UNEARTHING BUILDING POTENTIAL

A DESIGN PRIMER FOR RAMMED EARTH AND CEBS

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A DESIGN PRIMER FOR RAMMED EARTH AND CEBS

For the Center for Architecture Foundation
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UNEARTHING BUILDING POTENTIAL

This manual is a design primer for architects, designers, construction workers, and students interested in working with earth construction, specifically Rammed Earth and Compressed Earth Block, and for those that would like to expand their general knowledge of these construction methods.
The information here is provided so that the reader may learn more about the methods and materials involved in earth construction but should not serve as a substitute for using a qualified engineer, architect, or builder when building a structure.

GOALS OF THE MANUAL

- act as a design primer
- provide an introduction to techniques of building with earth
- help reader learn how to perform basic soil tests
- be a field guide for construction
- learn basic block and wall core tests
- review a case study building
- provide open source access to building construction equipment
- provide open source access to testing equipment
- above all -serve as a point of departure for further inquiry

Being comprised of the earth that lies beneath us, soil is the most abundant building material we have. If the appropriate soils can be found on a certain site, there is no cost for the material or transportation, which makes it an ideal candidate for remote construction. It is an all natural material in that it only changes from its natural state in terms of form and density, and at the end of its life, it may return to earth with little to no impact on the ecology.

While other materials like brick need wood for firing and can lead to deforestation, earth construction does not. A CRATerre study in Uganda found that each school house that was built with earth instead of fired brick saved 13m3 of wood from deforestation to fire the bricks. [1]

A CASE FOR USING EARTH

The all natural material is not subject to off-gassing; is not harmful to the adjacent environment; and, if utilizing manual labor, rammed earth has no carbon footprint in its life-cycle. Compare that to Masonry Concrete which uses many of the same materials like sand and gravel that has a carbon footprint of 172 metric tons per 100 square meters or steel and concrete construction at 241 and 333 metric tons respectively for the same area. [2][21]

MATERIAL	Embodied Carbon in construction [3,4,7]
CEB:	0-22 kgCO2/m3
CSEB:	57 kgCO2/m3
CMU:	105 kgCO2/m3
FIRED BRICK:	230 kgCO2/m3
FIELD BRICK:	547 kgCO2/m3

The process for unearthing, preparing, and compacting the material can be labor intensive, averaging 20-30 hours per cubic meter. [5] In developing markets this can be seen as a positive as it can provide jobs, stimulate bottom up economic growth and give an expanded workforce new skills. In developed markets where labor is expensive, mechanized systems can be used to prepare and compact soil making it an efficient system for constructing bearing walls as low as 2 hours per cubic meter. [5]

Another positive aspect of the all natural material is its ability to biodegrade or *earth-cycle* at the end of its life. The Environmental Protection Agency of the United States has reported that in one year in the US, Construction and Demolition waste amounted to 136 million tons. That is 2.8 pounds per resident per day. Construction and Demolition waste account for 15-30% of all solid landfill material in the US. [6]

The complex texture of rammed earth and CEBs give a rusticated aesthetic that, along with its sheer mass, creates a sense of monumentality. This mass and natural finish can be utilized to create an atmosphere of repose.

The mass of the material also serves as a thermal bank. The large walls buffer outdoor temperatures, meaning an outdoor temperature swing of 20-30F might result in an interior swing of 5-10F. During a warm day the walls absorb the heat making the interior cooler, and will then release the heat in the cool evening. Likewise the walls can absorb and release moisture in the air to create a more stable humidity level in the interior relative to the exterior. In this way the material breathes like a living organism.

[1] CRATerre
[2] MIT [21] AIMS
[3] Auroville Earth Institute. [4] Morton. [7] Embodied Energy
[5] Minke
[6] Environmental Protection Agency
Photo opposite: Masons at Butaro Doctor's Housing, MASS Design Group

A BRIEF HISTORY

From ancient times, the great civilizations have made use of earth as a building material. Mud bricks and rammed earth substituted for wood and stone. From Assyria to Babylon; Persia to Sumeria scattered remains of the earthen structures of these once mighty nations can be found. Earth has been used to make numerous temples, ziggurats, pyramids, forts, trenches and even dams. Some of these structures are over 10,000 years old. Dwellings made of mud bricks have been found in Turkestan as far back as 8,000 BCE and Rammed earth can be dated as far back as 5,000 BCE in ancient Assyria. [9]

In Egypt, in ancient Thebes and its Necropolis, built in 13th century BCE, are great examples of early mud structure. The Ramesseum is the temple of the royal cult of Ramses II, located in the Theban necropolis. It includes the huge ancient adobe walls of the Karnak Temple and the decorated clay coatings found in many tombs of the Valley of Kings and Valley of Queens. Other earth construction examples from Egypt are Memphis and its Necropolis – the Pyramid Fields from Giza to Dahshur built in the same time period. It is located in the necropolis of Saqqara, closest to the capital. [8]

In Arab regions, the more than 2500 year old city of Sana in Yemen is defined by an extraordinary density of cob, adobe and burnt brick, reaching several stories high on ground floors built of stone, and decorated with geometric patterns of fired bricks and white gypsum. [8]

Pueblo de Taos was built between 1000 and 1450 CE. It is situated in the valley of a small tributary of the Rio Grande and is a remarkable example of a traditional type of earthen architecture. It represents the culture of the Pueblo Indians of Arizona and New Mexico from the pre-Hispanic period. [8]

In Asia, the Fortress of Bam was made entirely of unbaked clay, mainly in the form of adobe masonry with mud mortar. The cultural landscape of Bam is an outstanding representation of the interaction of man and nature in a desert environment. [8]

[8] Joffroy
[9] Eternally Solar

Photo opposite: View to earthen Mosque in Mopti, Mali, photo: Iwan Baan

OVERVIEW OF EARTH CONSTRUCTION METHODS

1.3.1 RAMMED EARTH
Rammed earth is the compaction of moist soil between forms to create building elements.

EARTH

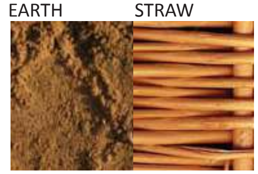
1.3.2 EARTH BLOCKS
Earth Blocks can be pressed, cut, tamped, or molded by forming earth into unit masonry.

EARTH

1.3.3 STRAW CLAY OR ADOBE
Building Elements that utilize straw as an additive to earth. These may be blocks or wall units whereas the straw acts in binding.

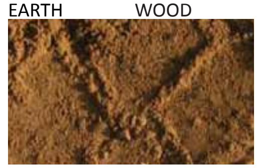
EARTH STRAW

1.3.4 WATTLE AND DAUB
A system of building that involves applying moist earth to a wooded framework to produce building elements.



EARTH WOOD

1.3.5 DIRECT SHAPING
The molding of a plastic earth loam without formwork.



EARTH

1.3.6 DUGOUT
Soft soil or porous lava is actually dug out of its place to create space in the earth.

EARTH

PROCESSES

excavate material | prepare material | mix material | add water | compact in form

excavate material | prepare material | mix material | add water | compact in form/press or cut

excavate material | prepare material | mix material | add water | compact in form/press or cut

excavate material | prepare material | mix material | add water | apply to structure

excavate material | prepare material | mix material | add water | shape wet soil

excavate material

[11] Houben & Guilluad
[10] Smart Shelter Foundation

SECTION 2: SOIL

2.1 SOILS

Soil is the broken down remains of rock, mixed with gases, vegetation, and decomposed organic material and comes in many forms and particle sizes. Rock can be broken down by natural forces such as wind, precipitation, and water flow. This breakdown is known as erosion. Soil can also be created and modified by animal and plant activity and tectonic and volcanic activity.

Soil composition

Soil is composed of minerals from rock degradation, gases that are internal to the soil, liquids or solvents, and organic matter from decayed organisms. The minerals within the soil are in various states of erosion and sedimentation and have various grain sizes.

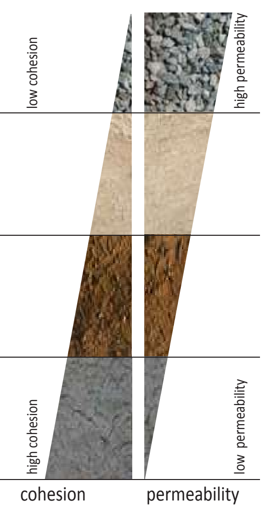
Soil particles are classified by their grain size:

Gravel: 2-20mm
The mechanical properties of gravel undergo no change with water
Gravel is very permeable

Sand: 0.075mm - 2mm
Sand is often composed of silica and quartz
Sand will not bind to itself or hold a form
Sand is very permeable

Silt: 0.002-0.075mm
Silt is Pulverized Rock
Silt fills voids in soil and can bind by friction

Clay: 0.002mm or less
Clay is cohesive and can be formed when wet
Clay particles are platelike and electrically charged
Clay is sticky when wet and hard when dry



Other types of soils:
Top Soil, humus, agricultural soil, and peat: which contain a high density of organic material and are unsuitable for earth construction. Black cotton soil, weathered volcanic rock, and high plasticity expansive clays pose issues with predictability. Laterite soils are the breakdown of granitic rock by chemical decomposition in tropical climates and contain iron oxide and aluminum. [10]

[10] Smart Shelter Foundation

SOIL PROPERTIES

SOIL PROPERTIES include a very wide range of chemical and physical properties. As this manual is only an introduction to building with soil we will be examining four key physical properties which relate specifically to the suitability and preparation of soil for earth construction.

FOUR BASIC PHYSICAL PROPERTIES

1 PARTICLE SIZE DISTRIBUTION:

Also referred to as gradation, granularity, or texture, particle size distribution is a description of the mixture of various grain sizes of the soil. It includes a mix of the aforementioned soil grains; gravels, sands, silts, and clays.

2 COMPRESSIBILITY:

Directly related to the particle size distribution compressibility is an important feature in earth construction because the compaction reduces porosity of the material. Moisture content of the compacted material is another factor that affects compressibility in that it relates to plasticity and cohesion discussed below.

3 PLASTICITY:

Plasticity refers to the ability of a material to submit to deformation without elastic failure. Plastic materials can be bent or formed without rupture. With regard to soil properties the moisture content is a large factor in its plasticity.

4 COHESION:

Cohesion refers to the capacity of the soil grains to remain together when a tensile stress is imposed. Clays are the most cohesive of soils. They act as binders in the way cement acts as a binder in concrete holding larger aggregates in place which when mixed properly can produce a monolithic material.

ENGINEERING PROPERTIES

UNDERSTANDING THESE FOUR BASIC PHYSICAL PROPERTIES WILL HELP US TO UNDERSTAND THESE ENGINEERING PROPERTIES:

ENGINEERING PROPERTIES

1 OPTIMUM MOISTURE CONTENT:

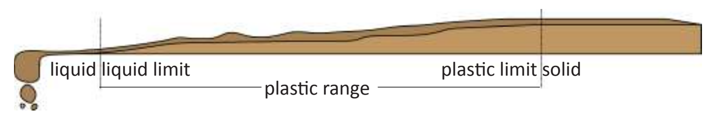
The OMC is the water content at which a maximum dry unit weight can achieved after a given compaction effort. Particle size distribution, moisture level, and compaction are factors in determining the OMC.

2 MAXIMUM DRY DENSITY:

This is the maximum density obtainable when compaction is carried out on a dry material.

3 PLASTICITY:

Defined opposite here, plasticity is measured by the Plasticity Index and falls with the Atterberg Limits shown below.



4 COMPRESSIVE STRENGTH:

The capacity of a material to withstand loads without fracture is referred to as its compressive strength. In building materials compressive strengths are measured by the axial, or vertical, load a material can withstand and is sometimes called bearing strength or bearing capacity.

PARTICLE SIZE DISTRIBUTION

PARTICLE SIZE DISTRIBUTION:

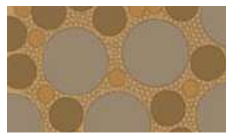
Also referred to as gradation, granularity, or texture, particle size distribution is a description of the mixture of various grain sizes of the soil. It includes a mix of the aforementioned soil grains; gravels, sands, silts, and clays.

SOIL STRUCTURE & SOIL TEXTURE

SOIL STRUCTURE

GRANULAR:
Gravely with little bonding by clay

FRAGMENTED:
Soil is crumbly course particles lump together by clay bonding



CONTINUOUS:
Mix of all size particles bonded by clay with few voids

A continuous mix of soil is required for earth construction but soil is rarely found in the state and continuity required for compaction. The soil grains will most likely need to be separated by sieving and reconstituted into a well graded continuous mix.

SOIL TEXTURE

The soil texture can be expressed in the proportions of various grain sizes: gravel - sand - silt - clay

Soils are classified by this makeup and referred to by the predominate grain listed as the soil with the secondary material listed as a preceding adjective. For example a gravely sand is predominately sand with a large enough concentration of gravel to influence the performance of the material.

Soils used for earth construction fall under the category below in various mixes.

Gravely:	rough, no cohesion, low shrinkage
Sandy:	gritty, no cohesion, low shrinkage
Silty:	fine, low cohesion, some shrinkage
Clay:	Very fine, high cohesion, high shrinkage

Course grains | Fine Grains

GRAVEL - SANDY GRAVEL - SAND - SILTY SAND - SILT - CLAYEY SILT - CLAY

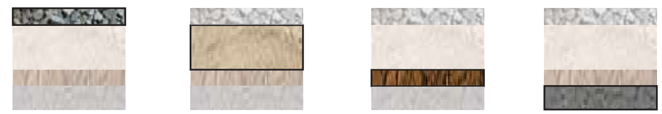
IDEAL SOIL MAKEUP

The top layer of soil on the earth's surface is called top soil, and in thriving ecoregions it is generally full of organic material from the decay of organisms mixed with nutrients and waste from plants and animals. Top soil is not used in compressed earth construction because of its organic content. The thickness of this layer varies from region to region but in most cases suitable soil can be found within one half meter of the surface.

FINDING THE SOIL

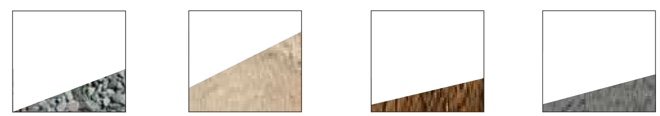
In the area between the topsoil and bedrock, the material for earth construction can be excavated. A variety of tests can be conducted on the soil to discover its in situ grading or Particle Size Distribution. The material can then be passed through sieves to separate the materials and ensure the material is broken down adequately before the mixing process brings the material to the optimum mixture for compaction.

IDEAL PARTICLE SIZE DISTRIBUTION FOR COMPRESSED EARTH CONSTRUCTION



GRAVEL - 15% | SAND - 50% | SILT - 15% | CLAY - 20%

The above represents the ideal where as the below is a representation of what is generally regarded as an acceptable range:



GRAVEL 0-40% | SAND 25-80% | SILT 10-25% | CLAY 8-30%

2.2 TESTING SOILS

THERE ARE TWO TYPES OF TESTS DISCUSSED IN THIS MANUAL: LAB TESTS, WHICH ARE THOROUGH AND CONCLUSIVE; AND FIELD TESTS, WHICH ARE USED TO BECOME GENERALLY FAMILIAR WITH THE CONDITIONS OF THE SOIL. BOTH ARE MEANT TO GIVE US IDEAS ABOUT PARTICLE SIZE DISTRIBUTION, OPTIMUM MOISTURE CONTENT, SO THAT FINISHED PRODUCTS (BLOCKS AND WALLS) CAN BE TESTED FOR ENGINEERING PROPERTIES SUCH AS COMPRESSIVE STRENGTH.

LAB TEST VS. FIELD TESTS

LAB TESTS - There are many tests that can be performed in a laboratory that can give good information on soil properties and its suitability for earth construction. This manual will look at a few tests that can tell us more about Optimum Moisture Content and Particle Size Distribution.

PLASTICITY - MOISTURE CONTENT

TESTS:
CONE PENETROMETER TEST - Tests for liquid limit
PROCTOR TEST - Tests for OMC
PLASTIC LIMIT TEST - Tests for the plastic limit

ATTERBERG LIMITS

- Liquid state: lots of water in soil, behaves like a fluid
- Plastic State: clay particles bind soil to resist deformation
- Solid State: completely dry, any deformation made causes rupture

PLASTIC INDEX - A high PI indicates likely hood of material being deformed.

EXAMPLES OF ATTERBERG LIMITS [3]

MATERIAL	LIQUID LIMIT	PLASTIC LIMIT
SANDY SOIL	20%<LL<30%	10%<PI<20%
SILTY SOIL	20%<LL<40%	10%<PI<25%
CLAYEY SOIL	25%<LL<50%	15%<PI<35%

PARTICLE SIZE DISTRIBUTION

TESTS:
HYDROMETER METHOD - Identifies clay content
SIEVING TEST - Identifies proportions of various grains

PLASTICITY

FINDING LIQUID LIMIT

LT.1

CONE PENETROMETER

The Cone Penetrometer is a testing apparatus used in the laboratory to test for the liquid limit. The Cone Penetrometer drops a steel cone into a cup of soil. The Liquid Limit is represented by the Moisture Content at which an 80g cone sinks exactly 20mm into a cup of re-molded soil.

FINDING OPTIMUM MOISTURE CONTENT

LT.2

PROCTOR TEST

The Proctor Test is carried out on the soil that has been sieved. Soil samples of various known moisture contents are weighted and compared to a dry sample. The various samples are compacted in a cylinder and the weights are recorded on chart. The charted result create a curve, the apex of which is considered the OMC.

FINDING PLASTIC LIMIT

LT.3

PLASTIC LIMIT TEST

The PLT determines lowest moisture content at which soil is plastic using the steps below:

1. Kneed 20g of slightly moist soil into a ball - Cracks should appear on the surface indicating proper moisture content.
2. Subdivide into 2 balls
3. Further subdivide both into 4 balls each
4. Roll them with hand on a glass plate to 3mm diameter threads
5. Re-mold and re-roll to dry further if necessary - until the threads shear transversely and longitudinally.
6. Weigh the sample at the point were shearing occurs
7. Collect and determine the moisture content at which the shear occurs
   MC = (wet soil mass - dry soil mass)/wet soil mass x 100%
8. Repeat test for all samples - valid results should be within 0.5%

PARTICLE SIZE DISTRIBUTION

LT.4

WET SIEVING TEST

In the Wet Sieving Test soil is washed and mechanically shaken through a series of up to 19 screens ranging from 4 to 0.075mm and materials are separated and categorized. Percentages of materials can be compared to the whole.

LT.5

HYDROMETER TEST

50-100g of soil is dried crushed and sieved to less than 2mm. 100g of Sodium hexametaphosphate is added for each 2l of water. 100ml of the solutions is mixed with 250ml of distilled water and is set overnight. The mixture is divided into 2 cups and is machine mixed. It is them put into beakers that are measured for temperature at a series of intervals and that is charted to find results.

LT.1 - [11][12]
LT.2 - [13]
LT.3,4 - [10] SSF [3] Auroville
LT.5 - [14]

Photo top right: Opera Village by Francis Kere Architects, photo: Iwan Baan

FIELD TESTING SOILS

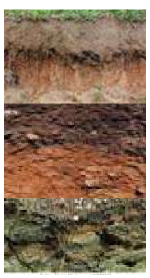
THE INITIAL GOAL OF TESTING THE SOIL IS TO HAVE A BASIC UNDERSTANDING OF THE SOIL MAKEUP TO SEE IF THE SOIL SEEMS SUITABLE FOR EARTH CONSTRUCTION. IF THE SOIL IS DEEMED SUITABLE IT CAN BE PROPERLY PREPARED AND TESTED FOR OPTIMIZATION. THE SOIL CAN THEN BE PRESSED INTO TEST BLOCKS OR WALL MOCK-UPS FOR FURTHER TESTING. THE TESTS DESCRIBED IN THIS SECTION ARE THE INITIAL TESTS AND OPTIMIZATION TESTS. THE SECOND ORDER OR UNIT TESTS WILL BE DESCRIBED IN SECTION 3 OF THIS MANUAL.

INITIAL FIELD TESTS

INITIAL FIELD TESTS

The initial tests described in this section are useful for understanding some of the properties of the soil previously discussed. They are not conclusive as to the suitability of the soil for earth construction but will give a basic indication of presence of organic material, particle size distribution, compressibility, and plasticity.
As many of the tests described here use the basic human senses - sight, touch, and even taste they are sometimes called sensitive tests.

PULLING SAMPLES



The soil from the site might not be continuous throughout so three or more samples should be taken from different areas. Test pits can be dug in those locations and samples of 10kg should be extracted as is set in a container marked with the location, date, and depth of extraction. Soil should be taken from homogeneous layers and should not be mixed with other soils prior to the initial field tests.

If the samples can be brought to a well lighted semi enclosed area it is better to protect them from rain, wind, and sun. Here the moisture content can be adjusted over time more easily.

TYPES OF INITIAL FIELD TESTS
SENSITIVE FIELD TESTS: Visual test, Touch Test, Smell Test, Taste Test, Luster Test
COMPRESSIBILITY FIELD TESTS: Compression Test, Drop Test, Crumbling Test
PLASTICITY FIELD TESTS: Shape Test, Elasticity Test, Thread Test, Cigar Test
PARTICLE SIZE DISTRIBUTION TEST: Wet Sieving Test
SHRINKAGE FIELD TEST: Alcock Test

SENSITIVE FIELD TESTS

SFT.1

VISUAL TEST
Spread a thin layer of soil on a flat surface
Note the distribution of fines vs. course grains
Remove stones and large gravel, and other foreign matter
Note color:
Red and dark brown may indicate iron in soil
White/gray/yellow may indicate foral, lime or gypsum
Green/light brown/black may indicate organic material

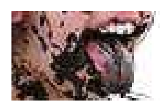
SFT.2

TOUCH TESTS
Remove as much gravel as possible and crush soil with hands
If it feels sharp and gritty the soil is composed of sandy particles
If it feels smooth like flour the soil is composed of fine particles.
If it is difficult to crush that indicates a predominance of dry clay
to verify this wet the soil to see if becomes sticky
Scratch Test - scratch with a fingernail or knife
If a powder comes off it indicates silt and clay
Polish Test - polish a lump with some moisture and fingers
If surface shines it indicates a high clay content

SFT.3

SMELL TEST
Immediately after taking sample from earth smell it, add water to enhance.
If the soil smells musty or rotten it may contain organic matter
Heat the material to see if smell increases

SFT.4



TASTE TEST
Take a pinch crush with teeth (do not swallow)
Courser material is more objectionable as if grinding teeth
Clays will feel smooth and powdery

SFT.5

LUSTER TEST
Without adding water form a cohesive ball with soil and cut in half with a knife.
A rough surface with large voids indicates gravel
A rough surface with small voids indicates sand
A smooth dull surface indicates silty soil
A smooth shiny surface indicates clayey soil

SFT.1-5- [10] SSF [3] Auroville

Photo top right: Opera Village by Francis Kere Architects, photo: Iwan Baan

COMPRESSIBILITY FIELD TESTS

CFT.1 COMPRESSION TEST

Take a handful of soil with a few drops of water and compress with hand

Soil that seems easy to compress likely contains a predominance of fines

Soil that seems difficult to compress may contain coarser grains

CFT.2 DROP TEST - to understand grain distribution and optimum moisture

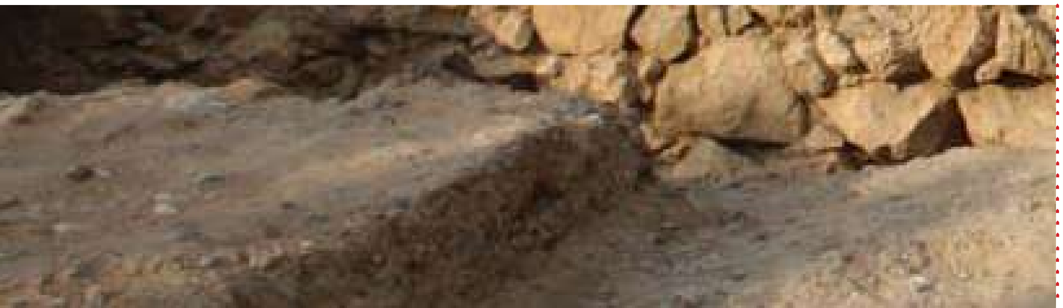
Add just enough water to a handful of soil to make a cohesive ball that does not stick to fingers and drop from shoulder height to a hard surface below.

- If ball stays intact - it may indicate a high clay content or high moisture
  - Create a dryer mix and repeat to see if it is the moisture content
- If ball breaks into 4-6 pieces it indicates continuous well graded soil.
  - It also indicates an optimized moisture content.
- If ball breaks into many pieces or crumbles it may indicate sandy soil
  - It may also indicate mix is too dry and should be repeated with more moisture to see if results change.

CFT.3 CRUMBLING TEST

Sieve soil with a 425 micron screen to extract the fine grains
Add enough water to the fines so that the soil can maintain a shape.
Make a few 25mm diameter balls and a few 6mm diameter balls.
Dry for 24 hours and crush them between finger and thumb.
Note if the dry strength is low, medium, or high:

NOTED PHENOMENON	DRY STRENGTH	CLAY CONTENT
If both sizes break easily	Low	Less than 10%
If only the smaller balls break	Medium	Between 10-20%
If neither size breaks	High	Greater than 20%



PLASTICITY FIELD TESTS

PFT.1 SHAPE TEST

Add just enough water to make a cohesive ball with a handful of soil that does not stick to hand and note plasticity as you form it into a shape:

DIFFICULTY	PLASTICITY	MATERIAL
Difficult to shape	Low	Gravel and sand
Quite Easy to shape	Medium	Silt and Clay
Very easy to shape	High	Clayey

PFT.2 ELASTICITY

Repeat Shape Test without adding water stretch the ball like an elastic band until it breaks into 2 parts and note the elasticity:

NOTED PHENOMENON	ELASTICITY	MATERIAL
Breaks apart easily	Low	Coarse Grains
Breaks but stretches some	Medium	Sandy/Silty soil
Breaks after a long pull	High	Clayey soil

PFT.3 THREAD TEST / CONSISTENCY TEST

Sieve with a 425 micron sieve and add just enough water to make 2cm balls that do not stick to fingers, and then roll into a thread 3mm thick.

- If it rolls to a diameter of less the 3mm it contains too much clay
- If it breaks at 3mm there is a good mix
- If it breaks before 3mm there is not enough clay or mix is too dry

PFT.4 CIGAR TEST

Sieve with a 425 micron sieve and add just enough water to make soil plastic but does not stick, and then roll into a thread 3 cm thick "cigar".
Slide the "cigar" over the edge of a table and note the length at which it breaks:

LENGTH	COHESION	MATERIAL
5 cm	Low cohesion	high sand low clay
5-15cm	Good cohesion	good mix of sand/silt/clay
> 15cm	Too much cohesion	too much clay

CFT.1-3- [10] SSF [3] Auroville
PFT.1-4- [10] SSF [3] Auroville

PARTICLE SIZE DISTRIBUTION FIELD TESTS

PSDFT.1 WET SIEVING TEST

1. Sieve soil with a 5mm screen
2. Heat 6600g of soil for 10-15 minutes in a steel pan over a fire
3. Let cool and separate 500g on scale
4. Place in 0.075mm sieve
5. Run water over the soil and separate the coarser grains
6. Let the grains dry and measure weight
7. Compare to the original sample
8. Courser grains should be 50-70%

FIELD SHRINKAGE TEST

FST.1 ALCOCK TEST

1. Create wood mold with interior dimensions of 60cm x 4 cm x 4 cm
2. The top should be open and the sides and bottom should be greased
3. Remove large gravel from the soil
4. Prepare the soil at the Optimum Moisture Content - see drop test
5. Press soil into mold leaving no gaps or bubbles but not compacted
6. Leave in sun for 3 days or shade for 7

NOTED PHENOMENON	INDICATION
Cracks into multiple pieces	Soil is high in sand and low in clay
Dries as one piece, cambers and shrinks	Contains too much Clay

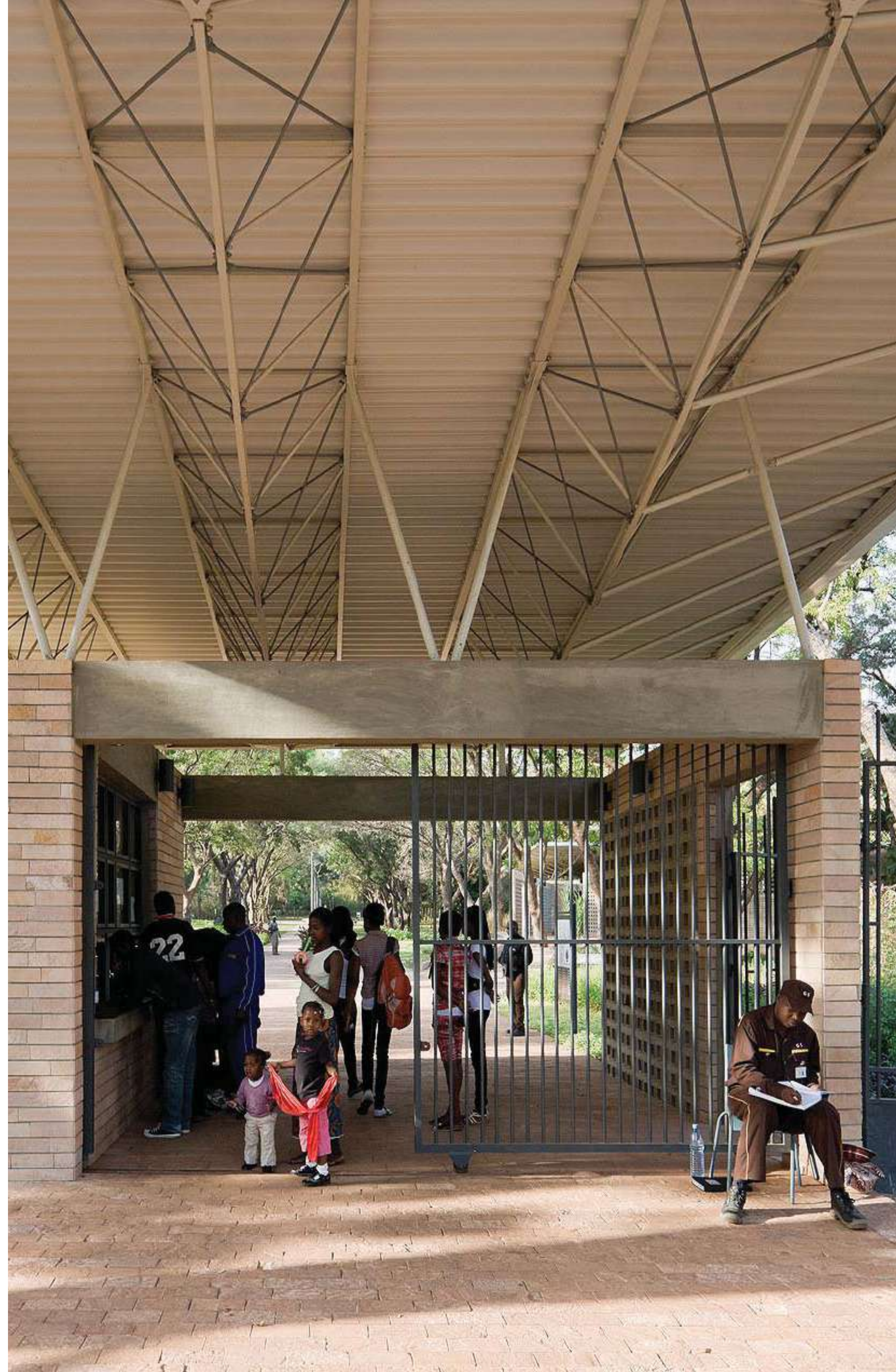
SHRINKAGE = ((60cm- Dried length)/60cm) x 100%
APPROXIMATE CLAY CONTENT = (Shrinkage Length/60cm) x 500%

Cracks into multiple pieces-
Soil is high in sand and low in clay

Dries as one piece, cambers and shrinks
Contains too much Clay

PSDFT.1- [10] SSF
FST.1- [10] SSF

Photo Opposite: Bamako Park by Francis Kere Architects, photo: Iwan Baan



SECTION 3: CONSTRUCTION TECHNIQUES

SECTION 3: CONSTRUCTION TECHNIQUES

There are many forms of earth construction that have been developed throughout history. Two that have remained popular and have undergone much engineering research are rammed earth and compressed earth blocks.

3.1 RAMMED EARTH

Rammed earth is an ancient technique of construction that is still prized today for its low environmental impact, its rusticated appearance, and its thermal mass. Simply put, rammed earth is the compaction of well-graded moist soil in forms to create building elements. The compaction is usually done in 15 cm lifts - vertical increments. In resource limited settings or small scale projects the soil is compacted by hand tools called tampers. In developed markets machinery can play a big role in the excavation and preparation of soil, as well as mixing, delivery, and compaction.

PROCESSES AND TOOLS - PRIMITIVE VS. MECHANIZED

Primitive

Mechanized

Monolithic Rammed Earth:
This is normally what is referred to when saying rammed earth where walls are rammed in place between removable forms. This creates a continuous monolithic element.

Precast or Tilt-up Panels:
Building elements can also be created off site or in panels on site to be hoisted into place. They are often pieced together with the a mud mortar the can make the panels looks like a monolithic unit.

BUILDING ELEMENTS

Walls | Floors | Furniture | Fireplaces | Roofs

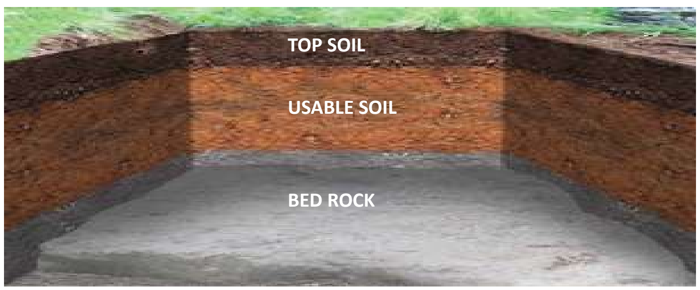
Furniture: Rammed earth chair by Eric Harris
Roofs: students of architecture at ETH

SOURCING THE MATERIAL

When sourcing soil for earth construction the best possible scenario is to be able to find well-graded easily-excavated soil from site to use. There is a smaller environmental footprint and less transportation effort required. Alternatively, if available, soil already mixed to specifications can be trucked to the site, saving time and effort in the preparation of the material.

EXCAVATION

As previously mentioned the soil for earth construction is found below the topsoil layer and above the bedrock layer. Topsoil should be removed and protected as this will be useful for landscape grading and planting but not building. The excavation area for unearthing construction material can be referred to as the quarry.



TIPS FOR EXCAVATION

1. Locate quarry where known suitable soil has been found
2. Locate quarry away from trees or where roots or large stone can be expected
3. If possible use the excavation site where buildings or retention ponds will go
3. Remove top soil and protect for future use in landscape
4. Design the excavation so that dirt can be taken out easily - ramps may be useful
5. Create a swale or curb around the uphill side of quarry to protect if from runoff
6. If soil is sieved in the Quarry the unwanted material can be discarded in place

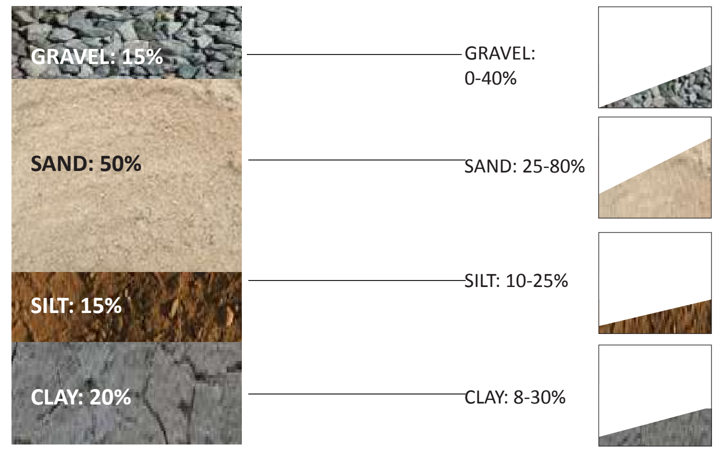
PREPARING THE EXCAVATED MATERIAL

The soil needs to be dry and any clumps of dirt should be pulverized using hand tools or machines. The material is sorted by use of sieves. Sieves of various sizes can be laid horizontally and shifted side to side while dirt is added, or screens can be placed at slight incline and dirt thrown by shovel to separate the grains. If the soil has been determined as well graded with the appropriate particle size distribution it may just need dried and pulverized before going the final wet mixing.

MIXING THE MATERIAL: Rammed Earth

There are many differing opinions on the ideal mix. The mix shown below is an average taken from several sources. Generally for rammed earth the course grains should be around 70% of the mixture and some clay - from 8-30% is needed to bind them.

IDEAL MIX ACCEPTED RANGE



DRY MIXING

The material is sorted by use of sieves and the soil can be reconstituted to the appropriate proportions. If the mixture is well-graded, dry, and free of clumps it can be mixed by shovel, mechanical tiller, mechanical mixer, or otherwise. If the engineer has determined that cement or another stabilizer needs to be added, it should be added now and mixed to a well graded consistency.

Primitive - shovel

Mechanized - tiller

WET MIXING

Once the material is thoroughly mixed, moisture is introduced to create the Wet Mix. The mixture should be at the predetermined Optimum Moisture Content - see Section 2 - this is enough moisture so that the soil can bind as compressed but not so much that it inhibits the binding. Time is now of the essence as the moisture level will change, and if cement or other stabilizer has been added, it is beginning to cure. The time between the wet mix and the compaction is called the Hold-back time and must be limited to an hour or less.

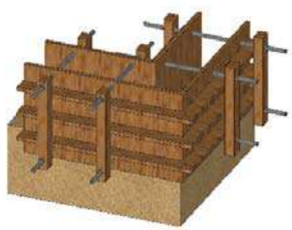
Primitive - shovel & can

Mechanized - mixer

FORMWORK

Formwork is the constructed or excavated sides of the wall that hold the soil as it is being compacted. They are generally removed after the earth is compacted to stand on its own, but not always, as lost formwork is a form that is left in place, or lost, after the wall is complete. There are many different types of forms used in creating rammed earth elements ranging from freshly cut bamboo, to aluminum industrial forms that can be reused thousands of times.
Formwork must be able to withstand the static load of moist soil pushing against it as it dries as well as the dynamic force of the compaction. Formwork is normally greased so soil does not stick to it, and clamps or ties are designed to release and reattach easily to make resetting efficient.

WOODEN FORMS



INDUSTRIAL FORMS

COMPACTION

Compaction utilizes physical energy to reduce the voids between particles making the material as dense as possible. This assures cohesion will occur between courser grains and the binders between them. It also makes the material less permeable so that moisture and vapor cannot infiltrate as easily.

Primitive - Hand tampers Mechanized - gas powered and pneumatic

The Optimum Moisture Content should be maintained throughout, working lift by lift until reaching the ringbeam. Forms can be removed immediately after compaction provided subsequent work will not affect the structural integrity of the wall. Walls that use a stabilizer should be dampened five times a day for three days. [3]

LABOR OPPORTUNITY

As can be seen, this process is labor intensive. It is always good in developing economies to leverage that potential as a benefit for the community. Much of the skills involved here can be taught very easily to community members who will then take pride in the project and further impact the community by continuing with this environmentally safe, economically responsible, and durable construction elsewhere. Money that might normally go to machinery usage or for unsustainable materials from large corporations with little regard for the environment or community is now used for providing jobs and training skills in under served areas.

LABOR OUTPUT:
Traditional systems: 10-30h/m3
Mechanized systems: 5-10h/m3 [5][11]

[3] Auroville Earth Institute
[5] Minke
[11] Houben & Guillaud

Photo bottom right: Laborers in Butaro Rwanda, MASS Design Group

3.2 COMPRESSED EARTH BLOCK

There are many kinds of earth block including; mudbricks, adobe, extruded earth, cut block, tamped blocks but this manual will be looking at the kind compressed with a press machine - either manual or mechanical - into blocks with high compression strength - higher than 2MPa. Where conditions allow and when supported by the testing of engineers only moist soil is required to create Compressed Earth Blocks (CEBs). Sometimes a stabilzer is required, such as cement or lime, to achieve the compression strength needed to make a building system. Blocks with added stabilizers are called Compressed Stabilized Earth Blocks (CSEBs).

TYPES OF C(S)EB SYSTEMS


Interlocking


Mortared


Confined Masonry


Reinforced Masonry

TYPES OF PRESSES

MANUAL PRESSES


CINVA ram


Aurom 3000

HYDRAULIC PRESSES


The Liberator


Hydraform

DIESEL

FACTORY OR OFF SITE PLANTS

Photo opposite: Laborers in Butaro Rwanda, MASS Design Group

SOURCING THE MATERIAL

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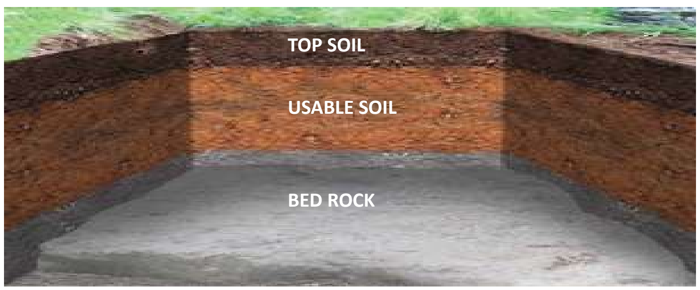

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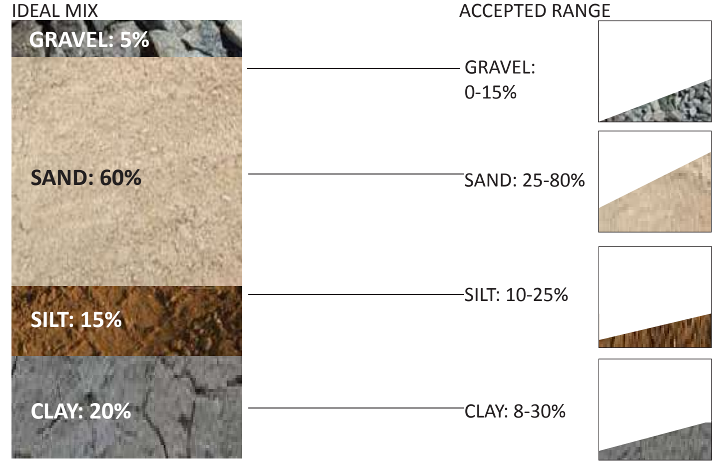
MIXING THE MATERIAL: CEB

There are many differing opinions on the ideal mix. The mix shown below is an average taken from several sources. Differing slightly from rammed earth the gravel content is reduced and gravel granules should be in the smaller range of gravel . Some sources prefer 2% or less gravel. This is because the form is smaller than with rammed earth. Here again 70% course grains to 30% fines.

IDEAL MIX — ACCEPTED RANGE



DRY MIXING

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Primitive - shovel

Mechanized - tiller

WET MIXING

Once the material is thoroughly mixed, moisture is introduced to create the Wet Mix. The mixture should be at the predetermined Optimum Moisture Content - see Section 2 - this is enough moisture so that the soil can bind as compressed but not so much that it inhibits the binding. Time is now of the essence as the moisture level will change, and if cement or other stabilizer has been added, it is beginning to cure. The time between the wet mix and the compaction is called the Hold-back time and must be limited to an hour or less.

Primitive - shovel & can

Mechanized - mixer

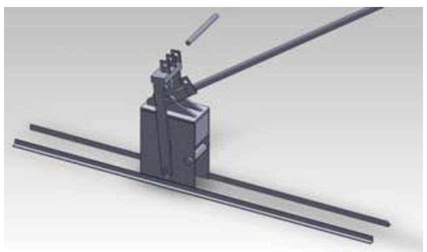
PRESSES

The production capacity of CEB presses vary greatly with the amount of mechanization involved. Mechanized presses can save time and labor costs but in developing markets the upfront expense is normally not justified. Manual presses also help generate more jobs as mentioned in the labor opportunity section, and have less of an environmental impact as they do not require fuel.

MANUAL PRESSES -Cinva Ram

The Cinva Ram was developed by the Chilean engineer Raul Ramirez at CINVA in Bogata, Colombia. The Cinva ram was developed as a proprietary product but Cinva -like models have been developed in DIY forums and schematics of the construction have been shared on many open source websites and shared all over the world.

PROCESS: The Wet Mix is added to the camber and the lever is pulled to compact



See full size schematics in section 6. [16]

PRODUCTION - 300 blocks per day

One person can produce up to 300 blocks per day including the preperation and mixing of soil, adding moisture and compaction. This is slower than molding blocks but the compression strength is much higher with the Ram.

HYDRAULIC PRESS -The Liberator

The Liberator is a hydraulic press that can be fabricated from open source schematics - though more complex than the Cinva Ram. The Hydraulic process allows for more compaction and greater compression strength of the blocks.

PROCESS: The Wet Mix is added to hopper and hydraulically pressed

Fore information, see section 6. [17]

DIESEL PRESS - Hydraform M7MI Super

Hydraform is based in South Africa and is one of many companies that have a range of products to produce CEBs. The below model includes a compressor as well as a mixer. Often machines are used to prepare the soil as well like the rotating sieve pictured (right) or a mechanical pulverizer.

PROCESS: The Wet Mix is added to the camber and the machine presses blocks.

PRODUCTION - 2500 blocks per day

PRODUCTION CHART

PRESS	TYPE	UNITS/DAY	COMPRESSION STRENGTH	
Cinva Ram	Manual	300	2-7MPa	[15]
Aurom 3000	Manual	850	5-8MPa	[3]
Liberator	Hydraulic		5-8 MPa	[16]
Hydraform M7MI	Diesel	2500	6-9MPa	[22]

[3] Auroville
[16] Opensource Ecology - Cinva
[17] Opensource Ecology - Liberator
[22] Hydraform
Photo bottom right: MASS Architect, Christian Benimana mixes soil with laborers in Butaro Rwanda, MASS Design Group

CURING

The curing or drying process of the blocks takes time. Time must be accounted for in a construction schedule and space should be allowed in the construction yard. If drying happens too quickly cracking can occur in the units making them unsightly and prone to failure.

DELIVERY TO THE DRYING YARD:

Wet blocks delivered to the drying yard should be:

- Protected from the sun and rain
- Carefully transported to the block piles
- Carried by gripping with flat palms on either side of the block on short sides

STORAGE OF BLOCKS IN YARD

Blocks should be stored as recommended by the press manufacturer, below are some common recommendations. CEBs should be:

- Protected from the sun by canopy or tarp
- Off the ground to prevent moisture wicking from grade or sheet flow of runoff
- Stacked in piles as recommended by press manufacturer - stored 1 unit high for 1 week then stacked no more than 5 high
- Kept wet by sprinkling water first week
- Stored for 14-28 days depending on the stabilizer - cement cures after 28 days

MASONRY

DRY MASONRY: DRY STACK - INTERLOCKING - MORTARLESS

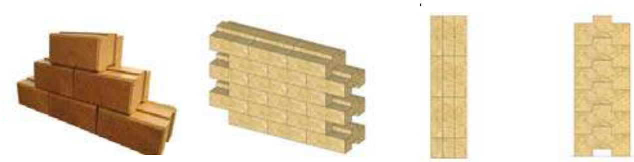


PHOTO AXON PLAN SECTION

MORTARED MASONRY

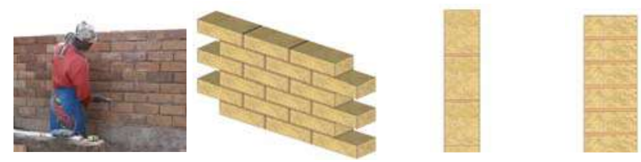


PHOTO AXON PLAN SECTION

CONFINED MASONRY - REINFORCED CONCRETE

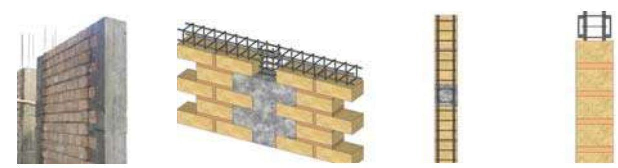


PHOTO AXON PLAN SECTION

REINFORCED MASONRY - INTEGRATED REINFORCEMENT

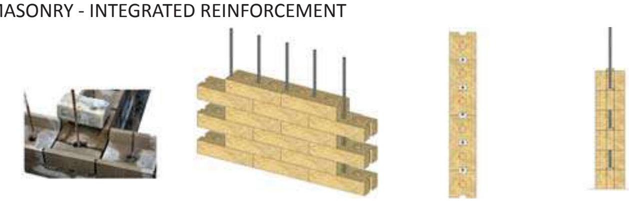


PHOTO AXON PLAN SECTION

TESTING UNITS

As with soil testing there are 2 types of tests that can be performed on constructed units: Lab Tests and Field Tests. Lab tests are more accurate but sometimes inaccessible. Field tests for finished units are generally regarded as more accurate than the soil tests previously discussed but should not be deemed conclusive without the help of an engineer or expert.

LAB TESTS

COMPRESSION MACHINE -
Available at professional testing laboratories, as well as universities, Compression Machines measure the Compressive Strength of cured blocks or core cylinders taken from rammed earth to give an indication as to how the building assemblies will perform.

FIELD TESTS

POCKET PENETROMETER

The penetrometer is a pocket sized tool that in freshly packed blocks works by recording the resistance to penetration by pushing the tip against the surface.

SCHMIDT HAMMER

The Schmidt Hammer, or Swiss Hammer, measures compressive strength by the impact of the hammer against the surface.

BENDING TEST

There are many ways to test for bending strength in blocks. Most systems, like this one from Auroville, support the edges of the block and apply measured pressure to the top in the center. The bending strength is ascertained from the weight at which the block fails.

COMPRESSION MACHINE

Many CEB press manufacturers make compressive strength testing machines for blocks. There are also plans available to make them from a common bottle jack. See section 6

FIELD TEST KIT

Some organizations have developed packages and instructions for testing soils and blocks. The one below is from the University of Bath and sells for 380 Pounds. For more information see section 6. [18]

[18] University of Bath
Photos:
Compression Machine: Test International (UK)
Pocket Pentrometer: Humbolt, Schmidt Hammer: SCCS,
Bending Machine: Auroville, Field Compression Machine: Hydraform
Field Test Kit: University of Bath

SECTION 4: DESIGN

SECTION 4: DESIGN

There is an old saying often quoted that, *earth construction needs a good hat and good boots.* Earth construction is most vulnerable at the top and base of the wall. There are many ways to ensure lasting earth construction but the best way is to design buildings that protect the material from the elements. [11]

4.1 DESIGN PRINCIPALS

In this section information is provided from various building codes and broad principals for design. The information is provided as a point of departure for the designer. As with any construction, a qualified engineer should be consulted before building.

SITING THE PROJECT

Preference is given for flat sites and not close to hills where runoff can come from. Sites should be well drained and away from flood plains. If possible the site should have soil that has been deemed suitable for earth construction and in or near areas where excavation is already planned.

BUILDING SCALE

Buildings made of earth construction are normally only one story. The weight of assemblies requires hefty structural systems to support on upper stories and opening become small as the building gets higher. There are some multi story buildings that utilize earth construction but such buildings are rare.

ENGINEERING INFORMATION CEB:

COMPRESSIVE STRENGTH: 3-5MPa for non-stabilized, 6-9MPa for stabilized
TENSILE AND SHEAR LOADS: Assume 0 unless designed otherwise by engineer
ECCENTIC LOADS = Do not use
YOUNG'S MODULUS: Assumed at E=200MPa
BENDING STRENGTH: .4-4MPA
POINT LOADS: Ring beams should be used to spread all point loads
SLENDERNESS: Restrained at top and bottom: h<10 [20] [11]

BLOCK:	AUROVILLE CLASS A (INDIA)	HYDRAFORM (SOUTH AFRICA)	WATERSHED (USA)
BLOCK TYPE:	CSEB	ISSB	CSEB
DENSITY:	2000kg/m3	1713kg/m3	2000kg/m3
COMPRESSIVE:	6MPa	7MPa	13MPa
WET COMPRESSIVE:	6MPa	7MPa	13MPa

[11] Houben and Guillaud
[20] NM Code
Chart from Manufacturers - Auroville, Hydraform, and Watershed

Photo opposite: Opera Village by Francis Kere Architects, photo: Iwan Baan

FOUNDATIONS

FOUNDATIONS

Although they are seen commonly in the developing world, Rammed earth foundations are not recommended. Moisture from ground water, as well as sheet flow runoff can seriously compromise rammed earth foundation and then the entire structure. Preferred methods for foundation construction include :

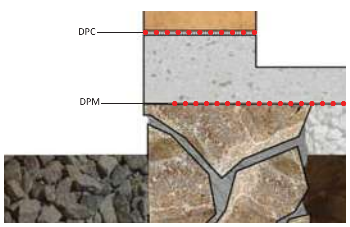
CYCLOPIAN:
A wall or foundation comprised of large rocks held together by mortar

CONCRETE MASONRY:
Masonry units site made or precast of concrete bonded with mortar

POURED CONCRETE:
Concrete that is poured in formwork usually with reinforcing bars (rebar)

FOUNDATIONS

Foundations should be below the frost line, waterproofed, well drained, and reinforced for rigidity and continuity.



DAMP PROOFING:
A continuous damproof membrane, damproof course, and - often - ant repellents are required at connection between foundation and base of wall and slab. Foundations may also be rendered with water-resistant concrete or bituminous parging.

DRAINAGE:
Ample drainage should be provided around the foundation. Permeable material such as gravel or rubble will allow for drainage to minimize hydrostatic pressure on the foundation which can lead to cracking and moisture infiltration. Drainage tiles or surface gutters are often used to move water quickly away from the building.

WALLS

BASE OF WALL

The base of wall is susceptible to damage from many sources including splash back from rain, sheet flow runoff, dew, plants, and animals. The best way to avoid damage at the base of wall is to have large overhangs and elevated base along with good drainage. Other protective measures are included below:

PROTECTIVE LAYER:
Cement Renderings are often provided at the base of wall to guard against elements

DRAINAGE:
Permeable surfaces or rain gardens at the drip line help guard against splash back

BUFFER ZONE:
A buffer zone can be helpful to keep animals from brushing or borrowing at base

WALL ASSEMBLIES

There are various systems of buildings with earth as described in previous chapters. Rammed earth walls have different constructions for different climates and seismic areas. Some are insulated and some are reinforced. C(S)EB walls include drystack, mortared, confined masonry and reinforced masonry each with their own construction detailing.

TYPOLOGIES

Rammed Earth and C(S)EBs are allowed in most areas as single and double family homes without special permission but have been used all over the world in commercial constructions provided adequate engineering has been conducted. The guides here are mostly geared toward residential construction.

WALL THICKNESS - RAMMED EARTH

Exterior walls should be 45-60cm thick and laterally supported by buttresses or intersecting walls at 7m. Buttresses are often not required for walls 60cm thick which are considered self buttressing. In most cases interior walls are allowable at 30 cm.

WALL THICKNESS - COMPRESSED EARTH BLOCK

Common masonry unit thicknesses include 15cm 20cm, 22cm, 24cm, and 30cm. As with Rammed Earth CEB walls should be laterally braced periodically in plan by buttresses or perpendicular walls.

Photo top right: Centre de l'Architecture en Terre by Francis Kere Architects, photo: Iwan Baan

OPENINGS

SOLID / VOID

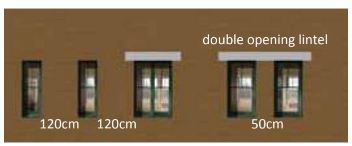
The total length of the openings should be less than 35% of the length of the wall. Where possible any opening in the plan should bridge the entire height from foundation to ring beam thereby not considered an opening in the earth construction and subject to the 35% rule but rather a break between walls.

PUNCHED OPENING:
Where not full height openings should conform to the 35% rule and have a lintel.

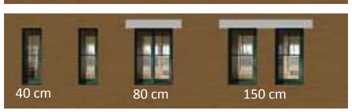
SOLID / VOID BREAK:
Breaks and the plan for full height openings are opportunities for vertical reinforcement and utilize the ringbeam as a lintel.

PUNCHED OPENINGS AND LINTELS

Care should be given to ensure that openings are given adequate spacing; are not more than 35% the length of the wall; and have properly sized lintels of appropriate material with adequate bearing on wall.



SPACING:
Openings should not be within 1 meter of each other or of the edge of the wall. Exceptions may occur with walls 60cm of thicker.



OPENING WIDTHS:
Openings of more than 60cm will require a lintel

BEARING OF LINTELS:
Lintels should have adequate bearing on the wall. Plan 30cm or more.

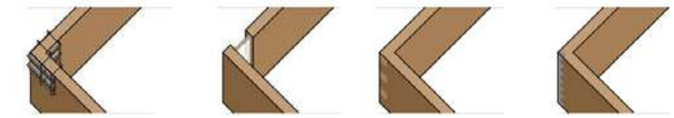
LINTEL SIZES: For the wall thickness listed below, plan for the lintel sizes shown when using reinforced concrete

WALL THICKNESS	OPENING	LINTEL SIZE [20]
45cm	60cm	15cm x 45cm
45cm	250cm	20cm x 45cm
60cm	60cm	15cm x 60cm
60cm	250cm	20cm x 60cm

CORNERS

RAMMED EARTH

EXTERIOR CONNECTIONS
Corner details can be problematic with rammed earth. There are a few different construction techniques to consider in the deign of exterior corners to maintain continuity and durability of the material.



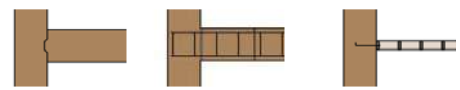
CONTINUOUS FORM: Corner forms can be constructed to make a seamless and rigid corner

BREAK IN WALL: The wall can simply be terminated at the corner with an opening placed as a break

OVERLAPPING: Overlapping forms can be used make a masonry bond appearance

COINING: Stones can be placed at the corners to protect the edges and create visual interest

INTERIOR CONNECTIONS
Interior to exterior walls need to be bonded together at their intersections to brace each other.



RE to RE: Keyed connection

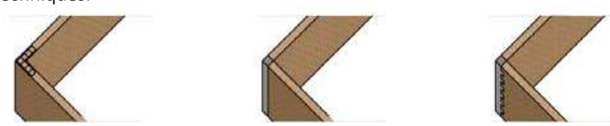
RE to ADOBE: Ladder Reinforcement

RE to STUD WALL: Anchor bolt

RE to OPENING: Anchors or nails

COMPRESSED EARTH BLOCK

EXTERIOR CONNECTIONS
Corners are easier with CEBs as they can be set like any masonry unit. When tying into a reinforced concrete frame there are a few different bonding techniques.



CONTINUOUS MASONRY: Ladder reinforcement, if req.

REINFORCED CONCRETE: Butt joint reinforced if req

CONFINED MASONRY: RC toothed into masonry

INTERIOR CONNECTIONS
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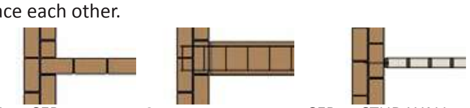


CEB to CEB: Masonry bond

CEB to RE: Ladder Reinforcement

CEB to STUD WALL: Anchor bolt

CEB to OPENING: Anchors or straps

[20] NM Code

Photo top right: Centre de l'Architecture en Terre by Francis Kere Architects, photo: Iwan Baan

TOP OF WALL

RING BEAM

Ring beams should always be provided to distribute point loads evenly to the wall assembly systems and provide rigidity to the building system.

REINFORCED CONCRETE:
RC ringbeams are the most common as they are rigid and easy to construct on the top of RE or CEB walls

TIMBER:
If engineering and resources will allow, timber ringbeams and/or lintels can be used with RE or CEB walls

ROOF ATTACHMENT

As previously mentioned no pointloads from roofing elements should be in direct contact with earth walls. Anchorage should instead be with the ringbeam that can evenly distribute loading or to another structural system in place.

SLOPING ROOF:
Rafters or trusses will bear and anchor to the ringbeam

LOW SLOPE ROOF:
Joist will bear and anchor to the ringbeam

PARAPET:
Earth Construction wall will continue past roofing system supported by another structural system

RINGBEAM SIZES: For the wall thicknesses below, plan for the ringbeam shown when using reinforced concrete

WALL THICKNESS	FULLY SUPPORTED	SPAN	RINGBEAM SIZE
45cm	Yes	N/A	30cm x 45cm
45cm	No	<3m	40cm x 45cm
60cm	Yes	N/A	30cm x 60cm
60cm	No	<3m	40cm x 60cm

OTHER BUILDING ELEMENTS

ROOF ELEMENTS

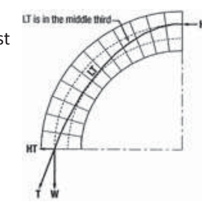
VAULTS
Vaulting can be done in either rammed earth or earth block and take very complex forms

CEB VAULTING

CEB BARREL VAULT

DESIGN OF VAULTING
Vaults have complex loading structures as their gravity load is converted to a load with both axial forces and lateral forces, or thrust at the base of the vault. To optimize the design, vaults become thicker at the base. Sometimes compression rings or steel ties are used.

HT= Horizontal thrust
LT= Line of thrust
W= Vertical load
T= Thrust



VAULT LOADING

SLABS AND FLOORING

RAMMED EARTH FLOOR
Rammed earth floors are extremely easy to fabricate as no forms are needed. A well drained and compacted substrate must be prepared where a Wet Mix of soil, stabilized or otherwise can be compacted by hand tampers or machines.

FLOOR COMPACTION: Traditional

FLOOR COMPACTION: Mechanical

WALL FINISHES

RE and CEB walls can be left natural or covered with a breathable material such as a rainscreen or permeable rendering.

When Rendering:
Bed joints should be held flush
Blocks should be wet before rendering
Blocks should be scarified for bonding

CEB Vaulting - ETH
CEB Barrel Vault - Auroville Earth Institute
Vault Loaded - Auroville redrawn by author

Photo top right: Centre de l'Architecture en Terre by Francis Kere Architects, photo: Iwan Baan

LATERAL STABILITY

Due to its mass and brittleness rammed earth is not recommended in seismic areas. Heavy building elements have been known to fall and kill people. There are several ways to make earth construction work in seismic areas; a few projects are shown below. As with any construction a qualified engineer should be engaged when working with rammed earth, especially in seismic areas.

CONFINED MASONRY

REINFORCED MASONRY

REINFORCED RAMMED EARTH

SEISMIC DESIGN

Below are some useful tips for design in seismic areas from the Smart Shelter Foundation:

Rule 1. Don’t build on slopes.
Stay at least 3 meters away from edges, or build retaining walls.

Rule 2. Use simple and symmetric shapes.
Do not make buildings that are shaped like an L, H, U or any irregular shapes. During a seismic event these will be subject to torsion, and the walls will crack.

Rule 3. Separate the building volumes.
Cut the building configuration into smaller pieces by creating a gap in between of at least 8 centimeters. Another option is to create a corridor between the volumes.

Rule 4. Maximum dimensions of volumes.
Maximum ratio of width versus length = 1 : 3.
Maximum free span of rooms = 6 meters.

Rule 5. Use light and rigid roofing system.
This is a good opportunity to create a rigid diaphragm. [10]

[10] Smart Shelter Foundation

Photo opposite: Gradebeam and reiforce concrete column for confined masonry at in Butaro, Rwanda, MASS Design Group

SECTION 5: CASE STUDY

5.1 BUTARO DR'S HOUSING MASS Design Group

These rural houses were built immediately adjacent the Butaro Hospital. The Butaro Hospital, also deigned by MASS and built by Partners In Health, is a teaching hospital that has caught the attention of many architectural publications and has won many awards for design. The homes are constructed with a reinforced concrete frame and CSEBs from soil found on site and were designed to attract doctors from urban Rwanda and all over the world to work in this remote and under-served environment. When PIH and MASS started building in this region there were 400,000 people with no doctor. Butaro Hospital now has doctors from the best teaching hospitals in the world and is rural Africa's only full cancer treatment center.

SCOPE OF WORK

Four 2-bedroom homes were built in Phase 1 on a hilly site roughly a two hour drive from the capital city of Kigali; Much of that is down a dirt mountain pass that often washed out during the rainy season. Transportation of material to the site was difficult, expensive and even dangerous. With that in mind, and along with MASS' commitment to low environmental impact, resources that were readily available were chosen for construction - volcanic stone and earth.

PROJECT IMPACT

30 people were trained in seismic compressed stabilized earth block construction processes — to in total make **29,000** blocks.

138 people learned masonry skills — **46** of whom became high-skilled, professional masons.

60 people received training in steel bending and carpentry.

50 people learned terracing practices, a skill valued to stabilize Rwanda's agricultural hillsides.

900 jobs created in the construction process.

400,000 US dollars distributed into the local and regional economies for replicable impact.

Project Impact from MASS Design Group

Photo opposite: Butaro Doctors' Housing, photo: Iwan Baan

PROCESS

MAKING BLOCKS

1. EXCAVATION	As the soil was excavated for the homes the topsoil was preserved in one location and the soil below that was used for creating the CSEBs. Additional pits were required to make the 29,000 blocks for the 4 homes. Manual labor was utilized in order to maximize the impact of the project by adding jobs and lowering the carbon footprint by not hiring heavy machinery.
2. SOIL PREP	The soil is set out in the sun in thin layers to dry and can be pulverized. Large rocks, gravel, and any roots or sticks can be seen and easily removed. Once the soil is dry it will be sieved through several screens to separate the particle sizes.
3-5. TESTING SOIL	The design and project management crew underwent the series of initial field tests described in section 2. Here we see the form test and visual tests.
6. DRY MIX	Once the soils grains were separated they were reconstituted by shoveling enough for one block at time, then mixed by hand and shovel to create an even distribution. Course sand, silt and clay were mixed with 5% cement for stabilization.
7. WET MIX	After all of the dry ingredients were thoroughly mixed, a predetermined amount of water was added to create the Wet Mix at the Optimum Moisture Content. At this point workers have a Hold back limit of less than one hour to press the block, though it was normally done in a matter of seconds.
8-10. LOADING	The Wet Mix is scooped up and loaded into the hopper which drops the mixture into the press chamber.
11. PRESS	Some presses only need one person to press the block, this machine the Auram 3000 however required two people. The long lever arm optimizes the effort to compact the soil in one push.
12. THE BLOCK	When the arm is raised a fully compressed block is released from the chamber.
13. TESTING	The block is then tested with a pocket penetrometer for compressive strength, marked with the reading and the date and taken to storage.
14. STORAGE	The block is moved by pressing with palms against the short sides of the block and taken to a storage area were it may be kept off the ground and out of the sun. It is staked one unit high and dampened for several days then stacked up to five units high.

Photos opposite: Butaro Doctors' Housing, MASS Design Group

PROCESS

CONSTRUCTION OF WALLS

1-2. MOCK-UPS The site foreman prepares wall mock-ups to verify dimensions and test durability. Once dry, the blocks can also be tested for compressive strength and bending individually.

3. LAYING BLOCKS Several different block types were produced and arranged in a number of coursing patterns before the masonry was optimized for construction.

4-5. MORTAR Although earth mortar is acceptable in some circumstances for CEB construction, a cement mortar was used on this project as it tied in with the reinforced masonry system.

6-7. REINFORCING Closeups of the reinforced masonry system. Semi-circle blocks mirror each other to create a circular chamber in which to place rebar and pour mortar, effectively creating columns within the CEBs.

8-11. CONFINED Two of the homes used Reinforced Masonry and two used Confined Masonry. Confined Masonry formwork is placed on the open sides of columns and utilizes the toothed masonry as forms to pour a reinforced concrete column that is integrated into the masonry.

12. RINGBEAM Once the wall was constructed to full height it acts as the bottom form for the ring beam. Boards were placed at the sides of the wall and rebar was set before a pour that saw an assembly line of 50 people or more passing small trays of concrete from the mixing areas to the homes to make a monolithic pour.

13. BUILDING View of the building shell nearing completion.

Photos opposite: Butaro Doctors' Housing, MASS Design Group

SOCIAL IMPACT

REGIONAL IMPACT

Since the Butaro Hospital was completed the district it serves has seen some radical changes in economic growth. Access to healthcare and employment opportunities at the hospital have brought people into the community and spurred investment in small businesses. The addition of the Butaro Doctor's Housing has impacted the region by attracting highly skilled doctors to this rural area. In Rwanda 88% of physicians work in urban areas. These doctors and the international specialist that train them normally rotate through regions like this rather quickly, now are seeking opportunities to stay here for years.

The construction of these and other projects by Partners In Health, and the Ministry of Health of Rwanda has created a vibrant community of laborers that have skills that are sought after not only in Rwanda but all over East Africa

PERSONAL IMPACT

Beyond the impact of the hospital and beyond the fortified labor forces, there are an untold number of personal experiences involved in any project like this. MASS' commitment to leveraging the construction process to create public impact and their comment to gender equity has had a profound impact on the social fabric. Below is just one story they documented to help keep their focus on the communities they serve in future projects.

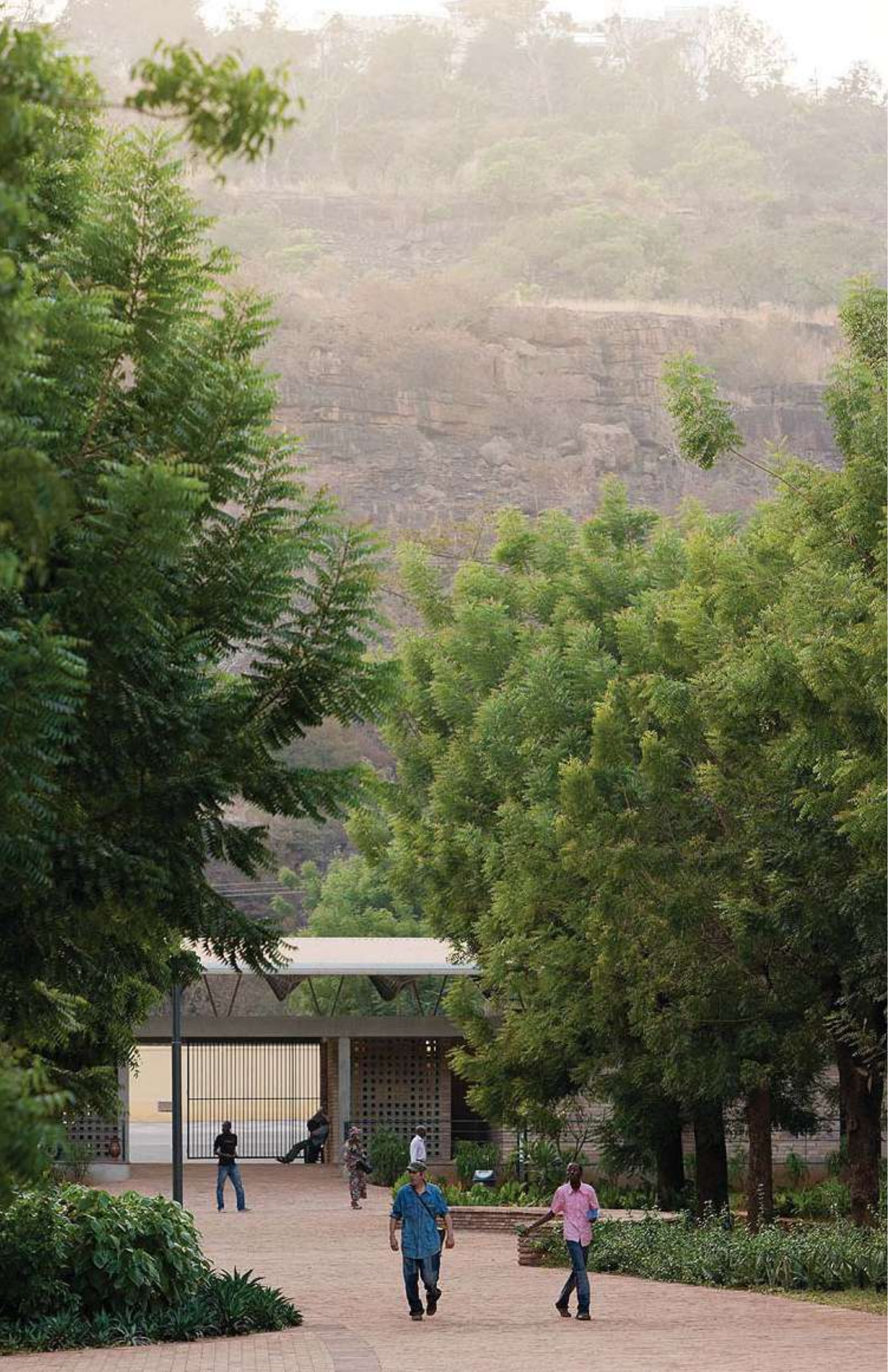
"Where I stand now I am happy; everything is because of the hospital project. Now we are many—nine women, all of them building — that's what we do really, we do miracles. I often thought that gender equity would never happen, except that when I look at where I am now, I think it can."

- Anne-Marie Nyiranshimiyimana,
One of the first female master masons who worked on the hospital and went on to lead a team on the Doctors' Housing project

Anne Marie's story - MASS Design Group

Photos opposite: Butaro Doctors' Housing, MASS Design Group photos: Iwan Baan

SECTION 6: FURTHER RESOURCES



SECTION 6: FURTHER RESOURCES

RESOURCES

Whether it is performing the hydrometer test or making a home compression machine, there are many resources to consider as you continue to learn more about earth construction.

PUBLICATIONS

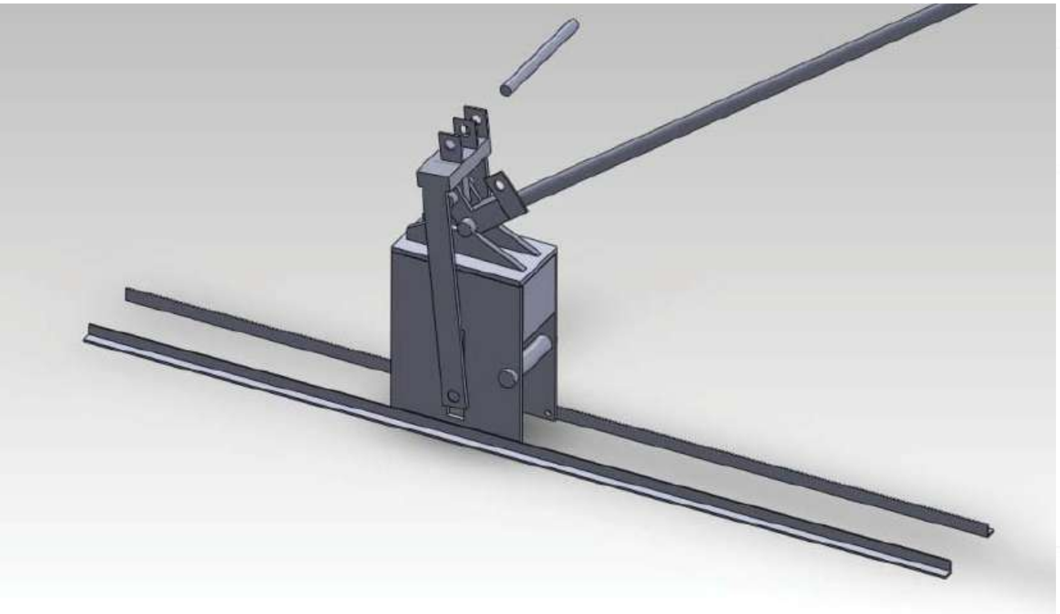
EARTH CONSTRUCTION: A comprehensive guide
Hugo Houben and Hubert Guillaud - Practical Action Publishing
BUILDING WITH EARTH: Design and Technology of a Sustainable Architecture
Gernot Minke - BirkHauser
MODERN EARTH BUILDING: Materials engineering, Construction, and Applications
Matthew R Hall, Rick Lindsay, and Meror Krayenhoff - Woodhead Pub.
RAMMED EARTH: Design and Construction Guidelines
Peter Walker, Rowland Keable, Joe Martin, Vasilios Maniatidis, BRE Press
Earth Masonry: Design and Construction Guidelines
Tom Morton, BRE Press

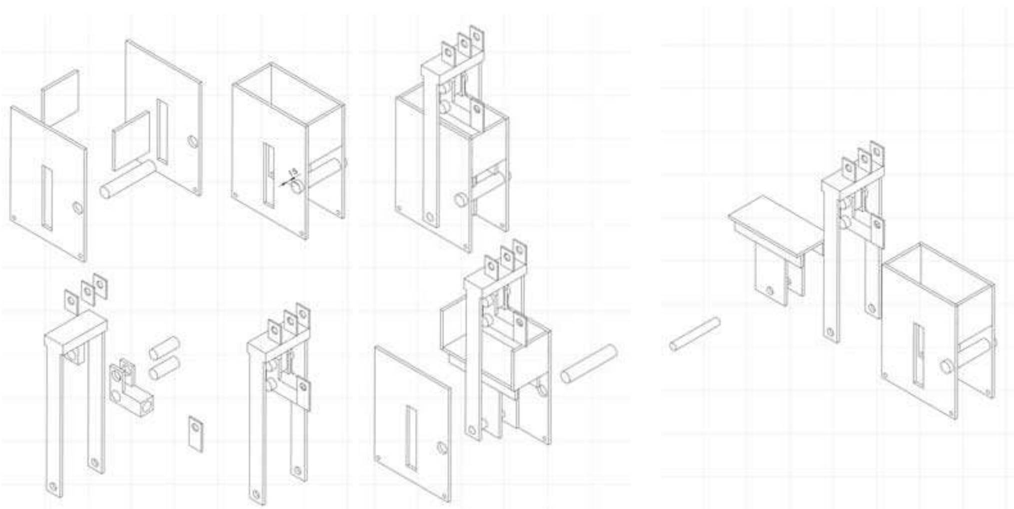
WEBSITES

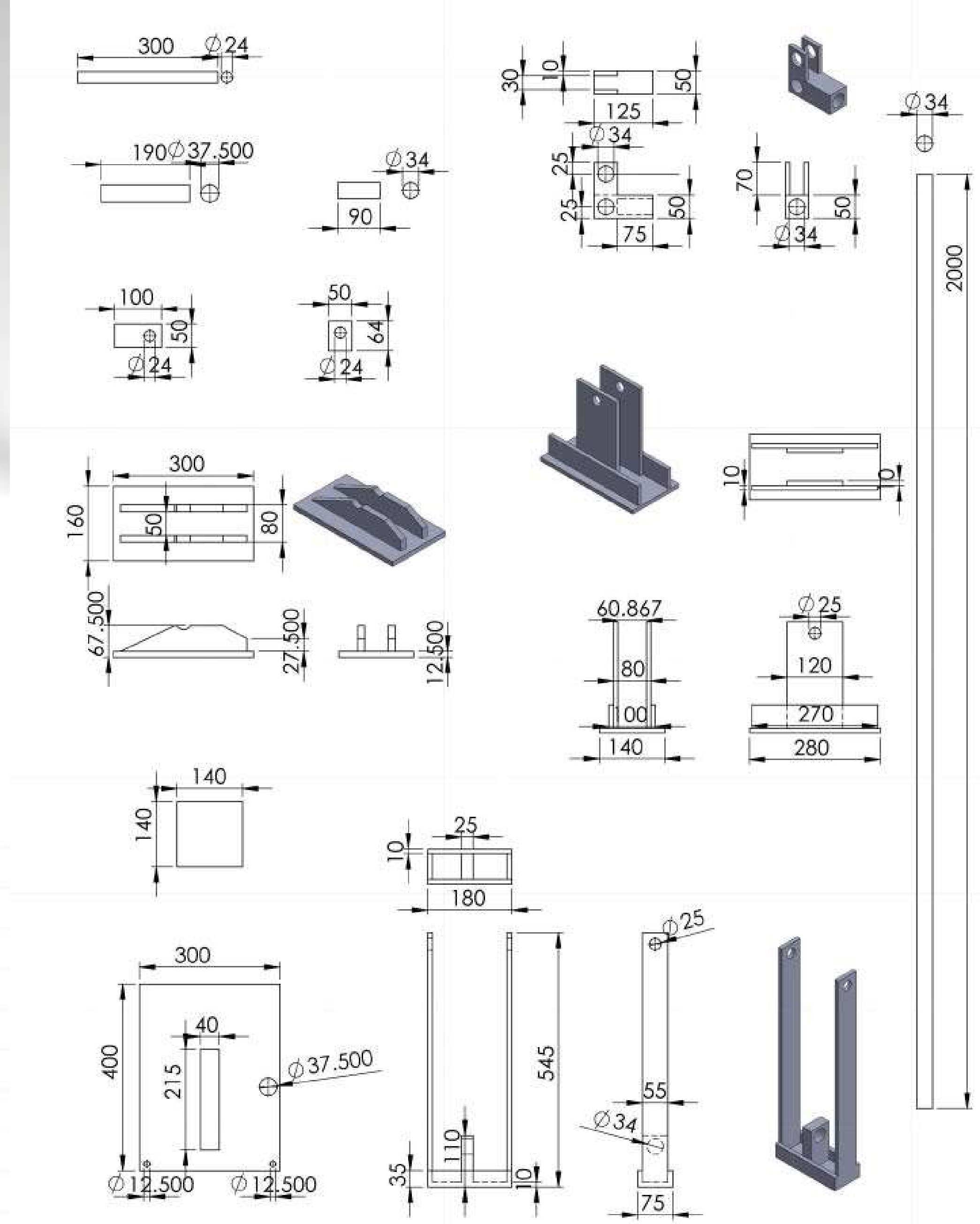
	Guidance	Training	Equipment	Consultancy
Auroville Earth Institute: earth-auroville.com	●	●	●	●
Open Source Ecology: opensourceecology.org	●		●	
Smart Shelter Foundation: smartshelterfoundation.org	●	●		●
BRE CICM: bath.ac.uk/ace/research/cicm/	●	●		
CRAterre: craterre.org	●	●		●
Earth Architeture: eartharchitecture.org	●		●	●
Lehm Ton Erde: lehmtonerde.at/en/	●			●
Hydraform: hydraform.com	●		●	

Photos opposite: Bamako Park by Francis Kere Architects, photo - Iwan Baan

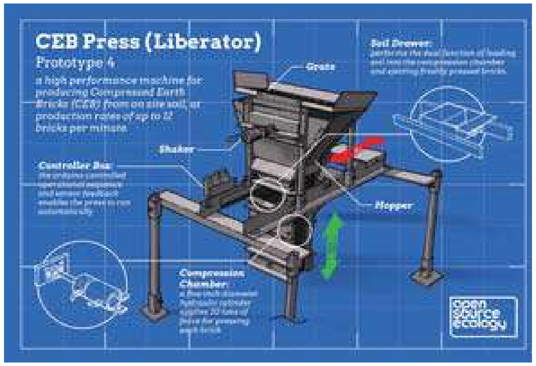
OPEN SOURCE PLANS FOR CINVA RAM





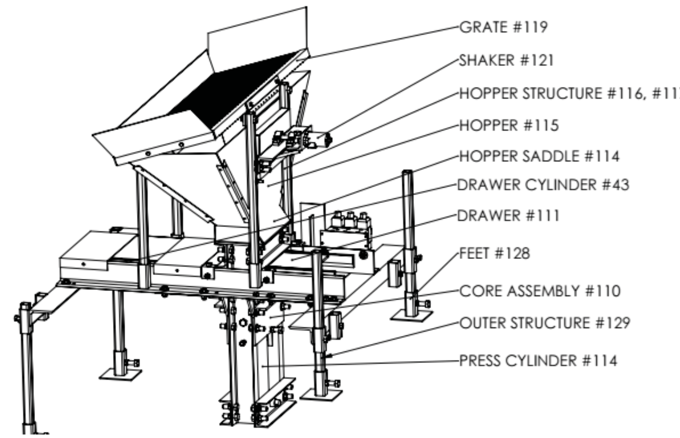


OPEN SOURCE PLANS FOR LIBERATOR



SPECIFICATIONS: (from open source ecology website)

Version 6 is our current model; exhaustive documentation release comming 4/30/15
Open source hardware, controller, and software (CC-BY-SA, GPL)
Controller includes automatic pressing and manual mode
Does NOT come with a power source - it is powered by a hydraulic power source, such as by our Power Cube or a tractor hydraulic take-off.
Full size bricks are 4”x6”x12”, plain flat-faced bricks
Brick height is adjustable from 1”-4”
Brick dimensional variations: +/- 1/16”. Soil uniformity will determine height uniformity of brick.
6 full-sized bricks per minute at 14 gallon per minute hydraulic flow. Brick pressing rate will increase with a higher hydraulic flow, up to the maximum rated flow of the hydraulic solenoid. At a flow >14 gpm, the secondary cylinder and shaker motor are throttled down to reduce their speed. Hydraulic solenoid valve is rated for a maximum of 30 gpm fluid flow at 3000PSI
Fuel consumption with Power Cube running at 14 gpm fluid flow - about 1 gallon per hour
System hydraulic pressure - 2300 psi
Comes with hydraulic quick couplers ready to be connected to a power source
Weight - 1700 lb
Moving: brick press is moved with forks. Footprint (with legs in the inner position) allows machine to be placed in the bed of a 3/4 ton pickup. It has adjustable legs for uneven terrain. Machine can be moved around on a trailer (not included)
Material cost: $4500-$6500 depending on sourcing; manual machine (without hydraulic solenoid, machine costs $1000 less in materials
3’x6’ grate for tractor loading. Includes soil deflectors
Includes hopper shaker to help soil move down the hopper
Known bugs: machine has currently been tested in multiple day production runs and is stable at 6 bricks per minute. When solenoid valve ran with 2 Power Cubes at 28 gpm fluid flow, the valve would lock up from time to time. May be software, solenoid design, or Power Cube stacking issues, and requires detailed analysis. This bug was not seen when a larger diesel engine was used to power the brick press in 2010 at 30 gpm fluid flow.



opensourceecology.org/wiki/CEB_Press

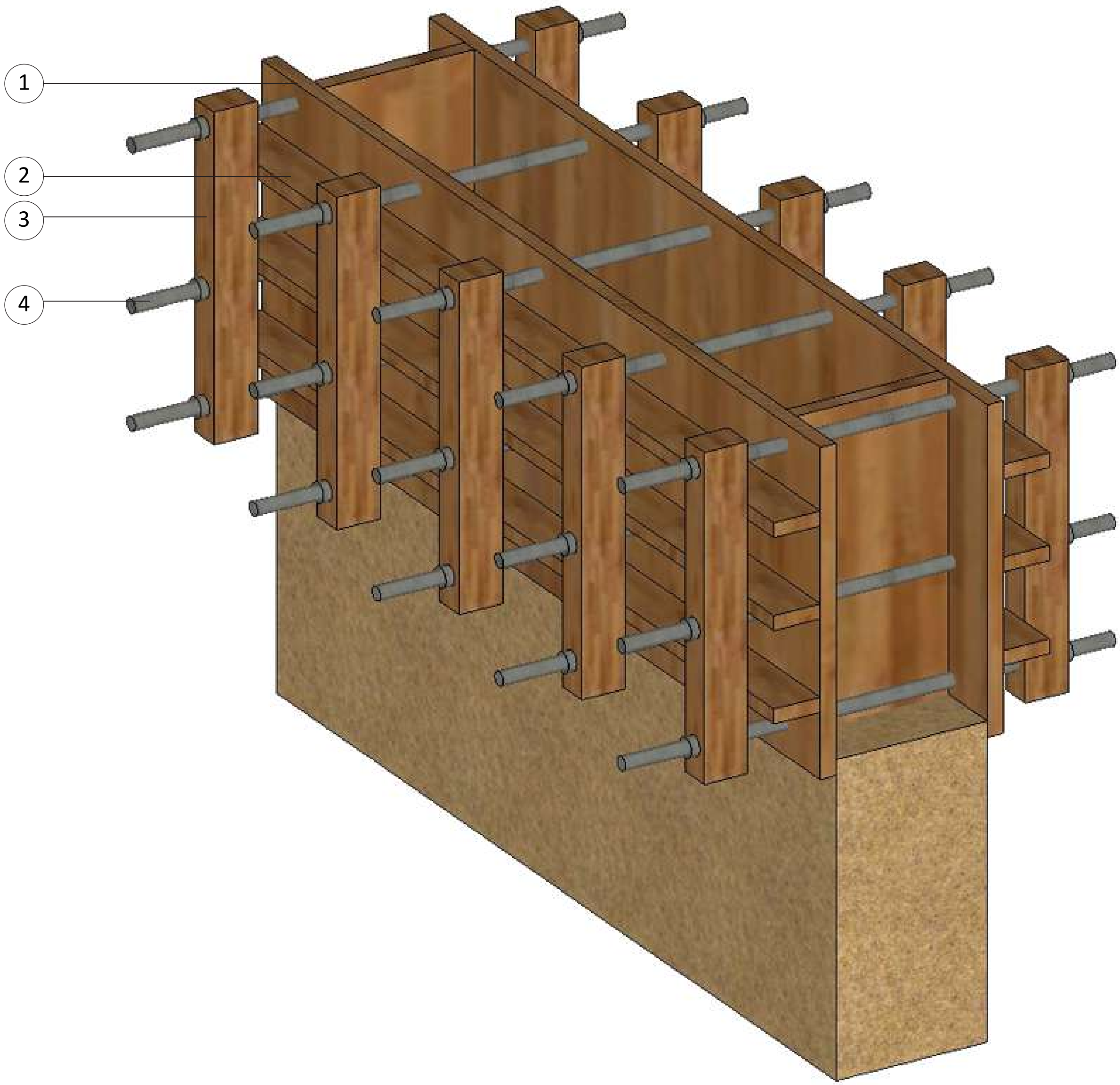
SOIL SIFTING STATION

PARTS:

1. 2x4 Wooden Screen Frame: 2′x 3′
2. Gravel Screen
3. Gravel chute - bent sheet metal
4. 2x4 Wooden Screen Frame: 2′x 3′
5. Coarse Grains Screen
6. Coarse Grains Chute: bent sheet metal
7. Gravel bucket
8. Course grains bucket
9. Saw horses
10. Frame
11. Wheel barrow with fine grains
12. Motorized assist to shake gravel pan

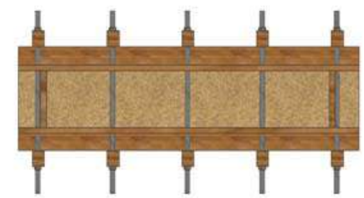
www.landscapejuice.com/2009/10/make-this-simple-garden-seive-for-45
3dwarehouse.sketchup.com/tos

FORMWORK SCHEMATICS



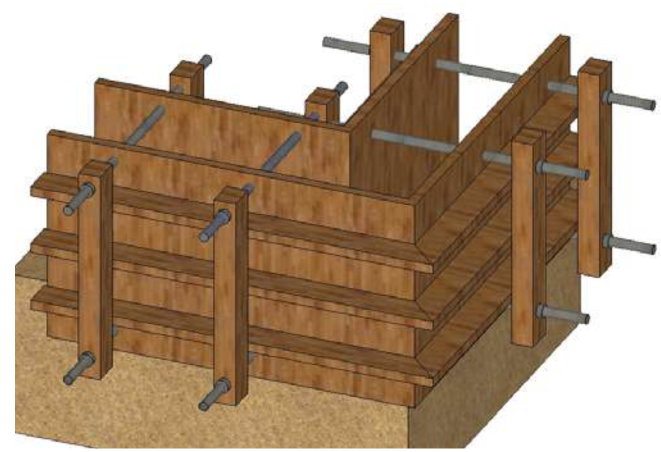
PARTS:

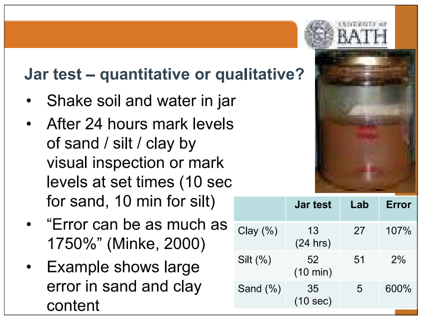
1. 4′x8′x1″ plywood sheathing
2. 2x6 walers @ 1 ft on center
3. 4x4 posts
4. 3/4″ Threaded rods w/ washers and bolts

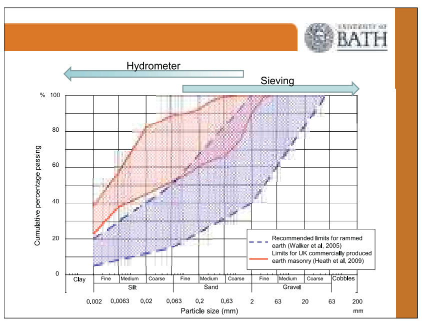


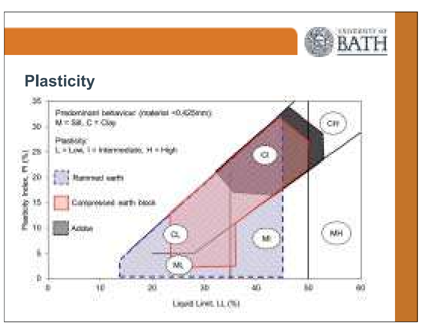
plan

elevation









FROM SITE:

This project consisted in the development of a low-cost, portable field laboratory/ test kit to determine the material properties relevant to earth construction, thereby allowing reliable quality control.

Compressed earth blocks (CEBs) and other forms of earth construction are extensively used in developing and disaster areas as a replacement for fired bricks and concrete blocks in small building construction.

There are a number of NGOs and other development organisations involved with this form of construction around the world.

Unfortunately the quality control on these projects is often limited to visual inspection of materials to determine their suitability for use, without knowledge of their engineering properties. This can lead to inefficient or unsafe use of materials.

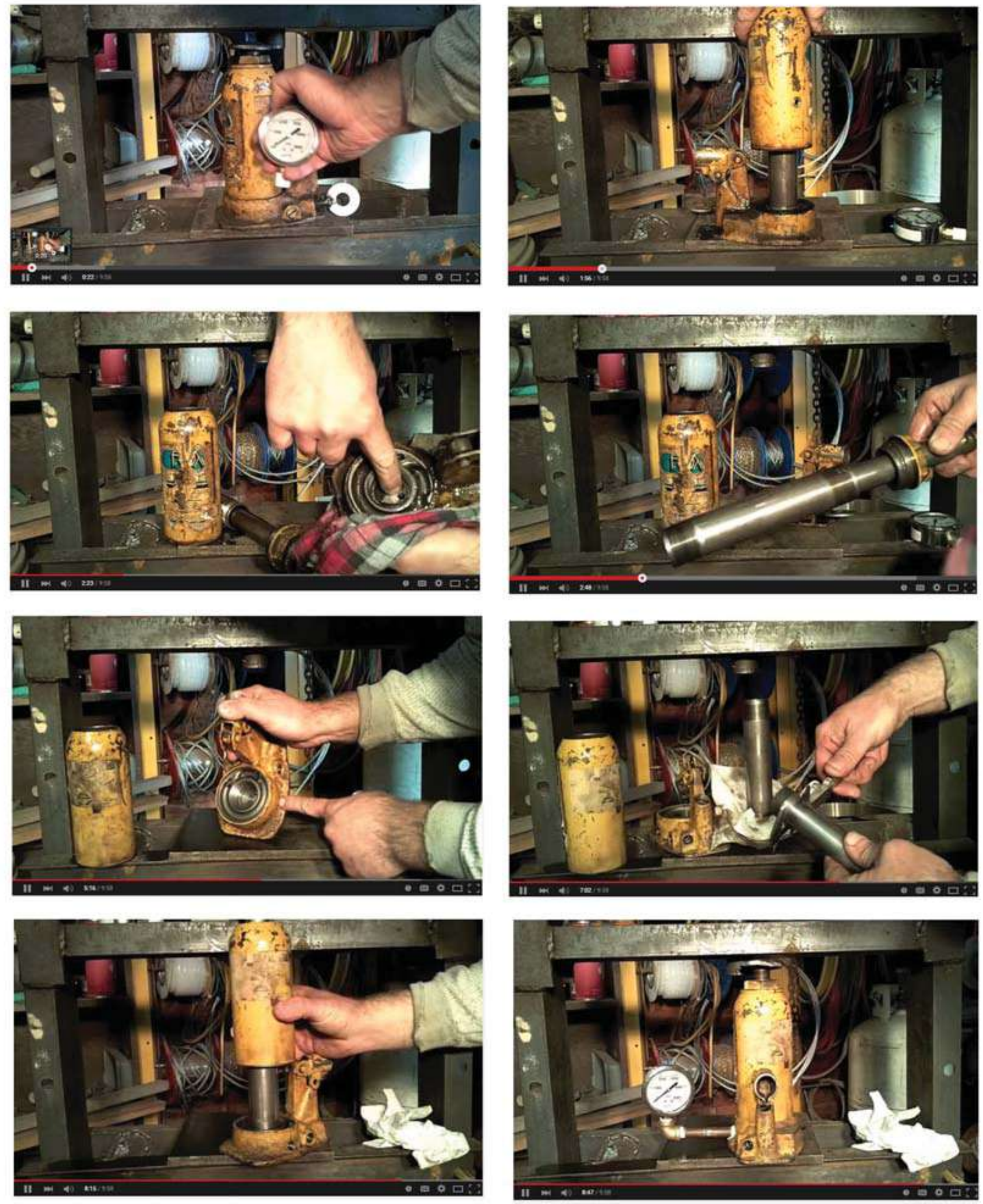
Research over the years has confirmed the required soil properties for both stabilised and unstabilised earth construction, but the tests normally have to be undertaken in a soils laboratory not available in many developing and disaster areas.

Therefore the project aimed to develop a low-cost, portable field laboratory/test kit to allow for reliable quality control of earth construction.

bath.ac.uk/ace/research/cicm/low-carbon-materials/

DIY COMPRESSION MACHINE

This youtube video can teach you how to put a gauge on a regular bottle jack to create a compression machine.



www.youtube.com/watch?v=ZBmxkWK_OFA

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Photo reverse (back cover): Francis Kere at Bamako Park by Francis Kere Architects, photo: Iwan Baan