

CONSTRUCTION OF A SUPERADOBE DOME

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Abstract—Superadobe Technology consists on filling long polypropylene sacks with a moist mixture of clay, sand, gravel and lime/cement; placing and compacting one on top of another forming concentric rings of decreasing radius and describing a double curvature monolith.

From the 26th of August till the 6th of September of 2017, a group of 10 students at the “Domoterra” Institute of Earthbag construction, in the province of Teruel, autonomous community of Aragon, Spain, participated in the construction of what would become a Superadobe domed shelter of internal diameter 4m, roughly 3.5m high with the capacity to enclose 17.5m² of habitable surface, using approximately 250m of polypropylene sack and 20 m³ of earth.

The structure advanced from an initial base cylinder of 0.5 m to the height of 2.1 m in 7 effective work days of 8 hours each day, and such an experience is taken into account together with existing literature, to describe the construction process of a Superadobe dome.

Keywords— Superadobe; Earth bag; dome; sustainability.

INTRODUCTION



Fig. 1. Superadobe Structure.

THE construction of natural structures as an alternative to conventional houses has extended over recent years in response to human and environmental crisis. Superadobe is a method for the construction of self-built shelters with the potential for sustainably reducing the world's current housing deficit: It's executable by common people, It's economical (earth being the main material used and no heavy construction

machinery is needed), and even for being a self-built technology, it has consistently exhibited good structural behavior against natural events such as earthquakes, floods, fire and high winds [1].

This, among other 'green' and self-built technologies, make it possible to build culturally sensitive shelters from ecological and accessible procedures and materials: adobe buildings, cob, bags of earth, bales of straw, among other technologies, are well known examples.

Even if these buildings have limited or no applications in industrial areas, they have extensive applications in human activity, specifically, as a solution for homelessness that should be included in construction codes [2].

Since materials used in construction greatly impact on the economy, the environment, and on the adaptability of society, the influence that construction activity has on sustainable development is paramount. Sustainable building materials: those that are profitable, that are socially accepted and which have a low environmental impact, are the focus of many researches which now exist, which back-up and contribute to the use of earth inside buildings [3]. Materials such as earth bags, whose ratio of polypropilene – to earth in the building's total mass is small, produces considerably lower CO₂ emissions, according to [4].

For thousands of years, materials such as adobe, hard soil and cob have been used for shelter, and approximately 30% of the world's population and 50% of the population of developing

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countries live in shelters of earth, and the conscience for its use is expanding today.

What follows is a description of how an earth quake-resistant, earthen monolith: a Superadobe dome of 17 m² area and more than 3.5 m of height, can be constructed by a team of 10 students with little more than soil, a bunch of hand- tools, good will, and good guidance.

THE PROCESS OF CONSTRUCTION OF A SUPERADOBE DOME

A. materials and preparations

1) Tools needed

Among other virtues such as being a social potentiator, one of the greatest virtues of Superadobe technology, is its relative accessibility: although training is necessary, it can be practiced by all peoples given that the techniques are learned, among other reasons because hardly any heavy machinery or expensive tools are required. The equipment that will be necessary for building a Superadobe dome includes comfortable/ resistant clothes for work, cap, sunglasses, reinforced boots, work gloves, impermeable gloves, a knife, and an indelible thick marker.

Besides this basic personal equipment, little more is needed: pointed tip shovels, spades, pickaxes, wheelbarrows, and a concrete mixer with a suitable power supply if possible. Also, for the plaster, trowels can work but hawks are ideal. Finally "rammers" or "stompers", which are used to strike filled polypropylene sacks in order to compact the mixture inside of them. Anything heavy but manageable, with a flat striking surface will do the job. It may be necessary to make a tool of this type, according to Figure 2.

2) Earth preparation and mixture

Domes in principle, are made with the sieved earth that is dug to make the foundations, and also with that which accumulates when cleaning the area of construction. This is the "base" construction material; local sieved soil. Yet additional soil from the site should be gathered and sieved, since a medium to big dome could demand more quantity of earth. (A dome of four meters in diameter consumes about 20 m³, or roughly 30 tons of soil.



Fig. 2. Handmade Rammers.

The behavior of the building through time depends fundamentally on the adjustment of the correct proportions of gravel, sand and clay, of the soil used in its construction.

We must first do several field tests at the foundation site and at the extraction area, and we must do jar granulometric tests and take mean values, making sure there are no important granulometric variations from the different sources to be used.

A jar granulometric test is done by picking up soil without remnants of organic matter from about 30 cm deep into the ground, and introducing it in a jar of glass of known volume, better square than cylindrical. Then, mixing its contents with water and leaving it stand 3 days. If we add salt, the process accelerates: about 3 spoonful's for a normal pot of chickpeas, for example.

To know the percentage of the granulometry, a ruler is used. We measure on one side of the jar, the different lengths of layers of stored earth, (the centimeters of clay, silt, sand, and gravel as they deposit with time and differentiate themselves in such layers). By doing this, we deduce the proportions in which each particle type is present in the soil of our site in a volumetric sense.

As we will read below, if we know the percentages (mean percentages) of each particle type in our soil, then we can correct or fix these proportions (by adding specific types of particles to our mixer), in order to make a mixture which is ideal for a Superadobe dome.

We look for 30% binding materials (20% clay and 10% a binding stabilizer) and 70% sandy soil (35% gravel and 35% sand). A rich variety of sandy soil particle sizes is desirable. The ideal binder, reinforcer or stabilizer, is lime.

Lime as a binder and stabilizer for the mixture, allows the passage of the environmental humidity of a house and the dome "breathes". The phenomenon is known as breathability. These qualities of lime will eliminate the possibility of condensation within the Superadobe walls. Lime also has the property of not letting rain water pass, hence turning our dome into a Natural Goretex.

Slaked lime comes from calcinating calcic rock, (its calcium carbonate), CaCO₃, and adding water to the resulting calcium oxide CaO, thus becoming Ca(OH)₂. This is calcium hydroxide.

It is not recommended that fresh air lime Ca(OH)₂ be used for construction (just watered live lime), as it is better to use air lime which has been submerged in water for at least six months, acquiring better properties for binding and hardening with time. Hydraulic lime is the same lime but with pzzolans and ashes that provide a more optimal qualities in low oxygen media and humidity, which allows an optimal setting for the foundation. It's much better (and also more expensive).

The reasoning used to prepare (or fix) the soil of our land for Superadobe construction is as follows:

If we do a jar granulometric test on the soil of our site (or many, and we take a mean result), and we obtain different mean volumes, namely C_n , for different particles n , then we would like to find what volume of each material n , namely X_n , we must add to our land in order to obtain desired proportions, namely Pd_n , of each material n , in the resulting mixture.

We can represent this by the set of equations $\frac{C_n + X_n}{V_f} = Pd_n$, where C_n is a known volume of particle type n within a given mixture or sample, X_n is an unknown volume of particle type n to be added to the given sample in order to obtain a desired proportion of particle type n , Pd_n , in an altered sample of final volume V_f . Manipulating each of these equations we find:

$$V_f = \frac{C_n}{Pd_n} + \frac{1}{Pd_n} X_n.$$

These are the equations of a line for every n . We want to find different positive X_n 's for a common positive V_f , and to do so we imagine a set of lines, each produced by an equation $V_f = \frac{C_n}{Pd_n} + \frac{1}{Pd_n} X_n$ of a given particle type n . Since all numbers $\frac{C_n}{Pd_n}$ are positive, all of the lines of the set intersect the V_f axis in a positive quantity. If we take the greatest of such quantities, say $\frac{C_g}{Pd_g}$, to be V_f , then the corresponding X_g is zero, and all other X_n values that satisfy $V_f = \frac{C_n}{Pd_n} + \frac{1}{Pd_n} X_n$ will be greater than X_g , or positive.

Having found this common V_f , we can solve the set of equations $X_n = Pd_n V_f - C_n$ for each particle n .

What follows is an example of how to use the reasoning above:

Suppose that Figure 3 represents the mean result of our local soil granulometry. Suppose now that we desire a soil for superadobe construction, with the following proportions:

Silt: 5% or less, Sand: 40%, Gravel: 25%, Clay: 20%, and Lime: 10%.

In order to use this local soil for construction, we must add different volumes X_n , of clay, sand, gravel and lime, to our land. Adding different volumes of specific particle types (sand, gravel or clay) to our 250 ml jar, until we get the d



Fig. 3. Granulometric jar test.

esired proportions within the jar (getting an unknown final volume of mixture V_f), will give us a valid approximation for **what proportions of specific particle types should be added to our local sieved soil (Fig. 3) in the preparation of the mixture for the actual construction.** To find these volumes needed, we first find V_f .

Step 1: We calculate the maximum ratio $\frac{C_n}{Pd_n}$, where C_n is the given volume of particle n in our jar, and Pd_n the desired proportion of such type of particle in our final mixture of volume V_f . For clay we have $\frac{C_n}{Pd_n} = 100\text{ml}/0.2 = 500\text{ml}$. for sand, $\frac{C_n}{Pd_n} = 80\text{ml}/0.4 = 200\text{ml}$, for lime we have $\frac{C_n}{Pd_n} = 0\text{ml}/0.1 = 0\text{ml}$, for gravel $\frac{C_n}{Pd_n} = 50\text{ml}/0.25 = 200\text{ml}$, and for silt, $\frac{C_n}{Pd_n} = 20\text{ml}/0.05 = 400\text{ml}$. We see that the greatest ratio among all of them is $V_f = 500 \text{ ml}$. This means that our final modified mixture, after adding different particle volumes to our 250 ml original soil, will be 500 ml in volume.

Step 2: We now solve the equations $X_n = Pd_n V_f - C_n$ for each particle n .

For silt, $X_n = 0.05 * 500\text{ml} - 20 \text{ ml} = 5\text{ml}$. For sand, $X_n = 0.4 * 500\text{ml} - 80 \text{ ml} = 120\text{ml}$. For clay, $X_n = 0.2 * 500\text{ml} - 100 \text{ ml} = 0\text{ml}$. For gravel, $X_n = 0.25 * 500\text{ml} - 50 \text{ ml} = 75\text{ml}$. For lime, $X_n = 0.1 * 500\text{ml} - 0 \text{ ml} = 50\text{ml}$.

Step 3: Now that we have the needed volumes to be added of each particle type, to our original 250 cc mixture as to obtain an ideal 500 mixture, we calculate the proportions of each individual component in our 500 cc final mixture as parts in 10.

Parts of soil from the site = $250\text{ml} * 10/500\text{ml} = 5 \text{ parts}$.
Parts of pure clay = $0\text{ml} * 10/500\text{ml} = 0 \text{ parts}$ (this means that all the clay needed for our mixture is already present in the regular soil).
Parts of sand = $120\text{ml} * 10/500\text{ml} = 2.4 \text{ parts}$.
Parts of gravel = $75\text{ml} * 10/500\text{ml} = 1.5 \text{ parts}$.
Parts of lime = $50\text{ml} * 10/500\text{ml} = 1 \text{ part}$.
Parts of silt = $5\text{ml} * 10/500\text{ml} = 0.1 \text{ parts}$, a quantity too small to be added.

In conclusion, to fill our sacks with the soil of this example, we must add to our mixer each time: **5 buckets of soil from our site (sieved), 2.4 buckets of sand, 1.5 buckets of gravel, and 1 bucket of air lime.** After that, we add water until final consistency is achieved, and we will have an ideal mix using our own earth from the site plus some purchased additions.

Hence, to construct a superadobe of, say, 20 cubic meters in this land, we should use 10 cubic meters of sieved soil from the site, and purchase: 4.8 cubic meters of sand, 3 cubic meters of gravel, 2 cubic meters of lime and 0.2 cubic meters of silt (silt can and should be disregarded in real practice, as it decreases mixture strength). In the case where there is some silt present in local soil (it is common in small percentages), it would be valid to set $Pd_n = 0.05$ or less as in our example as to solve the equations, disregarding the quantities of silt to be added in the end.

In general, we are looking for a mixture that enables Superadobe blocks with a compression resistance of $60 \text{ kg} / \text{cm}^2$ or better.

Notes on mixture:

- On window arches (will be discussed later), percentage of lime has to be increased up to 30% lime to ensure greater resistance. This could mean adding only sand, gravel and lime to the mixer in the correct proportions. After getting past windows to close the dome, we can again use only 10% lime and 20% clay with local soil (recommended values).
- The mixture inside the mixer is grabbed and squeezed in the hand to observe that it takes the shape given by our force but it should not drip water.
- We should discard stones (5cm diameter or more) from the gravel, because they can break the sack when compacting. Hence, **gravel must also be sieved, as the soil from the site.**

3) Dome orientation and location

We must first use common sense: choosing a flat area of perennial trees and rocks, or buildings that give us shade. Also, a Superadobe dome should be oriented according to the solar Axes.

Solar orientation is achieved empirically by a simple cane in the center of the ground. The sun since it leaves the 'solar east', sweeps a series of shadows, drawing a 'solar fan' to give us the shadow we need (South-North). This is, just the center of the fan and coincides with the solar noon.

Setting a straight line along the solar noon shadow with a rope, we will have the North axis. From there we will get a cross: another line at 90°, to have the East – West axis of the Dome (Figure 4, orange axes).

In the case where we build different modules, the overall structure is not fully symmetric in terms of its extension, and we should orient its greater length along the east-west solar axis

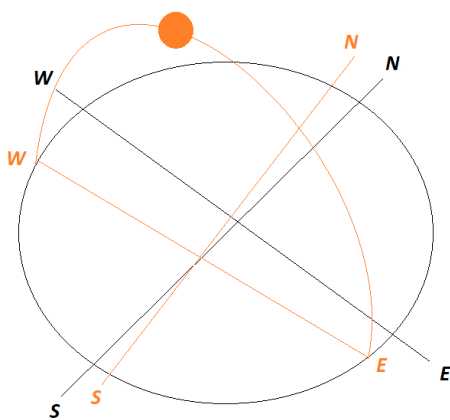


Fig. 4. Magnetic and Polar axis.

to make the most of the energy of the sun, so that the dome will warm us in winter.

The orientation of the dome with respect to the north and solar south is necessary also in the case where only one module is constructed, to orient the building's instances. Sleeping rooms can be oriented to the west or to the east to receive the warmth and light of the greatest direct angle sun from the afternoon or from the morning. To the south, which in our

latitudes, obtains a more regular stream of light, we might place common areas as living room or kitchen, which can also benefit from facing east to receive the morning sun. Bathrooms and laundry rooms may be placed at the northern side of the dome.

It is important to know the direction from where strong winds come in winter, as to avoid placing door or window openings facing these directions. Also, conducting previous studies when possible, we can detect electric currents or underground water currents that should be avoided as building sites. Studying possible terrain overall inclination we should opt for establishing our dome in the highest point of our terrain, as to avoid water accumulation surrounding the dome's foundations.

B. Execution

1) Foundation and drainage

The main foundation material is stone and gravel (with rich granulometry, ranging from rocks to sand). The use of gravel and rocks as Support of a building is optimal because it isolates moisture, unlike foundations with cement grout or concrete slabs. Gravel also perfectly supports the loading efforts which come from the building.

A dome has a huge weight of around 35 tons, but its weight is distributed equally around each circular section. The building does not need a concrete base, as it only needs to efficiently and evenly transmit the loads to the soil at a proper depth, and a gravel bed which is deep enough is good to do so.

The foundation in a dome, is a "continuous shallow foundation bed", consisting of stone and gravel as support and as moisture insulation by capillarity. Figure 5 illustrates a

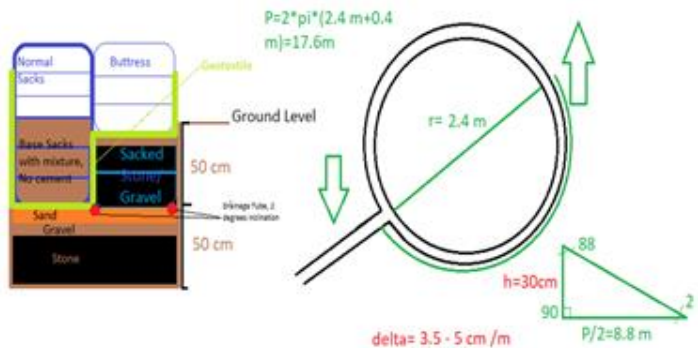


Fig. 5. Section of the Superadobe foundation, foundation disposition and inclination.

general foundation bed section, its insulation and the inclination of the drain pipe.

Typically for a Superadobe structure of 35 tons or less, a foundation trench 1 m wide and 1 m deep, will be 15 m² in surface (for a dome of 2.4-2.5 m of radius), and passing the ground a trivial amount of pressure, roughly 0.23 kg / cm².

The depth of 1m would enable us to find solid ground with more than sufficient bearing capacity to support the distributed weight of the building through an initial bed of stone, gravel and superficial sand, of depth 50cm.

Sacked stone and gravel occupying a width of 50cm on the outer foundation trench will act, together with the stone, gravel and sand bed, as a drainage barrier by capillarity.

One or two drainage pipes (with wholes performed on the top to allow the entrance of water, marked in red in Fig 5.) should circle the foundation, both of them above sand level (one along the exterior of the trench, the other circling around the outer edge of the base sack), and given an inclination of 2 degrees (going 3.5cm deep every meter of length, as in diagram above), respecting the natural terrain inclination as to catch water accumulation and drive it away.

Geotextile material should insulate the building foundation from the gravel barrier within the trench as seen in the diagram above as well, as marked in green in Fig 5.

2) Compasses

As seen in Fig. 6, two compasses must be set for the construction of a dome. The center compass (see below, centered at C) must already be set up prior the opening of the foundation trench, for with the aid of this central compass, the circle of the trench is drawn on the ground.

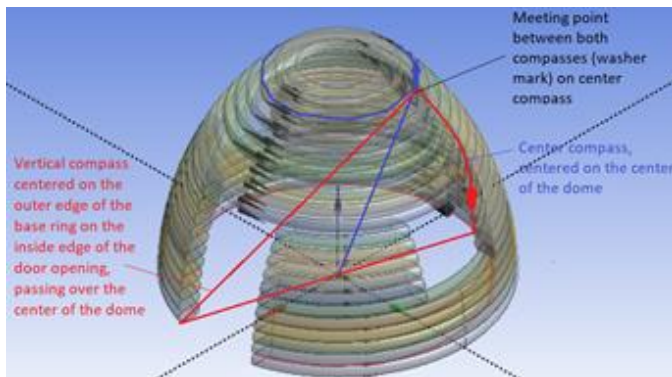


Fig. 6. Central and Vertical compasses.

The second compass (vertical compass) is the guide for describing the roof curvature (the second curvature) of the dome. Its center is set just on the outer edge of the base sack (the first sack over ground level), on the inner most edge of the entrance set - up. Since this second compass cannot fully rotate to guide the construction, the center compass, which is free to rotate 360 degrees, compliments it. It works by being adjusted to match the endpoint of the vertical compass at the exact height of the next ring (determined by touching the endpoint of the vertical compass with the center of a guide object, brick for example, with center mark at a height equivalent to one half of the filled sack height), and placed on top of the previous ring (figure 8).

3) Main procedure

Once the tools have been acquired and preparations made: the terrain has been leveled, the soil (seived), gravel (also seived), clay (if necessary) and sand accumulated onsite, the air/hydraulic lime is set up onsite, the mixer placed in a convenient place onsite, the central compass placed, the foundation trench opened and built with its drainage barriers, pipes and base rings, two repetitive processes begin: one around the mixer and the other around the compasses on the building site. The objective is the placement of the consecutive rings,

and the dynamics of this cycles (one taking place at the mixer area, and the other at the building area), involves two teams, one team per area, and having ideally three persons each (figure 7).

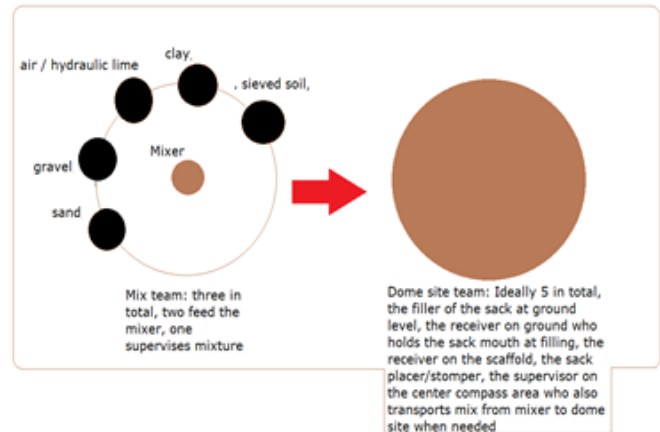


Fig. 7 . Site distribution.

The dynamics of the cycles are as follows:

Around Concrete Mixer: Conforming to the final proportions needed for gravel, sand and clay (which were calculated in the mixture preparation step in order to prepare the soil onsite and attribute the desired proportions), these piles, as well as the soil pile, should be gathered in proximity of the mixer (figure 9), and must have shovels and containers in the proximity of each, all with identic capacity.

The number of parts of each material is added to the mixer at the center in a correct order (generally the gravel first to help clean the mixer from previous loads and loosen material, then the soil, the sand, and then the clay). After the dry measures of these materials become homogenous in the mixer, the air lime and finally water are added to achieve final consistency of the mix).

After some time in the mixer, the mix can be taken and smashed with our hands to observe that the applied form remains and water does not drip. If the mix crumbles, we should apply more water. If it is too wet, we should mix more soil. If the mix results wet in previous attempts, we must use less water but always the same amount of air (hydrated, wet) lime.

The mixer, after the mix is homogenous and with the correct consistency (after 5-10 minutes mixing), is unloaded on a cartwheel and the mix transported (ideally not too far) to the building area to fill the sacks.

Three people at least should manage the mixer area, whereas one of them manages the mixer and the soil consistency inside adding water at the end, the other two, gather, transport and feed the corresponding quantities of different ingredients to the mixer. One of these two, can transport the final mix to the building area as well.

Ideally, after the mix is delivered to the dome area team, the two people in charge of feeding the mixer should begin gathering the different materials and feeding the mixer again, thus giving time for the mixer to prepare the mix while the other team places sack. This process repeats itself until the building is completed.

On the building area: When the mix prepared in the mixer area arrives to the dome area, it must be passed from the cartwheel to a bucket of manageable size to fill the mouth of the sack.



Fig. 8. Delivering mixture to the dome area.

The sack is extended from the sacks resting point at a given height to the ground.

The amount of mixture added to the mouth of the sack on the ground needs to be just enough for the strength of the person positioned on top of the structure turning and placing the sack (the sack placer). A third person is important at mid height on some kind of ladder or scaffold between the person on the ground and the placer of the sack at the top, in order to pass the load from the ground to the sack placer at the top, so that he or she does not bend down so much, in order to avoid losing equilibrium.

As the sack is being laid by the sack placer at the top, a person inside the growing structure measures the correct distance between the mark in the extended center compass, and the edge of the sack.

If the correct distance is not achieved (two fingers between the mark and the inner edge of the sack segment, before the sack is stomped), this person instructs the sack placer to rectify, either to pull the sack closer or farther from the center. After some length or portion of the ring is correctly placed, another person (ideally), or the sack placer (who is already atop of the

structure), must stomp (compact) the newly placed portion of sack all the way through. This adds stability to the growing structure and advances the work.



Fig. 9. Helping the placer of the sack. The dome team.

Note: As said before, the bag, when placed, is not compacted and the person on the inside of the structure must leave two finger's distance between the washer (compass mark) and the inner edge of the newly placed sack segment, as the bag spreads laterally when stomped and must touch the tip of the washer



Fig. 10. Measuring correct distance of the ring edge with the central compass.

after compacted. If it does not, two or three people using the scaffold if needed, can move the bag portion (pull or push in a synchronized manner) to reposition it further or closer to the center. **As the sack is being laid, its placement with respect to the center compass must be checked continuously so as not to have to rectify and lose time.**

Note: It is important to mention that one of the most demanding parts of the job carried out at the dome area, is that of the placement of the sack. As the rings are curved, and this curvature intensifies with each higher level, a sufficient amount of mixture must be successfully managed/ driven/ manipulated, while enough torsion (for the curvature) must be given to the portion of sack being placed, who's weight can range from 15-30 kg, all while trying to maintain equilibrium at a determined height over the previous ring's stomped surface (not greater than 35-40 cm wide).



Fig. 11. The sack placer.

Correct sack placement technique must be observed by the sack placer, especially in the sense of keeping safe and balanced at heights greater than one meter, and giving torsion to the sack so as to have a continuous final sack rather than fractured.

The stomping can give finishing angles to the surfaces and sides of the rings. A stomping inclination outward can be given to each ring, for the building to have an added mechanism to repel falling excess water out of itself.

Also, a sack should never be finished where the one on the bottom has finished.

This process at the dome area (sack filling, placement and stomping) is carried out once and again with every arriving cart of soil mixture until the ring is completed.

Stomping, Barbed wire placement, and measuring sack

length, wire length and compass length for the new ring placement:

After placing a new level / ring / superbloc, you must definitely trample at least 3 - 4 times along the stomper, as illustrated in the figure 11 (a person who is ideally strong and who, as the sack placer, is confident working on heights).



Fig. 12. Stomping the ring.

After a correct stomping, and using the scaffold if needed, a double line of triple point steel barbed wire must be "sewn" or stitched onto the upper surface of the newly placed ring. This can be done by the stomper or any other team member that understands the technique of stitching the steel onto the ring (by inserting the steel points in opposing directions) (figure 13).

Stitching must also be done in such way, that the double steel pattern not necessarily lies on the center of the rings upper surface but rather, more to the interior of the ring, to hold in place the next ring, as new rings tend more and more inward as height increases.

On the first rings, it will appear that the wall is straight (cylinder), but reaching 2/3 of the dome's height, it starts being clearly noticeable as the sacks are staggered, that they drastically become more and more inwards with each new layer. Barbed wire in these levels must be placed further into the dome so that the wire is just in the middle of the upper bag holding it in place.



Fig. 13. Stitching barbed wire to the ring.

After a whole sack (superblock) is completely filled, the mixer is stopped. Once the complete sack is placed, stomped and stitched, a measuring of the lengths of the next ring's sack and steel wire perimeters must be made and the corresponding cuts

made, overestimating on the safe side by 1-1.5 m. Then, the process of adjusting the center compass for the new ring (the center ring washer mark is set to match the length of the vertical compass where it will meet the midpoint of the next ring) must be carried out. Finally, the mixer can be turned on again and the previous process (main procedure) of soil mixing and sack placing begins again.

4) Mold placement and use for window and door openings

At a certain height range (at height 0.2 m – 0.6 m in the case of the main door, and at height 1 m-1.5 m in the case of windows, depending on the dome dimensions), molds must be placed on top of the newest ring to account for door or window openings.



Fig. 14. Mold / Frame for the main door.

With respect to placing the sack portions of each ring along the molds, the key is to work as described in the steps before, (guided always by the center compass), but with the exception that when the sack being placed encounters the mold at its foot, one must stop the sack, filling it a little more, and stomping it at the edge of the mold (fig 14).

Then, some rings higher, *when two or three levels remain until the height of the mold is reached, and the sack meets the mold, instead of being stopped, the sack must continue and be passed over the mold, being filled along the edges of the mold and given it an arch form over it, as to be self-sustaining, always respecting the vertical compass distances for each height level* (abiding by a mark made on the mold with indelible marker before being placed on its final position).

How to mark the mold with indelible marker before placing it on its final position:

Before placing the mold on its final position on the ring, it must be placed on the ring *on its final height*, and in such a way that its center is collinear with the origin of the vertical axis and the center of the dome. From this position, a trace mark through where the sack must pass over the mold should be made on the mold with a marker according to figure 15. All molds must have sufficient depth as to account for the dome's double curvature. Molds must stand out on the inside of the dome about 40cm, to account for the differences in radii experimented by each higher

ring, since the dome in height increments is closing up. (*Note that in this next figure, a formula is derived for the length of the arch theta that can be swept by the vertical compass across the ring; within the limits of the door frame. Theta measures 2 rads (4.28m), more than enough to encompass the width of any window or door frame.*)

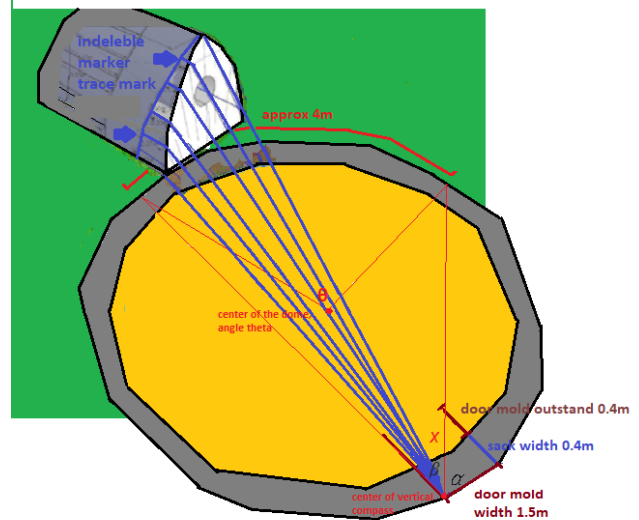


Fig. 15. Trace mark over a window mold.

Where:

$$x = \sqrt{(1.5m)^2 + (0.8m)^2} = 1.7m$$

$$\alpha = \sin^{-1} \left(\frac{0.8m}{1.7m} \right) \approx 28^\circ$$

$$\beta = 90^\circ - \alpha \approx 90^\circ - 28^\circ \approx 62^\circ$$

$$\theta = 2\beta \approx 124^\circ \approx 0.68\pi r \approx 2.14r \approx 4m$$

The ideal windows are of base 1 meter and height 1.5 meters. The ideal doors are of base 1.5 m wide by 1.80 m high. The final position of a window or door mold, should be set according to one of the two solar axes, as to keep the room orientation set before. Molds should be placed on top of bricks and long wood panels, so when the the sacks surrounding and over the molds harden, these bricks are moved through impact

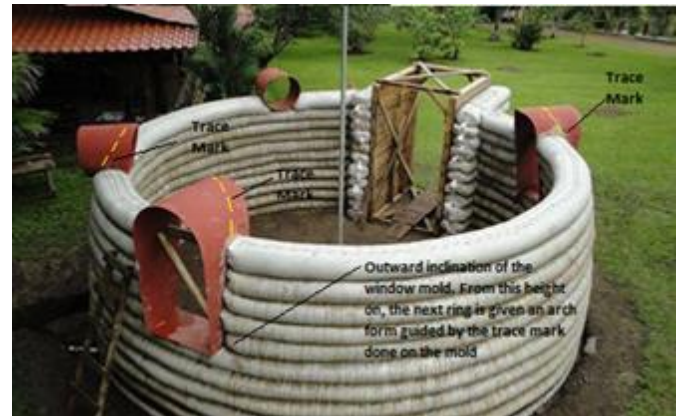


Fig. 16. Window molds prior the laying of the arched self-sustained ring on top.

and the molds then come easily out.

A final inclination outward of the molds can be achieved through the bricks at their base, as to help the structure with excess rainfall drainage.

We must not remove the mold base bricks and the molds until after 2 weeks at least for the mixture to acquire its final strength.

Once the whole arches of doors and windows harden, molds are removed tossing away the bricks. After the whole structure has been finished, the installation of definitive window and door frames on the structure openings can take place.



Fig. 17. Window opening after removal of the mold. Notice the self-sustainable arch form of the window according to the steps described above.

5) Buttresses and apses

Our domed superadobe is a revolved arch, and for this reason, the principles of the arch apply to it. Moreover, a buttress may support any kind of wall, as it is an architectural structure built against or projecting from a wall which serves to support or reinforce the wall, yet in the case of arches and domes, it prevents their destruction by counteracting the strong outward horizontal forces originated in them.

Our buttress occurs in the base of the dome, surrounding the first layers of sack above the ground as shown in the figure 18:



Fig. 18. Buttress of a guest dome at the Domoterra Institute.

While being constructed, buttresses connect to the base rings through barbed wire in the form of "s's", sewing the two sack rolls (the base sack and the buttress sack) together (Figure 19).

Buttresses are an extra wall around the dome, and their

height, for a dome of up to 2.4m in radius, must exceed the starting line of the curvature (Springline) in 50 cm (Figure 20).



Fig. 19. Sewing sacks from different rings with barbed wire.

For example: If after our foundation we build a cylinder wall of 50 cm, (3 rings or so), our springline will be at 50 cm above ground level. We would in this case, build the buttress together with the first six rings (the three first rings of the cylinder base wall plus the three rings that follow, of 50 – 60 cm high, which come after the initial 50 cm springline, so the the buttress would total one 1m-1.2m in height).

A single Superadobe module of radius greater than 2.5 m, is

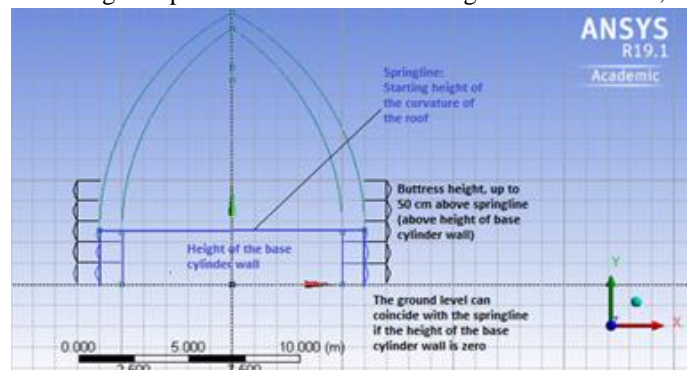


Fig. 20. Buttress.

not common and cannot be built unless very thick walls and buttresses are incorporated. These are common constraints among those who build superadobe, and they exist for an important reason, yet, as a side note, *it would be interesting to challenge these limitations, and to find alternatives that enable the construction of bigger single modules safely.*

The process of building apses will not be described in this article, yet the basic idea in their construction is to stop laying sack at the points of intersection of two domes, alternating between a sack on top from the main dome, and a sack on top from the apse in such points of intersection, abiding by the compass of each dome, as the apse has its own vertical and center compasses (figure 21).

All apses are valid, even the ones that have its center far from the main dome and intersect it in such a way that the height of the common arch is not enough for a person to pass. In these cases, a deep door mold should be used to guide the construction of a hall between the two domes. Yet, given a main dome, there exists a natural apse for it, because this 'perfect' apse, in contrast with all others, will also act as a buttress for the main dome.

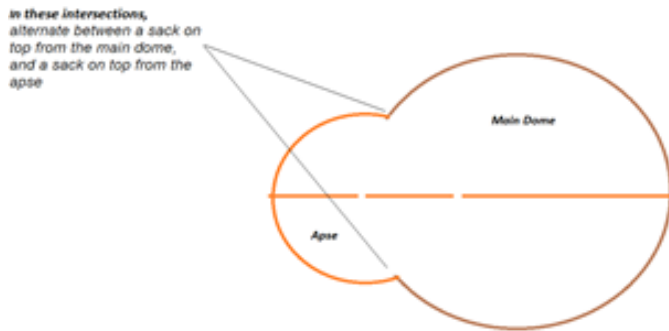


Fig. 21. A pair of points of intersection between main dome and apse, where the rings are sewn together and alternated.

The center of this ideal apse should have to coincide with the outer edge of the base sack of the main dome, and the line segment that passes through the outer edge of the base sack of the apse and the apex (top) of the main dome should form a 45 degree angle with the ground, as in the next figure 22:

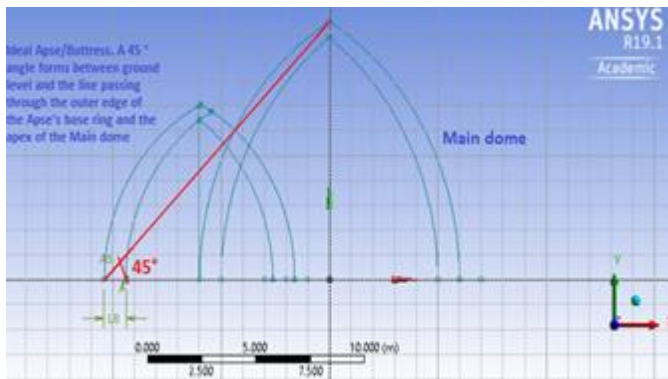


Fig. 22. An ideal apse.

6) Empirical design rules

From the experience of construction as carried out by me and also according to the available bibliography on the matter, one can put together a set of empirical rules that are somewhat implicit, but are always observed in the construction of these buildings as a direct result of applying its methods:

- A compressive resistance for the material which ranges from 60 to 80 K/cm², is safe for a dome not surpassing 5 meters in diameter.
- For an apse to act as a buttress to a central dome, its center should be on the outer edge of the central dome, and the line segment connecting its base rings outermost edge with the apex of the main dome must form 45 degrees with the ground.
- Typically for a Superadobe structure of 35 tons or less, a foundation trench should be 1 m wide and 1 m deep.
- In general, when building a dome of internal base diameter greater than 1.5 m, buttresses must be built for the building to be safe.
- Buttresses must always be built up to 50 cm above (3-5 rings above) the springline.
- Sack dimensions (filled), must be chosen as a function of

the domes internal base diameter, in accordance to table 1

TABLE 1: RELATION BETWEEN BASE DIAMETER, SACK WIDTH AND SACK HEIGHT

Diameter of internal Base (m)	Width of Sack (cm)	Height of sack (cm)
0 - 3	30	8.5
3 - 3.5	35	9.5
3.5 - 4	40	10
4 - 4.5	45	13
4.5 - 5	50	14

(The filling of the sack will reduce its nominal width in 7 cm - 12 cm).

- Having divided the dome in imaginary quadrants, only one opening (window or door) can exist on each quadrant, in such way the length of the remaining arch walls have bases of length (curved) equal or greater than 1.25 m (figure 23).

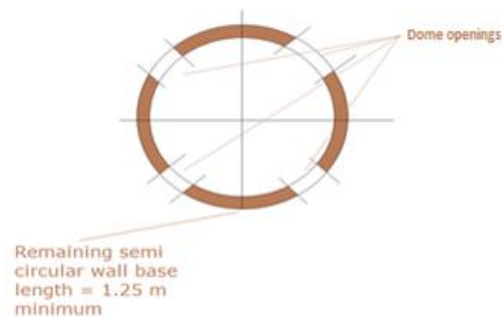


Fig. 23. Dome openings by quadrant.

- The first and foremost empirical rule for Superadobe construction, which together with the base diameter – sack width relation, is the most fundamental: The relation between vertical compass length and base radius / sack width. **It is never said, yet in practice, because the vertical compass is set just at the outer edge of the base ring, and extended through the center of the base up to the internal edge of the opposite sack portion, we have $rr=2rb+sw$, where rr is the length of the vertical compass. rb is the length of internal base radius, and sw is the sack's width (figure 24).**

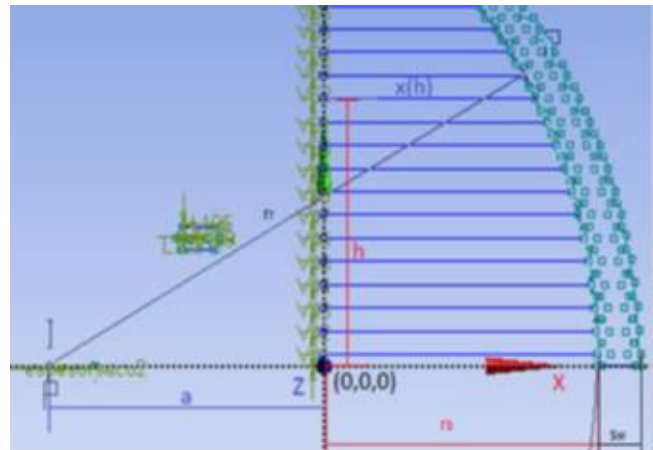


Fig. 24. Empirical rule of Superadobe construction: $rr=2rb+sw$.

Through finite element and other types of structural analyses, all of these notions and rules should be challenged, and their reasons understood.

7) Additional protection and levels

The supports for a small loft can be inserted directly into the wall above the level of the windows if the height of the dome is sufficient for a second floor. A suspended stepladder can be made by building the steps directly into the wall as cantilever. These can be placed to a depth of 0.3m being held in the wall, extending 0.7m into the dome. As the bending moments in the stairs could cause problems with plaster stability, it is beneficial to add further support to these [6].

Also, regarding water management, supports for awnings can be placed on the wall over the door and windows, extending out of the dome, and rebar lengths can be placed between rows with reo - mesh tied on, to provide a base for ferroconcrete gutters [6].

8) Waterproofing

Our Superadobe is very resistant to earthquakes, cold and heat, but It cannot efficiently resist water by itself, as water degrades our mixture and bag resistance. That's why our dome is recyclable and if we do not pay attention to the finishing, with the pass of time, water enters and undoes the structure in a few years.

Fabric of goretex type (a membrane for the control of water vapor and a 100% barrier to air infiltration) is recommended for the inner wall of the dome. When installed on the hot face of the internal insulation, the rate of heat lost by convection through the structure of the building decreases, and it offers a barrier to infiltration and air loss from living spaces within the building.

For the exterior, a membrane which should be extremely resistant to water must be included, tight to air and wind and, at the same time, high permeability to water vapor to avoid condensations inside the walls. In general terms, three layers of plaster are recommended and will be described below.

As for thermal insulation, it is a well-known fact that a Superadobe possesses a high thermal mass, providing high thermal inertia, minimizing the effect of temperature fluctuations. Thermal insulation is not discussed in this article, yet many passive strategies such as window orientation with respect to the sun, wind tunnels, chimneys, and natural and synthetic thermal insulation barriers might be used depending on the many possible weather patterns on the place where the dome is built.

Plaster general description:

The main additive of a general purpose superadobe plaster should be lime, as lime adheres well to different supports, is a natural and biological product, adapts to construction movements and prevents the appearance of cracks in the walls.

Also, during and after setting, lime mortars are permeable to water vapor yet impermeable to water. This way, they favor the evaporation of water contained in the walls that breathe.

Lime mortars are easily colored, which is also an aesthetic benefit. The impermeabilization mortar must be constituted by

a mixture of one or several binders (lime is most strongly recommended), sand, pure water and eventually other additives with thermal or other properties.

Description of three recommended plaster layers:

- ***The grout or first coat:***

Thickness of 1 to 5mm. To be used to "fill" all the slits between bag and bag: The channels between sack and sack provide good support for this first layer. The mixture should be composed of 4 measures of sand for 1 measure of lime. Cut or crushed straw can be introduced into the mixture to give more roughness to this first layer, for the next ones to hold onto better.

A mortar ball is grabbed with the hand and applied to the dome from bottom to top taking advantage of the cracks between sack and sack. It is important to work in discrete areas of the dome and finish, for example, 1.60m high throughout the perimeter of the dome, that is, the first layer must not be applied from the bottom of the dome up to its peak but rather in different phases: lower, middle and upper part of the dome.

The plaster may be applied with the trowel but it is very important not to "smooth" this layer, for its gripping surface should be rough, to facilitate the adhesion of the second layer (fig 25). **proponemos incorporar esta figura luego de la revisión).**

Hence, the mortar mixture that is used must have medium to thick sand. The optimum sand is quarry sand and has to be bought. It is possible to use the sand of the sack mixture or filter sand from the terrain, previously screening away the fine parts and impurities.

Finally, pressure is applied with the trowel, and a barbed brush or other abrasive tool is passed to generate furrows or patterns. We must wait for the plaster to lose water to "tighten", between 20 and 30 minutes depending on the weather. Water must be applied in the case of a sunny day. This tightening phase must be done once the layer acquires certain plasticity but has already begun to set (figure 25).

- ***The 2nd layer:***

Thickness of 15 to 20 mm. It ensures the waterproofing of the wall. Should be applied after seven days from setting of the previous layer for alternating dry and wet weather.

The wall is moistened previously on the cured last layer, and the second coating applied by projecting with the palette or throwing plaster balls against the dome.

The proportions are also 4 parts of sand by 1 part of lime. After the projection, a rule is passed over the wall. This layer must also be "tightened" with the trowel to eliminate the possibility of fissure generation. As in the first layer, this second one is to be expected to have plastic behavior. Apply water if it is necessary to tighten.

Finally, a toothed brush or a saw is passed to make patterns as in the first layer (figure 26) **(proponemos incorporar esta figura luego de la revisión).**

- ***The finishing layer:***

Thickness of 5 to 8 mm. It is used for decoration, also for protecting the wall and the two preceding layers. It is applied

on the body of the humidified second layer, after a minimum of 4 to 7 days since this second layer was applied (after 15 days if pure lime is to be used in this third coating, although the composition for this layer can also be 3 parts of fine sand per 1 part of lime).

After the projection is done throughout, the rule is passed, then pressure and work is applied to the drying mortar to obtain the finish wanted. This coating finish layer must be regularly "tight" with the use of a trowel.

In the smaller / more delicate areas such as arches of doors and / or windows, a metal spoon can be used to "tighten" the layer.

It is always important to wait for the plaster to lose water to be "tightened", between 20 and 30 minutes after initial contact with the dome depending on the weather conditions.

This last coat is naturally the most artistic of the three phases. We can customize the dome by drawing on the plaster while it is still fresh, or placing geometric shapes, stones, mosaics and / or ecological colors (figure 27) (*proponemos incorporar esta figura luego de la revisión*).

9) *Time and Cost:*

According to our experience, 40 m of foundation can be dug in three 8-hour days (for a straight walled regular adobe structure used for practice). As it was carried out by a team of 10 in this time frame, 40 m of foundation equates to 240 man hours. Hence, 0.17 m of foundation equates to one man hour. Similarly, 15 m of sack were laid per day on an average day on the domed structure. Since the team size was 10, 15m of sack equates to 80 man hours. Hence 0.1875 m of sack equate to one man hour.

A dome of internal base diameter of 4 m, vertical compass of 4.4 m length, base cylinder wall 0.5m high, sack width of 0.4 m and sack height of 0.2 m would have a total height of approx. 3.8 m, it would have some 36 m of foundation and roughly 250 m of sack, (having approx 20 m³ of earth and weighing 34 tons). It would need at least 1500 man hours of work: roughly 40 days of work carried out by a team of 5, working 8 hours a day.

An example budget of approx. \$2500 could be allocated on other documented projects[6]. The major costs involved include:

- Just over 20 cubic meters of sand, about \$250 .
- 30 cubic meters of building/plastering mix, \$750
- 10 tons of 20mm aggregate, \$250
- 1000m by 0.41m wide woven polypropylene: UV – stabilized, circular woven tube) \$600, which is about four times the length needed for two domes of this size (internal base diameter of 4 m, vertical compass of 4.4 m length, sack with of 0.4 m and a total height of building of about 3.5 m.)
- Earthworks \$300
- 2 rolls of high tensile barbed wire \$130
- Recycled windows \$85
- Materials for compass and tamper construction \$100 [6]

Another example of a dome project with a similar costs, carried out in Port-au-Prince, Haiti, is documented in [8].

10) *Conclusions:*

Although the following could be regarded as subjective, an important conclusion that I have drawn from the experience of building a Superadobe dome is that the method has the potential to bond the people who participate with one another. Teamwork and good faith was indeed the driving force behind the project: as is a tradition in many parts of rural Africa when a public building or the house of a member of a village is built or repaired, all members of a community work together regardless of who's home is it, or any other difference. This may have to do with the fact that satisfying a basic human need with one's own hands reminds of our fragility in life, as being there for one another makes us less fragile indeed.

Cities are overpopulated, and according to simple mathematical logic, they will become more overpopulated unless we look outside of cities to embody our compulsory population growth. At this growth rate, all construction companies working at full capacity could not satisfy the world's housing demands, so it makes sense to think of a modern world where families will be able to cover their housing needs for themselves, and Superadobe is in my opinion, an idoneous method to inspire this model.

We can imagine a sustainable model of population growth, where state and investors could provide with water, power, road and other basic infrastructure in areas outside of cities, and families themselves, including those with low income, with the use of earth, could take on the construction of the houses and community centers themselves, assuming the costs of labor in these spaces. This would dramatically lower project costs, and monthly payments to return the initial investment (public or private) would be lower than common mortgages of today. In such model, it is conceivable that investors will be able to achieve high interest rates on their investments in lower times.

Methods to safely build with one's own hands and low impact materials should exist and be constantly perfected, should be legalized, and what's more: encouraged, through such concerted projects between state, private entities and families, for the result of applying the technique described in this article is nothing less than an earthquake resistant house, with comparable functions of that of a counterpart apartment built in a conventional place, in a conventional way, costing 40 times more.

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