# 1:2 Scale Earthbag Shear Testing

Build Simple Inc., www.BuildSimple.org
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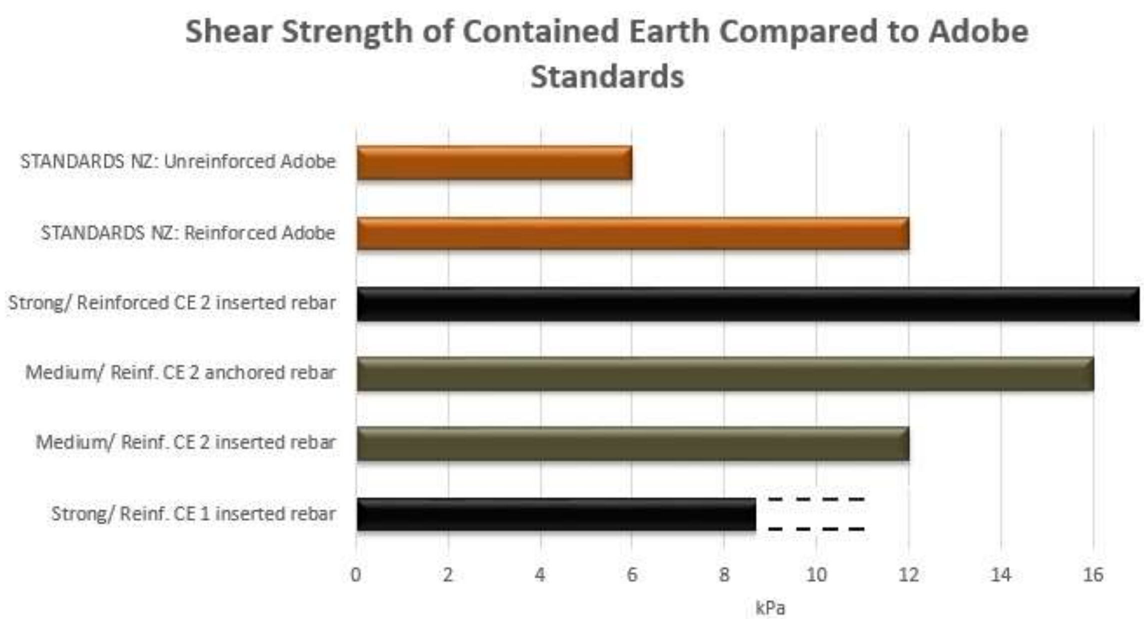
## 1 Executive Summary

In many parts of the developing world there is great demand for low-cost walls of local, sustainable materials. Earthbag has been spreading worldwide, as well as compressed earth blocks (CEBs) and rammed earth. In high seismic risk regions these heavy walls must be carefully reinforced. The confined and modular nature of earthbag, with intrinsic tensile reinforcement from barbed wire between courses show promise for vibration resilience.

More than 50 earthbag buildings in Nepal survived the recent quakes near villages where most stone, earth and brick buildings were severely damaged or destroyed. But how strong is this geo-textile technique?

Can it be structurally designed for use where earthquakes may be 2- 3 times stronger than the estimated 0.8 g forces that the ordinary earthbag buildings survived?

Recent tests show that reinforced earthbag built of medium strength soils can equal stringent strength requirements developed in New Zealand for adobe walls in 1.5 g risk areas. Reinforced strong soil walls can be 1/3 stronger than adobe strength guidelines.




But unreinforced earthbag built of non-cohesive weak soil may be only half as strong as recommended for unreinforced adobe in areas risking quake forces less than 0.6 g.

Soil strength matters.

Strong soil plus reinforcement creates walls with high ductility. Contained earth walls are deformable, but their fabric confinement prevents wall collapse when damaged. Barbed wire within walls can be detailed to prevent the gapping that leads to corner failure in adobe, and to give significant out-of-plane strength.

To complicate matters, unreinforced solid contained earth (also known as hiperadobe) can be much stronger than reinforced adobe guidelines, although similar to an unreinforced rammed earth wall it has limited ductility.

# 2 ABOUT EARTHBAG/ CONTAINED EARTH

The low cost and simple techniques used to build earthbag walls have fueled their spread worldwide where labor costs are low but manufactured materials are scarce.

Earthbag was developed about forty years ago by interlayering strands of barbed wire between tubes or bags made of non-bio-degradable polypropylene fabric filled with soil.

Contained earth (CE) is the type of earthbag wall that incorporates the strength of cured, cohesive soil by using it damp and tamping it to compact about 20%. Although earthbag builders traditionally use this type of building technique, the term contained earth can differentiate this strong medium from contained gravel used for water-resistant base walls and from contained sand.

Contained sand is any geo-textile building wall using a non-cohesive fill (whether non-cohesive soil is used, or if soil is inserted dry or not tamped or cured). Soil bag is the civil engineering term for contained sand, but is most often used in horizontal layers as road and structure footings. These have been proven to dampen vibrations.

Much research has been completed on soil bag strength. Researchers at the University of Bath have proven that contained sand wall strength, like soil bags, relies on the strength of the confining fabric more than the composition of the fill material.

Although engineers have been using this contained sand data to design contained earth walls, three tests by Build Simple Inc. (BSI) in 2011 and 2012 indicated that the strength of cohesive fill is important to contained earth wall strength. The recent 2016 tests more clearly separate the strength contributions of reinforcement type and soil fill strength.

# 3 IMPROVING REINFORCEMENT FOR CONTAINED EARTH

Engineers have recommended for best strength of earthen walls that a single length of rebar span from reinforced concrete footing to reinforced concrete bond beam (Standards New Zealand). Traditional earthbag reinforcement cannot do this. At most 5’ lengths of rebars are hammered into the damp earthen wall at half-height and again at the wall top (Hunter and Kiffmeyer). Longer rebar cannot be hammered into earthen walls. These short rebars overlap slightly within the wall, but cannot be attached to any footing.

Rebar placed externally can be anchored in a footing. Earthbag can be reinforced by connecting paired exterior rebar with strong wire ties across the walls. This ‘pins’ the entire wall length (Precision Structural Engineering), but is costly.

Rebar can be used less intensively in a similar way by pinning corners, and/ or buttresses and wall intersections. But pinned rebar is independent of barbed wire. Since barbed wire is the connection between the fill in each individual bag or tube and the building as a whole, engineers have suggested attaching barbed wire to rebar directly (M Taha).

Exterior rebar at wall ends and corners can be anchored in a footing and have barbed wire attached directly to it. Even if full RC footings are not being used, spot footings of concrete can brace vertical rebar against racking.

# 4 SOIL STRENGTH

Earthen building standards for New Mexico, US and New Zealand concerning rammed earth and adobe construction both require minimum strengths for building soil. But many builder trainers teach that any soil can be used in earthbag.

Earthen buildings are desired for their low cost, and are needed in rural regions with few professionals. Laboratory soil strength testing can cost hundreds of dollars in the developed world, and requires equipment that may not be available at the best engineering universities in some regions.

Cured samples of different soils range from weak enough that a brick size can be crushed under foot or broken between two hands, to so strong that the same size must be split with a metal tool. Stronger soils make stronger walls. Soil strength is usually discussed in terms of the pressure needed to crush a sample- unconfined compressive strength. This is measured in MPa (megapascals) or in psi (pounds per square inch).

| **Levels of Soil Strength**<br>Unconfined Compressive Strength | | | |
|---|---|---|---|
| PSI | Mpa | | |
| 150 | 1 | Very weak | Brick size samples cannot be moved for several days |
| **188** | **1.3** | **Low Strength** | **<u>'Standard'</u>** minimum for New Zealand non-engineered buildings |
| 250 | 1.7 | Moderate | 20% of samples for New Mexico allowed |
| 260 | 1.8 | | Gritty soils may not perform well in handful drop |
| **275** | **1.9** | **Strong** | **<u>'Special' grade</u>**/ average for New Zealand engineered buildings |
| 300 | 2 | | Required average strength/ New Mexico |
| 320 | 2.2 | Very Strong | Hard to crush pieces |

## 4.1 TESTING FOR SOIL STRENGTH

Adobe builders keep stocks of cured blocks. They can easily test some for strength by breaking over a measured span with a known weight (a simplified flexile strength test, which can be multiplied by 3 to approximate compressive strength).

Earthbag builders often begin building within a day or two of arriving at a site and choosing soil. Although tamped earth samples can be broken in the same way, full-size earthbag units require weeks to cure even in dry regions. Samples could be oven dried within a few days but are heavy to handle. Contained earth builders need to test small samples that can be dried quickly.

Current builder tests of damp soil do not reveal soil strength. The 'shake' or 'jar' test shows visible layers of different particle sizes as dissolved soil settles over 24 hours. It is not accurate for the proportion of clay

contained in a soil. And because different clays are stronger or weaker, it does not even hint at actual soil strength.

Dropping a damp, squeezed handful from 5’ height on a hard surface is useful to judge moisture levels for building. To pass, the ball must not shatter, but can break in 2- 4 pieces. This ‘handful drop’ test works better on stronger soils, but this author has one 230 psi clay soil that performs well while the 260 psi sandy builder’s fill used in the 2016 test wall series did not.

During 2015- 2016 BSI developed several types of simple tests for small cured samples.

A dozen 30 mm balls can be tested under the shoe of an average 130 lb/ 60 kg person. On average 2 balls of weak soil will break, but not 2 balls of moderate strength soil. The same person will not break (or barely be able to break) most single balls of strong soil in this way.

Top: Crushing balls under foot
Above: A small wood lever testing a tp roll sample

Fist-sized samples formed in a cardboard toilet paper roll dry almost as quickly and allow more accurate test results. A regional college or building advisor can set up a simple wooden lever less than a yard/ meter long and use known volumes of water as weight.

# 5 Previous Contained Earth Research

Earthen walls are heavy and need significant strength to resist horizontal motion in earthquakes. Rectangular buildings resist earthquakes when walls are strong enough to hold up the walls perpendicular to them. This type of strength against pressure along the wall is called shear strength.

Plastered wall portions of contained earth (CE) can be tested for shear strength similar to adobe wall strength research. Horizontal pressure is applied with a hydraulic jack near the top. The wall is stressed (if possible) to the Ultimate Limit Strength (ULS), when any added force causes motion without increasing pressure.

80% scale wall portions with several variables in addition to soil strength were tested by BSI during 2011 and 2012. The 2011 weak soil sample contained no rebar or strapping, but had cement tucked into notches between bags to anchor the barbed wire. The 2012 wall included a single heavy 5/8” diameter inserted rebar, was strapped vertically, and had plaster mesh of a very strong plastic.

Above right: Unreinforced 2011 wall of weak soil reached a low ULS
Right: Reinforced 2012 wall of strong soil resisted higher forces but did not reach ULS

Last winter BSI tests of half scale CE wall corners of strong soil indicated that two new reinforcement techniques were helpful to reduce damage to wall corners.

Left: Cord ties attached to barbed wire where it bends loop up to attach to barbed wire at next course
Below left: Exterior rebar at corner can be anchored in a concrete spot footing and have barbed wire attached to the rebar

Cord to tie the barbed wire to courses above and below at all corners and wall ends reduced gaps at severely strained corners. It did not reduce overall deformation, but did increase strength slightly.

Exterior rebar anchored in a concrete spot footing eliminated gapping and increased out-of-plane wall wall strength as well.

These tests were complicated by the fact that the mesh used to facilitate the planned small scale models allowed the soil fill to solidify between courses. These corner tests did not separate the effects of solid contained earth from the effects of exterior corner reinforcement.

Solid contained earth (walls built in mesh tubing that uses fill damp enough to solidify between courses, aka hiperadobe) is stronger than conventional modular contained earth. Modular contained earth is the conventional technique that has courses separated by solid woven fabric and joined only by bonds between the barbed wire and the cured bag fill.

Bottom left: Plastered solid CE wall portions currently in need of testing

BSI built three 80% scale cured solid CE wall portions during summer 2016. The unreinforced wall is already proving too strong for BSI's current test equipment. The other two walls will compare inserted rebar and anchored rebar. All three have used light plastic fishnet to strengthen their earthen plaster, and have a wood bond beam. These walls will be tested as soon as stronger equipment can be arranged.

# 6 MODULAR 1:2 CONTAINED EARTH TEST WALLS

## 6.1 SAMPLE CONSTRUCTION

BSI built, plastered, and cured four smaller scale wall portions during autumn 2016. Variables included soil fill strength and type of reinforcement. The two control samples had inserted rebar, and the two alternates had exterior rebar anchored in the testing base, with the barbed wire looped onto the rebar. Each wall used a light plastic fishnet under earthen plaster, and a wood bond beam that the rebar was also attached to.

One strand of 4 point high-tensile strength barbed wire was used per course, and rebar was 3/8" diameter, approximately half the cross-sectional area of the common #4/ half inch rebar.

Right: Modular CE of solid-weave bags built between anchored rebar
Below: Sample wall with inserted rebar at severe plaster damage stage

The two different soils used each had 3 laboratory compressive strength tests of tamped samples to confirm actual soil compressive strength.

The medium strength soil used was fill dirt purchased at a local landscape supply yard. These samples returned compressive strengths of 230, 270, and 290 psi (averaging 260 psi). This value is slightly lower than the 300 psi strength required by New Mexico for adobe. The stronger adobe soil, purchased from local NM Earth adobe manufacturer, returned strengths of 270, 330 and 350 psi (averaging 320 psi).

## 6.2 TEST SETUP AND PROTOCOL

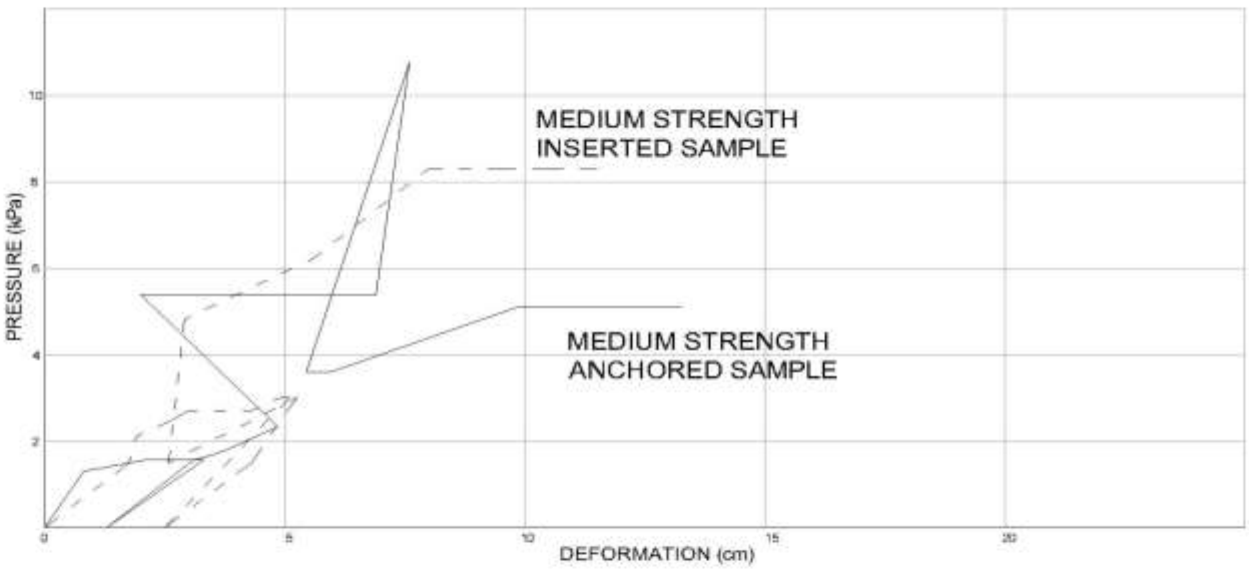
A hydraulic piston was placed between a vertical post built of three 2 x 10s. The piston base pressed against a ¼ inch thick steel plate, and the other end against a 6" x 8" piece of hardwood.

Fiberglass straps were used as diagonal bracing to counteract forces pushing the base and wall away from the post. A single strap was used vertically to prevent uplift of the near-force end and rotation of the sample wall.

Dimensional targets were either drawn on the wall sample or tacked to it, showing a grid of centimeters. A contractor's laser level device was located near enough to shine a constant beam on the 0 spot.

Pressure was increased in steps by hand pumping and read from a 10,000 psi 2-1/2" diameter gage. Photographs were taken immediately after the pressure notation to record the exact deformation. Some deformation readings may be slightly smaller than when the jack reached the noted value when the pressure slipped also.

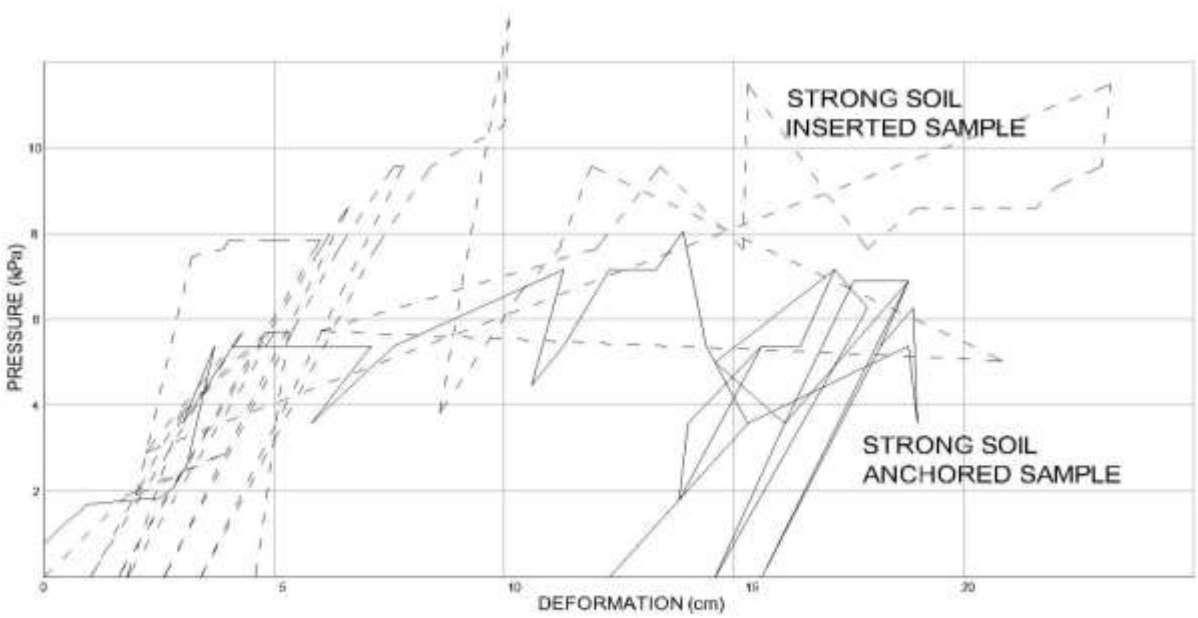
## 6.3 Test Results




**CONTAINED EARTH SHEAR TEST RESULTS**
1:2 WALL PORTIONS TESTED DECEMBER 2016

The medium soil strength walls were both tested to ultimate limit strength.

Although the walls made of stronger soil were severely deformed during testing, they did not reach ultimate strength.



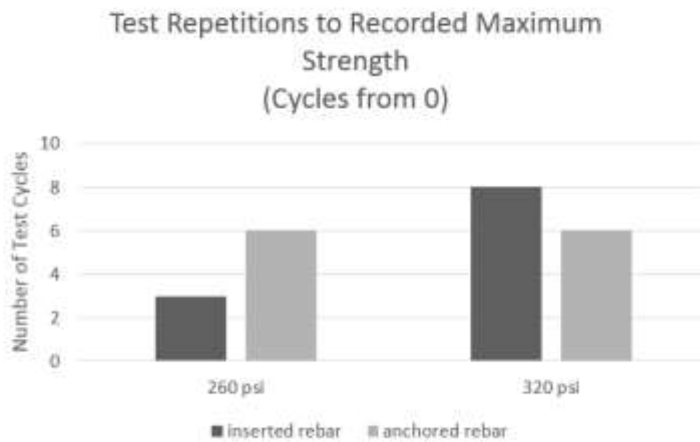

**CONTAINED EARTH SHEAR TEST RESULTS**
1:2 WALL PORTIONS TESTED DECEMBER 2016

The walls of strong soil resisted in-plane forces well but repeatedly twisted out of plane during testing. It was remarkable that neither of the walls overturned, although at times reaching as much as 15 degrees twist and a significant slope.

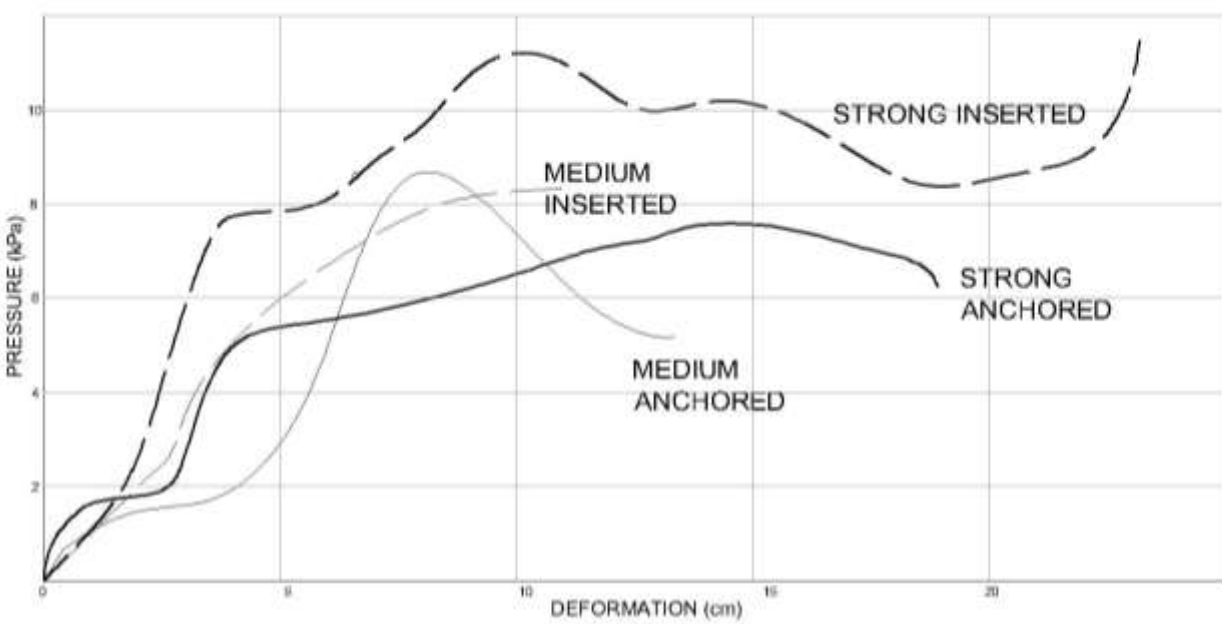
Left: Severe twisting of the strong soil reinforced wall

To counteract this twisting motion, pressure was released and reapplied more often to the stronger soil walls. Because these low-pressure phases were repeated, test results may be understated for the strong soil walls.

These 1:2 scale tests show a significant difference in wall strength between the two soil fills. Walls of stronger soil can withstand 2.7- 3.4 times as high forces before plaster begins cracking as weaker fill walls. Stronger soil walls withstand forces 3- 3.6 times stronger than medium strength soil walls before they reach 2% horizontal deformation.




While stronger soil walls survive higher pressure without reaching ULS, they also deform more without structural failure than walls of medium strength soil.

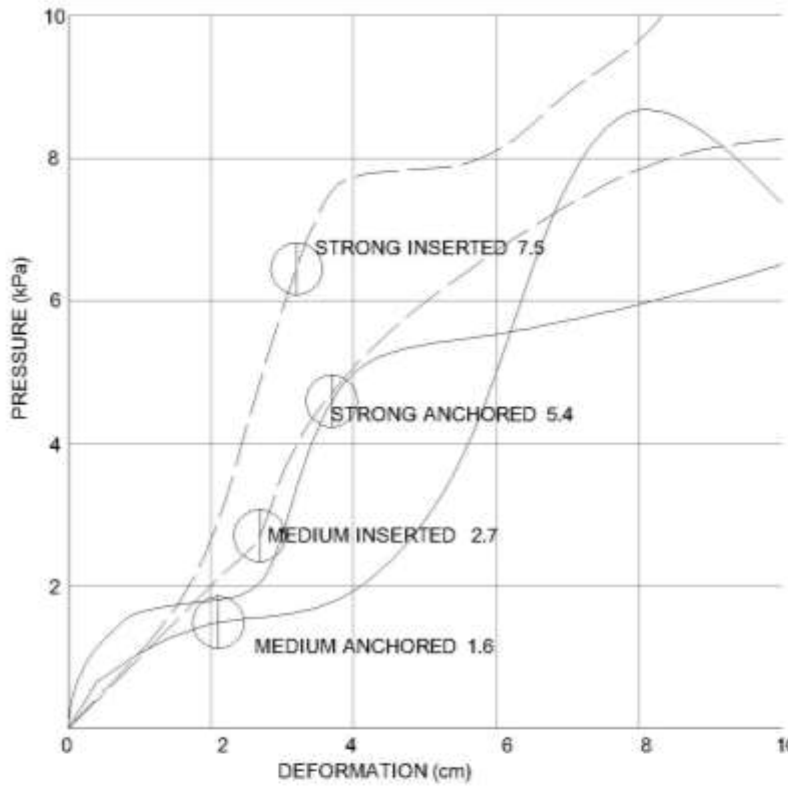



**CONTAINED EARTH SHEAR STRENGTH**
1:2 WALL PORTIONS TESTED DECEMBER 2016

The anchored rebar increases ultimate limit wall strength for the medium strength soil. Anchored rebar may decrease wall strength for strong soil walls.

The graph above shows approximate trendlines for the test data. Both of the inserted rebar walls show a gradual yielding with deformation increasing as pressure rises. Both of the anchored rebar walls show a stepped response to pressure increases, with significant loss of strength as wall damage progresses.

The graph at right compares the first crack strengths for these 4 test samples in the context of their stress-strain response. The pressure needed to cause the first major plaster crack appears to be close to the yield point.




**CONTAINED EARTH SHEAR STRENGTH AT FIRST CRACK**
1:2 WALL PORTIONS TESTED DECEMBER 2016

Both the strong soil anchored and strong soil inserted rebar walls show onset of plaster damage sat forces 2- 3 times higher than the medium strength soil walls.

All four walls remained stable after the end of testing. In the final pressure series on the strong anchored wall, pressure bent the rebar where it was anchored in the test frame, and also broke a small piece of the testing base.

# 7 DISCUSSION

These 1:2 scale wall results can also be compared to the earlier shear tests.

This may be due to the fact that rebar transmits stress best when surrounded by wall material. If walls with anchored rebar have a strong cement-based stucco, this may increase wall strength more than inserted rebar.

BSI's wall portions in 2011 and 2012 were built at 80% scale, very close to full-scale walls. Since they contain the same amount of rebar and barbed wire BSI assumes that they provide a conservative estimate of full-size wall strength. The solid CE walls currently in process of testing are also 80% scale.

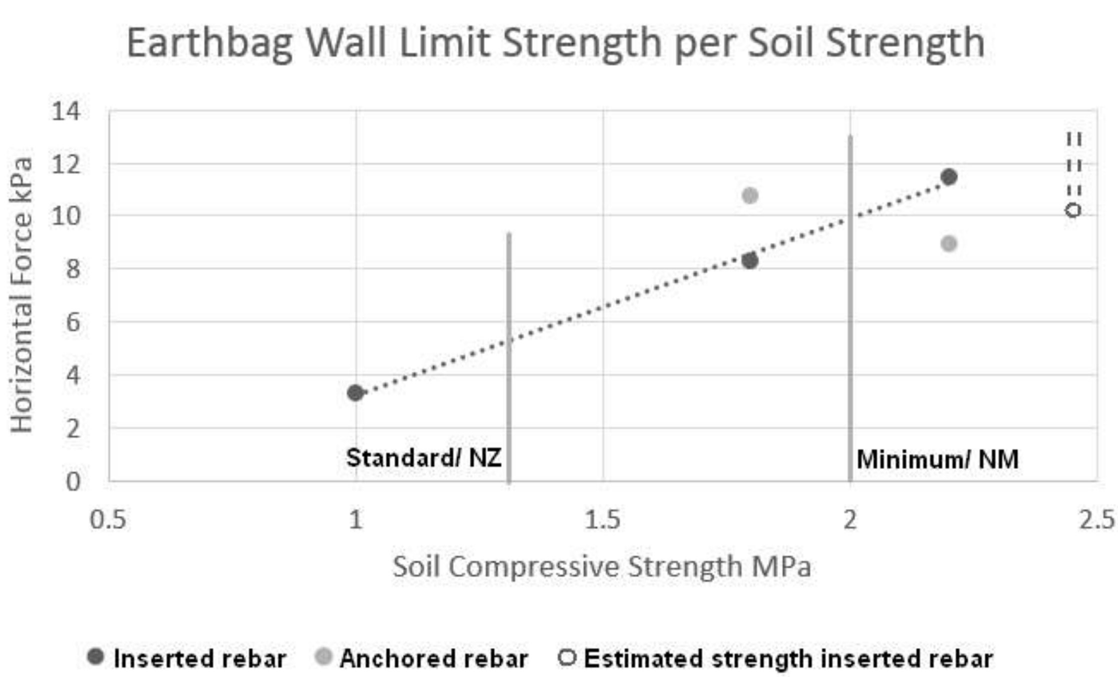
1:2 scale walls are probably weaker than full size walls. Because of the type of wall failure experienced in our static shear tests, we use a conservative estimate that full-size wall shear strength will be about 50% greater than 1:2 size tests.

In fired hollow brick walls, full-size tests show about 25% higher shear strength than 1:2 model tests. These walls fail by cracking of units, related directly to the compressive strength of the units, which is relatively higher in smaller sizes.

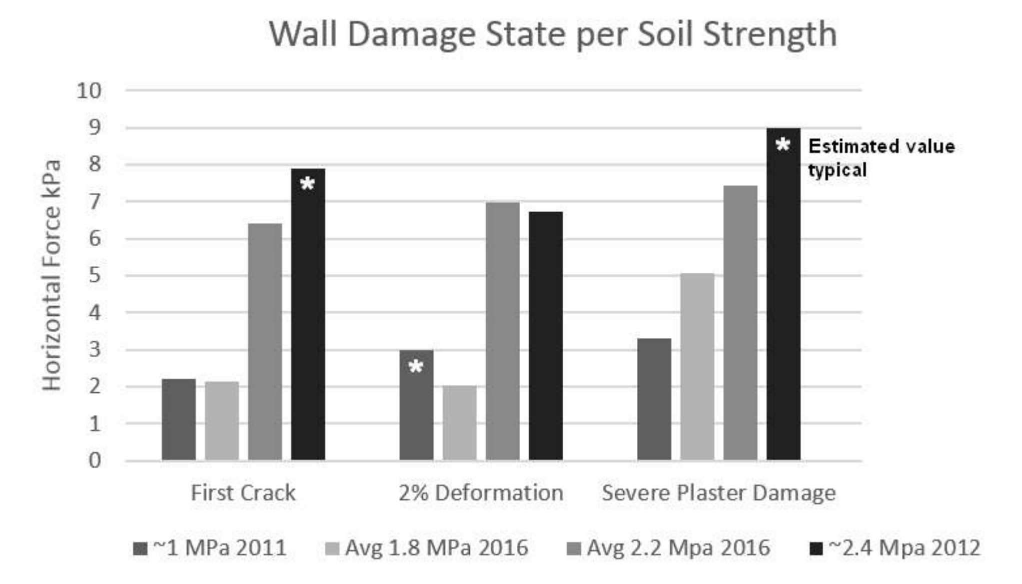
Earthbag test walls show little or no cracking of units. They fail mostly due to loss of bond between the barbed wire barbs and the cured bag fill, either by lifting between unstrapped courses to dislodge barbs, by chipping of weaker soil fills away from the barbs, or for strong soils by the barbs bending back. Since the 1:2 scale contained earth walls include 55% as much area of rebar and half as many barbs per wall length as full-size, it may be expected that full-size walls could be almost 2 times stronger than 1:2 walls.

Until further testing proves the exact relationship between 1:2 and full-size strength, we are assuming that the multiplier lies between 1.25 and 2. The average of 1.25 and 2 is 1.6, so we will use a conservative estimate that full size is 50% stronger than the test results for these 1:2 walls.

The graphs that follow include data from the 2011 and 2012 test walls, as well as adjusted values from the current small scale test walls.




Although the strong soil



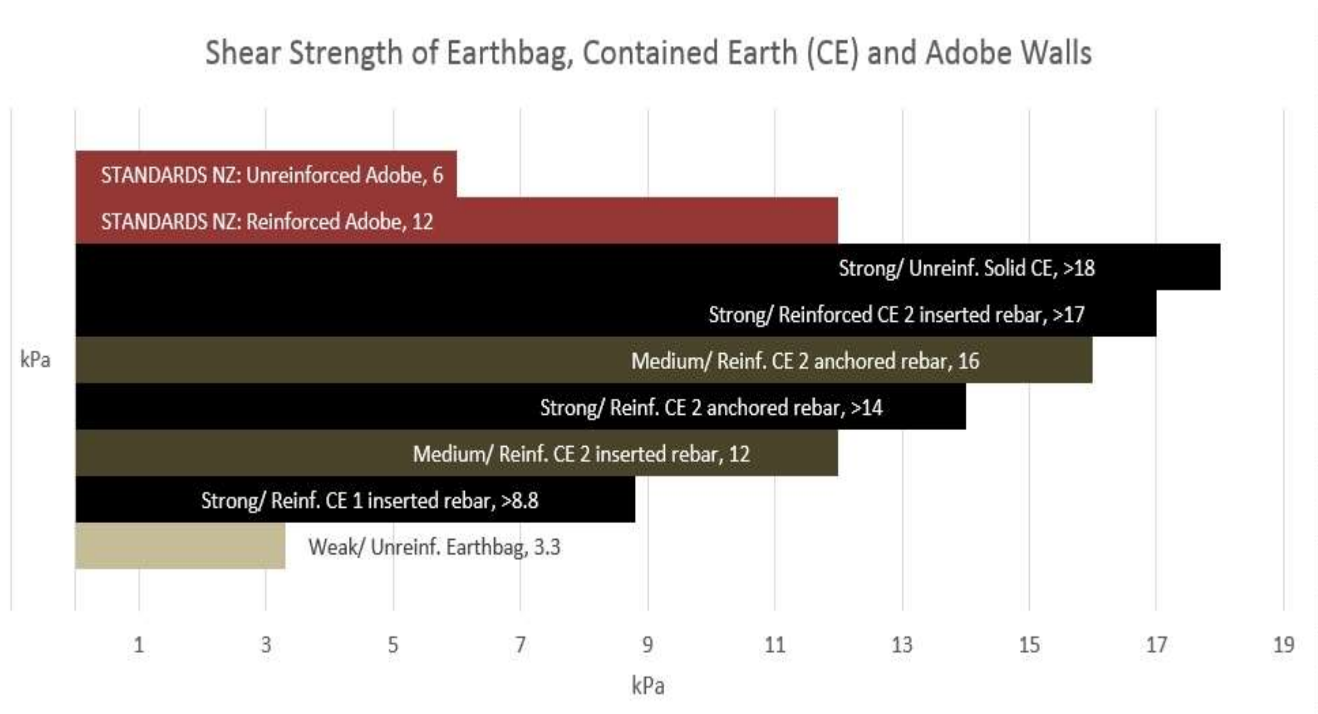

anchored rebar result seems lower than would be expected, the other results show a clear correlation for ULS strengths.

Future testing should include bracing of the test piston aligned with the wall.

Pressures causing first major plaster cracks and the minimal 2% deformation thresholds also correlate well to soil strengths in all the tests of contained earth and earthbag to date.

The bar graph below compares the earth building standards shear strengths to the various types of reinforcements in earthbag test walls. The two current 1:2 walls tested have rebar inserted at a spacing of about 30"/ 0.76 m on center, which might approximate full size rebar spacing of 4'/ 1.2 m or more on center. The two 1:2 walls with rebar anchored have the exterior rebar located at 36"/ 0.9 m spacing, which may be equivalent to 54"/ 1.4 m or more on center.

The strong soil reinforced wall with one inserted rebar may be equivalent to a slightly heavier rebar spacing of 5'/ 1.5 m on center.



In total BSI has tested 7 wall portions of different qualities of earthbag to severe damage states. One early low-strength soil wall lacking strapping or rebar did collapse by overturning in the direction it was built leaning. All other walls (more carefully built plumb) have remained standing and relatively stable after the end of testing. Although contained earth uses a low strength material, this offers strong hope that well-built contained earth walls can resist collapse even if their structural strength is exceeded by earthquake forces. Walls that do not collapse will save lives in earthquakes. They will also lesson immediate financial losses even if they need to be repaired in future.

| **Comparing Shear Tests of Adobe and Contained Earth Walls**<br>(All Samples with Low-Strength Plaster) | | | | |
|---|---|---|---|---|
| | Soil Compressive Strength | Scale | Tested Strength And Detailing | Estimated Strength Full Size |
| **Low- Medium Soil Samples** | | | | |
| Tests for New Zealand Adobe Code | Low strength<br>>190 psi | 1:1 | **6.4 kPa** ULS* (cyclic dynamic) | |
| | | | **11.9 kPa** ULS (cyclic dynamic) | |
| Modular CE 2011 | Low strength ≤190 psi (minimally cohesive silt)<br>80% thickness<br>100% barbs | 80% | **3.3 kPa** ULS (static)<br>No rebar, no strapping | |
| Modular CE 2016 | Medium Strength<br>Average 260 psi<br>1:2 thickness,<br><br>55% rebar area<br>50% barbs | 1:2 | **8.3 kPa** ULS (static)<br>2 inserted #3 rebar, strapping, fishnet mesh | x 1.5 = **± 12 kPa** |
| | | | **10.7 kPa** ULS (static)<br>2 anchored #3 rebar attached to barbed wire, strapping, fishnet mesh | x 1.5 = **± 16 kPa** |
| **Strong Soil Samples** | | | | |
| Modular CE 2012 | High strength<br>±300 psi<br>80% thickness<br>78% rebar area | 80% | **>8.8 kPa** (static)-<br>test frame failed<br>1 #5 rebar, strapping, strong mesh | |
| Modular CE 2016 | High strength<br>Average 320 psi<br>55% rebar area<br>50% barbs | 1:2 | **>11.5 kPa** (static)-<br>wall flexed out-of-plane<br>2 inserted #3 rebar, strapping, fishnet mesh | x 1.5 = **± 17 kPa** |
| | | | **>9.0 kPa** (static)-<br>wall flexed out-of-plane<br>2 anchored #3 rebar attached to barbed wire, strapping, fishnet mesh | x 1.5 = **± 14 kPa** |
| Solid CE strong soil wall 2016 | High strength<br>±300 psi | 80% | **>18 kPa** (static)-<br>stronger than piston<br>No rebar, no barbed wire, strapping, fishnet mesh | |
| *ULS is Ultimate Limit Strength; every additional force causes motion with no pressure increase | | | | |