Field Soil Tests for Use with Earthbag

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1 ABSTRACT

Earthbag construction is an intrinsically contained and reinforced technique in demand for rural areas of seismically active regions. Nepal recently added earthbag to their building code (Nepal Ministry of Urban Development 2017) because many earthbag buildings near devastated villages were unharmed by 0.7 g+ earthquakes (Stouter 2015).

But to survive stronger quakes, strong soil will be critical. Since earthbag building components are not cured before construction, soil tests must not cause long delays. Sedimentation tests currently used (Hunter and Kiffmeyer 2008) (Kahlili 2008) are inaccurate for particle size distribution, and do not reveal soil strength (Minke 2010). Soil tests must be completed in 24 hours, and must use simple equipment.

2 INTRODUCING EARTHBAG/ CONTAINED EARTH CONSTRUCTION

To clarify the type of earthbag (from many poorly defined alternatives) this author calls adobe-type soil with reinforcement chosen for seismic hazard 'contained earth' or CE. Earthen walls are usually built on doubled bags filled with gravel (contained gravel or CG).

CE uses damp sandy or clayey loam in tubes or bags of polypropylene fabric (common grain or sand bags) or mesh (larger vegetable bag fabric) to make a 380 mm thick wall (Figure 1). Courses are hand tamped to consolidate loose soil 20% to a 125 mm (5") course height.

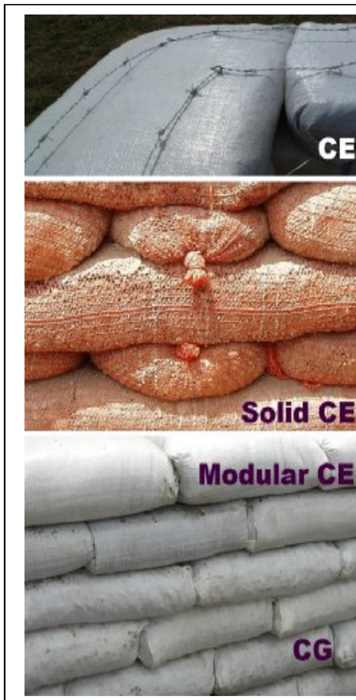

Figure 1: Types of earthbag

Strands of barbed wire on each course strengthen bed-joints and provide tensile reinforcement. Mesh tubing allows wall material to solidify between courses for 'solid CE'. 'Modular CE' uses slippery bags and relies on barbed wire at bed-joints. Steel rebar can be hammered into walls in 1.5 m (5') lenghts, or wall material can be built next to or around anchored rebar using slits in the fabric.

Walls are covered with plaster to prevent UV damage to the fabric forms, which can also contain wall material if damaged.

Engineering students first researched non-standard sand or dry soil fills and/ or uncured assemblies, relating them to soilbag strength formulas based on fabric strength. Shear tests now show that CE soil strength increases wall strength (Stouter May 2017). Code-required soil compressive strengths for adobe and/ or rammed earth make appropriate minimum, medium and high levels (Table 1) for contained earth in seismic risk regions.

Table 1: Soil Compressive Strengths Required by Codes

		Soil Strength	Source
Minimum Strength	New Zealand 'standard'	188 PSI/ 1,3 MPa	(Standards NZ 4298)
Medium Strength	New Zealand 'special'	260 PSI/ 1,8 MPa	
Strong	New Mexico minimum	300 PSI/ 2,1 MPa	(NM RLD 2017)

3 CE Samples for Testing

Full-scale units of modular CE in bags often weigh more than 50 kg (110 lb) and take a month or more to cure.

Dimensions of units vary, and sides are seldom parallel even when tamped between blocks (Fig. 2a). Bag samples also have round edges (Fig. 2b), but samples tamped in forms have higher density than without.

Earthbag units are not much denser than adobe blocks. Local adobe blocks ranged from 1740- 1900 kg/m³ (108-114 pcf), while earthbags of the same soil ranged from 1560- 1890 kg/m³ (100- 120 pcf). CE samples in wood forms ranged from 1700- 2000 kg/m³ (110- 125 pcf) density.

Fabric bags also slow curing of samples (Stouter January 2017).

Figure 2: Earthbag unit shapes and full-scale sizes

Initial slow curing is as important for earthbag as for other earthen techniques (Minke 2010). Units reach full strength when shade cured for 4 days before sun or oven curing, as three-point flexural strength tests of 35 modular samples at 50% scale tamped in rectangular forms showed (unpublished research). Full-size single units may need a week or more before speed curing.

But field testing cannot be pre-soaked or cured slowly. It must be compared to accurate full-scale sample strengths. Some clay soils may return lower strengths without slower pre-treatment, but if field tests indicate cause for concern, wise builders will then delay construction for better testing.

During February of 2017 Christian Ernstsen used the small samples described in this research to test building soils from multiple sites for CE homes in Nepal. Builders without access to lab testing were concerned about one site whose soil appears to be approximately 1,0 MPa (150 psi). The soil at several other sites all qualified as strong (above 2,1 MPa/ 300 psi compressive strength), and another site showed about 1,9 MPa (275 psi) or medium strength soil (Ernstsen 2016).

4 FIST-SIZED SAMPLES

Toilet paper tubes are common in most parts of the world. They make a convenient form for a small sample that can be more vertical than horizontal.

Five types of soil were chosen which had different strengths in prior flexile tensile strength tests using a hydraulic piston (Table 2).

SERIES 1: EVALUATING SOILS AND TECHNIQUES

Damp soil was hand-pressed into 40 mm lengths cut from 40 mm diameter toilet paper tubes (Fig. 3a). Samples did not fully cure at room temperature in 1 week, but were oven-cured at 100° C until weight remained the same on a digital scale for an hour.

Figure 3: Toilet paper tube crush test

After curing, cardboard was removed. Ends of samples were rubbed gently to remove any bumps. Weight from a bucket of water was applied by a simple wooden lever (Fig. 3b).

Average sample diameter varied between 39 and 43 mm, so crushing weight was divided by average cross-sectional area to calculate crushing pressure (Fig. 4). 25 samples were tested, showing a range of strengths in lever testing that related well to flexile strength (Table 2).

Fill and Mix soils showed that higher density increased crushing strength.

Most batches had one or two low outliers. Excluding the lowest value from each soil gave a standard deviation between 10 and 17 for the 3 weaker soils. The strong Mix soil had a standard deviation of 25, and the Adobe soil, of 79.

The average density of samples ranged from 1972- 2102 kg/m³ (123.1- 131.2 pcf) by soil, with standard deviations mostly from 3.4- 3.8 per soil, and only 0.5 for the clay sample group.

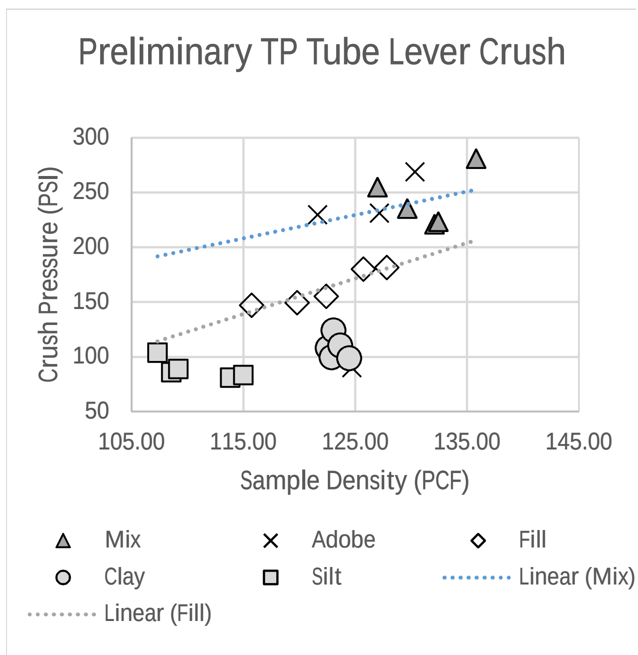

Figure 4: Crush pressures from first test series.

Table 2: Average Flexile Strengths Compared to Preliminary Mini-Crush Pressures (PSI)

	Mix	Adobe	Fill	Clay	Silt
Flexile Strength	139	129	84	untested	
Mini-Crush Pressure	249	205	167	111	91

Full-scale Compressive Strength

Four larger batches of soil were mixed for a wide range of strengths. Clay (fines from local decorative gravel) was not used because this weak soil was difficult to form and fragile while curing.

Handful drop tests are also used by earthbag builders to evaluate soil cohesion (Hunter and Kiffmeyer 2008). Both the weak and medium strength soils failed this type of test by breaking in too many pieces even with excess water. However, they hardened when tamped in bags.

Each soil was soaked 24 hours before making samples 380 mm (15") wide and as long. When dried they ranged from 107- 125 mm (4.2- 4.9") thick. Units were cured in the bag for several weeks under a fan with added heat until weights stabilized. Unconfined compressive strengths were tested in a laboratory following ASTM C67 standards (Table 3) on fully cured, cut units, mortared and stacked.

Table 3: Particle Sizes and Unconfined Compressive Strengths of BSI FullSamples

Soil	Approximate particle sizes evaluated by dry sieve process (% by weight)				Soil type	Average Strength[1]	Sample Strengths[1]
	Fines and fine sand <1 mm	Coarse sand 1 <2 mm	Agg-regate 2- 3 mm	Grav el >3 mm			
Very Strong	Similar aggregate to strong soil but too much flocculation for dry sieve evaluation				Sandy clay. (In-house mix).		370 PSI/ 2,55 MPa
Strong	43	16	19	21	Sandy clay for adobe. Semi-stabilized with asphalt these units routinely test at >2,1 MPa	320 PSI/ 2,18 MPa	270, 330, 370 PSI/ 1,86, 2,28, 2,41 MPa
Medium	44	19	20	18	Sandy clay. Gritty 'engineered fill'	260 PSI/ 1,81 MPa	230, 270, 290 PSI/ 1,59, 1,86, 2,00 MPa
Weak	90	3	6	1	Fine silty loam		150 PSI/ 1, 03 MPa

Despite poor handful drop performance, the average compressive strength of the medium soil was 39% stronger than NZ standard soil strength, and all samples met this strength. This very gritty soil made audible grating noises when squeezed, possibly stronger when tamped than in blocks made from liquid.

Comparing Mini-crush Cylinders to Compressive Strength

50 more small samples were made in slightly shorter TP tube sections. Light pressure was used to load soil in smaller layers. These firmed for a day at room temperature before oven-curing. This series showed a wider range of average densities, from 1794- 2210 kg/ m³ (112- 138 pcf) but standard deviation per soil type was 2- 4.3. Soil density was higher in samples with stronger soils.

[1] Amec Foster Wheeler report, November 10, 2016

Samples were rubbed on a brick to smooth the top and bottom if uneven.

5 of each soil type were tested with a hydraulic piston using a wood pressure plate. 5 of each were tested under a weighted wooden lever.

With one low outlier eliminated from each group, average piston and lever strengths showed a clear progression from weak to strong soils (Fig. 5). Although Series 2 samples did not have more uniform density than Series 1, they showed much lower standard deviation for tested strength, averaging 12.6 overall compared to the earlier 28. Deviation for strengths in Series 2 ranged from 5.5 to 20.1. The primitive lever tests showed consistently lower deviation than the piston tests.

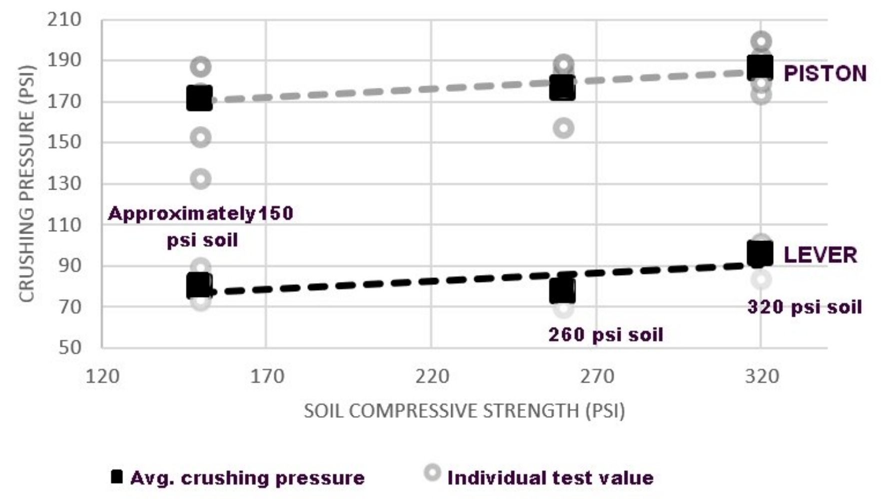

Figure 5: Results of series 2 tests with trendlines.

Table 4: Crush pressures for second test series

	Sample values (low value excluded) (PSI)				Average (PSI)	Standard deviation	Avg. Density (PCF)/ Standard deviation	Soil Unconf. Compressive Strength (PSI)	Ratio Test: UCS
Lever tests									
Very Strong	177.4	186.3	198.4	215.1	194	16.3	138/ 2.6	±370	1.9
Strong	83. 6	99.1	100.4	101.1	96	8.4	129/ 1.5	320	3.3
Medium	69.4	79.3	79. 6	81.7	78	5.5	126/ 4.5	260	3.3
Weak	72.9	73.8	83.2	89.6	80	8	112/ 2.7	±150	1.9
								Avg. ratio	2.6
Piston tests									
Very Strong	264.7	265.1	268.6	306.2	276	20.1	137/ 1.6	± 370	1.3
Strong	173.5	179.5	191.9	199.8	186	11.9	128/ 1.8	320 avg.	1.7
Medium	157.4	176.9	184.7	188.1	177	13.8	127/ 2.9	260 avg.	1.5
Weak	132.4	153.1	174.2	187.3	172	17.3	117/ 4.1	± 150	0.9
								Avg. ratio	1.3

Piston test results correlated more closely to compressive strength than lever tests. The average multiplier to find compressive strength from lever results was 2.6 with 0.84 deviation; for piston results these were 1.3 with 0.35 deviation.

One soil type with no laboratory unconfined compressive strength was used, a different batch of adobe like the strong soil. Results from this soil had high standard deviation for strength results even though densities showed deviation of only 5.7.

Comparing the weak, medium and strong soil results, a multiplier of 2 for lever test results should give a conservative estimate of unconfined compressive strength no more than 10% above actual soil strength.

Both medium and strong soils showed compressive strength averaged 3.3 times as great as lever strength, but several samples of weak soil should be lab tested for a more accurate averaged compressive strength before using the higher multiplier.

CONCLUSIONS

Builders need field tests to rule out weak soils and see whether additives improve medium strength soils. They need to compare relative strengths more often than to learn exact strengths. Stacked weights and a longer lever may make accurate measurement of very strong soil strength too difficult.

The toilet paper tube size samples often had low outliers, possibly from flaws like aggregate near the surface. It is important to test more than 5 samples and exclude these outliers before averaging.

Further tests should check whether a longer tube size is practical than these 1:1 height to width samples. A higher aspect ratio may reduce confinement by friction at the equipment surfaces and increase accuracy (Aubert 2016). Toilet paper tubes often are 105 mm long, providing about 2.6: 1.

More care should also be taken to be sure that the lever does not apply force to one side of the sample instead of evenly onto the top. Samples do not always have parallel ends that are perpendicular to their length. Thin mounting blocks should be used to fit the height exactly with sand to level both top and bottom surfaces.

Although it is tempting to try larger diameter samples, such as formed in 510 mm (2") inside diameter plastic pipe, increasing sample area can make even medium samples impossible to test with a small lever and one bucket of water.

Adobe builders recommend field tests of 200 mm (0.75") balls crushed between thumb and forefinger (Blondet 5), but finger strength varies greatly. Although the TP tube samples only provide approximate strength data, even smaller samples may be needed in some settings. Tests of 300 mm (1.25") diameter balls show that by crushing them under a shoe or under a foot on a piece of wood, different strengths can be approximately revealed (Stouter January 2017). A 60 kg (132 lb) person can crush two 0,6 MPa (80 psi) balls easily, one under each shoe. Standing on one foot they can crush a 1,0 MPa (150 psi) ball under a single soft-soled shoe. A 1,8 MPa (260 psi) ball will not crush under a shoe, but will easily break under the tester standing on a piece of wood. A ball of strong soil 2,1 MPa (300 psi) will barely crush under their full weight applied on a piece of wood.

Although 40 mm (1.5") diameter cylinders are small, knowledge of soil strength can improve the safety of earthen buildings (Morris 2011). If possible, another series of tests should compare small samples to unconfined compressive strength of full-scale earthbag samples tamped in upright bags with side confinement to produce soil masses of a higher aspect ratio (Aubert 2016).

5 ACKNOWLEDGEMENTS

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