes consolidation of the particles.

---

[6] 1% aqueous solution of methylene blue was converted to a 0.01 M concentration by adding 68 ml distilled water to 32 ml of 1% methylene blue solution.

Execution: The basic process is to add soil incrementally to a fixed amount of water; mix; measure the density (weight and volume) of each increment, and graph the result. For simplicity, a spreadsheet can be developed to do all the calculations (Figure 28. Water/Binder (Cupcake) Spreadsheet). The method is based on only the fine aggregates fraction (the paste) of the design mix. Figure 29 through Figure 33 below indicate the degree of water saturation and increasing stiffness.



Cup Cake Series
Wet Packing

Design input	Project:		Set up trials			Date:		27 Ma 22	
	Person:		cmd			Location:		Tyson	
	Series No:		127 Ma 22			π	3.14159		
	Spec Gra	H2O	1	Ca(OH)2	2.3	OPC	3.15	Fines %	65
	Cup V, ml	M	120.50	Deflocc HMF	2.48	User Mix Design %		Fines Stop	#30
	Mix Bits:	Name	Mk	Id	ρ g/ml				
	Soil 1, S1	Harris Fine:	S1	t	2.65	100.00		User Estimated W/B Ratio	
	Soil 2, S2	-	S2	u	2.62	0.00			
	Binder 1	Lime	B1	v	2.30	0.00		0.2	
	Binder 2	OPC	B2	w	3.15	0.00			
	SCM 1	-	M1	x	0.00	0.00		Est bulk dry solids	
	SCM2	-	M2	y	0.00	0.00		0.60	
	Defloc	SHMP	0.01	Defloc	2.48	0.00			
						Proced			
						Sample Cup Tare Wt	0.00		Count, N
	User Given Steps, %		50	12.5	12.5	12.5	12.5	0	5
	Batch Min Bulk Vol = (N)*CupV, m			602	Batch Mass, grams		957.20		

	Mix Bits	Id		Given Bulk Vol,ml	Density, g/ml	Solids, grams	Voids Ratio	Rx	ρ*Rx
Design Mix Solids	soil Solids	t		602.00	2.6500	957.20	0.000	1.0000	2.6500
	soil Soilds	u		0.00	2.6200	0.00	0.000	0.0000	0.0000
	Binder (B1	Lime	X % fines	0.00	2.3000	0.00	0.000	0.0000	0.0000
	Binder (B2	OPC	X % Fines	0.00	3.1500	0.00	0.000	0.0000	0.0000
	SCM (M1)	x		0.00	0.0000	0.00	0.000	0.0000	0.0000
	SCM (M2)	y		0.00	0.0000	0.00	0.000	0.0000	0.0000
	Admix A1	0		0.000	2.4800	0.000		0.0000	0.0000
	Sums			602.00		######		1.0000	2.6500
Mix H2O	t Water @ W/B		191.44	Batch H2O, ml & g		191.44			
	Total Binder Solids,g		957.20		Water Ratio, uw		0.318	by mass	

Figure 28. Water/Binder (Cupcake) Spreadsheet

Figure 29. Soaked.

Figure 30. Just above the point at which water completely fills the voids.

Figure 31. Wet side of optimum moisture density.

Figure 32. Near optimum moisture density.

Figure 33. Dry side of optimum moisture density.

Select the soil for the paste fraction of the design mix. Start with enough soil to fill a cup five times. Weigh the soil. Dry the soil to a constant mass by heating at 210-225° F until the difference between the soil weight and the previous recorded weight is less than 0.1%. Screen the dried soil with a 1:50 gold classifier sieve.

Decide on a target water binder ratio. For soil, that will probably be between 20 and 40% by volume, depending on the soil's water demand. If you pick 25%, enter 0.25 for the "User Estimated W/B" (water/binder) ratio on the spreadsheet. The spreadsheet will calculate the fixed amount of water to add to the mixing bowl. Add the water to the bowl.

The spreadsheet will also give you the weight of soil to add for each increment. Add the first soil increment to the mixing bowl and blend by gently stirring with a spatula. Let the mixture sit for 1 minute to hydrate. Then use the mixer to stir at the lowest speed for 3 minutes. For our research, a Kitchen Aid Classic mixer with a standard paddle was used.

For each soil increment, record the weight of the cup. Ladle or spoon the soil material to fill the cup approximately one-third full. The mix will be a slurry consistency at first and will stiffen after each increment is added to the bowl and mixed. It becomes increasingly difficult to get exact volumes for the material added to the cup as the paste stiffens. After each ladling, allow the material in the cup to consolidate by letting the cup drop approximately 50 mm (2") to a hard surface. Repeat this consolidation six times for each ladling. Ladling is complete when the cup is slightly over full. Use a spatula or other straight edge to level the mixture with the top of the cup. Weigh the cup and record the tared weight of the soil for each increment. Return the weighed soil to the mixing bowl after each weighing. Scrape the sides of the cup with a spatula or your finger to return as much soil as possible. The spreadsheet graphs the results. If the W/B ratio is in the correct range for the mix, there will be a peak or apex to the curve. (See Figure 34.)

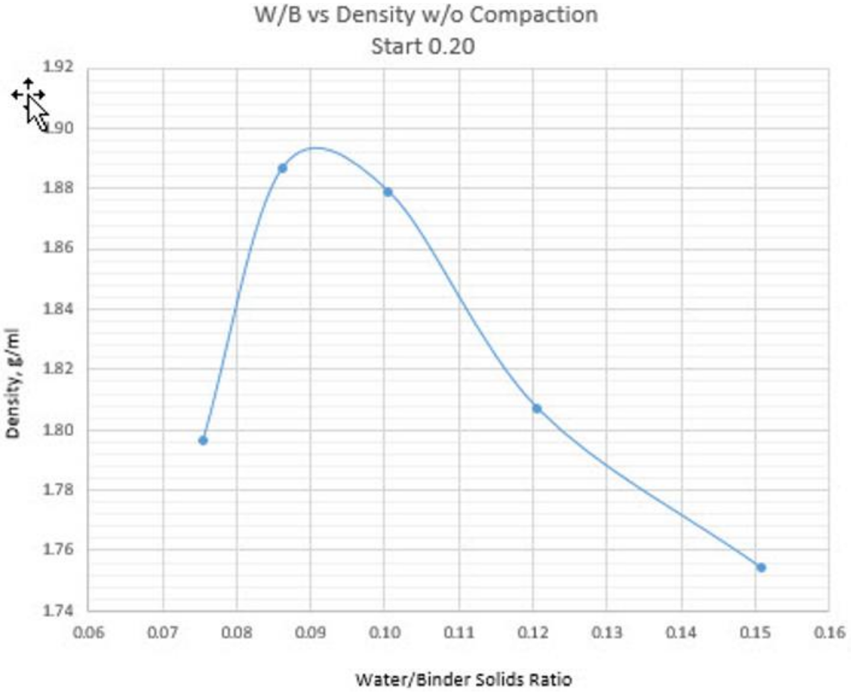


Figure 34. Cupcake Packed Soil Moisture Curve

If there is no peak, the W/B ratio was probably too wet for the soil. Perform the procedure again with approximately 20% less water.

If there is not a single smooth curve plotted, then probably the consolidation was incomplete due to air voids in one or more of the increments. Repeat the procedure from the beginning.

From the W/B ratio, you can extrapolate the water/solids ratio for any given volume of solids. Solids may include not only the soil but any binder or admixture added. As in ACI 211, the next step is to test the ratio of paste (water and fines you just tested) plus coarse aggregates (everything above the #40 screen) in the mix you propose to use.

Use the mix to make a test batch at a larger scale to make test blocks, cylinders, or whatever form you will on performing mechanical tests on.

Results: A straightforward method has been developed to assess the optimum water to binder (W/B) ratio. The technique used simple relatively inexpensive equipment and supplies and yields clear end point result for water compacted soils. The goal of the method is to assess the most efficient and effective use to test the inherent cohesion of a naturally available soil by itself or in concert with other binders.

Observations: The optimum W/B ratio can be clearly seen in the procedure and offers the prospect of ascertaining the total amount of water required by a given mix and the use of integrated deflocculant. The result here is seen as a great improvement over the informal addition of water as now practiced in soil mixing. The use of fine misting agricultural sprayers as well as the wet to dry mixing method proposed appear to greatly reduce the hazard of the formation of aggregations of fine particles and binders during the mixing phase. The use of deflocculants is indicated and will likely have a significant impact on results. The method may offer insight for the effect of mixing times on W/B but is not developed in this study.

APPENDIX B - MECHANICAL TESTING RESULTS BY BLOCK SERIES

Table 8. Series A0 Unit Test Data

Block Series	Specimen ID	Density (LBS/ft^3)	Age at Splitting Tensile (Days)	Splitting Tensile Strength (PSI)	Age at Unit Compression (Days)	Unit Compressive Strength (PSI)
A0	1	104.4	145	5	-	-
A0	2	105.7	145	5	150	130
A0	3	102.8	145	5	-	-
A0	4	105.7	145	5	150	120
A0	5	-	-	-	-	-
A0	6	105.7	145	5	-	-
A0	7	105.0	145	5	150	130
A0	8	105.7	163	10	-	-
A0	9	104.7	163	5	221	190
A0	10	105.1	163	5	-	-
A0	11	105.1	163	5	221	160
A0	12	103.9	163	5	-	-
A0	13	105.7	163	5	221	200
	Average	**105.0**	*Average*	**5**	*Average*	**155**

Table 9. Series A0 Prism Test Data

n Name Specimen Name	Mode of Failure	Compressive Strength of Masonry
A0: 1 8 1	1	50
A0: 10 ? 10	2	60
A0: 12 13 12	1	40
A0: 3 4 3	2	70
A0: 6 5 6	2	60
	Average	**56**

Table 10. Series A1 Unit Test Data

Block Series	Specimen ID	Density (LBS/ft^3)	Age at Splitting Tensile (Days)	Splitting Tensile Strength (PSI)	Age at Unit Compression (Days)	Unit Compressive Strength (PSI)
A1	1	110.5	94	20	-	-
A1	2	119.0	94	10	100	450
A1	3	114.0	94	15	100	450
A1	4	112.0	94	15	-	-
A1	5	112.3	-	-	-	-
A1	6	115.1	94	15	-	-
A1	7	111.4	94	15	100	520
A1	8	111.6	163	15	-	-
A1	9	111.2	163	20	221	530
A1	10	110.8	163	15	-	-
A1	11	111.1	163	15	221	490
A1	12	112.7	163	20	-	-
A1	13	112.4	163	20	221	700
	Average	**112.7**	*Average*	**16**	*Average*	**523**

Table 11. Series A1 Prism Test Data

Specimen Name	Mode of Failure	Compressive Strength of Masonry
A1: 10 11 10	3	150
A1: 12 13 12	1	220
A1: 2 4 4	1	180
A1: 5 ? 5	3	170
A1: 6 7 6	3	160
	Average	**176**

Table 12. Series A2 Unit Test Data

Block Series	Specimen ID	Density (LBS/ft^3)	Age at Splitting Tensile (Days)	Splitting Tensile Strength (PSI)	Age at Unit Compression (Days)	Unit Compressive Strength (PSI)
A2	1	117.4	94	**30**	100	**550**
A2	2	114.8	94	**40**	-	**-**
A2	3	115.2	94	**30**	100	**620**
A2	4	112.7	94	**30**	100	**520**
A2	5	114.4	94	**30**	-	**-**
A2	6	113.9	94	**25**	-	**-**
A2	7	112.7	163	**40**	-	**-**
A2	8	112.7	163	**35**	221	**860**
A2	9	112.7	163	**30**	-	-
A2	10	107.8	163	**35**	221	**910**
A2	11	108.2	163	**35**	-	-
A2	12	108.0	163	**40**	221	**920**
	Average	**112.5**	*Average*	**33**	*Average*	**730**

Table 13. Series A2 Prism Test Data

Specimen Name	Mode of Failure	Compressive Strength of Masonry
A2: 11 12 11	1	310
A2: 2 1 2	2	420
A2: 6 5 6	2	470
A2: 7 8 7	2	330
A2: 9 10 9	2	300
	Average	**366**

Table 14. Series A3 Unit Test Data

Block Series	Specimen ID	Density (LBS/ft^3)	Age at Splitting Tensile (Days)	Splitting Tensile Strength (PSI)	Age at Unit Compression (Days)	Unit Compressive Strength (PSI)
A3	1	113.8	96	**35**	109	**610**
A3	2	114.5	96	**40**	-	**-**
A3	3	113.6	96	**45**	109	**640**
A3	4	112.0	96	**30**	-	**-**
A3	5	112.9	96	**30**	109	**530**
A3	6	113.7	96	**30**	-	**-**
A3	7	112.5	150	**30**	-	**-**
A3	8	112.2	150	**35**	207	**860**
A3	9	112.2	150	**30**	-	**-**
A3	10	112.3	150	**35**	207	**910**
A3	11	113.6	150	**35**	-	**-**
A3	12	112.3	150	**30**	207	**750**
	Average	**113.0**	*Average*	**34**	*Average*	**717**

Table 15. Series A3 Prism Test Data

Specimen Name	Mode of Failure	Compressive Strength of Masonry
A3: 2 1 2	1	540
A3: 4 3 4	1	420
A3: 6 5 6	2	430
A3: 7 8 7	1	310
A3: 9 10 9	2	340
A3:11 12 11	1	390
	Average	**405**

Table 16. Series B0 Unit Test Data

Block Series	Specimen ID	Density (LBS/ft^3)	Age at Splitting Tensile (Days)	Splitting Tensile Strength (PSI)	Age at Unit Compression (Days)	Unit Compressive Strength (PSI)
B0	1	108.3	-	-	-	-
B0	2	108.5	-	-	-	-
B0	3	113.0	131	5	-	-
B0	4	116.9	131	5	136	150
B0	5	111.0	131	5	-	-
B0	6	112.8	131	5	136	120
B0	7	113.3	131	5	-	-
B0	8	114.5	131	5	136	150
B0	9	108.1	149	5	-	-
B0	10	110.8	149	5	207	210
B0	11	106.5	149	5	-	-
B0	12	109.7	149	5	207	220
B0	13	109.3	149	5	-	-
B0	14	112.1	149	5		190
	Average	**111.1**	*Average*	**5**	*Average*	**173**

Table 17. Series B0 Prism Test Data

Specimen Name	Mode of Failure	Compressive Strength of Masonry
B0: 11 12 11	1	60
B0: 5 6 5	1	70
B0: 7 5 7	3	50
B0: 9 10 9	3	50
	Average	**58**

Table 18. Series B1 Unit Test Data

Block Series	Specimen ID	Density (LBS/ft^3)	Age at Splitting Tensile (Days)	Splitting Tensile Strength (PSI)	Age at Unit Compression (Days)	Unit Compressive Strength (PSI)
B1	1	114.2	96	**10**	109	**330**
B1	2	114.8	96	**15**		
B1	3	115.0	96	**15**	109	**340**
B1	4	114.6	96	**15**		
B1	5	115.6	96	**15**	109	**340**
B1	6	114.1	96	**10**		
B1	7	113.2	150	**10**		
B1	8	117.8	150	**10**	207	**500**
B1	9	114.2	150	**10**		
B1	10	112.4	150	**10**	207	**430**
B1	11	113.8	150	**15**		
B1	12	114.5	150	**10**	207	**500**
	Average	**114.5**	*Average*	**12**	*Average*	**407**

Table 19. Series B1 Prism Test Data

Specimen Name	Mode of Failure		Compressive Strength of Masonry
B1: 11 12 11	1		140
B1: 2 1 ?	2		190
B1: 4 3 4	1		140
B1: 9 10 9	1		140
		Average	**153**

Table 20. Series B2 Unit Test Data

Block Series	Specimen ID	Density (LBS/ft^3)	Age at Splitting Tensile (Days)	Splitting Tensile Strength (PSI)	Age at Unit Compression (Days)	Unit Compressive Strength (PSI)
B2	1	117.5	96	**25**	-	-
B2	2	119.3	96	**30**	111	**770**
B2	3	119.6	96	**30**	-	-
B2	4	119.3	96	**30**	111	**800**
B2	5	120.4	96	**30**	-	-
B2	6	120.0	96	**30**	111	**770**
B2	7	115.8	129	**30**	-	-
B2	8	118.0	129	**30**	186	**1100**
B2	9	117.4	129	**25**	-	-
B2	10	118.2	129	**25**	-	**-**
B2	11	121.0	129	**30**	186	**1110**
B2	12	121.8	129	**25**	-	**-**
B2	13	117.9	129	**30**	186	**1100**
	Average	**118.9**	*Average*	**28**	*Average*	**942**

Table 21. Series B2 Prism Test Data

Specimen Name	Mode of Failure	Compressive Strength of Masonry
B2: 1 2 1	3	400
B2: 3 4 3	1	390
B2: 5 5 6	3	410
B2: 7 8 7	1	330
	Average	**383**

Table 22. Series B3 Unit Test Data

Block Series	**Specimen ID**	**Density (LBS/ft^3)**	**Age at Splitting Tensile (Days)**	**Splitting Tensile Strength (PSI)**	**Age at Unit Compression (Days)**	**Unit Compressive Strength (PSI)**
B3	1	116.7	46	**30**	-	-
B3	2	121.5	46	**35**	-	-
B3	3	119.6	96	**35**	-	-
B3	4	121.2	96	**30**	111	**830**
B3	5	120.9	96	**30**	-	-
B3	6	121.6	96	**25**	111	**810**
B3	7	119.1	96	**30**	-	-
B3	8	120.5	96	**25**	111	**860**
B3	9	117.3	129	**30**	-	-
B3	10	119.6	129	**30**	186	**1140**
B3	11	120.2	129	**30**	-	**-**
B3	12	120.5	129	**30**	186	**1330**
B3	13	120.4	129	**35**	-	**-**
B3	14	119.2	129	**30**	186	**1340**
	Average	**119.9**	*Average*	**30**	*Average*	**789**

Table 23. Series B3 Prism Test Data

Specimen Name	**Mode of Failure**	**Compressive Strength of Masonry**
B3: 11 12 11	1	350
B3: 13 14 15	1	400
B3: 3 4 3	2	430
B3: 5 6 5	3	480
B3: 7 8 7	7	410
B3: 9 10 9	1	380
		408