Report A3

Stabilised Soil Tanks for Rainwater Storage

Development Technology Unit

University of Warwick

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September 2000

This report is submitted as Milestone A5 under EU Contract ERB IC18 CT98 0276 : "Domestic Roofwater Harvesting in the Humid Tropics". That Milestone, under Task A – Technology, was originally to have been a report on the performance of underground tanks. Due to a re-sequencing of the research programme this Report A3 "Stabilised Soil Tanks for Rainwater Storage" has been substituted as the Milestone.

Contents

1. Introduction

The present cost of roofwater storage tanks is too high for many potential users. Warwick University, under an EU contract with three other partners, is investigating ways of reducing it within the specific context of the contract title above.

One cost-reduction strategy is to employ cheaper materials than hitherto. Soil ‘as dug’ is certainly cheaper than the metal, mortar or plastic commonly used for tank building. Stabilised soil *may* be cheaper provided not much stabilising additive is used. Although soil-based walling is widely used in housing, water tank walls pose special problems. They require of their materials two extra attributes, namely waterproofness and *tensile* strength that are only of minor importance in housing. Since soil is not impermeable and wet soil has no tensile strength, a process of material adaptation is required before soil can be recommended for tank construction.

Sections 2 to 4 of this paper review the various techniques of soil selection, stabilisation and construction. Section 4 addresses tank design using this material. Two promising technologies are identified, namely construction using stabilised soil blocks (SSB) and construction using stabilised or even unstabilised rammed earth (RE). Section 6 describes the theory, design, prototype manufacture and Ugandan field testing of SSB rainwater tanks. Section 7 covers the same sequence for RE tanks, but also includes the results of laboratory trials.

The paper finishes with conclusions and the identification of further work required to confirm the initial promise of SSB and RE construction. Four appendices cover cost comparisons, test data and detailed construction guidelines. (The guidelines are in the form of a free-standing Technical Release designed for use in mason training.)

Note on units: Both imperial (foot=0.3 m and inch=25 mm) and metric units are used in this report, reflecting the predominance of the former amongst builders in Equatorial countries and the greater ease of the latter for calculations.

2. Soil/earth building technology

Almost a third of the world’s population lives in unbaked earth housing. The technology used varies from country to country and region to region, and sometimes even from house to house. A wide variety of earth construction technologies are known to exist and a few are listed below.

- Adobe – sun-baked earth bricks
- Wattle and daub – a wooden lattice with daubed earth in-fill
- Compressed earth blocks – using a ram (of which there are many designs)
- Direct shaping – hand shaped earth
- Cob – coarse fibre reinforced balls of earth stacked and compacted lightly
- Dug-out – dwellings excavated from earth
- Rammed earth – earth compacted between shutters with a tamper

Of these seven variants, only two appear at all suitable for constructing (above-ground) tanks, namely stabilised soil blocks and rammed earth.

Figure 2.1 Buildings (a clinic and a latrine under construction) made from stabilised soil blocks in Tanzania

All the technologies mentioned above are ancient techniques that have been passed on from generation to generation. Many have only lost favour within the last century with the advent of modern building materials, particularly brick, cement and steel. They are still used widely in many developing countries where cement is prohibitively expensive for the poorer sections of society (see the map in Figure 2.2). In some cases cement is used in small quantities to ‘stabilise’ the earth, giving extra strength and impermeability. Earth building technology is seeing something of a revival in the West amongst groups keen to maintain traditional techniques and those who appreciate the superior properties of earth as a building material e.g. its thermal, aesthetic, environmental and cost advantages. Improved techniques have been developed by architects and engineers over the years.

Stabilised soil block (SSB) technology that has received a great deal of attention over the last few decades and is now seen as a mature technology with a good future in the building industry world-wide. It is a technology particularly suited to drier climates, although it is practised in many humid areas. Suitable earth is mixed with a small percentage (typically 5 – 10%) of cement and is compacted using a manual or hydraulically assisted ram or press (Figure 2.3). The compaction process can be static (slow squeezing) or dynamic (impactive), but the static process is more common.

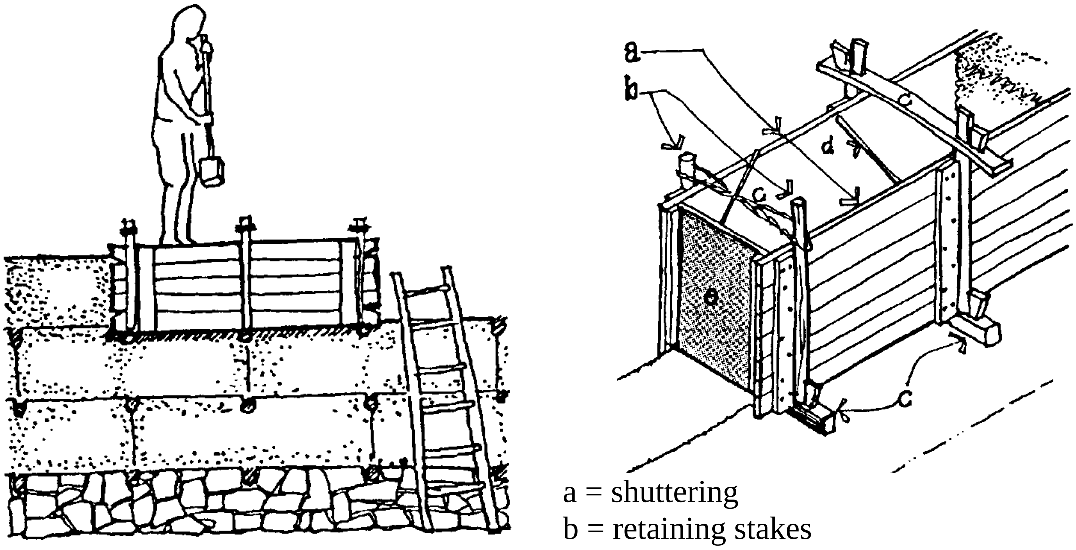
Static compaction pressure ranges from 2 MPa in manual lever machines up to 10MPa or more in machines with hydraulic assistance.

Figure 2.2 Map of the world showing areas where earth construction technologies are, or have been, widely used

Figure 2.3 A CinvaRam press being used to produce stabilised soil blocks in Africa

Rammed earth (RE) is a technique whereby earth is rammed, using a rammer or tamp, between two shutters. The shuttering is removed to reveal the wall, usually constructed in sections of a few feet long by a foot or two deep. The shuttering is then moved along and the next section of wall is rammed to form a continuous wall. The shuttering is then raised and placed on top of the first ‘lift’ to construct the subsequent ‘lifts’ (see Figure 2.4). Unlike SSB production, the RE wall is built in situ. Wall thickness for a typical two-storey house is in the region of 12 to 24 inches. Curved walls of rammed earth are not common, but are found occasionally where the technique is more developed. The curved sections are usually for decorative purposes.

Typically rammed earth has been used for the construction of housing. The technique has been used to successfully construct buildings of several stories that have lasted for centuries.



a = shuttering
b = retaining stakes

Figure 2.4 (i) rammed earth as practised in Morocco and (ii) basic elements of formwork or shuttering (from Norton[1997])

3. Soils - identification, classification and testing (field and laboratory methods)

3.1. Characteristics of soils

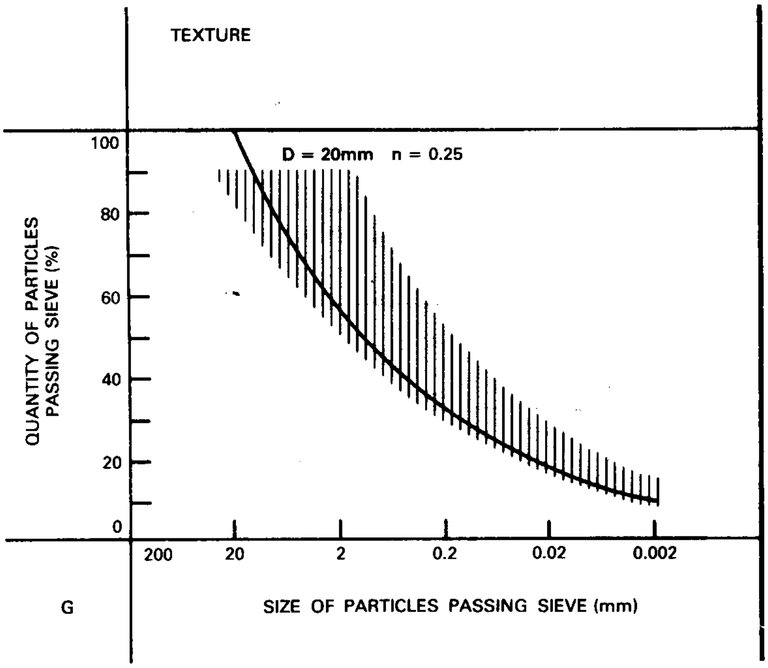
Not all soils are suitable for construction and methods have been developed for identifying those that are. For rammed earth (RE) construction a soil should be a mix of fine gravel, sand and silt with a small clay content. There should be no organic material present. Soil for stabilised soil block (SSB) construction needs to be of a higher fines content. However the actual soil used for either technique varies widely. Norton [1997] suggests the figures shown in Table 1 as suitable for rammed earth construction. The clay content should be sufficient to allow the soil to bind without causing excessive shrinkage. Soil varies widely in quality and content and so experimentation is required to find a suitable soil.

Table 3.1 – showing suitable values for soil particle distribution for rammed earth structures (Norton[1997])

Sand / fine gravel	45 – 75%
Fine sand / silt	15 – 30%
Clay	10 – 25%

Soil is generally characterised by 4 fundamental properties: texture, plasticity, compactibility and cohesion. These properties are described briefly below.

Determining the soil texture involves passing the material through a series of standard sieves and observing the fraction retained by each sieve, thus determining the grain size distribution. Further analysis is usually required to determine the fines content i.e. the make-up of the silt and clay passing through the finest practical (0.063 mm) sieve. Graph 3.1 shows the acceptable range for soil that is to be used for rammed earth structures. The ASTM-AFNOR standards and the decimal system standard for grain size distribution can be found on page 32 of Houben [1989].



Graph 3.1 Showing the acceptable particle distribution for a soil used for Rammed Earth construction (Houben [1989])

The Plasticity Index (PI) is an indicator of the plasticity of the soil. The PI is a function of the Liquid Limit (LL) and the Plastic Limit (PL) of the soil (together known as the Atterburg limits) and is a measure of the likelihood of the material to deform. LL is the % of water in a soil when it is changing from being ‘plastic’ to being ‘liquid’. PL is the water % at the boundary between solid and plastic behaviour. Numerically PI = LL – PL. There are agreed definitions of these transition points. Figure 3.1 shows on an Atterburg limits chart the type of stabiliser to be used with any particular soil.

The **compactability** of a soil defines its ability to be compacted to a maximum for a given compaction energy and degree of humidity {Houben 1994}. The compactability of a soil is measured by the Proctor compaction test (see Section 3.3).

Cohesion is a measure of the ability of a rammed soil to remain together when under tensile load. Cohesion is a function of the moisture content and the clay content (or other cementitious material) of the soil. Cohesion is higher when the moisture content is less than the PL. Cohesion increases with clay content, but so unfortunately does shrinkage.

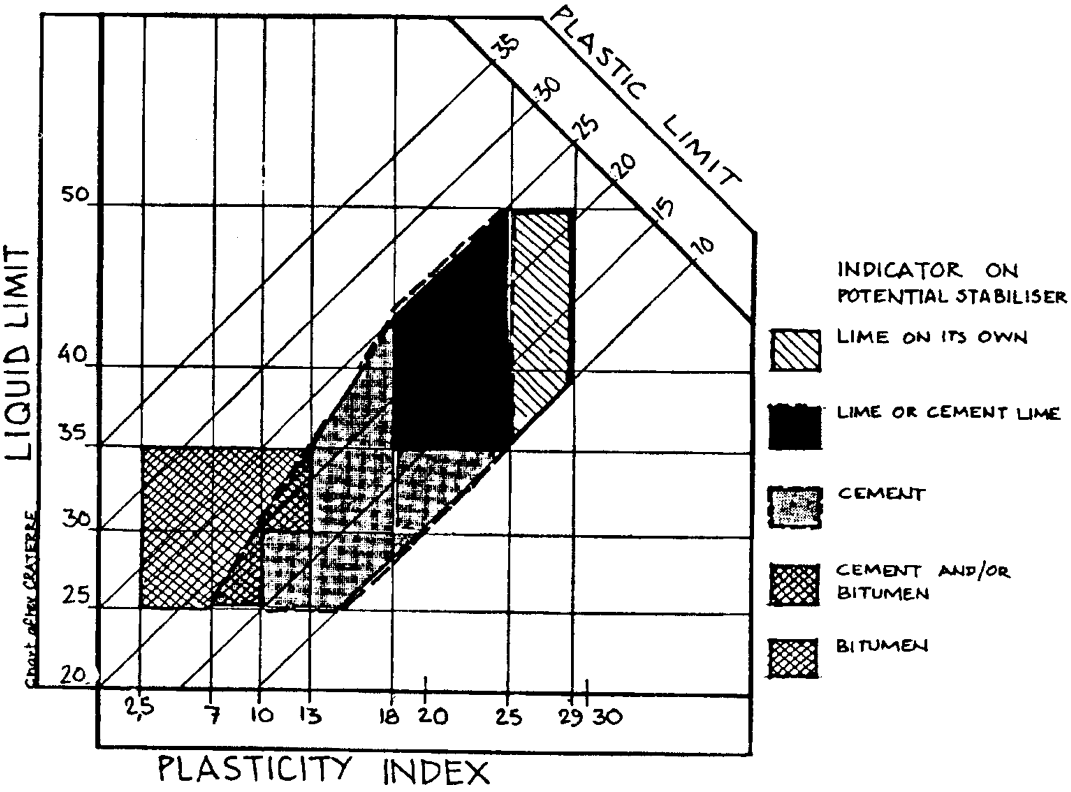


Figure 3.1 – The Atterburg limits chart (Norton[1997])

3.2. Soil suitable for rammed earth structures

A sieve analysis should indicate the ranges shown in Table 3.1 if a soil is to be used for earth construction.

Soil for use with rammed earth structures should be humid, i.e. not too dry and not too plastic, say in the region of 4% to 15% moisture content. The optimum moisture content (OMC) is defined later in this document and a method shown for determination of OMC.

3.3. Soil identification and classification

The suitability of a soil for building with is often established via three sorts of test – field tests, laboratory tests and construction trials.

Field tests

These are cheapest and come first. There are numerous initial sensory observations that can be made to help classify the soil in the field. These include:

- visual and tactile observation to analyse particle distribution
- sedimentation test to give more detailed particle distribution
- there are a number of tests to gauge (very roughly) clay content, including a simple test whereby a roll of clay is pushed over the edge of a table until it breaks - the length of the broken part gives an indication of the clay content
- drop test to determine optimum water content
- the smell of soil can sometimes give an indication of the presence of organic matter

More detail on these tests can be found in the relevant literature, especially Keable[1996], (Rammed Earth Structures – A Code of Practice).

Laboratory tests.
British Standard BS 1377 and corresponding standards in other countries cover the tests suitable for soils used in construction work. The tests are used to determine the main characteristics and suitability of the soil in question, as well as to give an initial idea of the performance of the material. The main tests that are used are described very briefly below:

A *'classification test'* is performed to determine the particle distribution of the soil. The test is carried out by passing the soil through a set of standard sieves (Figure 3.2). Material passing through the smallest sieve in the set is deemed to be a mix of clay and silt: these two components cannot be separated by further sieving.

Figure 3.2 – Wet sieving is the standard soil classification method

To determine the *'clay to silt ratio'*, the fraction of the soil passing through the last (0.063 mm) sieve is analysed using a hydrometer. The specific gravity of the liquid with its suspended particles, indicates its clay content. An alternative simpler test takes advantage of their different sedimentation rates to distinguish between clay and silt.

The compaction of a soil is dependent upon its moisture content. A *'compaction test'* is used to determine the maximum density of the material and the moisture content at which it occurs – called the optimum moisture content OMC. At maximum density the compressive strength of the soil will be greatest. To find the OMC a test is carried out using a simple compaction apparatus (see Proctor compaction test in Box 3.1) to compact a number of samples with different moisture contents. The samples are weighed and measured. The dry weight is then found after drying the compacted sample in an oven and the OMC is that moisture content which has produced the sample of greatest density.

Box 3.1 BS Ordinary Test (or the Proctor test) for compaction

This test uses a 2.5kg metal rammer with a 50mm diameter face that falls into a cylindrical mould of 105mm diameter. The drop height is kept at a constant 300mm to ensure consistent energy transfer between blows. The blows follow a pattern over the face of the sample to ensure repeatability and consistent compaction of the entire sample. Each sample made up of three layers of soil that has passed through a 20mm sieve and each layer is given 27 blows of the rammer. After compaction the sample is trimmed off to a set height that gives a constant volume of 1000cm³. This is then weighed and the density can be calculated.

In the previous section we touched briefly on the consequences of shrinkage. The *‘shrinkage box test’* measures this property and is simple to carry out. It involves measuring the shrinkage of a sample that is allowed to dry naturally over a period of 14 days. In practice, if the walls of a tank are constrained, say at the base, then cracking will take place if shrinkage is significant. Conversely, where a tank’s cylindrical wall is free to shrink without constraint no cracking will take place. If shrinkage is found to be too great, due to an excess of clay, the soil will have to be either modified or rejected.

‘Liquid and plastic limit tests’ can be carried out either in the field, although it is preferably to perform them in a laboratory. Some equipment is needed. See section 3.1 for more detail.
A *‘normal moisture content test’* is used to determine the normal moisture content of the material to be used. An oven and accurate scales is required.
To measure the rate at which water passes through a material requires a *‘permeability test’*. Sophisticated equipment is required.
For many applications of rammed earth walls (i.e. housing and larger buildings), it is the compressive strength that should be maximised, so *‘compressive strength tests’* are commonly applied to the material. *Wet* compressive strength, which is invariably less than *dry* compressive strength, is most commonly measured. Unfortunately little consideration is given to the *tensile* strength of the material which concerns us more in water tank design. Confusingly we have four possible strength measures: *dry compressive, wet compressive, dry tensile* and *wet tensile.*

Although Houben and Guillaud [1989] indicate reasonably good values for dry tensile strength of rammed earth (0.5 –1 MPa), little work has been directed at further increasing its value. For the application being considered here, the tensile strength of the material is of paramount importance. The OMC considered earlier is the moisture content that will optimise dry density (we could call this the DOMC , after Montgomery [1999]), and hence compressive strength. It is unclear to the author if this DOMC can be used to optimise dry tensile strength. Further investigation is required to find the water content to maximise dry tensile strength, which we could call the Tensile OMC (or TOMC). We then need to consider the wet tensile strength of the materials as this has great implications on the design of tanks to hold water.

Performance tests.
Even where we have applied field and laboratory tests to the raw material (soil) or to specimens prepared from it, it is still desirable to test samples of the walling during construction. In this way we can pick up not only soil variations but also imperfections in the construction process (such a deviations from intended proportions or procedures). These performance tests are usually applied either to samples drawn from batches in the construction process (e.g. every 50th block made) or to specimens sawn out of larger components.

Some of the tests that may be applied are:

- Wet and dry compressive strength
- Wet and dry tensile strength (modulus of rupture)
- Wet and dry bending strength
- Permeability
- Adhesion of render to walls

More details is available in the literature – see Houben

3.4. Calculating the quantity of soil required for a tank

The quantity of soil required for tank construction is calculated below. The quantity of soil required for tank construction is based on tank size, wall thickness and the density of the compacted material.

Weight of soil required $W = \pi (r_o^2 - r_i^2) H \times \rho_c$ (equation 2.1)

where
r_o = external radius of tank
r_I = internal radius of tank
H = height of tank
ρ_c = density of compacted material

For laboratory and development tests approximately 150 kg of soil is required.

4. Stabilisation of soils – methods for improving soil characteristics

Frequently one finds that the most readily available soil is not suitable for construction purposes. In such cases the main options are to

- bring in a suitable soil from elsewhere
- blend together different local soils
- add some sort of stabiliser.

Which option is chosen will usually depend upon their relative costs. However if wet strength is required, no natural soil is adequate and stabilisation (e.g. addition of cement) is essential. The physical characteristics of soil can be improved in a number of ways. Usually, the main reason to improve soil is either to obtain a suitable physical grading for a poor soil or to improve some other physical characteristic such as the strength, stability or water resistance of the soil.

Soil suitable for soil construction should be well graded with a suitable content of fines and larger particles (see Table 3.1). For raw soil, this is often not the case and soils have to be modified such that their grading is suitable for use. This will involve adding a material that is lacking in the raw material, removing unwanted particles by sieving or mixing a number of soils to obtain a suitable blend.

4.1. Additives and composite materials

A large number of additives and composites are available for adding to rammed earth. Their purpose is improve the properties of the material in one of a number of ways: *Chemical stabilisers* are added to the soil to bind or alter the grain distribution characteristics of the soil and hence improve its cohesion and stability. Common stabilisers include cement and lime, which are added in small quantities, say up to 10%, and can improve material strength and stability several fold. There is a wide range of synthetic additives available from specialist suppliers in some countries (Texas, USA is a good example, where earth building is a commonly practised building technique). They are not, however, generally available in developing countries and so we will not consider them in this work.

Waterproofing agents are available that reduce the permeability of soil structures. A commonly used water repellent is bitumen, which is mixed with the soil in an emulsion form. The emulsion is made using a solvent such as gasoline or kerosene diluted sufficiently to be mixed with the soil (Norton[1997]). Many synthetic waterproofing additives are available. Most earth walls, bearing in mind that such walls are used for buildings, are given a waterproof render, or a sacrificial coating. Renders and linings will be discussed later in the document.

Fibres can be added to increase the tensile strength of the material and help prevent cracking during the curing process. Straw is a common fibre additive and it also helps to reduce the weight of the material. Unfortunately it is only durable in permanently dry conditions.

Reinforcement is widely used to create a composite in which the matrix (e.g. soil) provides some properties and the reinforcement (e.g. steel wire or polypropylene or hessian rope) provides much of the tensile strength.

Box 4.1 Discussion of the effects of soil shrinkage on tank design, and design implications.

Upon drying a rammed earth wall will shrink as the moisture is drawn out of the structure and the clay, which is expansive (different clays having differing degrees of expansivity), shrinks. If the structure is constrained in any way, say for example, at the base of the tank, then this could result in cracking. For an unreinforced tank such cracking would seriously reduce tensile strength and could cause sudden and catastrophic failure of the structure. This needs to be considered when determining the OMC (or TOMC) and the author suggests that this area of rammed earth tank design needs further work at present. It is for this reason that some form of reinforcing could be used to give additional tensile (hoop) strength to the structure. Possible forms of reinforcement include:

- Externally applied steel packaging strap (as demonstrated by the author {Rees, 1999} on single skin brick tanks)
- Hoop wire rammed into the structure – ideally barbed wire would be used as it is cheap, strong and the barbs offer resistance to 'pull-through'.
- Fibre such as straw or short lengths of polypropylene rope can offer localised strengthening

Box 4.2 Stabilisation of soils (Montgomery[1999])

Stabilisation techniques can be broken down into three categories, Houben (1994): Mechanical, Physical and Chemical. Mechanical stabilisation compacts the soil, changing its density, mechanical strength, compressibility, permeability and porosity. Physical stabilisation changes the properties of the soil by acting on its texture, this can be done by: controlling the mixture of different grain fractions, heat treatment, drying or freezing and electrical treatment. Chemical stabilisation changes the properties of the soil by adding other materials or chemicals. This happens either by a physico-chemical reaction between the grains and the materials or added product, or by creating a matrix which binds or coats the grains.

Stabilisation fulfils a number of objectives that are necessary to achieve a lasting structure from locally available soil. Some of these are: better mechanical characteristics (leading to better wet and dry compressive strength), better cohesion between particles (reducing porosity which reduces changes in volume due to moisture fluctuations), and improved resistance to wind and rain erosion. Using one or more of the stabilisation techniques listed above, many of these objectives may be fulfilled. Optimum methods depend greatly on the type of soil, and a careful study of the local soil is necessary to suggest an effective method of stabilisation. In the case of mechanical stabilisation, the soil is compacted to a greater density, and there will always be an improvement in its mechanical properties with virtually any soil type. This is not true however with other forms of stabilisation, where different soil mixtures can lead to better or worse properties using the same technique. In the majority of cases mechanical stabilisation is used in conjunction with a common chemical stabiliser, such as cement. If the stabiliser and the soil are mixed together thoroughly and there is a suitable clay fraction in the soil, the compaction process reduces the quantity of chemical stabiliser required in the block. The increased density also increases the effectiveness of the cement matrix, given that the cement is left in a moist environment (the hydration period to let the cement cure) for at least 7-14 days. For details on selection of soils for cement stabilisation see Gooding (1993 - B).More details on the process of cement stabilisation can be found in Houben & Guillaud (1994) and Spence (1983).
(Source: Montgomery, David, http//:www.eng.warwick.ac.uk/DTU/buildingmaterials/index.html, 1999)

5. Tank design using stabilised soils

It is certainly inconvenient, and it can be dangerous, for a water tank to fail (because at some point in it the local stresses exceed that which the tank material can bear). We therefore need to be able to calculate the size and location of the peak stresses. Unlike other areas of structural design, stretching does not need to worry us much unless it is severe enough to cause the cracking of a superficial waterproof coat.

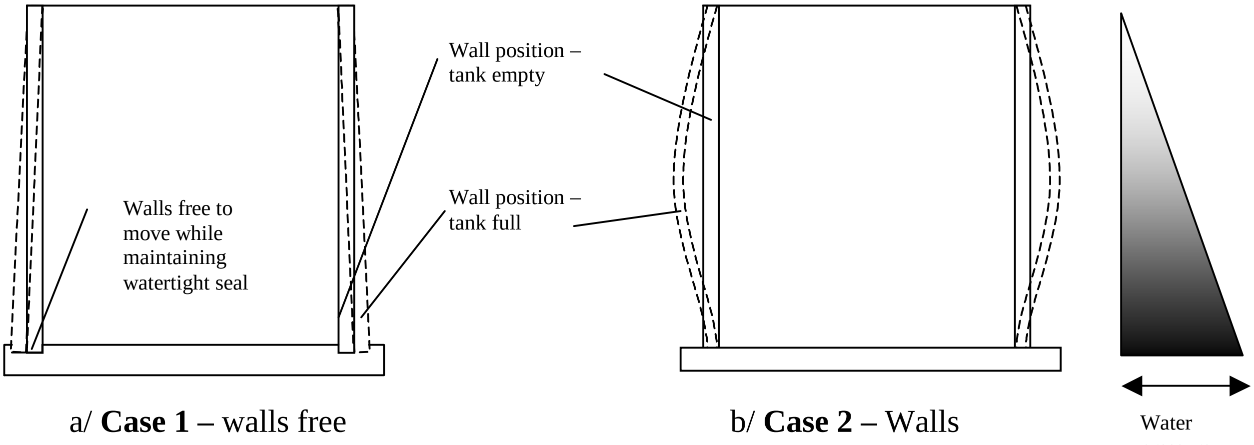
Our general design objective is to produce a safe watertight tank. This we can do either by using a single walling material that is both strong (in tension) and waterproof or by combining a strong material with a waterproof one. A wall of unstabilised soil is not waterproof and (when wet) doesn't have any tensile strength either. We therefore have either to stabilise it or to keep it dry by applying a waterproof skin to its inside face. In the latter case we must allow for the possibility that the skin will be punctured during the life of the tank – including some sort of reinforcing that may not save the tank but will prevent it bursting suddenly and dangerously.

5.1. The theory of stresses in cylindrical tanks

Tall cylindrical tank walls experience a horizontal tensile 'hoop stress' which is proportional to the diameter *D* of the tank, the local pressure *p* on the walls of the tank and the thickness of the tank wall *t* (Equation 5.1). As *p* increases towards the bottom of the walls, so too does the hoop stress.

$$\sigma_t = \frac{pD}{2t} \qquad \text{(Equation 5.1)}$$

However the stress in a cylindrical tank wall near to its base is also be affected by the type of joint between the tank base and tank wall. There are two obvious cases to consider as illustrated in Figure 5.1 below. In Case 1, the tank wall is made so that is free to move slightly at its base and yet still maintain a watertight seal. The water pressure against the wall will cause the diameter of the tank to increase until the hoop stress is wholly taken up by tensile stretching of the wall. (In the figure the increase in diameter is exaggerated here for clarity: in practice it might be less than 1 mm). The maximum hoop stress will be experienced at the base of the wall and will decrease linearly with height to zero at the top of the wall.



a/ **Case 1** – walls free to move relative to base

b/ **Case 2** – Walls joined to base

Figure 5.1 – The two cases for wall-to-base union in cylindrical tanks

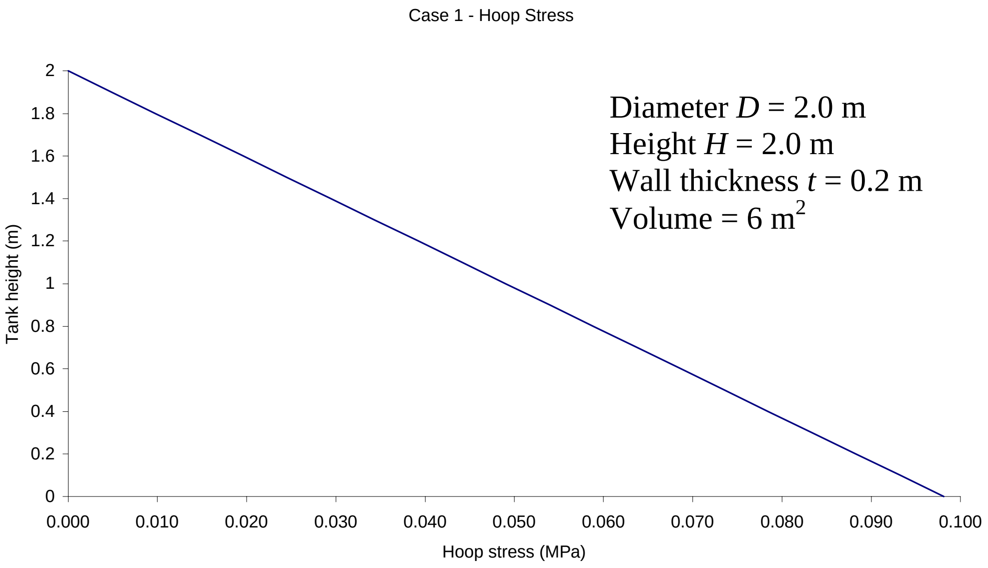


Figure 5.2 – Hoop stress in the tank wall for Case 1 (i.e. wall and base separate)

In Case 2, where the wall and base are monolithic i.e. the wall and base are continuous (and the base is assumed to be rigid), the situation becomes more complex. Bending and shear stresses are set up in the wall as a result of the restraining effect of the base slab. There now exists a combination of bending, shear and hoop stresses. The lower part of the wall is now constrained and is not free to move as in Case 1. The result is that a bending moment is generated in the wall that is a maximum at the joint of the wall and the base. This bending moment sets up vertical tensile stresses on the inner face of the wall of the tank that can be more than twice the magnitude of the horizontal hoop forces. Shear forces are also generated although these can generally be neglected as they are small in comparison the other induced forces. This is illustrated graphically in Figure 5.2

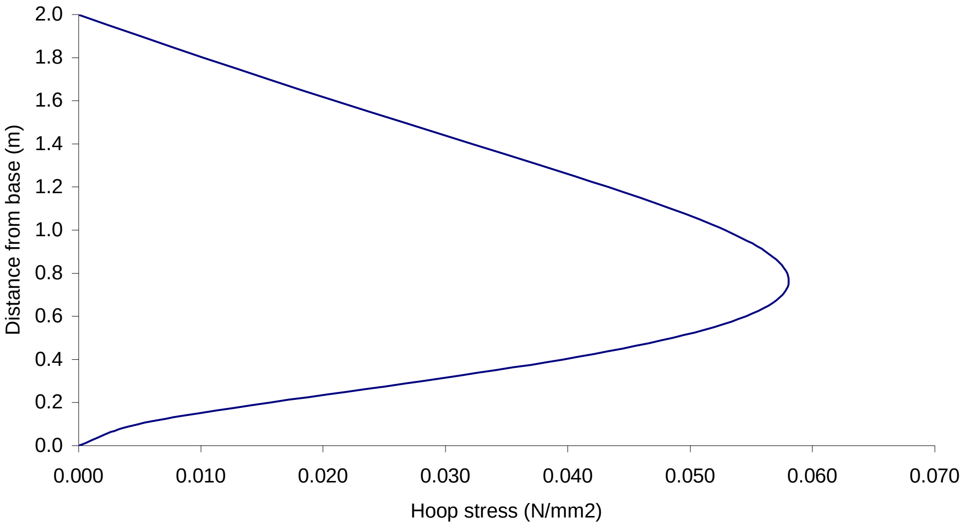


Figure 5.3 – Hoop stress for Case 2 (i.e. wall and base monolithic)
(*D*, *H* and *t* as in Figure 5.2)

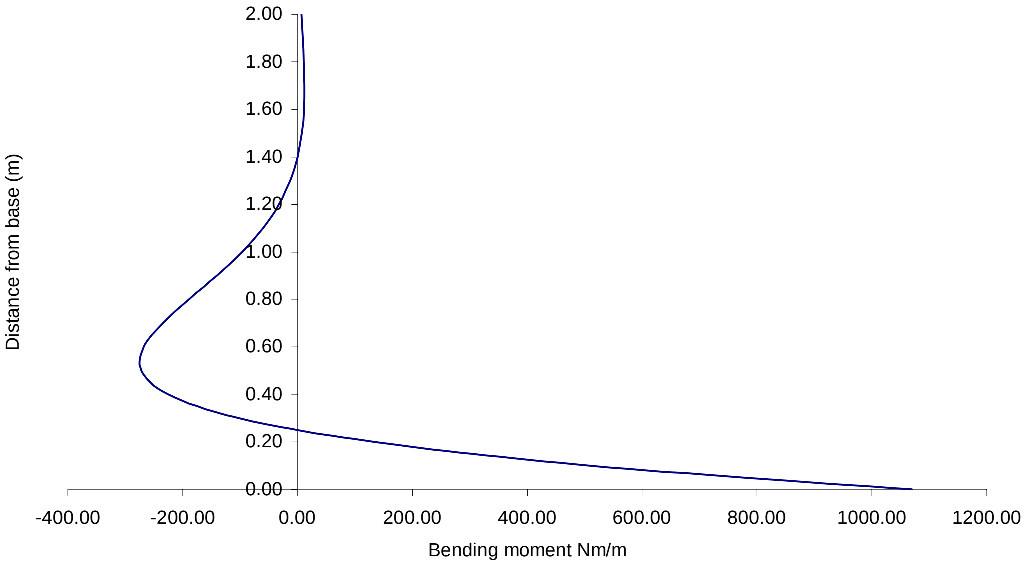


Figure 5.4 – Bending moment induced in tank wall for Case 2 (*D*, *H* and *t* as in Figure 5.2)

In Figure 5.2 we see that for Case 1 the hoop stress increases linearly from zero at the top of the tank wall to a maximum of 0.098 MPa at the base/ wall joint

In Figure 5.3 we see that for that Case 2 the hoop stress is a maximum of 0.058 MPa – less than in Case 1 – and occurs at 0.8m from the base (i.e. 0.4*H*). The hoop stress then drops off to zero at the base where the strain is zero. In Figure 5.4 we see the effect of the rigid constraint on the bending moment that is now induced in the wall. The maximum vertical tensile stress in the bottom of the inner face of the tank wall in Case 2 is 0.16 MPa, considerably more than the maximum hoop stress in either Case 1 or Case 2. So the tank is now vulnerable to cracking at the wall-base joint.

5.2. Conclusions from Section 5.1 and implied design considerations when using soil as a building material

Note:
Case 1 - wall is free to move at base (flexible joint)
Case 2 - wall and base are continuous (monolithic joint)
(assuming rigid base in both cases)

Table 5.1 Summary of conclusions from Section 5.1 and resulting design implications

Conclusions from Section 5.1	**Design Implication**
In Case 2 a bending moment is set up in the wall due to the constraint at the base of the tank. This is a maximum at the joint of the wall and the base and causes vertical stresses whose size is more than twice the maximum hoop stress. No bending moment is induced in Case 1.	Sliding base / wall joint are preferable to avoid complex stress regimes in the tank walls (see Box 4.1 below). These are difficult to achieve in practice.

The vertical stress cause by bending is very sensitive to changes in wall thickness as it is proportional to $1/t^2$; thus halving wall thickness will multiply stress by four. The hoop stress is only proportional to $1/t$.	Where a monolithic base / wall joint is used it is wise to use a good safety factor when considering wall thickness or to thicken the wall near the joint.
The maximum hoop stress for Case 2 is always less than that of Case 1 (for an identical tank profile) and is experienced at some point above the joint of the base and wall, typically 0.3H to 0.6H, but lower for very thin walled tanks.	Do not design the wall thickness to decrease with height in the case of monolithic tanks.
For a tank of identical profile, the maximum bending moment set up in Case 2 will be of greater magnitude than the hoop stress set up in Case 1 or Case 2 (see Figure 5.5).	A greater wall thickness is required for Case 2 than for Case 1. This implies more material usage and hence higher cost. On this point, it is worth bearing in mind that many materials will have a greater tensile strength than bending strength and so the problem will be compounded.
Deflection is greater for Case 1, as there is no constraint at the base to restrict movement of the wall.	Strengthening at the base can help reduce deflection for Case 1. This is important where renders are used to help prevent cracking due to excessive strain.

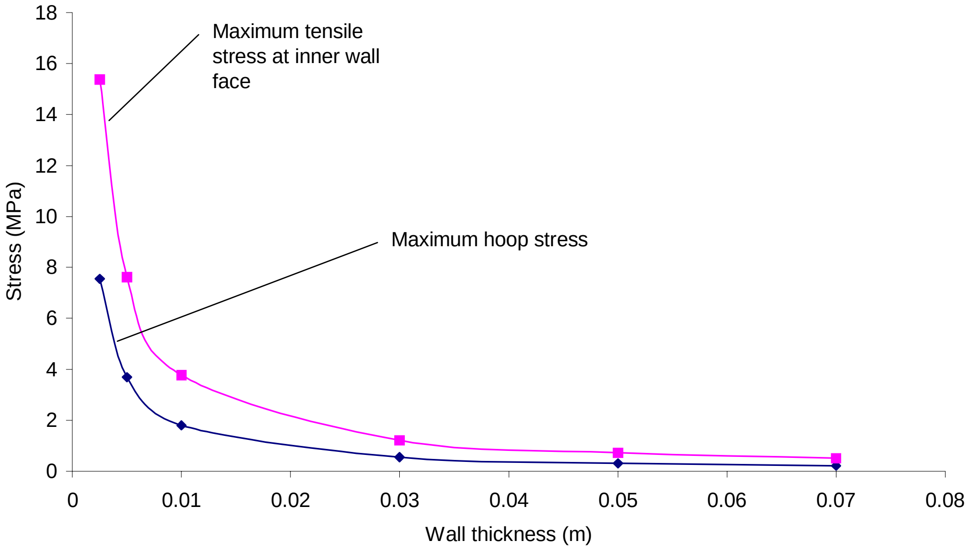


Figure 5.5 – The graph shows the relationship between hoop stress, maximum tensile stress due to bending and wall thickness. (*H* and *D* as for Figure 5.2) Note the significantly higher values for bending-induced tensile stress.

Box 5.1 Sliding / flexible base wall joints

Sliding of flexible joints between the wall and the base of a tank are common for large concrete storage. The reduction in stresses by using such a joint is well documented and the subsequent savings in materials well recognised. Such joints, in concrete structures, are usually effected using a bitumen layer between the base and the wall. The degree of movement in the wall is very small and the flexibility of the bitumen allows sufficient movement while maintaining impermeability.

The technique developed at the University of Warwick for work with soil tanks has been to lay two layers of polythene sheet beneath the wall of the tank. The sheets can have a smear of grease to help them slide across on another. The effect is to produce a 'sliding' joint that allows the wall and the base to act independently which, as pointed out in earlier, reduces stresses, simplifies tank design and leads to lower costs.

5.3. Spreadsheet design for rammed earth tanks

A spreadsheet has been developed at Warwick (Turner 1999) for aiding the design of cylindrical tanks. The spreadsheet allows the main variables to be entered and gives output in terms of design parameters. The main variables are tank diameter, tank height, material properties (or relative volumes in the case of composites), required safety factor and wall thickness. The outputs are given for both a tank with monolithic base and wall, and for a tank with separate base and wall. The outputs include maximum hoop stress, maximum bending moment, maximum deflection, maximum tensile stress on inside face of tank wall, maximum shear stress, tank volume and overall tank diameter. The spreadsheet allows the designer to play with the parameters until a satisfactory design solution is reached. Table 5.2 shows the general layout of the spreadsheet. The spreadsheet was used to design both the laboratory experimental tank and the field experimental tanks described and discussed in Section 7.

Table 5.2 Showing the input and output cells of the spreadsheet developed at Warwick to aid design of cylindrical tanks.

Data input section -
click on boxes for data input instructions

Parameter		**Value**	**Unit**
E (matrix)	e.g. soil	700	MPa
E (fibre)	e.g. steel	2.1E+5	MPa
po(matrix)		0.5	Poisson's ratio
po(fibre)		0.1	Poisson's ratio
thickness		0.20	m
tank rad		1	m
height		2	m
Vol. Fraction of fibre		0	0 – 1
po(total)		0.5	
E(total)		700	MPa
Volume		6.283	cubic metres

Output cells –for a Rammed Earth tank The output here is for a tank monolithic with base		
Tensile strength (of soil)	0.50	MPa
Safety factor required	4.00	
So design stress is	0.1250	MPa
Maximum hoop stress generated	0.0579	MPa
Position of max hoop force		m from base
Maximum bending moment	1069	Nm (always at base)
Maximum deflection	0.0033	mm
Position of maximum deflection		m from base
Maximum tensile stress on inner face of wall	0.16037	MPa (always at base)
Maximum shear stress	0.00021	MPa
Overall tank diameter	2.4	m

Output here is for tank wall unconstrained at base		
Tensile strength	0.50	MPa
Safety factor required	4.00	
Design stress	0.1250	MPa
Maximum hoop stress generated	0.098	MPa
Maximum deflection	0.1401	mm
No bending moment generated		

5.4. Construction principles when building with earth

There are several basic rules to follow when building with earth:

- The wall should be well protected from damp or wetness. Wet earth has less strength than dry and unstabilised earth will quickly become a mess of mud should it become saturated.
- Good foundations are used to protect the base of the wall from rising damp and often the first foot or two of wall above the foundation will be from stone or other impermeable material.
- Where a roof is fitted, the wall can be protected by using large overhanging eaves to prevent rain from hitting the wall directly.
- Renders or other coatings help to protect the wall from rain also. Practitioners colloquially use the phrase “good hat and boots” to describe the protection required – an overcoat doesn’t go amiss either!

The benefits of using earth as the construction material are numerous:

- low material cost (see cost comparison with ferrocement in Section 8)
- suitable material readily accessible locally in many parts of the world
- a well-known and widely-used technology in many parts of the world
- a simple technology that is easily taught to semi-skilled people

The drawbacks of using earth for tank construction are:

- not suitable for below-ground tanks or cisterns
- in the case of leaks serious problems can develop, especially if unstabilised earth is used
- high labour input – a problem where labour costs are higher

6. Stabilised soil block (SSB) tanks

6.1. Introduction

The work carried out on Stabilised Soil Block (SSB) tanks has been done in conjunction with Dr Moses Musaazi, a lecturer at Makerere University, Kampala and private entrepreneur working in the construction industry. Dr Musaazi also directs the Gatsby Trust in Uganda whose aim is to promote small-scale private enterprise through training. He has been working with SSB's for some time, both for low-cost housing and also for the construction of small too medium sized domestic rainwater storage tanks. Warwick University approached Mr Musaazi with the aim of working together to test the strength of the SSB tanks through practical experimentation.

A full report of the work that has been completed by Dr Musaazi is found in Appendix II.

6.2. The basic principles of SSB manufacture and construction

Stabilised, compacted, soil block technology is mature and widely used throughout the world. It involves compacting a suitable soil, which is often mixed with a small percentage (typically 5 – 10%) of cement, using a manual or hydraulically assisted ram or press. The compaction process can be static or dynamic, but the static process is most common. Static compaction pressure ranges from 2MPa (manual) up to 10MPa or more (hydraulic). This compaction reduces the voids in the material and hence it susceptibility to attack from water. Figure 2.3 shows a CinvaRam press being used on a building programme in Tanzania. Figure 6.1 shows some common press types.

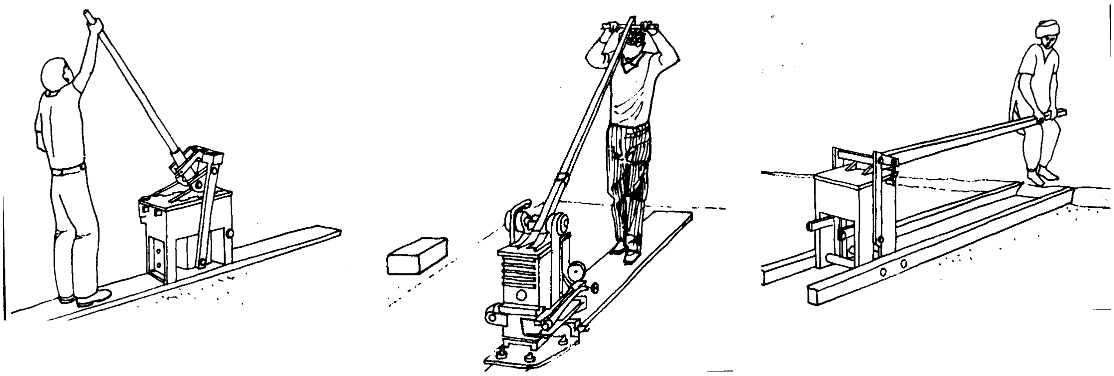


Figure 6.1 – A small selection of the many press types available for purchase (Houben^{1994})

Special moulds can be manufactured to produce blocks required for special purposes. In the case of the cylindrical tanks manufactured in Uganda, curved blocks were produced using the mould shown in Figure 6.2.

(**Figure 6.2** – Mould for producing curved blocks)

(**Figure 6.3** – Curved blocks after curing)

For information about tank linings and water extraction for SSB tanks see Section 7.2. These principles are the same for RE and SSB tanks.

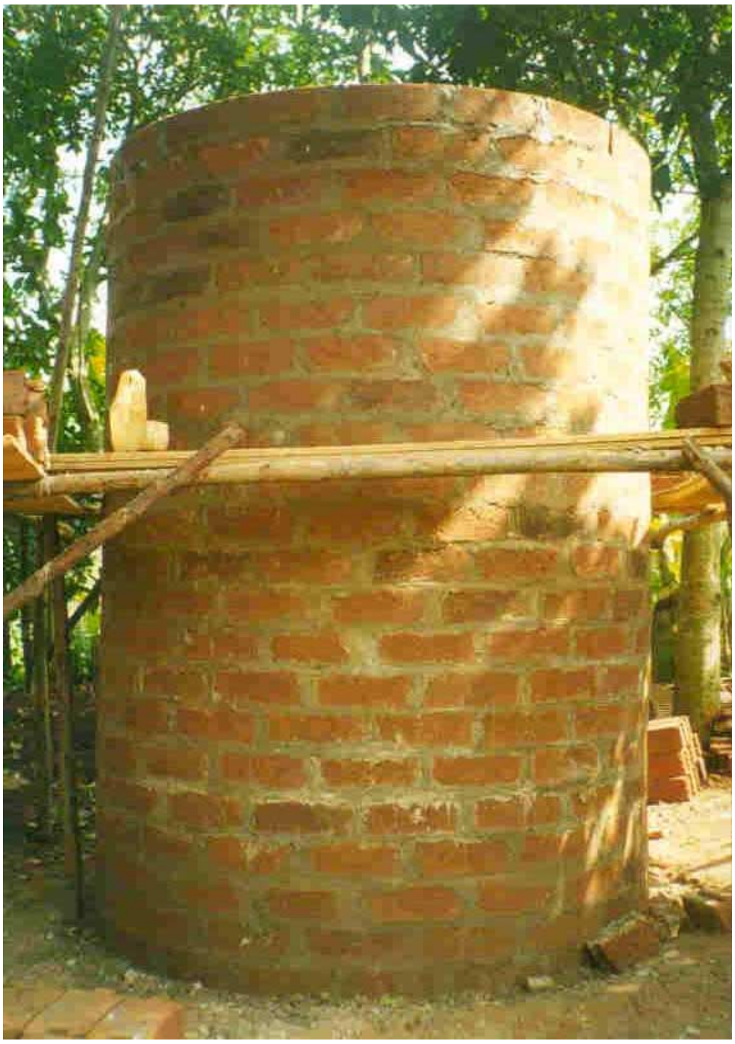
6.3. Field testing of SSB tanks in Uganda

Tests on SSB tanks started in March 2000 in Kampala. A small cylindrical tank (1.0m internal diameter, 2.1m height) was built and an attempt made to fit sealed covers to it. The tank was to have been pressurised by means of a header pipe fitted to the cover, however this proved impractical so it was simply subjected to the pressure (21 kPa) derived from its own height. The materials used are specified in the report in Appendix II. The soil used was stabilised with 5.25% OPC.

The experimental method was changed for subsequent tests and two tanks were built of the same curved end-interlocked SSBs. No reinforcing was included, but the tanks were rendered inside with a waterproof mortar. Details are:

Tank diameter (internal) in m	Tank Height in m	Code	% cement
1.67	3.8	SST1	5.25
1.00	5.2	SST2	3.27

SST1 was tested in July 2000 and failed dramatically when only part full. SST2 is still under test.



(**Figure 6.4** – A SSB tank of 1.67m diameter)

SST1, according to theory and using the *dry* tensile strength for the blocks from the literature, should have been able to withstand about 5 times the stress induced by the water pressure at which it burst (at 2.5m water pressure). There were, however, some irregularities:

- Some of the blocks analysed after the experiment seemed to have no wet strength and disintegrated completely in water.
- The tank was filled from a large water tanker. The waterproofing agent that was used in the cement render lining takes time to act and so water would have been passing through the tank lining and into the soil matrix. This would have reduced the strength to somewhere below the dry strength quoted in the literature.

SST2 by contrast was filled slowly by rainwater from a gutter and has sustained a pressure, 53 kPa corresponding to its full height, for many weeks despite being built with considerably less cement in the blocks than SST1. The peak stress in SST2 is 50% greater than that at which SST1 failed.

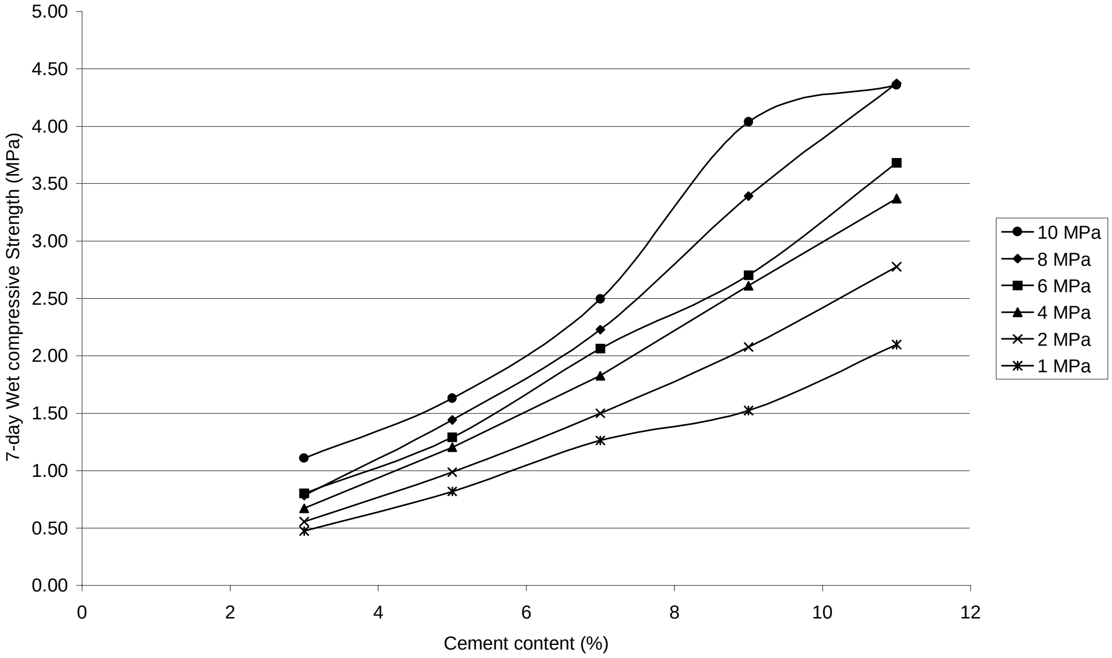
A further complication in the analysis of any tank made of blocks or bricks is uncertainty about how tensile forces travel from one block to the next. One route is via the mortar that separates blocks of the same course. Mortar does not have very high adhesion to blocks, although in this case the loose interlock between block ends would have provided some shear connection. The other route is via shear forces into, and then back out of, the overlapping blocks in the courses above and below the course of interest.

Three further but smaller SSB tanks have been built and sold.

6.4. Conclusions concerning SSB tanks

It is unclear exactly what was the failure mode of SST1. It appears that the lining was not sufficiently waterproof to prevent water passing to the stabilised soil matrix, causing the soil to rely solely on its wet strength. The maximum stress induced in the wall of the tank at 2.5m water pressure is 0.234 MPa. This is the maximum resultant tensile stress on the inner face of the tank wall due to both bending and hoop stresses (as calculated using spreadsheet by Turner [1999]).

If we look at Graph 6.1 we see that the 7-day wet compressive strength for the material (which has a 5.25% cement content and was compacted at about 2MPa, is about 1MPa. Similar figures are found in Houben for 28 day wet compressive strength – see Table 6.1. The usual rule of thumb for dry to wet strength ratio for soil is 5:1. So we see that the wet strength of the soil blocks would be in the region of 0.2 MPa, which is lower than the induced stress prior to failure. It could therefore be said that the tank performed better than might be expected.



Graph 6.1 Graph showing variation of 7-day wet compressive strength with cement content for a number of compaction pressures (Gooding [1993]).
Cement content = 5.25% in our case.

So for this diameter tank (1.67m), using the construction method outlined in Appendix V, and with the standard 2.2m height, the dry strength would give a safety factor of approximately 5. However, if the tank lining should fail, or if the tank should become saturated for any other reason, then the tank would be on the border of failure as the wet strength (~0.2MPa) is approximately equal to the induced stress (0.2026MPa).

Table 6.1 Compressive and tensile strengths for SSB's. All the above assume 2MPa compaction pressure an assume tensile strength to 0.2 x compressive strength

Source	Compressive strength	Estimated tensile strength
Gooding (see Graph 6.1)	1MPa (7 day wet)	0.2MPa
Houben	1 – 2MPa (28 day wet)	0.2 – 0.4MPa (estimated by author)
Houben	5 – 12 MPa (28 day dry)	1.0 – 2.4MPa (estimated by author)

The analysis above would hold if the subsequent tests on the SSB's from the tank debris had not shown that some of the blocks had NO wet strength. The only explanation for this is that these blocks failed before their minimum strength was reached.

6.5. Further work with SSB tanks

Further suggested work on this area of work includes the following:
full laboratory analysis of the soil (the soil used in Kampala was somewhat pozzolanic and was assumed to be superior to standard lateritic soil there)

- development tests to determine the soil / block performance (however there is some suspicion that the blocks in SST1 had been starved of their proper cement allocation)
- further full-scale tank tests with some modifications to improve tank performance
- investigate methods for improving tensile strength e.g. reinforcing with barbed wire
- further work to investigate the relationship between wet and dry tensile strength of stabilised soils

7. Rammed earth (RE) tanks

7.1. Introduction to RE tank development

The general aims of the work carried out on rammed earth tanks (RE) are listed below:

- to set out the theory of RE tank design and to investigate the options available for RE construction
- to develop the specification for an experimental laboratory tank and two experimental field tanks
- to develop the skills required (within the research team) to analyse soils for building, in both the laboratory and in the field
- to investigate soil modification techniques and methods to develop a soil suitable for tank construction
- to develop the tools and equipment required for RE tank construction

- to develop a technique suitable for rammed earth tank construction
- to develop a technique for tank lining using plastic sheet
- to test a rammed earth tank under laboratory conditions to verify the theory
- to build a number of tanks in the field to test the feasibility of the technology and its suitability to LDC skills
- to test a tank under field conditions, again to verify the theory
- to carry out a cost analysis of a RE tank to allow comparison with other tank types
- to develop guidelines for the manufacture of RE tanks

Three (3) RE tanks have, to date, been designed and constructed:

- A tank of 1.4m diameter and 1m height was built at the University (RE-UK*). The tank was from unstabilised soil. The aim was to test the general principle of construction and to allow for initial tests to be carried out on earth tanks. The tank was completed in May 2000 and simple tests carried out, but full tests are yet be to be carried out on this tank. The simple tests include; fitting experimental linings, applying steel strapping and filling the tank a number of times to test strength. The full tests are to include a pressure test to ascertain the actual strength of the tank and to allow comparison with the theory.
- Two tanks of stabilised soil of 2m diameter and 2m height were constructed at Kyera Farm, Mbarara in June and July 2000. The first (RE1*) was constructed to a high specification (see Section 6.4.2) with concrete base and masonry wall section to 0.35m high. The second (RE2*) was designed to be very low cost using predominantly stabilised earth. Both were stabilised with 4% cement and reinforced with barbed wire hoops at 75mm intervals (see Appendix IV for Rammed Earth Tank Construction Guidelines)

** Note:*
For easy identification of the three tanks, they have been labelled as follows
RE-UK - UK built tank
RE1 - Uganda high specification tank
RE2 - Uganda low specification tank

7.2. The basic principles of rammed earth construction

The general principles for building with earth are outlined in Section 5.4. and a full account of the rammed earth construction process used for the experimental tanks in Uganda is given in Appendix IV.

Some other points regarding RE construction are listed below:

- Availability of suitable materials is a key factor. If significant work is required in modifying the soil once it has been excavated, then the process can quickly become too costly.
- Wall thickness tends to be high, compared with modern materials. This is due to the relatively low compressive strength of the material and the variability in material quality. Compressive strength can be improved by using a small percentage (say 5% – 8% by weight) of cement mixed with the earth.

- Tensile strength is fairly low – in the region of 0.5 – 2.0 Mpa. The tensile strength can be improved by adding fibre or composite materials as well as by stabilisation with cement.
- The technique is characterised by high labour input and low material costs. This is well suited to many developing countries where labour is cheap and manufactured materials are costly.

The tools required for rammed earth construction can be few and of relatively low cost. In the West, sophisticated tooling has been developed, and sometimes costly pneumatic rams are used with steel shuttering, but in the less developed countries (LDCs) the tools have remained unchanged for centuries. Many designs of wood shuttering have been developed to meet the needs of the builder, but the principle actually varies little world-wide.

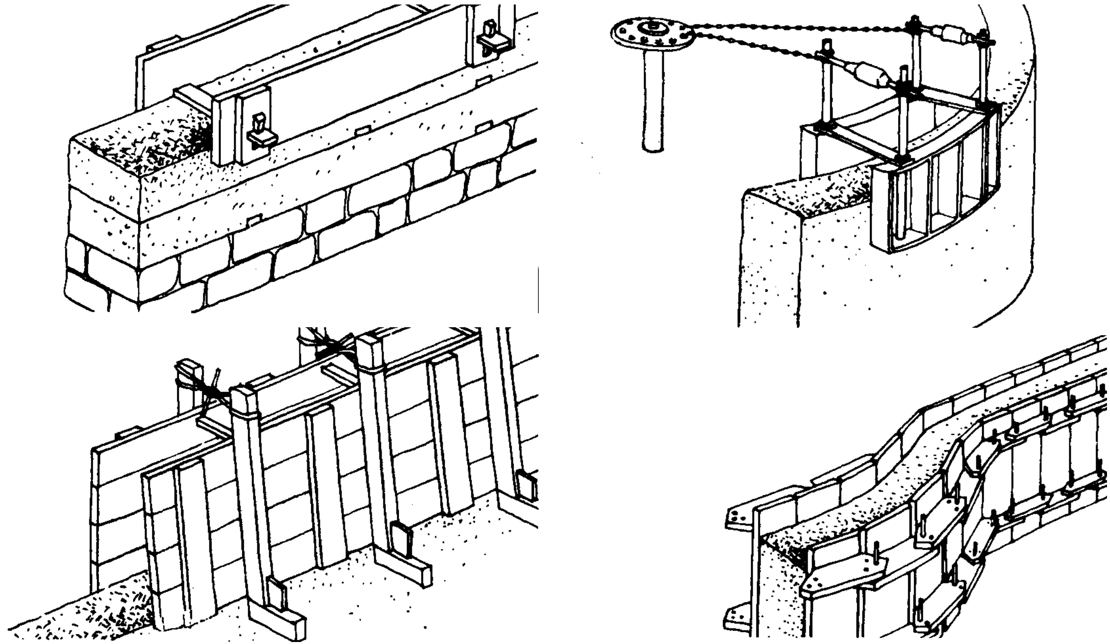


Figure 7.1 – Common types of shuttering used for RE construction (Houben^{1994})

7.3. Equipment for making cylindrical RE tanks

Shuttering Most shuttering used for RE construction is designed to be used for the construction of straight walls. There are few examples of shuttering for curved walls, and those shown in the literature seemed to be unsuitable for cylindrical tank construction. The shuttering was, therefore, designed by the author and manufactured at the University workshops (RE-UK) and by local carpenters (RE1 and RE2) - see Figures 7.2 and 7.3. The UK shuttering required some subsequent strengthening to prevent deflection when compaction was taking place. The second set of shuttering was suitably strengthened during manufacture.

- *Shuttering fabrication methods used in UK*

The materials and techniques used for the shuttering construction varied slightly between the UK and Uganda. In the West, plywood is readily available, whereas in Uganda it is not. Plywood is well suited to forming curved surfaces through lamination and so 4mm plywood sheets were used to form the curved faces of the mould – 3 layers glued together. Plywood (12mm – doubled up) was also used to form the main strengthening spines of the shuttering. The tie rods were from 12mm steel rod with T's welded on one end and threaded to sufficient length on the other. The nuts used were fitted with wings to make shuttering assembly easier. The end-stops were made for 12mm ply. The shuttering is shown in Figure 7.3.

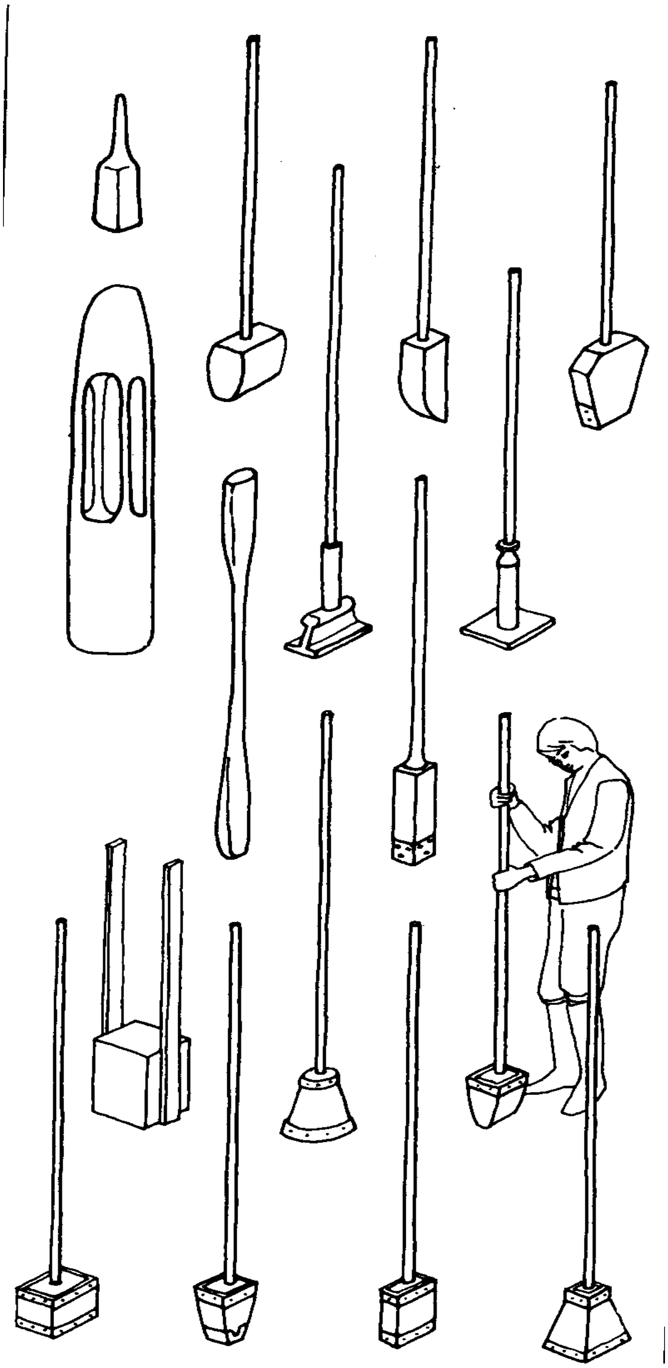


Figure 7.2 – Common types of rammers used for RE construction (Houben[1994])

- *Shuttering fabrication method used in Uganda*

In Uganda sawn hardwood timber is more commonly available and this was used for the construction of the shuttering. The curved faces of the mould were made using 25mm x 25mm strips of timber butted to one another and glued and nailed carefully to each other and to the main spines. The spines and end-stops were from hardwood. The work was carried out at a local workshop and needed constant supervision to ensure that the work was done in accordance with the drawings. The workshop had few power tools and most of the work was done by hand. Again, the tie rods were of 12mm steel rod with T's and threaded section. The shuttering is shown in Figure 7.4. Design drawings for the shuttering are shown in Appendix V.

Figure 7.3 – Shuttering manufactured in the UK

Figure 7.4 Shuttering manufactured in Uganda

- *Test for shuttering strength*

The standard test for strength of shuttering is that the mid point deflection of the shuttering, when loaded with a 150 kg weight (e.g. 3 bags of cement) should less than 3mm. Loading is mid point between the vertical stays.

- *Expected useful life of Shuttering*

Based on the experience in Uganda, where the shuttering was used to make two tanks, it is estimated that well-made shuttering should be good for the construction of between 15 and 20 tanks, with some maintenance required to repair any damage caused during ramming.

Rammers / tampers The tampers were manufactured at the University workshops and at a local workshop in Uganda. Drawings are shown in Appendix V. The handles were of hollow round section steel in order that the weight of the rammer can be adjusted by partially filling the handle with sand. The profiled 'V' rammer, used for creating a joint that helps prevent shear, was made using a piece of 50mm angle iron welded to the flat base of the rammer.

Covers The DTU ferrocement thin-shell cover was used on both RE1 and RE2 and a special sealed (pressure-resistant) cover is to be developed for RE-UK.

Tank linings

Experiments have been carried out with two types of tank lining:

- *Plastic lining*. Work on plastic linings has been underway for some time at the University by an MSc student. A technique has been developed for welding 250 micron construction or damp proof membrane (DPM) plastic sheet to make 'bags' (similar to large bin liners) that fit inside the tank structure to form a waterproof lining. The welding technique has been successfully developed but there are still problems to be overcome in relation to the quality of 'off-the-shelf' plastic sheet and failure of the lining due to abrasion.
- *Cement render lining with waterproofing agent*. This is a more traditional form of waterproofing for water storage tanks and was eventually used for both the field experimental tanks. Further investigation into the nature of render linings, with particular respect to permeability and the effects of waterproofing agents, is underway at the University.

7.4. Laboratory work on RE tanks

Aims of the laboratory experiments Between November 1999 and May 2000 laboratory tests were carried out at the University of Warwick. The work was carried out to allow the author to gain experience with earth building technology and to develop a technique suitable for building tanks from soil. The full aims of the work was as follows:

- to set out the theory of RE tank design and to investigate the options available for rammed earth tank construction
- to develop the skills required (within the research team) to analyse soils for building, in both the laboratory and in the field
- to investigate soil modification techniques and methods to develop a soil suitable for tank construction
- to develop the tools and equipment required for RE tank construction
- to develop a technique suitable for rammed earth tank construction
- to develop a technique for tank lining using plastic sheet
- to test a rammed earth tank under laboratory conditions to verify the theory with regard to:
  - hoop strength (reinforced and un-reinforced)
  - the effect of rain on stabilised soil
  - performance tests for soil:

- wet and dry tensile strength
- wet and dry bending strength
- wet and dry shear strength (all three to be carried out at experimental and applied levels)
- swell and shrinkage
- erosion
- abrasion
- passage of water
- compatibility (adhesion) with renders and mortars

Preparation for the laboratory experiments The test site was established in a disused water turbine testing sump in the university laboratory. The set up for the experiments was time consuming and the preparation of the site took several weeks, mainly fitting lighting and safety equipment to conform with university safety regulations

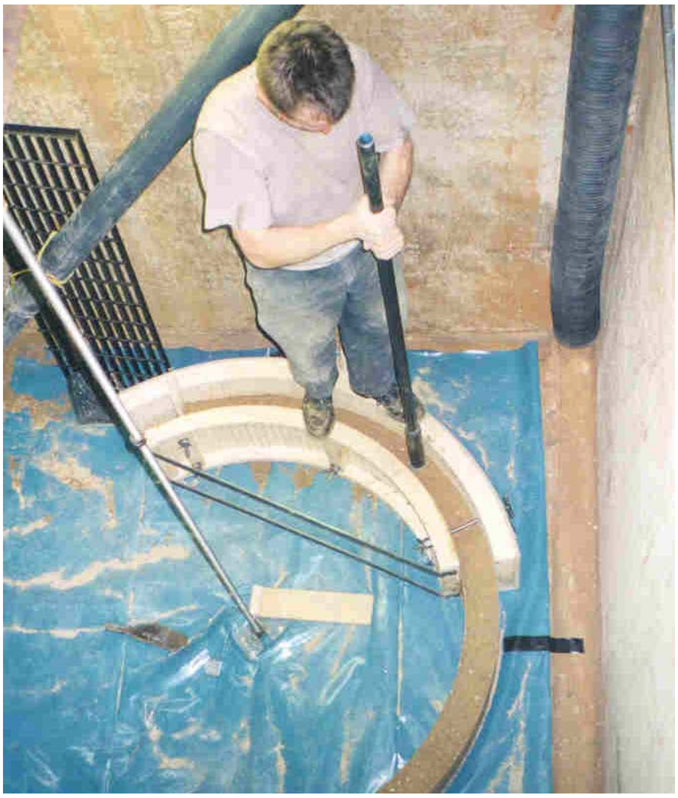


Figure 7.5 Showing tank test area at the university laboratory

Desk work to develop experimental tank specification

Sufficient deskwork was undertaken to formulate a specification for the RE tank. The theory of stresses in tanks is given in Section 4 along with detail of the spreadsheet used to analyse stresses and to develop the specification for the experimental tank. The specification is as given below:

Table 7.1 Specification for laboratory experimental tank

Tank internal diameter	1.40m
Depth	1.0m
Wall thickness	0.1m

Wall / base joint	‘slippery’ joint using plastic sheet
Section bonding	Polypropylene knotted rope to give tensile bond for vertical joints V channel ramming for better horizontal joints
Drying time	2 weeks in dry environment

Work carried out in the laboratory

Soil analysis What was thought to be a suitable soil was purchased from a local quarry and an analysis was carried out. The soil is known locally as ‘Hoggin’The soil was analysed using the standard wet sieving technique and the following results were obtained:

Table 7.2 Soil classification for Hoggin from Husbands Bosworth, UK, December 1999. Sample size 1500g, oven dried for 24hrs, wet sieved

Sieve Size (mm)	Weight retained	% retained	Description
20.000	220.6	14.87	Pebbles
6.300	394.6	26.59	Gravel
2.000	379.8	25.60	Gravel
0.420	222.5	15.00	Coarse sand
0.063	146.3	9.86	Fine sand
<0.063	120.0	8.09	Silt, fine silt and clay

Table 7.3 Results of a sedimentation test carried out on particles passing through 0.063mm sieve (from Table 7.2 above).

Time elapsed since agitation	Settled depth (mm)	% of total settled depth	Description	%age of total soil sample
1min	18	56.25	Sand	18.46
30 min	25	21.875	Silt	7.18
24 hrs	32	21.875	Clay	7.18

The soil was assessed and it was noted that:

a) there were many large stones >30mm
b) there was an excessive amount of material over 6.3mm in size – about 40% of total
c) there was insufficient clay for binding the material (7.18% of total material content)
d) there was insufficient sand in the soil

Soil modification It was decided that the soil should be modified. Several experiments were carried out to formulate a suitable soil and the following procedure was developed to prepare the required soil:

a) all large stones >30mm were removed
b) the soil was sieved to remove all particles above 10mm
c) the soil was then sieved again to isolate all particles between 5mm and 10mm
d) kaolin (china clay) was purchased and used to make up the deficiency in clay content

e) concrete sand was acquired to make up the deficiency in sand in the original soil

The final mix was as follows:

Hoggin <5mm	- 30%
Hoggin 5mm – 10mm	- 20%
Concrete (builders) sand	- 35%
Kaolin	- 15%

No stabilisation was carried out at this point and the material could therefore be recycled during the early tests.

Table 7.4 The sieve analysis for the modified soil (now known as Soil 4)

Sieve Size (mm)	Weight retained	%age retained	Description
6.300	83.80	9.16	Coarse gravel
2.000	232.10	25.37	Gravel
0.420	274.45	30.00	Coarse Sand
0.063	160.70	17.57	Fine sand
<0.063	163.80	17.90	Silt and clay

Soil 4 was used for all subsequent construction work in the laboratory.

Compaction tests and Optimum Moisture Content Compaction tests were carried out (as described in Section 3.3.2) on Soil 4 to determine the Optimum Moisture Content (OMC). The results show a moisture content of 9% to be optimum. However, in practice a figure of 8% was used as soil with 9% moisture content was too 'sticky' and caused the soil to stick to the rammers.

Liquid limit and plastic limit tests – the Atterburg chart Tests to determine the liquid and plastic limits were carried out and the results shown below:

Table 7.5 – LL, PL and PI Figures

Liquid limit	14.80
Plastic limit	9.59
Plasticity Index	5.21

Figure 7.6 – Early experimentation with ramming wall sections

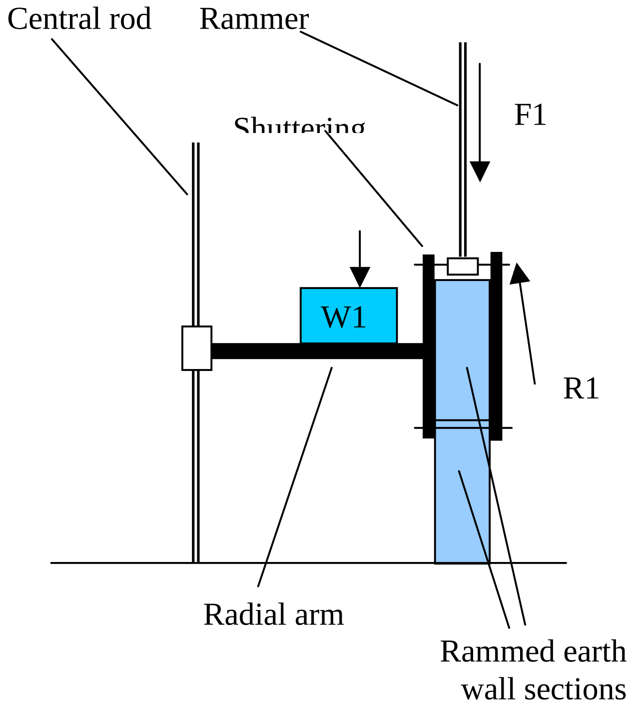
Initial ramming tests and developing the technique for RE tank construction The shuttering was developed in such a way that 3 sizes of wall thickness could be tried; 60mm, 80mm and 100mm. The reason for this was that it was doubtful if the smaller wall thickness (the lower lifts) would withstand the compaction blows of subsequent lifts.

Early tests showed a number of problems with the ramming technique:

- the shuttering was deflecting and causing the wall section geometry to loose its true curvature
- the 60mm thick wall showed signs of cracking when the shuttering was clamped to it for the subsequent section
- when ramming, a reaction caused the shuttering to bounce or lift slightly (see Figure 7.7)
- the geometry of the shuttering was crucial and problems were encountered due to slight irregularities in the geometry

These problems were overcome by some adjustments to the shuttering:

- strengthening was added to prevent deflection
- the wider setting was used to produce a wall of 100mm thickness
- radial arms were fitted to the shuttering to maintain centrality and to allow weights to be added to prevent 'bouncing' (see Figure 7.7)
- the geometry of the shuttering was corrected slightly as no allowance had been made for the width of the end stops



The ramming force, F1, causes a reaction in the shuttering, R1, which causes the shuttering to lift and hence cause deformation. The weight, W1 (two x 25kg bags of sand were used), counteracts R1 and prevents the deformation.

Figure 7.7 Showing the forces created through ramming and the measures taken to counteract these forces

Manufacture of experimental tank A tank of 1.4m diameter and 0.7m height was built in a disused turbine testing sump (see specification given in Section 6.3.3). The tank was built from Soil 4. The aim was to test the general principle of construction and to allow for initial tests to be carried out on earth tanks. The tank was completed in May 2000 and simple tests carried out, but full tests are yet be to be carried out on this tank The simple tests include fitting experimental linings, applying steel strapping and filling the tank a number of times to test strength. The fuller tests are to include pressure tests to ascertain the actual strength of the tank to allow comparison with the theory.

Figure 7.8 Showing the experimental tank in the sump at the university

Composite materials for added tensile strength Composite materials and reinforcement can be used to improve the strength of compacted soil. For improved tensile strength the added material should have good tensile properties and be malleable so that it can be rammed into the soil matrix. Some ideal materials include barbed wire, polypropylene fibre and straw.

External reinforcement for added tensile strength External reinforcement such as steel packaging strap, barbed wire, or plain fencing wire can be wrapped around the finished tank walls for added tensile strength.

Laboratory tests Due to time constraints and unforeseen problems with developing the technique for RE tanks, other planned laboratory tests have not yet been carried out. Tests are being undertaken at present to verify the theory with regard to:
hoop strength (reinforced and un-reinforced)
the effect of rain on stabilised soil

- performance tests for soil:
- wet and dry tensile strength
- wet and dry bending strength
- wet and dry shear strength (all three to be carried out at experimental and applied levels)
- swell and shrinkage
- erosion
- abrasion

- passage of water
- compatibility (adhesion) with renders and mortars

This work will be reported at a later date.

Conclusions and discussion concerning laboratory work on RE tanks Soil analysis was carried out for a locally sourced soil. The soil was modified to create a suitable soil for RE tank construction. The tools and techniques for RE tank construction have been developed.

Developing the technique for RE tanks proved to be more problematic and time-consuming than was originally thought, with much work needed to overcome geometry problems. The level of accuracy required, both in shutter manufacture and in the construction process, is higher than expected. Early tests show that the RE tank design has good potential.

Soil preparation time is high and so a suitable soil should be sought in the field that requires little preparation.

The problems encountered during the construction process meant that few further tests have yet been carried out.

Further laboratory work
Recommended further work is listed below:

- Manufacture of sealed cover and tank pressurisation equipment
- Pressure testing of the existing experimental tank
- Data logging to allow analysis of the stresses in the tank during pressurisation
- Performance tests to analyse the soils characteristics in use
- Experiments to determine the effects of cement content on stabilisation
- Experiments to determine the effect of cyclic loading on rammed earth tank walls (cracking, joint failure, etc.)
- Waterproof lining (resistance to penetration, fixing methods, liner penetration for off-take, etc)
- Wet strength tests of tanks

7.5. Field work

The principal aims of the field tests were:

- to test the technique developed in the laboratory for rammed earth tank construction
- to test the technique for tank lining using plastic sheet
- to build a number of tanks to test the feasibility of the technology and its suitability to LDC skills
- to test a tank under field conditions to verify the theory
- to carry out a full cost analysis of a RE tank to allow comparison with other tank types

Specification for 2 experimental field tanks

The specification for the two rammed earth tanks is given in the tables below. The specifications were drawn up using the results of the spread sheet analysis and with the specific aim of testing a) a tank using standard building guidelines for rammed earth construction (RE1) and b) a low-cost tank using predominantly stabilised earth and minimising the cement content (RE2).

High Specification RE Tank (RE1)

Tank internal diameter	2.0m
Tank external diameter	2.4m
Tank height	2.0m
Tank capacity	approximately 6 cubic metres
Concrete base thickness	100mm un-reinforced (on 100mm hardcore where ground is soft)
Concrete base diameter	2.8m
Soil wall thickness	0.2m
Soil make-up	10% clay, 15 – 30% silt, 50 – 70% sand, 10 – 20% garvel, 4% cement stabilisation
Reinforcement	barbed wire hoops at 50-60mm spacing in rammed earth sections steel reinforced cement hoops at spacing shown in drawing
Lower wall dimensions	350mm stone masonry, 0.2m thickness
Tank lining	waterproof render approx. 15mm thick (or plastic liner)
Cover	thin shell ferrocement cover
Water extraction	By gravity – washout also by gravity

Low Specification RE Tank (RE2)

Tank internal diameter	2.0m
Tank external diameter	2.4m
Tank height	2.0m
Tank capacity	approximately 6 cubic metres
Base	100mm stone with 50mm compacted stabilised soil, 2.8m diameter
Wall	Stabilised soil, 0.2m thickness
Reinforcement	barbed wire hoops at 50-60mm spacing in rammed earth sections
Soil make-up	10% clay, 15 – 30% silt, 50 – 70% sand, 10 – 20% garvel, 4% cement stabilisation
Tank lining	plastic liner
Cover	thin shell ferrocement cover
Water extraction	by handpump where plastic liner is used

Some of the design features and design considerations that were incorporated are outlined below:

- The wall sections were given a ‘V’ profile to prevent shear. The aim was to encourage better bonding and so reduce the likelihood of shear. The profile was achieved using a special ram with a V attached. See Figure 7.9.

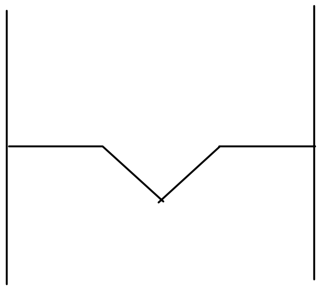


Figure 7.9 – Profile of the joint between 'lifts'

- The principle adopted for house construction of good protection at the base and overhanging eaves for protection from above were adopted, especially in the case of RE1
- The tank size is based on useful capacity and available catchment area
- Minimal cost – the general aim of this task is to reduce the cost of storage for rainwater
- The use of local materials as far as possible
- Durability – a minimum of 10 - 15 years life expectancy
- Easily constructed by local artisans in developing countries
- Foundations – these should be:
  - should be laid in a good sound soil
  - be protected against ingress of moisture
  - be protected against frost (not an issue in the Trpoics0
  - be protected from wind erosion – sand blasting in severe storms
  - be protected against animals, rodents, insects, etc
- Protection from surface water through good drainage (Houben pg 252) – ground to slope away from tank, ground gutters, moisture barriers,
- Foundations in unstable soils need to be considered – ground stabilisation may be needed

Work carried out in the field

The two tanks specified in the previous section were constructed at Kyera Farm. The procedure for their construction is outlined in Appendix IV. Each step of the work was carefully observed and monitored against the aims set out in Section 6.4.1. An initial field soil analysis was carried out to determine a suitable soil. Some modification was needed and then a full laboratory analysis was carried out on the modified soil.

Tests carried out in the field

Soil analysis – field tests
Three soils were analysed crudely in the field. The following tests were performed:

Sensory tests
The soil was analysed by feel, look and smell to test for initial suitability

Sedimentation test. The results are shown below:

Table 7.6 Results of the sedimentation test carried out in the field

Soil source	Soil code	T1	T2	T3	% sand	% silt	% clay
Murram from farm <4mm	S1	40	42.5	42.5	94	6	0
Anthill P <4mm	S2	22	53	53	37.7	62.3	0
RE2 excavation site <4mm	S3	53	59	59	89.8	10.2	0

Notes:
T1 = reading taken in mm, start time plus 1minute
T2 = reading taken in mm, start time plus 30 minutes
T3 = reading taken in mm, start time plus 24 hours
The murram has some organic material; good distinction between layers.
Anthill has little organic matter; poor distinction due to uniform colour.
RE2 excavation site high organic content; good definition.
Clay content is shown as 0% in each of the above. This is because further settling of the sand and silt after initial measurement caused final reading to be low.

A further sedimentation test was carried out to estimate the clay content. Tests were carried out on the murram and the anthill soil. Soil passing through a 0.075mm sieve was sedimented and readings taken at 20mins, 24hrs and 48hrs. From the readings obtained, the clay content was estimated to be:

Table 7.7 Results of tests to determine clay content of soils

Soil	**Clay content**	**Comment**
Murram from farm <0.075mm	4%	Again definition was difficult and the reading was not fully trustworthy
Anthill P <0.075mm	0%	Settling took place rapidly indicating little or no clay content

Soil modification

None of the three soils tested was fully suited to RE construction. However it was found that by mixing the larger particles of the murram (those retained on a 4mm sieve) with the crushed anthill soil, a suitable soil was developed. Stabilisation was provided by adding 4% cement. The cement percentage was kept deliberately low to save on cost. The final mix is shown in Table 6.8.

Table 7.8 Showing mix used for modified soil for RE tank construction

Material	**Quantity**
Crushed anthill soil	80%
Murram >4mm	16%
Cement	4%
Water	Added in sufficient quantity and checked using field test

Soil analysis – laboratory tests

An analysis of the modified soil was carried out at the Central Materials Laboratory, Ministry of Works and Housing, Kampala. The analysis is summarised below.

- *Sieve analysis*
  The full analysis is shown in Appendix III but a summary is given in Table 6.9

Table 6.9 Summary of sieve analysis for RE1 and RE2 tank soil

Classification	
Pebbles	0%
Gravel	21%
Coarse sand	17%
Fine sand	17%
Silts	10%
Fine silts	19%
Clays	16%

- *Other tests*

Table 7.10 Results from laboratory tests for construction soil

Test name	Testing for	Result
Hydrometer analysis	Specific gravity	Gs 2.65 (measured)
Atterburg limits(1)	Liquid limit	34
	Plastic limit	16
	Plasticity index	18
Normal moisture content	Normal moisture content	2%
Compaction and OMC(2)	Material density	1,930Kg/m^3 (Maximum dry density – MDD)
	Optimum moisture content	12%
Linear shrinkage	Linear shrinkage	10%
Permeability	Permeability	4.09 x 10^{-7} m/s
Unconfined compressive strength	Unconfined compressive strength	0.2MPa @ 95% MDD

Notes:

[1] Referring to the Atterburg Limits Chart in Figure 2.1, we can see that the ideal stabiliser for this soil is cement.

[2] A heavy compaction test was carried out to determine density and OMC:
The results are discussed in Section 6.4.7.

Water bearing test on finished tanks

RE2 was filled using a bowser. It was filled quickly using a motorised pump. The tank held water for about 8 hrs but damp patches appeared at the base of the tank. ‘Piping*’ caused loss of water which became critical after about 12hrs and there was a total loss of water after approximately 14hrs. As the wall became damper, 3 major cracks appeared in the tank wall. The possible reasons for the failure are discussed in Sections 6.4.7 and 6.4.8.

*Piping is a term used in the dam industry and is a mode of failure whereby water finds a path from one side of the dam wall to the other and the subsequent erosion of the wall causes failure.

Figure 7.10 The experimental rammed earth tank under construction at Kyera Farm, Mbarara, Uganda.

As a result of the failure of RE2, RE1 was relined and is awaiting slow filling by rain. RE1 has not yet be tested at full working water pressure.

7.6. Results of field and laboratory tests

Some observations regarding the laboratory tests:

- The results of the sieve analysis shows that the soil is suitable for RE construction.
- Referring to the Atterburg Limits Chart in Figure 2.2, we can see that the ideal stabiliser for this soil is cement.
- Compaction density (MDD) seems rather low – normally we would expect a MDD of at least 2000Kg/m^3.
- OMC seems rather high – this is normally in the range of 8 – 10%
- Permeability is high at 4.09 x 10^{-7}m/s. The norm for stabilised soil is 1 x 10^{-8}m/s.
- Unconfined compressive strength seems very low and this figure is not trusted.
- Linear shrinkage is also high.

The result of the water bearing test described in Section 7.4. was discouraging as far as the overall viability of RE tank technology is concerned. The failure highlighted a number of points:

- Soil tanks should have sufficient wet tensile strength to cope with total saturation in water. This has a strong impact on the design of such tanks and could result in excessive wall thickness.
- A tensile reinforcement should be included within the soil matrix to prevent catastrophic failure in the event of saturation.
- A good tank lining is critical. A poor leakage of the lining will cause rapid degradation of the wall.
- Where a waterproofing agent is used in a render lining it should be given adequate time to take effect. Follow the manufacturers instructions and where they are

lacking, fill the tank slowly, at no more than 200mm per day after 2 weeks of curing in a saturated environment.

7.7. Observations made regarding the RE tank construction technique and field tests

The construction technique developed in the laboratory was further refined in the field. The following observations were made:

- Soil preparation was initially very time consuming, until a groundnut sheller was acquired and modified to mill soil through a 4mm sieve (see Appendix IV). This reduced soil preparation time to about one tenth.
- RE construction is a time consuming process. The cost analysis in Section 6.5 shows how labour intensive the process can be.
- The shuttering used in the field had no radial arms and so the reaction discussed in Section 7.3 was dealt with by standing on the shuttering whilst ramming.
- The level of accuracy attained in the field was lower than in the laboratory. This was not a problem, however, as soil was cut away with a machete if the geometry was not perfect. This was more feasible in the field as the wall thickness of these tanks was higher.
- Some work was carried out to assess the feasibility of plastic liners for use with soil tanks. There were problems in a number of areas: finding good quality plastic sheet; finding plastic sheet of a suitable size; abrasion of liners when in use causing small puncture holes. The technique is not recommended for use at present.

Limitations of the field tests Time constraints were tight due the limited amount of time in-country. It was difficult to set up and execute proper tests during the limited time available, the construction process itself being very time consuming. The tests that were carried out were done so hurriedly and give only an indicative feel for the behaviour of the tank.

7.8. Conclusions, discussion and planned further work concerning RE tanks

Discussion The probable mode of failure of RE2 is outlined in this Section. It appears that water passed through the lining of the tank almost immediately the water was placed in the tank. It seems probable that the waterproofing agent had had insufficient time to act and that water was passing through the render under full water pressure. Alternatively, the lining was of poor quality and water passed through cracks in the lining. The water forced its way through the soil matrix under piping action until it emerged at the outer face of the wall, and the resultant erosion increased the ‘pipe’ area until the water could flow freely from the tank (see Figure 7.11).

The fact that cracks appeared in the tank wall mean that the wet strength of the soil was insufficient to withstand the forces exerted through normal working water pressure, which is not tolerable.

Figure 7.11 Failure of RE2 through ‘piping’ – this figure shows the leakage at the base of the tank and the crack running through the wall

Further work on RE Tanks A similar water pressure test will be carried out on RE1, as was carried out on RE2. This tank has been relined and will be filled with rain during the coming wet season (starting September 2000). Staff at Kyera Farm have been asked to observe the tank as it slowly fills.

The following is a list of further work that is recommended to clarify uncertainties regarding the technique:

- Performance tests on soil samples taken from field
- Further investigations into suitable levels of soil stabilisation
- Investigation of techniques for improving wet strength of stabilised soil
- Investigation of techniques for decreasing permeability of stabilised soil (e.g. inclusion of bitumen emulsion)
- Further field tests including destructive tank pressurisation tests
- Further work to develop suitable plastic or other flexible linings

8. Cost analysis

A cost analysis for an 11 cubic metre ferrocement tank and an 11 cubic metre rammed earth tank has been carried out

The bill of quantities for the ferrocement tank was taken from Gould and Nissen-Peterson, 1999. The rammed earth tank is an externally rendered tank fitted with a thin-shell ferrocement cover. It is also fitted with a plastic ‘sock’ lining as described later in this document. Hoop strength is augmented using barbed wire hoops spaced every 0.1m for the entire height of the tank. Cement content is 5% and moisture content of the soil is 8%. We have used material prices based on costs in Uganda as of August 1999. This allows us to make a realistic analysis using costs from a single location and an identical size of tank. We are therefore making a direct cost comparison. The cost comparison and relative benefits may change if the costing is repeated for a different location (with different prices). India, for example, has lower cement prices, which would impact greatly on this comparison. One pound sterling is roughly equivalent to 2440 Ugandan shillings (UGX) as of January 2000. Transportation costs for materials (other than sand) are not included.

The costing figures are shown in the table in APPENDIX I and the table is self-explanatory. Some points to consider are:

- Cement is the major cost in the ferrocement tank. There is little means of reducing the cost without reducing wall thickness. Transportation of cement can be costly if the site is remote.
- The cost, including labour, of the thinner walled rammed earth tank is about 80% that of the ferrocement tank. Material costs are about 72%. This reflects the higher labour input required.
- If suitable soil is available on site then the material costs of the RET can be reduced significantly.
- The RET wall sits on a concrete ring rather than a concrete disc. The base of the tank is of compacted earth. This helps reduce costs as concrete raft bases consume significant quantities of material and are therefore expensive.
- The RET wall is stabilised. The wall would have sufficient strength without stabilisation and the cost could be reduced further. Stabilisation is desired however in case of wetting of the wall.
- If stabilisation and reinforcing is omitted, the cost of the (thinner-walled) RET drops to 697,000 UGX or £278.28, 58.5% that of the ferrocement tank cost (including labour).
- Tooling costs, shuttering and moulds in particular, tend to be higher for the ferrocement tank, although for both tanks the moulds / shuttering can be reused many times.

9. General conclusions, discussion and plans for further work

9.1. Discussion

A number of stabilised soil tanks have been constructed and tested, using two different soil construction techniques. Two tanks have failed under test and the failures have been analysed in the relevant sections of the report. Two further tanks are still under test. Some important lessons have been learned from the initial tests and these lessons will be used to guide further research. The main lessons learned are listed here:

- When designing stabilised soil tanks one should take into consideration wet tensile strength of the material. It is inappropriate to use the dry tensile strength as the design strength value unless it can be guaranteed that water will never reach the soil matrix.
- A composite tensile member is recommended to prevent sudden catastrophic failure of a tank.
- Tank linings should be fully impermeable to prevent water reaching the soil matrix.
- Plastic linings

9.2. Recommended further work

Stabilised soil block tanks

- Full laboratory analysis of the soil
- Performance tests to determine the soil / block characteristics
- Further full scale tank tests with some modifications to improve tank performance
- Investigate methods for improving tensile strength e.g. reinforcing with barbed wire

Rammed earth tanks - Laboratory work

- Manufacture of sealed cover and tank pressurisation equipment
- Pressure testing of the existing experimental tank
- Data logging to allow analysis of the stresses in the tank during pressurisation
- Performance tests to analyse the soils characteristics in use
- Experiments to determine the effects of cement content on stabilisation
- Experiments to determine the effect of cyclic loading on rammed earth tank walls (cracking, joint failure, etc.)
- Waterproof lining (cyclic loading with a variety of ‘sharp’ objects to test resistance to penetration, fixing methods, liner penetration for off-take, etc)
- Wet strength tests of tanks

Rammed Earth Tanks - Field work

- Performance tests on soil samples taken from field
- Further investigations into suitable levels of soil stabilisation
- Investigation of techniques for improving wet strength of stabilised soil
- Investigation of techniques for decreasing permeability of stabilised soil (e.g. inclusion of bitumen emulsion)
- Further field tests including destructive tank pressurisation tests
- Further work to develop suitable plastic or other flexible linings

Other work

- Render linings for tanks – permeability tests and effects of waterproofing agent on render (both in early stages and longer term)
- Methods for reducing permeability of compacted soils (e.g. treatment with bitumen emulsion)
- Further experiments on the relationship between wet and dry strength in tension
- Tank linings from plastics
- Termite attack on soil tanks
- Sliding joint at base of tank

10. References and bibliography

1. DTU Roofwater Harvesting Programme, http://www.eng.warwick.ac.uk/DTU/rainwaterharvesting/index.html, DTU, School of Engineering, University of Warwick, UK, 2000
2. Gooding D., *Quasi-Static Compression Forming of Stabilised Soil-Cement Building Blocks*, DTU WP 40, Warwick University, 1993
3. Gould, John & Nissen-Petersen, Erik, *Rainwater catchment systems for domestic supply*, IT Publications, London, 1999.

4. Gray, W. S., *Reinforced concrete reservoirs and tanks,* Concrete Publications Limited, London, 1960.
5. Houben, H. & Guillaud, H., *Earth Construction - a comprehensive guide*, CRATerre-EAG, Marseille, 1989.
6. Keable, Julian, *Rammed earth structures: a code of practice*, IT Publications, London, 1996.
7. Montgomery D., *Dynamic Compaction of Soil for Low-cost Building Blocks*, DTU Working Paper WP53, Warwick University, 1999
8. Neville, A. M., *Properties of Concrete*, Addison Wesley, UK, 1997
9. Norton, John, *Building with earth - a handbook*, IT Publications, London, 1997.
10. Turner, Stephen, J., *Design of storage tanks for rainwater harvesting,* (dissertation), Department of applied mechanics, Indian Institute of Technology, Delhi, India, May 1999.
11. Watt, Simon B., Ferrocement water tanks and their construction, IT Publications, London, 1978.
12. *BS 1377, Soils for Civil Engineering Purposes*, BSI, UK, 1990.

APPENDIX I - Cost comparison between 11 cubic metre ferrocement tank and two rammed earth tanks (of wall thickness 0.2m and 0.3m).

					11 cub m ferrocement (Nissen-Peterson, 6 cm wall thickness)		**11 cub m rammed earth tank (wall thickness 0.2m)**		**11 cub m rammed earth tank (wall thickness 0.3m)**	
Item	**Specification**	**Unit**	**Unit cost**		**Quantity**	**Cost**	**Quantity**	**Cost**		
Cement	50 kg	bag	15,500		22	341000	11	170500	15	232500
Lime	25 kg	bag	10000	*	1	10000				
Sand	coarse and clean	tonne	30000		5	150000	7	210000	11	330000
Crushed stones	10 to 20mm	tonne	40000		2	80000	2	80000	2	80000
Rubble stones	100 to 500mm	tonne	30000		1	30000				
Bricks	variable	number	70		50	3500	100	7000	100	7000
Water	200 litre	oil drum			15	0	5		7	
BRC mesh	No 65	m	6000		24	144000				
Chicken mesh	25mm, 0.9m	m	3000		38	114000				
Twisted iron	12mm	m	2000	*	3	6000				
GI wire	3mm	kg	1,250		10	12500				
GI Pipe	38mm	m	7000	*	0.9	6300	1	7000	1	7000
GI Pipe	18mm	m	5000	*	0.9	4500	0.3	1500	0.4	2000
Tap, elbow nipple and socket	18mm	unit	15000		1	15000	1	15000	1	15000
PVC pipe	100mm	m	5000		2.2	11000				
PVC pipe	50mm	m	3000		3	9000	2	6000	2	6000
Coffee mesh	galvanised	m	3000	*	1	3000	1	3000	1	3000
Mosquito mesh	plastic	m	2000	*	0.5	1000				
Lockable door	steel	0.9 x 1.5	20000	*	1	20000	1	20000	1	20000
Reinforcing steel	8mm	10m lngth	10000				3	30000	3	30000
Plastic liner	custom made	unit	20000	*			1	20000	1	20000
Barbed wire	galvanised	roll 50m	50000	*			2.5	125000	2.5	125000
Skilled labour	mason, supervisor	day	12,000		10	120000	12	144000	14	168000
Unskilled labour	assistants	day	4000		20	80000	24	96000	28	112000
Totals		Total minus labour			UGX	960,800		695,000		877,500
					£	393.77		284.83		359.63
* estimated cost		Total with labour			UGX	1,160,800		935,000		1,157,500
					£	475.73		383.19		474.38

APPENDIX II - REPORT ON WATER TANKS FROM STABILISED SOIL BLOCKS

(by Engineer Dr. M. K. Musaazi PhD DIC, August 2000)

Machinery

Manual Block Press (by ApproTec Kenya): Specially modified by authorized manufacture (Makiga Engineering Services, Kenya) to make curved interlocking blocks. There are two Block Presses designed so that 13 blocks interlock to make a 1.0m internal diameter circle or 17 blocks make a 1.5m internal diameter circle.

Material

Murrum (red) soil or volcanic soil and Ordinary Portland Cement (OPC)

Material Preparation

Sieve soil with a 5mm wire mesh. Mix while dry with OPC in the ratio.
Cement : Soil = 1: 19

i.e. 50kg(l bag) of OPC makes 110 SSB blocks each of about 9kg. A little water is added to make the mixer just damp.

Block Making

Prepared material compressed by 40% to make one block at a time.
Two men make 330 blocks/day.

Curing and Drying of Blocks

Blocks are cured under a black Polythene sheeting for five days if made from murrum and for 2 days if from volcanic soil. Dried for 5 days under direct sunshine, after curing, before used to make tanks.

Tank Building

A 150 mm concrete base is made and blocks laid the following day. Blocks interlock to form a circle desired internal diameter.

Experience has shown that the internal diameter can be increased from design by as much as 0.5m without any noticeable distortion of the circle.

The blocks are laid using a 1:4 cement to sand ratio. One bag (50kg) of OPC lays about 200 blocks. The inside of the tank is plastered with fine sand, OPC and water proof cement (I kg added to 50kg of OPC).

Block Size:

Length = 280 mm
Width = 140 mm
Height = 110mm

Hence the tank wall is 140 mm thick plus 10 mm of plaster.

Tank Sizes

The size of course depends on the internal diameter and height. The tanks that have NOT failed number five as tabled below:

TANK NO.	DIMENSIONS	CAPACITY (Litres)	WHEN MADE MONTH, 2000	REMARKS
1	Int diam – 1.0m Height - 5.2m Block layers – 13 Total blocks – 507	5,800	March	Full up to 3.5m as of 1st August 2000
2	Int diam – 1.24m Height - 2.12m Block layers – 15 Total blocks – 240	2,500	March	Full to capacity as of 1st August 2000
3	Int diam – 1.20m Height - 2.12m Block layers – 14 Total blocks – 210	2,400	April	Full to capacity as of 1st August 2000
4	Int diam – 1.20m Height - 2.12m Block layers – 14 Total blocks – 210	2,400	April	Full to capacity as of 1st August 2000
5	Int diam – 1.20m Height - 2.12m Block layers – 14 Total blocks – 210	2,400	May	Full to capacity as of 1st August 2000

One tank that ruptured when trying to fill it with water had the following dimensions:

Int. Dia = 1.67 m
Height = 3.80 m
Blocks/layer = 19
No. of layers = 28
Capacity = 8.324 litres

Tank ruptured when about 2.5m full.

Possible causes of tank failure:

(i) Diameter too large, hence insufficient hoop strength
(ii) Filled too quickly with a tanker – this does not give the waterproofing agent time to work properly

(iii) Blocks from volcanic soil seem not to have been stabilised – broken blocks disintegrated completely when soaked in water. This could be due to poor workmanship, although the building team are known and trusted.

(Figure AII.1 – Tank built for experimental tests in Uganda)

(Figure AII.2 – failure of the SSB tank was catastrophic – the debris remaining after failure is shown here)

APPENDIX III - Sieve analysis for soil used at Kyera Farm

mm	% passing	%retained	Classification
50.0000	100	0	Pebbles 0%
37.5000	100	0	
20.0000	97	3	Gravel 21%
10.0000	94	3	
6.3000	87	7	
5.0000	84	3	
2.0000	79	5	
0.6000	75	4	Coarse sand 17%
0.4250	73	2	
0.3000	68	5	
0.2120	62	6	
0.1500	52	10	Fine sand 17%
0.0630	45	7	
0.0600	43	2	Silts 10%
0.0579	42	1	
0.0411	40	2	
0.0258	38	2	
0.0202	35	3	
0.0148	25	10	Fine silts 19%
0.0107	23	2	
0.0076	22	1	
0.0054	22	0	
0.0044	20	2	
0.0038	20	0	
0.0034	19	1	
0.0031	19	0	
0.0028	18	1	
0.0027	16	2	
0.0016	15	1	Clays 16%
<0.0016		15	

APPENDIX IV – Rammed Earth Tank Construction Guidelines

Including Shuttering and Rammer Drawings