INVESTIGATING THE COMPRESSIVE STRENGTH OF PLASTIC BOTTLES AS MASONRY

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CERTIFICATE OF ORIGINALITY

I hereby declare that this thesis entitled, “Investigating the Compressive Strength of plastic bottles as masonry” is the product of my own work except as cited in the references.

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Supervisor: Prof. Paul Thomas

Signature :________________________________

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Date : 6 June 2011

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This report has only been made possible with the help of many parties.

Above all, I would like to pay tribute to the incontrovertible help of GOD the almighty to have taken care of me through this course while ferreting knowledge that change the course of 'History'.

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DEDICATION

I dedicate this thesis to My father Kalumire Germain and my mother Zirimwabagabo Euphrasie for their love, support and patience.

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ABBREVIATIONS

- **PETE:** Polyethylene Terephthalate Ethylene
- **UN Habitat:** United Nations Human Settlements Programme
- **BPA:** Bisphenol A
- **UNESCO:** United Nations Educational, Scientific and Cultural Organi- -sation
- **ASTM:** American Society For Testing Materials
- **NZS :** New Zealand Standard
- **URE:** Unstabilised Rammed earth
- **SRE :** Stabilised Rammed Earth
- **MJ :** Mega Joule
- **kwh:** Kilo watt hour
- **GGBS :** Ground Granulated Blast-furnace Slag
- **HDPE :** High Density Polyethylene
- **f_u :** Average compressive strength of PETE bottles unit
- **f'_m :** Compressive strength of PETE bottles prism

ABSTRACT

Plastic bottles are increasingly becoming a menace to the environment due to the chemicals used in the manufacture, improper use and disposal. As noted by Plastics Industry (2011) reusing plastic bottles may seem safe , but a chemical found in reusable plastic bottles, known as Bisphenol A (BPA), is suspected of posing a health risk to humanbeings. Hence, the safest way of disposing plastic bottles is to recycle them, particularly they can be used in the construction of low cost housing. The UN Habitat for humanity (2007) rightly points out that the housing shortage particularly in Uganda ranges from 33% to 90% and it is estimated that approximately 60% of the Ugandan population lives in slums and shantytowns. Building with plastic bottles masonry is a possible solution to provide low cost housing to the housing shortage issues in Uganda.

Some people around the world have demonstrated that it is possible to build houses using plastic bottles filled with soil as masonry. For example, some eco-friendly projects have been achieved in Honduras, Central America by a non governmental organisation, Eco-Tech founded by Andreas Froese. However, there is a lack of engineering data about this earthen material that could be utilised by architects and engineers to inform theirs design construction decisions. This research provides a basic structural data about the plastic bottle masonry notably the compressive strength of the PETE bottles filled with damp soil as well as their compressive strength in masonry, and the type and properties of the soil used to fill the bottles along with the type and properties of the soil used for the mortar joints as a masonry manifests distinct properties due to the influence of the mortar joints (Kerali *et al.* 2007).

Keywords: Plastic, Bottles, Earth, Masonry, Compressive, Strength, Moisture

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

Despite the fact that soil remains one of the abundant and the oldest material with a long ancestral tradition in Uganda (Kerali *et al,* 2007), and it is also considered as being strong for construction, it is nevertheless not long-lasting on its own as it has little resistance when it is exposed to water. Duggal (2003) points out that the best way to provide adequate strength to soil is to stabilise it with stabilising agents such as lime and cement in low quantity. However, encapsulating damp unstabilsed soil in the plastic bottles resolves better its hurdle with water and moisture than stabilising agents, as the plastic bottles help to protect their contents, being a weather resistant material (Rajput , 2007). This reduces considerably the amount of stabilising agent that would have been used for the equivalent stabilised compressed earth blocks, hence the use of unstabilesd soil improves the PETE masonry low embodied energy rate.

Adam *et al* (2001) reveal the importance of mortars in bonding masonry components. They are utilised mainly to provide regularities in size, shape and surface finishes of blocks hence accommodating uniformity and stability to a wall. In doing so, any gaps between blocks are closed , preventing wind and rain from passing through the wall. He continues by saying that mortar has a further purpose in that it has some binding characteristics which improve both shear and compressive strength of the wall. For earth blocks construction there are various types of mortars that can be used for bonding the blockwork such as mud, lime and sand mixes, pozzolana, cement and sand mixes, cement and mud mixes, pulverised fuel ashes, and gypsum plaster.

According to Adam *et al* (2001) many factors contribute to the choice of mortar notably the availability and the quality of the materials, the design of the building, the economic aspects of the project, or the issues of durability.

In this research mud and cement-mud mix mortars are used for bonding the PETE bottles, and comparative analysis is made to reveal which mortar provides the best compressive strength to the wall specimen.

However, we assume that the bonding between the mortar and the PETE bottles is very poor because of the nature of the PETE bottles. As Rajput (2007) points out, PETE bottles are thermoplastic materials, they are linear polymers and their properties such as a high chemical resistance quality, high resistance to deterioration by moisture give them a very poor adhesive properties with mud and cement. Noteworthy, Plastic Industry (2011) makes clear that plastic bottles offer protection from impact damage, as well as from water and chemicals which might contaminate the contents of the bottle. This contribute considerably to the durability property of the PETE bottles, thus plastic masonry, should theoretically last for more than 1000 years before they start biodegrading (Rajput , 2007).

Jenkin (2006) draws attention to the fact that although earthen wall subjected to vertical loads responds well in compression, it still has a maximum load bearing capacity under which the maximum allowable stress is set. If it is exceeded, the wall is subjected to a number of failure mechanisms such as plane shearing, shear cracking and particurlarly delamination of the compaction planes for rammed earth, that lead to the collapse of the wall structure. Also, a wall may not perform its intended functions due to water penetration, and poor finishes (Jenkin, 2006). This is also applicable to PETE bottles masonry as its structural behaviour should be similar to the one of a typical earth wall structure.

Hence, it is important to have data on the maximum allowable stress that the PETE masonry can bear and the type of soil to be used for a confident design. This research intends to investigate the compressive strength of the PETE masonry to give engineers and architects basic data on the maximum load that a PETE wall can carry for a safe design. To achieve this objective, PETE bottles were filled with damp soil, bottles wall specimens were produced in laboratory environment. The bottles wall specimens were subjected to destructive tests, while 11 units (PETE bottles) were crushed to failure and theirs respective compressive strength was recorded.

1.2 PROBLEM STATEMENT

This research has been driven by two main concerns. First, the thriving problem with plastic bottle environmental issues. According to ENSO Bottles (2009), in the the 1960s plastic bottle production has been negligible but over the years there was an alarming increase in bottles produced and sold but the rate of recycling is still very low (see Fig 1). The PETE bottles that are not recycled end up in landfills or as litter, and they take approximately 1000 years to biodegrade (Rajput , 2007). This has resulted in plastic pollution problems in landfills (See Fig 2), water ways and on the roadside, and this problem continues to grow along with the plastic bottle industry.

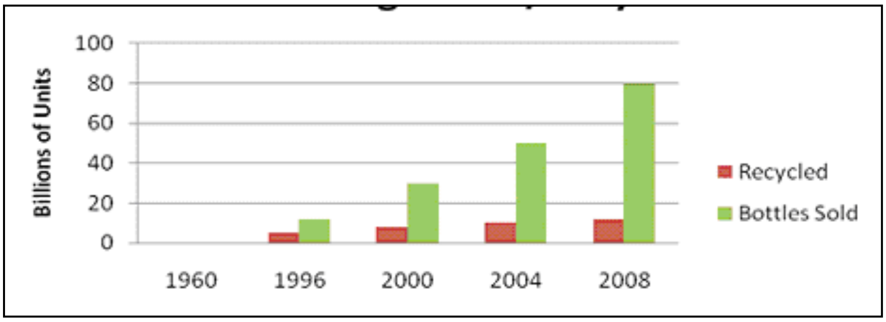


Figure 1: PET Bottles sales/recycled. Source: ENSO Bottles, 2009

Figure 2: PET bottles piled up as mountain of waste in Mperere landfill, Kampala Photo by Author, 2009

Second, the application of PETE bottles in construction as masonry without any structural behaviour data. This can provide a good amount of confidence in safety and durability design of structures built with PETE bottles. As a response to the PETE environmental concerns such individual (See Fig 3) and firm (See Fig 4 and Fig 5) such as Michael Reynolds (known as The garbage warrior), Echo-Tech (founded by Andrea Froese), and BUVAD (Butakoola Village Association for Development, a Ugandan Commmunity based organistion), took the innovative initiative of using PETE bottles as masonry. Unfortunately, none of them has done any investigation concerning the strength and structural behaviour of the PETE bottles as masonry

Figure 3: Michael Reynolds building a structure with cans bottles . Source: Bernard , 2008

Figure 4: Andrea Froeses standing near one of his PET bottles project. Photo by Andrea Froese

Fig 5: BUVAD project in Kayunga, Uganda. Source: Elizabeth, 2011

Furthermore, not all soils are suitable for construction. First the type of soil used to fill the bottles may have an influence on the strength of the PETE bottle masonry in the same frame of reference with earthen material. For example, Adam *et al* (2001) clearly draw attention to the fact that the compressive strength of compressed stabilised earth building blocks depends on the soil type, the compaction pressure used to form the block, and the type and amount of stabiliser. Second, the types of soil for optimum combination of cement stabilised mortar and the ratio of the mix of this cement-soil combination is difficult to determine and predict.

1.3 RESEARCH OBJECTIVES

The raison d'être of this research is to investigate the physical properties (density), the mechanical properties (strength) of PETE bottles masonry and the type and properties (Plastic limit) of the soil used to fill the PETE bottles as well as the soil used for the mortars. For this research, two soil samples were studied to identify the relationship between the soil type and the strength of the PETE bottles wall specimen produced.

In this dissertation the major task is to find out :

- the type and properties of the soil used to produce the PETE bottles wall specimen to appreciate which soil is more suitable for the PETE bottle masonry
- the moisture content of the soil used to fill the PETE bottles in order to evaluate the strength of the PETE bottles masonry in compliance with the compaction level of the soil in the bottle,
- the density of the PETE bottles along with the prism specimen to estimate the strength in comparison with rammed earth and stabilised compressed earth blocks (SCEB),
- the compressive strength of the PETE bottles as well as the compressive strength of the prisms specimen to get the allowable working stress for the PETE bottles masonry.

1.4 SCOPE

The scope of this research entails, first the research on the effect of the types of soil used to produce the PETE bottles masonry. Two types of soil samples were taken from two different locations in Nkozi, Uganda. Soil sample A was utilised as the infill main material for the PETE bottles prism specimen. The infill soil was damp soil with a moisture content amounting to 10 percent. Both soil samples A and B were used for the mortar and the stabilised mortar was made with the ratio 1:15 for cement and soil. The quantity of water added into the mix was 20 percent from overall dry weight of the cement and soil was used. A slump test and flow test was conducted to evaluate the consistency of the fresh mortar.

The standard test for soil classification was performed to identify the type and properties of the soil. The tests are sedimentation test and dry sieving method. Due to the laboratory limitation in testing instrument, the cone penetrometer method test to determine the liquid limit of the soil samples was not conducted.

The compressive strength of the PETE bottles and the compressive strength of the bottles wall specimen are obtained by a destructive test which was conducted by using compressive strength test on the 14th day. These tests are based on the specification of NZS 4298:1998. The new Zealand standards on earth buildings was the main standard adopted because of limitations in building construction standards manuals. Most of them wer rather expensive.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

PETE bottles, plastic rope, soil, portland cement, and water are the main material components to produce the PETE bottles masonry. Unfortunately there is no research that has ever been undertaken to determine structural behaviour of PETE bottles as masonry and that could have been an appropriate source of reference for a literature review in guiding this research . The few attempt that have been performed in building structure with PETE bottles were made by means of ‘trial and error according to Froese (Personal communication, 2008).

Consequently, I opted for a literature review dealing with earth materials notably rammed earth and stabilised compressed earth blocks to gather data on the materials used to produce earthen masonries such as soil types and properties, cement , and mechanical properties of earthen masonries. Furthermore, the literature review armed the research with a short history on bottles practice in construction to understand the reason why people used it in building their homes.

2.2 Application of Bottles In Construction

The application of bottles in construction is not a very recent technology. Seltzer (2000) reveals that the first example of known structure built with bottles is the William F. Peck's Bottle House (see Fig 5) located in Nevada (USA). It was built around 1902, and it required 10,000 beer bottles to be built.

Figure 6: William F. Peck's Bottle House. Source: Seltzer (2000)

Seltzer (2000) points out that because of the shortage of building materials, early mining camp settlers in Tonopah (Nevada) constructed their home out of unexpected innumerable objects collected at random. This included discarded bottles, coal oil cans and barrels, just to cite a few. These buildings were primarily made out of glass bottles used as masonry units (See Fig 6) and they were bound using mortar made out of adobe, sand, cement, clay and plaster (Krepcio, 2007).

In the course of time the phenomenon of bottle house spread all over North America and around the world especially in the region where there was an increase in housing demand due to population growth, and also where there was scarcity of building materials such as Argentina, Australia, Brazil, Japan, Russia and Serbia (Seltzer, 2000). The most famous examples are the Kaleva Bottle House (see Fig 7) - it houses now the Kaleva Historical Museum- built by John Makinen in the 1940's in Kaleva (Michigan) with bottles from a local bottling plant, and the Grandma Prisbrey's Bottle Village (see Fig 8 an 9) built

Figure 7:Bottle Brick montage. Source: Krepcio (2007)

in between 1956 and 1980 and it presents a succession of 13 sheds and other small structures on a small lot of land in Simi Valley, California (USA)

Figure 8: Kaleva Bottle House

Source: Krepcio (2007)

Figure 9: Grandma Prisbrey's Bottle Village exterior view

Source: Krepcio (2007)

Figure 10: Interior of one building of Grandma Prisbrey's Bottle Village

Source: Krepcio (2007)

However, plastic bottles praxis in construction is recent and it was adopted by such individuals and firm such as Michael Reynolds, known as The garbage warrior, Echo-Tech, founded by Andrea Froese, and BUVAD, a Ugandan community based organisation, in search of possible solution to the environmental concern of plastic bottles as well as seeking material for low cost housing to inspire cities that suffer from insufficient adequate housing.

2.3 RAMMED EARTH: A REVIEW

Maniatidis *et al* (2003) reveal that rammed earth (or pisé) is an ancient technique that dates back to at least 7000 BC in Pakistan. It has been used in many structures around the world , most notably in part of the great wall of China.

Rammed earth is form of soil that is just damp enough to hold together. The soil is tamped between shutters well supported to prevent lateral expansion with pneumatic tamper or hand hammers, and the compaction is normally done in 100-150mm layers
(Jaquin et al, 2009).

The work of Maniatidis *et al* (2003) reveals that rammed earth walls are often left as they are 'off form', and they can show a natural-looking strata pattern from the ramming process. Consistent workmanship is critical for both the appearance and the strength of rammed earth walls, so they indicate that site work has to be of high quality because an area of wall that is not mixed or rammed correctly can ruin the whole panel.

However, Jaquin *et al* (2009) states that one difficulty with the rammed earth method is that strict limits have to be placed on shrinkage to eliminate cracking. He draws attention to the fact that many soil types need sand to be added to reduce shrinkage. He refers to NZS 4298 for shrinkage preconstruction tests and the appropriate limits, compression and durability tests, and a simple on-site test for moisture content. He concludes that often cement or hydrated lime is added to improve the compressive strength and the durability of rammed earth , but successful structures are built using suitable soils without such additives.

A sandy crumbly soil (with a clay content around 15-30%) is best, as it is easily worked and has minimal shrinkage (Jaquin et al, 2009).

2.3.1 Advantages and limitations

Rammed earth construction is one cheap way of providing low cost housing since earth is an abundant resource, and a simple mechanism is used with semiskilled labour to produce it (Odul *et al*, 1985) . However, when using rammed earth as a low cost construction material for housing it should not be assumed that all housing problems will disappear (Maniatidis *et al,* 2003). They reveal that the advantages and limitations of rammed earth construction are multiple and complementary and they are as follow:

2.3.1.1 Advantages

- Ideally, its production is made on site itself or in the nearby area. Thus, it saves transportation, fuel, time and money. An appropriate use of materials considerably reduces construction cost and hence stimulates the economy;
- Well-designed rammed earth houses can withstand bad weather conditions without being damaged. Rammed earth walls are strong in compression and they can also be made strong in shear and tension through additives and reinforcement;
- Firewood is not needed to produce rammed earth . This saves forests, which are being depleted quickly particularly in Uganda, due to short view developments and mismanagement of resources. Also, rammed earth is ecologically friendly and its manufacture consumes less energy and pollutes less than fired bricks;

- Rammed earth walls are ideally suited for passive solar construction as they pro vides the natural comforts of balanced temperatures, humidity and noise control;
- Rammed earth is very good in fire resistance;
- Being produced locally, it is easily adapted to various needs: technical, social and cultural habits;
- It is a simple technology requiring semi skills and it is easy to get. Simple villagers will be able to learn how to do it in a few weeks. It allows also unskilled and unemployed people to learn a skill, get a job and rise in the social scale;
- The equipment for rammed earth is available from manual to motorized tools ranging from village to semi industry scale. They draw attention to the fact that the selection of the equipment is crucial, but once done properly, it will be easy to use the best adapted equipment for each case;
- Rammed earth can adapt itself to various needs, from poor income groups to well off people or government needs. Its quality, regularity and style allow a wide range of final house products (Maniatidis *et al* 2003, Jaquin *et al*, 2009, and Odul *et al*, 1985)

2.3.1.2 Limitations

According to the above rammed earth construction is advantageous, but there is some drawbacks of earth construction technology that makes it sometimes unpopular amongst professionals. According to Odul *et al* (1985) the two historical disadvantage of rammed earth has been water damage and labour intensity.

Odul *et al* (1985) reveal that the Australians solved the water damage by spraying the wall with a transparent plastic ideal for wall cleaning with a damp sponge, and labour intensity has been solved by the use of pneumatic powered tamping devices.

Maniatidis *et al* (2003) list the following weaknesses of unstabilsed rammed in building construction:

- It has extremely low tensile strength and its low load bearing capacity makes it unsuitable for supporting heavy roofs from large span building.
- It has a very high moisture absorption ratio which also contribute to its structural failure.
- When proper soil is not used, unstabilised rammed earth (URE) has a low binding strength for its particles and this contributes to its low compression strength.
- URE has a very high shrinkage and swelling ratio resulting in major structural cracks when exposed to different weather conditions.
- It has a low social acceptance due to counter examples by unskilled people, or bad soil and equipment.

2.3.2 Material for rammed earth

According to Maniatidis *et al* (2003) the evaluation and selection of soil for rammed earth is done by means of testing its particle size distribution by sieving and sedimentation. However, a study by Keable (1994 cited by Maniatidis *et al,* 2003) acknowledge the fact that the effect of difference in grading the physical characteristics of rammed earth still remains unclear.

Jaquin *et al* (2009) advises that in selecting soil for rammed earth first organic materials content should be avoided as they may lead to high shrinkage and possible bio deterioration as well as increasing susceptibility to insect attack, and they can interfere with action of stabilizers such as cement.

Furthermore Jaquin *et al* (2009) classifies engineering soils based on the relative size proportion of their main elements, namely gravel, sand, silt and clay. The New Zealand Standard grading limits used in the work are:

- Gravel: 60 mm to 2 mm
- Sand: 2.00mm to 0.06mm
- Silt: 0.06mm to 0.002mm
- Clay: less than 0.002mm

According to Maniatidis *et al* (2003) a wide variety of sub-soils have been used for natural rammed earth buildings, with the exception of uniform coarse sands and gravels with no cementing agents. Ideally the soil should have a high sand/gravel content, with some silt and just enough clay to act as a binder and help soil compaction. Any material coarser than 5-10mm should be sieved out (Maniatidis *et al,* 2003). They indicate that increasing gravel size reduces the compressive strength of rammed earth cylinders.

Maniatidis *et al* (2003) recommend that the minimum percentage of combined clay and silt should be between 20%-25% while the maximum between 30%-35%. Similarly, the minimum percentage of combined sand and gravel should be between 50%-55% while the maximum is between 70%-75%. They specify also soil for cement stabilized rammed earth. They indicate that the soil for cement stabilised rammed earth tends to have proportionally higher sand and gravel content and correspondingly lower fines content. They suggest that soil suitable for cement stabilization should have a significant sand content, at least greater than 50% and preferably closer to 75%, and at the same time low clay content, typically less than 25%.

Moreover, Maniatidis *et al* (2003) specify the liquid and plastic limit of unstabilised rammed earth. They describe soil plasticity as the ability of a soil to undergo unchangeable deformation while resisting an increase in loading.

According to Houben *et al* (1994 cited by Maniatidis *et al,* 2003) liquid limit for unstabilized rammed earth should be between 25% and 50% and the plastic limit between 10% and 25%). Jaquin *et al* (2009) propose additionally a Plasticity index as low as 15%. He reveals that plasticity index is the numerical difference between liquid and plastic limits. The plasticity index is an indication of the clay content and characteristics of the soil. The higher plasticity index is indicative of higher clay content and/or active clay mineral and that higher shrinkage will occur when the earth dries.

2.3.3 Properties of rammed earth

2.3.3.1 Dry density

Maniatidis *et al* (2003) draw attention to the fact that the dry density of soil in rammed earth applications is dependant on soil type and the moisture content during compaction. They indicate that knowledge of the dry density of rammed earth is important during design to calculate load for structural elements. A broad range of dry density values are provided for rammed earth, varying from 1,700 kg/m3 to 2,200 kg/m3 (Houben *et al*, 1994 cited by Maniatidis *et al,* 2003).

In order to achieve maximum density, Jaquin *et al* (2009) point out that it is important that the optimum moisture content, appropriate to the method of compaction, is used when ramming. They encourage a first approximation of the optimum moisture content by using the ‘drop test’. They describe the procedure as follow:

-a ball of moist soil, approximately 40 mm diameter, is compacted by hand.

-when prepared the soil ball is dropped onto a hard flat surface from a height of approximately 1.5m.

-when the soil is too dry the ball breaks into many pieces.

-when enough water has been added so that the ball breaks into only a few pieces, the soil is very close to its optimum moisture content. If the ball remains in one piece then the soil is too wet.

2.3.3.2 Compressive Strength

According to Jaquin *et al*(2009) the strength of rammed earth is very much dependent on the voids ratio of the soil after ramming, cohesive strength of fines content, aggregate strength and moisture condition during testing. He points out the fact that the density of the soil is a very important factor for the strength of the soil. Therefore, in the same way that it is difficult to give a specific value for the density, it is impossible to predict an exact value for the mechanical strength of a soil based on any kind of description with no laboratory testing.

The laboratory tests used for determining the compressive strength of rammed earth are similar to the ones used for concrete, bricks and blocks (Maniatidis *et al,* 2003).

A summary of the required specimen details for compression strength testing according to various standards around the world is presented in Table 1.

Maniatidis *et al* (2003) outline that the compressive strength is usually expressed in terms of the characteristic value and a height/width correction factor may be applied. The recommended design values for rammed earth are summarised in Table 2.

As stated previously the presence of cement increases the strength of rammed earth.

Hence the values proposed by different authors, as presented in Table 3, tend to be much higher that the ones proposed for unstabilised rammed earth.

Table 1: Compressive strength test specimen details for Rammed Earth.

Source: Maniatidis *et al*., (2003)

Reference	**Specimen details**					
	Cylinder		**Prism**			**Minimum number of specimens required**
	Diameter (mm)	**Height (mm)**	**Height (mm)**	**Length (mm)**	**Width (mm)**	
Bulletin 5; Earth-Wall Construction, CSIRO	150	110	150	150	1.3 x h	5
Standards Aus-tralia, 2002	150	300	N/A	N/A	N/A	1 sample for every 25-100m2
New Mexico Adobe & Rammed Earth Building Code (Tibbets, 2001)	N/A	N/A	102	102	102	N/S
NZS	N/A	N/A	N/S	N/S	2xh	5

Table 2: Compressive srtength for URE. Source: Maniatidis *et al*., (2003)

Reference	Compressive Strength
Bulletin 5; (Middleton, 1992)	0.7 N/mm^2
Standards Australia, 2002	0.4 - 0.6 N/mm^2
Standards Australia, 2002	0.5 N/mm^2

Table 3: Compressive Strength for Cement SRE. Source: Maniatidis *et al*., (2003)

Compressive Strength (N/mm2)			
	ACI Materials Journal Committee, 1990	Standards Australia, 2002	Houben *et al*., 1994
Sandy and gravely soils	2.76-6.89	-	-
Silty soils	2.07-6.21	-	-
Clayey soils	1.72-4.14	-	-
Cement Stabilized Rammed Earth	-	1-15	2-5

Altogether material selection is important to the quality of rammed earth. According to Jaquin *et al* (2009) the properties of soils used for rammed earth may be appraised using a variety of physical characteristics, including grading and plasticity. Maniatidis *et al* (2003) point out that recommendations for soil grading vary between reference documents, although there is broad general agreement. Nevertheless, they put across the fact that unsuitable soils can be readily identified by means of standard soil characterisation tests, such as grading. The physical characteristics of rammed earth may be measured in terms of its dry density, strength, surface finish and thermal properties (Jaquin *et al*,2009). They affirm that the physical properties are strongly related to material density.

Odul *et al* (1985) rightly point out that cement stabilisation is widely used to improve strength and durability of rammed earth. The evidence seems to indicate that Cement stabilisation improves the problems associated with using soil. Other forms of stabilisers, such as lime and natural fibres, are less widely used in rammed earth (Odul *et al*, 1985). In summary, soils suitable for rammed earth houses are broad and include sands with sufficient clay and silt, clayey silts, clayey gravels and gravel-sand-clay mixtures

2.4 STABILISED COMPRESSED EARTH BLOCKS: A REVIEW

The work of Deboucha (2011) reveals that compressed earth blocks (or bricks) is one of the contemporary lineage to the earth building technology more commonly known as the adobe block, dating from the 19th century.

Turning to Adams *et al* (2011), one finds that the approach of compacting earth to ameliorate the quality of moulded earth blocks is, however, far from new, and it was with wooden tamps that the first compressed earth blocks were produced. Odul *et al* (1985) similarly point out that the first devices for compressing earth probably date from the 18th century; in France, Francois Cointeraux, inventor of “New pisé” (rammed earth) designed the “Crecisé”, a device derived from a wine-press.

But the turning point with the use of presses and the way in which compressed earth blocks were used for architectural aims surged from 1952, following the invention of the famous Cinva-Ram press, designed by the engineer Raul Ramirez at the CINVA Centre in Bogota, as a result of a research programme for affordable houses in Colombia (Maïni, 2009)

According to Adams *et al* (2011) making compressed earth blocks in manual or motorised operated presses is now widespread practice around the world. He makes clear that the soil, raw or stabilised, for compressed earth blocks is a bit moistened, poured into a steel press and then compressed. Obonyo *et al* (2010) similarly draws attention to the fact that the contribution of soil stabilisation made it feasible to build storied buildings with thinner walls, which have a much better compressive strength and water resistance. Obonyo *et al* (2010) point out that with cement stabilisation, the blocks are cured for four weeks after manufacturing, and after this period of time, they are dry and can be used like common bricks with a soil cement stabilised mortar.

Rigassi (1985) asserts that the blocks are made from dry mix , often stabilised with up to 10% cement. The compression given by the machine compacts the soil particles together to make dense regular shaped bricks, usually around 300 x 300 x 130 mm in size. Adams *et al* (2011) point out that these blocks are the nearest thing on earth to concrete blocks in design, construction and finish consideration . Normally, sand- cement-earth mix is used for the mortar, although often a mix hydrated lime, sand and cement perform better (Deboucha, 2011) .

2.4.1 Advantages and limitations

The advantages and limitations of SCEB are rather similar to the one of rammed earth. Adams *et al* (2011) provide a summary illustrated in table 4.-

Table 4: Advantages and limitations of SCEB. Source: Adams *et al.* (2011)

Advantages	**Limitations**
• Soil is available in large quantity in most regions • Cheap and affordable: In most parts of the world soil is easily accesible to low income -groups • Ease of use: usually no very specialised machines is required • Suitable as a construction material for most parts of the building	• Reduced durability if not regularly maintained and properly protected, particuralarly in areas affected by medium to high rainfall • Low tensile strength: poor resistance to bending moments, to be used in compression such as bearing walls, domes and vaults

Advantages	Limitations
• Fire resistant : No combustible with excellent fire resistance properties • Beneficial climatic performance in most regions due to its high thermal capacity, low thermal conductivity and porosity, thus it can moderate extreme outdoor temperatures and maintain a satisfactory internal temperature balance • Low energy input in processing an handling soil: only about 1% of the energy required to process the same volume of cement concrete. This aspect was investigated by the Desert Architecture Unit which has discovered that the energy needed to manufacture one cubic metre of soil is about 36 MJ (10 kwh) while that required for the manufacture of the same volume of concrete is about 3000 MJ (833kwh). • Environmental appropriateness	• Low resistance to abrasion and impact if not sufficiently reinforced or protected • Low acceptability among most social groups: considered by many to be a second class and generally inferior building materials • On account of these problems: Earth as a building materials lacks institutional acceptability in most countries and as a result building codes and performance standards have not been fully developed.

2.4.2 Materials for SCEB

Soil, cement, sand and water are the main material components to produce Cement stabilised Earth Block and the quality of SCEB depends concisely on the type of soil, the water content in the mix, the type of press, the type and quantity of stabiliser, and the cure.

2.4.2.1 Soil type

According to Adams *et al* (2011) soil is a very complex material and knowledge about it is essential to production of good quality SCEB. They point out the first step is to build with raw earth which basic composition is clay, silt and sand, but it can present many variations due to geological characteristics of the clay. According Obonyo *et al* (2010), there are field test methods used to conclude about the granulometry composition and plasticity of the suitable soil for SCEB.

Obonyo *et al* (2010) acknowledge the fact that each construction technology with earth has the soil type appropriate for it. The most convenient soil for the production of adobes, for examples, is not good for obtaining rammed earth. They advise that in collecting the soil tests suitable to the production of SCEB, it should be taken without organic matter and other impurities and should be sieved through a 4 to 5 mm screen. They make clear that it is desirable that the soil has 10 to 20% of clay, 10 to 20% of silt, 50 to 70% of sand, and it is convenient that the soil has a plasticity and a no high liquid limit, in general 40 to 45%

2.4.2.2 Stabilisation

Stabilization is necessary to achieve a lasting structure, made out of SCEB, from local soil with the soil properties determining the appropriate stabilisation method (Adams *et al*, 2011).

Rigassi (1985) points out that the main objectives of stabilisation are to obtain better mechanical performances by increasing dry and wet compressive strength; to reduce porosity and variations in volume, swelling and shrinking with moisture content variations; and improving the ability to withstand weathering by wind and rain: reducing surface abrasion and increasing waterproofing.

Stabilization techniques can be broken down into three categories, (Houben *et al*, 1994 cited by Obonyo *et al*, 2010):

- Mechanical stabilization: This method is done by compacting the soil and changing its density, compressibility, permeability and porosity;
- Physical stabilization: This approach is achieved by changing the texture properties of the soil. This can be done by controlling the mixture of different grain fractions, drying or freezing, heat treatment and electrical treatment;
- Chemical stabilization: This technique is attained by changing the properties of the soil by adding other chemicals or additives.

The compressive strength of the soil can be improved by using the right stabilisation method. This will also improve its durability by increasing its resistance to erosion and water damage (Kerali *et al*, 2007).

The main categories of binders used for SCEB construction are cement, lime, bitumen, natural fibers and chemical solutions such as silicates (Houben *et al*, 1994 cited by Obonyo *et al*, 2010) as also outlined in NZS 4298:1998, New Zealand Standard.

According to Deboucha (2011), one of the best and easily available stabiliser is the cement. 4% to 10% of cement by weight can produce SCEB of excellent quality (Kerali *et al*, 2007). They reveal that the amount of stabiliser depends on the type of soil and also the requested strength. They assert that if the soil has a lot of clay, it will demand at least 6 to 10% of cement but if the soil is excessively sandy, larger rates can be requested. If the soil has a very good grain distrubution, 4% of cement is enough to give the SCEB blocks good quality. However, Oti *et al* (2008a, cited by Deboucha 2011) alternatively suggest that the most effective alternatives to Cement is the ground granulated blast furnace flag (GGBS), which has the potential to typically replace up to 80% of the Cement. They point out that GGBS has extremely low energy usage and CO_2 emission when compared with cement. The energy usage of one ton of GGBS is 1300 MJ, with a corresponding CO_2 emission of just 0.07 ton, while the equivalent energy usage of 1 ton of cement is about 5000, with at least 1 ton of CO_2 emitted to the atmospheres MJ Higgins (2007, cited by Deboucha, 2011).

2.4.2.3 Cure

As concrete, SCEB needs to be cured to avoid the fast exit of the mixture of water. A very effective method consists of covering the blocks so soon they are made with a plastic or the new bricks can be wet for at least seven days (Kerali *et al*, 2007).

2.4.3 Properties of SCEB

Table 5: Properties of SCEB VS other walling materials. Source: Adams *et al* (2011)

Properties	SCEB	Fired clay bricks	Dense concrete blocks	Aerated concrete blocks	Lightweight concrete blocks
Wet compressive strength (N/mm^2)	1-40	5-60	7-50	2-6	2-20
Miosture Mouvement(%)	0.002-0.2	0.00-0.02	0.02-0.005	0.05-0.10	0.04-0.08
Density(Kg/m3)	1700-2200	1600-2100	1700-2200	400-950	600-1600
Thermal conductivity (W/m˚C)	0.81-1.04	0.70-1.04	1.00-1.70	0.10-0.20	O.15-0.70

2.4.3.1 Density and thermal properties

According to Adams *et al.* (2011) SCEB are denser than several concrete masonry products such as aerated and lightweight concrete blocks, and various types of bricks have densities within their same range of for example: clay, and concrete bricks The high density of SCEB may be considered as disadvantage when the blocks have to be transported over a long distance, however, it is too little consequence when they are produced at or near the construction site (Adams *et al*, 2011) .

2.4.3.2 Moisture movement

Building materials with high porosity when used for wall construction may expand slightly in wet and dry conditions and such movement may result in cracking and other defects to the building (Adams *et al*, 2011). Deboucha (2011) points that expension of SCEB may vary according to the properties of the soil, some soils expand or shrink more than others. However, Adams *et al* (2011) point out that the addition of a stabiliser reduces this expansion. Nevertheless, there may be greater movement in structures built with SCEB than those using alternative construction materials. However, Proper manufacture and construction methods will reduce such movement (Deboucha, 2011).

2.4.3.3 Compressive strength

The above discussion reveals that the compressive strength of stabilized compressed earth building blocks (that is, the amount of pressure can resist without collapsing) depends upon the soil type, type and amount of stabilizer and the compaction pressure used to form the block. Furthermore, the maximum strengths are obtained by proper mixing of suitable materials and proper compacting and curing (Deboucha, 2011). In practice, Adams *et al* (2011) assert that typical wet compressive strengths for compressed stabilized earth building blocks may be less than 4 N/mm^2.

They reveal that some soil when stabilised with hydrated high calcium lime give wet compressive strengths in the range of 6 - 8 N/mm^2, strength suitable for many building purposes. It also competes favourably, for example, with the minimum British Standard requirements of 2.8 N/mm^2 for precast concrete masonry units and load bearing fired clay blocks and of 5.2 N/mm^2 for bricks (Deboucha, 2011). He continues by saying that where building loads are small (e.g. in the case of single storey constructions), a compressive strength of 1 - 4 N/mm^2 may be sufficient.

CHAPTER 3

EXPERIMENTAL WORK

3.1 Methods And Methodology

A normative and positivism paradgim research methodology encompassing an exploratory and experimental research (Olweny, 2010) was used to collect data for assessing the compressive strength of the PETE bottles as masonry. A background study and a literature review were conducted to arm the research with methods of investigating the compressive strength of earthen materials with particular attention to rammed earth and stabilised compressed earth blocks.

PETE bottles were collected from the surrounding community. The size of the bottles amounted to 60mm diameter, 200mm length, the bottle top diameter 30 mm, and 500ml volume. The PETE bottles were filled with the soil specimen (tagged as SI-UMU-A), gathered from a site located in Nkozi as described in Appendix A.

The soil properties test of the soil specimen SI-UMU-A, SM-UMU-A and SM-UMU-B, were carried out to identify the type of soil and soil properties of the soil. These tests included

Sedimentation test, Moisture Content Test, Dry Sieve Analysis and Plastic Limit Test. The liquid limit test was not carried out because of equipment limitations. These tests were carried out to provide information about the granulometric composition and plasticity of the soil specimen, to identify the relationship between properties of the soil and the strength of the PETE bottles masonry.

Specimens of cement-soil mortar prism were constructed from plastics bottles: 350mm x 200mm x 700mm. The specimen prisms, having slenderness ratio i.e. height/thickness = 3.5 were produced in the material laboratory of Uganda Martyrs University. Saman (2006) points that under the American Society of Testing and Materials (ASTM) standards C1314-03b, masonry prisms to be tested in laboratory should consist of a minimum of two units with height to thickness ratio between 1.3 and 5.

For the purpose of investigation, four PETE bottle walls were built with unstabilised mortar while four PETE bottle prisms were built with 1:15 mix ratio of cement (CM IV/ 32.5N)soil mortar, in order to determine whether the use of cement stabilisation provides more strength to PETE masonry in comparison to unstabilised earth mortar. The PETE bottles were joined together, using nylon rope that were purchased from a local hardware shop.

A first compressive strength tests was carried out on eleven PETE bottles specimens, although I scheduled to conduct compressive tests on forty PETE bottles specimens. but, the bending testing machine (used as a compressive testing machine) failed during the tests (See Fig 11).

A second compressive strength tests were performed on PETE bottle wall specimens at 14 days. According to the results of tests carried, the mortar joint has a minimum influence on the strength of PETE bottles masonry. The mortar effect on the strength of the prism specimen was only considered as providing stability factor

Figure 11: Capacitor that failed during test: Photo by Author

to the walls. Since the mortar is not taken as mere binder between the PETE bottles, its effect in the compressive strength is negligible. However, it was included in the research as it provides stability to the PETE bottles masonry.

3.2 Materials for PETE bottle masonry

3.2.1 Soil

The soil specimens (see table 8) were taken from two different sites as described in Appenix A. Samples were extracted from excavated homogenous layers and below approximately two meter from the top of soil to make sure that all the organic matters were not included in sample.

The weight and quantity of the samples were dependent on the number of PETE bottles wall specimens that was prepared for the test and with some additional soil to conduct the soil tests. Each prism specimen required 54 PETE bottles.

The soil sample SM-UMU-A contained various sizes of grain, from very fine dust up to pieces that were too large to be used for the mortar. Thus, the oversized elements were manually removed (see Fig 12), using a 4mm screen. For this research, 3 types of standard tests for soil classification was performed to determine the properties of the soil .

These tests are sedimentation test, dry sieving method, and test for determining plastic limit.

Table 6: Annotation for soil specimen

Annotation	Meaning
SI	Soil used to fill the bottles
SM	Soil used for the mortar
A and B	Type of soil in relation to the location

Figure 12: Sieving the soil specimen SM-UMU-A. Source: Personal collection

Before filling the PETE bottles, the soil specimen SI-UMU-A were tested to ensure that it fulfilled the requirement outlined in the literature review, established for earthen masonries. The soil test was conducted also on the soil Specimen SM-UMU-A and SM-UMU-B. These tests were carried out in laboratory environment and they conformed the specifications of the NZS 4298:1998.

3.2.2 PETE Bottles

Polyethylene Terephthalate Ethylene (PETE) bottles are thermosplastic materials (Rajput, 2007). He asserts that this type of plastic are polymers and with or without cross-linking and branching, and they soften on the application of heat, with or without pressure and require cooling to be set to a shape.

The following properties of polyethylenes are pointed out by Rajput (2007)

- Wax like in appearance, translucent, odoureless and one of the lightest plastics.
- Flexible over a wide temperature.
- High dialectic strength.
- Chemically resistant.
- Do not absorb moisture.
- Their dielectric losses and dielectric constant are low

Furthermore, Rajput (2007) and The Engineering ToolBox (2011) provide mechanical properties of HDPE (High Density polyethylene) that can be affiliated to PETE mechanical properties and they are shown in table 7.

Although, the PETE bottles when filled with soil is not theoretically homogenous and continuous, it will be considered as a composite material because it is made of two materials: PETE bottles and soil. According to Thomas (2008), a composite materials is composed of two different materials featured by their modulus of elasticity and their allowable working stress. But in order to engage in any structural calculation method, Thomas (2008) accurately draws attention to the fact that some general hypothesis should be set such as:

- A material is continuous (no gaps), homogeneous (same properties in all points) and isotropic (same properties in all direction) .
- A plane section perpendicular to the centre line of the element, before loading remain plane and perpendicular to the centre-line after loading (Navier, 1826 and Bernoulli, 1694 cited by Thomas, 2008).
- It is assumed that elastic deformations are very small compared to the cross-sectional sizes of the element. Therefore, deflections do not alter the horizontal position of the loads and the internal forces remain regular.
- The principle of BARRE de St VENANT. It suggests that the manner the loads are operating has only a confined impact and the difference between two loading systems fade rather rapidly when one moves away from the point of application of the loads .

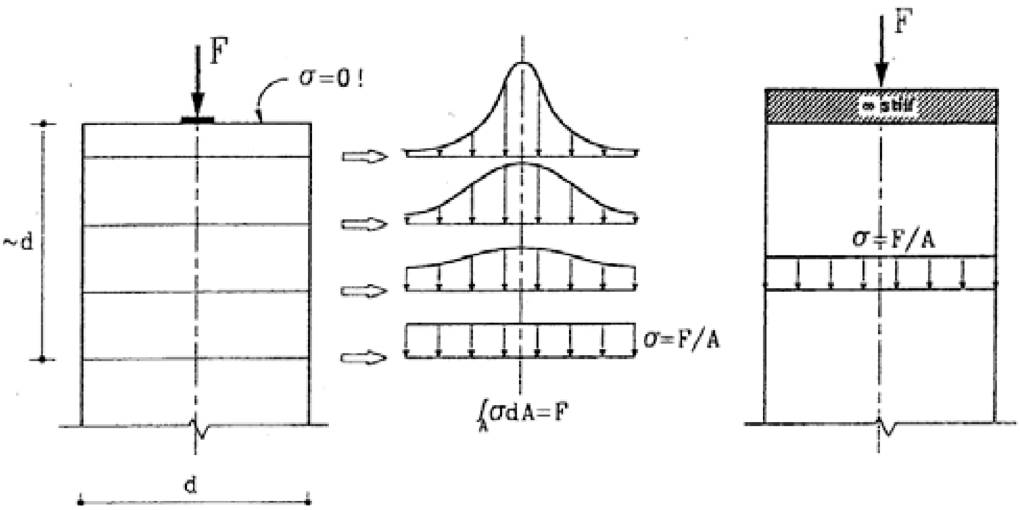


Figure13: Distribution of stress over a vertical axially loaded element

Source: Thomas (2008)

Bearing in mind that mechanical properties of PETE bottles (see Fig 14), when set side by side with HDPE mechanical properties, may have an influence on PETE bottles masonry structural behaviour, the above may help in further PETE bottles masonry structural investigations.

Table 7: Mechanical properties of HDPE. Source (Rajput, 2007)

Properties	**HDPE(High density Polyethylene)**
Density (kg/m^3)	95-140
Softening point (°C)	90-100°
Thermal Conductivity (W/mK)	0.42-0.55
Thermal expension (1/K)	$120x10^{-6}$
Specific Heat Capacity (J/kg°C)	2100-2310
Tensile strength (N/mm^2)	200-300
Compressive strength (N/mm^2)	20-30
Coefficient of Friction	20-25
Young's modulus (N/mm^2)	550-1050

Figure 14: PETE bottles used in the research: Photo by author

3.2.3 Nylon Rope

Nylon rope is gotten from coal, petroleum, air and water (Rajput, 2007). It is a polyamide thermoplastic produced by series of condensation reaction between an amine and organic acides. Rajput outlines the properties of nylon as follow:

- Good abrasion resistance.
- Tough and strong but flexible too.
- High impact strength.
- Absorb water which causes reduction in strength and impact properties
- Resistant to most of the solvents and chemicals
- High softening temperatures and thus moulding becomes difficult.

Additionally, The Engineering Toolbox (2011) provides data about mechanical properties of Nylon illustrated in Table 6.

Table 8: Mechanical Properties of Rylon Rope. Source: The Engineering ToolBox (2011)

Properties	**Nylon Rope (1to 5mm)**
Weight (kg/m)	0.013
Safe Load (Safety Factor 12) (kN)	0.326
Minimum Breaking Strength (kN)	3.91
Density (kg/m^3)	1150
Tensile Modulus (N/mm^2)	2000 - 3600
Tensile Strength (N/mm^2)	82
Specific Modulus	2.52
Specific Strength	0.071
Maximum Service Temperature (^oC)	75 - 100
Yield Strength (N/mm^2)	45

Nylon rope has a very high tensile strength. As the nylon rope is used as the main binder for the PETE bottles masonry, hence further research is needed to investigate its effect on the the shear strength, the bending strength, the tensile strength, the modulus of elasticity, the shear modulus and the ductility factor on the PETE bottles masonry, as these properties are determinant for investigating the resistance of a masonry (Curtin, 2006).

The nylon rope (see fig15) that is used in this research had a diameter amounting to 3mm

Figure 15: Nylon rope used in the research
Photo by author

3.2.4 Water

Water is in a similar way like cement, an active component in mortar. For cement-sand mortar, without water no hydration can be attained, hence no strength can be achieved. Water is responsible for the workability of a fresh mortar. Although, the effect of the mortar is not taken into account in this research, as soil and cement are not able to bond with PETE bottles due to its properties, 20 percent of the overall weight of the cement and soil was used to determine the quantity of water to be used in the mix. A slump test and a flow test were conducted to evaluate the consistency of the fresh mortar.

3.3 Soil Tests

3.3.1 Sedimentation test

Although sedimentation test for fine particles presents satisfactory results Rigassi (1985) advises that sedimentation test with the addition of salt should not be exceptionally adopted because it overestimates the amount of fine fractions and does not promote efficient dispersion.

Method

The first step consists in taking a transparent cylindrical jar or bottle of at least 1/2 litre capacity that is filled with approximately 1/4 soil and 3/4 water.
The second step is to seal the top of the transparent bottle using your hand and to

shake well. After 45 minutes, the same operation is repeated. The final step is inherent in leaving the content of the bottle to settle for at least 24 hours, and afterwards the sedimentation layers are measured accordingly.

Implications

The coarse material (gravels) are set on the bottom, followed by sands, then silts, with clays at the top.

The depth of each layer gives an indication of the proportion of each type of material. These proportions are only approximate: the layer of gravel, which contains many voids, will seem relatively "deep" compared to that of clay, which will have very few voids.

Nevertheless, the test shows if the soil has a rather reasonable distribution of all types of material or if on the contrary it contains too much of one type. The relative proportions, and hence percentages, of each fraction can be determined by measuring approximatively the depth of each layer (see Fig 16 and Fig 17).The results are reported in chapter 4.

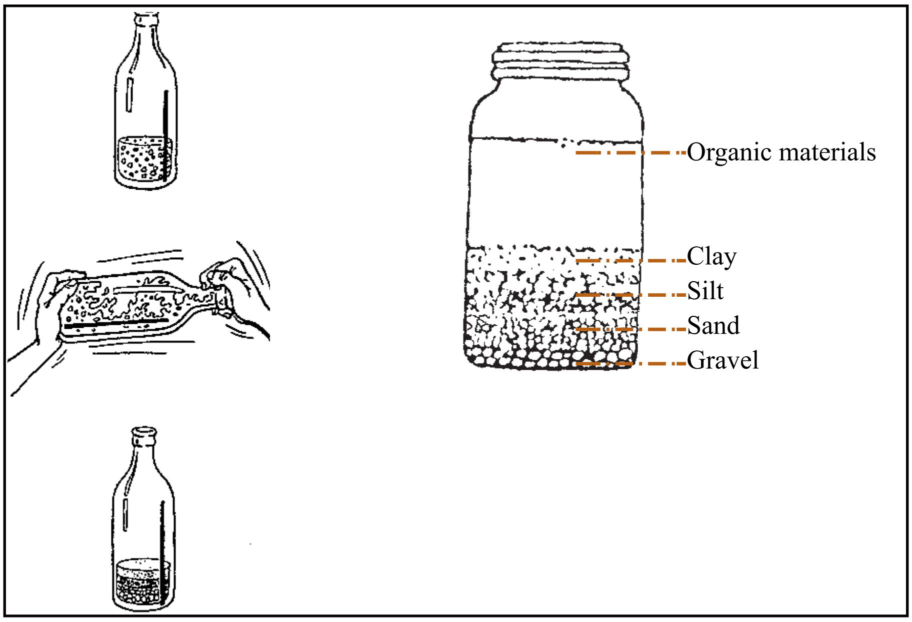


Figure 16: Sketch of sedimentation test procedure. Source: Rigassi (1985)

Figure 17: Sedimentation test showing organic materials, water, clay , silt, sand and gravel Photo by Author

3.3.2 Dry Sieving Test

Equipment

In the Uganda Martyrs University laboratory the available sieve equipment is a R20 series (see fig 18) with 10 sieves ranging from 0.063mm up to 31.5mm. As the largest size of soil aggregate that is permissible in a typical adobe blocks amount to a 20mm, 8 sieves were selected to perform the test. The soil specimen SM-UMU-A was sieved in advance to remove all the soil aggregate with very large size with a 4mm screen. Additionally, an electromechanical sieve shaker model: Control 15-D040(see Fig 19) was used to support the sieve test. An electronic scale model Kern model CB12KI, range 12kg, 1 digit corresponding to 1g(see Fig 20), was used to weigh the soil.

Figure 18: The sieve plates used for the dry sieving test. Photo by Author

Figure 19: The electromechanical shaker with sieve plates.

Photo by Author

Method

The first step in the sieve analysis is to thoroughly mix up the soil specimen that will be used for testing. Prepare at least 500g for each soil specimen.

The size of the soil particles determines the maximum sieve size (8mm for SI-UMU-A and 4mm for SM-UMU- A and B).

- Stack the sieves in decreasing order and the receiver goes on bottom
- .Put the sample and the lid.
- Install stacked sieves in electro-mechanical shaker and shake for at least 10min.
- Finish the operation by a manual check for the larger particles.
- Weighing of the individual retained refusals (weighing accuracy linked to the scales: 1g of total mass) The results are reported in Chapter 4.

Figure 20: Electronic balance model Kern model CB12KI. Photo by authors

Figure 21: Sieved soil specimen on plates ready for weighing. Photo by authors

3.3.3 Plastic limit test

Method

Samples of about 70 g soil pastes is prepared and they are placed on the mixing plate (see Fig 22). Each soil paste is allowed to dry partially on the plate until it become plastic enough to be shaped into a ball.

- Roll the ball of the soil between an open flat hand and a glass plate until the heat of the hands dries the soil sufficiently for slight cracks to appear on its surface.
- Divide the sample into two sub sample of about 10g each and carry out separate determination on each portion.
- Divide each sub sample into four more equal parts and treat each part as specified in the process below
- Mold the soil in the fingers to equalize the distribution of moisture, then form the soil into a thread about 6mm (see fig 24) diameter between the first finger and thumb of each hand.
- Repeat the process until the thread shears both longitudinally and transversely when it is rolled to about 3mm diameter.
- Do not gather the pieces of soil after they crumble. In order to reform a thread and to continue rolling, the first crumbling point is the plastic limit.
- Gather the portion of the crumbled soil thread together.
- Transfer the crumbled soil to a container (see fig 25) and determine the moisture content of the soil in the container. The results are reported in Chapter 4.

Figure 22: Soil paste on the mixing plates

Source: Personal collection

Figure 23: Shaping the soil into a ball

Source: Personal collection

Figure 24: Soil formed into a thread of 6mm

Source: Personal collection

Figure 25: Crumbled 3mm soil thread

Source: Personal collection

3.3.4 Moisture content test

The test is conducted on the soil specimen SI-UMU-A and on the the soil specimen SM-UMU-A and SM-UMU-B.

Method

A kilo of the damp soil SI-UMU-A is prepared while only 70g of the crumbled thread of soil SM-UMU-A and SM-UMU-B is used.

- After the mass of the soil plus the container is recorded, place the soil specimens in the oven model CONTROL 10-D1390 (seee Fig 26) with a maximun temperature capacity of 200°C and an accuracy of +/- 5°C.
- Dry the soil specimen within 24 hours at a constant temparature of 120°C.
- Weight the dried soil specimens and record the respective moisture contents. The results are reported in Chapter 4.

Figure 26: Soil specimen in the oven model CONTROL 10-D1390. Photo by author

3.3.5 Slump test

Equipment

The test device used to determine the consistency of the fresh mortar consists of a truncated conical steel mould with a bottom diameter of 200mm; a top diameter of 100mm, and a height of 300mm; a truncated funnel with a lower diameter of 100mm; a stiff metallic support and a steel tamping rod with rounded ends diameter of 16mm and a length of 600mm

Procedure

The first step consists in moistening the inside of the truncated mould and the metallic support.

- Centre the mould on the plate and fill it in three layers of equal height.
- Tamp each layer 25 times with tamping rod and truck off the top layer with the rod.
- Just after the filling operation, remove the mould carefully and vertically.
- Measure the settlement of the mortar cone (see Fig 27). The results are reported in Chapter 4.

Figure 27: Measuring the slump of the fresh mortar. Source: Personal collection

3.3.6 Flow test

Equipment

The test device used to determine the consistency of the fresh mortar with the flow test consists of a wooden square board with a side length of 700mm, covered with a steel plate weighing 16kg, with the board hinged along one side to the base board and the top table is able to be lifted up over 40mm; a truncated conical steel mould with a bottom diameter of 200mm, a top diameter of 130mm, and a height of 200mm, a truncated funnel with a lower diameter of 100mm; and a square wooden tamper with the side length of 40mm

Procedure

The first step consists in moistening the inside of the truncated mould and the metallic support.

- Cnetre the mould on the plate and fill it in two layers of equal height.
- Tamp each layer 10 times with tamping rod and truck off the top layer with the ro
- Just after the filling operation, remove the mould carefully and vertically.
- Lift the top table to its maximum (40mm at free hand) and leave it to fall freely, and repeat the operation 15 times.
- After the fresh mortar spread over the top table, measure the two diameters parallel to the side of the table (see Fig 28).
- The average value gives the flow of the mortar. The results are reported in Chapter 4.

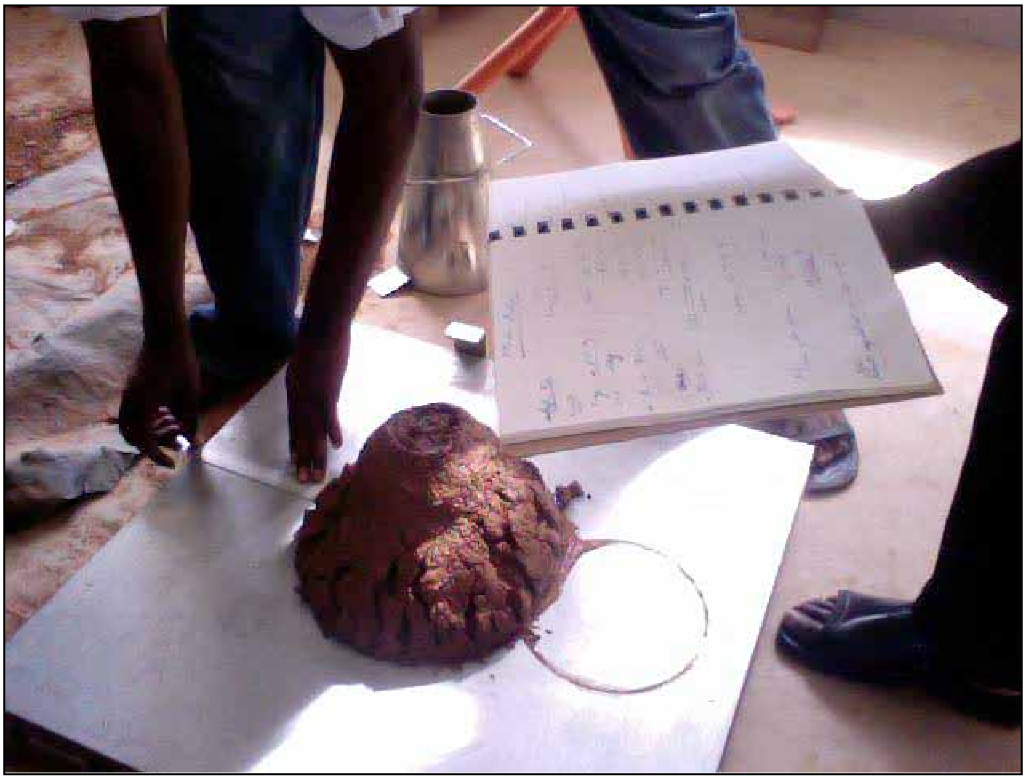


Figure 28: Measuring the flow of the fresh mortar. Source: Personal collection

NB: It is important to note that the slump test and the flow test are not soil tests but concrete test

3.4 Producing the PETE wall Specimens

The operation begins with making provision for all the materials such as PETE bottles, soil, sand, Cement, water and the frame to support the bottles wall specimen during construction. The frame size depends on the effective size of the bottles wall specimen.

The bottles wall specimen size adopted amounts to 350mm length, 200mm depth and 700mm height. This is by reason of the limitation in size of the compressive installation support. The volume of the prescribed bottles wall specimen required 54 PETE bottles; Hence, the size of the wooden support frame (outside measurement) prepared is: 20mm thick, 390mm long, 240mm deep and 720mm high (see Fig 29 and Fig 30);

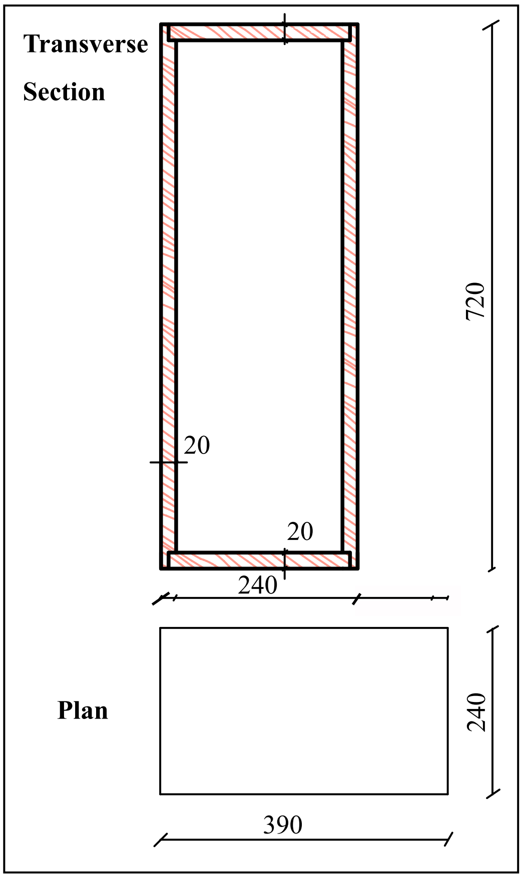


Figure 29: Measurements of the wooden frame support, Scale 1:10

Figure 30: Image of the wooden frame support. Photo by author

• Fill the PETE bottles (see Fig 31) with the soil specimen SI-UMU-A in 4 layers by compaction with a steel bar at a moisture content amounting to 10.1%.

• Place a polythene sheet on the inner face of the wooden frame support to protect it against moisture;

• Two types of mortars are prepared (see Fig 32). The first mortar has 37kg of soil SM-UMU-A without cement and the second has 35kg of soil SM-UMU-B with 1:15 ration cement CM IV/ 32.5N.

• Addd water amounting to 20 percent from overall dry weight of cement-soil mix;

Figure 31: Filling the PETE bottles

Source: Personal collection

Figure 32: Mixing the mortar

Source: Personal collection

• Build the bottles wall specimens (see Fig 33) using the PETE bottles laid according to their longitudinal axis, and tied together with a nylon rope on their two extremity (see Fig 34 and Fig 35) to prevent horizontal displacement.

• To prevent expansion, protect the bottles wall specimen using a 120x35x9 steel clamp. The results are reported in Chapter 4.

Figure 33: Building the bottles wall. Source: Personal collection

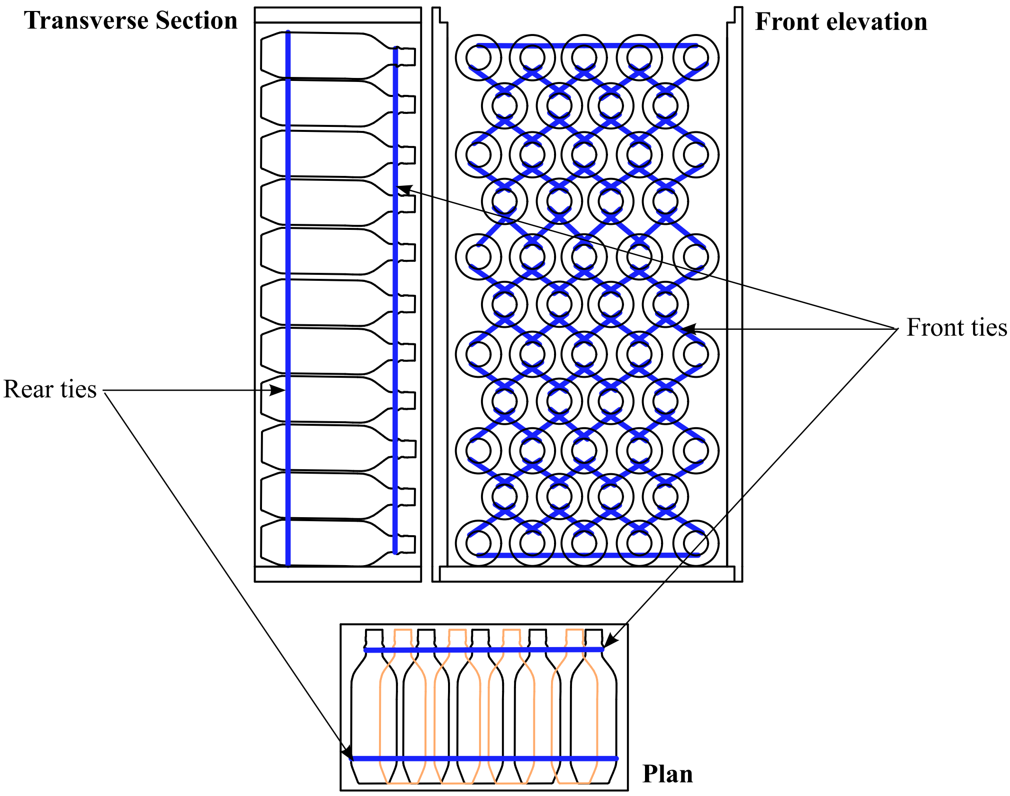


Figure 34: Bottles wall specimen Drawing, Scale 1:10

Figure 35: Sewing the front ties.

Source: Personal collection

Figure 36:Rear ties.

Source: Personal collection

3.5 Compressive test

According to several researchers, compressive strength is one of the most important properties of masonry in structural design. Saman (2006) points out that the specified compressive strength of a masonry assemblage (f'_m) , is used to determine its allowable axial and flexural compressive stresses and shear stresses.

Saman (2006) additionally drew attention to the fact that the compressive strength of the masonry assemblage can be evaluated by the properties of each constituent material, called the "Unit testing method," or by testing the properties of the entire masonry assemblage, termed the "Prism Testing Method" as a function of the mortar type and the compressive strength of the unit employed to construct the masonry.

In order to have reliable and confident data on the compressive strength of PETE bottle masonry, Thomas (2011) advised to perform both the single bottle testing method and the bottles wall testing method. This is also attributable to the fact that there has never been any structural behaviour investigation concerning the PETE bottle masonry, hence it is very difficult to predict its compressive strength using one method because the nature of the PETE masonry is different with other types of masonries which bottles wall compressive strength depend on the strength of the type of mortar used. For instance, Mamlouk (2009) reveals that numerous researchers accurately correlate the brick masonry assemblage compressive strength with several factors such as prism height to thickness ratio, brick unit compressive strength, mortar type, hollow versus solid brick units, the mortar joint thickness and the grout. He reveals a rule of thumb relationship between prism compressive strength and unit compressive strength where the f'_m is approximately 80% of the unit compressive strength.

Furthermore, Saman (2006) suggests an equation that links the unit compressive strength of clay masonry to its assemblage compressive strength, given as follow:

$\mathbf{f'_m = A(400 + Bf_u)}$ where A= inspected masonry; B= type of mortar ; f_u = average compressive strength of brick unit ; and f'_m = specified compressive strength of masonry

Following the above, the two methods for determining the compressive strength of masonries were adopted. The unit testing **(single bottle test)** method was carried on 11 PETE bottle units (named PB-SA 1to 11) , using a bending testing machine 100KN capacity, model CONTROL 53-C0900 (See Fig 37), while the bottles wall testing method **(Bottles wall test)** was carried on 8 PETE bottle bottles wall specimens (see table 9), using two hydraulic jack (RC 106 n° D5001 C and n° D 3702 C), individual capacity 101kN, stroke 150mm, a manual operated high pressure pump (ENERPAC P392) with a maximum pressure of 700 bar provided with a 250 bar dial gauge (approximatly 33kN per jack) and a 700 bar dial gauge (approximatly 101kN per jack) . A modified steel frame support was used to accommodate the testing process (See Fig 38.)

Figure 37: Bending testing machine
Photo by author

Figure 38: Hydraulic long ram jack machine installed on a modified steel frame support
Photo by author

Table 9: Annotation for PETE wall

Annotation	Meaning
S	Bottles wall specimen with stabilised mortar
US	Bottles wall specimen with unstabilised mortar
A	Soil SM-UMU-A
B	Soil SM-UMU-B
L 1 to 3	Lateral support are provided
N 1 to 2	No lateral support are provided

Procedure

Single Bottle test method

- First, clean the bearing surface of the plate to remove any loose grit.
- Put the PETE bottle specimen in the testing machine relatively to its longitudinal axis, at the centre coinciding with the axis of the machine.
- Make a final check of the correct positioning, and then apply the load up to failure.
- Consider the first cracks that appears on the PETE bottle specimen as the failure point
- Stop the machine and record the cross section area of the PETE bottle in contact with the platen using a vernier calliper (see Fig 39).
- Record the maximum load at failure as well as the rate of loading (N).The results are reported in Chapter 4.

The crushing strength is calculated as follow:

$$\text{Compressive strength} = \frac{\text{Maximum Load (KN))}}{\text{Cross section Area (mm2)}}$$

Figure 39: Recording the cross section area of the PETE bottle in contact with the platen
Source: Personal collection

Bottles Wall test method

- Clean the bearing surface of the concrete plate to remove any loose grit.
- Put the bottles wall specimen in the testing machine and position the hydrolic cylinders at an eccentricity e_x= t/2= 100mm, e_y= l/3= 115mm. The distance between the cylinders head amounted to 120mm (See Fig 40 and Fig 41).
- Put thet load distribution steel sections on top of the bottles wall specimen to uniformly distribute the load;
- Make a final check of the correct positioning, and then apply the load up to failure.;

The maximum load at failure is recorded as well as the rate of loading (N)

The crushing strength is calculated as below:

$$\text{Compressive strength} = \frac{\text{Maximum Load (KN))}}{\text{Cross section Area (mm2)}}$$

This test was conducted with consideration of the effects of lateral supports especially vertical lateral on the resistance of a wall, as walls without lateral support tend to have less strength and stability than a wall with lateral support when subjected to horizontal or vertical forces (Curtin et al, 2006). Thus, 5 bottles wall specimen (see Fig 40) were tested without vertical lateral support while 3 bottles wall specimens (see Fig 41) were tested with the support.

Figure 40: Bottles wall without vertical lateral support. Photo by author

Figure 41: Bottles wall with vertical lateral support: Photo by author

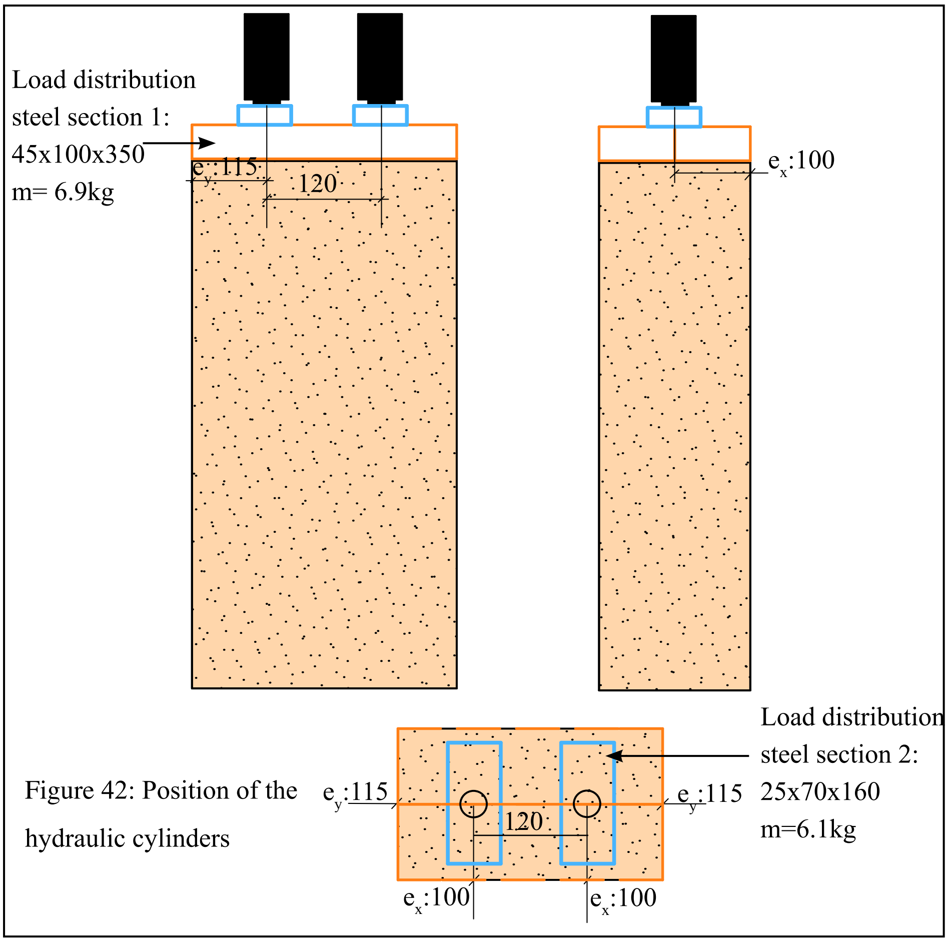


Figure 42: Position of the hydraulic cylinders

Figure 43: Position of the hydraulic cylinder. Photo by author

CHAPTER 4

RESULT AND ANALYSIS

4.1 Results of soil tests

4.1.1 Sedimentation test results.

Two types of soil were tested: SI-UMU-A /SM-UMU-A and SM-UMU-B. SM-UMU-A was sieved with a 4mm screen and yield SM-UMU-B. The sedimentation test was conducted on the two SM soils. Each layer of the soil deposited on the glass flask were measured as well as the water and the values got are as follow:

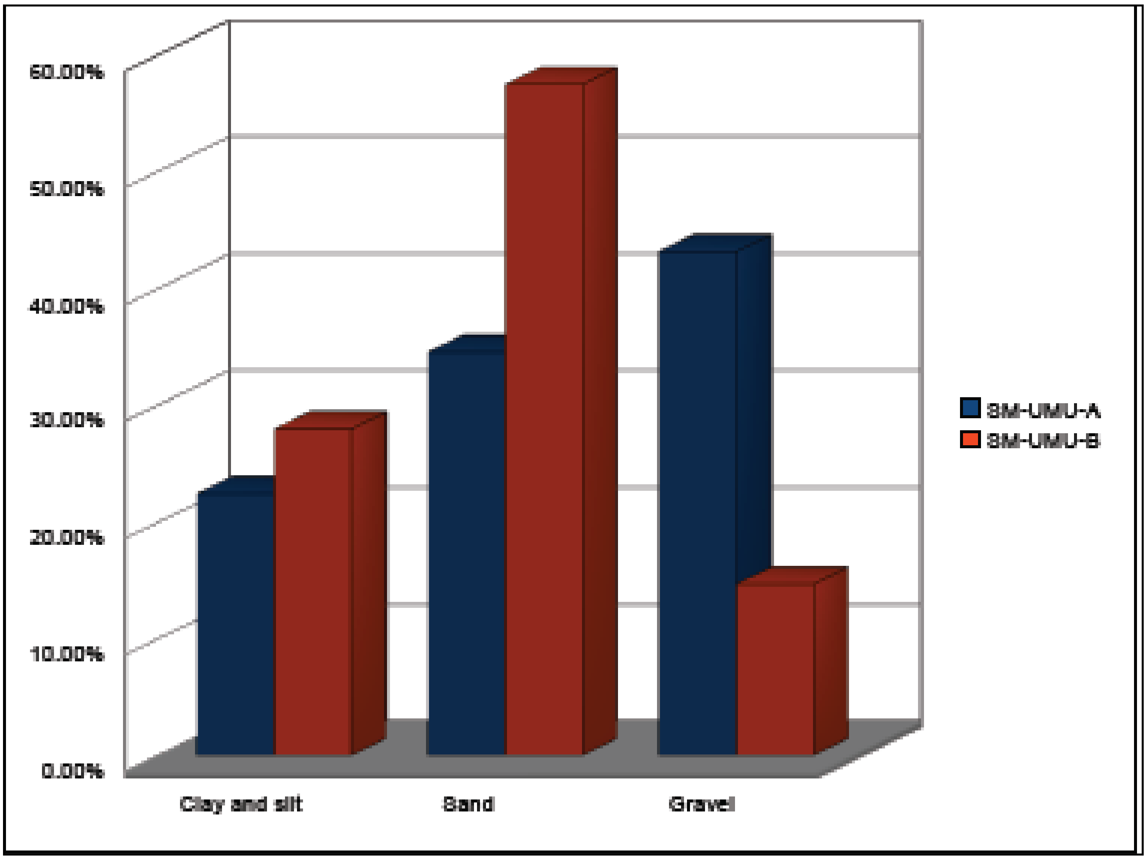
Table 10: Recorded Values for Sedimentation Test

Recorded Values(mm)	SM-UMU-A	SM-UMU-B
Flask content	96	96
Water	38	35
Clay and silt	13	17
Sand	20	35
Gravel	25	9

Table 11: Sedimentation test Result

	SM-UMU-A	SM-UMU-B
Clay and silt	22.4%	27.9%
Sand	34.5%	57.4%
Gravel	43.1%	14.7%

Table 12: Sedimentation test result Chart



Analysis and Observations

The laboratory classification of the soils taken from below the top soil at approximately two metres shows that soils tested contained a range of soil particles reported as follow: 43.1% of gravel for SM-UMU-A and 14.7% for SM-UMU-B; 34.5% of sand for SM-UMU-A and 57.4% for SM-UMU-B; 22.4% of clay and silt for SM-UMU-A and 27.9% for SM-UMU-B;

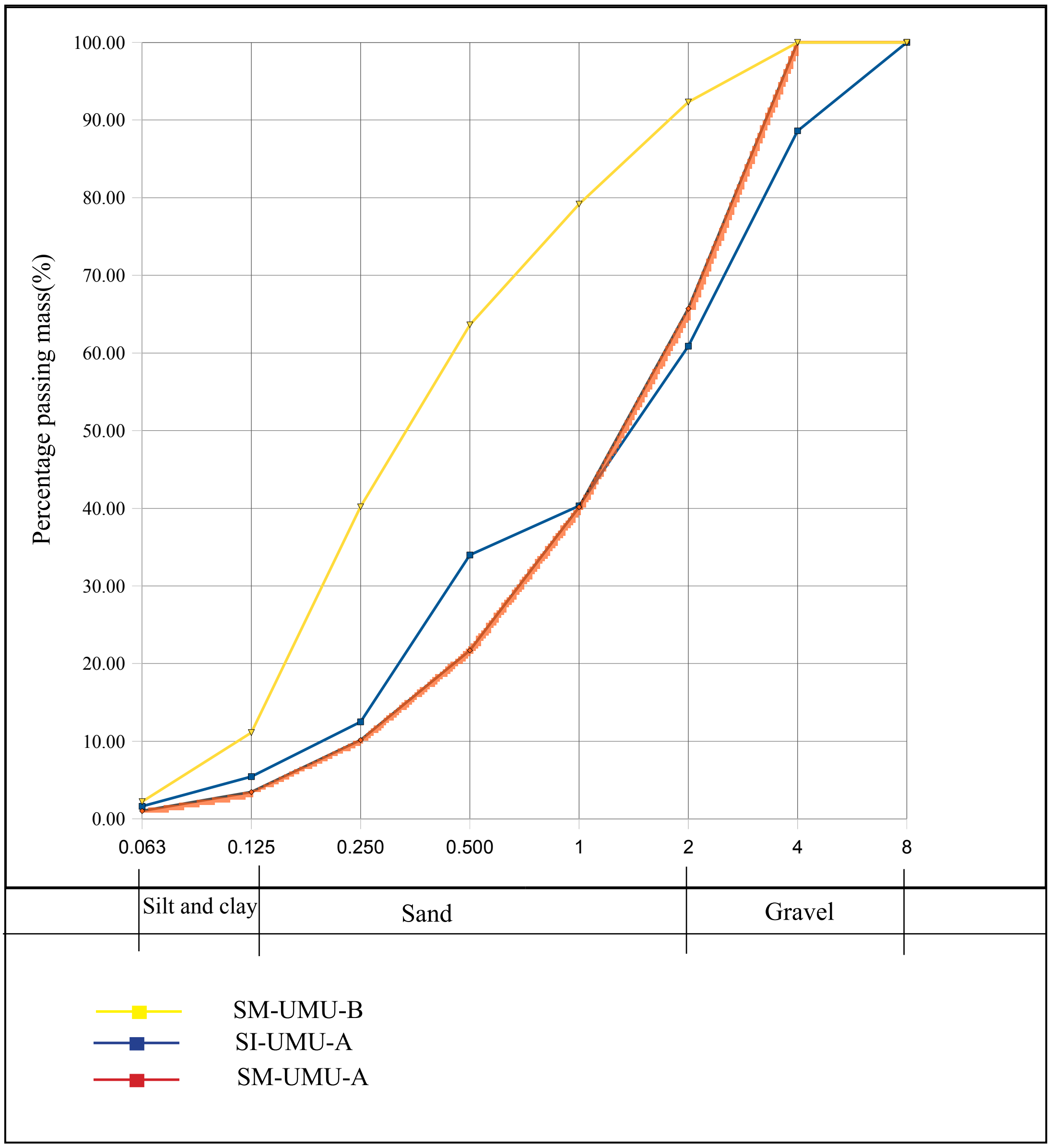
4.1.2 Sieve analysis test results

The mass retained on each individual sieve and in the receiver was determined by weighing. The individual retained mass was deducted from the total mass and yielded the cumulated passing masses (see Table 13). These masses were divided by the total mass of the sample to get the cumulated passing percentage(see Appendix G).

Table 13: Sieve test result

Test sieve size	SI-UMU-A	SM-UMU-A	SM-UMU-B
mm	Cumulated Passing Mass(%)	Cumulated Passing Mass(%)	Cumulated Passing Mass(%)
8	100	100	100
4	89	100	100
2	61	65.72	92
1	40	40	79
0.5	34	22	64
0.25	13	10	40
0.125	5	3	11
0.063	2	1	2
Receiver	-	-	-

Table 14: Sieve test result Chart



Analysis and Observations

The results got from the dry sieve analysis revealed the following distribution of particles: for SI-UMU-A approximately 40% of the soil particles were gravel, over 50 % were sand and less than 10% were silt and clay; for SM-UMU-A around 35% of the soil particles were gravel, over 55 % were sand and less than 10% were silt and clay;

for SI-UMU-B nearly 5% of the soil particles were gravel, over 85 % were sand and less than 10% were silt and clay.

All the three soil specimen show a great amount of sand, a relatively high amount of gravel for SI-UMU-A and SM-UMU-A, and a slight amount of clay and silt. Hence they can be classified according to NZS 4298:1998 as Silty or Clayey Sand for SM-UMU-B and slightly silty or clayey gravel and sand for SI-UMU-A and SM-UMU-A.

From the Dry sieve analysis and the sedimentation test we can relate the relationship between the particles size of the soil specimen with the best soil specimen to be utilised to fill the bottles for a better compaction and for producing the best Cement Stabilised mortar. From the literature review, the proportions of particles of soils that are recommended for the manufacture of compacted earthen blocks (Houben *et al.*, 1994 cited by Obonyo *et al.*, 2010) are: Gravel:0-40%; Sands:25-80%; Silts 10-25% Clays 8-30%, soil classified as sandy soil (Rigassi, 1985).

Hence, SM-UMU-A and SI-UMU-A were the ideal soil to use to fill the PETE bottle (SI-UMU-A was used to fill the bottles.) and SM-UMU-B was the best soil to produce the cement stabilised mortar- SM-UMU-A produced 3 PETE bottles wall specimen with unstabilised mortar and 2 PETE bottles wall specimen with cement stabilised mortar, while SM-UMU-B produced 3 PETE bottles wall specimen with cement stabilised mortar.

4.1.3 Moisture content test results

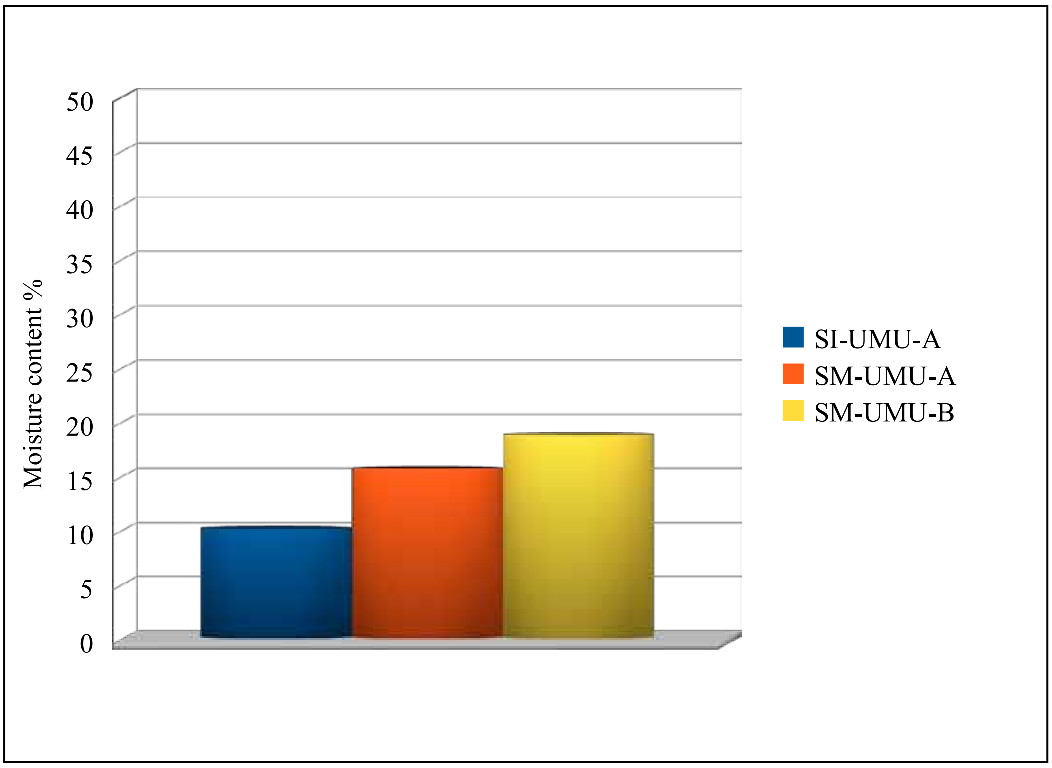
The soil specimen SI-UMU-A, SM-UMU-A and SM-UMU-B were dried at constant temperature of 120°C within 24 hours, and then they were left to cool. Their respective mass was recored and yielded their moisture content. This test provided also data for the plastic limit test . The calcualtion are obtained as follow:

$$\text{Moisture content} = \frac{\text{Mass of damp soil - Mass of dried soil}}{\text{Mass of dried soil}} \times 100$$

Table 15: Moisture content results

Mass	Unit	SI-UMU-A	SM-UMU-A	SM-UMU-B
Mass of container	g	513	515	517
Mass of damp soil + container	g	1513	589	593
Mass of damp soil	g	1000	74	76
Mass of dried soil + container	g	1421	579	581
Mass of dried soil	g	908	64	64
Moisture content	%	10.1	15.6	18.7

Table 16: Moisture content results Chart

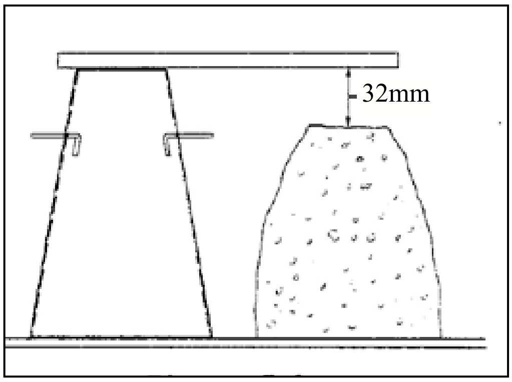


4.1.4 Slump test results

In order to evaluate the consistency of the fresh mortar, the test was undertaken on the following mix proportions:

- Soil= 35kg
- cement= 2.3kg
- water= 7.5l

Slump= 32mm



The slump consistency (see table 17) is between 10<S<50 (class 1).

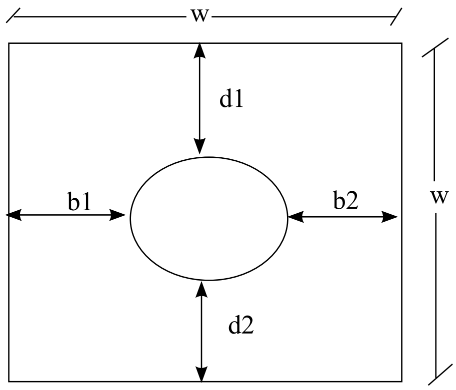
Table 17: Slump consistency classes. Source: Thomas (2008)

Class	S1	S2	S3	S4	S5
Slump(mm)	10 to 40	50 to 90	100 to 150	160 to 210	≥220

4.1.5 Flow test results

The flow of the mortar was calculated as follows:

$$F = \frac{(w-(d1+d2)) + (w-(b1+b2))}{2}$$



The recorded values were:

w= 700mm

d1= 195mm

d2= 219mm

b1= 198mm

b2= 210mm

F= (700- (195+219)) + (700-(198+210))/2= 289mm ≤ 340 (class F1)(see table 18)

Table 18: Flow consistency classes. Source: Thomas (2008)

Class	F1	F2	F3	F4	F5	F6
flow(mm)	≤340	350 to 410	420 to 480	490 to 550	560 to 620	≥630

Analysis and Observations

The results from the flow test and the slump test revealed that the mix had a consistency affiliated to class S1 for the slump test and F1 for the flow test. This implies that the mortar had the right amount of water for workability reasons that is linked to the strength of the mortar (Thomas, 2008).

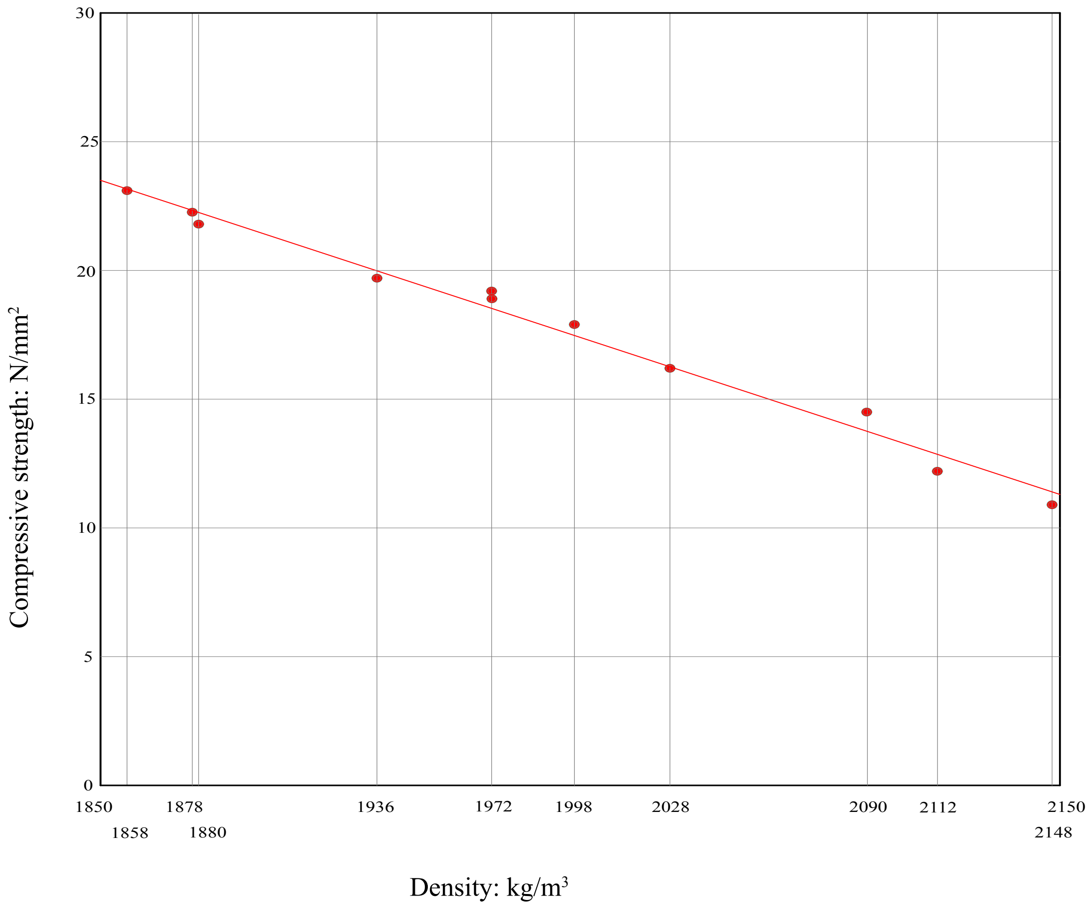
4.2 Results of Compressive tests.

4.2.1 Single Bottle compressive strength test results

The following equation was used to calculate the density of the PETE unit specimen:

Density = mass/volume

Table 19: Single bottle compressive strength Versus PETE bottles unit density Chart



Analysis and Observations

The PETE bottles units exhibited a rather complicated state of stresses (see Fig 44) under the compressive force that commends further research in order to equip the PETE bottles masonry technology with efficient and reliable structural and stress analysis data. However, one should bear in mind that the stresses induced by the compressive force included tensile stresses in the axis perpendicular to the axis of action of the applied load (σ_z),

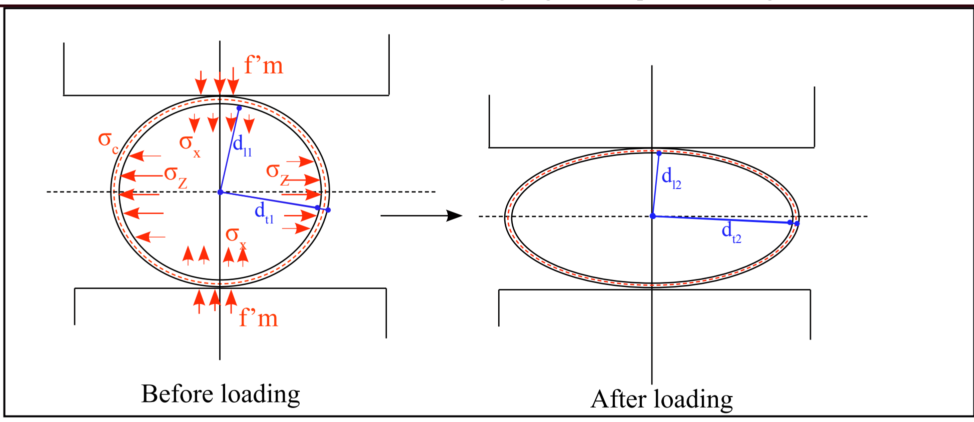


Figure 44: Distribution of stresses in the PETE unit

compressive stresses (σ_x) parallel to the axis of action of the applied load and normal stresses σ_c (circumferential to the spherical surface of the PETE bottles) induced by the pressure caused by σ_x. It was observed that these stresses caused deformations that were increasing as the acting force increased. The tensile stresses caused elongation (see Fig 45) of the PETE bottles unit ($d_{t2} > d_{t1}$) and was the main cause of their failure (the PETE bottles were cracking where the tensile strength was high) with the addition of the normal stresses, while the compressive stresses and the corresponding shortening ($d_{l2} < d_{l1}$) tended to increase the strength of the PETE bottles unit as the applied load increased (see Fig 46).

Figure 45: PETE bottle A4 unit under compression Source: Author

Figure 46: PETE bottle A4 at failure Source: Author

The results got from the unit compressive strength tests ranged between 10.9 N/mm^2 and 23.1N/mm^2 and when compared with the unit compressive strength of some masonry blocks, these results fall in the same range. For example, the masonry units produced in Uganda have the following compressive strength: compressed earth blocks have a compressive strength less than 6 N/mm^2; that of adobe blocks less than 4 $N/mm^{2,}$, while fired bricks compressive strength lies between 5 and 9 N/mm^2 and that of concrete blocks are between 5 and 7 N/mm^2 (Kerali *et al,* 2007). Also, Adams *et al* (2001), provided compressive strength of some masonry units with rather large value intervals notably 1 to 40 N/mm^2 for stabilised compressed earth blocks, 5 to 60 N/mm^2 for fired bricks, 10 to 55 N/mm^2 for calcium silicate bricks, 7 to 50 N/mm^2 for dense concrete blocks, 2 to 6 N/mm^2 for aerated concrete blocks, and 2 to 20 for concrete blocks.

Conceivably, one of the most important observation made about the PETE bottles structural behaviour is the correlation between the density and the compressive strength of the PETE bottles . It was observed that the PETE bottles with the lowest density had the highest compressive strength, while for all others earthen materials and masonry units it is the direct contrary, a certainty exposed in the literature review. For example, the data provided by Adams *et al.* (2001), showed that for stabilised compressed earth blocks with density ranging from 1700 to 2200 $kg/m^{3,}$ the compressive strength will respectively fall between 1 to 40 N/mm^2, meaning that the compressive strength increases with an increase in density.

The compressive strength- density relationship of PETE bottles, is explicable with the fact that the PETE units filled, with moist soil is a composite material and both materials undergo the same strain with the corresponding stresses causing the failure to the PETE bottles (Thomas, 2008).

The tensile stresses, induced by the compressive forces on the PETE bottles filled with the compacted soil, tended to push the soil outward perpendicularly to the axis of action of the applied load, and consequently caused normal stresses, circumferential to the spherical surface of the PETE bottles, thus an increase in the applied load caused an increase in the tensile stresses pushing then the soil toward the PETE bottles.

Consequently, the circumferential normal stresses in the PETE units increased and at the failure point the stresses broke the PETE unitss. Therefore, if the density of the PETE unitss was low, the rather little amount of soil undergoing the strain caused by the tensile stresses would have caused small circumferential normal stresses in the PETE units and would have increased as a matter of fact the compressive strength of the PETE units.

However, it can also be assumed that the moisture content of soil to be loaded in the PETE should should be slightly high, as soil with high moisture content have a low compaction rate that yield a low density. The compression rate of earthen material is function of the optimum moisture content of the soil. A relatively low moisture content, as recommended by the literature review on earthen materials, yield the best density for the compressed earthen masonries (Maniatidis *et al*, 2003).

4.2.2 Bottles Wall compressive strength test results

One of the most important factor in the analysis of the compressive strength of the PETE bottles wall specimens that was not undertaken is the calculation of the density of the bottles wall specimen. This is ascribed to the lack of balance with a capacity above 100kg in the laboratory in view of the fact that the bottles wall specimen had a weight above 100kg.

Table 20:Unstabilised bottles wall compressive strength Versus stabilised bottles wall compressive strength Chart

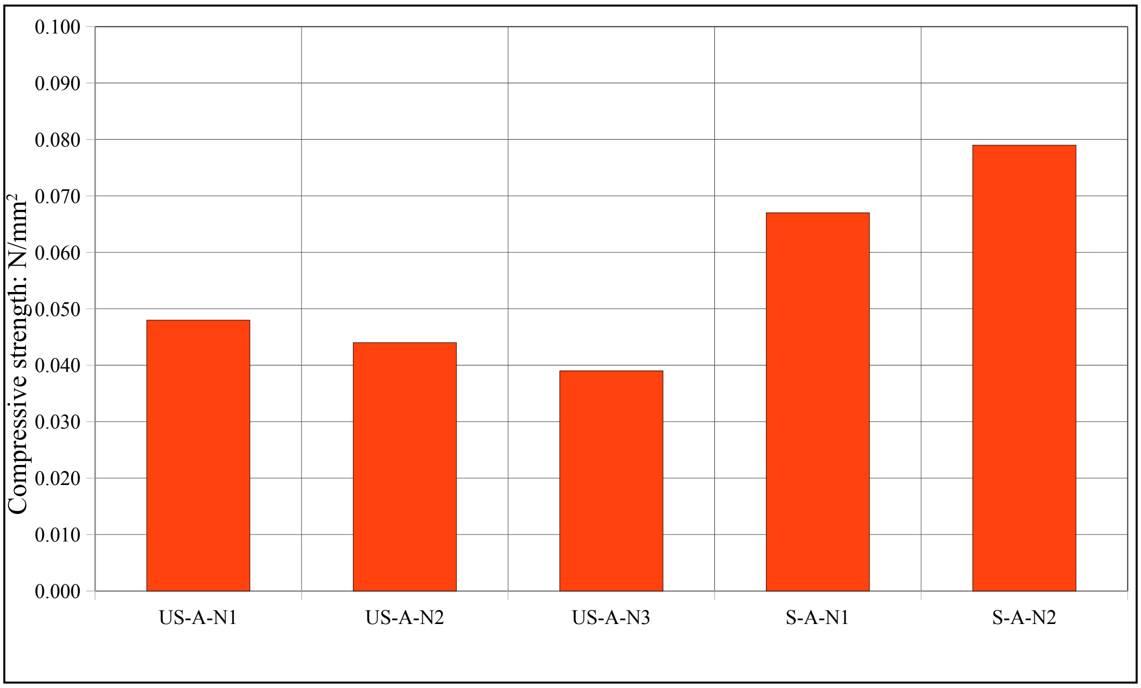
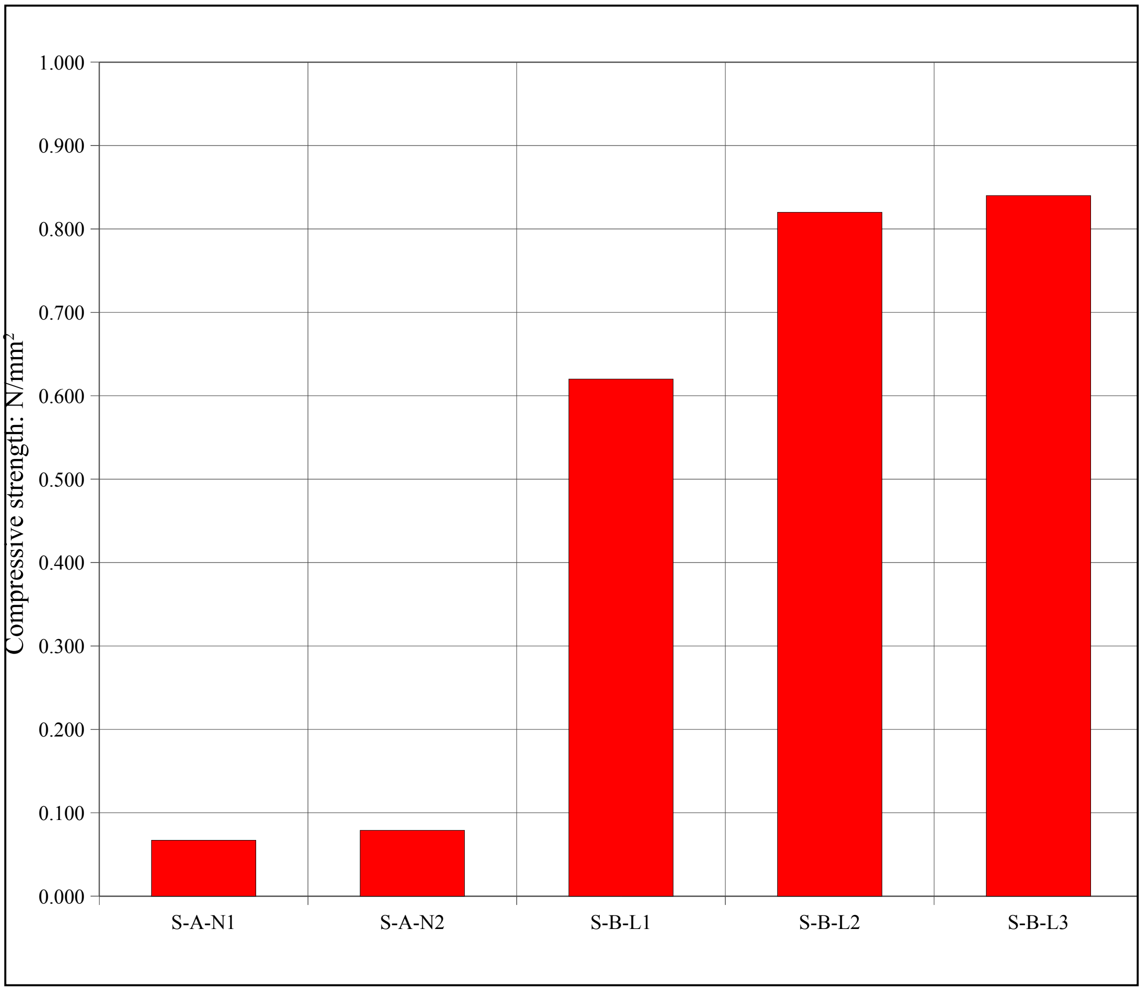


Table 21:S-N bottles wall compressive strength versus S-L bottles wall compressive strength chart



Analysis and Observation

The results obtained from the bottles wall compressive strength varied from 0,048 to 0.84 N/mm^2. Set side by side with the data from the literature review on the compressive strength of rammed earth and stabilised compressed earth blocks, it is evident that the PETE bottles masonry can be confidently used as a load bearing masonry. Maniatidis *et al* (2003) revealed that a typical load bearing rammed earth wall has an established compressive strength that lies betwenn 0.4 to 0.7 N/mm^2, while load bearing stabilised compressed earth walls have compressive strength around 0.5 to 1.8 N/mm^2 (Felix, 2009; Heath *et al* ,2009; Maïni, 2009).

It has been registered that the compressive test results from the bottles wall specimen built without lateral support showed a slight difference in between the compressive strength of the specimen built with stabilised mortar and the one built without cement stabilised mortar. Hence, it is recommended to built PETE bottle masonry with cement stabilised mortar from a sandy soil, as it gives the PETE masonry a better strength than an unstabilised mortar.

Although the influence of the mortar joint was not considered in this research, it is clear that adequate mortar may contribute to the compressive strength of the PETE bottles masonry, hence there is a need for further research to investigate the influence of the cement stabilised mortar on the strength of PETE bottles masonry, while bearing in mind that the bond in between the PETE bottles, in the masonry assemblage depends considerably also on the nylon rope and it should not be put aside.
Furthermore, the results on the bottles wall compressive test revealed that there was a very large variation in the compressive strength results of the bottles wall specimens built with vertical lateral support relatively to the one built without vertical support.

One important observed factor that influenced the compressive strength of the bottles wall specimen was the mode of failure. The bottles wall specimen tested without lateral support failed due to bond failure (see Fig 48 and Fig 49). Due to limitations in equipment that could have measured the strain induced by the compression force on the bottles wall specimen (deformations of masonry in laboratory environment are usually measured with strain gauges, available in many model), thus some properties of the PETE unitss masonry could not be established such as the stress-strain relationship, the modulus of elasticity, the shear modulus and a concise analysis of the bond failure. However, the bottles wall specimen built with vertical support demonstrated a large resistance against shear failure. While they revealed very small elastic deformation (they did not recover their original height after failure), the compressive forces tended to give more strength to the masonry assemblage as the load increased (see fig 50 and Fig 51).

Figure 47: S-A-N1 Bond failure
Source: Author

Figure 48: US-A-N1 Bond failure
Source: Author

Figure 49: S-L-1 before failure. Source: Author

Figure 50: S-L-1after failure. Source: Author

CHAPTER 5

CONCLUSION

Based on the findings from the tests conducted and the literature review, it can be concluded that the proportion of the soil is an important aspect in producing PETE bottles masonry with adequate compressive strength.
The three soil specimen tested fell within the ideal limit in particle size distribution, thus producing PETE bottles masonry with commendatory compressive strength when compared to the compressive strength of different types of earthen masonries.

It was observed that the stabilised soil specimen SM-UMU-B produced the highest compressive strength PETE wall specimens with a provision of vertical lateral support than the stabilised SM-UMU-A because the PETE wall specimens built out of them did not have vertical lateral support.

Moreover, all three soil specimen had a low plastic limit with an average moisture content of 10.1% for SI-UMU-A, 15,6% for SM-UMU-A and 18.7% for SM-UMU-B, all of them lying in the range specified by NZS 4298:1998 of 2 to 30% for the suitable soil for cement stabilization.

The mix ratio may play an important role in determining the suitable soil-cement mortar for PETE units masonry, as it was noticed that though in theory the mortar have little influence in the bonding strength of the PETE bottles, the cement stabilised mortar provided a rather better compressive strength to the bottles wall specimen than the unstabilised mortar. Besides, the properties of the soil can be a factor of producing the higher strength in **Cement Stabilised mortar PETE bottles masonry**.

It was noticed that there was a clear relationship between the density and the compressive strength of the PETE bottles tested . From the PETE bottles investigated, it was noted that parameters such as moisture content of the soil can influence the compressive strength of the PETE bottles in terms of the compressive effort put during compaction that on the other end influenced greatly the density of the PETE bottles. It was discovered that to improve the PETE bottles compressive strength , the soil should have a slightly higher moisture content, in order to have a low compression rate that will result in a low density PETE bottles .

From the compression strength tests conducted on the PETE units and walls, the findings revealed that the PETE units can be confidently used as masonry but it is commended that a complete structural investigation is undertaken in order to acquire sufficient and reliable structural behaviour data that can boost the utilisation of PETE units as masonry. It is recommended that the structural research to be engaged, should comprise the following investigations:

- Flexural bending strength ,
- Flexural bond strength of mortar,

- Shear strength,
- Tensile strength,
- Modulus of Elasticity,
- Combined compression and bending,
- Out- of plane flexural capacity,
- Design for shear,

and Modulus of rupture to cite just a few.

Finally, this research has demonstrated that plastic bottles masonry has structural potentialities and it can be recommended in the building industry, especially in providing low cost housing, because its use may reduce considerably the impact of plastic bottles on the environment.

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APPENDICES

APPENDIX A

LOCATION OF SOIL SPECIMENS

The soil specimens were gather from Nkozi, in the compound of the Uganda Martyrs University. Uganda Martyrs university is located approximately 3km from Kayabwe, a small town about 82km from Kampala along the Kampala-Masaka highway.

Figure 51: Location of Nkozi, Uganda

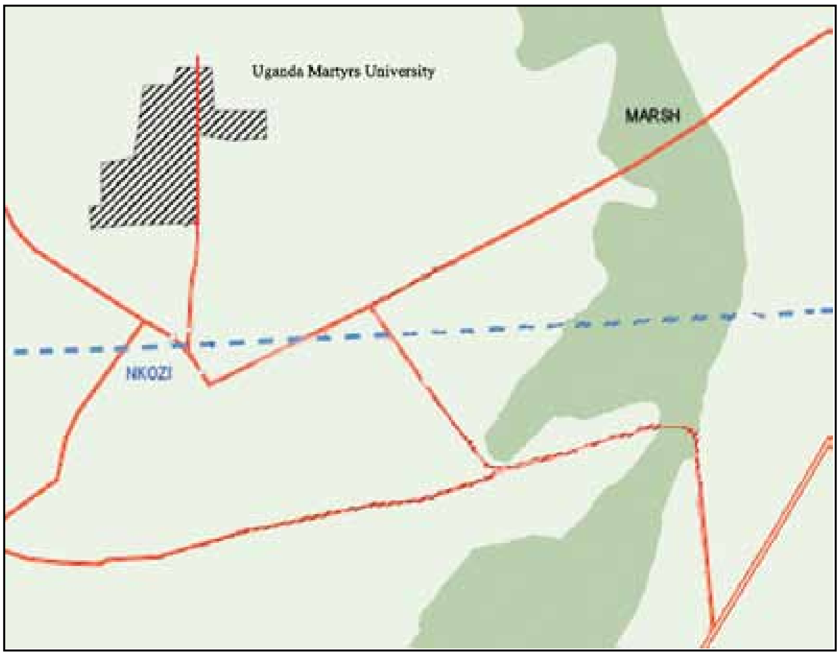

Figure 52: Location of Uganda Martyrs University

APPENDIX B

DATA OBTAINED FROM SIEVE ANALYSIS TESTS

Data anlysis: Specimen SI-UMU-A

Total mass of dry soil = 500g

Sieve Size (mm)	Individual retained Mass (g)	Cumulated Passing mass (g)	Cumulated Passing mass (%)	Cumulated Passing mass (% Rounded)
8	57	496	100	100
4	137	439	88.51	89
2	102	302	60.89	61
1	81	200	40.32	40
0.5	57	119	33.99	24
0.25	35	62	12.50	13
0.125	19	27	5.44	2
0.063	6	8	1.61	2
Receiver	2	-	-	-

Total Mass After sieving: 496g

Error: 0.8%

Data anlysis: Specimen SM-UMU-A

Total mass of dry soil = 500g

Sieve Size (mm)	Individual retained Mass (g)	Cumulated Passing mass (g)	Cumulated Passing mass (%)	Cumulated Passing mass (% Rounded)
4	O	493	100	100
2	169	324	65.72	66
1	126	198	40.16	40
0.5	91	107	21.70	22
0.25	57	50	10.14	10
0.125	33	17	3.45	3
0.063	12	5	1.01	1
Receiver	5	-	-	-

Total Mass After sieving: 493g

Error: 1.4%

Data anlysis: Specimen SM-UMU-B

Total mass of dry soil = 500g

Sieve Size (mm)	Individual retained Mass (g)	Cumulated Passing mass (g)	Cumulated Passing mass (%)	Cumulated Passing mass (% Rounded)
4	O	495	100	100
2	38	457	92.32	92
1	65	392	79.19	79
0.5	77	315	63.63	64
0.25	116	199	40.80	40
0.125	144	55	11.11	11
0.063	44	11	2.22	2
Receiver	11	-	-	-

Total Mass After sieving: 495g

Error: 1.0%

APPENDIX C

DATA OBTAINED FROM COMPRESSIVE STRENGTH TESTS

1. Unit compressive strength test results

Sample	Diameter (mm)	Length (mm)	Width (mm)	Volume (l)	Area (mm^2)	Mass (g)	Density (kq/m^3)	Failure Load (KN)	f_u (N/mm^2)
A1	60	154	25	0.5	3,850	968	1936	76	19.7
A2	60	154	25	0.5	3,850	1,014	2028	64	16.2
A3	60	154	25	0.5	3,850	986	1972	73	18.9
A4	60	154	25	0.5	3,850	939	1878	86	22.3
A5	60	154	25	0.5	3,850	1,056	2112	47	12.2
A6	60	154	25	0.5	3,850	986	1972	74	19.2
A7	60	154	25	0.5	3,850	999	1998	69	17.9
A8	60	154	25	0.5	3,850	940	1880	84	21.8
A9	60	154	25	0.5	3,850	1,045	2090	56	14.5
A10	60	154	25	0.5	3,850	929	1858	89	23.1
A11	60	154	25	0.5	3,850	1,074	2148	42	10.9

2. Prism compressive strength test results

Sample	Length (mm)	Height (mm)	Depth (mm)	Area (mm^2)	Failure load (KN)	f'_m (N/mm^2)
US-A-N1	350	700	200	70,000	3.32	0.048
US-A-N2	350	700	200	70,000	3.05	0.044
US-A-N3	350	700	200	70,000	2.78	0.039
S-A-N1	350	700	200	70,000	4.71	0.067
S-A-N2	350	700	200	70,000	5.55	0.079
S-B-L1	350	700	200	70,000	43.29	0.62
S-B-L2	350	700	200	70,000	57.45	0.82
S-B-L3	350	700	200	70,000	58.86	0.84