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ORIGINAL ARTICLE

A Study on Eco Friendly Cost Effective Earthbag House Construction

Rajesh Kumar Jain
Bharat Group of Colleges,Punjab
Email: rajmeerutcity@gmail.com

ABSTRACT

The weakest specimens showed maximum compressive strengths ranging from 115 kN/m to 135 kN/m. The lowest load deformation response was observed for the Gf 9 specimen group, at 0.7 kN/mm. The strongest and stiffest results were observed for the 3-bag soil-filled specimen, with load deformation responses ranging from 8 kN/mm to 15 kN/mm, and compressive strength ranging from 1100 kN/m to 1300 kN/m. Strength and stiffness values for medium soil-filled specimens measuring 510 mm x 910 mm were in the same range as the values for the small specimens. There was little difference in stiffness between specimens filled with topsoil and those filled with a 4:1 ratio of topsoil to masonry sand, though small sample size prevents a meaningful statistical analysis of the variance between the two fill materials. Beyond material properties, climatic conditions must also be considered to ensure optimal selection of building materials.

Keywords: *Earthbag, Polypropylene , Soil characterization, Compression , Tensile strength.*

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INTRODUCTION

Earthbag construction is an inexpensive method to create structures which are both strong and can be quickly built. It is a natural building technique that evolved from historic military bunker construction techniques and temporary flood-control dike building methods. Normally the foundation cost comes to about 10 to 15% of the total building and usually foundation depth of 3 to 4 ft. The scarcity and cost of durable building materials is regularly identified as one of the main obstacles to better housing standards. The vernacular architecture which ascribes to a particular concept and its own aesthetics was not necessarily designed or built by professionals [9].The goal of sus -tainable construction is to reduce the environmental impact of a constructed facility over its lifetime. As issues of climate change related to global warming are addressed, much attention is paid to the energy consumption and greenhouse gas emissions. Environmental life cycle assessment (LCA) can be defined as the compilation and evaluation of material and energy consumption as well as the potential environmental impacts of these through the life cycle of materials. The goal of sustainable construction should be considered for closed-loop material flows, i.e. recovering deconstructed materials so that materials collected at the end of life of a building which can then be linked back into material flow in the same or different condition and functionality after recovery. Every year millions of new buildings are being constructed and on the name of modernity new construction materials are being introduced. The world today has encountered with global warming and climate change. Besides other contributors, extraction of natural resources as building materials itself consume energy, cause environmental degradation and contribute to global warming. Buildings are the largest energy consumers and greenhouse gases emitters, both in the developed and developing countries. Earthbag housing is a simple form of earth-based construction wherein large bags are filled with granular material, compacted and laid horizontally in a running bond to form the core of a wall system. The charm or attraction of earthen architecture is the inherent connection to the environment[23].Polypropylene bags are currently favored by the earthbag building community for their strength, resistance to decay, and affordability, but natural materials such as burlap have also been used. Barbed wire is typically laid in between each course of earthbags to provide shear strength, as the friction between successive courses of bags is low, especially when polypropylene bags are used. It's easy to posit that earthbag construction uses the least energy of any durable construction method. Unlike concrete, brick or wood, no energy is needed to produce the necessary materials other than gathering soil. With on-site soil being used, practically no energy is expended on transportation and unlike rammed earth construction, no energy is required to compact the soil. The energy intensive materials that are used plastic (for bags & twine), steel wire, and perhaps the outer shell of plaster used in relatively small quantities compared to other types of construction. The buildings last a long time; however, when they are no longer useful they may simply erode with no serious threat to the environment, or even be recycled into new Earthbag constructed buildings.

MATERIAL AND METHOD

Mechanical Methods, Maturity Method and Methods based on Acoustics are used to test the properties of material.

Testing Program

The tests were conducted with three main sets. The first set for compressive tests to determine the load-deflection with respect to bag size and soil properties. In the second set granular materials used to fill the bags . The ultimate strength and load deflection of the polypropylene textile were tested in third set. Compressive tests of unplastered earthbags was carried according to Dunbar & Wipplinger, [13], which was in turn based on a modified version of ASTM E 447[1]. Three different types of fill were selected for investigation and their densities, specific heat and thermal conductivity in a range of materials are presented in Table 1.

Table-1 Densities, specific Heat and Thermalin a Range of Materials

Material	**Density** (Kg/m^3)	**Specific heat** (kJ/kgK)	**Volumetric heat capacity** Thermal mass (kJ/m^{3}K)
Water	1000	4.166	4186
Concrete	2240	0.892	2055
AAC^1	500	1.93	552
Brick	1700	0.910	1290
Stone (Sandstone)	2000	0.905	1800
Fiber Cement Sheet (compressed)	1700	0.907	1530
Earth Wall (Adobe)	1550	0.835	1292
Rammed Earth	2000	0.843	1675
Compressed Earth Blocks	2080	0.847	16498

AAC; Autoclaved Aerated Concrete is a precast structural product made with all-natural raw materials

The first material investigated was crushed granite with a nominal diameter of 12.3 mm, second one was topsoil and the third material selected was a mixture of topsoil and masonry sand, mixed in a 4:1 ratio by volume (soil : sand) using a portable mixer. This was done to determine if a 20% increase in sand content would produce measurably different earthbag behaviour. Masonry sand, whose composition is governed by ASTM C 144[3] was used as the sand additive (Table-2).

Table2-Specifications given in ASTM 144 for the allowable particle size distribution of masonry sand

Sieve No.	**Diameter (mm)**	**Percent Passing**			
		Natural Sand		**Recycled Sand**	
		Lower Bound	Upper Bound	Lower Bound	Upper bound
4	4.75	100	100	100	100
8	2.36	95	100	95	100
16	1	70	100	70	100
30	0.6	40	75	40	74
50	0.3	10	35	20	40
100	0.15	2	15	10	25
200	0.075	0	5	0	10

The size of Polypropylene bags were 460 mm X 760 mm, 510 mm X 910 mm, and 630 mm X 1010 mm and field construction techniques as per Hunter & Kiffmeyer [15]. For the topsoil and sandy soil filled bags, filling was performed and were laid flat and compacted by repeated blows from a length of 35mm X 85 mm lumber. A representative bag was weighed 87.0kg.The load distribution plates were of wood with capacity of (850 kN) . The hemlock beams were connected laterally with 18 mm threaded rod inserted through holes drilled at the neutral axis, at the midpoint and approximately 100 mm from each end. The stroke rate was increased to 4 mm/min for the rest of the granite filled bags,and 8 mm/min for the soil-filled bags. At the maximum stroke rate of 8 mm/min, the time between starting the test and failure was in the range of 10-20 minutes. Only two LPs (linear potentiometers) were used on the tallest specimens (Gf9). Data from all sensors was obtained using DT Measure Foundry data acquisition software. The letter naming conventionly used for each combination of bag size and fill, where in the first letter signifies bag size (S-small -460 mm X 760 mm, M-medium-510 mm X 910 mm) and the second letter signifies fill type (G – granite, T – topsoil, S – sandy soil).

	3 Bag Stack	6 Bag Stack	9 Bag Stack
Gravel Fill(Gf)	Gf3(2 Tests)	Gf6(3 Tests)	Gf9(3 Tests)

Determining the compressive strength of earthbag specimens, soil particle size all granular materials were analyzed according to the provisions in ASTM D 421[4], as well as ASTM D 422 [5]. Tensile Testing of Polypropylene bag fabric was done under the requirements of ISO 13934-1[16 &17] and according to ASTM D 4595[7] (Table 4).The U test requires that each sample have a minimum of three values in order to determine the critical value at significance levels of 0.05 or smaller [12].

Table 4- Tensile properties of Geotextiles by the Wide Width Strip method (ASTMD 4595-05)

Individual data						Average	S.D	% C.V
Breaking Strength(kN/m)	7.5 7.3	7.0	7.2	7.5	7.3	7.3	0.2	3.23
Breaking Strength(Ib/in)	36.8 37.2	37.2	36.3	37.8	38.3	37.28	1.3	3.21
Elongation at Break(%)	25.9 25.6	27.3	28.5	27.7	28.9	27.6	1.0	3.13
Strength at 5% Elongation(kN/m)	2.5 1.9	2.7	2.3	2.8	2.4	2.54	0.4	16.8
Strength at 5% Elongation(Ib/in)	17.3 10.5	14.1	13.5	12.7	12,1	13.9	2.0	14.6
Strength at 10% Elongation(kN/m)	3.7 4.2	4.2	4.5	3.9	4.3	4.1	0.3	8.10
Strength at 10% Elongation(Ib/in)	23.9 21.8	21.4	24.3	23.7	22.4	23.1	1.8	8.17
Cross Direction								
Breaking Strength(kN/m)	7.1 7.0	6.9	7.3	7.0	6.8	7.2	0.2	2.2
Breaking Strength(Ib/in)	39.0 38.8	39.5	40.2	37.9	39.2	39.1	0.9	2.4
Elongation at Break(%)	29.1 25.7	27.5	28.6	26.8	27.9	26.9	1.7	4.2
Strength at 5% Elongation(kN/m)	2.5 2.1	2.1	2.0	2.2	2.2	2.2	0.0	1.9
Strength at 5% Elongation(Ib/in)	12.1 13.0	12.3	12.0	11.8	12.0	13.06	0.2	1.5
Strength at 10% Elongation(kN/m)	3.5 3.9	4.0	3.7	4.2	3.9	3.8	0.0	0.0
Strength at 10% Elongation(Ib/in)	25.3 23.0	23.5	22.2	25.0	22.2	23.6	0.2	0.2

RESULT AND DISCUSSION

The results confirm that the topsoil contains a higher proportion of clay and silt particles than the sandy soil, which is to be expected given the addition of sand particles to the sandy soil . The topsoil is composed of 37% silt and clay particles by mass, where as the sandy soil is 27% silt and clay particles. The results further show that the sandy soil is composed of 70.5% sand particles by mass, whereas the topsoil is composed of 59.2% sand particles(Table 3 & Figure 5). The plot of displacement (as measured by the LPs) versus machine stroke for specimen SGf5 (a typical SGf specimen) showed uniform plate displacement. LPs 2 and 4 initially measured negative displacement due to the fact that, upon contact with the loading head. The rates of displacement measured by LPs 1 and 3 are higher from 0 to 8 mm of machine stroke, as this was the amount of stroke required to level the top-plate. The load versus deformation plot for this trend line is shown in Figure 6. There is a the variation in the slope of the load-deformation response from low to high loads. The polynomial trend line equation was used to correct all subsequent tests. There is a significant difference in the material properties and structural performance of earthbags filled with soil and those filled with a coarser granular material such as granite gravel. In general, gravel specimens fail at much lower loads than soil-filled earthbags. This is due to the abrasive action of the gravel, which causes tearing at the interface between bags, leading to loss of fill material and,

Figure-1-Folded and pinned bag closure

Figure-2- Earthbag Construction

Figure-3- Earthbag Construction

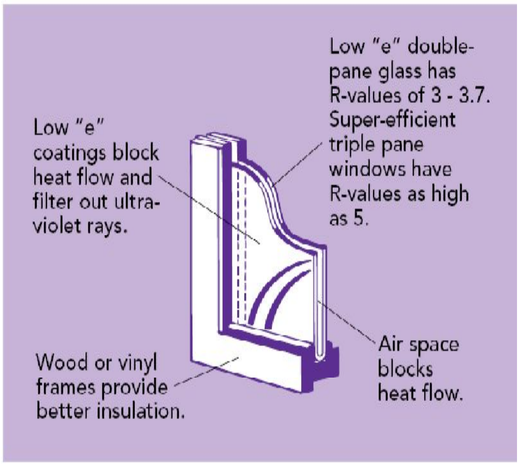

Figure-4- Comparison of the R values of SB walls

Table 3- Results of particle size distribution analysis of Sandy soil and Topsoil

Sandy Soil		Topsoil	
Grain Diameter (mm)	**Percent Passing**	**Grain Diameter(mm)**	**Percent Passing**
19.050	100	18.050	100.00
9.515	98.84	9.325	98.29
4.650	96.27	4.850	97.32
2.000	93.62	2.000	923.11
0.795	90.2	0.795	87.48
0.500	77.4	0.502	85.26
0.250	56.24	0.250	68.34
0.106	32.97	0.108	44.56
0.077	26.97	0.075	37.29
0.0342	15.9	0.0323	22.57
0.0227	10.32	0.0218	17.60
0.0133	6.92	0.0127	11.75
0.00927	6.75	0.00901	9.03
0.00657	4.82	0.00747	6.28
0.00325	2.12	0.00331	2.77
0.00137	1.38	0.00129	0.43

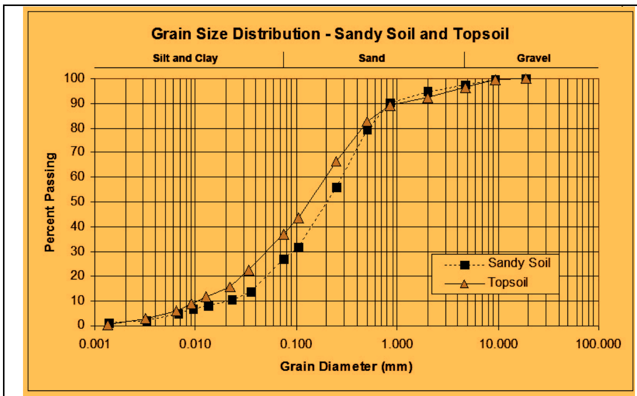

Figure-5-Grain size distribution curve results for sandy soil and topsoil.

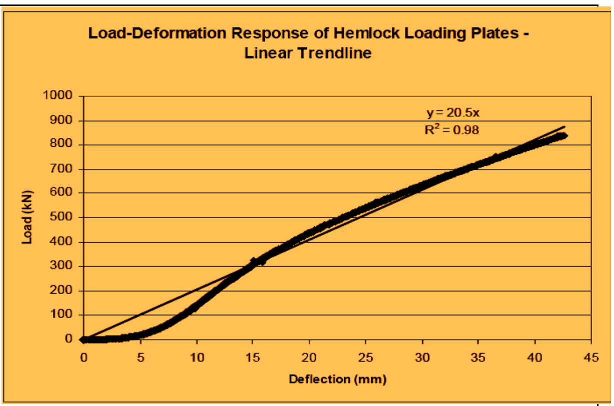

Figure-6-Load versus deformation plot for hemlock plates, with linear trend line

Table-5 Measured lateral to Vertical deformation ration and associated R^2 value for specimens SGf

Specimen	Calculated Lateral-to- Vertical Deformation Ratio	R^2 Value of Trend Line
SGf2	1.022	0.992
SGf3	0.755	0.936
SGf4	0.806	0.957
SGf5	0.774	0.979

subsequently, compressive strength. There were also substantial differences in stiff -ness between the granite and soil filled bags, as measured in terms of the ratio of load to de -formation at ultimate. Even including the two anomalously strong granite-filled specimens, all soil-filled specimens were stiffer than any of the granite-filled specimens. A summary of ultimate load, corrected values for earthbag deformation at ultimate load, as well as deformation at 50, 100, 200 and 300 kN are presented in Table 6.

Table-6 Summary of test results for SGf and MGf specimens

Test	Ultimate Load (kN)	Earthbag Deformation at Ultimate (mm)	Stress at Ultimate (MPa)	Stiffness at Ultimate (kN/mm)	Load per Metre (kN/m)
SGf3	309	165	1.17	2.11	477
SGf4	433	142	1.37	3.05	672
SGf5	351	110	1.27	3.11	537
SGf6	838	131	2.88	7.22	1290
SGf7	845	125	2.92	7.78	1300
MGf1	501	170	1.29	3.03	659
MGf2	715	158	1.89	4.32	954
MGf3	710	176	1.74	4.38	841
MGf4	689	166	2.07	4.87	1050
MGf5	877	176	2.29	5.67	1131

Riley & Palleroni [19] observed a typical strength range of 12 kN/m to 18 kN/m for typical residential construction using 38 mm x 140 mm stud framing. Straw bale housing has been shown to compare favourably with conventional stud framing, with published strength values ranging from 20 kN/m to 80 kN/m for plastered straw bale specimen tests [21], and 30 kN/m for full-scale (2.44 m x 2.44 m) wall tests [22]. By comparison, the lowest strength values for the small 9-bag granite-filled specimens, range from 122 kN/m to 144 kN/m. The values for soil-filled specimens are an order of magnitude higher, ranging from 1123 kN/m to 1327 kN/m. Nominal stiffness of the bags was calculated by dividing ultimate strength by earthbag deformation at ultimate. Finally, the length of the bags was used to calculate the capacity of the specimens in terms of kN per metre of wall length. Figure 8 shows the load vs. stroke plots for tests SGf1-7.

Test SGf6 was run at a stroke rate of 8 mm/min, rather than 4 mm/min showed significant stronger and stiffer performance than the first round of tests. However, specimen SGf7 displayed similar behaviour to test SGf6 in terms of both strength and stiffness, which suggests that the effect of the higher loading rate was insignificant. A statistical analysis was performed to determine the statistical significance of the values for SGf6 and SGf7 relative to specimens SGf3-5.When determine the critical value at significance levels of 0.05 or smaller, the results verify the null hypothesis that the values for SGf6 and SGf7 come from the same normal population as the values for SGf3, SGf4 and SGf5 with a significance level of greater than 10%. As such, it is possible that the large values for specimens SGf6 and SGf7 represent the large variability of earthbag specimen strength. It is possible that variability in terms of textile strength may have influenced the results. In addition to ultimate load and vertical deformation, tests SGf2 to SGf5 were run with to measure the lateral deformation of the middle bag of each specimen. A sample plot of lateral expansion versus vertical deformation for specimen SGf2 is presented in Figure 9. The average ratio for these specimens is 0.823, though it should be noted that specimen SGf2 is higher than the values measured for specimens SGf3, SGf4 and SGf5. The average ratio for these last three specimens is 0.756. When tested in accordance with ASTM 178 [2] , the null hypothesis that all values come from the same population is disproved at a significance level of 2.5%, suggesting that the anomalous value may be discarded and the average ratio of specimens SGf3-5 taken to be a representative average of the ratio of the small granite-filled specimens. The results are presented in Figure 4 & Table 5 which gives the slope of the trend line (i.e. the ratio of lateral expansion to vertical compression) and the R^2 value (coefficient of determination) for each trend line. The average ratio for these specimens is 0.823, though it should be noted that specimen SGf2 is higher than the values measured for specimens SGf3, SGf4 and SGf5. The average ratio for these last three specimens is 0.756. When tested in accordance with ASTM 178 [2], the null hypothesis that all values come from the same population is disproved at a significance level of 2.5%, suggesting that the anomalous value may be discarded and the average ratio of specimens SGf3-5 taken to be a representative average of the ratio of the small granite-filled specimens. Audible crackling of the specimens typically began at loads of around 100-150 kN, with loud, constant crackling by no later than 200 kN, suggesting shifting of gravel and snapping of textile fibres. The ultimate strength and stiffness of the 9-bag specimens (Gf9) was less than the 6-bag stacks (Gf6). The load-stroke plots for the Gf9 specimens are presented below in Figure 10.However, the first topsoil-filled specimen tests exceeded the capacity of the available testing machinery, and it was thus not possible to obtain 5 ultimate load values. As such, it was decided to run two tests of each soil-filled specimen type to determine the load-deformation characteristics of these specimens between 0 kN and 840 kN. The results for the sandy soil-filled earthbag specimens were similar in behavior to the topsoil-filled earthbags in terms of strength and load-deformation characteristics. Given the widely held belief in the earthbag building community that high sand content can lead to suboptimal structural performance, it was anticipated that the sandy soil specimens would have lower strength and/or stiffness than the topsoil-filled specimens. Numerically, the small granite filled specimens had an average stiffness of 2.75 kN/mm (not including specimens SGf6 and SGf7). The average observed stiffness of the small topsoil-filled and sandy soil filled specimens were both calculated to be 12.1 kN/mm. The average stiffness of the small topsoil and sandy soil specimens were measured to be identical at 12.1 kN/mm for both fill types. A graphical comparison of the stiffness of the small granite-, topsoil- and sandy soil-filled specimens is presented in Figure 11, with values grouped by specimen type. For the medium topsoil and sandy soil specimens, the average stiffnesses were 10.2 kN/mm and 9.54 kN/mm, respectively. Thus, it appears that the average stiffness of the small soil-filled specimens is higher than that of the medium soil-filled specimens. The bag size can affect the specimen strength and stiffness. For the small granite-filled specimens, the average load at failure was 358 kN (excluding specimens SGf6 and SGf7). The medium granite-filled specimens had an average load at failure of 695 kN. This yields a ratio of small-to-medium ulti -mate loads of 0.51. Since the higher strength of the medium bags is likely due to their larger bearing area, it is important to note that the ratio of small-to-medium bag bearing areas is 0.78. Thus, there appears to be an increase in strength relative to bag area for the medium bags, though the significance of this relationship cannot be accurately determined due to small sample size. The small granite filled specimens had an average stiffness, measured in terms of millimetres of deformation at ultimate load, of 2.75 kN/mm (excluding specimens SGf6 and SGf7), while the medium specimens had an average stiffness of 4.28. The ratio of small to medium specimen stiffness is 0.64. However, it is possible to examine the relationship between bag size and specimen stiffness at the machine's maximum load of 840 kN. At this load, the average stiffnesses of both the small topsoil and sandy soil specimens were 12.1 kN/mm. The ratio of small-to-medium specimen stiffness for the topsoil and sandy soil specimens is 1.27 and 1.18, respectively. By comparison, the reciprocal of the small-to-medium bag area ratio of 0.78 is 1.28, which suggests an inverse relationship between bag size and stiffness for soil-filled specimens, though the sample size is too small to determine if this correlation is statistically significant. Bag size can vary, depending on manufacturer and builder preference, but the most common size for housing construction is approximately 460 mm wide and 760 mm long (nominally specified as 18"X30").This particular size is sometimes known as a "50 Pound Bag"(Hunter and Kiffmeyer,2004). This size has been accepted by the earth bag community as having an optimal balance of strength and workability, based on construction experience. According to the Unified Soil Classification System (USCS), silt and clay particles are those with diameters less than 0.075mm, sand particles have diameters between 0.075 and 4.75 mm, and gravel particles have diameters between 4.75 and 76.2 mm [11]. This volumetric instability effects on cohesion and stability and subsequently compressive strength. Specifically, the amount and rate of deflection of an earthbag wall under service loads is likely to be affected by the relative fractions of sand and clay particles. In aggregate, sand particles are much less compressible than clay particles, and they typically reach maximum compressive deformation quickly upon being loaded. Clays, on the other hand, tend to be highly compressible, and deform much slower than sands under load [20] . In order to bring earthbag construction in to the mainstream for both developing and developed contexts, knowledge of service state behaviour is critical, since housing residents typically demand durable structures with a minimum of cracks, and are not likely to have confidence in a technology with poorly understood long-term response to loading (Figure 6,7). To date, laboratory testing of earthbag technology has been virtually nonexistent.

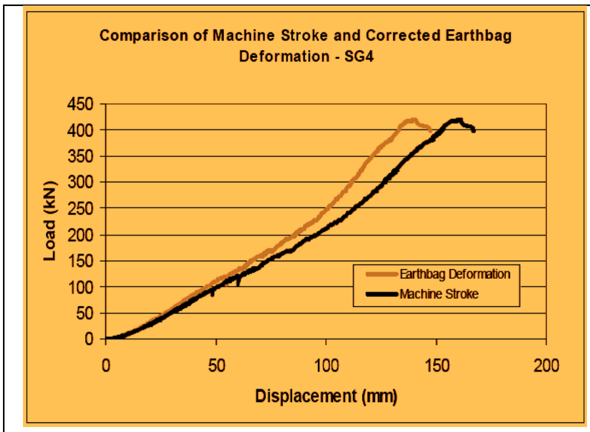

Figure-7-Load versus machine stroke and load versus earthbag deformation, specimen SGf4.

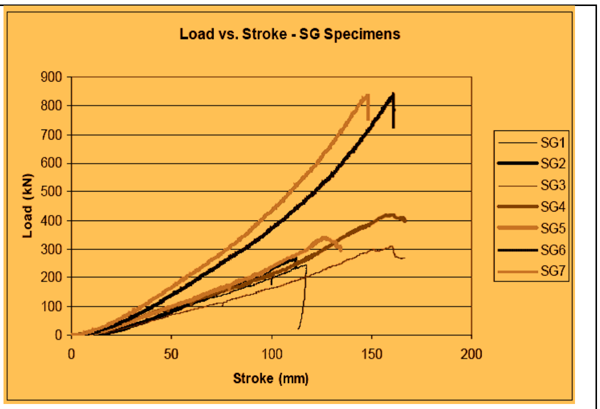

Figure-8-Load versus stroke, all SGf specimens

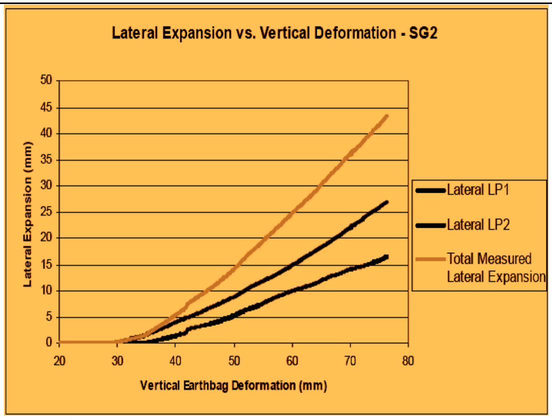

Figure-9-Lateral expansion versus vertical earthbag deformation, specimen SGf2

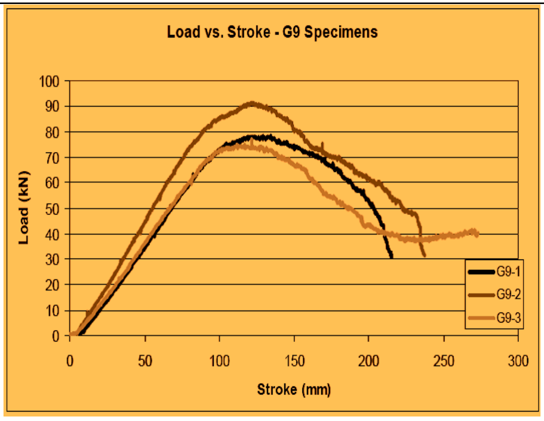

Figure-10-Load versus stroke, Gf9 specimens

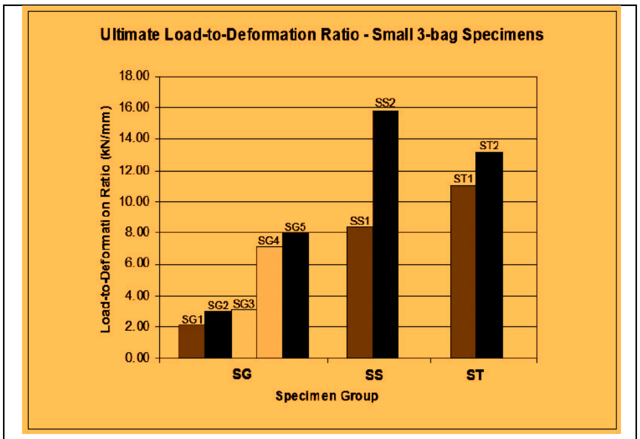

Figure-11-Stiffness of SGf, ST and SS specimens as measured by ratio of ultimate load to deformation at ultimate

Earthbag construction

The walls can be curved or straight, domed with earth or topped with conventional roofs. Curved walls provide good lateral stability, forming round rooms and/ or domed ceilings like an igloo. Buildings with straight walls longer than 5 m (16.4 ft) in length need either intersecting walls or bracing buttresses or piers added. International standards exist for bracing wall size and spacing for earthen construction in different types of seismic risk areas, most notably the performance-based standards of New Zealand:4299 [18] recommended by the ASTM International in their Standard Guide for Design of Earthen Wall Building Systems E2392 / E2392M[6] .Until more complete structural testing is available to co-relate earthbag bracing need and performance to adobe, cement-stabilized buttresses and mortar anchors to hold barbed wire at stress points can be used for public buildings in high seismic risk areas.

To improve both friction between each row of bags and finished wall tensile strength barbed wire is often placed between the courses(Figure 4). Twine is also sometimes wrapped around the bags to tie one course to the next, serving to hold the in-progress structure together and add strength. Rebar can easily be hammered into walls to strengthen corners and opening edges and provide more resistance against overturning. The structure is typically finished with plaster, stucco or adobe both to shed water and to prevent any degradation from solar radiation. This construction technique can be used for emergency shelters, temporary or permanent housing and barns.

Environment friendly

All walls constructed for housing will allow some movement of air and heat at the same time creating some resistance to these flows based on the individual component R values of the wall system's U value (Figure 4, Table 5). Thermal resistance is referred to as an (R) value, while the reciprocal of R is the conductivity (C) of the wall material.

$$C= 1 / R$$

The rate of heat and air flow is a useful concept in understanding the comparisons of wall materials and their thermal conductance. The thermal transmittance is the surface resistance plus the rate of heat transferring per unit of measurement through the wall, denoted as a (U; the thermal transmittance) value, also referred to as the reciprocal of the sum of the system R values.

$$U= 1 / R1 + R2+ \dots Rn$$

The emissivity (ɛ) or thermal absorptivity (α) of a wall is dependent on its material make-up, density, mass (thickness), ambient air temperatures (on both sides of the wall), and solar radiation. Once the thermal capacity (*cp*) of a wall and the time or rate of energy movement is known, then a comparison of wall types can be considered on a level plane for efficiencies.

The U factor is the capacity of a material to transfer heat or cold. The U value and the mass are useful information to consider for more equitable comparisons. Based on the R value alone, there is no comparison of the R values of SB walls (R3 to R19 per inch, depending on the construction) to that of RE walls which have poor thermal resistance (R0.4 per inch) [8] . The wood by itself without insulation and moisture barrier will have a higher resistance to heat transfer. Wood has a lower R value than fiberglass insulation, for example, based on the relative thickness of the two materials. For example; a 2x4 of wood has an R value of 1.25 per inch totaling a 4.375 component R value (Commonwealth Scientific and Industrial Research Organization (CSIRO)[10]. The inclusion of thermal mass in building design is only a part of an integrated approach to sustainable design.

Earthbag Building Insulation

Energy performance on most buildings can be improved with insulation, including those made of earth such as adobe and earthbag structures. Although most earthen structures are located in hot, dry climates, there is increasing demand for low-cost, eco-friendly earth building techniques in cold climates. This article explores innovative methods for insulating earthbag buildings, which extends their building range to cold regions.Recycled polystyrene (Styrofoam) is another good possibility. Another possibility is adding foam board or foam insulation on the exterior of earthbag walls, as explained in the 4th option. The Table 9 below compares the approximate R-values of five low cost insulating materials that could be used in earthbags. Plastic bags recycled into plastic bags .If plastic does not break down for a thousand years, this building is sure to last several lifetimes. If it covered with adobe or plaster, plastic does not degrade. Dunbar & Wipplinger(2006) observed ultimate stresses for sand,rubble and soil-filled earthbags of 0.30 MPa, 0.40 MPa, and 2.14 MPa, respectively. By comparison, the stresses range from 1.10 MPa to 2.98 MPa for crushed granite filled specimens, and 2.33 MPa to 2.98 MPa for both sandy soil and topsoil filled specimens, for the 3-bag configuration most similar to the West Point tests[13]. The tests are not indicative of specimen failure, but rather the limitations of available testing equipment. Even the weakest specimens observed outperformed the published strength values of conventional housing by a factor of nearly 10. This confirms the notion that excessive deflection is likely to govern the design of earthbag structures, highlighting the need for an examination of the stiffness of plastered earthbag assemblies.

Beyond the quantitative results the specimens confirm that earthbag construction is a low-technology building technique which can be easily learned by those not trained in the construction trades. This, combined with the high strength values observed for all small specimens, suggests that small (457 mm x 762 mm) bags are the optimal size for earthbag construction, providing a good balance between strength and ease of manipulation.(Table 6, 7). Table 8 presents a summary of embodied energy values for several common construction materials, taken from Hammond & Jones [14]. The value for rammed earth is presented, as there is currently no published value for earthbags. This is likely to be an overestimate of the embodied energy of the soil fraction of earthbag housing, as it is not necessary to construct formwork or use mechanized compaction devices for earthbag housing, as is required of rammed earth. It should be noted that the embodied energy of polypropylene is much higher than all other common building materials presented in Table 8 but also that polypropylene makes up a small fraction of the total mass of an earthbag wall. The results of the tests also clearly highlight the effect of stack height on earthbag specimen strength and stiffness. The data suggest that earthbag strength and stiffness decay exponentially as stack height increases. An inverse relationship between stack height and specimen strength and stiffness (in terms of kN/mm) makes intuitive sense, since an equivalent deflection will compress a short specimen more as a percentage of its total height than the same deflection applied to a taller specimen. The above discussion of the relative merits of straw bale, earthen and bamboo housing in the context of material availability, climactic suitability, trades availability and architectural preference indicates that earthen housing is the most suitable choice for housing construction in the coastal region .

Table7- Test results for polypropylene textile, machine diection

Specimen	Breaking Strength (kN/m)	Elongation at Break (%)	Load at 5% Elongation	Load at 10% Elongation	Specimen	Breaking Strength (kN/m)
M1	6.5	30.0	3.1	4.8	C1	7.2
M2	7.0	27.3	2.7	4.4	C2	6.8
M3	6.3	28.9	2.5	4.0	C3	7.4
M4	7.2	29.5	2.3	3.9	C4	7.0
M5	6.3	31.6	2.6	3.4	C5	6.5
M6	6.7	30.2	1.9	3.5	C6	6.8
Mean	6.6	29.5	2.5	4.0		6.9
Standard Deviation	0.2	1.0	0.4	0.3		0.2

Table-8 Embodied energy values for common construction materials

Material	Embodied Energy (MJ/kg)
Concrete	0.95
Brick	3.0
Softwood	6.7
Gypsum (for use in drywall or plaster)	1.9
Rammed Earth	0.58
Polypropylene Textile	93.2

Table-9- Approximate R-values of five low cost insulating materials

Material	R Value/inch	R value for a typical 15" thick earthbag wall
Rice hulls	3	45
perlite	2.7	40
Vermiculite	2.13	32-36
Extruded polystyrene	3.6 -4.7	54-70
Molded polystyrene (low density)	3.85	58

CONCLUSION

From an ultimate limit states perspective, however, failure of the plaster skins is not likely to impact the ultimate strength of the earthbags themselves. Earthbag housing is a structurally sound technology in the context of vertical compressive loads, further knowledge of plastered behaviour, behaviour under in-plane and out of plane shear loading, as well as behaviour under uplift forces, is required in order to develop comprehensive, empirically based design recommendations for earthbag housing. With regard to constructability and material availability, earthbag housing is a very attractive construction technique. The advantages include high strength, lightweight, improved resistance to corrosion and fatigue, superior damage tolerance and the ability to be tailored to meet specific applications, compared to traditional steel and reinforced concrete structures.

RECOMMENDATION

There exists an opportunity for the implementation of alternative construction techniques in deve- loping countries, and specifically in south Asia. The wide availability of alternative construction materials, coupled with the generally inexpensive and low-technology nature of their related construction techniques, makes them well suited to use in developing countries. Housing may also be suitable, though significant attention should be paid to moisture-related concerns, wet climate.

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