# Enhancing Strength and Durability of Adobe Bricks by Introducing Bio-inspired Stabilisers

A thesis presented for the degree of

Doctor of Philosophy

School of the Built Environment

School of Construction Management and Engineering

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# I. Declaration

I confirm that this is my own work and the use of all material from other sources has been properly and fully acknowledged.

**Amal Balila**

Monday 21st August 2017

# II. Publications

1. Balila, A., Vahdati, M., Lees, T., Nortcliff, S. (2016). **Sustainable bio-inspired stabilisers to enhance the strength, durability and structural stability of adobe bricks used for the construction of houses in the outskirts of Khartoum**. *In proceedings of the Young Researchers' Forum III, Innovation in Construction Materials, paper number (25), Imperial College London, London, UK.*
2. Balila, A. (2016). **My muddy summer holiday**. Successfully selected to be *Presented at the University of Reading Graduate School Research Image Competition 2016.*
3. Balila, A. (2014). **A future vision of low-cost housing in Sudan: Biomimicry of Termite Mounds.** Successfully selected to be presented at *the University of Reading Graduate School Research Three Minutes Thesis Competition 2014.*
4. Balila, A., Vahdati, M., Nortcliff, S. (2014). **A future vision of low-cost sustainable housing in Sudan: Biomimicry of Termite Mounds**. *A poster presented at the School of Construction Management and Engineering Doctoral Conference, University of Reading, UK.*
5. Balila, A., Vahdati, M., Nortcliff, S. (2013). **A future vision of low-cost sustainable housing in Sudan: Biomimicry of Termite Mounds**. In the proceedings of the *School of Construction Management and Engineering Doctoral Conference, University of Reading, UK.*
6. Balila, A., Vahdati, M. (2013). **Wall Materials and Techniques Available for Low Cost Housing in Khartoum from a Sustainability Point of View**. *In the proceeding of the 1st International DelPHE Conference, Construction Management in Developing Countries: Education, Training, Research and Practice, Khartoum, Sudan.*
7. Balila, A., Vahdati, M., Nortcliff, S. (2013). **A future vision of low-cost sustainable housing in Sudan: Biomimicry of Termite Mounds**. *Earthen Construction Symposium, University of Durham, UK,* http://community.dur.ac.uk/charles.augarde/earth/symp/AmalBalila.pdf
8. Balila, A. (2011). **A future vision of low cost housing in Sudan (innovative technologies regarding earth architecture)**. A poster Presented at the *Food security and poverty alleviation under changing environmental conditions: Challenges and opportunities in Sudan, International Symposium, Khartoum, Sudan.*

# III. Awards

1. Institute of Materials, Minerals and Mining Award for excellence in presentation of a paper award (2016), Imperial College London, London, UK.
2. Annual Doctoral Research Conference, School of Construction Management and Engineering award for the best poster certificate (2013), University of Reading, UK.

# IV. Abstract


The aim of this study is to enhance the strength and the durability of adobe bricks by introducing bio-inspired stabilisers. This research was inspired by the high strength and durability of the termite mounds. The study investigates the stabiliser behind such strong natural constructions. The termite builds its mounds by incorporating a glycoprotein from its saliva to cement the sub-soil particles together. Biomimicry has been used as an approach to investigate the potential for the use of the termites' construction stabiliser in adobe bricks.

Three different glycoproteins sourced from the waste of the meat industry were identified as potential stabilisers in adobe bricks. Bovine serum albumin from cows' blood, mucin from porcine stomach and gelatine from cold-water fish skin were the three stabilisers used in this study. A fourth stabiliser was made up of several chemicals which together aimed to mimic the termites' saliva glycoprotein. Two soils were used to prepare adobe bricks for testing. The main soil used in this study was sourced from Devon in the UK. The second soil was sourced from Mayo neighbourhood in Khartoum, Sudan and it was only used in key tests. Adobe bricks were made and stabilised with different concentrations of these bio-inspired stabilisers. Controlled unstabilised adobe bricks were used for comparison. The bricks were tested for their unconfined compressive strength and erosion resistance.

The main conclusion in this study is that, bovine serum albumin which is a glycoprotein derived from cows' blood and considered as a by-product of the beef industry, has proved its potential to be used as stabiliser in earth construction. The use of 0.5 by weight percent of bovine serum albumin resulted in 41% and 17% increase in the compressive strength of the Sudanese and the British adobe bricks respectively. In addition, the use of 5 by weight percent of bovine serum albumin resulted in 202% and 97% increase in the compressive strength of the British and Sudanese adobe bricks respectively. Furthermore, the use of 0.1, 0.2 and 0.5 by weight percent of the bovine serum albumin resulted in 30%, 48% and 70% reduction in the erosion rate of the British adobe bricks respectively. The use of 0.5 by weight percent of the bovine serum albumin resulted in 97% reduction in the erosion rate of the Sudanese adobe bricks.

The other stabilisers tested did not result in a significant improvement in unconfined compressive strength of the adobe bricks. However, the use of 0.1and 0.2 by weight percent of mucin from porcine stomach resulted in 28% and 55% reduction in the erosion rate of the British adobe bricks respectively.

# V. Dedication

*I dedicate this thesis to the memory of my second father and inspiration*

*Dr. Mohamed Yagoub Shaddad,*

*To my beloved father and mother*

*&*

*To my sisters, brothers, nieces and nephews*

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# 1. Introduction

## 1.1 Motivation

There were two motives behind this research which they played a vital role in shaping this study, these motives are summerised as follow:

- Poor urban population in developing countries, such as Sudan, rely on mud as the main construction material for building their houses. Enhancing the durability of this building material is a desirable goal in order to provide sustainable housing in these countries.
- Developed countries, such as the United Kingdom, rely heavily on fired clay bricks for house construction. Providing an alternative to fired bricks is also a desirable goal in order to address sustainability, energy and carbon footprint issues.

In the following section, these two motives will be discussed in more detail.

### *1.1.1 The first motive*

The first motive behind this research was the case of construction materials in developing countries such as Sudan. For instance, Khartoum the capital of Sudan, has witnessed the same fate as many other cities in developing countries which is the movements of people from rural areas toward it. The continuous movement from rural areas to urban areas, urbanization, is one of Khartoum's problems. Variable drivers were behind these movements, for example being the capital is one of the drivers. People are constantly seeking a better living lifestyle, so they move to Khartoum in search for that. In addition, other factors such as famine, drought and conflicts in some parts of the country are also considered as drivers for such movements (Eltayeb, 2003). However, the movements were not only limited to those internal ones, it was also accompanied by movements from neighbouring countries such as Chad, Ethiopia and Nigeria. These movements usually were taking place during wars and conflicts in these countries. All these movements together resulted in the horizontal expansion of the city, Figure 1-1 , with most of this expansion being residential (Eltayeb, 2003). In fact the city expanded in diameter from 16.8 km in 1955 to 802.5 km in 1998 (Eltayeb, 2003).

According to the last population census in 2008, Khartoum accommodated 29% of the urban population of the country (Habitat, 2008). However, 60% of Khartoum's population are considered as poor (Habitat, 2009). Out of this poor population, 76.2%

of the families have a monthly income around $ 156 and 92.8% have no more than $234 (Eltayeb, 2003). Most of this poor population cannot afford to live in the city centre of Khartoum, since the land and services prices in the centre are very high. For instance, in 2009 the cost of one square meter in the centre of Khartoum was between $1250 to $ 2000 (Elzobier, 2009). As a result, the urban poor targeted the outskirts of the city as a place to live, where they can afford living expenses (Osman, 2010).

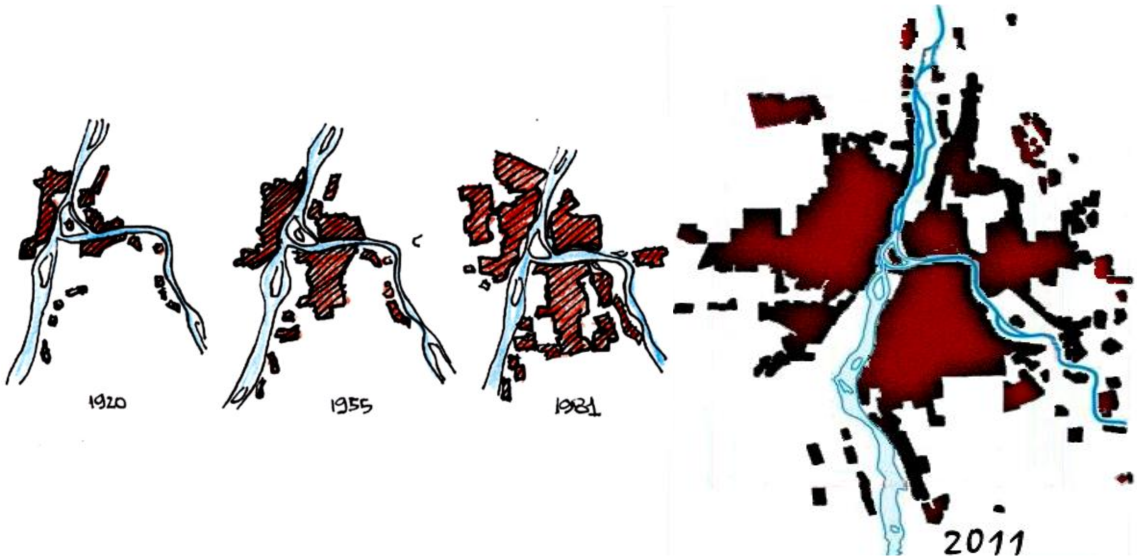



**Figure 1-1:** Expansion of Khartoum, *Source:**1920-1981** Quoted in (Habitat, 2009), **2011** is adopted from (Beckedorf, 2012)*

Most of Khartoum's outskirts poor lives in outer slums and squatter settlements (Eltayeb, 2003). These outskirts face three main problems which affect the development in these areas (Eltayeb, 2003, Habitat, 2009), Figure 1-2.

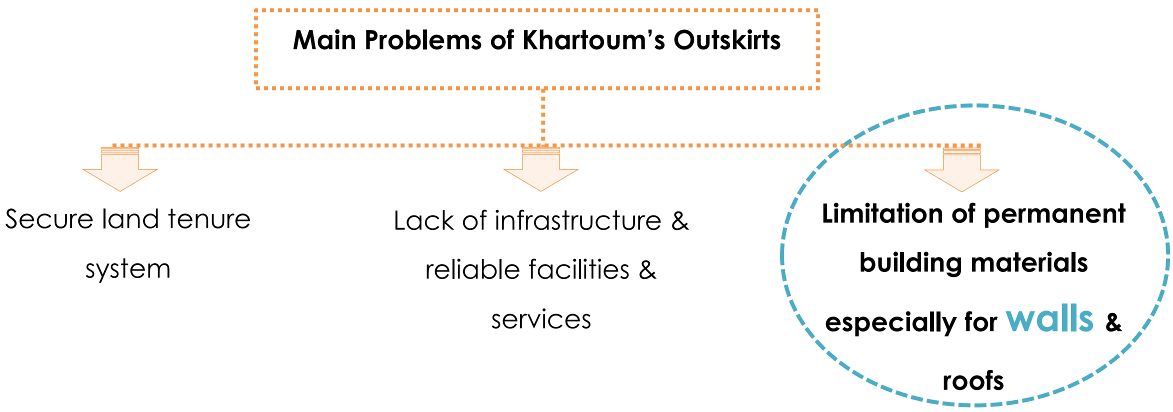



**Figure 1-2:** Main problems of Khartoum's outskirts, *Source: Adopted from(Eltayeb, 2003, Habitat, 2009)*

In 2008, the UN-Habitat mentioned in its report that when the internationally recognized measures for housing conditions such as status ownership, building materials, number of rooms, number of people per house, existence of latrine and kitchen and the availability of external fence around the house are used to assess housing conditions in Khartoum, then Khartoum will fall short with 60% of existing houses in poor conditions (Humanitarian Policy Group, 2011). All previous mentioned problems collectively are behind this deterioration of living conditions in houses in Khartoum. However, the same problems are the barriers that slow the delivery of sustainable housing for urban poor in the capital city.

In the Sudanese context, the breakdown of the cost of the construction reveals that building materials' cost, labour cost and sub-contracting cost might reach up to 85% of the total cost of the building, whereas land and services cost just 15% (Elseed, 2004). Building materials cost around 60% of the total cost of the construction (Elseed, 2004). On the other hand, wall materials alone constitute the largest share (Abdalla, 2001).

In Khartoum, 93% of the population live in simple houses and 43% of the houses are built from non-durable building materials (Humanitarian Policy Group, 2011). Mud, sacks, carton and fabric, Figure 1-3, are the most popular building materials in urban poor areas of Khartoum (Humanitarian Policy Group, 2011). These building materials are used usually to build the walls, but sometimes they may be used in roofs as well. These materials are used by the urban poor because they are cheap, available and their techniques are well known. However, building with these materials leads to very weak structure houses which are not durable and cannot resist rain and humidity.

**Figure 1-3:** Simple houses built from the non-durable building materials (mud, sacks, carton and fabric) in the outskirts of Khartoum, *Source: Author's collection, January 2013*

Mud is a popular building material in urban poor areas (Adam and Agib, 2001). Houses built out of mud need maintenance annually before each rainy season (Adam and Agib, 2001). The cost of the maintenance is very high if it is compared with individuals' income. On the other hand, in the event of heavy rains, these walls may collapse and so they act as safety hazard for their inhabitants. In the case of wood, straw and sacks, they are considered as non-durable building materials and unsafe. Generally, in the Sudan, local building materials are confined to a very limited list (brick, mud, cement blocks, stone blocks, corrugated iron sheets, cement). Although, some of these materials are produced locally, the final price is still not affordable for the urban poor. The high prices of the local materials usually come from the cost of the transportation of the final product to the local markets (Elkhalifa, 2011). The cost of the transportation sometime increases due to the unbalanced distribution of the production units all over the country (Elkhalifa, 2011). This results in the concentration of the production units in specific areas which are closer to some cities while far away from others. For instance, to reflect the effect of the transportation on the final price of the local products, in December 2010, a sack of cement costs only $ 9.97 in Khartoum, while it costs $ 20.74 in Nyala in Southern Darfur (west part of the country) (Elkhalifa, 2011). The increase of the price here occurred due among other factors to the transportation of the product to Nyala which is far to the west of the country. On the other hand, locally produced building materials cannot secure the total demand (Elkhalifa, 2011). As a result Sudan like many least developing countries turns to depend on imported building materials to cover this deficit (Abdalla, 2001, Elkhalifa, 2011). These imported building materials face price problems similar to the locally produced ones. The problem comes from the fees that are imposed on these imported products when reaching the main port of the country (PortSudan) (Elkhalifa, 2011). All these problems of locally produced and imported building materials lead the urban poor of the Greater Khartoum to continue sticking to their old and traditional building materials and techniques.

In developing countries, for example in Sudan soil construction techniques are popular and used in most of urban and rural areas (Adam and Agib, 2001). Almost 80% and 90% are the percentage of earth construction in the Sudanese urban and rural areas respectively (Adam and Agib, 2001). In fact, it could be said that the earth still remains as the main and popular building material for the sheer majority of Sudanese in urban and rural areas (Elseed, 2004). Also a research done by CRATERRE (the International Centre for Earthen Architecture) in 1983 mentioned that just 5% of Sudanese houses had walls of bricks and stones (Amenagement, 1984). Actually, this is still being reflected in the capital Khartoum, since only 6.2% of its' population live in flats and 0.3% live in villas and luxurious houses (Murillo et al., 2008 in (Humanitarian Policy Group, 2011)). The most popular soil construction techniques in Sudan are cob and adobe (Adam and Agib, 2001), Figure 1-4.

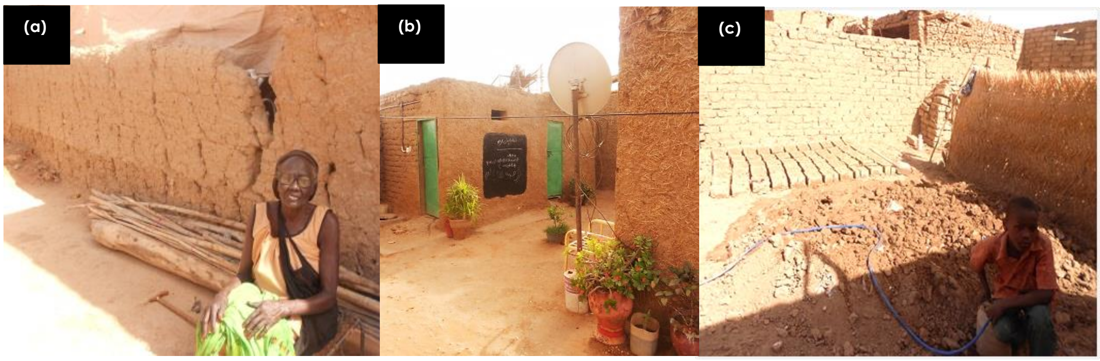



**Figure 1-4:** Earth houses in Khartoum urban areas, Sudan. (**a**) Cob wall (**b**) Adobe wall (**c**) Adobe brick making by young kids during their summer school holidays. *Source: Author's collection, January 2013*

*Jalous* is the name of the cob technique in the local tongue. This construction technique is still being used in some parts of Sudan till today, Figure 1-5. It is similar to the well-known earth technique that called Cob (Amenagement, 1984). In this technique the walls are constructed gradually in horizontal layers (Amenagement, 1984) that made from a mixture of straw, gravel and clay (Adam and Agib, 2001). The horizontal layers laid over each other and each layer must dried out before the next one is laid over in order to get its full strength to support the above new one (Amenagement, 1984). The outer surface of the mud wall is covered with a traditional mixture that is called *Zibala*, Figure 1-5. *Zibala* is used to protect the wall against the rain and other erosion factors (Amenagement, 1984). *Zibala* is a mixture of animal dung, mud and straw (Osman, 2010). The *Zibala* mixture is usually left for up to seven days before it is ready to be used in order for the fermentation process to take place. This fermentation process gives the *Zibala* mixture the strength it needs to be suitable for using as wall render. However, despite that the cob technique is still available in many urban and rural areas in Khartoum; another technique which is called adobe starts to replace it.


**Figure 1-5: (a)** Cob (*Jalous*) house in urban poor areas in Khartoum, Sudan, **(b)** cob wall covered with *Zibala* render, **(c)** closer view of the *Zibala* render. *Source: Author's collection, January 2013*

Adobe is another traditional way to build houses' walls in Sudan. Nowadays, this technique is more used than the *Jalous*. People think about *Jalous* as an old technique. They see it as a time-consuming method when it is compared with adobe. However, both techniques only differ in the way the mixture is moulded. The *Jalous is moulded* with hands only, but the adobe is moulded using simple wooden moulds to create bricks. The bricks are left to dry in the direct sun (Battelle, 1979). After the brick dries, they are used directly in building walls and mud is used as a mortar between bricks. During the drying process, the bricks are laid on a flat ground on their surface. The above surface which usually faces the direct sunlight dries faster before the lower surface that faces the ground, Figure 1-6. This leads to the bending of the longitudinal axis of the brick, which results on uneven surface that affects the construction later (Battelle, 1979). Furthermore, when the bricks are removed from the mould and the mud mixture is still wet and soft; the angles of the edges of the brick change and this result in the change of the brick standard size. Also the softness of the mixture which is made from only soil and water leads to that the bricks cannot be placed straight on their edges for drying after they removed from the mould, so they are placed on their edges after reach acceptable degree of dryness in order to complete the full drying process (Battelle, 1979). Because walls built using this adobe technique are mainly made from a mixture of soil and water only, they have a very short lifespan if they are not regularly maintained after each rainy season. As a result of the absence of the regular annual maintenance; the lifespan of these buildings will not exceed 10 to 15 years (Battelle, 1979, Amenagement, 1984).

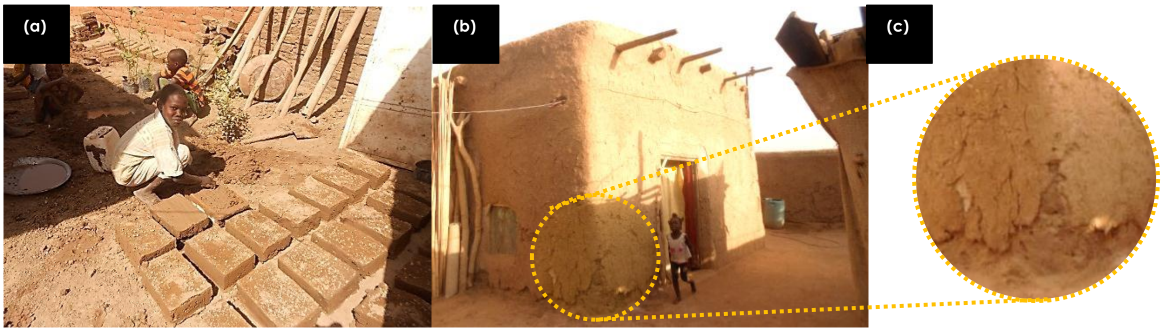



**Figure 1-6:** (**a)** Kids making adobe bricks during their summer school holiday and leave them on their bottom surface to start the drying process in the sun before turning them to their edges, **(b)** wall base eroded by the rain due to the absence of wall bases, **(c)** closer view of the erosion on the wall base

Most of the time walls that are built using one of these traditional building techniques have no foundations. However, if a foundation is found; the depth of it will be different from location to another depending on the soil conditions (no standards are available for the depth of the foundation) (Elkhalifa, 2011). Often the wall bases are eroded while the wall is built directly over the ground level without any base to protect the wall from rain ponds, Figure 1-6**.** In addition, the *Zibala* layer must be redone almost every rainy season, and this considered as an additional maintenance cost. However, if the walls are not maintained annually, they may collapse during rainy season and act as safety hazards for the house inhabitants, Figure 1-7.


**Figure 1-7:** Destruction of houses in Khartoum by heavy rains in August 2013, *Source: Reproduced with permission of Nafeer initiative, Sudan (https://www.facebook.com/gabaileid)*

To enhance the strength and the durability of the traditional available mud techniques against weather factors, introduction of new techniques were taken place. As an example, a technique called *Gishra* in the local tongue which means crust in English was used and still is being used in many parts of Khartoum. In this technique, the wall is built in two layers (outer and inner), the outer is built from fired red bricks and the inner layer is built from adobe (Elkhalifa, 2011). The red brick protects the adobe from being eroded by annual rain and wind. The outer layer may be left without rendering or could be rendered by plaster depends on the occupants' preferences. The inner surface in most cases is rendered using sand mortar. Although this technique is reducing the annual maintenance cost; it costs more than adobe technique. However, it is still cheaper than building the wall completely from red bricks.

In addition to this new technique, many other techniques that include the use of stabilisers (especially cement, lime and bitumen) and compaction were introduced to the local people by researchers, organisations and governments. Techniques, such as Compressed Stabilised Earth Blocks or Compressed Stabilised Soil Blocks (CSEBs or CSSBs) and Stabilised Soil Blocks (SSBs). However, most of these initiatives did not widely accepted among local people and did not been adopted as was expected. This was attributed to the following points:

- Every time there was a good chance for the application of new technique of earth on a real project, the project failed due to inefficiency and sometimes unavailability of machines and also due to problems and complications in the construction and the project management itself. Thousands of housing projects in Dar Essalam neighbourhood in Omdurman and Kalakla neighbourhood in Khartoum were failed due to the aforementioned problems (Ahmad et al., 2002, Construction, 2006, Elkhalifa, 2011)
- Most of the new techniques involve expensive stabilisers such as cement, lime and bitumen
- The new techniques are complicated and need trained people to deal with them and without the education and training no one could deal with the machines involve in the construction, so these techniques were no longer suit do-it –yourself projects

- Sometimes the new techniques include machinery rent which increases the total construction cost make it unaffordable to middle and lower classes of the population

Despite the above-mentioned problems, in Sudan compressed stabilised soil blocks which were stabilised using cement were successfully tested and proved their workability as a building material in the construction of an experimental school in El Haj Yousif in Khartoum North, Figure 1-8. The blocks in this experimental school proved its ability to deal with and resist the weather conditions (Adam and Agib, 2001). The production of the blocks in this project was done by manual machine (Elkhalifa, 2011).

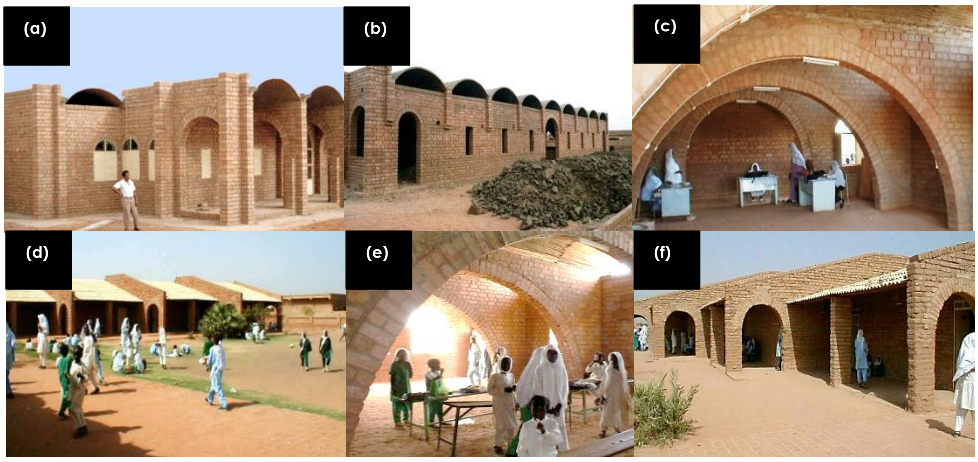



**Figure 1-8:** Compressed Stabilised Soil Blocks (CSSBs) at El Haj Yousif School in Khartoum North, Khartoum – Sudan, *Source: **(a)** Adopted from (Adam and Agib, 2001), **(b, c, d, e & f)** Are Author's collection*

From all the above, it is clear that there is a real problem regarding the dielivery of sustainable housing for the urbam poor of Sudan. The urban poor cannot afford expensive building materials such as cement and red brick. As a result, they rely on mud as the main building material that they can afford. However, the urban poor cannot afford some of the famous stabilisers such as cement and lime which are known for their ability to enhance the strength and the durability of mud as a building materials. As a result, the urban poor use unstabilised mud to build their houses. The use of the unstabilised mud results in non-durable walls which need annual maintenece. The annual maintenance is costly and it is considered as one of the main problems facing the urban poor of Sudan. As it has been addressed earlier, new mud techniques which involve machinery failed in the context of the Sudanese urban poor housing projects. So, introducing bio-inspired stabilisers which could be added to mud using the same old earth techniques the urban poor familier with could help in the dielevry of sustainable housing in urban poor areas in Sudan.

### 1.1.2 The second motive

The main architectural characteristic of the rural and urban areas in the United Kingdom (UK) is the wide spread use of fired clay bricks (Bloodworth et al., 2001). The vast majority of the old buildings in the UK were built using clay bricks. This building material is still in high demand (Bloodworth et al., 2001). The UK Government's 2017 White Paper on "Fixity our broken housing market" sets out Government’s plans to boost the supply of new homes in England. In this report, the Secretary of State for Communities and Local Government by Command of Her Majesty presented that the UK needs from 225,000 to 275,000 or more homes per year to keep up with the population growth (DCLG, 2017). In fact, in the UK bricks are not only used in residential buildings but they are also used in other five different types of buildings which are commercial, educational, healthcare, retail and industrial (Association, 2011).

The production of the clay bricks incorporates five different stages, clay preparation, brick forming, drying, firing and inspection and packing. In general, all these stages consume energy, however, the firing process along with the drying are the most intensive stages. In 2007 the total bricks produced in the UK was 6 million tonnes which is 2.5 billion clay bricks (Trust, 2010). There are two types of carbon dioxide emitters in the UK brick industry, Figure 1-9. The first carbon dioxide source is from the electricity. Electricity is used in the clay preparation stage, brick forming, air movement fans in the drying and firing stages, setting of the bricks during the inspection stage and to compress air throughout the production plant. 19 percent of the total $CO_2$ emitted by electricity consumption in the UK each year (166,000 tonnes of $CO_2$) is emitted by the brick industry (Trust, 2010). The second carbon dioxide source is from burning the fossil fuels to dry and fire the bricks. The fuel consumption in the brick industry represents 82% of the $CO_2$ emissions. This because in order to achieve the clay bricks in its final well-known shape and quality, the bricks are fired in kilns at temperatures between 900 °C and 1100 °C. In total, the brick industry sector emits one million tonnes of $CO_2$ per year (Trust, 2010)

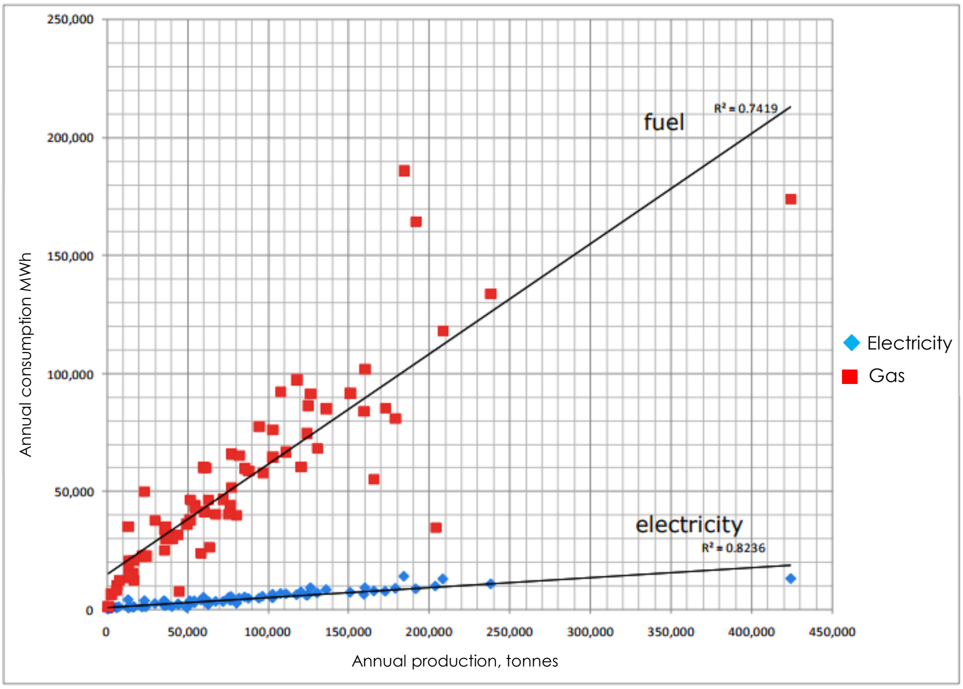



**Figure 1-9:** Energy consumption at 73 brick factories across the UK, *Adopted from (Trust, 2010)*

Figure 1-9 above shows that the consumption of the fuel is higher than the electricity in the brick sector. This is because the drying and the firing of the bricks are highly dependent on the burning of fossil fuels.

One very popular way to decrease the carbon dioxide emissions is to use air-dried earth bricks as a construction material. Today, roughly around one third of the world population lives in houses made either totally or partially from earth (Minke, 2006, UNESCO, 2009). In fact, 50% of this population is living in rural and urban areas in the developing countries (Houben and Guillaud, 1994). However, in the developed countries there is a different story regarding the earthen heritage. For instance, in the UK earth construction techniques died with the industrial revolution about 250 and 100 years ago (Morton, 2008). Post the industrial revolution, new building materials such as concrete, steel and red brick dominated the market and people turned to favour these new construction fashions over the old traditional earth construction techniques. As a result, earth buildings were neglected and most were left without any maintenance facing the severe damp weather of the UK (Morton, 2008). Only in the past 40 years here in the UK, some movements have started in order to recognise the importance of earthen buildings and value them. As a result of these movements, more earthen buildings were recognised as heritage that should be saved and conserved (Morton, 2008).

Following the above two mentioned motives, earth as a construction material could play a vital role in the delivery of sustainable housing in the developing countries and also could be a way to partially replace the reliance on the red brick in wall construction in the developed countries. If the quality of earth as a construction material could be improved and as a result could be adopted by both the developing and the developed countries, then this will lead to a reduction in the emission of the greenhouse gases such as carbon dioxide in developed countries and in the developing countries this will decrease the cost of the annual maintenance and also it will lead to more resilient bricks.

## 1.2 Earth as a building material

Earth as a building material has many advantages over industrial and conventional building materials (Adam and Agib, 2001, Binici et al., 2004, Minke, 2006, Namango, 2006, Quagliarini and Lenci, 2010, Pacheco-Torgal and Jalali, 2012), as follows:

- Soil is an abundant and sustainable source of material that is used in its natural state.
- Affordable and accessible for all population groups.
- Soil needs simple equipment during the construction process, so it is ideal for do-it-yourself construction.
- Soil as a construction material is suitable for building many elements of the building (walls, roofs and floors).
- Soil is a fire resistance building material.
- Using soil as a building material helps in the cleaning of the indoor air by absorbing pollutants (Minke, 2006).
- Soil is a green building material and has the least embodied energy (Heathcote, 2002, Delgado and Guerrero, 2005, Piattoni et al., 2011).
- Soil has a high thermal capacity which maintains and balances the thermal performance (Heathcote, 2002).
- Soil is a reusable building material (Piattoni et al., 2011).

However, despite the above mentioned advantages, earth has three main disadvantages if it is compared with industrial available building materials in the market today as follow (Minke, 2006):

- Quality of earth as a building material cannot be controlled or linked to a fixed standard (Delgado and Guerrero, 2005) like many industrialised building materials such as concrete, since different soils lead to different earth composition and perhaps different end product quality
- Earth as a building material shrinks during the drying process and produces cracks (Quagliarini and Lenci, 2010) that affect the material overall strength
- Earth does not resist water and as a result protection of earth surfaces against rain is important

The above three disadvantages highlight that earth as a building material when it is used in its natural state (unstabilised) has limited durability (Chmeisse, 1992, Heathcote, 2002) .

## 1.3 Stabilisation of earth as a building material

Lack of durability is considered as the main drawback of earth as a building material. To enhance the durability of earth as a building material, stabilisation was introduced (Burroughs, 2001, Kerali, 2001). Stabilisation of the soil is not considered as a new trend to enhance the durability of the soil mixture, since it was found to be used in Greece in the Mediterranean dating back to 4600 BC (Hossain and Mol, 2011). The use of straw stabilisation was established there and then spread to other parts of the world (Hossain and Mol, 2011). However, the scientific stabilisation as known today was introduced recently. Actually, it was first introduced in road construction around 1920s (Adam and Agib, 2001). Stabilisation means to modify the properties of the soil-water-air system of the soil (Houben and Guillaud, 1994). This means to improve the soil by bonding and aggregating its particles more, increasing strength and stiffness, increasing durability, enhancing soil workability, and limiting the absorption of water (Chmeisse, 1992, Vilane, 2010). This stabilisation could be achieved by three different ways as follow (Adam and Agib, 2001, Burroughs, 2001, Zami and Lee, 2009):

- Mechanical stabilisation, which could be achieved by controlling the soil density and pore size by the use of compacting pressure. This compaction could be manual or mechanical. Rammed earth and some stabilised soil blocks are some examples for this mechanical stabilisation.

- Physical stabilisation which is sometimes called granular stabilisation could be achieved by controlling the grain size distribution i.e. the use of different grain fractions on the mixture. Other ways to change soil physical properties include the use of special heating mechanisms, freezing and electrical treatment in order to have better structural properties.
- Chemical stabilisation by the introduction of chemicals and /or materials and are known as additives or stabilisers. These stabilisers change the chemical properties of the soil mixture and strengthen the bond between the soils' grains. This introduction of chemicals sometimes could lead to the creation of a new building material.

The strategy of stabilisation depends a lot on the type of the soil (Lima et al., 2012). As a result understanding the soil type is essential to achieve best results of stabilisation (Obonyo et al., 2010). In the stabilisation, one or a combination of more than one stabiliser could be used together to work as binder and to enhance the durability of the soil mixture (Obonyo et al., 2010). However, to get the potential benefits of the stabilisation, the stabiliser amount, type, combination of the stabilisers and the age (curing time after stabilising) are important (Obonyo et al., 2010, Hossain and Mol, 2011). Scientific research listed and tested more than 130 material that could work as stabilisers (Lal 1995 in (Zami and Lee, 2009)). Some of these stabilisers are famous and well-known as cement, lime, gypsum, straw, animal dung, Table 1-1. This table shows some stabilisers, their advantages and disadvantages. For instance, some stabilisers are famous and widely used such as cement, they are expensive and are considered as unsustainable and their manufacturing process is harming the environment. Cement manufacturing process considered as the major contributor of $Co_2$ emissions globally with 5% of global emissions (Alavéz-Ramírez et al., 2012), Table 1-1. On the other hand, other cheap, natural and sustainable stabilisers such as straw and animal dung result in a product which lacks durability and needs annual maintenance which is costly (Adam and Agib, 2001), Table 1-1. Fibres such as straw, sisal, hemp, elephant grass, coconut, oil palm and bagasse when used to stabilise soil, their properties should be investigated first prior to use. These fibres differ in their properties which will affect the mechanical and physical properties of the earthen units produced. Properties such as dimensions (length and diameter) are important because they affect other properties such as water absorption and modulus of elasticity (Danso, 2016). Other important properties such as specific weight of the fibre, tensile strength, water absorption and the microscopic texture by using Scanning Electron Microscopy (SEM) are also important to be known prior to the use of the fibre as potential stabiliser in earth construction.

## 1.4 Inspiration

Termite is one of many organisms (i.e. ants, worms ...etc.) that inhabit the soil (Robert et al., 2007). There are around 3000 species of termites that are different in their living spaces and diet habits (Kaschuk et al., 2006, Robert et al., 2007, Sarcinelli et al., 2009). Some live in wood-dwelling while others live in earthen nests (Robert et al., 2007, Millogo et al., 2011). Generally, termites live in tropical and subtropical regions (Millogo et al., 2011) and their existence in a location largely depends on the temperature at that location and the availability of rainfalls (Robert et al., 2007). The group which lives in earth nests builds a magnificent piece of architecture that is called termite mounds, Figure 1-10. These mounds differ in shape and size from place to place and from species to another, Figure 1-10. Mounds could reach 9 meter in height and 20 to 30 meter in diameter at the base of the mound (Robert et al., 2007, Millogo et al., 2011).

These mounds are considered as the tallest non-human structure on earth (Elmahdi, 2008). Akhmad 2005 in Elmahdi 2008 compared the scale of the termite mounds to human structures by assuming that the human size is equal to an average termite, he found that the mound height is equivalent to around 180 story building of human's structure (roughly around 600 meter high) (Elmahdi, 2008). This was also confirmed by a BBC documentary which assumed that if the termite mounds are built in human terms and the termite size is equivalent to human size, then its mound will stand a mile in height and humans have not yet reach such heights in construction (BBC, 2009). These mounds have different shapes that correspond to the climate where they exist. For example, mushroom shaped mounds are built to easily drain the rain water, Figure 1-10. Also mounds have many other different shapes such as: spiral and conical shape, wedge shape with sharp end edges and domed shape, Figure 1-10, (Robert et al., 2007). Termites build very durable hard structures (Udoeyo et al., 2000, Kaschuk et al., 2006, Cosarinsky, 2011, Tilahun et al., 2012), that last for decades in very violent climatic conditions in rainforests of Africa and South America and sclerophyll forests, savannahs and woodlands of Australia (Jouquet et al., 2004, Robert et al., 2007). The rainfall rate in these climates is around 1200 mm per year (Jouquet et al., 2004). In fact, rain is considered as one of the most destructive climatic factors to earth structures. Regularly soil of earth structures is eroded and pealed mainly by the rain (Jouquet et al., 2004). Particularly, rain affects the soil by breaking and detaching the aggregation of soil particles, weakening the bond between these particles and removing and eroding the soil layers (Jouquet et al., 2004). Despite the differences in the soil (Hesse, 1955, Abe et al., 2009) and climate, these termite earth nests stand for many years with the same construction quality.

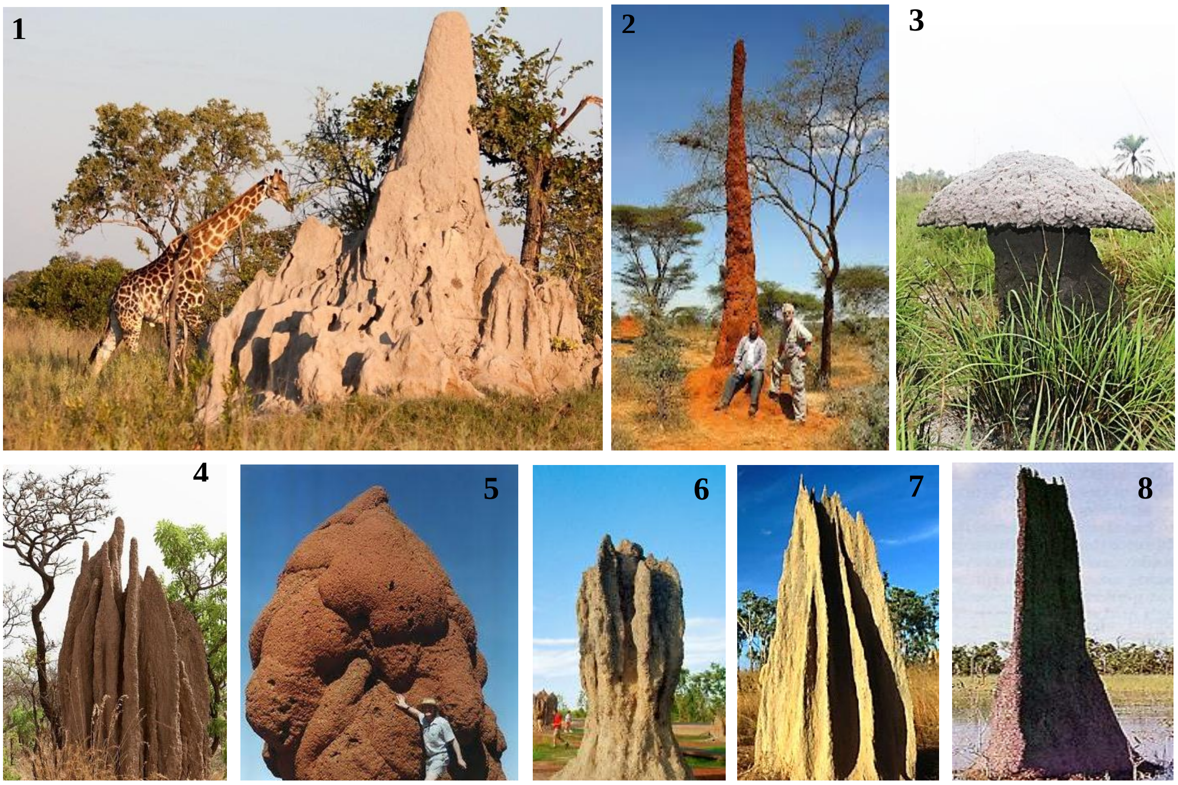



**Figure 1-10:** Different shapes and sizes of termite's mounds
***Sources:***
*(1) http://www.getintravel.com/okavango-delta-botswana/a-giraffe-walks-behand-a-termite-mound-in-the-bushland-of-the-okavango-delta-in-botswana/*
*(2) http://www.flickr.com/photos/niall_crotty/435523657/*
*(3) http://www.sareptiles.co.za/forum/viewtopic.php?f=9&t=16223*
*(4) http://www.johangerrits.nl/galleries/?/1.Travel/Ghana/318+-+Termite+mound+.jpg*
*(5) http://tywkiwdbi.blogspot.co.uk/2009/10/termite-mound.html*
*(6) http://www.jcehrlich.com/blog/searching-for-termites/*
*(7) http://www.art.co.uk/products/p14125123-sa-i2856750/posters.htm*
*(8) http://www.savanna.org.au/all/termites.html*

**Table 1-1:** Some stabilisers advantages & disadvantages

| Stabiliser type | Stabiliser | Advantages | Disadvantages | References |
|---|---|---|---|---|
| Fibres | Fibres (straw, sisal, hemp, elephant grass, coir (coconut fibre), etc.) | • improve the strength of the material significantly<br>• inclusion of fibres in soil increases the compressive strength until an optimum strength is reached and then further fibres inclusion reduce the strength of the block<br>• the inclusion of fibres in the soil blocks reduced the density of the blocks, and as the fibre content increased the density of the blocks reduced, so fibre stabilised blocks are suitable for lightweight construction<br>• inclusion of fibres increases the workability of the soil<br>• soil that reinforced with fibres are more durable, tougher and more ductile if compared with soils without fibres | • excessive amounts of fibres weaken the final product and increase the water absorption | (Tang et al., 2006), (Stulz and Mukerji, 1993, Danso, 2016) |
| | Straw (wheat, barley, etc.) | • stop and prevent the appearance of cracks during the drying process while it acts as a reinforcement for the material<br>• increase the dry compressive strength by at least 15% when compared to materials without straw | • the material should be kept dry in order to preserve the same compressive strength<br>• when the material exposed to water the straw deteriorates and thus affect the mechanical properties of the material | (Ngowi, 1997, Adam and Agib, 2001, Quagliarini and Lenci, 2010) |
| Binders | Rice Husk Ash (RHA) | • could work as an alternative to cement and lime<br>• reduce the cost of the construction especially in rural areas in developing countries | • available only on tropical and sub-tropical areas of the world<br>• give the best results when it is used with lateritic soil only | (Rahman, 1986) |

| Stabiliser type | Stabiliser | Advantages | Disadvantages | References |
| --- | --- | --- | --- | --- |
| Binders | Cassava Starch | • suitable to be used as light weight curtain walls (the addition of cassava starch decreases the dead load of the walls' material) | • recommended to be used in internal and interior walls only and areas of low exposure to moisture<br>• the walls need further protection from water exposure; while it faces least durability performance when exposed to water, despite the fact that cassava slows the rate of the water absorption | (Ponjul, 2011) |
| | Sugarcane Bagasse Ash (SBA) and Lime | • improve the mechanical and durability properties of the soil<br>• it could substitute cement stabilisation (lower energy consumption in manufacturing and hence less pollution) | • lose most of its compressive strength (65%) when immersed in water | (Alavéz-Ramírez et al., 2012) |
| | Cow-dung | • increase the cohesion between the soil particles with the nitrogenous organic compounds available on it which act as a glue and enhance the binding | • the glue lost its stability and effect if is exposed or subjected to excessive moister and water | (Ngowi, 1997, Adam and Agib, 2001) |
| | Cement | • best stabiliser and the most widely used<br>• increase the material water resistance<br>• increase the material strength in very short period of time (about 28 days)<br>• increase the compressive strength of the soil<br>• the blocks remain dimensionally stable even when in contact with water | • expensive especially in developing countries<br>• works better with soils that have high sand content and low clay content<br>• uneconomical when is used with clayey soil (more cement is needed)<br>• its manufacturing process consumes high energy<br>• consequent environmental damages and pollution caused by the released of the greenhouse gases during cement production (the major contributor of $CO_2$ emissions globally with 5% of global emissions)<br>• the addition of cement as a stabiliser in earth construction lessens the embodied energy differential between the earth blocks and conventional materials (red bricks and concrete) | (Ngowi, 1997, Adam and Agib, 2001, Burroughs, 2001, Kerali, 2001, Browne, 2009, Harper, 2011, Ponjul, 2011, Alavéz-Ramírez et al., 2012, Lima et al., 2012, Egenti et al., 2013) |

| Stabiliser type | Stabiliser | Advantages | Disadvantages | References |
| --- | --- | --- | --- | --- |
| **Binders** | Lime | • less intensive than cement in embodied energy<br>• increase compressive strength<br>• reduces water absorption and makes soil less sensitive to changes in moisture content<br>• improve soil workability, reduce soil shrinkage | • work the best with clayey soil<br>• more lime is required to achieve results similar to cement (this is uneconomical in areas such as developing countries and also more fuel is needed for its' manufacturing, which leads to more environmental pollution as a result)<br>• stabilisation requires and uses great amount of water | (Ngowi, 1997, Burroughs, 2001, Harper, 2011, Ponjul, 2011, Egenti et al., 2013) |
| | Bitumen | • makes soil resistance to water absorption<br>• increase soil strength | • works the best with sandy soil, clayey soil needs more amount of bitumen<br>• is not available and not a traditional material in most of developing countries<br>• expensive to be imported<br>• high cost of preparation, while it needs heating for the mixing process<br>• stabilisation effectiveness depends very largely on mixing, so it should be done very carefully otherwise an adverse reaction could happen especially in hot climates (too much mixing and heating can increase water absorption after drying)<br>• require considerable amount of water in the production | (Ngowi, 1997, Adam and Agib, 2001, Burroughs, 2001, Ponjul, 2011, Egenti et al., 2013) |
| | Gypsum | • traditional material available in most Mediterranean and Middle Eastern countries<br>• during manufacturing, it requires less temperature for calcination (low embodied energy if compared with lime and cement) | • Works better with sandy soils | (Adam and Agib, 2001) |
| | Ground Granulated Blast Furnace Slag (GGBS) | • by-product of steel industry<br>• reach better durability when more GGBS is used | • the use of more and higher content of GGBS slows the curing time of the blocks | (Harper, 2011) |
| | Pulverised Fly Ash (PFA) | • by-product from coal fired power stations | • require other additives in order to stabilise the soil (water and a source of alkali, usually calcium hydroxide) | (Harper, 2011) |
| | Cement Kiln Dust (CKD) | • by-product of the cement manufacturing | • environmentally unfriendly (high embodied energy) | (Harper, 2011) |

## 1.5 Aim and objectives

The aim of this study is to enhance the strength and the durability of adobe bricks by introducing bio-inspired stabilisers.

To achieve this aim, the following objectives are pursued:

1. To investigate how the termite constructs its mounds and identify the biological stabiliser behind these durable constructions.
2. To find a scientific approach by which these termites' biological stabilisers could be used for human benefits and in a larger scale.
3. To identify biological components that are inspired by the termites' mound construction technologies that could be used as stabilisers in earth construction.
4. To determine the properties of the soils to be used for making adobe bricks using these bio-inspired stabilisers.
5. To make a variety of adobe bricks using these soils and the termite bio-inspired stabilisers.
6. To test the adobe bricks stabilised with the different biological stabilisers for their strength and durability.
7. To discuss the results from (6) and compare the stabilised adobe bricks' strength and durability to the control unstabilised adobe bricks' strength and durability and also to the available strength and durability results for stabilised earth units from the literature.

## 1.6 Structure of the thesis

This thesis is comprised of seven chapters. Because of the nature of this research and its multidisciplinary approach, each chapter contains literature that is relevant to the chapter. However, there is a chapter which is called the literature review which contains the general literature for each discipline that is part of the study.

Chapter 1 introduces the motivation behind this research, the advantages and limitations of earth as a building material, the stabilisation, inspiration, aim and objectives and the structure of the thesis.

Chapter 2 reviews and highlights the literature that is relevant to each discipline that is involved in this multidisciplinary study.

Chapter 3 is devoted to the selection criteria of the soils chosen as part of the experimental work in this study, the classification tests of these soils and their results, the adsorption mechanisms of the bio-inspired stabilisers by clay minerals, the selection criteria of the bio-inspired stabilisers used to stabilise the adobe bricks, the selection criteria of the strength and durability tests. This chapter also includes the results of the preliminary experiments that were used to develop the mixing, moulding, drying and testing methods used later in the main tests in this study.

Chapter 4 presents the compressive strength results along with the general structure of the experimental tests.

Chapter 5 presents the accelerated erosion test results.

Chapter 6 discusses the results from chapter 4 & 5 in the light of the relevant literature.

Chapter 7 concludes the thesis and outlines recommendations for future work.

# 2. Literature Review

## 2.1 Overall view of earth construction

### 2.1.1 Background

Earth is considered as the first available choice of building materials that humans ever used, and the history of it usage is dated back to the age of humans themselves on earth (Houben and Guillaud, 1994, McHenry, 1998, Reddi et al., 2012). Earth as a construction material is also well known throughout the ancient civilizations (Houben and Guillaud, 1994, Quagliarini and Lenci, 2010). It was originated in the Levant geographical region which includes modern today's countries of Turkey, Israel, Jordan, Lebanon, Palestine and Syria (Schroeder, 2012). For instance, mud was used by the old Egyptian in about 1500 BC to build many of their homes and religious buildings (Minke, 2006). Most of earth techniques known today were used in the Egyptian civilization, Assyrian civilization, Ancient Roman buildings, old cities of Iran (e.g. Yazd city), Figure 2-1, old pyramids of Mexico and Great Wall of China. The age of most of these earth buildings is more than 3200 years (Minke, 2006). In modern history, earth could be found in great and iconic buildings and cities all over the world. For instance, the large mosque of Djenne in Mali built in 1935 which is considered as the largest earth building on the world, Figure 2-2, skyscrapers of Shibam city in Yemen built 2000 years ago, Figure 2-3, which is also called Manhattan of the desert (Walsh, 2007 ), and Bobo Dioulasso Grand Mosque in Burkina Faso built around 1880, Figure 2-4.

Today, roughly around one third of the world population lives in houses made either totally or partially from earth (Minke, 2006, UNESCO, 2009). In fact, 50% of this population is living in rural and urban areas in the developing countries (Houben and Guillaud, 1994). However, in the developed countries there is a different story regarding the earthen heritage. For instance, in the UK earth construction techniques died with the industrial revolution about 250 and 100 years ago (Morton, 2008). Post the industrial revolution, new building materials such as concrete, steel and red brick dominated the market and people turned to favour this new construction fashions over the old traditional earth construction techniques. As a result, people completely abandoned and neglected earth buildings and most of the buildings left without any maintenance facing the severe damp weather of the UK (Morton, 2008). Only in the past 40 years here in the UK, some movements start in order to recognise the importance of earthen buildings and value them. As a result of these movements, more earthen buildings were recognised as heritage that should be saved and conserved (Morton, 2008).

**Figure 2-1:** Yazd City, Iran, *Source:* *http://www.iranreview.org/content/Documents/Yazd_Bride_of_Desert.htm*

**Figure 2-2:** The Large Mosque of Djenne Built in 1935, Mali, *Source:* *http://i.imgur.com/fYFoX.jpg*

**Figure 2-3:** Shibam City Built 2000 Years Ago, Yemen, *Source:* *http://ritemail.blogspot.co.uk/2013/02/manhattan-of-desert-shibam-yemen.html*

**Figure 2-4:** Bobo Dioulasso Grand Mosque Built around 1880, Burkina Faso, *Source:* *http://upload.wikimedia.org/wikipedia/commons/0/03/Moschee_von_Bobo-Dioulasso.jpg*

### 2.1.2 Earth as a building material

In order to understand earth and the possibility of its use as a building material, understanding its composition and properties is crucial. Soil as a free and an abundant material is different from place to place and even sometimes from one spot to other in the same place. Soils are formed by the weathering of the parent rocks and the process of the soil formation is a very long process. The weathering could be physical, biological or chemical (Houben and Guillaud, 1994, Beckett, 2011). Each soil characteristics reflect the original parent rocks which are made from (Al-Khafaji and Andersland, 1992, Beckett, 2011). The parent rock eroded and disintegrated physically due to the expansion and contraction as a result of changing of the temperature and the pressure when many climatic factors such as rain, wind, sun heat and frost act (Al-Khafaji and Andersland, 1992, Minke, 2006). In addition to the thermal effect of the climatic factors, the mechanical movements of glaciers, water, wind, volcanos and landslips also assist in the breakdown and the grinding of the rocks (Houben and Guillaud, 1994). These movements transport soil from place to place and keep changing the soil profile (Al-Khafaji and Andersland, 1992). The chemical changes in the rocks are due to hydration, oxidation, carbonation and the chemical effects of plants (Al-Khafaji and Andersland, 1992). After this stage, the biological weathering factor is taken place. The flora and fauna live in the soil make many different chemical alterations to the soil which resulted in what is called humus (Houben and Guillaud, 1994). The flora and fauna come to action with the availability of the growing vegetation on the surface of the ready formed soil. In fact, the changes these biogens do in the soil and the final humus properties depends on the type of the parent rock, the prevailing climate and the vegetation available in the region (Houben and Guillaud, 1994). At this stage of soil development, the soil is homogeneous and so far, its physical, biological and chemical characteristics remain constant. On the other hand, other changes might happen which depend mainly on the climate and the topography of the region. These changes are usually in the shape of vertical movements which could be either downwards or upwards (Houben and Guillaud, 1994). The downwards movements of the soluble minerals are usually occurring in the humid climate and it is called leaching. In the dry climates the soluble minerals travel upwards to further enrich the surface soil (Houben and Guillaud, 1994). In general, the climate of the area, the time or the age, the topography, geological history and the parent rock all together will influence the final soil properties. The physical erosion results on different grain sizes of the soil that range from very fine particles to big rocks, but all at the end share the same properties of  the parent rock (Beckett, 2011). However, these grains when they exposed to the chemical decomposition, some of them remain the same and never react or change such as quartz while others change to be new product (Al-Khafaji and Andersland, 1992).

In general, the soil as final product of the above formation and configuration process, it consists of the assemblage of the minerals all together which considered as the solid part, the gases in the form of air and the liquid which is mainly water (Al-Khafaji and Andersland, 1992, Houben and Guillaud, 1994, Beckett, 2011), Figure 2-5. The surface energy of the water available in the soil matrix is the main reason for the adhesion between the soil particles. This adhesion occurs between the soil particles irrespective of the types of the particles (clay, silt, sand).

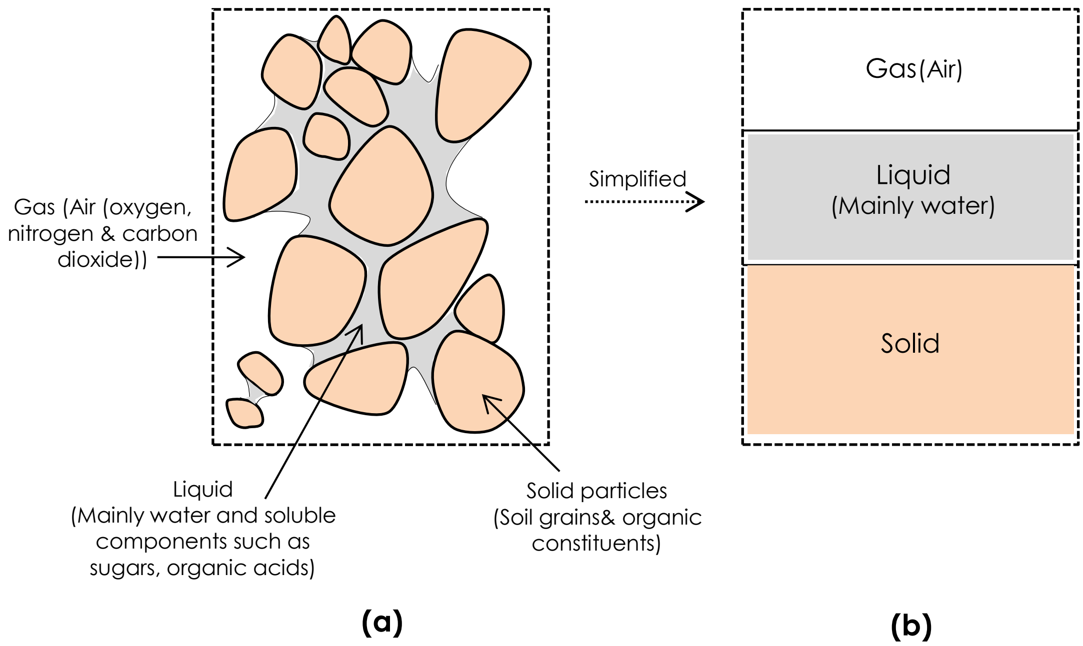



**Figure 2-5:** Simplification of complex soil in (**a**) to a three-phased diagram (**b**)

*Reproduced from (Al-Khafaji and Andersland, 1992, Cizer et al., 2006, Beckett, 2011)*

The soil could be either completely dry when there are no liquid voids or fully saturated when the voids all filled up with water. The air voids could be controlled and decreased in order to increase the mass of the soil by bringing the soil particles close to each other's by compaction (Al-Khafaji and Andersland, 1992). The solid part of the soil could consist of only one mineral such as in the case of the sand deposit which is dominated with quartz, or could be a mixture of minerals that includes gravel, sand, silt and clay.

Soil grains are different in size, shape and the physical properties. For instance, the clay is considered as the only cohesive particle in the soil that has the ability to react with water. The rest of the particles, the gravel, the sand and to some extent the silt are not cohesive and don't react with the water (Al-Khafaji and Andersland, 1992). As a result, the clay is considered the cement or the binder that bind the rest of the particles. On the other hand, the rest of the particles act as fillers in the soil matrix (Minke, 2006).

### *2.1.3 Characteristics and properties of soil minerals*

The disintegration and the decomposition of the rocks result in different sizes of products ranging from 200mm (pebbles) to less than $2\mu m$ (colloids). The properties of each of these mineral products are in Table 2-1. From the colloids section in Table 2-1, it is clear that clay minerals act differently with water and thus results in different swell and shrinkage scenarios in practice. Also, due to the importance of the reaction of the soil with water in the construction industry in general and in earth construction in specific, it is important to look at clay minerals in details and understand their reaction with water.

### *2.1.4 Clay minerals and their behaviour towards water*

For instance, two clayey soils with similar percentages of soil particles (gravel, sand and clay) they will have completely different soil properties. The clay minerals with their unique properties (cations exchange capabilities, plastic behaviour when wet, catalytic abilities, swelling behaviour, and low permeability's) will play an important role in defining the soil general properties (Guggenheim, 1997). Different clay minerals have different colloidal properties (Young, 2012). But in general clay minerals made primarily from the chemical weathering of mica and feldspars (Al-Khafaji and Andersland, 1992, Houben and Guillaud, 1994, Young, 2012).

Clay minerals consist of many micro-sheets which are arranged together to create what is called micelles or fine crystals (Houben and Guillaud, 1994). The stacking structure of these sheets, the bonding between the sheets and the exchanging of the ions (aluminium and silica) in the atomic structure, all together will determine the crystal properties and as a result the mineral properties of the final mineral (Young, 2012, Bell, 2013).

**Table 2-1:** The properties of soil particles after the disintegration and the decomposition of the parent rock

| Particle Name | Particle Size | Description |
|---|---|---|
| **Pebbles** | 20mm to 64mm | In the order of the soil grains, it comes after the boulders (>200mm) and the cobbles (60mm-200 mm). Depending on it is age and history of formation, it is edges could be either sharp for new formed ones or round for old ones that moved by water or ice(Houben and Guillaud, 1994). |
| **Gravel** | 2mm to 20mm | It includes very fine, fine, medium and coarse. Usually is rough and small. It is very important in many industries and construction is one of them. It also affects the water movement inside the soil and other soil mechanical properties. |
| **Sand** | 0.06mm to 2mm | Sand and gravel are considered the skeleton of the soil and they determine many of its mechanical properties (Young, 2012). Sand usually made from quartz or silica. Sand, gravel, pebbles are considered as the soil particles that lacks cohesion(Al-Khafaji and Andersland, 1992). The surface of these particles doesn't absorb the water, so these particles do not swell and as a result they do not shrink (Houben and Guillaud, 1994). |
| **Silt** | 0.002 to 0.06mm | Silts are mainly made from fine quartz, but with smaller grain size compared with the sand. silts are usually have round shape with smooth edges (Bell, 2013). Silt and sand share the same physical and chemical properties and the only difference is the grain size (Houben and Guillaud, 1994). Due to its small grain size; soil internal friction increases and result in more stable soil. The water could adhere to the surface of the silt particle and gives the soil some cohesive properties. As a result the silty soil could have small-scale swell and shrinkage properties (Houben and Guillaud, 1994). |
| **Clay** | < 0.002 (2$\mu m$) | Clay is called the fine-grained soil. Is referred to the material that exhibit plastic behaviour when mixed with appropriate amount of water (Guggenheim, 1997, Giese and Van Oss, 2002). As a result, it swells and shrinks. Its properties are completely different from other soil grains(Houben and Guillaud, 1994). Clay particles are hydrated alumina-silicates, formed from the chemical weathering and leaching process of rocks(Beckett, 2011). The common groups of clay minerals are kaolin, illite, montmorillonite, palygorskite, chlorite, vermiculites and halloysites. |
| **Colloids** | < 0.001 mm (1$\mu m$) | Sometimes it is glue like paste that found to stick small sand particles to the soil(Houben and Guillaud, 1994). They consider as the most active part of the soil and assists on the determination of the soil chemical and physical properties. There are two types of colloids in the soil; organic and inorganic. The organic colloids are generated from the decomposition of the organic matter in the soil; e.g. humus. Inorganic colloids such as clay minerals (silicate clays (alumina-silicate minerals)), crystalline and poorly crystalline types), hydrous oxides, etc. All colloids (organic & inorganic) have the ability to absorb, hold and release ions. However, the organic colloids are most active in chemical reaction in the soil compared with the inorganic. In general, both colloids have a very high surface area per unit mass (specific surface area) and also, they have electrically charged surface that is usually a net negative surface charge. This electricity charges are important on the exchange of the cations between colloids. The cations exchange in the soil is very important because it allows plants to have the important nutrients they need from the soil. On the other hand, soil swells and the shrinks as a result of the wetting and drying cycles. In general, clay colloids are the one responsible for the shrinking and swelling of the soil. This happens when the soil expands and contracts due to the water movements between the clay layers. This movement of water and degree of swelling and shrinking is different between the different clay minerals (kaolin, illite, montmorillonite and palygorskite)(Buchanan et al., 1993). |

The sheets are made from either an atom of silica surrounded by four oxygen atoms or aluminium atom enclosed by six hydroxyl group (OH) (Al-Khafaji and Andersland, 1992, Houben and Guillaud, 1994, Anderson et al., 2010). In the second scenario where the atom is enclosed by the six hydroxyl group, the central atom could be aluminium, iron or magnesium (Al-Khafaji and Andersland, 1992). The silica when it is enclosed by the four oxygen atoms it is called tetrahedral unit and when the aluminium surrounded by the six hydroxyl groups is called octahedral unit, Figure 2-6.

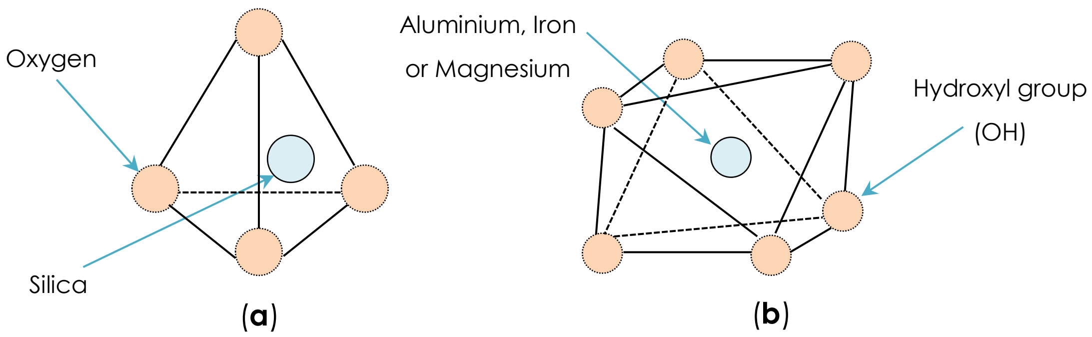



**Figure 2-6:** Sheets made up the clay minerals (**a**) Tetrahedral unit (**b**) Octahedral unit

The way these tetrahedral and octahedral units attach and interact with each other resulted in different types of clay minerals. During the attachment of these units to each other, they usually share either oxygen or hydroxyl ions (Al-Khafaji and Andersland, 1992). The simplest example of clay mineral consists of one tetrahedral sheet and one octahedral sheet (1:1) and is called kaolinite (Houben and Guillaud, 1994). The two sheets share oxygen atoms which results in a very strong chemical bond between the layers that restrict the movement of this inner layer (Frost, 1998). As a result, the charges within these units is balanced (Williams et al., 2005, Aroke et al., 2013). Kaolinite is well packed and has a stable structure which is not easy to break (Miranda-Trevino and Coles, 2003). Furthermore, kaolinite is very stable when in contact with water (Al-Khafaji and Andersland, 1992, Houben and Guillaud, 1994). Water cannot enter between the sheets and so, kaolinite experience less shrinkage when is compared with other clay minerals such as smectite (Al-Khafaji and Andersland, 1992). In addition to these properties, the abundance of this clay mineral makes it very attractive to be used in different industries. Paper, paint, ceramic, rubber, pharmaceutical, drugs industries are just few to name (Murray, 1963, Aja and Randy, 2013, Aroke et al., 2013).

Similar in structure to kaolinite is halloysites. It is composed of (1:1) tetrahedral to octahedral sheet. However, the difference is in the inner layer where water molecules are located (Al-Khafaji and Andersland, 1992, Joussein et al., 2005). As a result of the presence of these water molecules, the spacing between the layers is larger than in the kaolinite (Joussein et al., 2005). These water molecules are used to differentiate kaolinite from halloysites (Joussein et al., 2005). This clay has the ability to lose these water molecules very easily and also reversibly easily obtaining them (Joussein et al., 2005). Halloysites similar to kaolinite has been used extensively in many industries such as pest repellents, household, food and personal products, cosmetics, plastics, high-tech ceramic applications and in water purification (Joussein et al., 2005).

Identifying the type of the clay mineral assists in understanding the reaction that might happen when adding the water. Also, being aware of the type of the clay mineral gives an indication of the suitability of the soil to be used as building material or it needs to be enhanced before it is used.

### *2.1.5 Main disadvantages of soil as a building material*

As it has been mentioned before in section 2.1.1, soil has been used as a building material for many years in most of the old civilizations. However, the use of soil in the unmodified natural state relying only on the natural binding forces of the clay minerals and also sometimes in the modified state has three main disadvantages. These disadvantages are holding soil back from being recognized in the mainstream building materials market today. These three disadvantages have been summarised as follow:

- Quality of earth as a building material cannot be controlled or linked to a fixed standard (Delgado and Guerrero, 2005) like many other industrialised building materials such as concrete, since different soils lead to different earth composition and perhaps different end product quality (Minke, 2006).
- Earth as a building material shrinks during the drying process and produces cracks that affect the material overall strength (Minke, 2006, Quagliarini et al., 2015). In addition, for the binding forces of clay to work out and for achieving workability, optimum water content is needed for the reaction to take place.

Due to the evaporation of this water over the drying period, the cracks develop and the linear shrinkage ratio is usually between 0.4% and 12% depending on the earth construction technique and the water content added in the initial material preparation (Minke, 2006).

- Earth does not resist water, as a result protection of earth surface against rain is important (Minke, 2006). The protection could be incorporated throughout the architectural design process (e.g. use of roof overhangs and stone bases for walls to protect them from ground water) or by applying render layers as protection coat to the earthen structural elements (e.g. walls).

These three disadvantages result in the limited durability associated with earth as building material (Chmeisse, 1992, Heathcote, 2002).

### 2.1.6 Stabilisation as a notion

To overcome the above mentioned problems and on the other hand to enhance the durability of the earth, stabilisation was introduced (Burroughs, 2001, Kerali, 2001). Stabilisation means to modify the properties of the soil-water-air system mentioned in Figure 2-5 in order to achieve a better quality end product suits the application assigned to it (Houben and Guillaud, 1994). Usually stabilisation is used in the engineering applications such as road construction and building purposes. Stabilisation in general improves the soil engineering properties; however, in choosing a stabiliser is important to decide what parameter needs improvements because the same stabiliser might improve a parameter and reduce another (Minke, 2006). Therefore, the following points are very important to be considered before selecting a stabiliser in earth construction (Houben and Guillaud, 1994):

- Understanding the properties of the targeted soil.
- The parameters where improvements are required.
- The construction techniques that will be adopted in the construction project.
- The cost and delays expected when stabilising the soil.
- The cost of the maintenance during the life of the project after the completion of the construction.

Stabilisation works on either the structure of the soil (the physical which is the grains) or the texture of it (Houben and Guillaud, 1994). This could be achieved by one of three different actions, Figure 2-7.

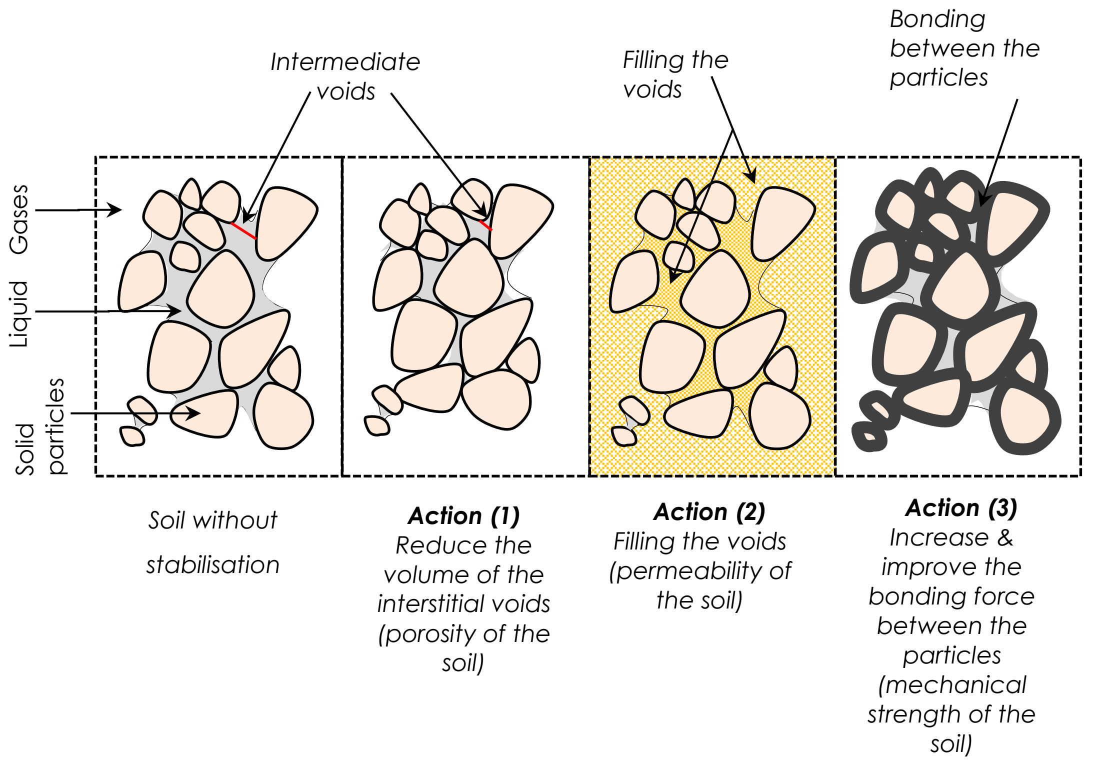



**Figure 2-7:** Different actions of stabilisation in the soil matrix,
*Source: Produced from the literature about stabilisation in page (74) from (Houben and Guillaud, 1994)*

### 2.1.7 The story of stabilisation

Stabilisation of soil is not considered as a new trend to enhance the durability of the soil mixture, since it was found to be used in Greece in the Mediterranean dating back to 4600 BC (Hossain and Mol, 2011). The use of straw stabilisation was established there and then spread to other parts of the world (Houben and Guillaud, 1994). On the other hand, stabilisation in the old civilizations was introduced mainly in the roads industry. This was mainly due to the fact that the busiest roads used for trade and other purposes were turned completely to mud ponds during the rainy season and in the dry season these roads were saturated completely with dust as a result of carts and people movements (Chmeisse, 1992). So, Egyptians along with Persians and Greeks, all work extensively in road stabilisation. However, the Romans were the most successful ancient civilisations in mastering road stabilisation (Chmeisse, 1992). They succeeded to build 80,000 km of very strong roads. The roads are made from different layers. The base was a heavy manually arranged stones followed by a layer of small stones and then a layer of broken tiles and covered with the last layer which was a combination of brick and chalk cemented using pozzolan mortar (Chmeisse, 1992). These roads were very strong and were needed few maintenances even after hundred years after the fall of the Roman Empire in Europe. In the modern history, the industrial revolution and the invention of the vehicles in the developed countries demand more durable roads network for transportation. This demand led to the development of the road stabilisation and also to the development of the thick one size pavement which is made up of 25 mm broken stones in the developed countries (Chmeisse, 1992). This road construction system was later used in the construction of the first highways in America. However, with the continuous economic growth and the increase of vehicles number, the pressure on these roads was immense. This resulted in continuous and expensive maintenance for these roads so they can tackle the new transportation growth. By this time, the need for more durable and economical roads arises. As a result, concrete was introduced for the construction of main roads and soil stabilisation was developed to be used in secondary roads (Chmeisse, 1992). In America, soil stabilisation of roads was first introduced in 1906. However, in Europe soil stabilisation of roads wasn't introduced till around 1930. But in general, soil stabilisation was used extensively during the Second World War between 1939 and 1945 (Chmeisse, 1992, Adam and Agib, 2001).

### 2.1.8 Approaches of stabilisation

All the above mentioned stabilising actions are intended to improve and enhance the soil properties by bonding and aggregating its particles more, increasing strength and stiffness (dry and wet compressive strength, tensile and shear strength), increasing durability (more resistant to abrasion and erosion due to the wind-driven rain), enhancing soil workability, resulting in more intact cohesive soil, reducing swelling and shrinkage when in contact with water and limiting the absorption of water in general (Chmeisse, 1992, Houben and Guillaud, 1994, Adam and Agib, 2001, Vilane, 2010). The enhancement of the soil could be achieved using one or a combination of the three following approaches (Houben and Guillaud, 1994, Adam and Agib, 2001, Burroughs, 2001):

- ***Mechanical stabilisation:*** which could be achieved by controlling the soil density and pore size by the use of compacting pressure. Compaction used to reduce the air void volume in the soil matrix. This compaction could be achieved either manually or mechanically. The change in the density leads to changes in the compressive strength, permeability and porosity. The results of the compaction depend highly on the type of the soil under compaction, the moisture content during the compaction process and the pressure applied to achieve the compaction. In general, each soil has optimum moisture content where compaction effort will result in the maximum density and the best results possible. Usually below and above this moisture content the density will always be lower than when the moisture is the optimum. So, monitoring the soil moisture content during compaction is very important. Mechanical stabilisation is one of the stabilisation procedures that could be either used alone or with other stabilisation procedures. Rammed earth and some stabilised soil blocks are some examples of this mechanical stabilisation.

- ***Physical stabilisation:*** which is sometimes called granular stabilisation, could be achieved by controlling the grain size distribution. For example, the use of different grain fractions on the mixture or by mixing two or more soils together to achieve the desired soil suitable for a specific application. This granular stabilisation acts on the texture of the soil. Granular stabilisation is usually used along with compaction and/or chemical stabilisation. In general, granular stabilisation is complicated and difficult to accomplish. It depends on being aware of the properties of all the soils that are going to be involved in the stabilisation prior to start the stabilisation. Also, many trials must be made to find the best combination that matches the desired final soil specifications. For all these combinations, plasticity test is a requirement to match with the targeted specifications. On the other hand, there are other techniques to change soil physical properties apart from using granular stabilisation. The use of special heating mechanisms, freezing, drying, and electrical treatment in order to have better structural properties are some examples for techniques used in the physical stabilisation of soil.
- ***Chemical stabilisation:*** the introduction of chemical or product which is technically known as additive or stabiliser to the soil matrix and as a consequence the properties of the soil are modified and improved is defined as chemical stabilisation. These stabilisers change the chemical properties of the soil with one of two mechanisms:
    - Physicochemical reaction between the stabiliser and the soil grains or

- The stabiliser creates a material that binds the grains or coats them.

However, sometimes when the stabilisers react with the soil, a brand-new material is formed. For example pozzolana which is material containing reactive silica and / or alumina which in its natural state has no binding property, however when it is mixed with lime in the presence of water, will set and harden like cement (Malhotra and Mehta, 1996). They are an important ingredient in the production of an alternative cementing material to Ordinary Portland Cement (OPC).

### 2.1.9 Methods of stabilisation

Generally, there are six methods of stabilisation and a single stabiliser could work the soil in a combination of these methods (Houben and Guillaud, 1994). However, these six methods are the breakdown of the three different actions of stabilisation mentioned before in Figure 2-7. So, stabilisation could:

- Increase the density of the soil which could be done either mechanically or physically. The first mechanical approach depends on disposing the air inside the soil matrix only without changing the grain size distribution. This means that the compaction will rearrange the particles in the soil matrix affecting the structure of them not the size. In the second physical approach, the grain size distribution completely changes with the introduction of new grains to fill the air voids in the soil. The mechanical densification by compaction could be done without using a stabiliser or with the use of binders or waterproofing agents. This mechanical densification by compaction improves the soil mechanical strength, permeability, porosity, compressive strength, dimension stability and durability.
- Reinforce the soil by creating a network that reduce the movement of the soil particles. Reinforcement is done by using a physical stabilisation approach. This reinforcement works on the level of the aggregation between the grains. In the reinforcement, the reinforcing agent increases the resistance of the soil to the tension forces, thermal expansion and water action. It also reduces the bulk density of the material which results in a lighter material with better insulation

properties. Vegetable / plant (e.g. straw, sisal, coconut and hibiscus fibre), animal (e.g. horse hair and sheep wool fibre), mineral and synthetic fibres (e.g. polyester, plastic, scrap tire rubber, polyethylene, steel, glass wool and polypropylene fibres) are stabilisers that reinforce the soil.

- Link clay minerals by a stable chemical bond. In this method, a stabiliser acts as a catalyst in the reaction between clay minerals inside the soil. It helps to link the negative and positive charges of the clay compositions. Polymers and some acids are examples for the stabilisers that assist in the creation of the bond between clays in the soil. Another way for this bond to be created is by the reaction between the stabiliser and the clay. This method results in the creation of a strong bond and new material that has better qualities. The above-mentioned example of pozzolana in the previous section is an example for such reaction. Usually this type of reaction depends on the quality and the quantity of the clay minerals present in the soil.
- Bind the soil particles by creating a cementing 3D matrix. This method is different from the linking bond despite the fact that both of them are chemical stabilisation. In the linking bond, the reaction happens either between the clay compositions or between the stabiliser and the clay. However, in this binding method the reaction does not depend on the clay minerals. Although a reaction could take place between the clay and the stabiliser but it is not the main reaction that lead for the binding action. Furthermore, clay minerals quality and quantity will only affect the efficiency of the reaction and may have an effect on the mechanical properties of the end product. In this method of stabilisation, the reaction primarily occurs within the stabiliser or between the stabiliser and the sand grains in the soil matrix. As a result of this reaction, the voids in the soil matrix will be filled with insoluble material. This material will also surround the grains and cement them together in one intact unit that withstand soil movements. OPC is the famous stabiliser that creates this kind of bonds in the soil. Some adhesives and resins also capable of creating such bond.

- Block the movement of the water and its vapour inside the soil. This method is known as waterproofing. As mentioned before in (section 2.1.2), clay minerals are very sensitive to water. So, in order to block the water movement inside the soil matrix and to terminate any future water absorption by the soil, controlling the sensitivity of the clay minerals towards the water is crucial. On the other hand, changing the nature of the water moves inside the soil it could also help in stopping the water movements. Waterproofing of a soil could be achieved by using one of the following three mechanisms:
    - Drying the water that is available in the soil pores. This is done by adding a drying agent to the soil. By doing this, the soil moisture content is controlled and the variation of it across the soil reduces, the pressure in the soil that was due to the presence of the water and the water vapour in the pores will also reduce. The evaporation rate will also reduce and the surface tension will increase.
    - Ions attached to the clay plates in the soil easily dissolve in the water and this affects the soil waterproofing characteristics. In order to stop this and to modify the soil waterproof properties, these soluble ions could be replaced with other ions that do not dilute in the water. This is called iron exchange and is conducted until reach a stable soil matrix that has ions strongly fixed to the clay plates and do not react with water anymore. Some acids are used to achieve this waterproofing stabilisation method.
    - This third mechanism works on the molecular level on the clay plates. Molecules are introduced and fixed to one of the ends of the clay plates on the outside of the compact aggregate. The other free ends that are not attached to the clay plates are impervious to water. Some quaternary amines and resins have the ability to work using this molecular mechanism.
- Subjecting a soil to a wetting cycle followed by a drying one will lead the soil to shrink after swelling. When the soil saturated completely with water it swells. However, the evaporation of this water results in the shrinkage of the soil. These repetitive actions of swelling and shrinking will deteriorate the soil. This is why using a waterproof layer as a render for

the walls will protect the soil from going through such reactions. The use of waterproof layer sealed the soil particles and this method of stabilisation is called imperviousness. It is very effective method to reduce surface erosion resulted from the action of rain water. Waterproofing could be achieved by one of the following methods:

- The first method is by filling all the soil voids, cracks and pores with the stabiliser that is a waterproof. This stabiliser will inter the micro level of the soil block and sealed all possible access to the water. Asphalt (Bitumen) emulsion is one of the best examples for waterproofing stabilisers. In fact, asphalt when is added to the soil is neither increase nor decrease the strength of the soil (Middleton, 1987). So, it is just used for the sake of the waterproofing. Usually asphalt works better with sandy and sandy-gravel soils and if it is used with silty or clayey soils more quantities of asphalt is needed to achieve same level of waterproofing.
- The second method is by using a material that when it is in contact with any amount of water will swell, absorb all the water and expand to protect the water from reaching the layers sitting above it. Bentonite is one of the materials that have this property. So, it is used as waterproofing membrane. When bentonite is installed as waterproof membrane, it absorbs all the natural water that is available in the soil beneath it and trapped that water inside so the water is no longer free to move around (Arthur and Doehler, 1961). Bentonite is able to absorb water up to 10 times its own weight (Asad et al., 2013). Mainly for this water absorption property, bentonite is used as waterproof in many engineering applications.

The following section will focus on some stabilisers with reference to their history of use, stabilisation mechanisms and their properties as soil stabilisers.

### *2.1.10 Popular stabilisers*

In this section, the focus will be on the two most famous stabilisers in the modern history of earth construction which they are lime and cement.

### 2.1.10.1 Lime: History and stabilisation mechanisms

Lime is the popular name for the chemical substances oxides and hydroxides of calcium and magnesium (Burroughs, 2001). In the stabilisation process lime is added to the soil in the presence of water. Lime is considered as the oldest stabiliser ever used in soil stabilisation (Burroughs, 2001). It was used by the Romans and the Greeks in the stabilisation of roads (Bell, 1996, Burroughs, 2001). Even today, lime is the most used soil stabiliser in earth construction (Oliver, 2008). However, the sophisticated and scientific use of lime in the recent history was in the United States of America in 1924 to strength highways (Houben and Guillaud, 1994, Bell, 1996). Today, lime is widely used in many construction practices such roads, railroad, airports runways, backfill for bridges, slopes, canal, retaining wall and under foundation slabs (Bell, 1996). In soil stabilisation, lime is used in many different chemical compositions. Quicklime ($CaO$) is considered the most concentrated form of lime (Burroughs, 2001). Hydrated lime ($Ca(OH)_2$) is another form of lime which is resultant from the addition of sufficient amount of water to the quicklime (Bahobail, 2012), see equation (2). Hydraulic lime is also a kind of lime that is used in earth stabilisation (Oliver, 2008). In general, regardless of the type of the lime, they all work in soil with one or more of the following actions:

- ***By flocculation:*** Is the process responsible of improving the workability of the clay but it does not add to the strength of the soil (Bell, 1996). It depends on the cations exchange between the clay particles and the lime. When the lime is added to the soil, the metallic ions on the surface of the clay start to exchange with the calcium ions in the lime. This reaction changes the density of the electrical charge around the clay particles make them clustering closer to each other like flocs (Bell, 1996). The amount of the cations exchange depends on the exchange capacity of the soil (Houben and Guillaud, 1994, Burroughs, 2001). This reaction blocks the penetration of water (Minke, 2006). This reaction of lime is similar in all soils regardless of the type of the soil. However, the reaction could differ in its strength and time that is taken for the reaction to complete. The reaction mainly depends on the type of the clay minerals. For example, the expandable clay minerals (montmorillonite) react with lime very quickly and lose plasticity when it is compared with the reaction of lime with kaolinite minerals. During this reaction; the lime is fixed in the soil and only the cations exchange reaction is taken place. No other reactions happen inside the soil, until this reaction is finished. This is called lime fixation. Maximum changes and modifications in the soil properties are reached when adding the optimum amount of lime (Burroughs, 2001). The point where reaching these maximum modifications and where no further changes could be done in the plastic limit of the soil is called the fixation point. Usually the amount of lime needed to reach fixation point and to improve soil plastic limit is small and it is between (1% and 3%), by weight (Burroughs, 2001). However, to increase the strength of the soil more lime is needed for other reactions to take place (Bell, 1996).

- ***By pozzolanic reaction:*** This is the reaction that increases the soil strength and it happens along with the flocculation (Bell, 1996). The excess lime that does not involve in the flocculation reaction will be involved in this pozzolanic reaction (Bell, 1996).The pozzolanic reaction is considered as the dominant reaction when using lime as a stabiliser to increase soil strength (Houben and Guillaud, 1994). When adding lime to a soil it increases the pH level of the soil by making the soil environment more alkaline (Burroughs, 2001, Yong and Ouhadi, 2007). The lime increases the pH of the soil to be between 12.3 and 12.4 which is far above the pH of the natural soil (Bell, 1996, Burroughs, 2001). This increase in the pH leads to the reaction between the soil constituents and the lime to take place (Bell, 1996, Burroughs, 2001, Yong and Ouhadi, 2007). The silica and aluminium from the soil reacts with the calcium from the lime creating different cementing agents (Bell, 1996, Burroughs, 2001, Bharath et al., 2014). These cementing agents are the factors behind the increase on the strength and the durability of the soil stabilised with the lime (Burroughs, 2001). They work along with the flocculation reaction to bond the soil particles together which strengthen the soil overtime (Bell, 1996). These cementing agents usually are in the form of hydrated calcium silicates and hydrated calcium aluminates (Burroughs, 2001). This pozzolanic reaction is very slow and time dependent and might take up to several years. So, a soil will continue gaining strength as long as the reaction is going on. But, for the maximum reaction to continue, the pH in the soil pores should remain around 12.4 (Bell, 1996). This reaction is affected by the type and concentration of the clay (soil inherited properties), the type and the percentage of the lime which will affect the pH level, temperature and curing time. Although, all these factors affect the strength of the resultant material, soil inherited properties are considered the main controlling factor and even it determines if a reaction can take place. This due to the fact that some soils have limited reactivity with lime despite increasing/decreasing lime quantities, curing time and temperature or even changing the source of the lime. These soils are called non-reactive. On the other hand, there are other types of soil that have pozzolanic properties and react with lime are called reactive soils. Some of the soil properties determine and affect its ability to react with lime to create a pozzolanic strong material. Among other soil properties and characteristics; soil pH, natural drainage, organic matter (organic carbon), clay mineralogy, availability of excessive exchangeable sodium, weathering of the soil, carbonates availability, are influencing the ability of a soil to react with lime to produce strong and durable material (Burroughs, 2001). For example, when comparing the reactivity of montmorillonite soil to kaolinite soil with lime; montmorillonite reacts very quickly and gain strength in short time compared to kaolinite. But when comparing the increase on the strength over time; montmorillonite develops less increase on strength compared to kaolinite (Bell, 1996).

- ***By water absorption:*** This is mainly concern with the quicklime. Quicklime (calcium oxide (CaO)) is made by the thermal decomposition of the calcium carbonate (CaCo3), see equation (1), (Houben and Guillaud, 1994, Hassibi, 1999). Calcium carbonate is the chemical term referred to the well-known limestone that is abundant in the earth's surface landscape. The process of heating the limestone to produce the quicklime is called calcinations and it is done with the aid of very high temperature (average of 900°C) (Lawrence, 2006, Eleni et al., 2014). Quicklime is unstable in the presence of water and carbon dioxide (Houben and Guillaud, 1994, Hassibi, 1999). So, when quicklime is mixed with the soil; it reacts with water if it is added or even with the water that is already available in the soil to create more stable version of lime which is called calcium hydroxide Ca(OH)2 (Houben and Guillaud, 1994), see equation (2). Due to the sensitivity of the quicklime and the precautions that must be followed when in handling and/or storing; it is rarely used in soil stabilisation. Instead is used to prepare the soil prior to the stabilisation process.

$$CaCO_3 \text{ (Limestone)} + Heat \rightarrow CaO \text{ (Calcium Oxide)} + CO_2 \text{ (Carbon Dioxide)} \quad (1)$$

$$CaO\ (Calcium\ Oxide) + H_2O\ (Water) \rightarrow Ca(OH)_2\ (Calcium\ Hydroxide) + Heat \quad (2)$$

The process to produce calcium hydroxide is known commercially by hydration or lime slaking. The lime slaking process releases great amount of heat (Hassibi, 1999, Lawrence, 2006). The calcium hydroxide is known commercially as hydrated lime and it is the most form of lime that is used in soil stabilisation (Burroughs, 2001). When quicklime is used to stabilise the soil, enough water is needed to make sure that the hydration reaction is fully complete before the quicklime is ready for any hardening action in the soil. Commercially, to produce hydrated lime minimum amount of water is used to just change quicklime to hydrated lime and as a result the hydrated lime is in the powder state (Hassibi, 1999). The dry process is called dry hydration. However, if excess water is used the process is called slaking and the resultant hydrated lime will be in the slurry state (Hassibi, 1999). On the other hand, there is another type of lime that is not sensitive to water like quicklime and it is also used in soil stabilisation. This type of lime is called hydraulic lime and it is a resultant of the hydration of impure calcined limestone. The original calcined limestone contains impurities in the shape of clay proportions. The impure limestone used to produce the hydraulic lime is called argillaceous limestone (Ruskulis, 2008). So, during the hydration process it only sets under the water and the water only enough for the quicklime to change into powder. As a result, the hydraulic lime is only available in the powder state (Lawrence, 2006). The properties of the hydraulic lime depends mainly on the quantity and type of the clay minerals presence in the limestone (Ruskulis, 2008). There are two types of hydraulic lime; one is called natural hydraulic lime and the other one is known as artificial hydraulic lime. The natural one is better as stabiliser when compare to the artificial one (Houben and Guillaud, 1994).

- ***By carbonation:*** Carbonation happens when calcium hydroxide (hydrated lime) reacts with ambient carbon dioxide ($CO_2$) to create weak calcium carbonated cements ($CaCo_3$), (Houben and Guillaud, 1994), see equation (***By carbonation***). In general, this reaction happens in all lime base materials and when the carbonation is taken place a drop in the pH level is occurred (Eleni et al., 2014).

$$Ca(OH)_2\ (\textit{Calcium Hydroxide}) + CO_2\ (\textit{Carbon Dioxide}) + H_2O\ (\textit{Water}) \rightarrow CaCO_3\ (\textit{Calcium Carbonate}) + 2H_2O\ (\textit{Water}) \quad (3)$$

This reaction is considered as the main and only hardening reaction in plain and pure lime mortars and the second in hydraulic lime base mortars which hardening with a hydraulic set mainly (Cizer et al., 2006, Lawrence, 2006). In lime mortar applications, carbonation is responsible of improving the mechanical properties of the mortar and also of changing the pores structure affecting its ability to transport water (Lawrence, 2006). However, despite the fact that this carbonation reaction is favourable in lime mortar applications; it is considered as undesirable inherited reaction in lime soil stabilisation (Jawad et al., 2014). Carbonation process consumes the calcium ions in the lime to create the calcium carbonate (Gourley and Greening, 1999, Jawad et al., 2014). However, the calcium carbonate crystals resultant from this carbonation reaction has the same chemical formula of the natural limestone, but it has a weak bonding properties (Jawad et al., 2014). On the other hand, calcium carbonate is not effective as soil stabilising agent in its original form (Gourley and Greening, 1999). As a result of the carbonation process less amount of calcium is left behind for a pozzolanic reaction to take place (Bagoniza et al., 1987, Houben and Guillaud, 1994, Jawad et al., 2014). Hence, carbonation reaction is unfavourable in soil stabilisation because it decreases the strength of the soil. Many previous researches on the stabilisation of road bases using lime as soil stabiliser confirm that carbonation has an effect on the strength of the soil overtime (Bagoniza et al., 1987, Gourley and Greening, 1999). Carbonation reaction takes months and sometimes years to finish (Lawrence, 2006). The reaction involves five stages including the production of the calcium carbonate at the end, see Figure 2-8.

The carbonation reaction depends mainly on the relative humidly, slightly affected by temperature and independent from the $CO_2$ concentration (Shih et al., 1999, Cultrone et al., 2005). The amount of water or water vapour available in the pores of the materials is crucial for the dissolution of the carbon dioxide and the calcium oxide/or calcium hydroxide. Both high and low levels of relative humidity affect the whole reaction process. Since, low humidity means no water for the reaction to take place, and high humidity hinders the dissolution of the carbon dioxide (Lawrence, 2006). As a result the optimum relative humidity is between 40% to 80%; but 60% is found to be the optimum humidity for the maximum carbonation reaction (Van Balen and Van Gemert, 1994).

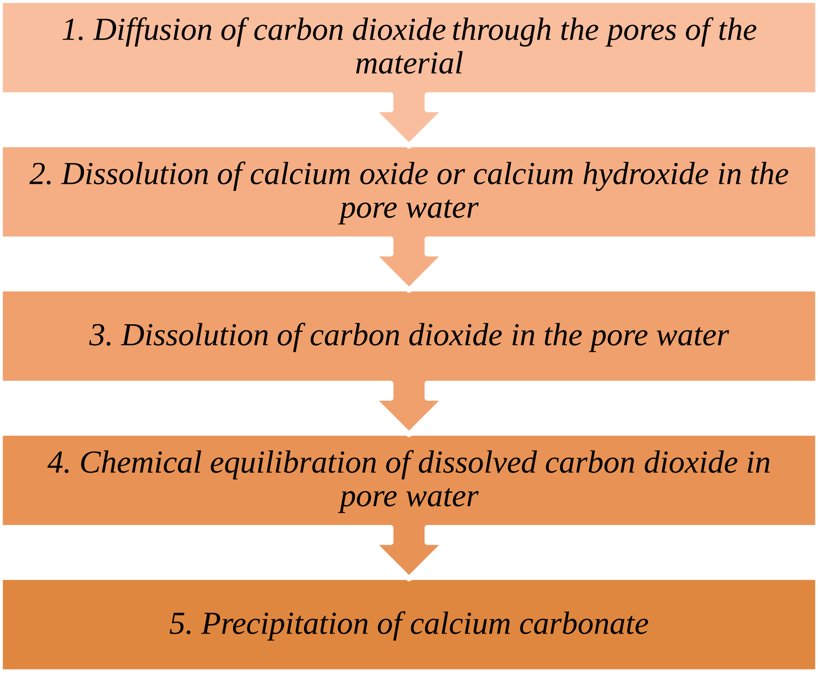



**Figure 2-8:** Carbonation reaction *Source: Reproduced from (Cizer et al., 2006, Lawrence, 2006)*

On the other hand the optimum temperature for maximum solubility of both the carbon dioxide and the lime is 20° C (Cizer et al., 2006). However, some research used curing temperature around this figure such as 25° C which was used by (Cultrone et al., 2005), and  23° C used by (Winnefeld and Böttger, 2006).

#### 2.1.10.2 Lime and soil properties

This section is intended to shed a light on the use of lime as stabilising agent in different parts of the world and explores the changes on the soil mechanical and physical properties as a result of the addition of lime. The section will be based on reviewing published experimental data available in the literature.

From reviewing the literature on lime-soil stabilisation in road and also in earth building construction, many factors affect the quality of the final stabilised soil. Among these factors, type of clay minerals is considered as a key in lime-soil stabilisation. Different clay minerals react differently in the presence of lime. (Bell, 1996) tested the effect of lime on the mechanical and physical properties of three famous soil minerals; montmorillonite, kaolinite and quartz. One of the interesting results of this research was there is a little relationship between the cations exchange capacity and the increase on the overall strength for all these different minerals. This cations exchange lead to the flocculation and the aggregation of the soil particles and is known as the initial stage on lime stabilisation. It is usually affect the workability of the soil and it is not lead to any increase in strength. Different clay minerals reach different workability degree with the addition of lime. For instance, kaolinite and quartz increase plasticity with lime addition and in contrast, montmorillonite plasticity index declined with the increase of the lime content. Addition of lime to expansive soils such as montmorillonite reduces soil shrinkage, swell and water absorption properties, Figure 2-9. Also (Bell, 1996) tested two natural soils from Teesside in the United Kingdom. The soils differ in their constituent (the first soil (Upper Boulder Clay): Illite 25-40%; kaolinite 20-30%; chlorite >5%; quartz 5-35%; calcite >5%; dolomite >5% and the second soil (Tees Laminated Clay): Illite 17-43%; kaolinite 23-34%; chlorite 9-19%; quartz 4-26%; calcite 2-7%; dolomite 3-7%). Due to the difference in the percentages and types of the clay minerals on both soils, these soils react differently with lime. The plastic and liquid limits and the plasticity of the second soil, Tess laminated clay, was higher than the first soil.

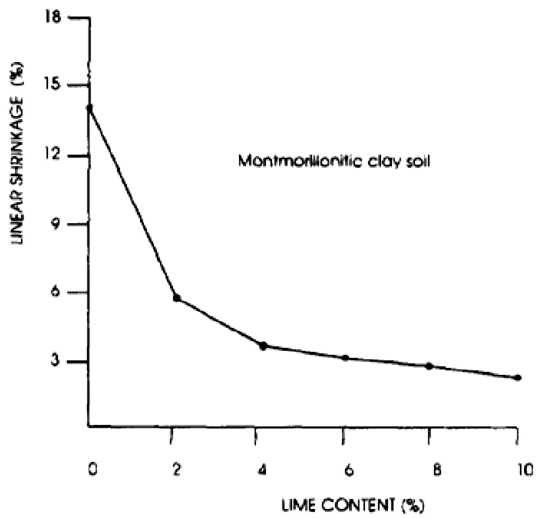



**Figure 2-9:** The influence of lime content on the linear shrinkage of montmorillonite clay mineral. *Source: Adopted from (F. G. Bell, 1996)*

However, not only the clay minerals affect the degree of the reaction between the soil and the lime, but also the presence of other minerals such as gypsum and sulphate products could affect the lime-soil reaction. Gypsum is one of the soluble minerals that found in soil and gypseous soils are widespread all over the world (Aldaood et al., 2014). Usually to reduce the cost of construction of any earth structure, engineers rely on the soil available on or near the site (Kuttah and Sato, 2015). Gypseous soils are very strong in the dry state due to the cementing effect of the gypsum, however in wet state they loss this strength (Ahmad et al., 2012). This why they collapse and led to many engineering problems to structures constructed on or with these soils (Ahmad et al., 2012, Aldaood et al., 2014). However, to enhance the properties of this soil lime is used. When these soils stabilised with lime, they witness great improvement in the engineering properties. However, these improvements declined with time due to the production of the expansive minerals (Aldaood et al., 2014). On the other hand, the enhancement of the gypseous soil properties with the addition of lime is a function of the gypsum percentages in the soil. (Aldaood et al., 2014) found that lime enhanced the properties of the gypseous soil and the availability of the gypsum in the soil lead to positive results when the amount of the gypsum in the soil not exceed 5% regardless of the curing conditions. Usually, above 5% of gypsum in the soil affects negatively on the strength of the soil when stabilised with lime. (Bell, 1996) found that lime reduce the swell, water absorption and control the shrinkage of the soil. Conversely, (Aldaood et al., 2014) concluded that adding lime to gypseous soil does not appear to reduce swell potential of the soil and shrinkage because of the formation of the expansive minerals (ettringite) especially when the soil left to cure for long periods. On the other hand, (Bell, 1996, Millogo et al., 2008) investigated the addition of different percentages of lime on the compressive strength development of the soil. (Bell, 1996) tested 2, 4, 6, 8, 10 by weight % of lime for his two sets of experiments. The author compacted both experiments soil in the optimum moisture content and stored them to cure inside polythene tied containers in 20°C. However, the curing time was different between the experiments, some are tested after one year and others were tested after 28 days of curing. The author left the samples to cure for this long period of one year to allow for the reaction products (Calcium silicate hydrate (CSH) and Calcium aluminate hydrate (CAH)) to build up. On the other hand, (Millogo et al., 2008) tested lime percentages of 4,6,8,10,12% and compared the results to the un-stabilised control soil. The author stored the samples in room temperature for 30 days following the traditional way of curing in Burkina Faso. (Bell, 1996) found out that lime addition affects the soil final dry density and optimum moisture content for the same compaction effort. The moisture content has a positive relationship with the addition of lime. In contrast, the maximum dry density has a negative relationship with the addition of lime. Lime also enhances the compressive strength of the soils regardless of the clay minerals. The clay minerals gain strength in different ways and degrees. For example, montmorillonite gain strength very quickly at the initial stage even with the addition of small quantities of lime and its maximum strength is achieved with the addition of only 4 by weight % of lime, Figure 2-10. Kaolinite and quartz gain strength with the addition of lime too, but they need more lime to reach their maximum strength, Figure 2-10. On all the minerals, the relationship between the amount of the lime and the compressive strength was not linear where the strength increased with the addition of lime until it reached a point of an optimum lime content beyond which strength either continuous in a steady mood or declined, Figure 2-10.

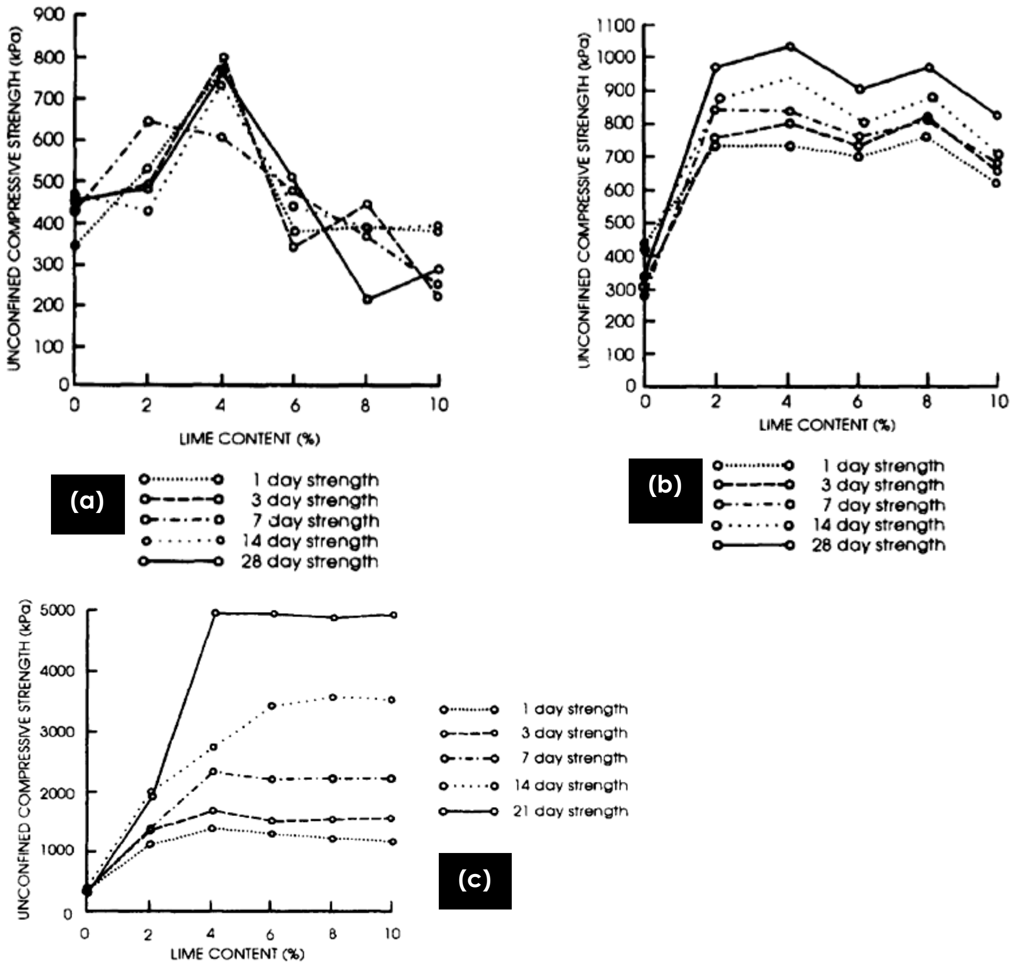
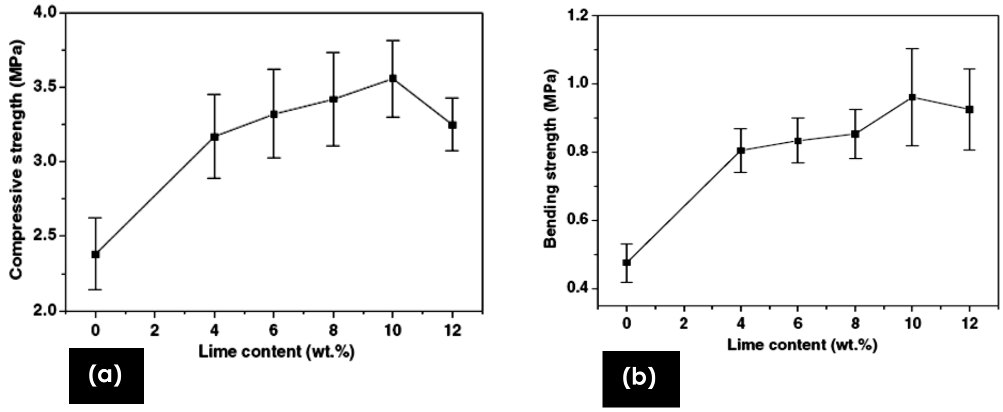



**Figure 2-10:** Unconfined compressive strength of **(a)** montmorillonite, **(b)** kaolinite & **(c)** quartz, with different by weight percentages of lime. *Source: Adopted from (F. G. Bell, 1996)*

(Millogo et al., 2008) tested a soil that was predominant with kaolinite and quartz (Kaolinite 30%, Quartz 65%, Goethite 2%, K-feldspar 2%). The author was in agreement with (Bell, 1996) regarding the enhancement of the compressive strength and water absorption potential with the addition of lime. He found that beyond 10 by weight % of lime addition, the compressive and also the bending strength declined, Figure 2-11. This conclusion is also in agreement with (Bell, 1996) results of the soils predominant with kaolinite, Figure 2-10.



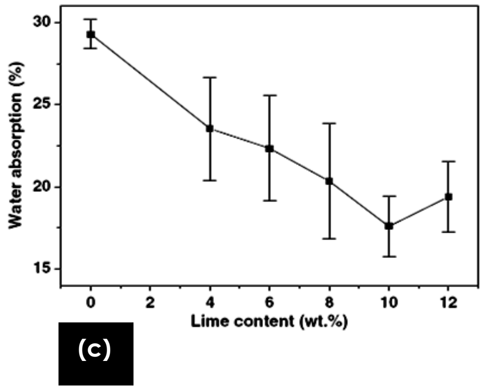




**Figure 2-11:** The effect of the increase of the % of lime on the soil properties (compressive and bending strength and water absorption) *Source: Adopted from (Millogo et al., 2008)*

Another study was conducted by (Ninov et al., 2007) on a sandy-silty Illite clay soil from Bulgaria also was in agreement with (Millogo et al., 2008) and (Bell, 1996) on the enhancement of the compressive strength by the addition of lime. (Ninov et al., 2007) suggested that the compressive strength of the stabilised soil using lime is obtained in two stages. An initial stage which is taken place in the first months up to the sixth month of the age of the material and a final stage which is achieved depending on the length of the storing time. The initial stage is where a rapid reaction between the free lime and the clay minerals is taken place and usually 50% of the material final strength is achieved during this stage. The strength in this stage is due to the gel like pozzolanic products result from the reaction between the lime and mainly the clay minerals. However, in the final stage more pozzolanic reaction is taken place but gaining strength slowdown and is not fast as in the initial stage. Also, the previous pozzolanic reaction from the initial stage continues to be more in-depth reaction. This stage continues to happen till there is no available free lime in the material and it usually takes between 6 to 12 months in total. This stage may lead to higher compressive strength depending on the storing period. In this research the storing period was only six months and the compressive strength by the end of this storing time was between 5 to 6 MPa. (Millogo et al., 2008) mentioned on their paper the storing temperature and the curing period, but there was no mention to the way these bricks were stored during these 30 days. So, one of their observations was the development of the calcite in the samples due to the reaction between the lime and the atmospheric carbon dioxide. The carbonation reaction was dominant due to the availability of the calcium from increasing the quantity of the lime. The carbonation reaction reduces the amount of the calcium available for the pozzolanic reaction to produce the cementing gels. This might be due to the way the bricks were stored in contact with the atmospheric carbon dioxide. In contrast, (Bell, 1996, Ninov et al., 2007, Al-Mukhtar et al., 2012, Aldaood et al., 2014, Aldaood et al., 2014, Di Sante et al., 2014, Hotineanu et al., 2015) tried to avoid the contact of their samples with the carbon dioxide and also to control the moisture content within their samples using many different ways. Some of them cured their samples in sealed polythene containers, closed thermostatic vessel saturated with water vapours, others wrapped their samples using cling film and coated with paraffin wax, wax paper and some of them left their samples in plastic bags. So, in lime stabilization, blocking the admittance of carbon dioxide is crucial in the development of the strength of the stabilised soil.

On the other hand, when using lime as a stabiliser, one should make sure that the lime is mix thoroughly with the soil and a homogenous mix is achieved because this will affect the strength growth which may lead to the failure of the whole design. (Bell, 1996) has also tested the effect of lime on two soils with different properties. Both soil witness strength enhancement and they reach their maximum strength when adding lime between 4% to 6% by weight. The author noticed that the maximum strength is affected by the amount of water added during the mixing and usually the soils reach their maximum strength when the water is in excess of the optimum level. The strength is also affected by the curing time and temperature, Figure 2-12. The strength increased with aging but the most noticeable increase is usually within the first week. Temperature is also an important key in gaining strength and usually temperature above 30°C lead to significant increase on the strength (Bell, 1996), Figure 2-13.

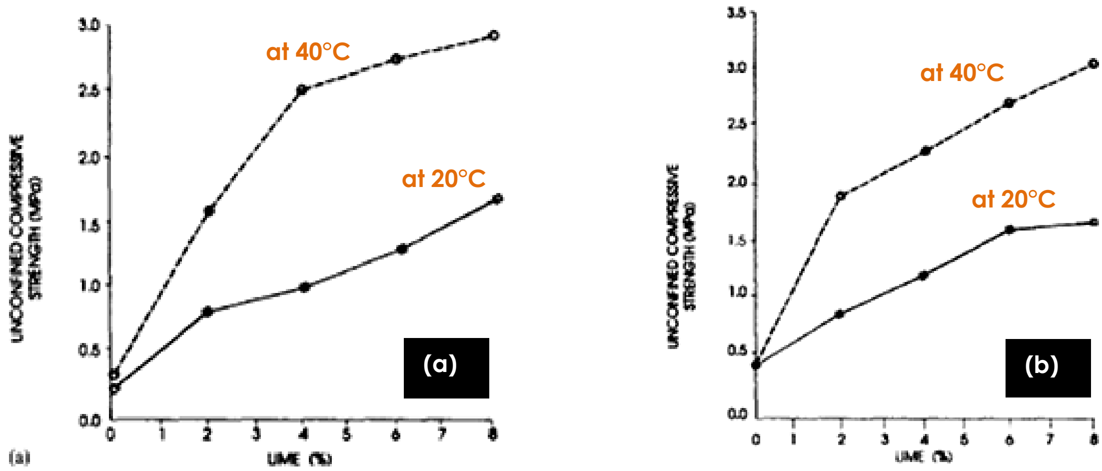



**Figure 2-12:** The influence of temperature on the unconfined compressive strength of **(a)** Tess Laminated Clay and **(b)** Boulder Clay, mixed with different by weight percentages of lime and cured for a week. Source: Adopted from (Bell, 1996)

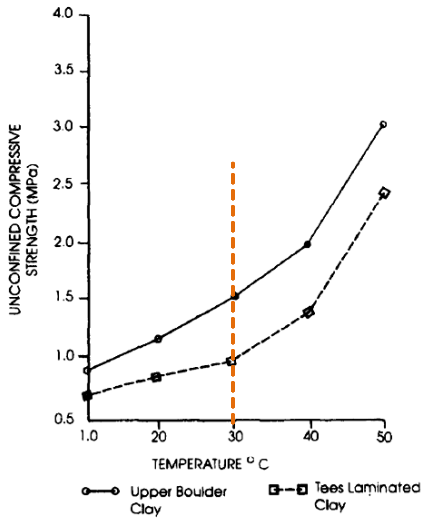



**Figure 2-13:** The influence of curing temperature on the development of the unconfined compressive strength after one-week curing. *Source: Adopted from (Bell, 1996)*

### 2.1.10.3 Cement: History and stabilisation mechanisms

Cement is crystalline compound of calcium silicate and other calcium compounds having hydraulic properties. The name of the famous cement known today (Portland cement) was given by Joseph Aspdin in 1824 who was a Leeds builder or bricklayer and whom has the famous patent number 5022 in the history of the hydraulic cements (Blezard, 2003). Aspdin chose the name Portland cement based on the famous Portland stone which was a limestone quarried in Dorset and was very popular to its high reputation for quality and durability. However, Aspdin's early Portland cement was not the cement which is known today, instead it was just a hydraulic lime. But

Aspdin 1824 patent was the start point to use the name Portland cement for cement known today (Blezard, 2003). Aspdin's younger son, William Aspdin, was the one who produced the first Portland cement known today in 1843 (Blezard, 2003, Ludwig and Zhang, 2015). Portland cement is made by heating limestone (calcium carbonate) with other materials such as clay to 1400° C– 1450° C in a kiln in a process known as calcination (Neville, 1995, Taylor, 1997). This process releases carbon dioxide. The calcination process results in the production of the calcium silicate which is a cementing agent and also known as clinker. The clinker then is added to gypsum to create the well-known Portland cement. Gypsum is added to regulate the setting time only (Huntzinger and Eatmon, 2009).

The first-time cement used as stabiliser was in roads in the United States of America in 1915. The boom in using cement for stabilisation of roads and runways construction was in 1953. After that cement popularity increased and its applications widen to cover public work and construction. It's by far the most studied building material and the knowledge of its techniques is completely covered by research. Cement in soil reacts in two different ways as follow, (Houben and Guillaud, 1994):

- The cement reacts with itself or with the sand and this will form the hydrated cement mortar
- Or it may react with the clay in the soil, this happen in three different phases as follow:
    - The water will start the formation of the cement gel (Calcium Silicate Hydrates and Calcium Aluminium Hydrates) on the surface of the clay minerals. During adding the water to the cement, lime generated as a product of the reaction and then it will start reacting with the clay in the soil. As a result, the lime quickly is used up and the clay starts to degenerate.
    - The hydration process continues and encourages the disaggregation of the clay particles in the soil.
    - The cement gels glue the clay particles and other soil particles (such as sand) in a very strong bond. which will result in strengthen the soil.

During the cement stabilisation of the soil, not all the soil particles are affected by the cement reaction, however, only sand and clay are affected.

#### 2.1.10.4 Cement and soil properties

Cement is widely used as stabiliser in earth construction (Riza et al., 2010). Most of the soils can be stabilised using cement and their mechanical properties will improve (Houben and Guillaud, 1994). The cement is added in the range between 5 to 10 by weigh percent. If less than 5 by weight percent of cement is used to stabilise earthen units, the bricks will be too fragile for easy handling. However, using cement in quantities above 10 by weight percent is not economical (Walker, 1995). The strength of the earthen units stabilised by cement is affected by the plasticity of the soil, moulding timing, moulding moisture content, drying and curing overall period and curing settings (Houben and Guillaud, 1994). Due to all these parameters that should be taken into consideration when stabilising soil using cement, the compressive strength of the earthen units for using the same percentage is vary considerably, Table 2-2.

**Table 2-2:** Compressive strength of cement stabilised earthen units from the literature

| Percentage | 0.5 – 3% | 5% | 6 – 10% | Earth technique | Test unit | Reference |
|---|---|---|---|---|---|---|
| Cement | - | 5 | 10%: 13 | Stabilised soil block masonry units | MPa | (Gavigan et al., 2012) |
| | - | 1.79 | - | Compressed earth blocks | MPa | (Arumala and Gondal, 2007) |
| | - | 1.03 | 7%: 1.31<br>10%: 2.00 | Adobe | MPa | (Alam et al., 2015) |
| | - | 4%: 2.5 | 6%: 3.5<br>8%: 4<br>10%: 4.5 | Cement-stabilised cylinders | MPa | (Bahar et al., 2004) |
| | 2.5%: 1.03 | 1.53 | 7.5%: 2.84 | Compressed stabilized earth blocks | MPa | (Waziri and Lawan, 2013) |
| | - | 3.9-5.5 | 10%: 6-8 | Adobe | MPa | (Vilane, 2010) |
| | 3%: 5 | - | 6%: 6.5<br>9%: 9 | Unfired clay bricks | MPa | (Miqueleiz et al., 2012) |

### *2.1.11 Earth construction techniques:*

Earth as a building material has different techniques. Some techniques are very old and were used by most of the ancient civilizations, such as: adobe (unbaked brick or sundried brick), cob and rammed earth. In fact, these techniques are still being used today in many parts of the world.

#### 2.1.11.1 Adobe

Adobe in history is a handmade mud bricks which is dried in sun and open air. Back in history adobe was stabilised using straw, a practice which is still available in some parts of the world. The mud mixed by hand and feet and then moulded using wooden or metal moulds, (Houben and Guillaud, 1994), Figure 2-14.

**Figure 2-14:** Adobe construction technique, *Source:* *http://hopebuilding.pbworks.com/w/page/19229916/Denied%20steel%20and%20concrete%2C%20Palestinians%20build%20mud%20brick%20homes%20in%20Gaza*

### 2.1.11.2 Cob

Cob is an earthen technique which results in forming monolithic walls. It is done by preparing mud balls and then stack them over each other's and press them using hands and sometimes feet. Cob similar to adobe could be stabilised with straw. This technique is roughly disappeared and people who build with earth are rarely using it, (Houben and Guillaud, 1994), Figure 2-15.


**Figure 2-15:** Cob technique, **(a)** shows how earth balls look when they placed in the wall before they pressed by hands, **(b)** shows how the final cob wall look with all the layers, Source: **(a)** https://www.flickr.com/photos/91288026@N00/416602546/, **(b)** https://www.youtube.com/watch?v=qTjxbRtqZ3Y

### 2.1.11.3 Compressed earth blocks

The compressed earth bricks technique has been practised for centuries using the very simple technique of compressing the mud in moulds. However, the same technique is no longer such a primitive one and it changes to be very mechanized. Manual and hydraulic presses are used in many countries, (Houben and Guillaud, 1994), Figure 2-16.


**Figure 2-16:** Compressed earth blocks technique, **(a)** how the block looks straight after production, **(b)** blocks stacked over each other after production, **(c)** Holm English Medium School in Khartoum, Sudan built completely using compressed earth blocks, **(d)** the interior of the school showing the exposed compressed earth blocks. *Source: Author's collection*

### 2.1.11.4 Rammed earth

This technique is done by using wooden frameworks and then the soil in compacted inside the frameworks using rammers. It is similar to cob in producing monolithic walls. However, the difference is that the rammed walls are compacted using rammers and the cob is tamped using only hands and feet, Figure 2-17, (Houben and Guillaud, 1994).

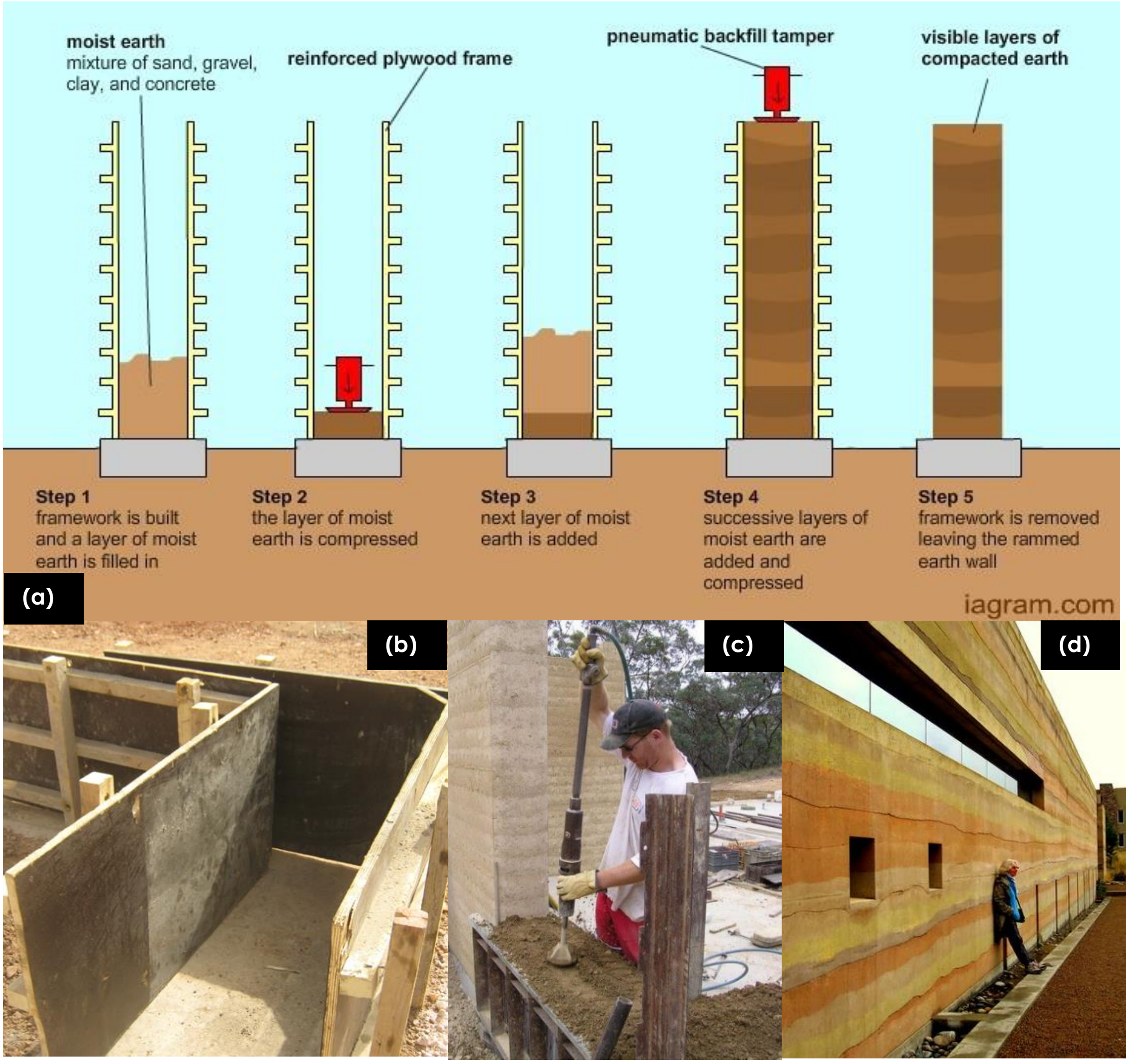



**Figure 2-17:** Rammed earth technique, **(a)** steps used to construct rammed earth wall along with the wooden framework and the rammer used to compact the soil, **(b)** the look of the wooden framework before it is filled with the soil, **(b)** the rammer used to compact the layers of soil used to build the rammed earth wall, **(d)** the final look of the wall with the different colours for the soil layers used in the construction of the wall. *Source:*

***(a)*** *https://www.pinterest.co.uk/pin/539446861605633784/*

***(b)*** *http://rammed-earth.org/project-sudan/*

***(c)*** *https://www.pinterest.co.uk/pin/778559854302782648/*

***(d)*** *https://www.pinterest.co.uk/pin/440860250994555171/*

## 2.2 Earth as a building material in the animal kingdom

### *2.2.1 Termite as an earth builder*

There are two species responsible of building the earth mounds, soil-feeding termites and fungus-growing termites (Contour-Ansel et al., 2000). The main building material for both species is soil. This soil either used straight away or as a material originally derived from soil. For example, some species use their faeces as a building material, but these species completely depend on soil as their diet (Contour-Ansel et al., 2000, Kaschuk et al., 2006, Sarcinelli et al., 2009). According to Malaka (1996) and Lee and Wood (1971) in (Robert et al., 2007), there are four types of mounds structure depending on the construction material as follow:

- Mounds built completely from re-packed transported soil particles (termites transported the soil particles by their mandibles)
- Mounds constructed mainly from re-packed transported soil particles with a trace of termite's excreta (faecal)
- Mounds mainly build from termite's excreta with the addition of re-packed transported soil
- Mounds build entirely from excreta consisting of organic matters from plant ingested from soil

In general, termites built their mounds using sub-soil collected from different soil depths (Jungerius et al., 1999, Kaschuk et al., 2006, Abe et al., 2009, Sarcinelli et al., 2009, Cosarinsky, 2011, Tilahun et al., 2012, Mujinya et al., 2013). Soil depth is different from space to another, for example some termites collect the soil from only 60 to 150 cm (Hesse, 1955), while others collect it from 3 meters depth (Adekayode and Ogunkoya, 2009). In general, this soil is derived to an area in the surface in a shape of compound aggregate before start the mound building (Jungerius et al., 1999). Table 2-3 below compares two types of mounds building termites (their diet habits, species percentage, construction technique, building material and the structural stability of their mounds). The two species are: soil-feeding termites and fungus-growing termites.

**Table 2-3:** Comparison of two types of mounds building by two different species of termites

| Soil-feeding Termite | Fungus-growing Termite |
|---|---|
| **Diet:** Soil that contains mineral elements bound with decomposed organic matter **(Brauman, 2000, Contour-Ansel et al., 2000, Kaschuk et al., 2006, Sarcinelli et al., 2009)** | **Diet:** Plant matter taken from the surrounding ecosystem (Contour-Ansel et al., 2000, K.O.K and A.V, 2012) |
| **Species Percentage:** 75% of termite species **(Brauman, 2000, Kaschuk et al., 2006, Sarcinelli et al., 2009)** | **Species Percentage:** 25% |
| **Construction Technique:**<br>Tiny soil particles CEMENTED together by the termite faeces and salivary secretion **(Brauman, 2000, Contour-Ansel et al., 2000)** | **Construction Technique:**<br>Soil pellets CEMENTED together by termite saliva (Hesse, 1955, Bruinsma, 1979, Jungerius et al., 1999, Contour-Ansel et al., 2000, Udoeyo et al., 2000, K.O.K and A.V, 2012) |
| **Characteristics of Mound Walls Building Material:**<br>• Faeces contain twice as much organic matter as the surrounding soil (the organic matter (OM) in mound walls is different in chemical composition from the original OM, while it affected by the gut enzyme digestive system (chemical breakdown due to the alkaline (PH) in the gut). The organic carbon and organic nitrogen almost 10 times the surrounding soil **(Brauman, 2000, Contour-Ansel et al., 2000, Kaschuk et al., 2006, Abe et al., 2009)**<br>• Saliva is a watery enzyme containing fluid that lubricate food and initiate the digestion **(K.O.K and A.V, 2012)**<br>• Saliva in termites contain two cellulose digestive enzymes **(K.O.K and A.V, 2012)**:<br>  ○ β-1-4-glucanase that start the splitting of the cellulose<br>  ○ β-glucosidase that changes and degrades cellobiose to glucose<br>• Saliva main organic ingredients are: digestive enzymes (amylase, invertase, various proteases, and lipases) **(K.O.K and A.V, 2012)**<br>• Most of the aggregate (96%) > 2 mm in diameter<br>• 35% clay content **(Contour-Ansel et al., 2000)**<br>• 37% silt **(Contour-Ansel et al., 2000)**<br>• Organo-clay material 25.2% **(Contour-Ansel et al., 2000)**<br>• High sugar content (15 times more sugar than fungus-growing termite). This sugar of plant origin<br>• Glucose around 5.19 mg $g^{-1}$ in the walls (this glucose is originated from cellulose) **(Contour-Ansel et al., 2000)** | **Characteristics of Mound Walls Building Material:**<br>• Low concentration of organic matter (OM) (Contour-Ansel et al., 2000, Abe et al., 2009)<br>• The soil contain little or no hums (Contour-Ansel et al., 2000)<br>• Saliva is a watery enzyme containing fluid that lubricate food and initiate the digestion (K.O.K and A.V, 2012)<br>• Saliva in termites contain two cellulose digestive enzymes (K.O.K and A.V, 2012):<br>  ○ β-1-4-glucanase that start the splitting of the cellulose<br>  ○ β-glucosidase that changes and degrades cellobiose to glucose<br>• Saliva main organic ingredients are: digestive enzymes (amylase, invertase, various proteases, and lipases) (K.O.K and A.V, 2012)<br>• Most of the aggregate (89%) <0.5 mm in diameter (most of it (75%) is > 0.1 mm in diameter, (50%) > 200 μm in diameter) (Contour-Ansel et al., 2000)<br>• 30% clay (Contour-Ansel et al., 2000)<br>• 13% silt (Contour-Ansel et al., 2000)<br>• 27% organo-clay mineral (Contour-Ansel et al., 2000)<br>• Low sugar content (Contour-Ansel et al., 2000)<br>• Glucose is only 0.3 mg $g^{-1}$ in the mound walls (Contour-Ansel et al., 2000) |

| Soil-feeding Termite | Fungus-growing Termite |
|---|---|
| **Structural Stability: (Contour-Ansel et al., 2000)**<br>• Greatest structural stability (Garnier-Sillam and Harry, 1995 in **(Kappler and Brune, 1999, Brauman, 2000)**<br>• Very resistance to breakdowns<br>• The aggregate remains intact after immersion in water (excellent aggregation capacity) | **Structural Stability: (Contour-Ansel et al., 2000)**<br>• Compared to walls of soil-feeding termites; it is not very stable (moderate stable structure), however the mounds are stable and resistance in the natural environment in the field<br>• The aggregate breakdown immediately after immersion in water |

The above table gives a comparison of the two building termites, the soil-feeding and the fungus-growing. However, despite the differences in their diet habits and building materials, both build very strong well-structured mounds that resist water and rainfalls (Abe et al., 2009, Sarcinelli et al., 2009). Both mounds are constructed from very fine soil particles from the sub-soil. The clay content (clay and silt) is very high and it is worked as a binder to increase the cohesion of the soil and also to resist rain water (Jouquet et al., 2006, Cosarinsky, 2011). This clay also enhances the structural stability of the walls' soil (Jouquet et al., 2006, Abe et al., 2009, Tilahun et al., 2012). In fact, this information complies with the results of some research in earth walls. For instance, Evans (1980) in (Heathcote, 2002), notes that soil with more than 30-35% clay are more coherent, has more stable aggregate, resists rainfalls and erosion. On the other hand, Crowley (1998) in (Heathcote, 2002), confirms the increase in the durability with the increase in the clay content.

The outer walls of these mounds act as the barrier between the mound and the external environment, so it is hard, massive and resistant (Abe et al., 2009). Also, the structural stability enhanced by the combination of the binding agents in the soil mixture of the mound walls (Contour-Ansel et al., 2000). However, the structural stability of fungus-growing termite mounds is considered poor relatively to the soil-feeding termite mounds. In the field these fungus-growing termites stand for ages and resist weathering (Contour-Ansel et al., 2000). In fact it sometimes lives for more than 70 years (Jungerius et al., 1999).

### 2.2.2 *Mechanical properties of Termite's end product: the mound*

The compressive strength and the bending strength of the termite mounds soil were tested and the results showed that the values were in the range of the required ones for adobe bricks (Millogo et al., 2011). The shrinkage was lower in this research, and this attributed to the absence of the swelling clay minerals (Millogo et al., 2011). This gives an indication that these termites select the particles that they used for their mound construction (Mujinya et al., 2013). Termite mound soil has higher compressive resistance when compared with the compressive resistance of some crude bricks from different soil types (Millogo et al., 2011). Actually, the termite mound soil is strong as cement-stabilised bricks (Millogo et al., 2011). For its strength termite mound material had been used as a surface for tennis courts in some schools in villages in Africa (Udoeyo et al., 2000). Soil of termite mounds also had been used in Australia, Zimbabwe, Mozambique and America for building many sport courts, earth bricks for houses, line water tanks, building floors, footpaths and stoves, used for plastering, it is also used as soil amendment (Tilahun et al., 2012) and for constructing traps (Morrow, 2003).The strength of the soil of the termite mounds is attributed to:

- Chemical nature of the cemented binding agents (from faeces and/ or saliva)
- Physical nature of the particle-size distribution

### 2.2.3 *Biomimicry*

Biomimicry "from bios, meaning life, and mimesis, meaning to imitate, is a design discipline that seeks sustainable solutions by emulating nature's time-tested patterns and strategies. In Biomimicry, nature is taken as model, mentor, and measure" (Asknature, 2013). Biomimicry takes and studies Nature's models and then emulates these forms, processes, systems, and strategies to solve human problems in a sustainable way (Asknature, 2013). As a Mentor by viewing and valuing nature and learn from it (Asknature, 2013). On the other hand, Biomimicry is using an ecological standard to judge the sustainability of the innovations and it stands on that after 3.8 billion years of evolution, nature has learned what works and what lasts (Asknature, 2013). These ideas from nature is mimicked and implemented in many fields such as engineering, architectural design, computer modelling and general design (Elmahdi, 2008).

## *2.2.4 Biomimicry in architecture & construction*

### 2.2.4.1 Learning from termite mounds

In fact, termite mounds were mimicked many times before. As an example the architecture of the termite mounds inspired many architects to design more environmentally, efficient and climatic building designs (French and Shiday, 2010). Most of these building designs mimicked the passive cooling system inside the termite mounds, Figure 2-18, (French and Shiday, 2010). Actually, termites moderate the temperature inside the mound at (30°C) all year (Korb and Linsenmair, 1999). Termites are doing this by the use of the architectural conical shape supported with internal galleries, chambers, chimneys and external surface ventilation pores and holes, Figure 2-18. Buildings such as the Eastgate Building in Zimbabwe, Portcullis House in United Kingdom and the Council House (CH2) in Australia are examples for buildings that were mimicked the passive cooling ventilation system of termite mounds, Figure 2-19, (French and Shiday, 2010). These buildings have massive savings in energy bills, since they consume 10% only of the energy that is needed by similar buildings that cooled by using conventional strategies (French and Shiday, 2010).

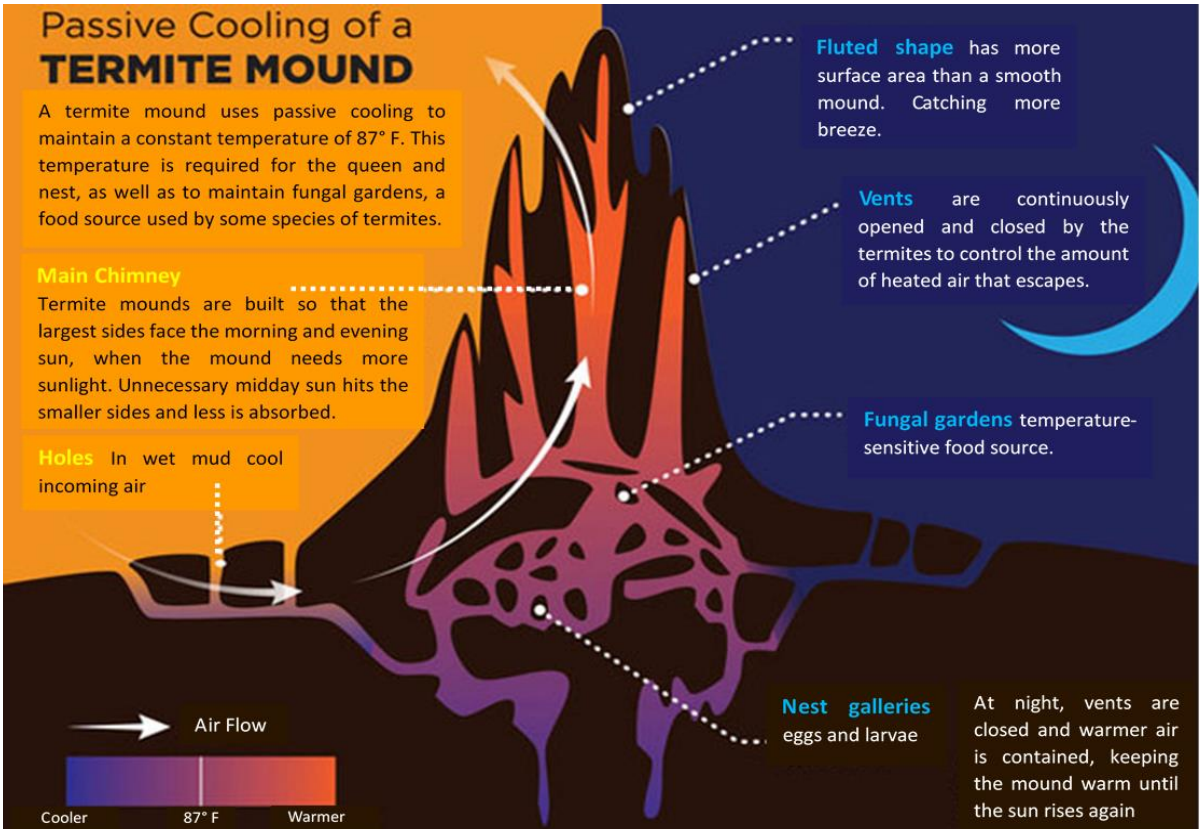



**Figure 2-18:** Passive cooling strategy of termite mound which many architects have mimicked to design more environmental friendly building.

*Source: http://rt-bi.nl/wp-content/uploads/2015/03/Termiet-02.jpg*


**Figure 2-19:** Passive cooling strategy of termite mound was mimicked by architects to build more environmental building designs (**a**) Council House 2 (CH2) Building, 2006, Melbourne, Australia (**b**) Eastgate Building, 1996, Harare, Zimbabwe (**c**) Portcullis House, 2001, London, UK,

*Source:*
***(a)*** *http://www.miglas.com.au/downloads/CH2_article.pdf*
***(b)*** *http://source.co.zw/2014/11/green-buildings-legislation-for-harare-mayor/*
***(c)*** *http://www.webpages.uidaho.edu/arch504ukgreenarch/CaseStudies/PortcullisHouse.pdf*

### 2.2.4.2 Learning from birds' nest

In addition, Biomimicry is also had been tested and used in earth construction. *Andorinha-dos-beirais* bird's earth nest, Figure 2-20, was investigated by a group of researchers from Portugal. Their research revealed that the earth nest of this bird possibly contains glucose sugar which is added during the construction process by the birds (Silva et al., 2010). The research highlighted the probability of increasing the nest material quality by this added sugar (Silva et al., 2010). The authors also suggested the exploration of the use of some glucose to the soil mixture of earth construction and to test the quality of the final product.


**Figure 2-20:** Andorinha-dos-beirais bird's earth nest, *Source:*
***(a)*** *http://birdwatchingalentejo.com/house-martin-huiszwaluw-mehlschwalbe-adorinho-dos-berais-avion-comun/*
***(b)*** *http://jcduarte.net/Viagens/?p=2620*
***(c)*** *http://projetoandorinha.no.sapo.pt/andorinhas.htm*

### 2.2.5 Magical Termite's stabiliser (chemistry of the bio-adhesive)

In 1972 a researcher and his colleagues from the Department of Chemistry at the James Cook University of North Queensland in Australia investigated the soil mound of *Coptotermes Acinaciformis* termites in Australia. They have noticed that the exterior wall of the mound of this termite is extremely hard and resistant to water compared with the soil around the mound. They set experiments to identify the adhesive these termites incorporated during the construction of their mounds. They used the soil from around the mound as a control for their comparison. They found that the mound soil differed in its composition from the control soil sample. They found two components which were available in the soil mounds but were missing in the control soil. They concluded that these two components were introduced to the mound soil by the termites during the construction process. The first component was a mixture of polysaccharides of the hemicellulose group. This component was derived from the termites' faeces from the incomplete digestion of the plants. The second component which the authors believed was the adhesive the termites used to cement and glue the soil particles together to build the mounds was a glycoprotein. The authors suggested that this might be the secret chemicals behind the strength and the erosion resistance of the exterior walls of the mounds of these termites. The authors suggested that this might be secreted by the termites, (Gillman et al., 1972).

### 2.2.6 Glycoproteins

''Glycoproteins can be simply defined as proteins which have carbohydrate covalently attached to their peptide portion'' (Spiro, 1970, Tabasum et al., 2017).

Glycoproteins are abundant in animal tissues, in plants and microorganisms. The percentage of carbohydrate units in the glycoprotein is different in different types of glycoproteins (Tabasum et al., 2017). Glycoproteins have several vital functions in the bodies of animals, microorganisms and plants. They serve as lubricants, protection from acids in the digestive system, filters, supportive structures, binders, transporters and have clotting mechanism (Spiro, 1970). In nature polysaccharides, glycoproteins and proteins are the three defined types of biological polymers that are used to form gels (Smith, 2002). The concentration of these three gels is similar but the inside structure and the mechanical properties are different. For instance, the concentration of the protein and the carbohydrate, the size of the end polymer and the existence of the crosslink are the main three properties that characterize adhesive gels (Smith, 2002). These features give the opportunity to distinguish the type of the gel. In glycoproteins, the protein and the saccharine are linked to result in very complex product with a large mass compared to the other gels. Polysaccharides are considered the base of most available important gels in the market. Polysaccharides usually form a very viscous solution which is not cross-linked but in order to form a gel, they should be cross-linked, Figure 2-21. For example, gum is a large and very concentrated polysaccharide that is popular as adhesive (Smith, 2002).

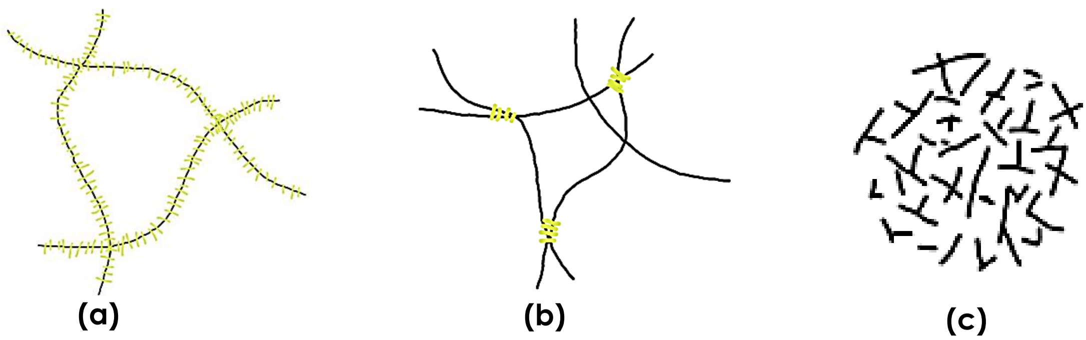



**Figure 2-21:** Diagram for the common gels (**a**) Mucus from mammalian with a non-cross-linked glycoprotein (**b**) Polysaccharide gel (when it is a gel, usually it is cross-linked) (**c**) Gelatine gel and is a cross-linked network of protein, (Smith, 2002).

## 2.2.7 Gelatine

Gelatine is derived from the collagen which is a type of glycoprotein (Tabasum et al., 2017). In the ancient era, the gelatine had been used as a biological adhesive. 8000 years ago, the people who had lived in what is called the Middle East today, they used glue from animal tissues. Also 3000 years after the people from the Middle East, ancient Egyptians used glue made from animal collagen as adhesive to glue their furniture parts. On the other hand, people from the new Stone Age who lived in caves near the Dead Sea knew the strength of the glue made from collagen and they used it for several applications. Discoveries from the Egyptians temples and pyramids proved the use of the animal glue at that time. The glue was made from the collagen of the hides and bones of the animal. To prepare the glue these bones and hides were boiled and then the glue was extracted. The extracted gelatine when has cooled down was also consumed as an edible gelatine which was part of the diet during that time in many regions and also an alternative source of protein when meat became scarce (Gareis and Schrieber, 2007).

In general, all gelatines are derived from the collagen protein which is the most protein available in both humans and animals' bodies. Collagen is family of proteins and more than 26 different types have been known today. Collagen is mainly available in the skin, bones and cartilage. Collagen and gelatine share the same chemical constituents which is long chains of amino acids connected by peptide bonds, however they have different physical properties. For example, collagen is insoluble in water but gelatine is soluble in water. Gelatine is sourced from mammalian and fish. For example, it sourced from bovine (cows), porcine (pig), poultry and cold and warm water fish skin and bones. Gelatine consists of 85 to 92% protein and the remaining percentage is minerals salts and moisture that was left after the drying and the extraction of the gelatine (Gareis and Schrieber, 2007). In modern gelatine industrial time, bones, hides and also skin of some animals are used as the raw material for the gelatin production. The gelatine produced is used to prepare glue which is used in several industries. Collagen is also used to prepare edible gelatine which has high nutritional value and is used in preparing lots of foods such as desserts, ice-cream,

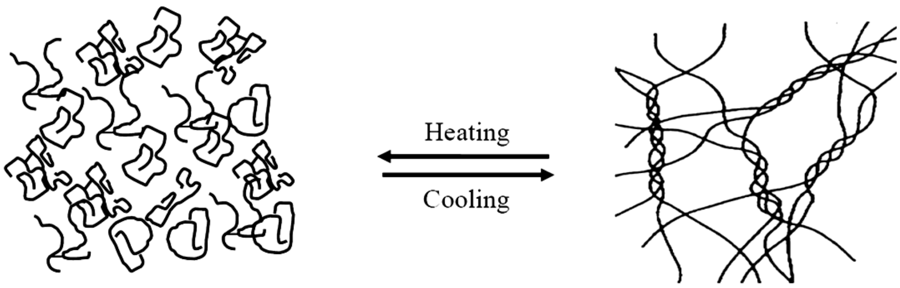



**Figure 2-22:** The thermos-reversible gelling process for gelatine (Haug and Draget, 2009)

marshmallows and also in pharmaceutical and medical applications, cosmetic industry and in photography (Gareis and Schrieber, 2007). The most important properties of gelatine, making it so useful in several areas is its ability to form thermos-reversible gels, Figure 2-22 (Haug and Draget, 2009).

In general, the functional properties of gelatine are divided into two main functions, (Gareis and Schrieber, 2007):

a) Properties associated with gelling:
   i. Gel formation, strength, gelling time, setting and melting temperature and viscosity.
   ii. Texture
   iii. Thickening
   iv. Water binding
b) Properties associated with surface effects:
   i. Emulsion formation and stabilisation
   ii. Protective colloid function
   iii. Foam formation and stabilisation
   iv. Film formation
   v. Adhesion/ cohesion

The transition between gel and liquid state in the gelatine mainly depends on the type of the gelatine used, the temperature, the ratio of water to the gelatine and other parameters (Gareis and Schrieber, 2007). One of the oldest characteristics of gelatine is surface adhesion and it has been known for more than 8000 years. The binding properties of gelatine depend on both adhesion and cohesion. Cohesion is related to the interaction between the gelatine molecules in the system. On the other hand, adhesion is connected with the interaction between the gelatine molecules and other components in the system. To fully cover a surface and to ensure the binding of its particles to each other, gelatine concentration is the key for that. By using high concentration of gelatine, the adhesion forces starts to build-up and results in gel formation upon cooling (Gareis and Schrieber, 2007).

Different types of animal products were used in earth construction. They were mainly used to stabilise the wall render and they were rarely used to stabilise the walls themselves (Houben and Guillaud, 1994). Animal glues prepared from horns, bones, hooves and hides were the main source for the stabilisers (Houben and Guillaud, 1994). These animal glues are gelatine. So, using gelatine as stabiliser in earth construction is not new. As mentioned before, gelatine could be sourced from different animals; however, most of the gelatine that is produced worldwide comes from cows and pig skin. In Europe, pig skin is the main source for gelatine and was superseded the cows gelatine in the 1990s after the outbreak of the BSE (bovine spongiform encephalopathy, (mad cow disease)) (Haug and Draget, 2009). In other parts of the world and due to religious restrictions, cow's gelatine is dominant. After the outbreak of the BSE, research started to look for alternative to bovine's gelatine. In the fish industry, skin and bones usually thrown away as waste, (Gudmundsson and Hafsteinsson, 1997) and (Choi and Regenstein, 2000) suggested that the use of fish skin and bones for gelatine extraction will have environmental benefit (waste management) as well as economical benefits. Fish gelatine has been extracted from two fish families, the cold-water fish such as cod, salmon and Alaska Pollack, and the warm water fish such as tilapia, Nile perch and catfish. The main purpose was to use the fish gelatine in the food industry. However, recent studies identified the collagen from fish as potential allergen regardless of the fish species (Hamada et al., 2001), and this has resulted in limited use of it in the food industry.

## 2.3 Summary

1. Earth as a construction material could play a vital role in construction of walls, if its durability as the main drawback could be improved.
2. Termite mounds could be used as an inspiration to improve the quality of manmade earth walls.
3. Studies on termites' mounds proved their strength and durability which make these magnificent structures worth studying.
4. Biomimicry is the approach that could be used to use the termite construction technique for the benefit of humans.
5. Termites construct their mounds by gluing sub-soils using their saliva.
6. The main chemical which termites use as adhesives is a glycoprotein.
7. In nature, glycoproteins are among the three well-known biological polymers that are used to form gels.

# 3. Methodology

*Soil selection criteria, soil classification tests, stabilisers selection criteria, strength & durability tests selection criteria and preliminary experiments*

## 3.1 Soils Selection & Classification Tests

### 3.1.1 Introduction

This chapter aims to address the selection criteria behind choosing the two soils used in this study, the steps used to prepare the soils prior to use, the soil classification tests methods and results, the stabilisers selection criteria, strength & durability tests selection criteria and the results of the preliminary experiments which help with conducting the final tests in this study.

### 3.1.2 Selection, preparation and storing of the soils

Two different and popular soils from two different regions were used to prepare adobe bricks. One of the soils has been brought from Devon in the United Kingdom. The Devon soil was the main soil that was used in this study due to it is availability and low cost. The second type of soil used was from Khartoum/Sudan. Only a small quantity of soil (50 kg) was brought and was used in tests due to the limited quantities approved by the licence issued to import the soil.

#### 3.1.2.1 The selection criteria of the British soil

Devon was chosen because it is the centre of earthen buildings in Southern England (Walker and International, 2002). In addition, Devon contains more earth buildings than any other county in the United Kingdom (Trust, 1992). The vast number of the earth buildings in Devon gives an indication of the soil suitability to be used in earthen construction. The soil was supplied by J & J Sharpe Ltd. The company is based in Devon and specialises in the repair, renovation, and conservation of old buildings. They also manufacture and supply readymade cob blocks and supply sub-soil for making adobe bricks. The total amount of soil used from Devon in this study was 925 kg.

#### 3.1.2.2 The preparation and storing of the British soil

When the soil was delivered, it was moist, so to achieve constant initial moisture content, it was air-dried at room temperature for two weeks. Achieving this initial moisture content was a crucial step in the preparation of the bricks in later stages because this initial moisture content will assist in controlling the amount of water the soil will need to achieve a workable mixture when preparing the bricks. The drying process was done by spreading the soil on the laboratory floor, Figure 3-1 . During these two weeks, the soil was overturned every two days to ensure even drying. After the two weeks period, the soil was ground by a heavy metal roller to remove the large clumps. The roller was applied over the soil several times until all large clumps were crushed. After that, the soil was sieved using a 10 mm sieve mesh to remove bigger particles and other materials that sometimes happen to be present in soils (tree roots, etc). The soil was then transferred into an airtight plastic barrel to retain the initial moisture content.

**Figure 3-1:** The British soil from Devon spread out on the laboratory floor in order to be dried out to reach an initial constant moisture content

#### 3.1.2.3 The selection criteria of the Sudanese soil

Mayo neighbourhood, one of many squatter settlements surrounding the capital of Sudan, Khartoum, was chosen as the location to source the second soil used in this study. The selection criterion was mainly dependent on the distance of the soil location from Khartoum's city centre, Figure 3-2. In addition to Mayo's proximity to Khartoum's city centre, it is one of the largest in size and highly populated squatter settlements. As mentioned before, only small amount of soil (50 kg) was imported from this location. This amount was used in key tests.

### 3.1.2.4 The preparation and storing of the Sudanese soil

The soil was delivered in a plastic sack inside a small airtight plastic barrel. The soil was kept inside the Overseas Soil Storage in the University of Reading for a couple of months and then moved to the laboratory in the Engineering Building where the brick preparation and testing undertaken. The soil was completely dry and as a result, no air-drying process was needed. The soil was finely grained, so it did not go through grinding processes. The soil was kept in its original plastic barrel to keep the initial moisture content. The soil was only sieved using a 10 mm sieve mesh immediately prior to the preparation of the bricks.

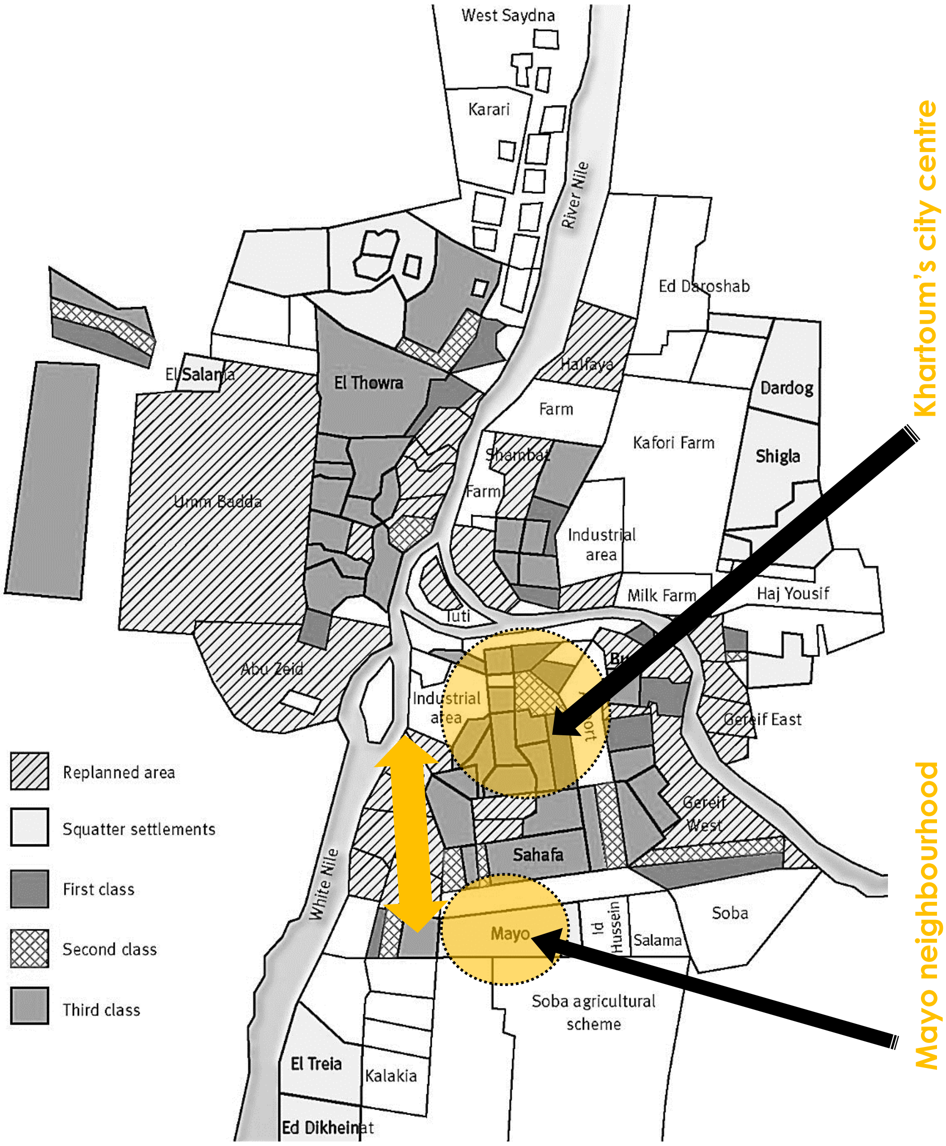



**Figure 3-2:** This map shows the proximity of Mayo neighbourhood to Khartoum's city centre, *(Humanitarian Policy Group, 2011)*

### *3.1.3 Classification tests*

Despite what has been mentioned in the previous section about the selection criteria of the soils and their suitability for making adobe bricks based on the experience of the local people in these regions, classification tests are crucial to make sure that these soils are suitable for making adobe bricks and that they meet standards. This section consists of the tests conducted to determine the soil properties:

- The moisture content.
- The liquid limit.
- The plastic limit.
- The particle density (specific gravity).
- The particle size distribution (dry sieving, wet sieving, and sedimentation).
- pH test.
- X-ray diffraction for clay mineralogy.

Methods used along with the results and their analysis will be covered in this section. These tests were carried out in accordance with the British Standard (BS 1377-2: 1990). All the tests apart from the pH test and the x-ray diffraction were conducted by the author at the Geotechnics Laboratory at the Department of Civil and Environmental Engineering at Imperial College London. The pH test was also conducted by the author at the Department of Geography and Environmental Science at the University of Reading. The X-ray diffraction test was conducted by the Natural History Museum in London.

#### 3.1.3.1 Determination of moisture content: *Oven-drying method*

The objective was to determine the available water in the soil before using it to prepare the bricks. The moisture content is determined as a percentage of the soil specimen dry mass. The main apparatus used include a drying oven capable of maintaining a temperature of 105 °C to 110 °C, corrosion-resistant container (moisture content tin), a scoop and a balance readable to 0.01g, Figure 3-3.

Three samples from the soil were used to determine the moisture content of the soil. The moisture content tins were cleaned and dried and then weighed to the nearest 0.01g. Then three soil samples were placed in the tins and the tin lids were replaced. Each tin with the soil sample and the lid was weighed to the nearest 0.01g. After that, the lid was removed and the tin with the soil sample and the lid separately were placed in the oven to dry at 105 °C to 110 °C. The soil samples were considered completely dried when the differences in successive weights of the cooled sample at intervals of 4 hours did not exceed 0.1 % of the original mass of the sample. After finishing drying, the soil samples were removed from the oven and allowed to cool to room temperature. Then the lid was placed and the tin was weighed to the nearest 0.01g, Table 3-1.

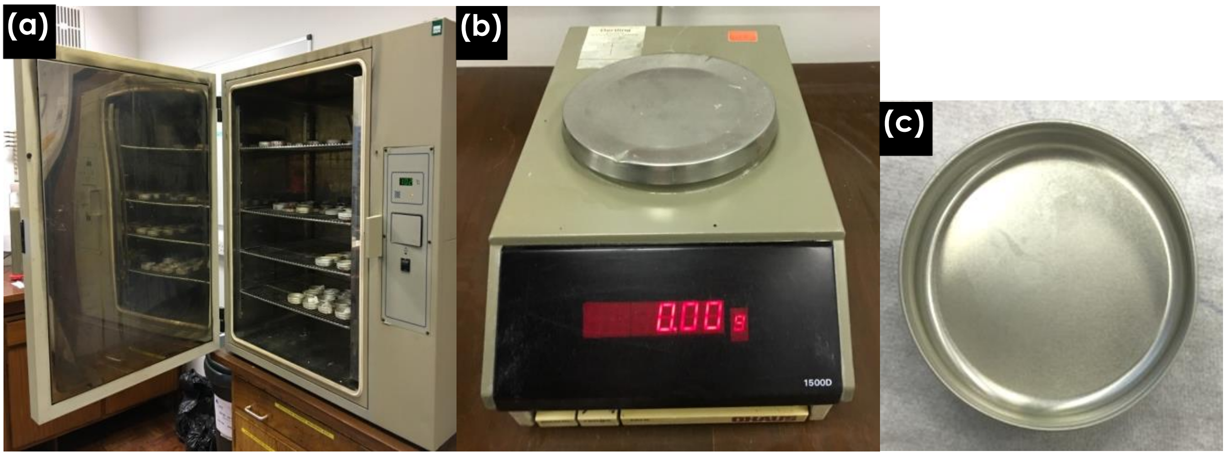



**Figure 3-3:** Main apparatus used to determine the moisture content **(a)** the drying oven **(b)** the balance readable to 0.01g **(c)** moisture content tin

**Table 3-1:** Moisture content test results of the British & the Sudanese soil

| Specimen ref. | Soil type | Mass of container ($m_1$) g | Mass of wet soil + container ($m_2$) g | Mass of dry soil + container ($m_3$) g | Moisture content (*w*) % $w=\left(\frac{m_2-m_3}{m_3-m_1}\right) \times 100\%$ | Average (*w*) % | Standard deviation |
|---|---|---|---|---|---|---|---|
| 1 | British Soil | 5.57 | 46.17 | 45.58 | 1.47 | 1.43 | 0.0006 |
| 2 | British Soil | 5.68 | 34.13 | 33.72 | 1.46 | | |
| 3 | British Soil | 5.70 | 37.59 | 37.16 | 1.37 | | |
| 1 | Sudanese Soil | 5.68 | 26.53 | 26.01 | 2.56 | 2.53 | 0.0012 |
| 2 | Sudanese Soil | 5.68 | 25.94 | 25.42 | 2.63 | | |
| 3 | Sudanese Soil | 5.69 | 38.97 | 38.19 | 2.40 | | |

Table 3-1, shows that the British soil contained 1.4% natural moisture and the Sudanese soil contained 2.5% moisture before preparing the bricks for the tests.

### 3.1.3.2 Determination of the liquid limit: *Cone penetrometer method*

The British Standards Institute (BS1377-2, 1990) defines the liquid limit($\mathbf{w}_L$)as the empirically established moisture content at which a soil passes from the liquid state to the plastic state. Also, the liquid limit provides a mean of classifying a soil, especially when the plastic limit is also known. The cone penetrometer method was chosen instead of the Casagrande apparatus method because it is a static test which is dependent on the soil shear strength, it is easier to perform and gives more reproducible results. Apparatus used were: 425 µm sieve, a flat glass plate, two palette knives, a penetrometer with a smooth polished stainless-steel cone with angle of 30 ±1°, metal cup, moisture content tin, wash bottle containing distilled water, and stopwatch readable to 1 second, Figure 3-4. Total sample of 500 g of soil was sieved using 425 µm sieve which yielded a total of 300 g of soil ready to be used for the liquid limit test. Distilled water was added to the soil and thoroughly mixed to prepare a paste and the moisture content of the paste was calculated following the oven dry method in section 3.1.3.1. Then the paste was placed on the flat glass plate and mixed using the two palette knives.

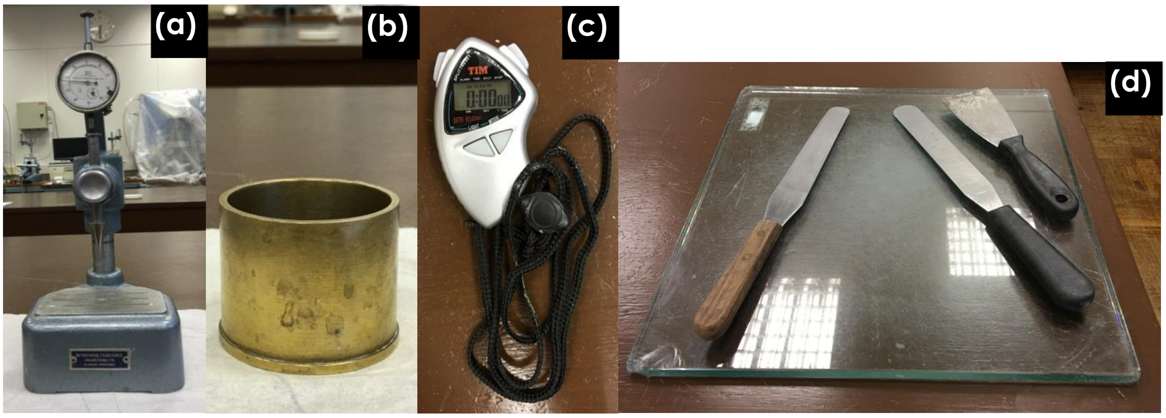



**Figure 3-4:** Main apparatus used to determine the liquid limit **(a)** penetrometer **(b)** metal cup **(c)** stopwatch **(d)** flat glass plate & two palette knives

Distilled water was added to the paste and thoroughly mixed until the cone penetration reading was about 15 mm. After that, the mix was pushed into the metal cup using the palette knife and care was taken to ensure no air was trapped. After filling the cup, the excess soil was scrapped using the knife to give a smooth level surface. Then the cup was placed in position in the penetrometer under the cone and the cone was slightly and carefully released to just touch the top surface of the soil. By freely moving the metal cup under the cone, the cone marked the surface of the soil and so this ensures that the cone touches the soil surface and in the right position. The stem of the dial gauge was lowered to contact the cone shaft and the reading was recorded to the nearest 0.1 mm which was corresponded to the initial dial gauge reading. Then the cone was released for a period of 5 ±1 second (using the stopwatch) and the stem of the dial gauge was lowered again to record the penetration. The difference between the initial and final dial gauge readings was corresponded to the cone penetration. Then a moisture content sample was taken from the metal cup where the cone penetrated and the moisture content was determined using the same method specified in section 3.1.3.1. The cone penetration readings were repeated twice for each corresponding moisture content and the average was calculated and used for the liquid limit. Then the soil was removed from the cup and back to the glass plate and distilled water was added in increments to change the soil moisture content gradually from the dry state to wet state. This water was added so that the penetration of the cone will be in the range between 15 mm and 25 mm. The same steps mentioned before for filling the cup and measuring the penetration along with taking samples for moisture content testing were conducted.

By the end of this test, two data sets were available, the cone penetration and its corresponding moisture content. These results were plotted in a linear scale plot and the line of the best fit was drawn, Figure 3-5 & Figure 3-6. The liquid limit ($\boldsymbol{w}_{\mathrm{L}}$) is the moisture content corresponding to 20 mm penetration. The liquid limit is expressed as a whole number.

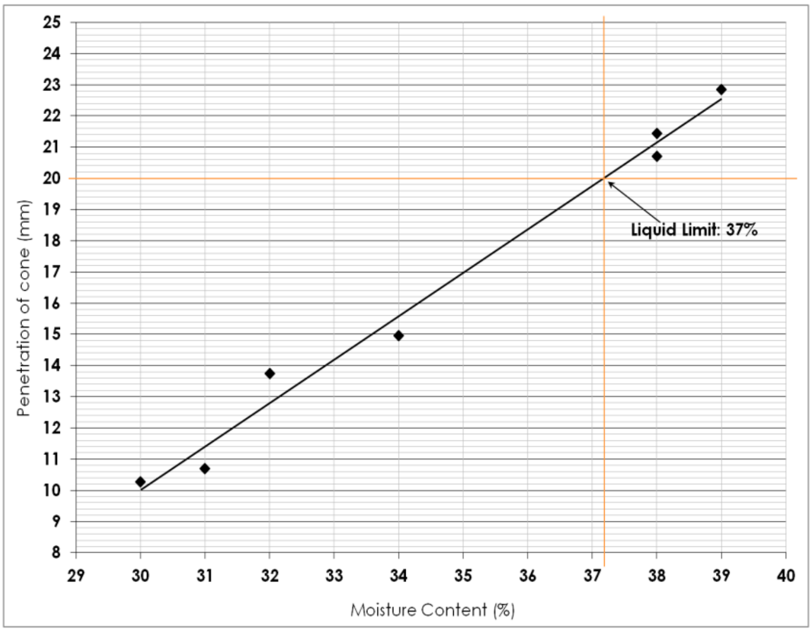



**Figure 3-5:** Liquid Limit ($\boldsymbol{w}_{\mathrm{L}}$) of the British soil

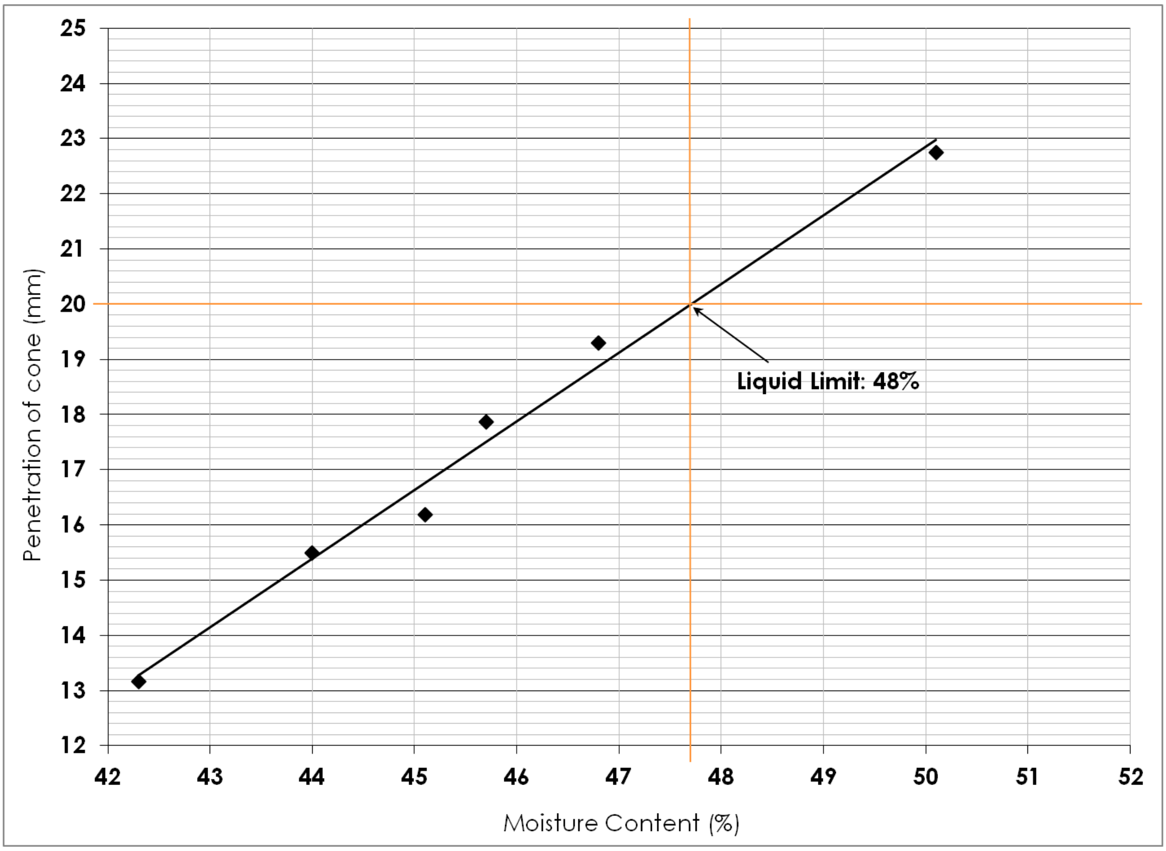



**Figure 3-6:** Liquid Limit ($w_L$) of the Sudanese soil

Figure 3-5 shows the cone penetration and the moisture content results of the British soil. The liquid limit of the British soil is **37%** and it corresponds to 20 mm penetration. Figure 3-6 shows the cone penetration and the moisture content results of the Sudanese soil. The liquid limit of the Sudanese soil is **48%** and it corresponds to 20 mm penetration. The difference in the liquid limit between the British and the Sudanese soil was due to the difference in the percentage of the total clay in the soil and the types (swelling and non-swelling) of the clay minerals between the two soils. The Sudanese soil has 12.5% clay compared with 5.3% for the British soil. Out of this percentage of clay for both soils, the percentage of the smectite which is a swelling clay mineral was 32% in the British soil compared with 63% in the Sudanese soil. The total of the non-swelling clay minerals (kaolinite, chlorite and illite) was 68% and 37% for the British and the Sudanese soils respectively.

### 3.1.3.3 Determination of the plastic limit

The British Standards Institute (BS1377-2, 1990) defines the plastic limit ($wp$) as the empirically established moisture content at which a soil becomes too dry to be plastic. Apparatus used were: a flat glass plate, two palette knives, 3 mm diameter rod about 100 mm long and moisture content tins, Figure 3-7. During the preparation of the soil paste for the liquid limit test in section 3.1.3.2, 20 g of the soil paste was kept aside in an airtight plastic bag to be used to determine the plastic limit.

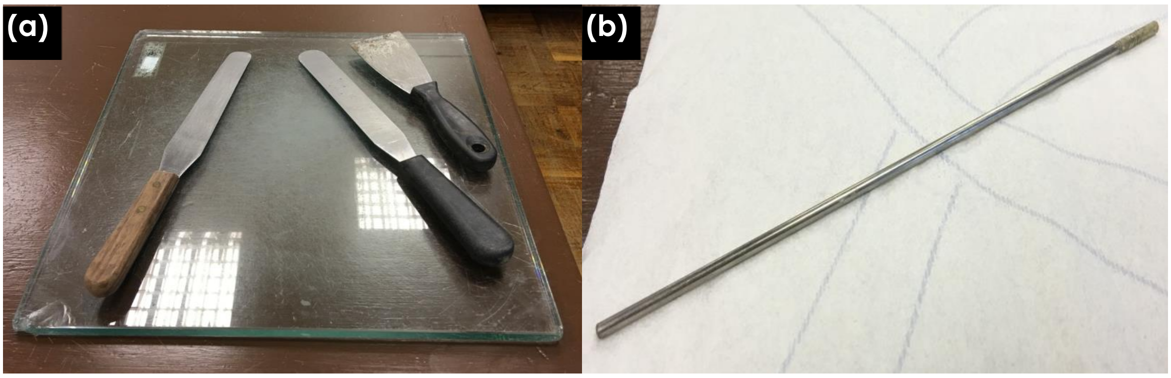



**Figure 3-7:** Main apparatus used to determine the plastic limit **(a)** flat glass plate & two palette knives **(b)** 3 mm rod

The soil was left on the glass plate for partial drying until it was plastic enough to be shaped into ball. Then the ball was rolled between the fingers and the palms of the hand to ensure the transfer of the heat from the hand to the ball. The heat will evaporate some of the moisture from the ball and will result in slight cracks on the surface of the ball. The ball was then divided into two identical balls each of 10 g. Then these two subsamples were divided into four equal small balls. Each ball was then moulded separately. Each ball was moulded between the fingers to ensure equal distribution of the moisture over the ball. After that, the ball was rolled into a thread by applying a uniform rolling pressure over the ball between the fingers and the glass palette. The first thread was 6 mm in diameter and then was reduced to 3 mm. After doing this rolling, the 3 mm diameter thread sheared longitudinally and transversely. When the shear of the thread was achieved, the crumpled pieces of the soil were collected in a moisture content tin, Figure 3-8. The tin was placed in the oven to calculate the moisture content using the method specified in section 3.1.3.1. For the rest of the small balls, the same rolling steps were conducted and the moisture content was calculated, Table 3-2.

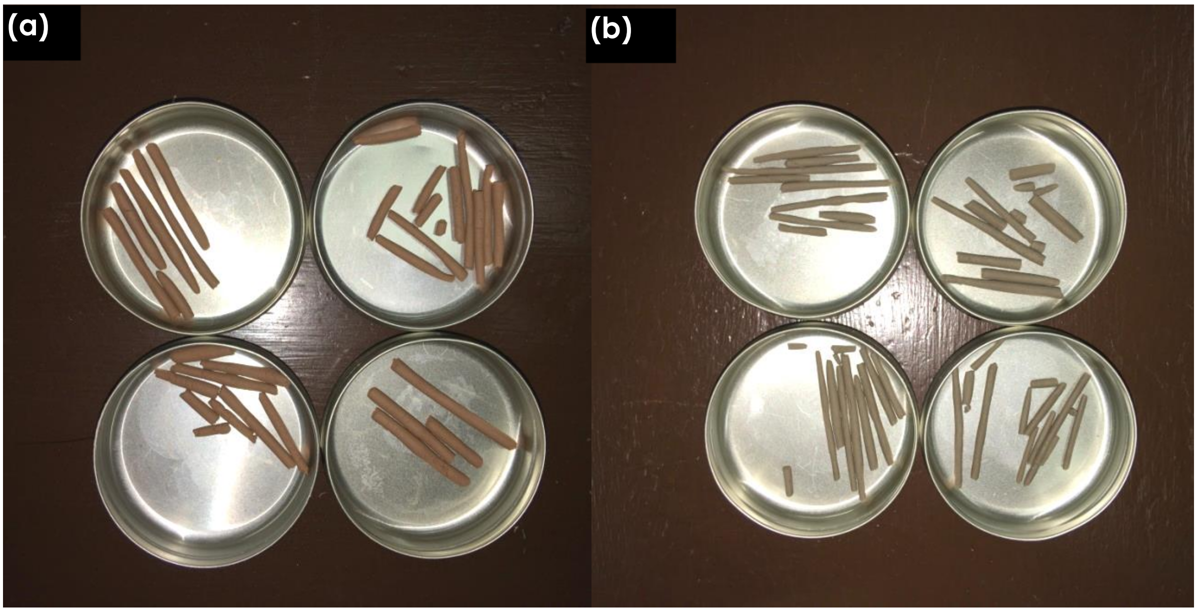



**Figure 3-8:** Plastic limit threads after oven drying for both soils **(a)** The British soil **(b)** The Sudanese soil

**Table 3-2:** Plastic limit results of the British and the Sudanese soils

| Specimen ref. | Soil type | Mass of container ($m_1$) g | Mass of wet soil + container ($m_2$) g | Mass of dry soil + container ($m_3$) g | Moisture content ($w$) % $w=\left(\frac{m_2-m_3}{m_3-m_1}\right) \times 100\%$ | Average ($w$) % | Standard deviation |
|---|---|---|---|---|---|---|---|
| **1** | **British Soil** | 5.69 | 10.23 | 9.46 | 20.4 | **19.40** | **0.762** |
| **2** | **British Soil** | 5.71 | 10.20 | 9.48 | 19.1 | | |
| **3** | **British Soil** | 5.69 | 9.20 | 8.65 | 18.6 | | |
| **4** | **British Soil** | 5.68 | 9.90 | 9.21 | 19.5 | | |
| **1** | **Sudanese Soil** | 5.68 | 9.14 | 8.50 | 22.70 | **21.70** | **1.915** |
| **2** | **Sudanese Soil** | 5.58 | 10.29 | 9.40 | 23.3 | | |
| **3** | **Sudanese Soil** | 5.68 | 9.74 | 9.01 | 21.90 | | |
| **4** | **Sudanese Soil** | 5.68 | 8.94 | 8.42 | 18.98 | | |

### 3.1.3.4 Derivation of plasticity Index & discussion of the results of the liquid and the plastic limits

The difference between the liquid limit ($\boldsymbol{w_L}$) and the plastic limit ($\boldsymbol{w}$p) is expressed as the "plasticity index" ($\boldsymbol{I}_P$).

$$\boldsymbol{I}p = \mathbf{w}l — \ wp$$

The plasticity index of the British and the Sudanese soils along with the summary of the liquid and the plastic limit are presented in Table 3-3 below.

**Table 3-3:** Summary of the liquid & plastic limit and the plasticity index for the British & the Sudanese soils

| Soil type | Liquid limit ($w_L$) | Plastic limit ($w$p) | Plasticity index ($I_P$) |
|---|---|---|---|
| **British** | 37% | 19.4% | 17.6% |
| **Sudanese** | 48% | 21.7% | 26.3% |

Figure 3-9 below, shows the zone which represents the maximum and minimum liquid limits and plasticity index for soils suitable for the production of adobe bricks. The acceptable liquid limit is between 31% to 50% and the acceptable plasticity index is between 16% and 33% (Houben and Guillaud, 1994). Based on the results of the liquid limit and the plasticity index in Table 3-3 above, the British and the Sudanese soils are in the zone of soils suitable for adobe brick making.

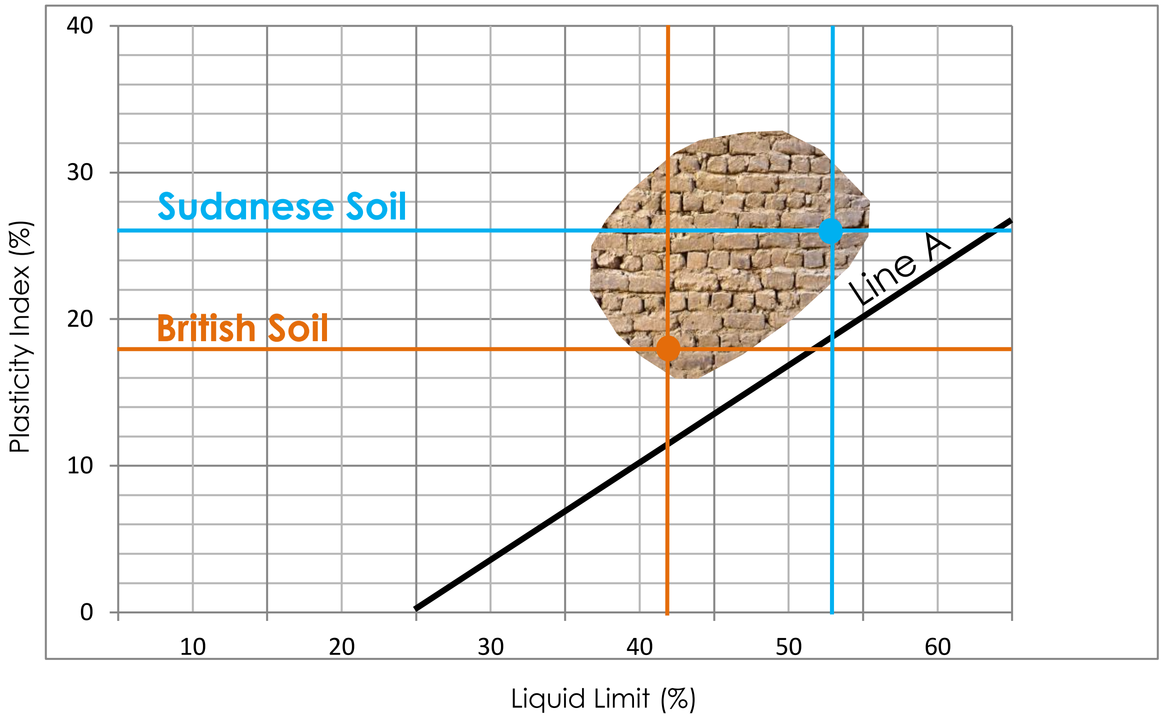



**Figure 3-9:** Plasticity nomogram showing recommended areas for liquid limit and plasticity index of soil suitable for adobe bricks, along with the liquid limit and the plasticity index of the British and the Sudanese soils, *(Houben and Guillaud, 1994)*

On the other hand, the British and the Sudanese soils could be classified according to their plasticity. Figure 3-10 shows the plasticity chart for the soil classification. The results of the British and the Sudanese soils indicate that both soils are classified as intermediate plasticity clay (CI) (BS5930, 1999).

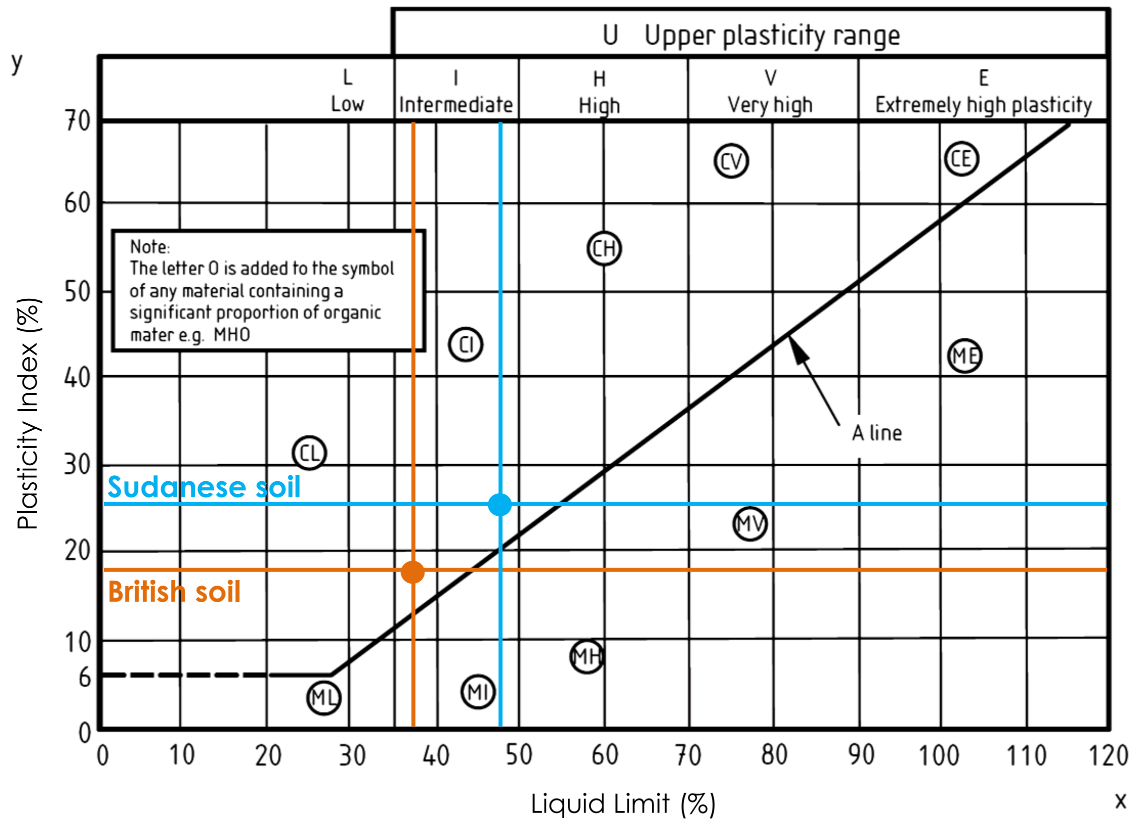



**Figure 3-10:** Plasticity chart for the classification of fine soils and the finer part of coarse soils passing 425 µm. The British and the Sudanese soils are shown in the graph, *(BS5930, 1999)*

The liquid, plastic limits and the plasticity index results of both soils could be compared with results reported from previous studies on adobe bricks (Bahar et al., 2004, Degirmenci et al., 2007, Kouakou and Morel, 2009, Lertwattanaruk and Choksiriwanna, 2011, Bharath et al., 2014, Illampas et al., 2014, Millogo et al., 2014).

### 3.1.3.5 Determination of particle size distribution

To determine the proportion of particles of different sizes in the soil, dry and wet sieve tests along with sedimentation test were conducted. Also, the particle density test (specific gravity) of finer particles was conducted. The results of the particle density test were used in the calculations of the sedimentation test. Dry and wet sieve were conducted to compare the results of both types of tests and the final results were plotted accordingly.

#### *3.1.3.5.1 Dry sieving method*

The apparatus used for this test were: test sieves (9.5 mm, 3.35 mm, 2 mm, 1.18 mm, 600 μm, 425 μm, 300 μm, 212 μm, 150 μm, 63 μm and appropriate receiver), balance readable to 1.0 g, balance readable to 0.1 g, mechanical sieve shaker and drying oven capable of maintaining a temperature of 105 °C. A quantity of about 201.5 g of the British soil and 201 g of the Sudanese soil were oven dried at 105 °C overnight. Then the sieves were arranged and fitted over each other, the largest sieve in size was in the top and the finest one in the bottom followed by the receiver, Figure 3-11.Then the sieve set was transferred to the mechanical shaker, Figure 3-11, and the soil was placed on the top of the sieve set. The shaker was covered with the shaker glass lid and locked. The soil then was shaken for 10 minutes using vibration (Amplitude: 1 mm).

| **Sieves arrangement** |
|---|
| 1. **9.5** mm |
| 2. **3.35** mm |
| 3. **2** mm |
| 4. **1.18** mm |
| 5. **0.6** mm |
| 6. **0.425** mm |
| 7. **0.3** mm |
| 8. **0.212** mm |
| 9. **0.15** mm |
| 10. **0.063** mm |
| 11. **Receiver** |

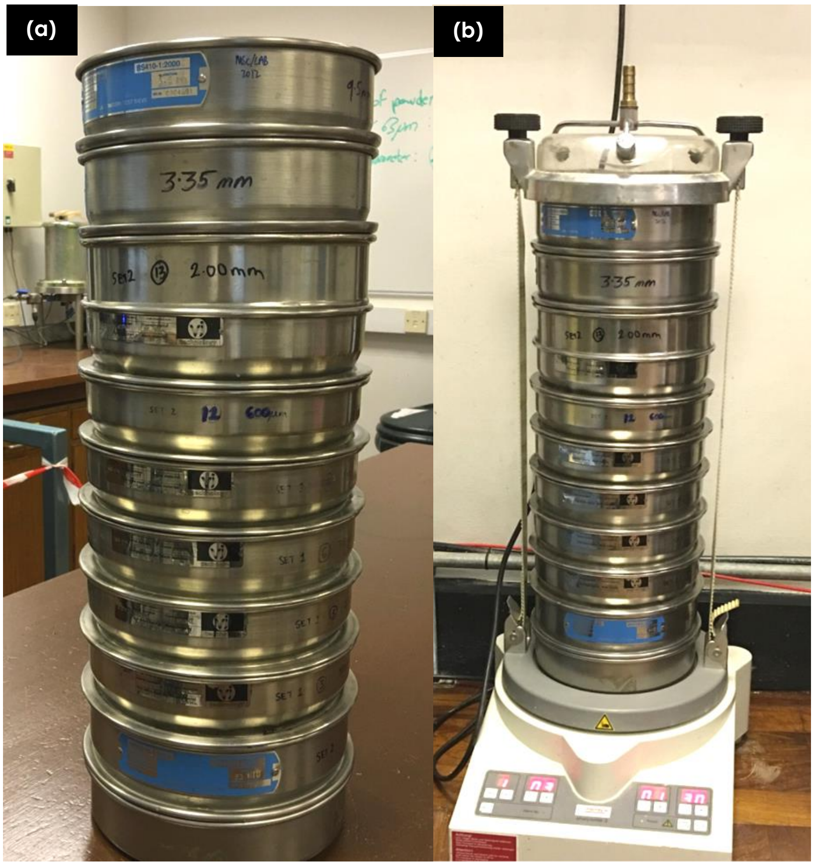



**Figure 3-11:** Dry sieve method, **(a)** sieve set along with the sieve arrangement **(b)** the mechanical shaker with the sieve set, glass cover, and the soil

After the ten minutes of shaking was finished, the mass retained on each test sieve was weighed and then the percentage that passed each sieve was calculated, Table 3-4 and Table 3-5.

**Table 3-4:** Dry sieve test results of the British soil

| No | Sieve Size (mm) | Weight remained (g) | Weight passing (g) | Passed (%) | Remained |
|---|---|---|---|---|---|
| 1 | **9.5** | 4 | 197.5 | 98 |  |
| 2 | **3.35** | 70.3 | 127.2 | 63.1 |  |
| 3 | **2** | 27.8 | 99.4 | 49.3 |  |
| 4 | **1.18** | 35.5 | 63.9 | 31.7 |  |
| 5 | **0.6** | 23.9 | 40 | 19.9 |  |
| 6 | **0.425** | 7.7 | 32.3 | 16 |  |
| 7 | **0.3** | 5.8 | 26.5 | 13.2 |  |

| No | Sieve Size (mm) | Weight remained (g) | Weight passing (g) | Passed (%) | Remained |
|---|---|---|---|---|---|
| **8** | **0.212** | 5.2 | 21.3 | 10.6 |  |
| **9** | **0.15** | 4.1 | 17.2 | 8.5 |  |
| **10** | **0.063** | 10.6 | 6.6 | 3.3 |  |
| **11** | **Receiver** | 6.6 | | |  |

Table 3-4 shows the result of the dry sieve test of the British soil and it shows that only 3.3% passed the 0.063 mm sieve which means that the British soil has only 3.3% fine particles (silt and clay).

**Table 3-5:** Dry sieve test results of the Sudanese soil

| No | Sieve Size (mm) | Weight remained (g) | Weight passing (g) | Passed (%) | Remained |
|---|---|---|---|---|---|
| **1** | **9.5** | 0 | 201 | 100 |  |
| **2** | **3.35** | 0.1 | 200.9 | 99.95 |  |
| **3** | **2** | 0.6 | 200.3 | 99.65 |  |

| No | Sieve Size (mm) | Weight remained (g) | Weight passing (g) | Passed (%) | Remained |
|---|---|---|---|---|---|
| **4** | **1.18** | 25.9 | 174.4 | 86.8 |  |
| **5** | **0.6** | 49.5 | 124.9 | 62.1 |  |
| **6** | **0.425** | 22.7 | 102.2 | 50.8 |  |
| **7** | **0.3** | 20.5 | 81.7 | 40.6 |  |
| **8** | **0.212** | 21.2 | 60.5 | 30.1 |  |
| **9** | **0.15** | 15.4 | 45.1 | 22.4 |  |
| **10** | **0.063** | 31.8 | 13.3 | 6.6 |  |
| **11** | **Receiver** | 13.3 | | |  |

Table 3-5 shows the result of the dry sieve test of the Sudanese soil and it shows that only 6.6% passed the 0.063 mm sieve which means that the Sudanese soil has only 6.6% of fine particles (silt and clay).

However, and despite the fact that adobe brick is considered the least restrictive technique when it comes to soil selection (Middleton, 1987), the soil needs to have clay content between 5% and 29%, Figure 3-12, to be suitable for adobe bricks production (Houben and Guillaud, 1994). From Table 3-4 and Table 3-5, the silt and clay percentages together are 3.3% and 6.6% for the British and the Sudanese soils respectively. This means both soils have clay content less than 5%.

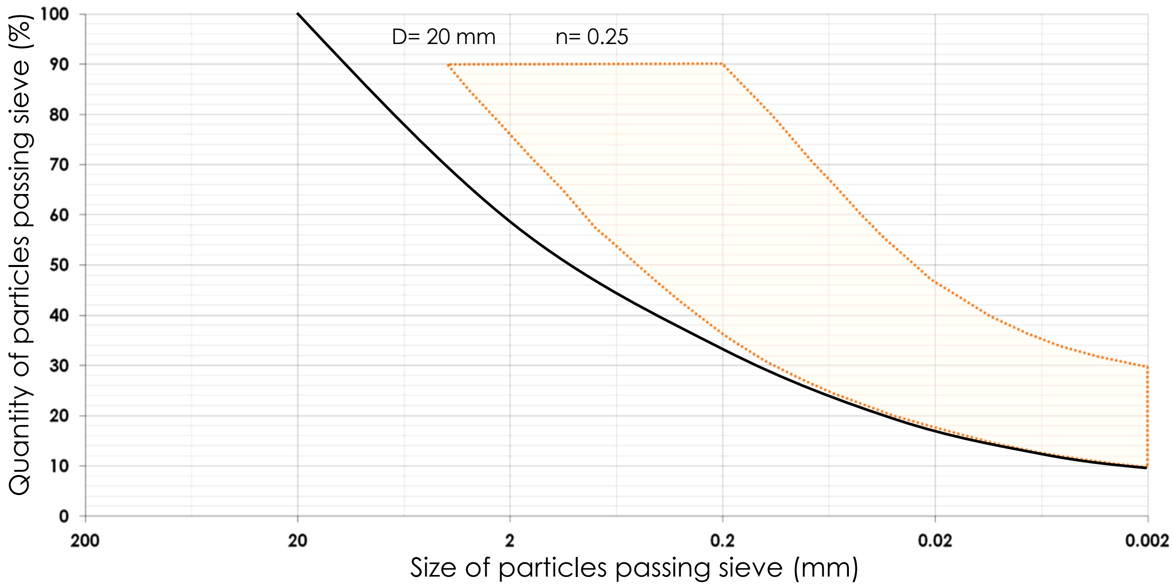



**Figure 3-12:** Granularity nomograms showing recommended area for particle size distribution of soils for adobe bricks (clay <0.002mm, silt 0.002–0.06 mm, sand 0.06–2 mm, fine gravel 2–6 mm, medium gravel 6-20 mm), *(Houben and Guillaud, 1994)*

The results of the dry sieve for both soils contradict with the results of the plastic and liquid limits and the plasticity index in section 3.1.3.4. The plastic and liquid limits tests results showed that the soils were of intermediate plasticity which indicates that the soil has reasonable quantities of fine particles (clay and silt) which are responsible for cohesion and plasticity. As a result of this contradiction, wet sieving method and sedimentation were used to determine the particle size distribution. Particle density test (specific gravity) was also conducted in order to determine the particles density that was needed in the sedimentation results calculations.

#### *3.1.3.5.2 Wet sieving method*

The apparatus used for this test were: test sieves (9.5 mm, 3.35 mm, 2 mm, 1.18 mm, 600 µm, 425 µm, 300 µm, 212 µm, 150 µm, 63 µm and appropriate receiver), balance readable to 1.0 g, balance readable to 0.1 g, plastic bucket, a corrosion-resistant tray and bowl, wash bottle containing distilled water, sodium hexametaphosphate powder (used as dispersant solution), moisture tins used to dry the soil particles, and drying oven capable of maintaining a temperature of 105 °C.

A quantity of 201 g of the British soil and 205 g of the Sudanese soil were oven dried at 105 °C overnight. Then each soil was soaked in a corrosion-resistant bowl filled with distilled water and sodium hexametaphosphate (concentration of 2 g/L). The soil was stirred frequently and left for 1 hour in the solution. Then the sieves were arranged and fitted over each other, the largest sieve in size was at the top and the finest one at the bottom followed by the receiver and the plastic bucket was placed under the receiver. Then the soil was washed a little at a time through the sieves. Moisture tins were weighed and labelled. The remaining soil particles on each sieve were carefully transferred to the moisture tin and weighed. Then all the moisture tins were placed to dry in the oven overnight, Figure 3-13. The wet soil passed the 63 μm was placed in a corrosion-resistant tray and also left to dry in the oven, Figure 3-14. After the soils were completely dried, they weighed and the mass was recorded.

The results of this test were completely different from that of the dry sieving test. The fine particles passed the 63 μm were 24.3% and 65.2% for the British and the Sudanese soil respectively, Table 3-6. Sedimentation test was conducted because the amount of the soil which passed the 63 μm was more than 10% (BS1377-2, 1990). As a result, the percentages of coarse, medium, and fine silt, and clay were determined and the results obtained from the sedimentation test was linked to the wet sieve test results and plotted in one graph.

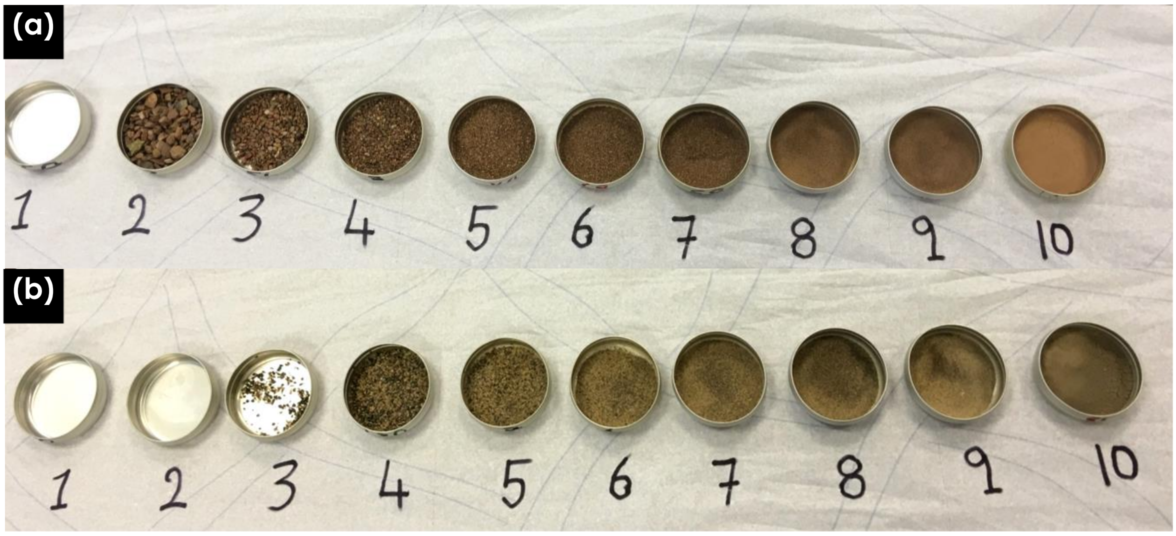



**Figure 3-13:** Wet sieve results for **(a)** the British soil **(b)** the Sudanese soil (for sieve sizes (from 1-10) refer to sieves arrangement in Figure 3-11.


**Figure 3-14:** Soil particles passed 63 μm sieve after the wet sieve for **(a)** the British soil **(b)** the Sudanese soil

**Table 3-6:** Wet sieving results for the British and the Sudanese soils

| Sieve No | Sieve Size (mm) | Passed (%) British soil | Passed (%) Sudanese soil |
|---|---|---|---|
| 1 | **9.5** | 100 | 100 |
| 2 | **3.35** | 80.19 | 100 |
| 3 | **2** | 72.08 | 99 |
| 4 | **1.18** | 60.50 | 93 |
| 5 | **0.6** | 52.39 | 86.33 |
| 6 | **0.425** | 49.09 | 83.04 |
| 7 | **0.3** | 44.98 | 80.41 |
| 8 | **0.212** | 40.99 | 77.52 |
| 9 | **0.15** | 37.27 | 75.25 |
| 10 | **0.063** | **24.25** | **65.20** |
| 11 | **Receiver** | | |

Before conducting the sedimentation test, particle density test (specific gravity) was conducted. This test was used to determine the density of the fine particles smaller than 2 mm. The results of this test were important in the calculations of the particles size in the sedimentation test later.

#### 3.1.3.5.3 Determination of particle density (specific gravity): Small pyknometer method

As it has been mentioned before, this test is used to determine the particle density for particles finer than 2 mm. The soils were sieved using 2 mm sieve and resulted in 100 g of each soil which were left to dry in the oven in 105 °C overnight. Then the soils were kept in airtight containers. The apparatus used for this test were: four 50 mL density bottles (pyknometers) with stoppers for each soil, Figure 3-15, a vacuum desiccator with protective cage, a balance readable to 0.001 g, a small spoon and a wash bottle containing distilled water. This test was performed in a constant-temperature room.


**Figure 3-15:** 50 mL density bottles (pyknometers) with stoppers

The density bottles and the stoppers were cleaned and dried and then weighed with the stopper to the nearest 0.001 g ($\boldsymbol{m_1}$). Then the soil was added straight from the airtight container to the density bottle and the stopper was placed and the bottle was weighed to the nearest 0.001 g ($\boldsymbol{m_2}$). After that distilled water was added from the wash bottle to cover the soil in the density bottles, Figure 3-16. The bottles were placed inside the vacuum desiccator without the stoppers and the protective cover of the desiccators was placed, Figure 3-16. The desiccator was evacuated gradually to ensure that all the air trapped in the soil was evacuated. The density bottles were left in the vacuum desiccators for about 4 hours until no loss of air was apparent.

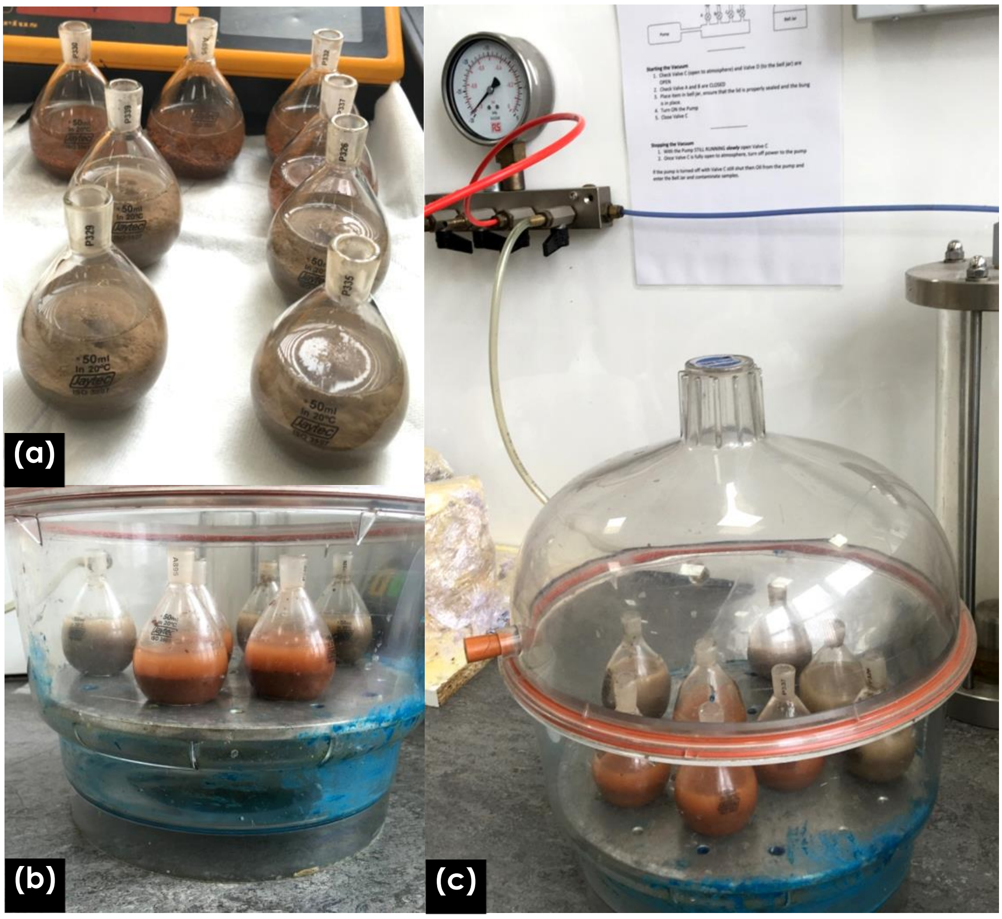



**Figure 3-16:** The density bottles **(a)** filled with soil and distilled water **(b)** & **(c)** the 8 density bottles inside the vacuum desiccators

After four hours in the vacuum desiccators, the density bottles were removed from the vacuum desiccators and filled completely with the distilled water and the stoppers were placed. Then the bottles were carefully wiped and weighed to the nearest 0.001 g (***$m_3$***). The contents of the bottles were then removed and the bottles were washed and cleaned and filled with the distilled water and the stoppers were inserted back. Then the density bottles were wiped from the outside for any excess water to be dried and then they were weighed to the nearest 0.001 g (***$m_4$***), Table 3-7. The particle density ($p_s$) then was calculated using the following equation:

$$ps = \frac{m2 - m1}{(m4 - m1) - (m3 - m2)}$$

**Table 3-7:** Results of the particle density test for the British and the Sudanese soils

| No | Soil Type | Weight of bottle ($m_1$) g | Weight of bottle & soil ($m_2$) g | Weight of bottle, soil & water ($m_3$) g | Weight of bottle & water ($m_4$) g | Particle density ($\rho_s$) mg/m3 | Average ($\rho_s$) mg/m3 | Standard deviation |
|---|---|---|---|---|---|---|---|---|
| **1** | British | 32.4988 | 51.8888 | 93.8089 | 81.6013 | 2.70 | **2.71** | **0.014** |
| **2** | British | 33.1828 | 50.8983 | 94.4120 | 83.2511 | 2.70 | | |
| **3** | British | 31.7165 | 49.3243 | 91.4952 | 80.4138 | 2.70 | | |
| **4** | British | 31.7461 | 50.1358 | 92.8348 | 81.1857 | 2.73 | | |
| **1** | Sudanese | 31.9598 | 54.8015 | 98.0371 | 83.6600 | 2.70 | **2.69** | **0.019** |
| **2** | Sudanese | 31.6672 | 54.5844 | 95.8449 | 81.4984 | 2.67 | | |
| **3** | Sudanese | 31.3333 | 53.5911 | 95.4152 | 81.3753 | 2.71 | | |
| **4** | Sudanese | 32.8612 | 57.5181 | 97.5056 | 82.0908 | 2.67 | | |

From Table 3-7, the particle density of the British and the Sudanese soils was 2.71 mg/m$^3$ and 2.69 mg/m$^3$ respectively. These densities are crucial for the calculations of the sedimentation test results for the full graph of the particle size distribution in the next section.

#### *3.1.3.5.4 Sedimentation test: Hydrometer method*

For this test, the soil used was only the soil that passed the 63 µm sieve after the wet sieve test, Figure 3-14 in section 3.1.3.5.2. The test was conducted in a constant-temperature room. The apparatus used for this test were: hydrometer, Figure 3-17, four 1 L graduated glass measuring cylinders with parallel sides two of them with stoppers, a balance readable to 0.01 g, a stopwatch readable to 1 second, a thermometer, an engineer's steel rule, wash bottle containing distilled water, a funnel and sodium hexametaphosphate solution.

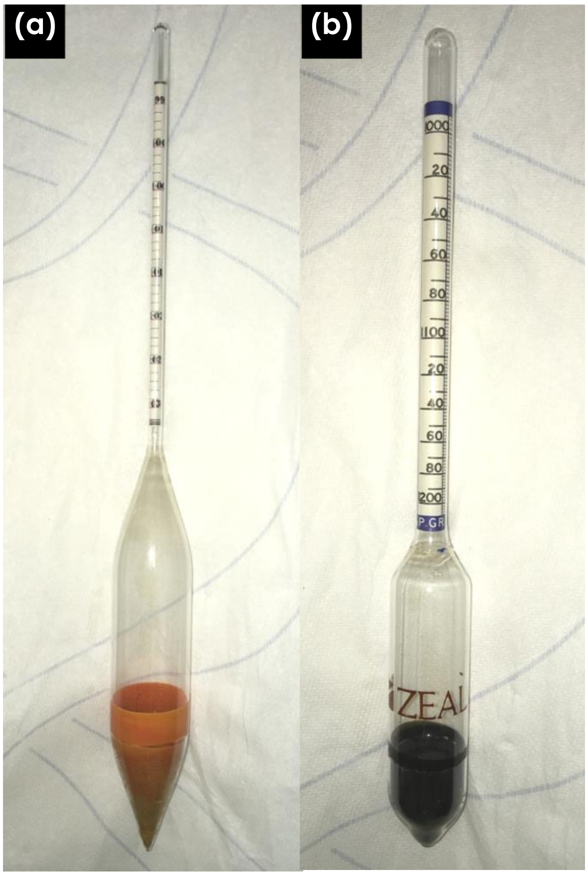



**Figure 3-17:** Hydrometers used for the sedimentation test **(a)** used for the British soil **(b)** used for the Sudanese soil

These hydrometers were calibrated as follow, Figure 3-18:

1) The volumes of the hydrometers were determined by weighed them to the nearest 0.1 g and then their mass was recorded in milligrams.
2) The distance (L) which is the distance between the 100 mL scale marking to the 1000 mL scale marking on the sedimentation cylinder was measured in mm.
3) The distances from the lowest calibration mark on the stem of the hydrometer to each of the other major calibration marks ($d_1$, $d_2$, $d_3$, etc) were measured and recorded.
4) The distance (N) from the neck of the bulb to the nearest calibration mark was measured and recorded.
5) The distance (H) which is corresponding to a reading ($R_{h'}$) and it is the sum of (N) and each of the $d_s$ ($d_1$, $d_2$, $d_3$, etc) was calculated.
6) The height of the bulb as the distance (h) from the neck to the bottom of the bulb was measured and recorded.

7) The effective depth ($H_R$) which is corresponding to each of the major calibration marks ($R_h$') was calculated in mm using the following equation:

$$\mathbf{HR = H + 0.5\left(h - \frac{Vh}{900}L\right)}$$

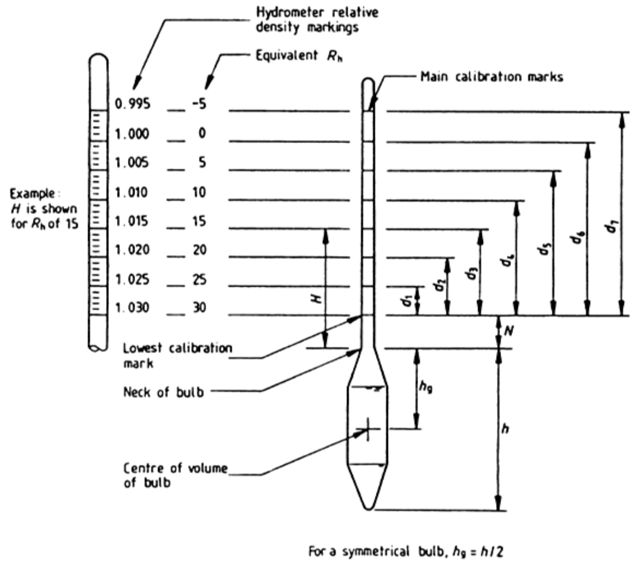



**Figure 3-18:** Essential measurements for calibration of the hydrometer, (BS1377-2, 1990)

The linear relationship between the effective depth ($H_R$) and the major calibration marks (Rh) was plotted, Figure 3-19 & Figure 3-20, and the liner equation of the relationship was then used to give the effective depth of the suspension, the relative density of which is given by the hydrometer reading. It allows for the rise of the liquid in the graduated cylinder (BS1377-2, 1990).

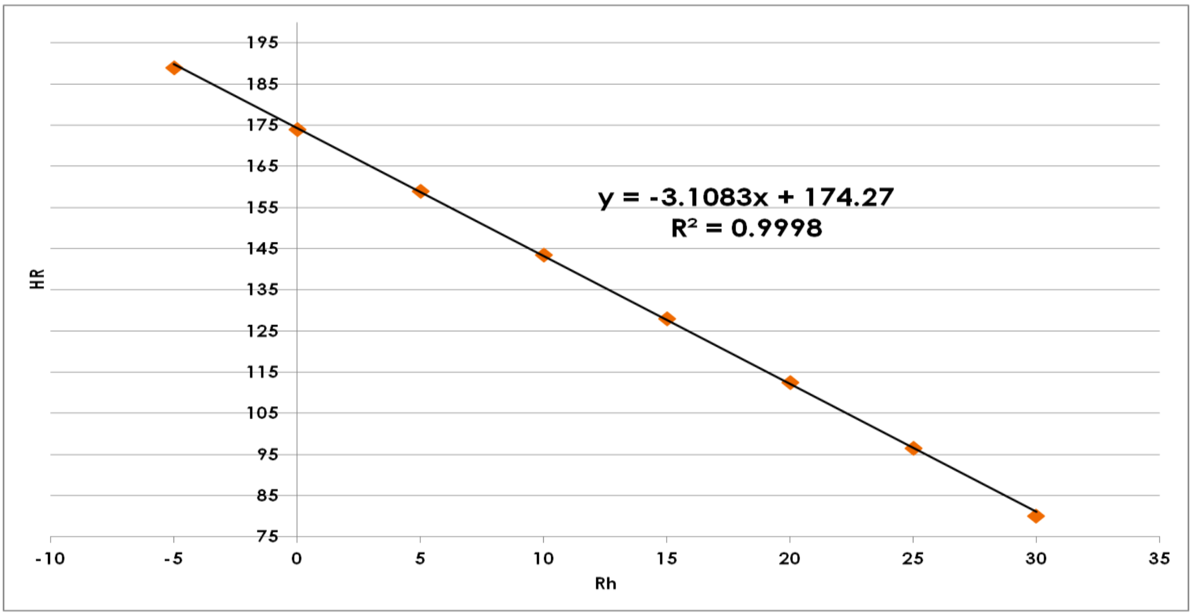



**Figure 3-19:** Equation of the calibration of the hydrometer used for the sedimentation test of the British soil

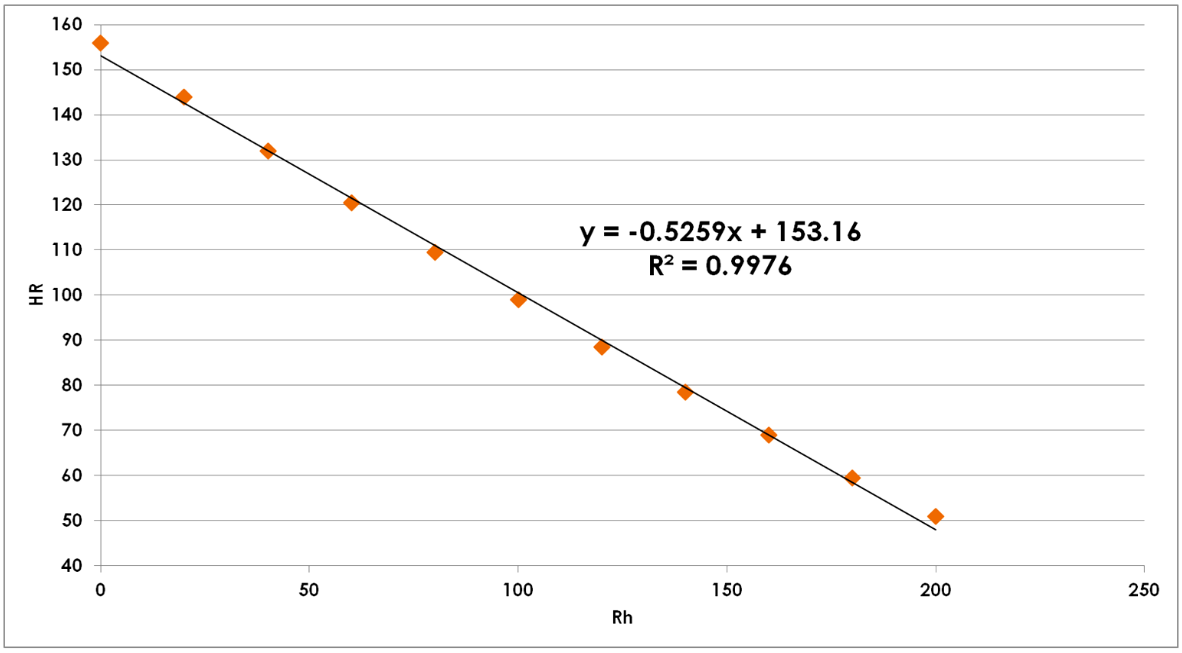



**Figure 3-20:** Equation of the calibration of the hydrometer used for the sedimentation test of the Sudanese soil

After the calibration of the hydrometers, the meniscus correction ($C_m$) was obtained. This was added to the $R_h$' reading at the end to give the true reading of $R_h$' referred to as $R_h$. This meniscus correction was introduced because the suspension of the soil in the water resulted in unclear water which will affect the readings of the hydrometer. The meniscus correction ($C_m$) was obtained as follow:

1) The hydrometer was inserted in 1 L cylinder containing 800 mL of water.
2) Then the 1st reading, the lower limit, was recorded by slightly placing the eye below the plane of the surface of the liquid.
3) Then the 2nd reading, the upper limit, was also recorder by placing the eye above the plane of the surface of the liquid.
4) The difference between the lower limit and the upper limit was then recorded as the meniscus correction ($C_m$).

After the above steps were completed, the sedimentation cylinders were prepared by adding sodium hexametaphosphate powder (used as dispersant solution) to distilled water (concentration of 2 g/L) and they were shaken thoroughly until all the powder dissolved. Then the soil was added using a funnel, Figure 3-21. Another cylinder which was contained only sodium hexametaphosphate powder and distilled water was shaken and left aside which was used to record the reading in the dispersant $R_o$'. The sedimentation cylinder was shaken vigorously end-over-end about 60 times in 2 minutes. Then the hydrometer was inserted immediately and the readings were reordered after 0.5, 1, 2, 4, 8,15, 30, 60, 120, 240 minutes and then every day for 8 consecutive days. After 0.5, 1, 2 and 4 minutes, the hydrometer was removed from the sedimentation cylinder, rinsed in distilled water and placed in the dispersant solution, Figure 3-21. After 8 days, the water was clear and the hydrometer readings were constant, Figure 3-22. Despite the fact that this test was conducted in a constant-temperature room, a thermometer was placed inside the dispersant solution all the time and the temperature was recorded every time a reading was taken.

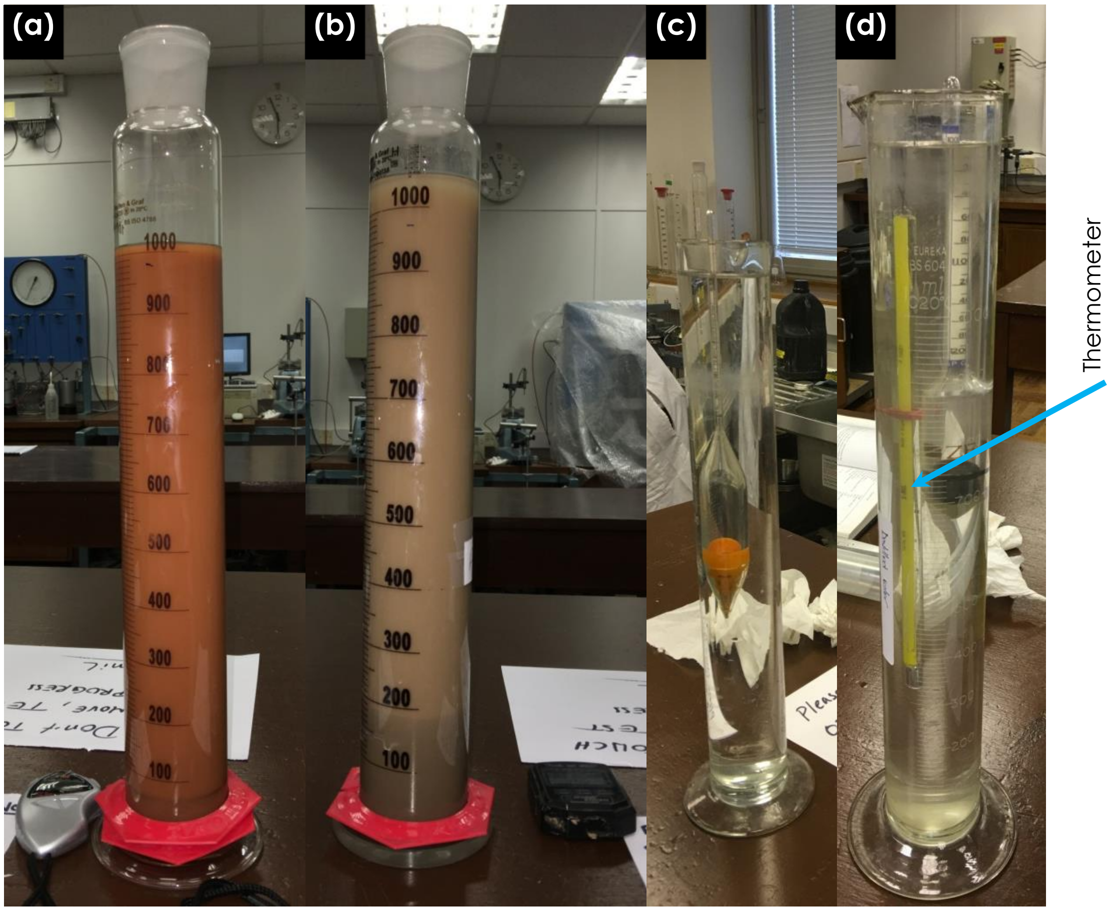



**Figure 3-21:** First day of the sedimentation test **(a)** the British soil **(b)** the Sudanese soil **(c)** the dispersant solution for the British soil **(d)** the dispersant solution for the Sudanese soil


**Figure 3-22:** The sedimentation test after 8 days **(a)** the British soil **(b)** the Sudanese soil

The results of the sedimentation test were plotted and linked with the results of the wet sieve in section 3.1.3.5.2. In the same graph, the results from the dry sieve in section 3.1.3.5.1 was plotted for comparison of the results between the two test methods, Figure 3-23 & Figure 3-24 below.

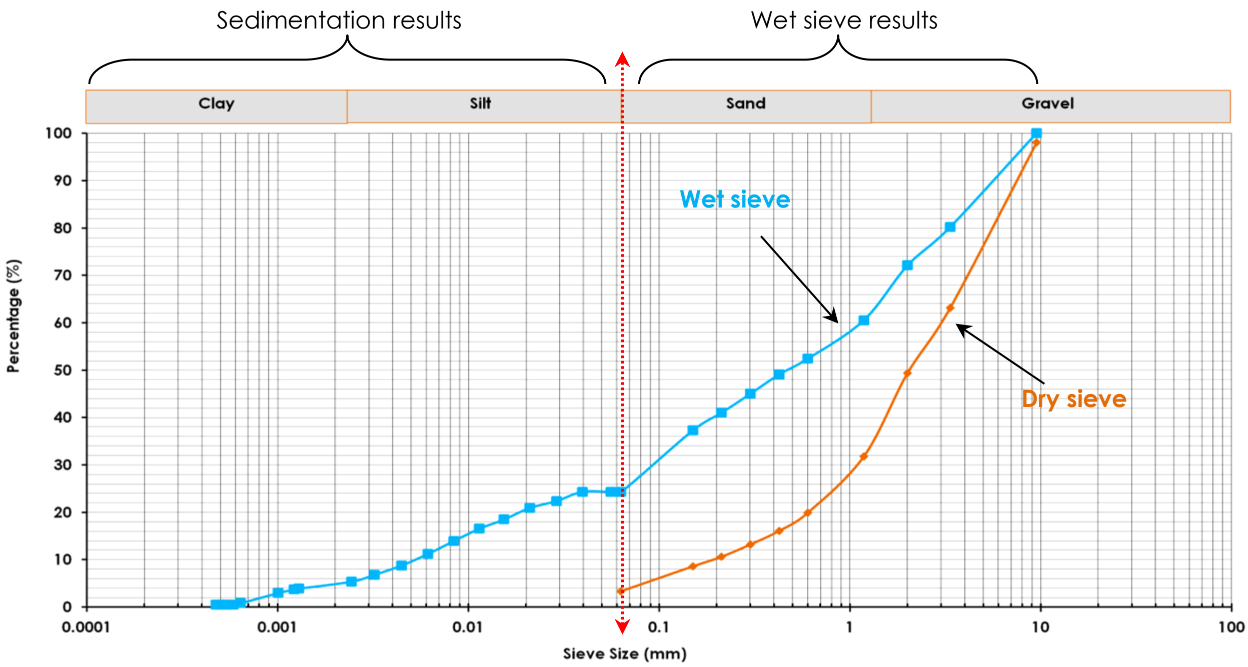



**Figure 3-23:** Particle size distribution of the British soil, dry sieve, wet sieve, and sedimentation test results

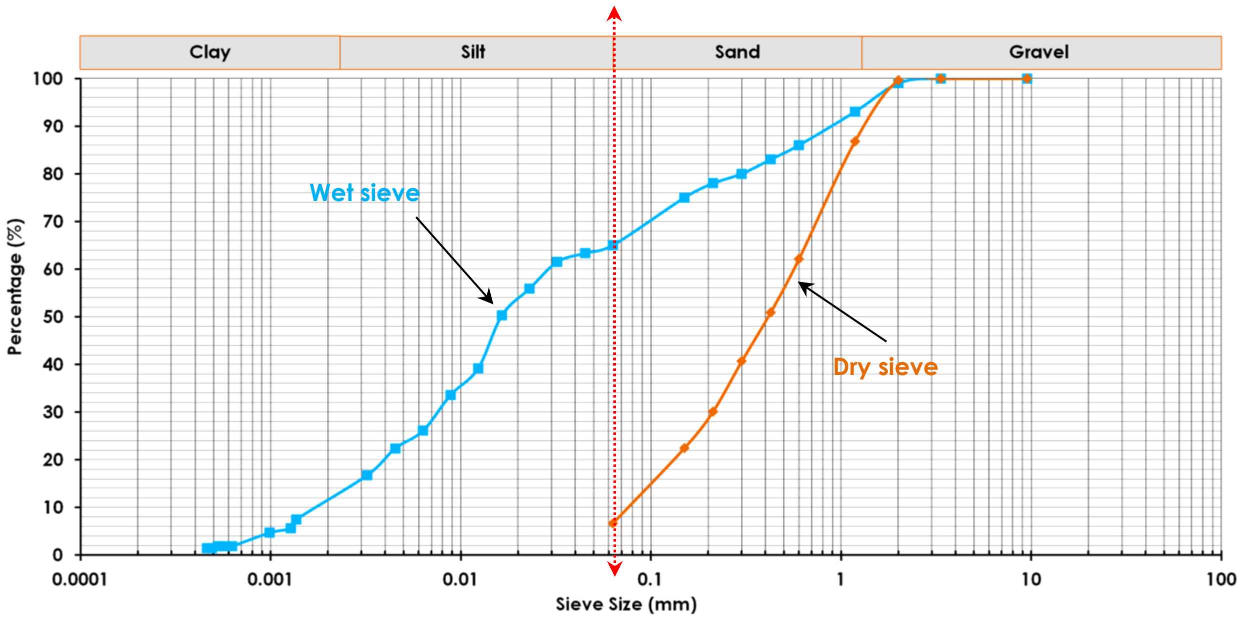



**Figure 3-24:** Particle size distribution of the Sudanese soil, dry sieve, wet sieve, and sedimentation test results

From the results of both the dry sieve and the wet sieve conducted in this section, it is worth mentioning that dry-sieving is not suitable for identifying the particle size distribution of soils for adobe brick fabrication. Thus, it is recommended to use the wet-sieving as the method to identify particle size distribution for soil that is intended to be used for adobe brick production.

From Figure 3-23 & Figure 3-24 above, the following table of the particles percentages for each soil could be drawn.

**Table 3-8:** Summary of the particle size distribution tests for the British and the Sudanese soils

<table>
<tr><th>Soil type</th><th>Test type</th><th>Clay (%)</th><th>Silt (%)</th><th>Sand (%)</th><th>Gravel (%)</th><th>Total (%)</th></tr>
<tr><td rowspan="2">British</td><td>Wet Sieve + Sed*</td><td>5.30</td><td>18.70</td><td>38.00</td><td>38.00</td><td>100</td></tr>
<tr><td>Dry Sieve</td><td colspan="2">3.50</td><td>30.50</td><td>66.00</td><td>100</td></tr>
<tr><td rowspan="2">Sudanese</td><td>Wet Sieve + Sed*</td><td>12.50</td><td>52.50</td><td>29.50</td><td>5.50</td><td>100</td></tr>
<tr><td>Dry Sieve</td><td colspan="2">7.00</td><td>83.00</td><td>10.00</td><td>100</td></tr>
</table>

**Sed: Sedimentation*

From Table 3-8 above, the percentage of clay on both soils after conducting the wet sieve test and the sedimentation is above the lowest limit suitable for adobe brick making which is 5% (Houben and Guillaud, 1994). This means both soils are suitable for adobe bricks making based on the clay percentage. The results of the wet sieve along with the sedimentation are in agreement with the results of the plasticity of both soils in section 3.1.3.4. The total percentage of the finer particles (the clay and the silt) which are responsible of the cohesiveness and the plasticity of the soil for the Sudanese soil (65%) is higher than the percentage for the British soil (24%). This higher percentage of silt and clay in the Sudanese soil explains the higher results of the liquid and plastic limits and the plasticity index of this soil compared with the British soil, (Table 3-3). However, according to (Bengtsson and Whitaker 1986) in (Danso, 2015), the percentage of clay and silt together for adobe brick is between 20 and 50%. The clay and silt percentage of the British soil (24%) is inside the suitable percentage, however, the Sudanese soil clay and silt percentage (65%) is higher than the maximum limit. On the other hand, the percentage of the sand and gravel together for adobe brick in (Bengtsson and Whitaker 1986) in (Danso, 2015) is between 50 and 80%, from the wet sieve the percentage of the sand and gravel of the British soil is 76% and it is within the limits, but the Sudanese sand and gravel percentage from the wet sieve is below the minimum percentage and it is only 35%. As a result, the Sudanese soil lacks the coarse particles and has higher finer particles. This high percentage of fine particles will result in less workable mixture which will be so sticky when water is added to prepare the adobe brick. As a result, the Sudanese soil will need some modification before it is ready to be used for adobe bricks making. The suggestion is to modify the soil by introducing some coarse particles such as natural sand roughly up to 40% by weight. This 40% of sand will then result in a soil that is suitable for adobe bricks making (the soil will have 39% clay and silt, and 61% sand and gravel).

#### 3.1.3.6 Determination of the soils' pH

The pH test was conducted by the author at the Department of Geography and Environmental Science at the University of Reading. The test was conducted in accordance with the analysis of agricultural materials - Ministry of Agriculture, Fisheries and Food (Great Britain, 1981). The apparatus used were: 50 ml centrifuge tubes, automatic dispenser set at 25 ml, end over end shaker working at 20 - 30 rpm and a pH meter. Also, some reagents were required such as: pH buffers 4.00 and 7.00 for each buffer one tablet was placed in a 150 ml beaker and dissolve in approximately 50 ml of ultra-pure water. Once dissolved, it was transferred to a 100 ml volumetric flask and more ultra-pure water was added to make up to the mark. Then 10 g of air dried soil was sieved using a 2 mm sieve and then transferred to a 50 ml centrifuge tube. After that, 25 ml of ultra- pure water was added to the soil in the 50 ml centrifuge tube. Then the tubes were caped and placed in the shaker for 15 minutes. The shaker was placed in a controlled temperature room (20 °C). After the 15 minutes of shaking was finished, the pH meter was calibrated before used to determine the pH of the soils. The calibration of the pH meter was done by using the pH 4.00 and 7.00 buffers. After the calibration was done, the pH electrode was washed using ultra-pure water and dried with soft tissue and then placed in the soil suspension, the pH was recorded when the number on the screen of the pH meter was settled. The electrode was rinsed with ultra-pure water and dried with soft tissue in-between each sample reading. Also, the calibration of the pH meter was done frequently between the samples. The temperature of the soil was taken along the pH readings.

The pH test results and the temperature for the British and the Sudanese soils are in Table 3-9 below. It is clear from the pH results that the Sudanese soil is more alkaline than the British soil.

**Table 3-9:** The pH test results and the temperature for the British and the Sudanese soils

| Soil type | pH | Temperature (°C) |
|---|---|---|
| **British** | **7.784** | **23.8** |
| **Sudanese** | **8.497** | **24.2** |

### 3.1.3.7 X-ray Diffraction

The X-ray diffraction test (XRD) was conducted by the Natural History Museum in London.

#### *3.1.3.7.1 Methods*

To quantify clay-bearing samples it is necessary to carry out two types of XRD analyses, a clay mineral analysis and a whole rock analysis. The whole rock analysis provides information about which minerals are present in the sample. However, identification of clay minerals in the whole rock analysis is rather limited. Therefore, a clay mineral analysis is usually required for unambiguous identification of the clay minerals. Both types of XRD analyses were carried out for the soil characterization of this study.

#### *3.1.3.7.2 Clay mineral analysis*

The two samples were suspended in distilled water and the clay size fraction (<2 μm) was mechanically separated using a centrifuge. Oriented clay aggregate mounts were prepared on glass slides for the XRD measurements. More details on identification of clays using clay aggregate mounts can be found in (Moore and Reynolds, 1997). To identify the clay mineral species in the samples, the oriented mounts were analysed using the XRD after four preparation steps: (1) air dried (2) after glycolation with ethylene glycol (3) after heat treatment at 400 °C and (4) after heat treatment at 550 °C. The XRD measurements on oriented clay aggregate mounts were carried out using an X'Pert Pro MPD from Panalytical. The XRD was set up in Bragg-Brentano geometry using a cobalt X-ray tube, sample spinner, iron filter and X'celerator detector. Tube operation conditions were 40 kV and 40 mA. The divergence slit was set to 0.25°, and the measurements were carried out between 3 and 40° 2Theta, at a step size of 0.017° and a time per step of 100 s.

#### 3.1.3.7.3 Whole rock analysis

The samples were wet-milled using a McCrone Micronizer Mill (Retsch). After milling the fine powder was placed in a circular flat-plate sample holder. The XRD measurements of the whole rock samples were carried out with the same XRD instrument as described in the previous section. Measurements were carried out using the same settings except the measurement range was between 3 and 120° 2Theta. The measured XRD patterns were evaluated for phase identification with the Highscore Plus software (Panalytical) in combination with the PDF-4 database from International Centre for Diffraction Data.

#### 3.1.3.7.4 Mineral quantification

The mineral proportions were calculated with the Rietveld refinement method using the BGMN software (Bergmann et al., 1998). This method calculates an XRD pattern from crystal structure data of the assigned mineral phases. Crystal structure data of all minerals were taken from the BGMN database. Differences between the calculated and measured XRD pattern were minimized in a least-square minimization calculation by adjusting structural parameters and the scale factor. More details about the Rietveld method can be found in (Young, 1995).

#### 3.1.3.7.5 Results

The assignments of minerals to peak in the XRD patterns are shown in Figure 3-25 and Figure 3-26 for the whole rock analysis and Figure 3-27 and Figure 3-28 for the clay analysis. Table 3-10, Figure 3-29 and Figure 3-30 summarize the results of the mineral quantification. The major phase in both soils is quartz. Other non-clay minerals have proportions below 10 wt%.

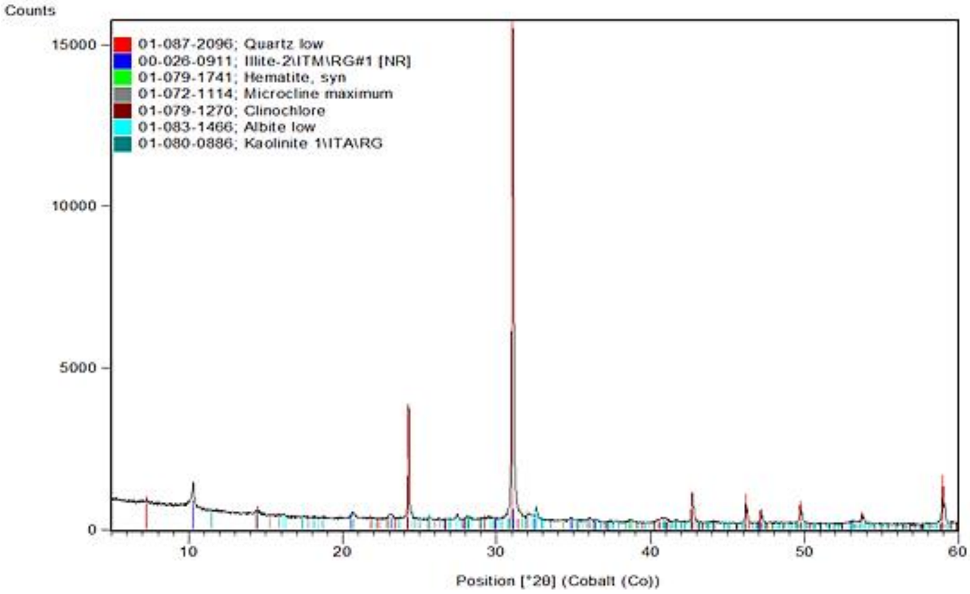



**Figure 3-25:** XRD pattern and mineral identification (whole rock analysis) of Devon soil, United Kingdom

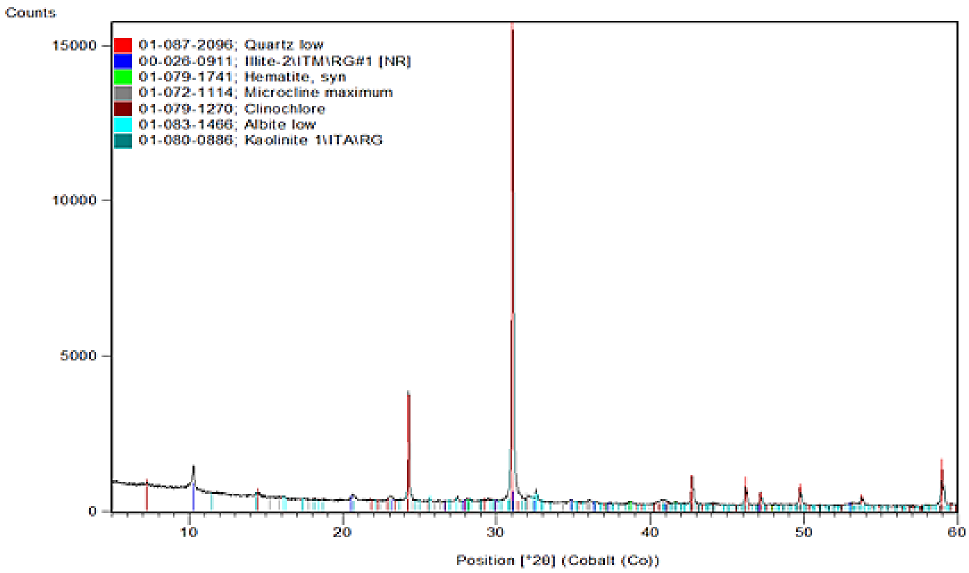



**Figure 3-26 :** XRD pattern and mineral identification (whole rock analysis) of Mayoo soil, Khartoum, Sudan

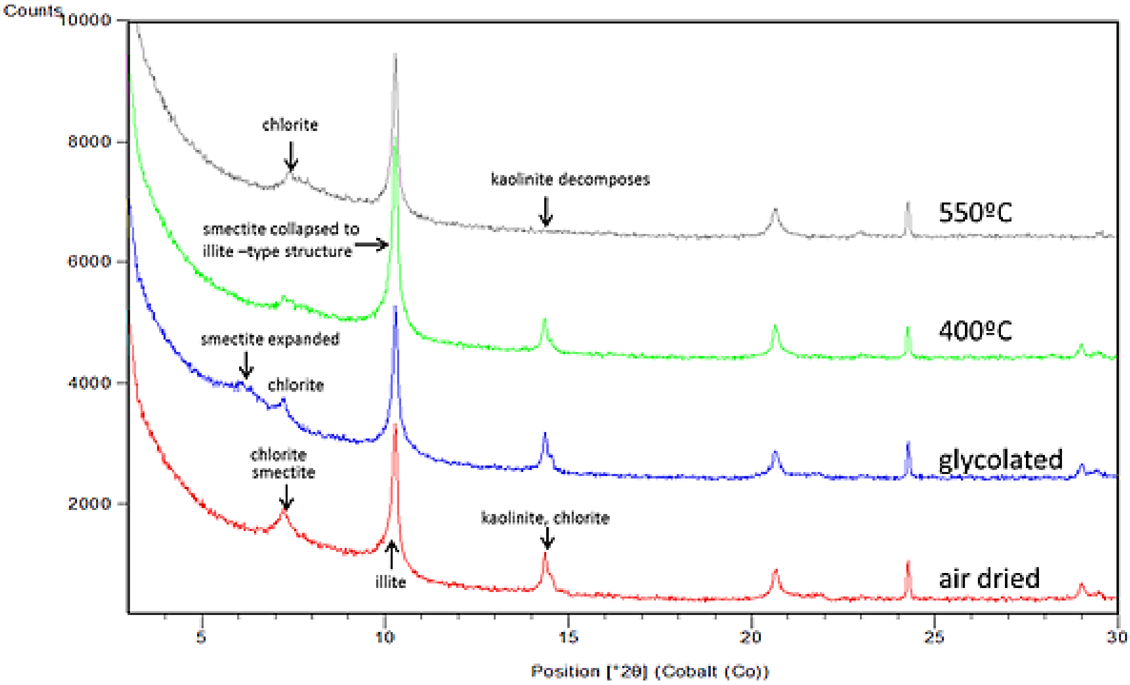



**Figure 3-27:** XRD pattern of clay size fraction of soil from Devon, United Kingdom after various treatments. Indicative changes to clay minerals are shown

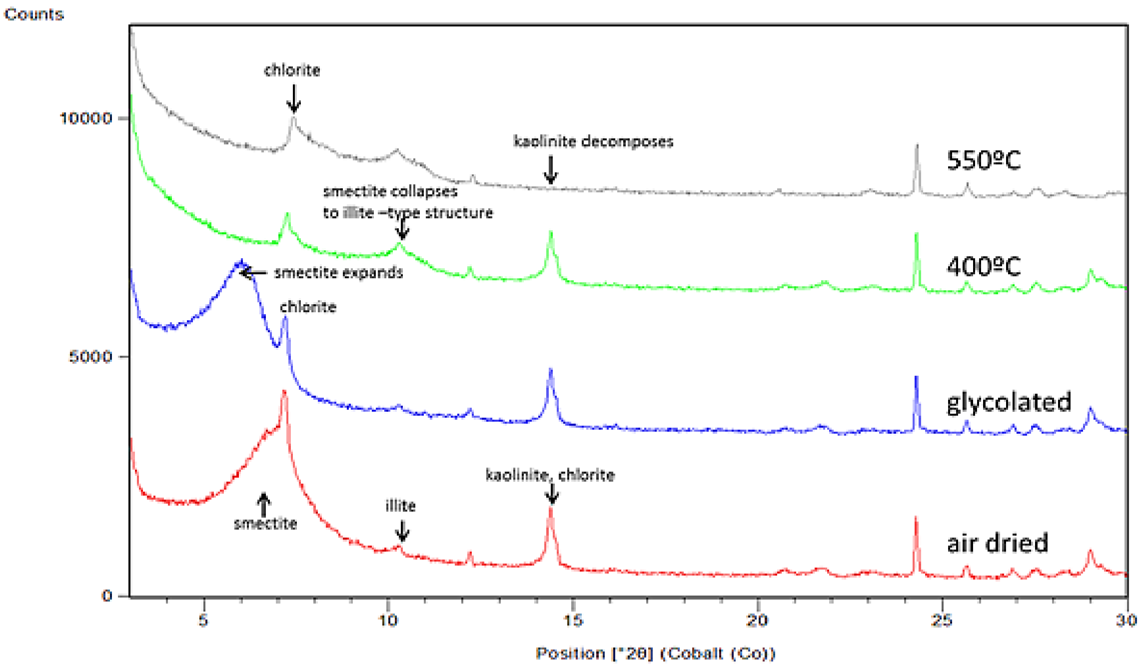



**Figure 3-28:** XRD pattern of clay size fraction of soil from Mayoo, Khartoum, Sudan after various treatments. Indicative changes to clay minerals are shown

**Table 3-10:** Mineral quantification of the soils using the Rietveld method (in weight%)

| | Devon soil | | Mayoo, Khartoum soil | |
|---|---|---|---|---|
| | Phase proportion | estimated error | Phase proportion | estimated error |
| ***Non-clay minerals*** | | | | |
| Quartz | 59.8 | 3.0 | 48.1 | 2.4 |
| Na-feldspar (albite) | 4.4 | 0.9 | 9.5 | 1.9 |
| K-feldspar (microcline) | 6.4 | 1.3 | 4.5 | 0.9 |
| Calcite | - | - | 7.8 | 1.6 |
| Hornblende | - | - | 1.9 | 0.4 |
| Hematite | 1.5 | 0.7 | - | - |
| ***Clay minerals*** | | | | |
| Smectite | 8.9 | 2.7 | 17.8 | 5.4 |
| Kaolinite | 0.9 | 0.5 | 4.0 | 2.0 |
| Chlorite (clinochlore) | 3.1 | 1.5 | 3.7 | 1.8 |
| Illite/mica* | 15.0 | 3.0 | 2.7 | 0.5 |

Chemical formulas: Quartz $SiO_2$, Na-feldspar $NaAlSi_3O_8$, K-feldspar $KAlSi_3O_8$, calcite $CaCO_3$, hornblende $Ca_2Mg_4(Fe,Al)(Si,Al)_8O_{22}(OH)_2$, hematite $Fe_2O_3$, smectite $(Na,Ca)_{0.3}(Al,Fe,Mg)_2(Si,Al)_4O_{10}(OH)_2.nH_2O$, kaolinite $Al_2Si_2O_5(OH)_4$, chlorite $(Mg,Fe)_5Al(Si_3Al)O_{10}(OH)_8$, illite $(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}(OH)_2(H_2O)$

* illite is structurally very similar to mica, illite and mica cannot be distinguished with powder XRD methods

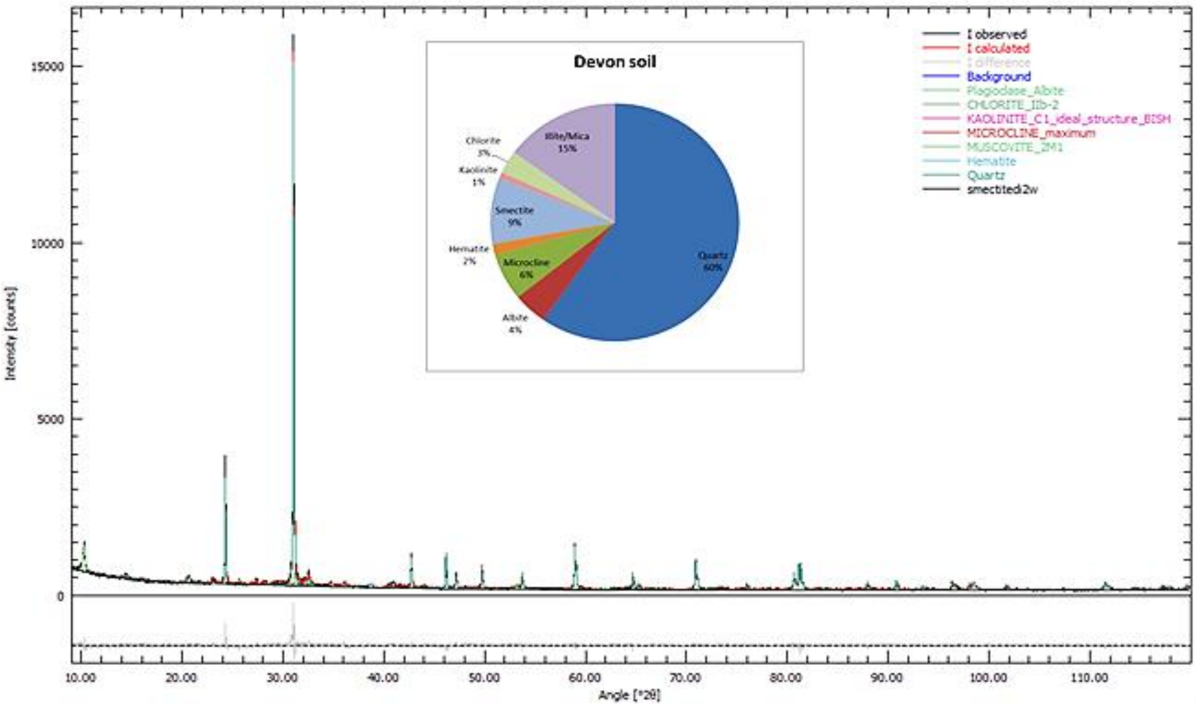



**Figure 3-29:** Phase quantification of soil from Devon, United Kingdom. Measured and calculated patterns are in very good agreement ($R_{wp}$=7.63%, $R_{exp}$=5.98%, $X^2$=1.28)

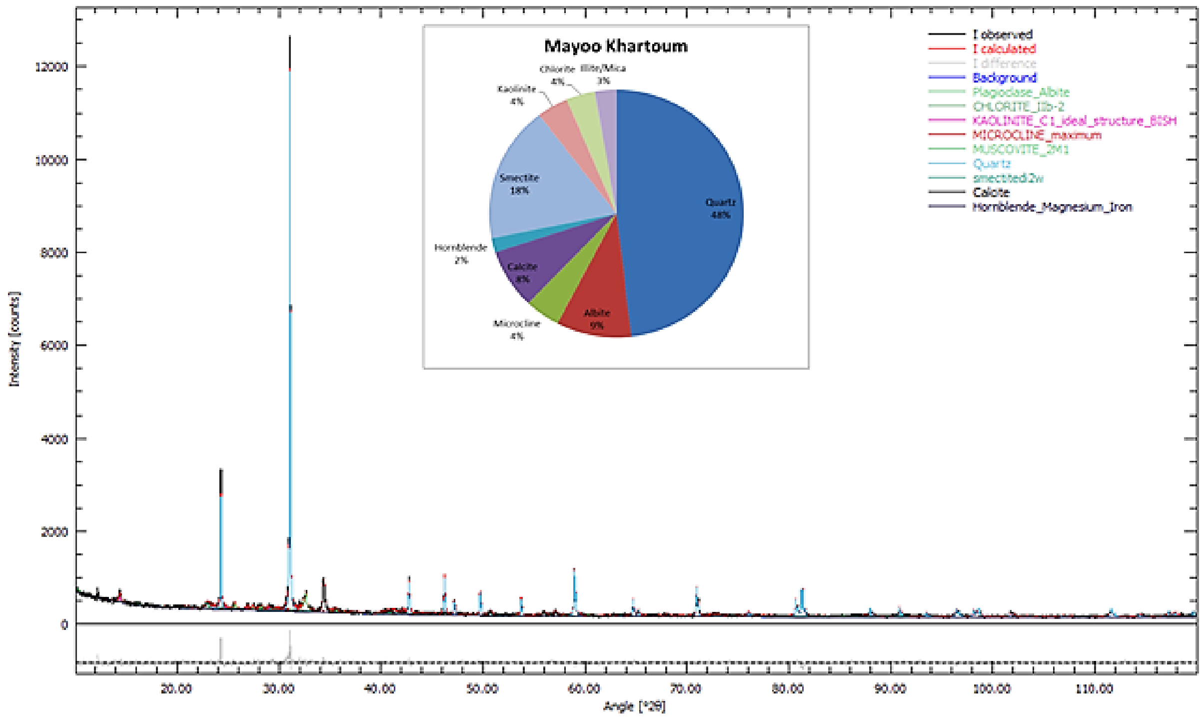


**Figure 3-30:** Phase quantification of soil from Mayoo, Khartoum, Sudan. Measured and calculated patterns show a very good agreement ($R_{wp}$=7.42%, $R_{exp}$=6.17%, $X^2$=1.20)

### *3.1.3.7.6 Summary of the results*

The clay minerals in both soils are smectite, illite, kaolinite and chlorite. The major clay mineral of the Mayoo Khartoum soil is smectite (18 wt%). The crystal structure of smectite can incorporate variable amounts of water. The smectite structure expands with water addition and has some plastic properties. The Devon soil has much less smectite (9 wt%) but higher amounts of the less expandable illite (15 wt%). The red-brown colour of the Devon soil is caused by small amounts of hematite. A comparison of the proportions of the clay minerals in both soils is shown in Figure 3-31 and Figure 3-32 below.

From Figure 3-31 and Figure 3-32, it is clear that the two soils are different in their clay mineralogy. The Sudanese soil has double the quantity of the smectite clay mineral when it is compared with the British soil. In addition, the Sudanese soil has lower quantities of the less expandable clay minerals (illite, kaolinite and chlorite). In contrast, the British soil has high percentage of the less expandable clay minerals. The difference in the clay mineralogy between these two soils will has an impact on the adobe bricks made using these two soils and also on how these soils will respond to the stabilisers. Furthermore, the difference in the clay mineralogy between the two soils will also has its implication on the strength and the durability of the adobe bricks made using these two soils.

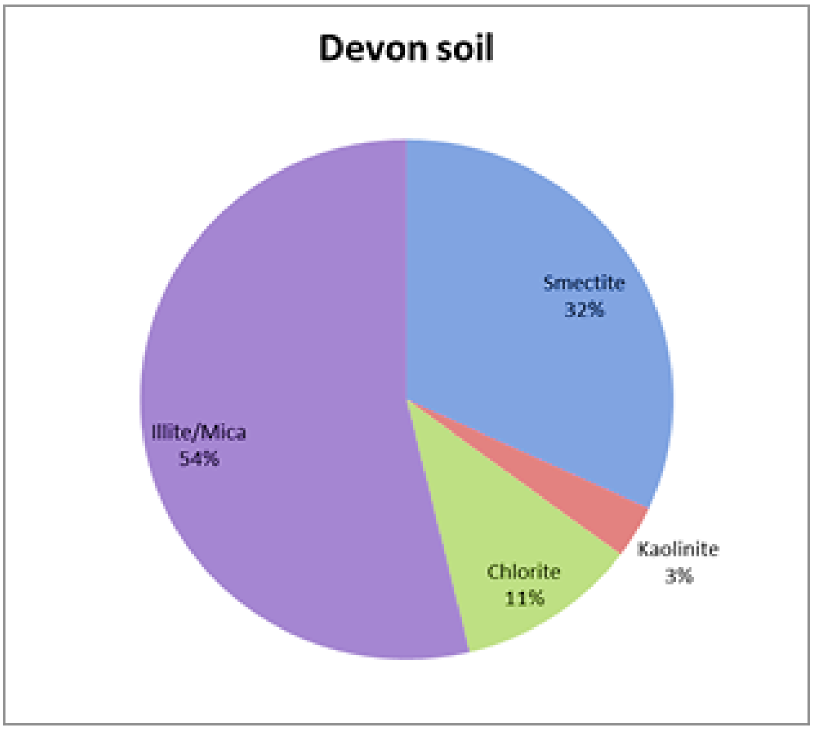



**Figure 3-31**: Proportions of the clay minerals in the soil from Devon, United Kingdom

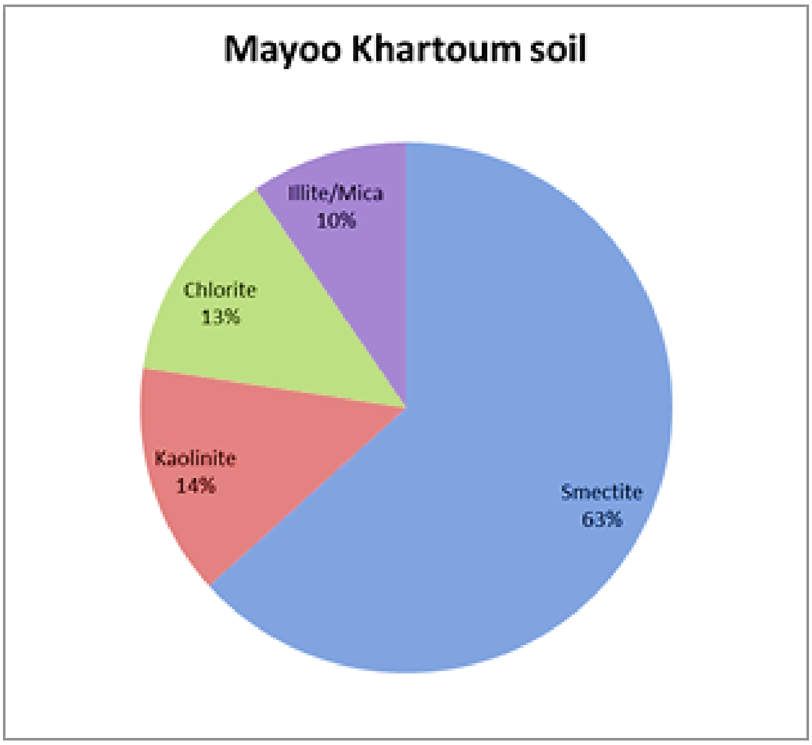



**Figure 3-32:** Proportions of the clay minerals in the soil from Mayoo, Khartoum, Sudan

## 3.2 Stabilisers' (glycoproteins)

The aim of this section is to address the adsorption mechanisms of glycoproteins by clay minerals, the selection criteria for the stabilisers used in this study and their general characteristics as glycoproteins.

### *3.2.1 Adsorption mechanisms of glycoproteins by clay minerals*

Clay minerals have the ability to adsorb organic polymers such as amino acids, proteins and glycoproteins in natural environment (Lambert, 2008, Yu et al., 2013). The adsorption and binding of these organic polymers have different applications such as enzyme immobilization, protein fractionation, adsorption of protein in wine and poultry industry, genetic information storage, bio-sensing, bio-nanocomposites, bio-functional materials, soil chemistry, drug delivery and earth's biochemical evolution and origin of life (Larsericsdotter et al., 2005, Alkan et al., 2006, Yu et al., 2013, Lepoitevin et al., 2014, Della Porta et al., 2016). In general, the adsorption of these organic polymers is a complex process governed by different factors such as cation exchange, electrostatic interactions, hydrophobic affinity, hydrogen bonding and van der Waals forces (Yu et al., 2013, Della Porta et al., 2016). Furthermore, there are two main factors affecting the adsorption process of these organic polymers by the clay minerals. The first factor is the type of the clay minerals available for the adsorption of the organic polymers (Yu et al., 2013). Clay properties such as surface area, cation exchange capacity, charge density and degree of swelling are affected the amount of the organic polymers adsorbed (Yu et al., 2013). The second important factor is the properties of the organic polymers adsorbed. Properties such as the type, structure and molecular size of the organic polymer affect the selection of the adsorption sites on the clay minerals (Yu et al., 2013).

Along with the above two main factors affecting the adsorption of the organic polymers, e.g. glycoprotein, there are many other external factors affecting the process. The pH of the solution (the medium) where the clay minerals and the glycoprotein are in, is the most important external factor in the adsorption of the glycoproteins by the clay minerals because it affects the surface charge of the clay minerals and the degree of the ionization of the protein molecules (Trans and James 2012 in (Yu et al., 2013)). Depending on the pH of the solution, the proteins could be negatively, neutral or positively charged. At a pH of the solution below the isoelectric point (pI) of the protein, the net molecular charge of the protein is positive. The molecular charge of the protein is zero (neutral) when the pH of the solution is equal to the pI of the protein. This means that the protein will encounter the minimal repulsive forces when the solution pH is equal to the pI of the protein. However, the molecular charge of the protein is negative when the pH of the solution is above the pI of the protein (Yu et al., 2013). In addition, the pH of the solution also affects the surface charges of the clay minerals. For instance, when the pH of the solution is below that of the pI of the protein, the surface charge of the clay minerals is positive. The surface charge is zero when the pH of the solution equals to the pI. When the pH of the solution is above the pI, the surface charge of the clay is negative. This means, when the pH of the solution is below the pI, both the glycoprotein and the clay minerals have positive charges and the adsorption takes place through cation exchange. These positive charges on both the glycoprotein and the clay decrease with the increase of the pH of the solution until the pI of the protein is reached. The decrease of the positive charges results in minimizing the electrostatic repulsion between the clay surface and the glycoprotein, and hence results in increasing the amount of the glycoprotein adsorbed by the clay. The maximum adsorption of the glycoprotein by the clay surface occurs when the pH of the solution reaches the pI of the protein. On the other hand, when the pH of the solution is above the pI of the protein, both the glycoprotein and the clay surface are negatively charged and thus the electrostatic repulsion between them increases leading to the decrease of the adsorption of the glycoprotein by the clay surface (Yu et al., 2013).

The temperature of the medium is another external factor which affects the amount of the glycoprotein adsorbed by the clay surface. Some of the literature highlighted that there is a positive correlation between the amount of the adsorbed glycoprotein and the increase of the temperature of the medium (Sun et al 2007 and Bajpai and Sachdeva 2002 in (Yu et al., 2013)). This is because the adsorption process of the protein into the clay is a diffusion- controlled process and the increase of the temperature of the medium increases the diffusion of the glycoprotein in the surface of the clay and hence results in increasing the adsorption of the glycoprotein molecules by the clay minerals (Yu et al., 2013).

The contact time between the protein and the clay minerals is an important factor. Most of the literature highlighted that the maximum time needed for clay minerals to reach the adsorption equilibrium of proteins ranges between 20 minutes up to three hours and when the adsorption equilibrium of the protein by clay minerals occurred additional contact time will not affect the adsorption process any more (Yu et al., 2013).

The dielectric constant of the medium where the clay minerals and the glycoprotein are present is one of the external factors that affects the adsorption process. In general, the adsorption of the proteins into the clay minerals increases with the increase of the dielectric constant of the medium. In contrast, the adsorption of the protein decreases with the decrease of the dielectric constant of the medium. The addition of some solvents such as alcohols affect the dielectric constant of the proteins and therefore affect the degree of the adsorption of the glycoproteins by the clay minerals (Yu et al., 2013).

The last external factor that affects the adsorption of the proteins by the clay minerals is the ionic strength and the external electrolyte (Lambert, 2008).For instance, the metal ions in the clay minerals may influence the adsorption process due to the increase of the ionic strength ( Kalra et al. 2003 in (Yu et al., 2013)). This increase of the ionic strength will increase the ionic exchange for the electrostatic adsorption and therefore it will decrease the adsorption. The strength in the ion exchange will not affect the adsorption through the covalent bond (Lambert, 2008). This shows that there are different adsorption mechanisms for the adsorption of the protein into the clay minerals (Yu et al., 2013).

## 3.2.2 The clay minerals and the glycoprotein properties

There are eight important parameters affecting the adsorption of the glycoprotein by the clay minerals. These parameters are as follow, Table 3-11:

**Table 3-11:** Parameters affecting the adsorption of the glycoproteins by the clay minerals

| **Parameters affect the clay minerals to adsorb the glycoproteins** | **Parameters affect the glycoproteins adsorption by the clay minerals** |
|---|---|
| The quantity of the swelling and non-swelling clay minerals in the soil | Classification of the protein and conformational changes upon adsorption |
| The adsorption sites on the clay minerals | Concentration of the protein |
| The specific surface area of the clay minerals | Molecular size of the protein |
| The charges on the clay minerals (pH related) | The charges on the protein (pH related) |

### 3.2.2.1 Parameters affect the clay minerals to adsorb the glycoproteins

Knowing the clay minerals types is important. In general, clay minerals have permanent negative and variable surface charges (Yu et al., 2013). However, each clay mineral has different glycoprotein capacity and adsorption sites which affect the overall adsorption of the glycoprotein. On the other hand, each type of glycoprotein has its unique properties which affect its adsorption mechanisms and quantities. Understanding how these two factors interact is crucial because it will have its effect on the results of the compressive strength and erosion resistance of the adobe bricks later.

From the result of the X-ray diffraction in section 3.1.3.7, the British soil consists of 54% illite/mica, 32% smectite, 11% chlorite and only 3% kaolinite. The smectite is a swelling clay mineral which swells by hydration and shrinks by the dehydration process. The swelling leads this mineral type to expand, Figure 3-33, by increasing the repulsive forces between the interlayers of the clay minerals. In contrast, the interlayers of the non-swelling clay minerals such as kaolinite, chlorite and the illite undergo very negligible expansion when in contact with water. As a result, the spacing between the interlayers of these minerals remains constant (Velde, 1992). From the x-ray diffraction results of the British soil in section 3.1.3.7, the total amount of the swelling clay minerals is 32% compared with the amount of the non-swelling clay minerals collectively of 68%

Furthermore, from the result of the X-ray diffraction, the Sudanese soil consists of 10% illite/mica, 63% smectite, 13% chlorite and only 14% kaolinite. This means that the total amount of the swelling clay minerals is 63% compared with the amount of the non-swelling clay minerals collectively of 37%.

In addition, the clay minerals differ in their adsorption sites for proteins. For instance, the adsorption sites for both kaolinite and illite are only on the external surface of the mineral because they are classified as non-swelling clay minerals and thus the protein cannot access the interlayers of the minerals. On the other hand, the adsorption of the protein occurs on both the interlayers and the external surfaces of the swelling clay minerals such as smectite (Yu et al., 2013). Generally, the montmorillonite (the smectite

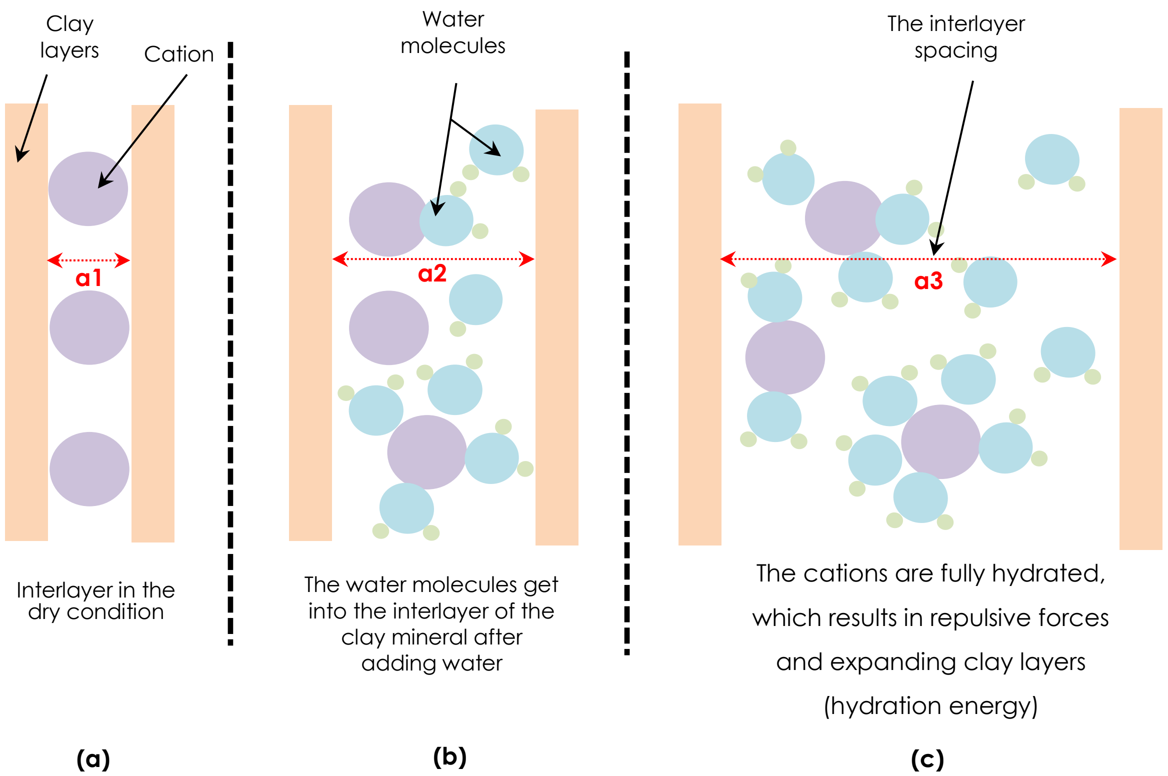



**Figure 3-33:** Schematic illustration of the clay-water interaction in swelling clay minerals such as Smectite (montmorillonite). (a) is the dry condition of the clay mineral with the interlayers, the interlayer spacing **a1** is the smallest when it is in this dry state. (b) the clay mineral with the interlayers after adding the water, the water molecules get into the clay interlayer increasing the interlayer spacing from **a1** to **a2**. (c) the clay mineral in the fully hydrated state, the adsorption of the water molecules increases the repulsive forces between the clay interlayers and as a result increasing the interlayer spacing to its maximum of **a3**.

swelling clay mineral) exhibits higher adsorption capacity than kaolinite and illite (non-swelling clay minerals) (Yu et al., 2013).

The particle size of the clay minerals is also an important factor, because it affects the surface area of the mineral. The smaller the particle size of the clay, the larger the surface area and corresponding surface forces (Al-Khafaji and Andersland, 1992). The specific surface is the surface area per unit mass of soil (Al-Khafaji and Andersland, 1992), and as it has been mentioned before, the specific surface area affects the amount of glycoprotein adsorbed by the clay minerals (Yu et al., 2013). For example, montmorillonite has a high specific surface (800 $m^2/g$) compared with kaolinite which has specific surface between 10 – 20 $m^2/g$ (Al-Khafaji and Andersland, 1992).

The charge on the clay mineral is important since it affects the adsorption of the protein. As has been mentioned before clay minerals have permanent negative and variable surface charge (Yu et al., 2013). In fact, kaolinite generally has neutral charge on the surface (Rolfe et al., 1960, Schulze, 2005) and positive and negative charges on the edges (Rolfe et al., 1960). As a result, the edge surfaces in kaolinite are considered as the source of charges in the mineral. In contrast, montmorillonite have imbalance charges along its surface and edges (Rolfe et al., 1960). However, despite the known charges of the kaolinite and montmorillonite, their charges are pH dependent and will change according to the pH of the medium (Yu et al., 2013).

#### 3.2.2.2 Parameters affect the glycoproteins adsorption by the clay minerals

There are two types of proteins, hard proteins and soft proteins. Hard proteins are the proteins with high internal stability and on solid surfaces they are adsorbed without changing their structural conformation (Nakanishi et al., 2001, Lepoitevin et al., 2014). The amount of the adsorbed hard protein on hydrophilic surfaces is usually small unless there is electrostatic attraction (Nakanishi et al., 2001). Soft proteins are type of proteins with low internal stability. These type of proteins change their conformation and structure to adapt to the surface upon adsorption (Nakanishi et al., 2001, Lepoitevin et al., 2014). These soft proteins have the ability to be adsorbed even on electrostatically repelling surfaces (Nakanishi et al., 2001).

The adsorption of the soft protein is governed among other factors by the protein concentration in the medium. The higher the concentration of the protein, the greater the protein adsorbed and this means the adsorption of the protein has a saturation curve. Lower concentration of protein in the medium does not cause significant structural changes on the protein upon adsorption. However, increasing the concentration of the protein in the medium affects the conformation of the protein by two different steps. The first step is a fast adsorption of the protein in contact with the surface without the protein changing its conformation. The second step is slower and the total amount of the adsorbed protein by the surface increases as a result of the protein changing its conformation and structure to adapt to the surface (Nakanishi et al., 2001). Due to these conformational changes on the protein, the adsorption of the protein is irreversible even at room temperature (Nakanishi et al., 2001). On the other hand, even if the protein does not go through any structural changes during the adsorption, the adsorption could be still irreversible. In addition, in the case of adsorption of higher concentrations of protein, the protein favours surface crystallization and thus the protein crystallized on the surface may yield a more closely packed arrangement than the randomly deposited one occurring at a low bulk concentration (Nakanishi et al., 2001).

Another important factor affecting the amount of the adsorbed protein by a surface, is the molecular size of the protein. If a protein size is bigger than the average pore diameter of a clay mineral, the adsorption of the protein will be very low because its size will affect its access to the interlayer of the clay minerals restricting the adsorption to be more external surface and edges based (Yu et al., 2013).

### 3.2.3 Selection criteria of the stabilisers

Four different glycoproteins have been chosen as stabilisers. Four main criteria were behind the selection of these chemicals, Figure 3-34.

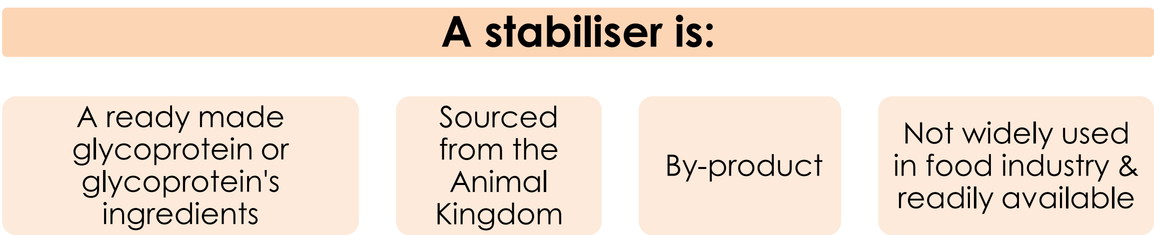



**Figure 3-34:** selection criteria for the stabilisers

Following the above selection criteria and to fulfil the aim of this study, the following chemicals were selected for investigation and testing as possible binders (stabilisers) for adobe bricks, Table 3-12.

**Table 3-12:** Detailed selection criteria of the stabilisers

| No | Chemical | Selection criteria | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Type | Source of origin | | | | | Habitat | Availability | Cost per 0.1% purified glycoprotein which is 3 g (£)* |
| | | | Source | Order | Class | Phylum | Kingdom | | | |
| **1** | Termite glycoprotein (Termite's saliva ingredients) | 16 different chemicals (monosaccharide of the hemicelluloses, amino sugar, amino acids & sialic acid), believe to be the ingredients of the termite's glycoprotein | Termite | Isoptera | Insecta (Insect) | Arthropod (invertebrate animal) | Animalia (Animal) | Terrestrial or arboreal (land or tree) habitat | The chemicals are readily available in the market | **14.31** |
| **2** | Mucin | Glycoprotein Type I[1]: By-product of meat industry | Porcine | Artiodac-tyla | Mammalia (Mammal) | Chordata (vertebrate) | Animalia (Animal) | Terrestrial habitat (land) | Readily available in the market | **2.27** |
| **3** | Serum albumin | Glycoprotein Type I[1]: By-product of meat industry | Bovine | Artiodac-tyla | Mammalia (Mammal) | Chordata (vertebrate) | Animalia (Animal) | Terrestrial habitat (land) | Readily available in the market | **3.37** |
| **4** | Gelatine | Glycoprotein Type III[2]: By-product of fish industry | Fish | Cyprinif-ormes | Actinopterygii | Chordata (vertebrate) | Animalia (Animal) | Aquatic habitat (water) | Readily available in the market | **0.59** |

*[1]Typical glycoproteins, [2] Collagens glycoproteins (Shylaja and Seshadri, 1989), *The cost calculations based on Sigma Aldrich costs for 2017.*

The selection of these stabilisers was to test a variety of biological gels available in nature that could be sourced and readily available from the animal kingdom. All the stabilisers apart from the termite's glycoprotein are by-products of either the meat or the fish industries and their utilization is limited in the food processes. The majority of the waste in the meat industry is produced during the slaughtering process. Slaughter house waste consists of the portion of a slaughtered animal that cannot be sold as meat or used in meat-products. The waste of the meat industry in general consists of skin, bones, tendons, the contents of the gastro-intestinal tract, blood and internal organs (Jayathilakan et al., 2012). Although, there are many cheap meat by-products, there are many health concerns regarding their consumption for human diet. As a result, they have been directed to be used for non-food uses (Jayathilakan et al., 2012). The by-products from beef, pig, and sheep represent 66, 52 and 68% of the live weight respectively (Jayathilakan et al., 2012). Table 3-13 shows the average quantity of the different by-products from the beef, pig and sheep.

**Table 3-13:** By-products as a percentage of market live weight, U.S. Department of Agriculture (2001) in (Jayathilakan et al., 2012)

| Item | Beef | | Pigs | | Sheep | |
|---|---|---|---|---|---|---|
| | % | kg | % | kg | % | kg |
| **Market live weight** | | 600 | | 100 | | 60 |
| **Whole carcass** | 63.0 | 378.0 | 77.5 | 77.5 | 62.5 | 37.5 |
| **Blood** | 18.0 | 4.0 | 3.0 | 3.0 | 2.4 | |
| **Fatty tissue** | 4.0 | 24.0 | 3.0 | 3.0 | 3.0 | 1.8 |
| **Hide or skin** | 6.0 | 36.0 | 6.0 | 6.0 | 15.0 | 9.0 |
| **Organs** | 16.0 | 96.0 | 7.0 | 7.0 | 10.0 | 6.0 |
| **Head** | | | 5.9 | 5.9 | | |
| **Viscera (chest and abdomen)** | 16.0 | 96.0 | 10.0 | 10.0 | 11.0 | 6.6 |
| **Feet** | 2.0 | 12.0 | 2.0 | 2.0 | 2.0 | 1.2 |
| **Tail** | 0.1 | 6.0 | 0.1 | 0.1 | | |
| **Brain** | 0.1 | 6.0 | 0.1 | 0.1 | 2.6 | 0.156 |

Table 3-13 above only includes the by-products sourced from the waste of the meat industry. However, fish and poultry industries both have by-products that are generated from the industries' waste. In general, fish used for direct human consumption in the world excluding China accounts for 74.2% (65.0 million tonnes of the total 87.6 million tonnes) (Vannuccini, 2003). This leaves about 25.8% as waste which cannot be used for direct human consumption (Vannuccini, 2003). In the fish industry, skin and bones were usually thrown away as waste (Gudmundsson and Hafsteinsson, 1997). However, Choi and Regenstein are one of many who have suggested the use of fish skin and bones for gelatine extraction. They have recommended that, this will have an environmental benefit (waste management) as well as economical benefits (Choi and Regenstein, 2000).

In the next part of this section, each one of the stabilisers will be discussed in more details. The discussion will cover the general background about each stabiliser along with its characteristics as glycoprotein.

### 3.2.4 Characteristics of the Termite's glycoprotein ingredients

In general, glycoprotein could be extracted either straight from the animal or synthesized. Nowadays, there are two dominant methods to synthesize glycoprotein. Both methods are trying to achieve the production level of a truly natural glycoprotein which is homogenous in its composition and in its chemical structure. The first method is called biosynthesis and in this method prokaryotes such as bacteria and yeast are cultured and used to produce glycoproteins (Baumeister, 2004). However, despite the fact that this method is cheap and easy, the bacteria lacks the ability to produce glycoproteins that are homogeneously similar to the mammalian one (Baumeister, 2004). In addition, the yeast cells have very limited and restricted glycosylation process (the way they link the carbohydrate (saccharine) to the protein to produce the final glycoprotein) (Baumeister, 2004). As a result, both prokaryotes produce heterogeneous glycoproteins which are different from the glycoproteins available in nature. In addition, other animal's cells such as the Chinese hamster ovary (CHO) cells have been used in biosynthesis of the glycoprotein. CHO has been chosen because it represents a mammalian production system. CHO cells can manage glycosylation and produce more complex glycoprotein (Baumeister, 2004). However, there is still a problem with the glycoproteins produced using the CHO. In nature, the glycosylation process involves hundreds of enzymes and transporters that are different from the cells of one organ to another inside the same animal (Baumeister, 2004). So, the glycosylation process as a result is different from one species to another inside the animal kingdom itself. This why the CHO cells are still limited in their glycoproteins production and they produce little amounts of recombinant glycoproteins. These cells were mainly introduced to produce the therapeutic proteins for humans. On the other hand, to enlarge the scale of the production to create more recombinant glycoproteins is costly and will result in heterogeneous glycoproteins (Macmillan and Bertozzi, 2000, Baumeister, 2004, Nettleship, 2012). Added to the above mentioned biosynthesis methods, insects and plants cells are also used as production lines to produce glycoproteins (Ghaderi et al., 2012).

The other method for engineering the glycoprotein is by chemical synthesis. This could be either a total synthesis or a semi synthesis. However, total synthesis is costly and inefficient for large scale production (Masania, 2010). Chemical synthesis is used and seen as an alternative to the biological synthesis to produce more specifically defined glycoproteins (Bonduelle and Lecommandoux, 2013). This chemical synthesis theoretically is achievable but is still under development from a practical perspective. So far successful attempts were made to produce simple glycoproteins, but the technology still lacks the ability to assemble complex glycoproteins with homogenous chemical and biological structure (Macmillan and Bertozzi, 2000). Generally, understanding the glycoprotein structure and function still remains not fully understood due to the difficulty to obtain homogenous glycoproteins (Bonduelle and Lecommandoux, 2013). Despite the fact that the science has so far succeed in producing complex proteins, to link these proteins to saccharine in order to prepare homogenous glycoprotein similar to the natural one, still remains a challenge (Bonduelle and Lecommandoux, 2013).

However, due to the following points all together, a mixture consists of the basic chemicals (the ingredients) of the termite's glycoprotein were used as one of the four stabilisers used in this study, Table 3-14, Figure 3-35 & Figure 3-36:

- The unpracticality of obtaining a true termite's saliva which contains the glycoprotein that is considered as the bio-adhesive/ stabiliser the termite uses to glue the soil particles together to construct its mounds.
- Due to the challenging procedure to engineer a true homogenous glycoprotein which has been addressed above.

The chemicals used to prepare the termite's saliva ingredients glycoprotein were extracted from (Gillman et al., 1972) study results.

**Table 3-14:** Termite's Glycoprotein ingredients (Gillman et al., 1972)

| No | Chemical | Type | Total in 1.28 g glycoprotein in 1Kg of mound soil (g) | Total % in the Glycoprotein |
|---|---|---|---|---|
| 1 | Glucosamine | Amino Sugar | 0.067 | 5.2% |
| 2 | Xylose | Monosaccharide of the hemicelluloses group | 0.389 | 42.19% |
| 3 | Galactose | Monosaccharide of the hemicelluloses group | 0.072 | |
| 4 | Glucose | Monosaccharide of the hemicelluloses group | 0.025 | |
| 5 | Mannose | Monosaccharide of the hemicelluloses group | 0.019 | |
| 6 | Rhamnose | Monosaccharide of the hemicelluloses group | 0.019 | |
| 7 | Arabinose | Monosaccharide of the hemicelluloses group | 0.017 | |
| 8 | Aspartic Acid | Amino Acid | 0.089 | 52.34% |
| 9 | Serine | Amino Acid | 0.007 | |
| 10 | Glutamic Acid | Amino Acid | 0.069 | |
| 11 | Glycine | Amino Acid | 0.125 | |
| 12 | Alanine | Amino Acid | 0.024 | |
| 13 | Valine | Amino Acid | 0.117 | |
| 14 | Isoleucine | Amino Acid | 0.044 | |
| 15 | Leucine | Amino Acid | 0.192 | |
| 16 | Sialic Acid | A substance present in saliva which consists of acyl derivatives of neuraminic acid | 0.0030 | 0.27% |

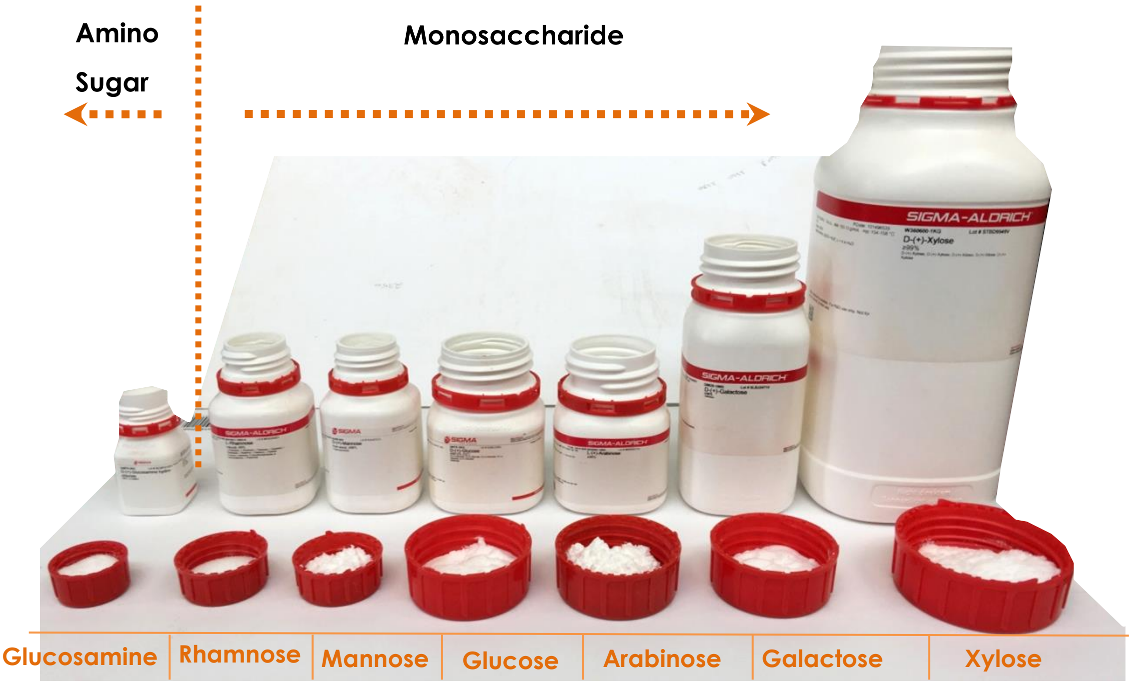



**Figure 3-35:** Ingredients of the termite's glycoprotein (Amino sugar & Monosaccharides)


**Figure 3-36:** Ingredients of the termite's glycoprotein (Amino Acids)

As has been mentioned before regarding the challenges in obtaining a homogenous glycoprotein, the above termite glycoprotein's chemicals will be mixed using distilled water in the laboratory environment only without following any complex steps. Conducting biosynthesis and/ or chemical synthesis to prepare the termite's glycoprotein was beyond the scope of this study. However, a reaction between the glycoprotein's chemicals might occur after mixing them using the distilled water. Based on the simple steps that will be used to prepare this stabiliser, the chemical reaction between all the chemicals definitely will not lead to the production of a glycoprotein, but the presence of the monosaccharide as part of the chemicals mixture will have its effect on the soil.

Monosaccharide is the building blocks of the polysaccharides. In general, polysaccharides are one of the biological polymers that are used to form gels in nature and so it has adhesive properties (Smith, 2002). It also known that the availability of the polysaccharides in the soil lead to the creation of a bond between the soil aggregates, so it affects the structural stability of the soil in general and the erodibility of the soil in particular (Ahmed and Hussain, 2008). This aggregation is attributed to the cementing effect due to the interaction between the clay minerals and the polysaccharides (Tan, 2011). By interacting with soil clays, the polysaccharide is thought to change the properties of the clay surfaces with respect to adsorption of water (Tan, 2011). In addition, the availability of monosaccharide and/or polysaccharides in mound soil built by some termites have shown that there is a significant relationship between the stability of the aggregate, resistance to erosion and the sugar content of the mound soil (Contour-Ansel et al., 2000). According to all the above-mentioned points, it is thought that the presence of the monosaccharide (42.2%) in the ingredients of the termite's glycoprotein will serve as a natural adhesive that will help to glue soil particles together. As a result, the decision was made to use the termite glycoprotein's chemicals as one of the stabilisers to be tested in this study. All the chemicals for the termite's glycoprotein were purchased from Sigma–Aldrich, United Kingdom.

### 3.2.5 Characteristics of the Mucin

As the termite uses its saliva to cement the soil particles during the mound construction, (Lee and Foster, 1991), the main glycoprotein in termites' saliva is mucin. Therefore, the mucin was chosen to substitute the termite's saliva glycoprotein which is also mucin. Mucin is the main constituent and the key component of mucus (Kočevar-Nared et al., 1997). Mucus is secreted in many systems inside the body, such as the respiratory, digestive and the reproductive system (Taylor et al., 2003, Bansil and Turner, 2006). Mucus has a wide range of functions such as lubrication, hydration, defensive barrier, protective layer and exchangeable media for nutrients and gases (Tabak, 1990, Wu et al., 1994, Kočevar-Nared et al., 1997, Bansil and Turner, 2006, Maleki et al., 2008). Mucus is elastic, viscous and sticky (Tabak, 1990, Kočevar-Nared et al., 1997). Mucus mainly consist of 95% water, glycoprotein mucin, salt, protein and lipids (Bansil and Turner, 2006). However, mucin is the component that is responsible for the elasticity and viscosity properties of the mucus (Bansil and Turner, 2006). In general, mucus secretion is not limited to the vertebrate animals (human, cattle, monkeys and pigs .etc.) but it is also secreted by the invertebrate as well (Smith, 2002, Maleki et al., 2008). As example, insects such as termites secret mucus in their digestive system (Mau and Südekum, 2011). Mucin is a large glycoprotein consisting of 80% to 90% carbohydrates (Smith, 2002, Bansil and Turner, 2006), and the remaining 20% is the core protein which all these carbohydrates are attached to (glycosylation) (Bansil and Turner, 2006).

In this study, mucin was sourced from the porcine stomach (by-product of pig industry). Mucus forms the protective cover for all epithelial surfaces. The major structural component of mucus is gel-forming mucin. There were two available mucin sources to select from, one was from the porcine stomach, and the other one was from bovine submaxillary glands (salivary glands that are located beneath the floor of the cow's mouth). In this study, the mucin from the porcine stomach was selected based on cost grounds. For example, 100 g of porcine mucin costs £77.90, while 1 g of bovine mucin costs £249.50. The mucin from the porcine stomach was purchased from Sigma–Aldrich, United Kingdom, Figure 3-37.

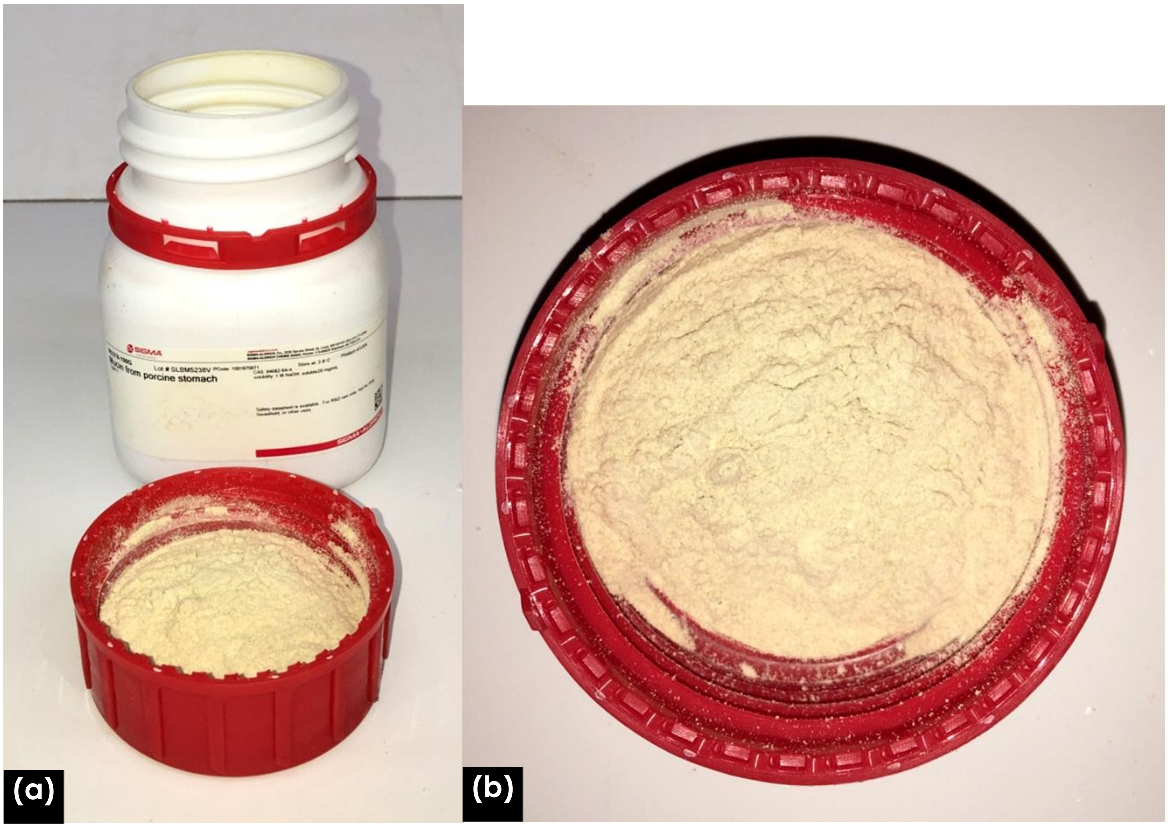



**Figure 3-37:** Porcine Mucin, purchased from Sigma–Aldrich, United Kingdom **(a)** The purchased container **(b)** A closer look at the porcine mucin.
***Description:*** Porcine mucin *was a very fine yellowish powder,* ***Type:*** *Type II,* ***Composition:*** *Bound sialic acid, ~1%,* ***Storage temperature:*** *2-8°C*

### *3.2.6 Characteristics of the Bovine Serum Albumin*

Serum albumin was first noticed by the Greek physician Hippocrates in the year 400 BC as white foam on urine of a patient with chronic renal disease (Peters Jr, 1995). However, the first one to notice the serum albumin in blood was the French physiologist, C. Denis in 1840 when he conducted the first ever recorded dialysis by placing blood serum in a sac of intestine immersed on water (Peters Jr, 1995). Denis noticed that there was a portion of the protein which was soluble in water without salt and he referred to it as albumin (Peters Jr, 1995). Serum albumin is available in the systems of many animals such as human, bovine, pig, sheep, rats, horses, frogs, and salmon (Tai, 2004). In fact, during the Second World War, sourcing a stable substitute for blood plasma was crucial and hence the war was the motive behind producing pure albumin protein (Peters Jr, 1995). The Laboratory of the Harvard Department of Physical Chemistry at the Harvard Medical School in 1940, was the first laboratory to purify and produce the albumin from the bovine plasma using cold ethanol method which is still in use today (Peters Jr, 1995). Bovine plasma was chosen as source for the albumin due to its abundance (Peters Jr, 1995). The Harvard project ceased in 1943 after the death of two volunteers due to serum sickness which resulted from the differences between human and bovine albumin (Peters Jr, 1995). After that the production of pure serum albumin from human plasma was established (Peters Jr, 1995).

Bovine serum albumin (BSA) is one of the by-products of the beef industry. BSA is sourced from the cow's blood. The animal's blood contains valuable proteins which have been discarded as waste and are also responsible of serious environmental pollution. However, disposing the animal blood in a well-organized and environmental manner is a complicated process and also very expensive. This is why extracting the valuable proteins from the blood and utilizing them is important to reduce pollution and also to generate more profit from the blood waste (Ofori and Hsieh, 2011, Ofori and Hsieh, 2012). BSA is one of the major components of the bovine plasma and accounts for 52–60% of the plasma (Naveenraj and Anandan, 2013). BSA affects the functional properties of the cow's plasma proteins (Mandal et al., 1999) in (Enomoto et al., 2008). The plasma is the part of the blood that remains after the removal of the cellular elements (red blood cells, white blood cells, platelets) (Ofori and Hsieh, 2012). The plasma contains different proteins (albumin, globulins, fibrinogen, and more than 100 smaller proteins) (Bah et al., 2013). For example, in the cattle, the blood consists of 67.45% plasma and 32.55% cellular elements (Gorbatov, 1988) in (Bah et al., 2013). BSA is a large globular protein (Enomoto et al., 2008), and the most studied protein over the years (Tai, 2004). The interest of studying this protein over the years was mainly due to its abundance and its high concentration in the blood (50 g of BSA per every litre of blood) (Tai, 2004). BSA plays a vital role in the life of the cows. It is the protein that is responsible of stabilising the physical environment of the blood (maintaining colloidal osmotic pressure in blood), transport metabolites (nutrients, hormones and fatty acids), protective agent (toxic waste handler), and as a factor in lipid metabolism, etc. (Peters Jr, 1995, Naveenraj and Anandan, 2013). Albumin has been used in different fields and applications such as being used as a model protein, in clinical and pharmaceutical practices, as reagent in laboratories, in food chemistry and as a standard solution in chemical analysis (Atmeh et al., 2007). In general, there is considerable concern about using blood proteins in food industry (Ofori and Hsieh, 2012). Some consumers concern is due to religious orders or cultural and ethical belief. Others believe that the animal blood is contaminated and hence toxic (Ofori and Hsieh, 2012). Moreover, using bovine serum albumin in food products has resulted in allergic reaction for some consumers (Ofori and Hsieh, 2011). Due to the above concerns, the utilization of animal blood proteins in the food industry is limited (Ofori and Hsieh, 2012).

In this study, BSA was sourced from the cow's blood and was purchased from Sigma–Aldrich, United Kingdom, Figure 3-38.

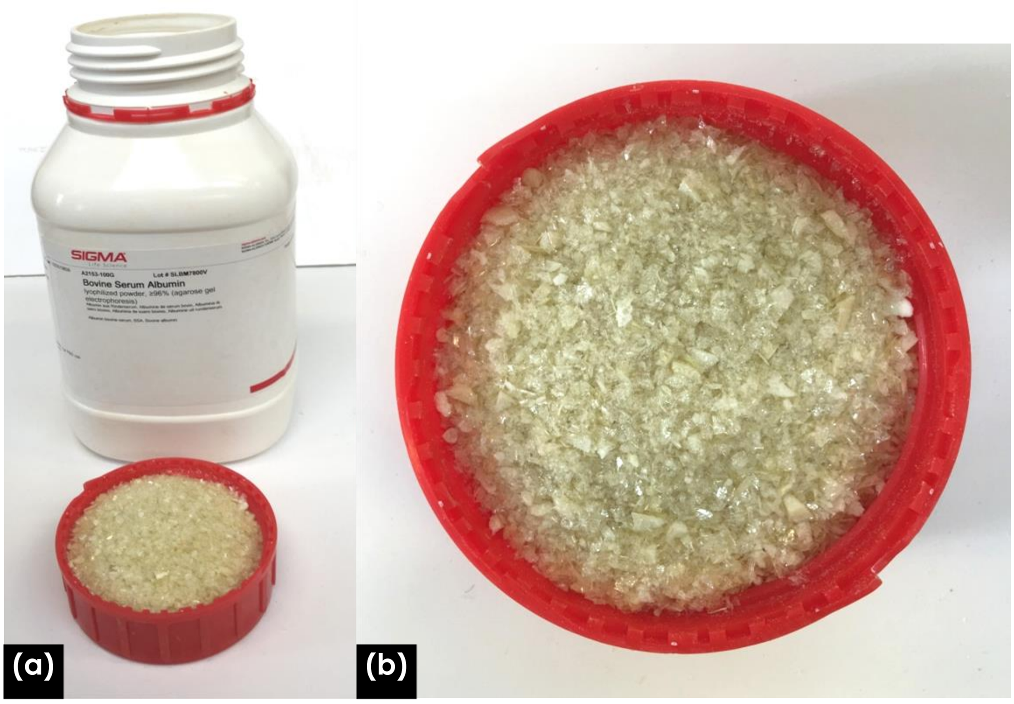



**Figure 3-38:** Bovine Serum Albumin (BSA) purchased from Sigma–Aldrich, United Kingdom **(a)** The purchased container **(b)** A closer look at the BSA.
***Description:*** *BSA was of yellowish colour medium size flakes,* ***Assay:*** *≥ 96% (agarose gel electrophoresis),* ***Form:*** *Lyophilized powder,* ***Storage temperature:*** *2-8°C*

### 3.2.7 Characteristics of the Gelatine from cold water fish skin

In the ancient era, gelatine had been used as a biological adhesive. 8000 years ago the people who had lived in what is today called the Middle East, used glue from animal tissues. Also, 3000 years after the cave people from the Middle East, ancient Egyptians used glue made from animal collagen as adhesive to glue their furniture parts (Gareis and Schrieber, 2007). Similarly, people from the new Stone Age who lived in caves near the Dead Sea knew the strength of the glue made from collagen and they used it for several applications. Discoveries from the Egyptians temples and pyramids has provided proof of the use of the animal glue at that time (Gareis and Schrieber, 2007). The glue was made from the collagen of the hides and bones of the animal. To prepare the glue these bones and hides were boiled and then the glue was extracted. The extracted gelatine when cooled down was also consumed as an edible gelatine which was part of the diet during that time in many regions and also an alternative source of protein when meat became scarce (Gareis and Schrieber, 2007).

In general, all gelatines are derived from the collagen protein which is the most abundant protein in humans and animals' bodies. Collagen is one of six different groups of glycoprotein when glycoproteins are classified based on their functions (Tabasum et al., 2017). Collagen is a unique type of glycoprotein (Shylaja and Seshadri, 1989). In fact, more than 26 different types of collagen are known today. Collagen is mainly available in the skin, bones, and cartilage. Collagen and gelatine share the same chemical constituents consisting of long chains of amino acids connected by peptide bonds, however they have different physical properties (Gareis and Schrieber, 2007). For example, collagen is insoluble in water but gelatine is soluble in water. Gelatine is sourced from mammals and fish. For example, it can be sourced from bovine (cows), porcine (pig), poultry and cold and warm water fish skin and bones. Gelatine consists of 85 to 92% protein and the remaining percentage is minerals salts and moisture that was left after the drying and the extraction of the gelatine (Gareis and Schrieber, 2007). In modern gelatine production, bones, hides, and also skin of some animals are used as the raw material for the gelatine production. The gelatine produced is used to prepare glue which is used in several industries. Collagen is also used to prepare edible gelatine which has high nutritional value and is used in preparing many foods such as desserts, ice-cream, marshmallows and also in pharmaceutical and medical applications, cosmetic industry and in photography (Gareis and Schrieber, 2007).The most important properties of gelatine, making it so useful in several areas is its ability to form thermo reversible gels, Figure 3-39, (Haug and Draget, 2009).

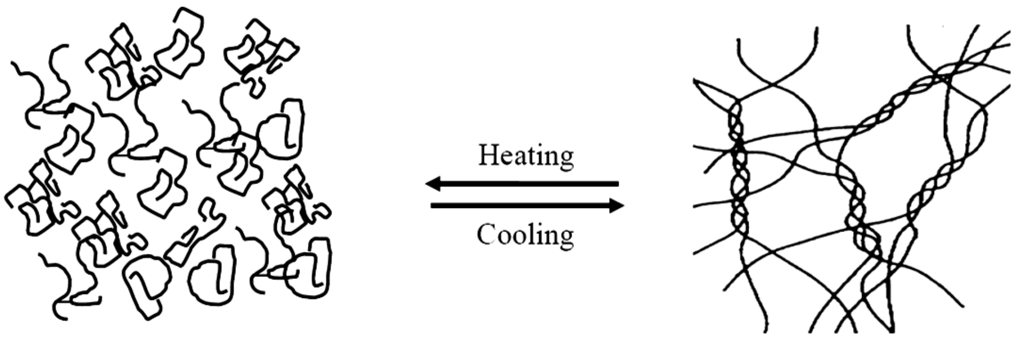



**Figure 3-39:** The thermo reversible gelling process for gelatine (Haug and Draget, 2009)

In the past, different types of animal products have been extracted and used in earth construction. These products were mainly used as stabilisers in rendering walls and were rarely used to stabilise the walls themselves (Houben and Guillaud, 1994). Animal glues prepared from horns, bones, hooves and hides were the main source for the stabilisers used to render earth walls (Houben and Guillaud, 1994). These animal glues are gelatine. So, using gelatine as stabiliser in earth construction is not new. As mentioned before, gelatine could be sourced from different animals, however, most of the gelatine that is produced worldwide comes from cows and pig skin. In Europe, pig skin is the main source for gelatine and superseded the cows gelatine in the 1990s after the outbreak of the BSE (bovine spongiform encephalopathy, (mad cow disease)) (Haug and Draget, 2009). In other parts of the world and due to religious restrictions, cow's gelatine is dominant. After the outbreak of BSE, research started to look for alternative to bovine's gelatine. In the fish industry, skin and bones are usually thrown away as waste. However, (Gudmundsson and Hafsteinsson, 1997) and (Choi and Regenstein, 2000) have suggested that the use of fish skin and bones for gelatine extraction will have environmental benefit (waste management) as well as economical benefits. Fish gelatine has been extracted from two fish families, the cold-water fish such as cod, salmon and Alaska Pollack, and the warm water fish such as tilapia, Nile perch, and catfish. The main purpose was to use the fish gelatine in the food industry. However, recent studies have identified the collagen from fish as potential allergen regardless of the fish species (Hamada et al., 2001), and this has resulted in limited use of it in the food industry.

In this study fish gelatine was selected as a potential stabiliser in the earth construction. Bovine gelatine which was historically used in soil stabilisation in earth construction was not a preferred choice because of the high demand of using it in the food and other industries. Gelatine from cold water fish skin which was the only available fish gelatine in Britain was purchased from Sigma–Aldrich, United Kingdom, Figure 3-40**.**

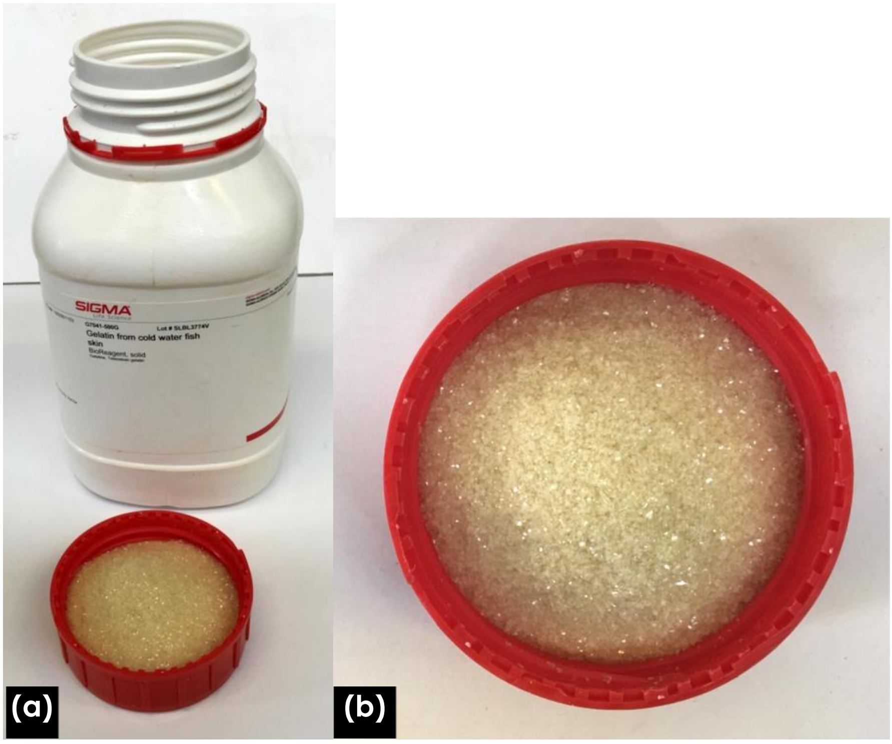



**Figure 3-40:** Gelatine from cold water fish skin purchased from Sigma–Aldrich, United Kingdom **(a)** The purchased container **(b)** A closer look at the fish gelatine. ***Description:*** *Fish gelatine was of light yellow colour fine flakes,* ***Storage temperature:*** *Room temperature.*

### 3.2.8 Summary

This section addressed the selection criteria of the glycoproteins used as potential stabilisers for adobe bricks made using the British and the Sudanese soils. All the glycoproteins (mucin, bovine serum albumin and the gelatine from the cold-water fish skin) apart from one glycoprotein (termite's saliva ingredients) were by-products of either the meat or the fish industries. The adobe bricks made using these glycoproteins were tested for their strength and durability.

## 3.3 Strength and durability tests selection criteria

### 3.3.1 Strength tests: Introduction

Earth bricks and blocks have been used in buildings to construct walls, these walls are either loadbearing or non-loadbearing. In loadbearing, the bricks should withstand their own weight in addition to the dead and the live load lay upon them. For this reason, the walls should be strong enough to tackle such load. In the case of the non-loadbearing walls, the walls should be strong enough to withstand their own weight only (Walker and International, 2002). Different tests are used to determine the mechanical properties of the earth units. For example, compressive strength test, tensile strength test, and flexural test (modulus of rupture, or bending strength test). However, compressive strength test is considered as the most widely used and accepted test to determine the strength and the quality of the wall units (bricks/ blocks) (Morel et al., 2007, Riza et al., 2010, Aubert et al., 2016).

### 3.3.2 Compressive strength test

Generally, when using bricks/ blocks to form walls, arches, vaults and columns, the bricks/ blocks are mostly subjected to compressive stress and low tensile stress which usually could be neglected (Fernandes et al., 2010). Compressive strength test is a method used to assess the ability of a material to withstand compressive loads and it gives an indication of the mechanical properties of the material under investigation. Compressive strength has been widely accepted as an important test to determine the quality of the material under investigation (Morel et al., 2007, Hassan and Bukar, 2009). Easy application of the compressive strength test when it is compared with other tests (resistance to abrasion and flexural test, etc.) and the fact that other properties could be improved if higher compressive strength is achieved, are the factors behind the wide acceptance of compressive strength as a reliable measure to determine the quality of the bricks/blocks (Azeez et al., 2011). However, compressive strength is not considered as a replacement for the durability tests, but could be looked at as a control measure for durability (Heathcote, 2002). Compressive strength of the bricks/ blocks is influenced by many factors. Type of clay minerals, particles distribution of the raw material, mixing and preparation methods used to produce the earth units, compaction pressure applied and the moisture content of the mixture are among the factors affecting the compressive strength (Minke, 2006).

The compressive strength in this study was used to determine the ability of the bricks to resist the applied load in compression. The compressive strength test was performed on all bricks in accordance with Bulletin 5 (Earth wall construction) and the Australian earth building handbook (Middleton, 1987, Walker and International, 2002). Instron 4206 test machine was used to conduct the compressive strength test, Figure 3-41.

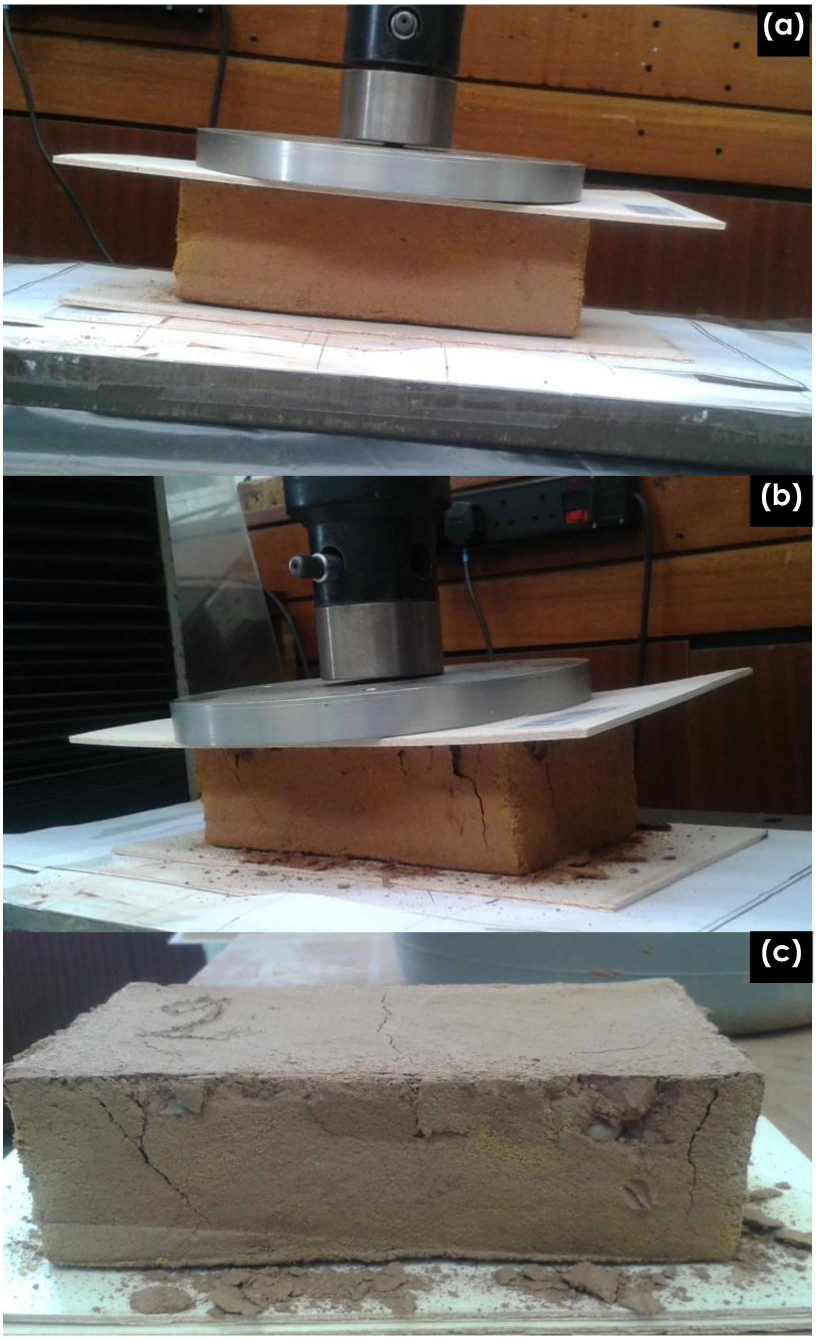



**Figure 3-41:** The adobe brick under the compression load using an Instron 4206 machine, **(a)** the setting of the brick sandwiched between two plywood pieces, **(b)** the adobe brick during the compressive strength test, **(c)** the brick after the end of the compressive strength test showing the mode of failure.

The load was applied continuously on the bricks without shock up to failure at a rate of 2.5 mm/min (Middleton, 1987). Usually the brick's surfaces under testing need to be flat and parallel to ensure the even distribution of the load (Morel et al., 2007).Test was performed until the failure of the brick and then the failure load (which is the maximum load the brick can stand) was recorded. During the compressive strength test conducted in this study, the maximum load used to calculate the compressive strength was determined by the load that resulted in the mode failure shown in Figure 3-41 above. When the brick's edges disintegrated, this was considered as the failure point for the brick and then the machine was stopped and the failure load was recorded. In this mode of failure, the disintegrated edges will result in increasing the load on the remaining specimen, and leading to complete failure The compressive strength then was calculated using the maximum applied loading and the cross-sectional area of the face of the brick under compression (Walker and International, 2002).

In general, the compressive strength is highly affected by the shape and the dimensions of the brick under testing because of the confinement produced during the test due to the friction between the brick surface and the machine steel plates (Aubert et al., 2016). The confinement delays the failure of the brick under testing by limiting the lateral expansion of the brick and thus resulting in increasing the compressive strength. The confinement occurs on the top and the bottom surface of the brick under testing. To reduce the effect of this confinement, the brick under investigation is usually sandwiched between two plywood pieces (4 mm to 6 mm thick) (Walker and International, 2002). This geometry effect on compressive strength is greater in the case of adobe bricks (Morel et al., 2007). Adobe bricks are manually produced and they have greater variations in their geometry and their dimensional stability (Morel et al., 2007). This geometry effect is minimised by applying a geometrical correction factor that is used to standardize the compressive strength results (Morel et al., 2007). As a result of applying this correction factor, the unconfined compressive strength is obtained. This correction factor takes account of the effect of the aspect ratio of the unit under testing. The aspect ratio is defined as the ratio between the thickness of a specimen and the height (height/thickness) (Walker, 1997, Aubert et al., 2016). The correction factors that are used to convert the confined compressive strength to the unconfined compressive strength are the same factors used for fired bricks, and they are called Krefeld's correction factors (Morel et al., 2007, Aubert et al., 2016), Table 3-15.

**Table 3-15:** Aspect ratio correction factors (Middleton, 1987)

| **Aspect ratio (H/W)** | 0.40 | 0.45 | 0.50 | 0.55 | 0.60 | 0.65 | 0.70 | 0.75 | 0.80 | 0.85 | 0.90 | 0.95 | 1 | 3 | ≥ 5 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Krefeld factor (ka)** | 0.50 | 0.52 | 0.53 | 0.55 | 0.57 | 0.58 | 0.60 | 0.62 | 0.63 | 0.65 | 0.67 | 0.68 | 0.70 | 0.85 | 1 |

The aspect correction factors in Table 3-15 above are derived using a linear interpolation. These correction factors were applied for each specimen's confined compressive strength to convert it to the unconfined compressive strength. For each sample tested, six specimens were used and the average unconfined compressive strength was obtained. The samples were arranged based on the stabilisers concentrations tested. Also, the unconfined compressive strength of the Unstabilised adobe bricks was obtained and used for comparison.

Earth bricks as many other brittle materials such as ceramics, concrete and stones, the size, the shape of the specimen and the end conditions will affect the specimen compressive strength (Page and Marshall, 1985). Therefore, the compressive strength of the same sized specimens, is not a true indication of the actual compressive strength of the material (Page and Marshall, 1985). The brittle material fracture occurs as a result of one of the following, (Carter and Paul, 2011):

- Crack formation or crack initiation
- Growth and expansion of cracks

When a crack initiates and expands across a brittle material then it will lead to the break and separation of the material into many pieces. For instance, a brittle material when it is placed under compression, the surface flaws and microcracks closed up and transmit the compressive stress. However, even if the crack expands over the whole specimen, the specimen may still have a very high compressive strength (Carter and Paul, 2011). Usually the failure of the brittle material under compressive stress depends on the length of the largest microcrack in the specimen which differs from specimen to another. The microcrack and surface flaws are originated from the heterogeneity of the material itself along with the production process. There is a high probability that larger cracks and flaws will be available in large specimen compared with small specimen (Chawla and Meyers, 2009). This means that the strength will decrease with the increase of the size of the specimen (Basu et al., 2009). Due to the difference in the strength from specimen to another, the strength of the brittle material cannot be expressed by Gaussian or normal distribution (Chawla and Meyers, 2009). However, the strength of the brittle materials can be explained by the Weibull distribution which is a statistical distribution named after the Swedish engineer Waloddi Weibull (Chawla and Meyers, 2009, Askeland et al., 2011). The Weibull distribution is an indicator of the variability of strength of materials resulting from a distribution of flaw sizes (Askeland et al., 2011).

For the compressive strength test, scaled- bricks were used instead of full-size bricks. The use of the scaled bricks will allow to conduct more tests, speed up the production process and investigate different percentages of the stabilisers. In addition, by using scaled bricks less quantities of the stabilisers (the glycoproteins) will be purchased and this will help with controlling the budget available for the laboratory experiments.

In general, in earth construction scaled- bricks could be used to represent full-size bricks for compressive strength test (Walker and International, 2002). Scaled- bricks were also introduced and tested for their feasibility to be used as representative of the full-size bricks for compressive strength test in previous research (Maskell et al., 2013, Maskell et al., 2014). *Maskell et al.* used scaled-bricks on testing compressive strength of extruded earth masonry units. The authors concluded that the difference in the compressive strength between the full-size bricks and the scaled-bricks was due to the difference in the moisture content (Maskell et al., 2013). The authors used 1:3 linear scale (1:27 volumetric scale) to prepare their scaled-bricks. However, in the present study linear scale of 1:2 (1:8 volumetric scale) was used to prepare the scaled-bricks. The selection of this scale was based on results of previous studies. *Mohammed et al.* tested the compressive strength of different scales (prototype, half, fourth and sixth) of solid burnt clay bricks and they concluded that the compressive strength of the masonry units increases as the scale is reduced (Mohammed et al., 2011). One of the findings of their tests was that the half linear scale was proven to have the same compressive strength as the full-size brick (Mohammed et al., 2011). Based on all the above-mentioned points, scaled bricks were used to test the compressive strength in this study.

### 3.3.3 Durability tests: Introduction

Durability is defined as the resistance of building materials to the functional deteriorations overtime (Heathcote, 2002). In general, there are three different types of durability based on its causes. Physical durability that is caused by physical actions such as the erosion of earth walls by wind-driven rain. Chemical durability is resulted from a chemical reaction such as the deterioration of some building material due to the acid rains (corrosion on limestone, sandstone, and marble) and the rusting of steel elements in some buildings (Heathcote, 2002). Biological durability, which is happened due to fungal, bacteria and insects' attacks. For example the rot appears on timber parts and buildings after fungal attack (De Belie et al., 2000). In earth buildings, the main cause of functional deterioration overtime is the physical durability, which is caused by the wind-driven rain and results in the surface erosion of the material (Heathcote, 2002). Erosion similar to compressive strength is influenced by many factors, (Heathcote, 2002):

1) The raw material properties in general and the percentage of clay in particular.
2) The availability of stabilising agent along with the natural available binder in the soil, the clay.
3) The compaction pressure the soil encounters during the preparation of the earth's units.
4) The freeze thaw cycle and airborne salt attacks which leave the earth's surface vulnerable to wind-driven rain attacks.
5) The direction of the wall in the design and if it faces the rain direction.
6) The texture and the protective coating layer of the end earth surface.
7) The wetting and drying cycles will stress the earth surface and leave it more susceptible to rain attacks.
8) The structural defects such as micro and macro cracks which will leave the earth material less resistance to the erosion by wind-driven rain.

There are three general types of durability tests in earth construction. Some tests are indirect which do not directly measure the erosion mechanisms, however, they can be used as an indication of the durability and the quality of the material under service. Wire brush tests, drip tests, strength tests such as compressive and wet/ dry strength ratio tests, permeability and slake tests, and surface hardness tests are examples of the indirect tests (Heathcote, 2002).  The second type is called the accelerated tests, which try to simulate the rainfalls in the nature. The concept behind these tests is to increase the deterioration factor (the wind-driven rain) and reduce the test time. Most of the spray tests and some types of the drip tests are examples of the accelerated tests (Heathcote, 2002). The third type of durability tests is called simulation tests. These tests are trying exactly to simulate the natural conditions (the degradation factor and the time). The tests are not accelerated and they could last for hours and sometimes for days. Some types of spray tests are considered as simulation tests.  These simulation tests resulted in more accurate and precise results closer to the results in the nature, however, they are considered unpractical due to the long time needed to run the tests along with the sophisticated equipment needed to run them (Heathcote, 2002).

From all the three types of durability tests mentioned above, accelerated tests in general and spray tests in particular are the most practical and accurate tests. Spray tests are easy to perform, they simulate the action of the wind-driven rain and the test covers big part of the surface of the brick / block (Heathcote, 2002).

### 3.3.4 Accelerated Erosion Test: Bulletin 5

The Commonwealth Experimental Building Station in Australia developed this spray test and usually is known as Bulletin 5, which refers to the name of the document where this test contained (Middleton, 1987, Heathcote, 2002). This test is also available in the Australian Earth Building Handbook (Walker and International, 2002), and in the New Zealand Materials and workmanship for earth buildings [Building Code Compliance Document E2 (AS2)](NZS4298, 1998). This test is used to determine the erosion resistant of the bricks. The erosion test rig used in this study is shown in Figure 3-42and Figure 3-43 below.

For the erosion test, full-size bricks were used for both soils (the British and the Sudanese). Each brick was sprayed continuously for one-hour with a water jet or until the brick was fully penetrated in less than the hour. The water jet pressure was 50 kPa. The brick was located 470 mm away from the water jet. A shield was used to cover the brick and only a limited area of the face of the brick was exposed to the water jet.

The limited exposed are was either 150 mm or 70 mm diameter depend on the brick size. The water jet was stopped at intervals of 15 min to measure the depth of the erosion. The depth of the erosion was measured in millimetres by using 10 mm diameter flat-ended metal rod. The maximum erosion depth in one hour was divided by 60 to give the rate of erosion (*D*) in mm per min. However, when the brick was fully penetrated in less than an hour, the rate of erosion (*D*) was calculated by dividing the thickness of the brick by the time taken for the full penetration to occur. The total amount of water discharged in one minute during this test was 29.6 l/min, which resulted in 100 meters volume of water in one hour. This amount of water is equivalent to 85 years of rainfall in Sydney in Australia where this test was developed.

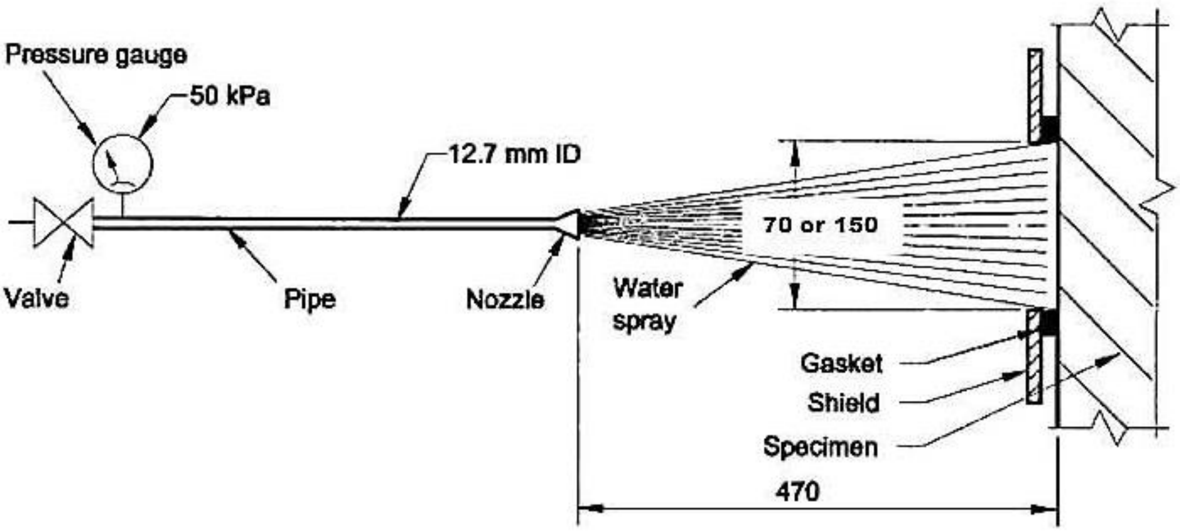



**Figure 3-42:** Erosion spray test rig arrangement (NZS4298, 1998)

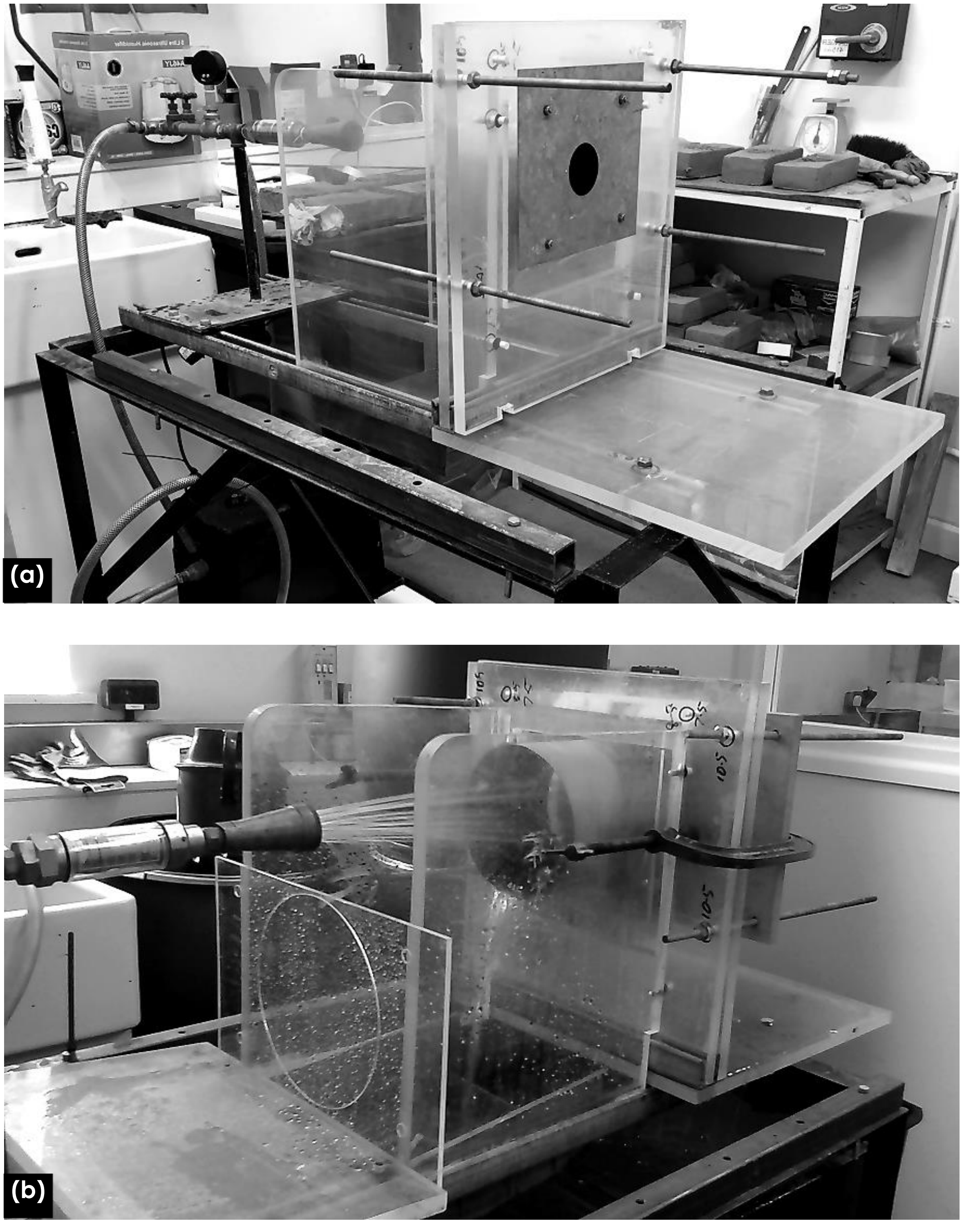



**Figure 3-43: (a)** The accelerated erosion test rig **(b)** The water jet hit on the brick face during the test

## 3.4 The preliminary experiments:

### 3.4.1 Introduction

The preliminary experiments were conducted to investigate the effect of the moisture content on the strength and erosion properties of the bricks and also to identify the moisture content which results in the maximum compressive strength and minimum erosion depth. This moisture content will be used to prepare the controlled bricks (the unstabilised bricks) later on. The relationship between the moisture content, the compressive strength and the erosion depth was investigated by producing different bricks with different moisture contents and then test them. In addition, the relationship between the moisture content, workability and density was also addressed. Different mixing methods and drying environments were identified and compared. These preliminary experiments were crucial to improve the production methods, to be more familiar with the soil type and also to be able to sort out any issue that might arise before starting the main experiments. These preliminary experiments were carried out using the British soil only without adding any stabiliser. This section will discuss the preparation of the bricks, the tests conducted and the results. The section will cover the following:

- The relationship between the workability of the mud mixture and the moisture content.
- The effect of the moisture content on the rate of the erosion.
- The effect of the moisture content on the compressive strength.
- Best mixing method.
- Different drying methods available.
- Investigate other related factors that might affect the results

### 3.4.2 Bricks preparation

All the bricks were prepared using a mixture of British soil and distilled water only without adding any stabilisers. The bricks were mixed manually on a mixing tray (cement mortar sand plastering mixing tray) using hands and trowel. Different bricks were made using different moisture contents (10% up to 33%). The bricks were made using a wooden mould, Figure 3-44. The size of the bricks used was the one that is used in the UK small-scale mass produced earth bricks (Morton, 2008).

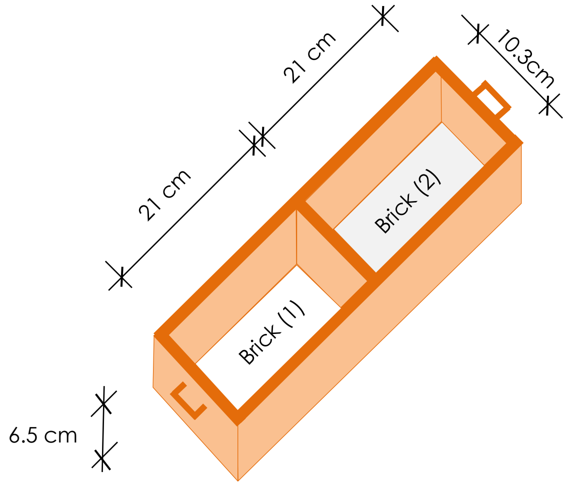



**Figure 3-44:** Wooden mould used to prepare full-size British adobe bricks

The wooden mould was soaked in water and sand dusted prior to moulding to avoid the mud mixture to stick to the mould. The mud mixture was placed inside the mould and spread over by hand. During moulding the bricks, much attention was given to press along the inside edges of the mould and the corners to control the overall geometry of the bricks and to ensure that all the brick surfaces had enough pressure. The mould was filled up to the top edge and a wooden scraper was used to level the top surface. Then by using a wet hand, the surface was smoothed and the mould was removed.

### 3.4.3 Workability& moisture content relationship

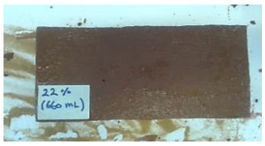
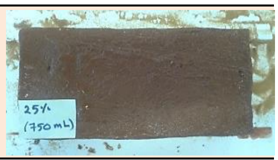
The first step was to find out the moisture content that will result in a workable mixture. The general rule in making the moulded adobe bricks is that the moisture should be enough to acquire an easy mixing, moulding and removing from the mould (Walker and International, 2002). Having the right moisture content will result in no or small slump during the brick production which will give the brick the final proper shape. Slump is not preferred during the brick production because it will affect the final shape of the brick.

The Japanese Association of Concrete Engineers defines the workability as "*that property of freshly mixed concrete or mortar that determines the ease and homogeneity with which it can be mixed, placed, and compacted due to its consistency, the homogeneity with which it can be made into concrete, and the degree with which it can resist separation of materials*" (Bodenlos and Fowler, 2003, Koehler et al., 2003). Workability in concrete is measured by using different methods. Roughly 61 different testing methods are applied and used to measure concrete workability (Koehler et al., 2003). One of the famous methods and widely used is the slump test (Koehler et al., 2003). The test determines the workability (Walker and International, 2002) and gives an indication of the water content (Koehler et al., 2003). In earth construction, different workability tests have been used. For example, slump test has been used before to determine the water content of stabilised adobe bricks (Vilane, 2010). In addition, flow table test (one of the workability tests) was used to determine the workable water content of lime stabilized adobe blocks (Sarkar et al., 2012). However, despite the use of different concrete workability tests in earth construction, it is clear that both materials (the concrete and earth) have completely different properties. Thus, in this research the author avoided to use concrete workability tests and stick to the basic principle indicated before to determine the optimum moisture content for adobe bricks. The optimum water content is the water that lead to an easy mixing, moulding and gives controlled shape for the bricks (Walker and International, 2002).

To determine the optimum moisture content for this soil, different bricks were made using different moisture contents. During the preparation of the bricks, the mixtures were observed for their easy mixing, moulding, removal from the mould and the final shape of the bricks. Table 3-16 shows the different moisture contents tested.

Based on the results of the plastic limit in section 3.1.3.3, the plastic limit of the British soil was 19.4%, thus the testing of the optimum moisture content will start from moisture content above 20%. The use of 21% moisture content has resulted in mixtures that were manageable during moulding the bricks. However, the bricks were sagged during the removal of the mould, see the brick pictures in Table 3-16.

**Table 3-16:** The different moisture contents tested during the preliminary experiments

| Moisture content (%) | Density (kg/m³) | The mixture | The brick |
|---|---|---|---|
| **21%** | 2137 |  |  |
| **22%** | 2101 |  |  |
| **23%** | 2034 |  |  |
| **24%** | 2029 |  |  |
| **25%** | 1993 |  |  |
| **30%** | 1813 |  |  |
| **33%** | 1705 |  |  |

Furthermore, increasing the water content above 21% by reaching 22%, 23% and 24%, has positive impact on the mixing, moulding and removal from the mould. The resulted bricks were in a good shape with straight edges and flat top surface. Then the water content was increased to reach 25%, the mixture was too moist. The 25% moisture content mixture was sticky and not easy to mould. After the removal of the mould, the brick slumped and did not have straight edges similar to the earlier moisture contents (22%, 23% & 24%). The last stage in investigating the effect of the moisture content on the workability was to test higher water contents. This was done by testing 30% and

33% moisture contents, Table 3-16. The mixture from both moisture contents (30% and 33%) was too moist and slurry. It was also too sticky during moulding and this has affected the mould removal at the end. The bricks were distorted straight after removing the mould. As a result, the end bricks neither have flat surface nor straight edges. From the above experiments, it was clear that workability has a very strong correlation with the moisture content. The workability reduces with either very low or very high moisture content. Very high moisture content will reduce the stiffness of the soil and results in very weak adobe bricks(Sidibe, 1985). It will also increase the shrinkage on the brick surface during the drying process (HABTEMARIAM, 2012).

The results of the effect of moisture content on the workability of the brick mixture could be analysed in relation with the liquid and plastic limits test results in section (3.1.3.2 & 3.1.3.3). The liquid limit of the British soil was 37%, and this could explain the change on the behaviour of the mixture of this soil from plastic (dough) to liquid (slurry) when reaching higher water content (30% & 33%). The plastic limit for this soil was 19%, which could explain why in water content below 20% (10% & 15%) the soil was too dry to shape and mould. Furthermore, the plastic limit could explain why in moisture content above 19% (20% up to 25%) the soil was plastic and thus workable. This test of the relationship between the workability and the moisture content has resulted in a range of moisture contents that are workable and produce regular shape bricks. Although different documents refer to different optimum moisture content for adobe brick such as around 30% (Walker and International, 2002) and 16 to 20% (Sidibe, 1985), the above test proved that for this soil from Devon the optimum moisture content is in the range between 22% and 24%.

Since, all these moisture contents (22%, 23% & 24%) are workable, more tests were needed to select the moisture content that will be workable, more resistant to erosion and resulted in higher compressive strength. In the following sections, this moisture content range will be investigated for its density, compressive strength and erosion resistant. By the end of these sections, the selected moisture content will be taken forward as the potential moisture content for the production of the controlled samples of the unstabilised British adobe bricks.

### 3.4.4 Density& moisture content

For every soil that is used to prepare adobe bricks there is a certain moisture content which results in the maximum dry density and hence the maximum strength (Fenton, 1941) in (Clifton, 1977). There is a good correlation between the moulding water content and the final dry density. When adding the water to the soil during mixing, the water occupies and fills the inter-granular voids of the soil (Kouakou and Morel, 2009). During the drying process, this water evaporates from these inter-granular voids. This water evaporation process causes the bricks to shrink and develops the porosity of the soil, Figure 3-45, (Kouakou and Morel, 2009). The porosity or voids ratio is defined as the volume of voids in the soil expressed as a percentage of the total volume (Houben and Guillaud, 1994). This porosity has a positive relationship with the moulding water content. Thus, an increase in the moulding water content will lead to more shrinkage and porosity and lower the dry density, Figure 3-45, (Kouakou and Morel, 2009).

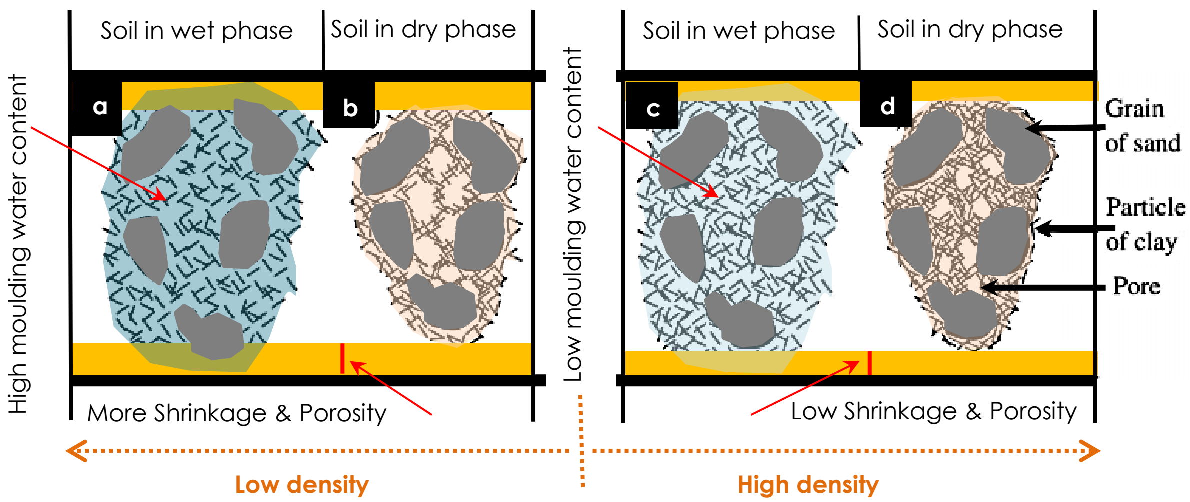



**Figure 3-45:** Diagram of soil structure during wetting and drying periods **(a)** & **(b)** soil of high moulding water content **(a)** The soil during the wet phase **(b)** The soil after drying **(c)** & **(d)** soil of low moulding water content **(c)** The soil during the wet phase **(d)** The soil after drying, *(Kouakou and Morel, 2009).*

This inverse relationship between the moisture content and the dry density was clear when compare the dry densities of the range of the potential moisture contents mentioned before in section (3.4.3). For instance, small change in the water content has high implication on the density of the brick, Figure 3-46.

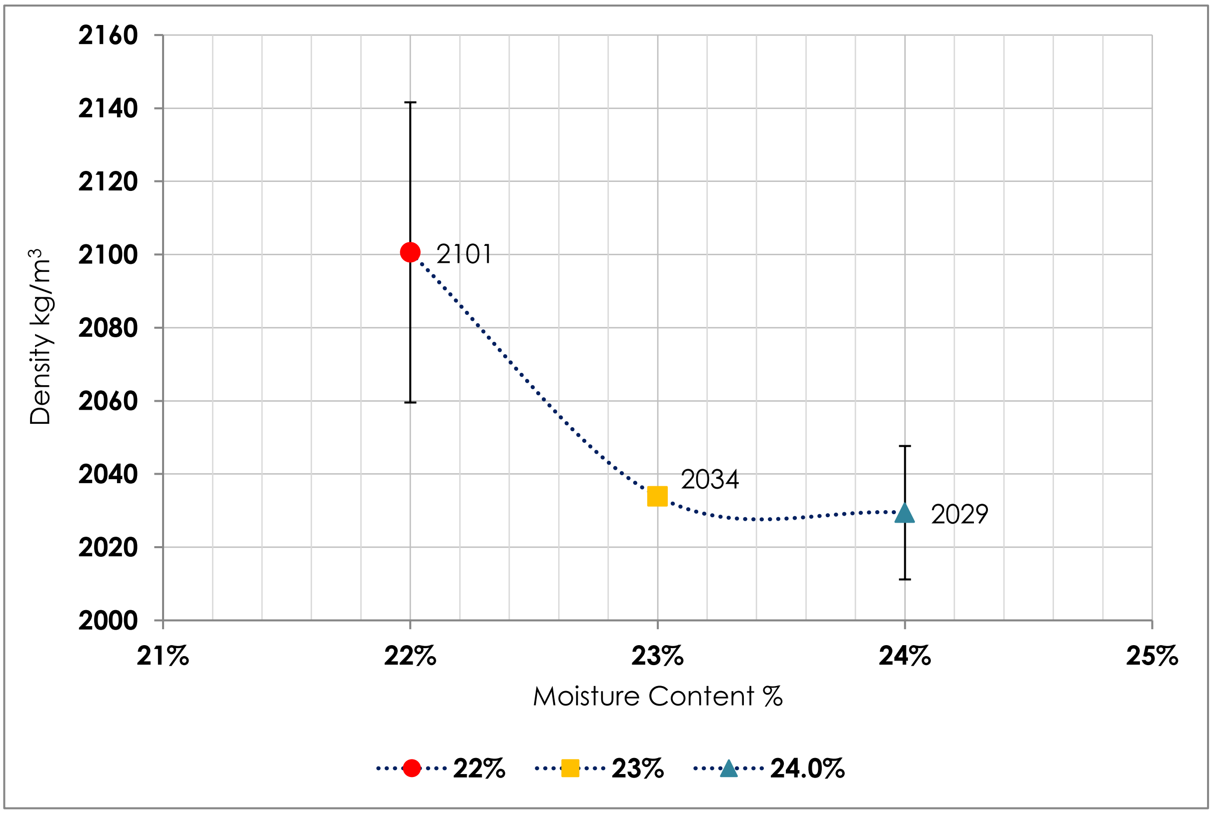



**Figure 3-46:** The effect of the increase of the moulding water content on the dry density of the British unstabilised adobe bricks, *the error bars stands for the standard error*

Figure 3-46 shows the relationship between the moulding moisture content and the dry density of the bricks. As it shows, a percent difference on the water content has a dramatic reduction on the density. All these moisture contents (22, 23 & 24%) have resulted in workable mixtures. However, there is a direct relationship between the dry density and the compressive strength. Higher density resulted in stronger bricks (Kouakou and Morel, 2009). The difference in the densities here is not due to compaction effort difference. All these bricks were mixed and moulded manually and there was no mechanical compaction effort used during the production. The bricks only encountered manual moulding pressure which is usually used when preparing adobe bricks. However, the difference on the densities were attributed to shrinkage and porosity effects which are resulted from the evaporation of the water from the pores during the drying process. Investigating the compressive strength of these moisture contents was crucial to decide which moisture content resulted in the higher compressive strength.

### 3.4.5 Compressive strength & moisture content

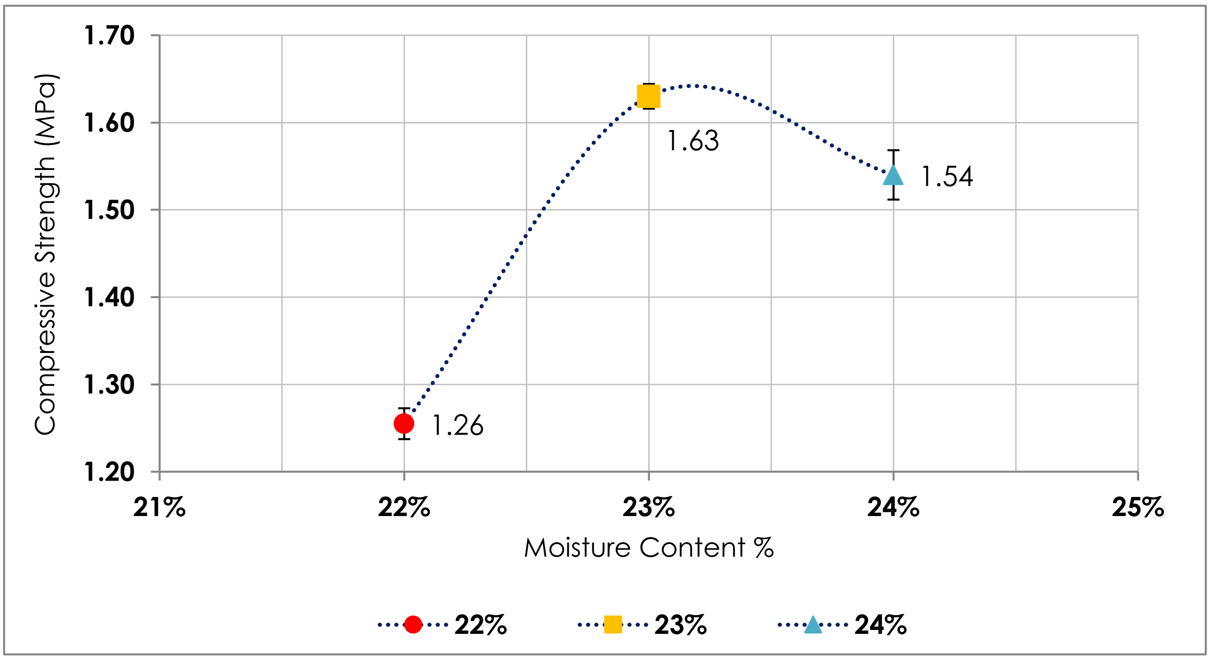



**Figure 3-47:** The relationship between the moisture content and the compressive strength of the British unstabilised adobe bricks, *the error bars stands for the standard error*

The graph in  shows that the maximum unconfined compressive strength was achieved when the moisture content was 23%. The lowest compressive strength was obtained when the moisture content was 22%. In general, increasing the density (densification) through compaction and using a binder are two different methods to increase the compressive strength of a soil (Walker and International, 2002). Densification improves the strength, compressibility, porosity, durability and the dimensions of the end product (Walker and International, 2002). Achieving the maximum densification is done by using either manual compressive machine e.g. machines that are used to produce compressed stabilized earth blocks or mechanical such as using tampers when building with rammed earth. Although, both techniques were not used when producing these conventional adobe bricks, the densification that increases the compressive strength has not been achieved during these set of tests. As a consequence, and regardless of the high density of the brick made using

22% moisture content compared to the density of other bricks, Figure 3-46, the compressive strength was the lowest. The only explanation available for this low compressive strength was that the mixture used to make these bricks (22% water content) lacked the water required for the binder reaction to take place. The binder in this case was only the natural clay minerals themselves. When enough water is available, the clay will have the ability to bind the soil particles together. In general, clay is widely used as stabilizer in earth construction (Walker and International, 2002). However, for the reaction to take place in adobe technique, enough water is needed otherwise the binder will not work and the strength will not improve. In other earth techniques that depends on the compaction and densification, the optimum moisture content is defined as the water content that is necessary to reach a percentage of the maximum compaction (Delgado and Guerrero, 2007), so very low moisture content will give high compressive strength.

In the bricks with the 24% moisture content, the density was the lowest between the three samples, but the bricks had a compressive strength higher than the brick with 22% moisture content and lower than the 23% moisture content. In these bricks, more water was available for the reaction between the clay minerals to take place. However, the surplus water will occupy the pores between the clay particles and upon drying, this water will evaporate leave micro cracks behind which will lead to an earlier failure upon loading and thus low compressive strength.

### *3.4.6 Erosion resistant & moisture content*

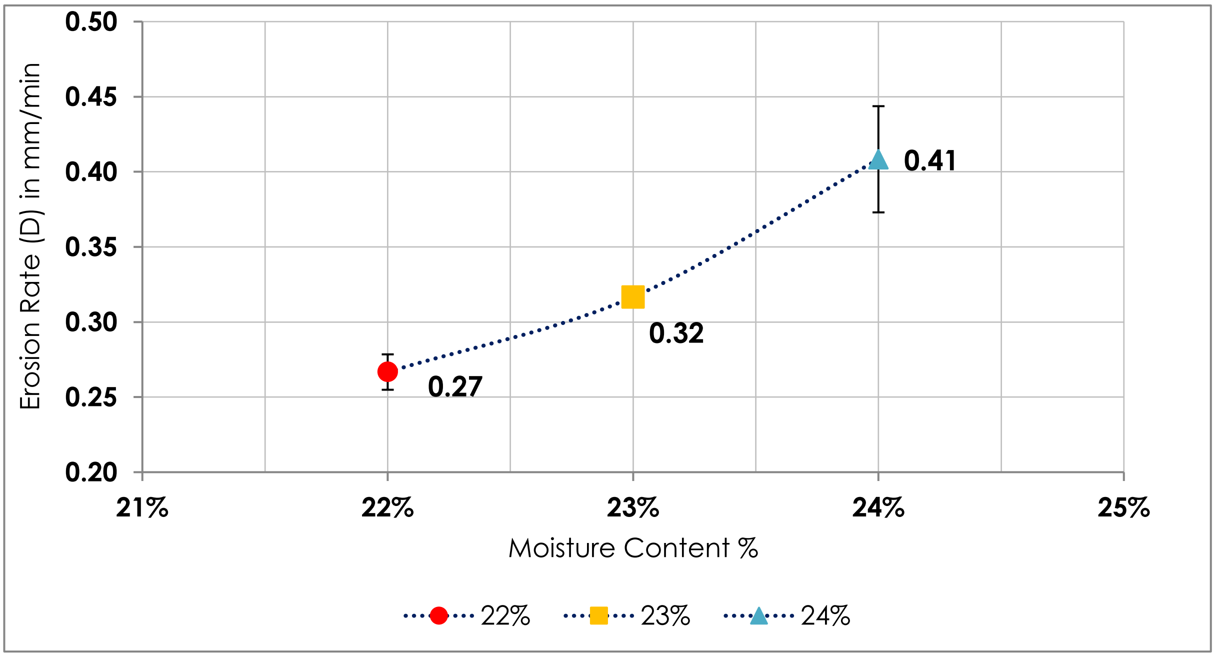



**Figure 3-48:** The relationship between the moisture content and the erosion rate of the British unstabilised adobe bricks, the error bars stands for the standard error

Figure 3-48 shows the result of the accelerated spray erosion test on the British unstabilised adobe bricks with the three different moulding moisture contents. The accelerated erosion test is considered as one of the tests that are used to determine the durability of an earth building material (Heathcote, 2002). From the graph in Figure 3-48, it is clear that there is a direct relationship between the moulding moisture content and the erosion rate of the bricks. In one hour, the erosion rate increased from 0.27 to 0.32 and then to 0.4.1 mm/min when the moisture content increased from 22, 23 and 24% respectively. This implies that the increase in the moulding moisture content resulted in the decrease of the erosion resistant of the adobe bricks. The increase in the water content will fill the pores between the soil particles. However, upon the evaporation of this water, the left air pockets behind will decrease the surface aggregation and this will leave the surface of the brick vulnerable to erosion by wind-driven rain.

From all the above investigations, moulding moisture content ranging between 23% - 24% has proven to be the best for this British soil from Devon. This range of moisture content has resulted in the best workable mixture during the moulding process. In addition, it has resulted in the highest compressive strength and lowest erosion rate. This range of moulding moisture content will be adopted as the standard moulding moisture content to prepare the unstabilised British adobe bricks in this study.

### *3.4.7 Best mixing method*

Mixing mud by hands, feet or using handy tools such as shovel and hoe are the traditional methods of mixing mud for making adobe brick (Sidibe, 1985). In these preliminary experiments, manual mixing using mixing tray was investigated, Figure 3-49.


**Figure 3-49:** Manual mixing using mixing tray to prepare the unstabilised British adobe bricks for the preliminary experiments

However, working clay after adding the water needs a lot of effort to achieve a consistent homogenous mixture. So, it wasn't easy or feasible to mix big quantities such as six kilograms, this method led to mix very small quantities to have a homogeneous and consistent mixture. Mixing small quantities delayed the production process. Therefore, to speed up the production, to keep the consistency of the mixture and to ensure the possibility of the reproducibility of the tests, mechanical mixing was introduced. *Houben et al.* refer to the use of mechanical mixers to mix mud for adobe making (Houben et al., 1994). In their book, they referred to different types of mechanical mixers such as the concrete mixer (the drum), the drill mixer that is used to prepare concrete mortar and paints, render mixers …etc. In this research both the drum concrete mixer and the drill were tested for mixing the mud for adobe bricks' production. the drum was tested as first choice. However, the mud mixture was stuck to the surface of the drum made it impossible to have a homogenous mixture. In addition, the scrapping of the mud from the inner surface of the drum during the mixing to enable the production of a homogenous mixture delayed the production process instead of speed it up. The last choice available was using the drill mixer, Figure 3-50, to mix the mud. This method has resulted in a very homogenous mixture and speed up the production process, Figure 3-50. As a result, the drill mixer was adopted as the standard mixing method to produce the unstabilised and stabilised adobe bricks produced during this study.

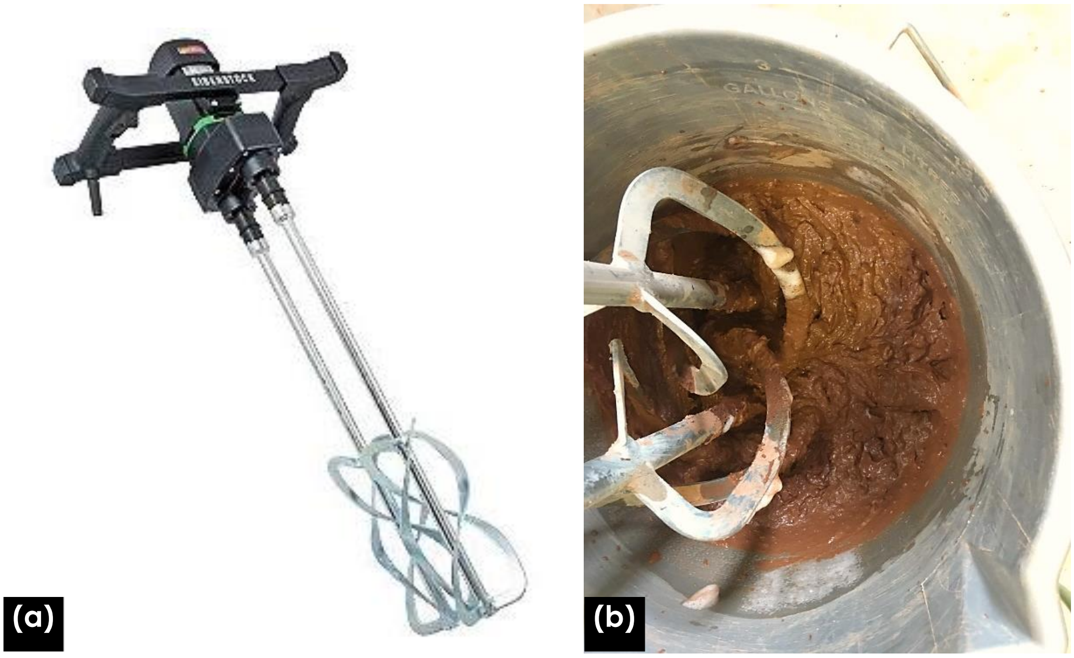
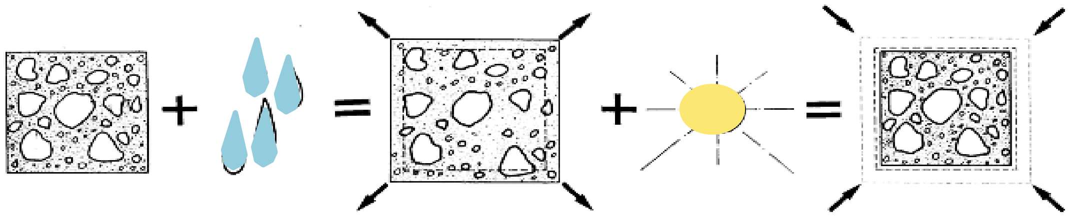



**Figure 3-50: (a)** EZR22, twin paddle mega mixer (drill mixer) used to prepare the unstabilised and stabilised adobe bricks **(b)** The drill mixer in action

### 3.4.8 Different drying methods

The general rule in the drying of the unstabilised adobe bricks is to keep the bricks away from direct sun and wind and to avoid leaving them in a humid environment (Sidibe, 1985, Rigassi, 1995, HABTEMARIAM, 2012). Rapid drying is not preferable, because it leads to the appearance of cracks on the surface of the bricks and thus weaken the bricks (HABTEMARIAM, 2012). The strength of the abode bricks greatly depends on the degree of the micro-cracking due to the drying shrinkage. Slow drying results in less cracks and more strong blocks (Vargas et al., 1986, Blondet et al., 2003). The rapid drying will evaporate the water from the inside of the brick very quickly. The force that the moisture created to escape from the inner part of the brick pushes the surface apart and leaves it with many micro and macro cracks (HABTEMARIAM, 2012). The cohesion when making and drying the adobe bricks works in two different phases as follow, Figure 3-51, (Aedo, 2002):



**Phase 1:**
The earth absorbs water and the clay begins to inflate. This is a long process which requires time.

**Phase 2:**
The earth dries, the volume of the clay decreases attracting to it the other components which are completely dry and tied.

**Figure 3-51:** The phases of cohesion in adobe production adopted from (Aedo, 2002)

Based on the two drying phases mentioned in Figure 3-51, rapid drying such as the use of an oven to dry the bricks was excluded from the drying options available.

Another drying option that was investigated in order to select the best drying option in this study was to simulate the conditions of the desired geographical location. This method was used in the literature before. In the relevant literature, this was achieved by air drying the bricks in a room with temperature higher than 15 °C and constant relative humidity for couple of weeks (Molnár, 2002, Harper, 2011, Aubert et al., 2013). These settings could be done by using electric heaters, a standard radiator and a domestic dehumidifier keeping the room temperature and humidity constant. In addition, the bricks could be placed on racks in the room to allow air to circulate around them and they should be turned once a day to try to ensure the bricks dried evenly (Considine et al., 2007). This option was tested and the bricks were placed in an open rack to allow airflow, Figure 3-52. The room was aided with portable fan and a dehumidifier. The room was located on the ground floor and it had a large window which was exposed to sun in the afternoon. The temperature in this room was monitored throughout the day and it was found to exceed 30 °C which it was not good for the drying of the bricks.

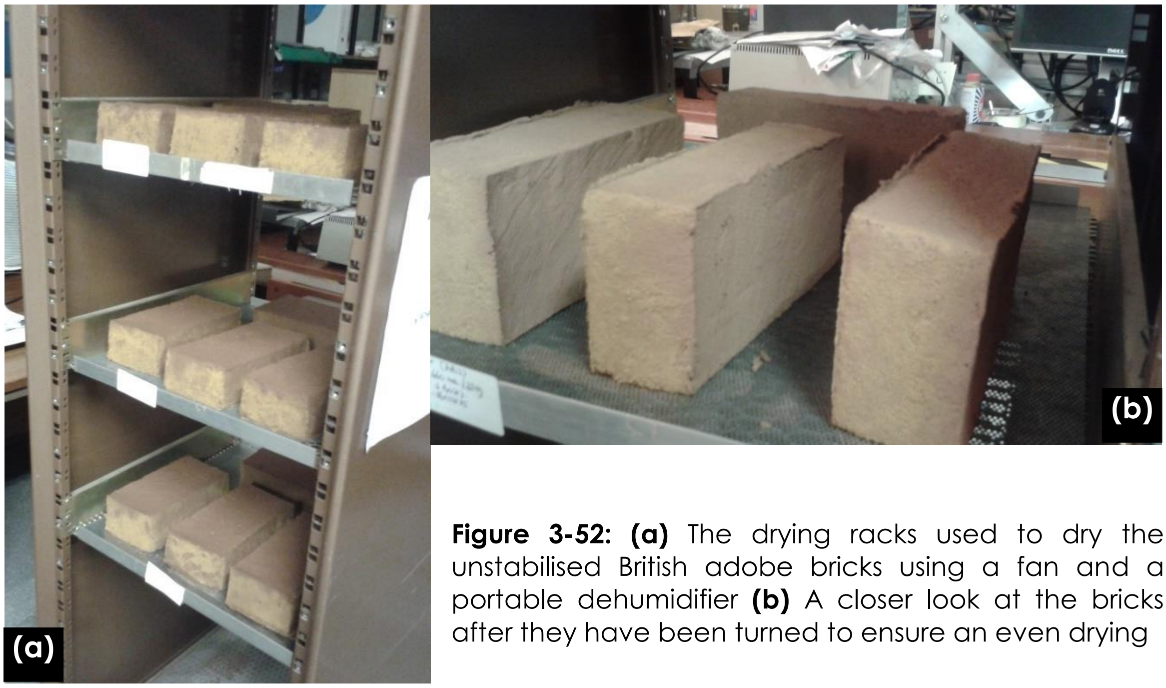



**Figure 3-52: (a)** The drying racks used to dry the unstabilised British adobe bricks using a fan and a portable dehumidifier **(b)** A closer look at the bricks after they have been turned to ensure an even drying

As a result of the fluctuation of the temperature in this room throughout the day, the experiment was moved to another room in the basement floor. At this point an electric heater was added along with the dehumidifier and the fan. In the basement floor, the room area was big and it was impossible to control the temperature and humidity using the domestic electrical heater, the dehumidifier and the fan.

As a result, other methods of drying were investigated. In the literature some authors relied on using stationary thermo-hygrometric conditions for several weeks to dry their bricks (Lenci et al., 2012). This method of drying ensure constant temperature and humidity settings for all the experiments and thus, there will not be variability in the drying methods over the period of the study. In this research, a controlled environmental chamber was used to dry all the bricks for several weeks, Figure 3-53. The settings for the temperature and the humidity followed the origin of the soils used to prepare the bricks. For the British bricks, the environmental chamber set to replicate the temperature and the humidity of the summer in Reading, United Kingdom. For the Sudanese soil, the temperature and the humidity were set to represent the conditions in Khartoum, Sudan.


**Figure 3-53:** The environmental chamber used to dry the adobe bricks in this study

### 3.4.9 Scaled size bricks for compression test

As has been mentioned before in section 3.3.2, the use of the scaled bricks will allow more tests to be conducted, speed up the production process and investigate different percentages of the stabilisers. In addition, by using scaled bricks less quantities of the stabilisers (the glycoproteins) will be purchased and this will help with controlling the budget available for the laboratory experiments.

At the beginning the idea was to mould the scaled bricks and to do so, a small mould was prepared. However, the moulding and the removal of the scaled bricks from the mould was hard and resulted in very poor quality of bricks. Many attempts were made to enhance the quality of the scaled bricks such as modifying the mould design to ease the removal of the bricks, but the bricks prepared were still of poor quality and have irregular shape. During the moulding, the bricks were sticking to the internal side of the mould making it very hard to remove them from the mould. As a result, a decision was made to change the method of making the scaled bricks. The new method was to cut the small bricks from the full-size bricks. By doing this, more representative bricks were easily made. This method is one of the methods mentioned in the Australian earth building handbook  for preparing a specimen to conduct a compressive test (Walker and International, 2002).

In the present study, the scaled-bricks were prepared by cutting the full-size bricks into small bricks following the previous mentioned half linear scale (section 3.3.2) using a segmented blade "snap-off blade" utility knife. Eight scaled-bricks were generated from each full-size brick, Figure 3-54. After cutting the full-size bricks into small ones, the surfaces of the small ones were levelled and smoothed using a wooden spatula and water. This was done to make the small bricks look similar to the regular adobe bricks with all surfaces smooth. On the other hand, as has been mentioned before compressive strength requires flat and parallel surfaces. The scaled-bricks were dried in controlled cabinets with fixed temperature and humidity for 28 days prior to testing. The temperature and humidity settings were based on the soil groups (British or Sudanese).

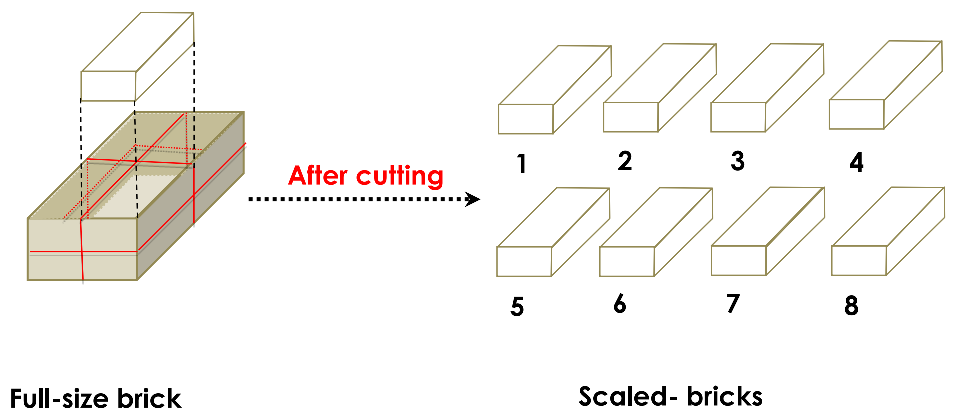



**Figure 3-54:** Cutting full-size brick to prepare scaled-bricks using the linear scale of 1:2 (1:8 volumetric scale)

# 4. Unconfined Compressive Strength Test Results

*Along with the general structure of the experimental tests*

## 4.1 Structure of the experimental tests

In this study, the compressive strength and erosion resistance of the adobe bricks were the focus of the experimental tests. In general, two types of soils and four potential stabilisers were used in the tests. The experimental tests were structured and designed in order to test the research hypotheses. The tests were built around investigating the research three hypotheses. The following sections will address these three hypotheses in more details.

### *4.1.1 The first hypothesis:*

***"The addition of the glycoprotein to the British adobe bricks will enhance the bricks' unconfined compressive strength and increase their erosion resistance to the wind-driven rain''***

Testing this hypothesis was achieved by structuring the tests into four different phases based on the glycoprotein's concentration. The concentrations of the glycoprotein used to test this hypothesis started from as low as 0.1 by weigh percent up to 0.5 by weight percent. The lowest glycoprotein concentration (0.1%) was used based on the findings of Gillman et al. According to the analysis that they conducted on a soil mound of *Coptotermes Acinaciformis* termites in Australia, the glycoprotein concentration in 1 kg of the mound soil was 0.1% (0.1 by weight % of glycoprotein) (Gillman et al. 1972). The tests used to investigate this first hypothesis were divided to four different phases. The phases were started by using the lowest concentration of glycoprotein which was 0.1 % and then the glycoprotein concentration in the adobe bricks was increased to 0.2, 0.3, 0.4 and 0.5 by weight percent. The unconfined compressive strength results of the British adobe bricks made using the above-mentioned glycoprotein concentrations were compared with the unconfined compressive strength of the unstabilised British adobe bricks (the control sample). The phases used to test this first hypothesis will be discussed in the following sections.

#### 4.1.1.1 Phase one

In this phase, the British adobe bricks were stabilised using 0.1 by weight percent glycoprotein. These stabilised British adobe bricks were tested for their unconfined compressive strength and erosion resistance. The results were compared with those of the unstabilised British adobe bricks which were referred to as the control sample.

#### 4.1.1.2 Phase two

Based on the results obtained from phase one above, the concentration of the glycoprotein was doubled and 0.2% glycoprotein stabilised British adobe bricks were produced. The British stabilised bricks from this phase were tested for their unconfined compressive strength as well as erosion resistance. The results were compared with those of the British unstabilised adobe bricks, the control sample. By the end of this phase, the stabiliser which had resulted in the lowest unconfined compressive strength from phases one and two was eliminated and excluded from further investigations.

#### 4.1.1.3 Phase three

The glycoprotein concentrations tested in this phase were: 0.3, 0.4 & 0.5 by weight % of glycoprotein. The British stabilised bricks from this phase were tested for their unconfined compressive strength only. The results were compared with those of the British unstabilised adobe bricks, the control sample. By the end of this phase, the glycoprotein which had resulted in the highest unconfined compressive strength was identified for further investigations.

#### 4.1.1.4 Phase four

The test conducted in this phase was based on the results obtained from phase three above. The British stabilised adobe bricks which had the highest unconfined compressive strength from phase three were tested for their erosion resistance.

### *4.1.2 The second hypothesis:*

***"The addition of the glycoprotein to the Sudanese adobe bricks will enhance the bricks' unconfined compressive strength and increase their erosion resistance to the wind-driven rain"***

Due to the small quantity of the Sudanese soil imported, only one glycoprotein was tested. The glycoprotein which had resulted in the highest unconfined compressive strength from the first hypothesis tests was used in this second hypothesis. The Sudanese stabilised adobe bricks were tested for their unconfined compressive strength and erosion resistance. The results were compared with those of the Sudanese unstabilised adobe bricks, the control sample.

### *4.1.3 The third hypothesis:*

***"The addition of higher concentrations of glycoprotein to the adobe bricks will continue to enhance the unconfined compressive strength of the bricks"***

In this third hypothesis both the British and the Sudanese soils were used. However, there were differences in the concentrations of the glycoprotein tested. Three different glycoprotein concentrations were selected to be tested using the British soil and only one glycoprotein concentration was used for the Sudanese soil. This difference in the glycoprotein concentrations selection between the two soils was solely based on the availability of the British soil compared with the limited quantity of the Sudanese soil. The maximum concentration of glycoprotein tested in this hypothesis (the cap) was 5 by weigh percent. Only the glycoprotein which had resulted in the highest compressive strength was used to test this hypothesis.

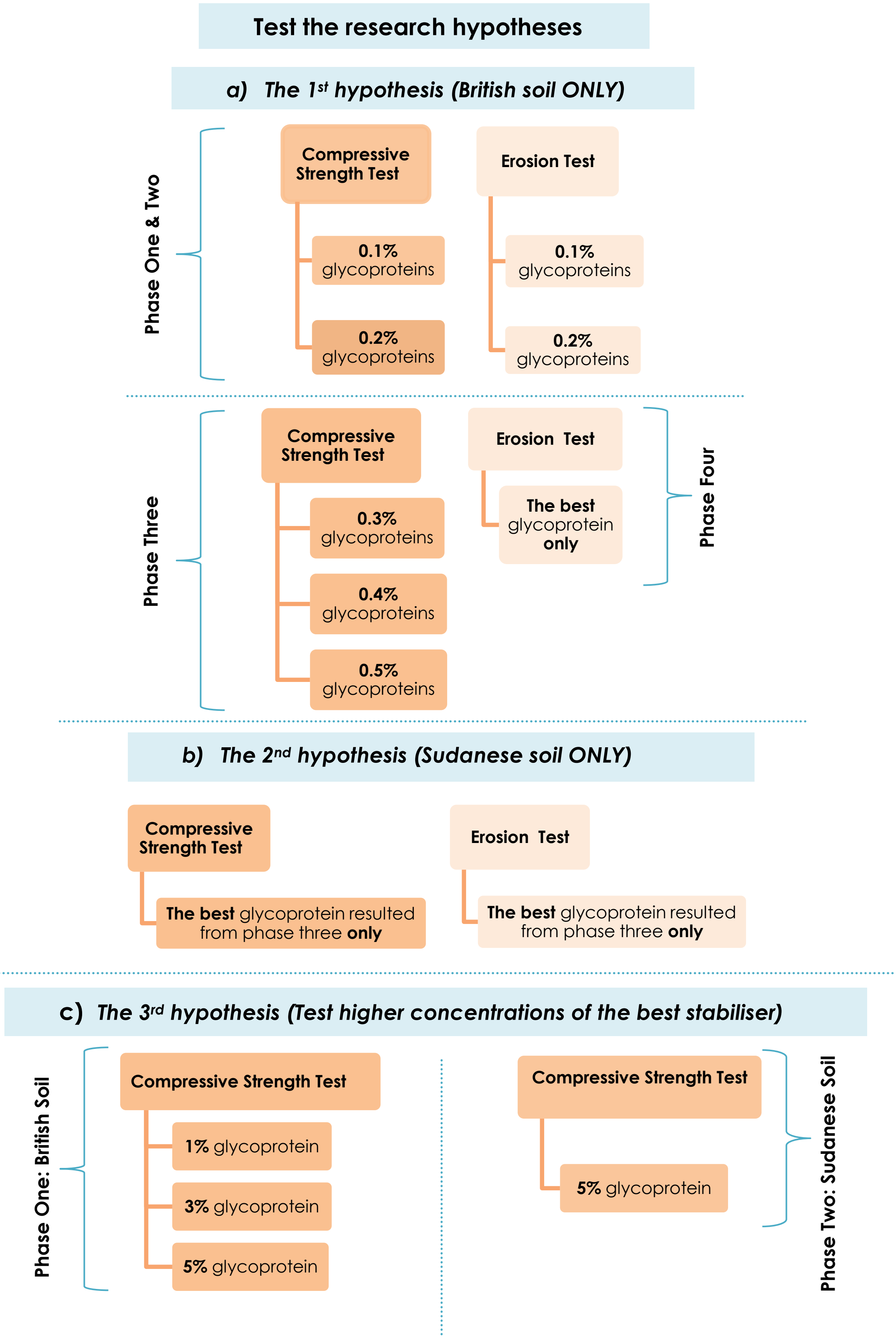
#### 4.1.3.1 Phase one: The British soil

Three different glycoprotein's concentrations were tested (1, 3 & 5 by weight %). The bricks were tested for their unconfined compressive strength only. 5% was used as the maximum concentration for the glycoprotein because it corresponded to the lowest effective concentration used for cement in adobe bricks stabilisation as reported in (Walker, 1995). The results from this phase were compared with those of the British unstabilised adobe bricks (the control sample).

#### 4.1.3.2 Phase two: The Sudanese soil

Due to the limited available quantity of the Sudanese soil imported, only the highest concentration of the glycoprotein was tested which was 5 by weight percent. The results were compared with those of the Sudanese unstabilised adobe bricks (the control sample).

### 4.1.4 Structure of the experimental tests: Summary



## 4.2 Unconfined compressive strength

The compressive strength test was performed on all bricks in accordance with Bulletin 5 (Earth wall construction) and the Australian earth building handbook (Middleton, 1987, Walker and International, 2002). This chapter investigates the effect of the addition of the glycoprotein on the compressive strength of the adobe bricks. It will include the preparation of the unstabilised and the stabilised bricks. It will also cover the results of the bricks' compressive strength along with the analysis. The chapter is divided into sections based on the experiment tests structure in section 4.1.

## 4.3 Preparation of the unstabilised British adobe bricks

The unstabilised adobe brick was prepared with a mixture of British soil and distilled water only. The soil was sieved using a 10 mm mesh sieve and then added to the measured known quantity of distilled water. The quantities of the British soil and the distilled water used are in Table 4-1. For each compressive strength test, six scaled bricks were used. The size of the full-size brick used was the same as that used in the UK small-scale mass produced earth bricks (Morton, 2008). To prepare these six bricks, two full-size bricks were prepared first. Each of these full-size bricks was made from a different mixture of the same composition to allow testing for repeatability. To prepare a full-size brick, the British soil and the distilled water were mixed using an electrical drill mixer (EZR22, twin paddle mega mixer), Figure 4-1, until a homogenous mixture was obtained and the mixture was ready for moulding. The moulding was done using a wooden mould which was moistened with water and dusted using sand prior to the moulding. This helped with the removal of the mould later at the end of the moulding process.

**Figure 4-1:** EZR22, twin paddle mega mixer used to prepare the unstabilised and stabilised adobe bricks

The moulding was done in layers and enough pressure was applied to each layer along the surface and attention was paid to the edges and the corners of the brick to ensure a regular shape later. This pressure was applied by hand and also by using a 5 kg metal weight, Figure 4-2. The decision was made to use this weight so as to mimic the hand pressure usually used when moulding traditional adobe bricks. In addition, the use of this weight controlled the amount of compaction the adobe bricks experienced during the production and this ensured the reproducibility of the bricks.


**Figure 4-2:** The 5 kg metal weight used when preparing the adobe full-size bricks

After the moulding process was completed, the extra mud was removed using a scrapper and the top of the brick was smoothed using wetted hands and then levelled. Then the mould was removed and the top level of the brick was levelled again. The bricks were left in the laboratory for 16 hours (overnight) for initial drying. In the morning, the bricks were dried enough to be cut into small bricks. A segmented blade "snap-off blade" utility knife, Figure 4-3, was chosen to cut the bricks instead of using a wire. It was thought that the availability of small gravel in the bricks might affect the wire cutting and this why a segmented blade was chosen.


**Figure 4-3:** The segmented blade or "snap-off blade" utility knife that was used to cut the full-size brick into scaled-bricks

Using the linear scale of 1:2 (1:8 volumetric scale) mentioned and discussed before in section 3.3.2, the full-size brick was cut into eight small bricks, Figure 4-4.

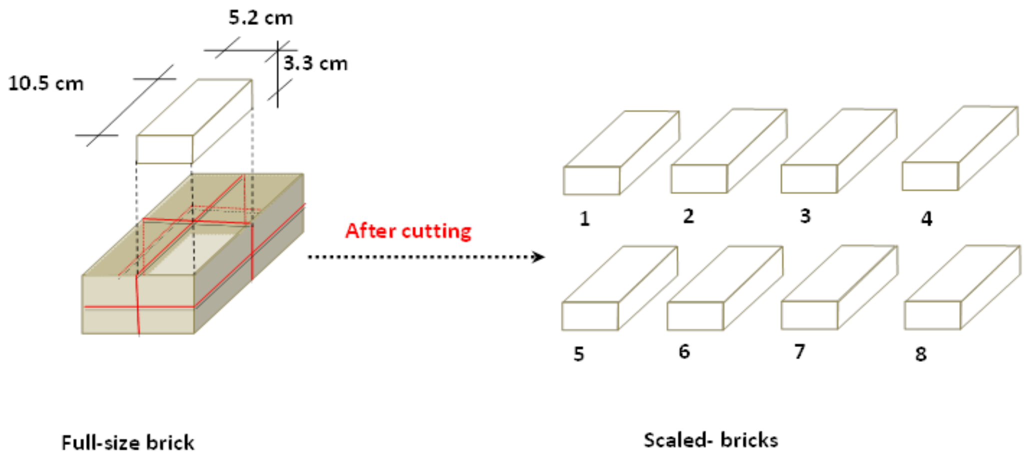



**Figure 4-4:** From a full-size British adobe brick into scaled-bricks using a utility knife. The cutting take place after the bricks dried for 16 hours (overnight) in the laboratory environment

The small bricks were smoothed on all the surfaces to ensure their flatness and evenness using a flat wooden piece and water. The scaled-bricks were left in the laboratory for another 16 hours for initial drying. The bricks were then labelled and moved to dry for 28 days in a controlled environmental chamber, Figure 4-5. The drying settings were representative of temperature and humidity in summer in Reading, UK. The temperature was set between 17 – 22 ° C and the humidity between 60% - 65%. During the drying process, the bricks were turned frequently to ensure even drying.

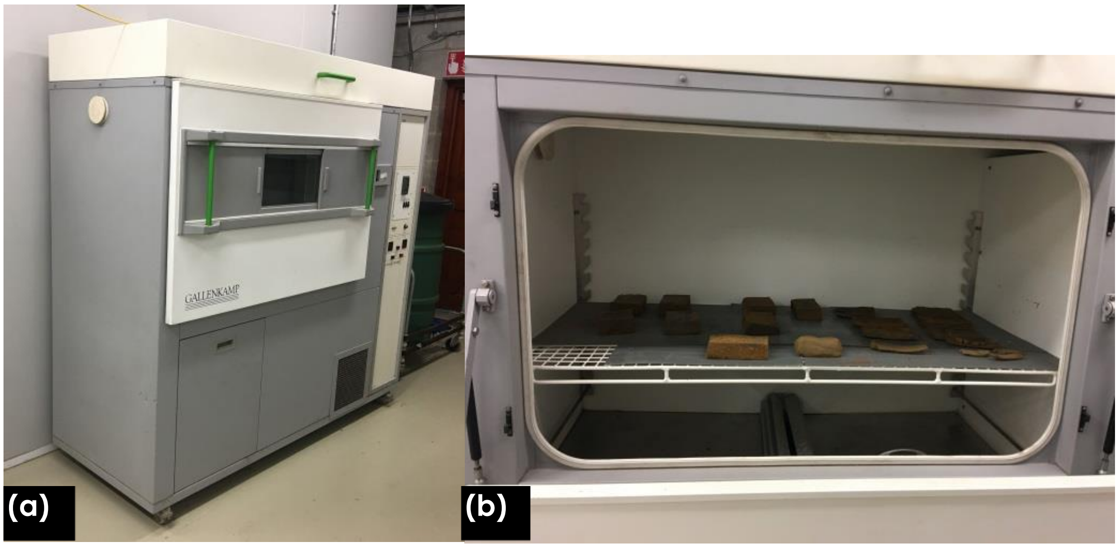



**Figure 4-5:** The controlled environmental chamber where all the bricks drying process in this study was taken place. The chamber was temperature and humidity controlled. **(a)** The chamber from the outside. **(b)** The chamber from the inside

**Table 4-1:** Unstabilised and glycoprotein stabilised adobe bricks mixing proportions (stabiliser (glycoprotein), distilled water and British soil). The proportions is to prepare one full-size British adobe brick

| **Glycoprotein percentage to the dry soil (%)** | **0%** | **0.1%** | | | | **0.2%** | | | | **0.3%** | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Type of glycoprotein** | ***No glycoprotein (Unstabilised)*** | ***Bovine serum*** | ***Fish gelatine*** | ***Mucin*** | ***Termite*** | ***Bovine serum*** | ***Fish gelatine*** | ***Mucin*** | ***Termite*** | ***Bovine serum*** | ***Fish gelatine*** | ***Termite*** |
| **Quantity of glycoprotein (g)** | 0 | 3 | 3 | 3 | 3 | 6 | 6 | 6 | 6 | 9 | 9 | 9 |
| **Quantity of distilled water (mL)** | *708 (23.6%)* | 732 (24.4%) | 747 (24.9%) | 741 (24.7%) | 696 (23.2%) | 750 (25%) | 768 (25.6%) | 831 (27.7%) | 729 (24.3%) | 825 (27.5%) | 774 (25.8%) | 774 (25.8%) |
| **Quantity of soil (g)** | *3000* | 2997 | 2997 | 2997 | 2997 | 2994 | 2994 | 2994 | 2994 | 2991 | 2991 | 2991 |

**Table 4-1:** *Continued*

| Glycoprotein percentage to the dry soil (%) | 0.4% | | | 0.5% | | | 1% | 3% | 5% |
|---|---|---|---|---|---|---|---|---|---|
| **Type of glycoprotein** | ***Bovine serum*** | ***Fish gelatine*** | ***Termite*** | ***Bovine serum*** | ***Fish gelatine*** | ***Termite*** | ***Bovine serum*** | ***Bovine serum*** | ***Bovine serum*** |
| **Quantity of glycoprotein (g)** | 12 | 12 | 12 | 15 | 15 | 15 | 30 | 90 | 150 |
| **Quantity of distilled water (mL)** | *765 (25.5%)* | 837 (27.9%) | 759 (25.3%) | 750 (25%) | 804 (26.8%) | 753 (25.1%) | 720 (24%) | 744 (24.8%) | 660 (22%) |
| **Quantity of soil (g)** | 2988 | 2988 | 2988 | 2985 | 2985 | 2985 | 2970 | 2910 | 2850 |

## 4.4 Preparation of the stabilised British adobe bricks

All the stabilised British adobe bricks for the compressive strength test were prepared in the laboratory environment following the sequence in Figure 4-6 below. However, the only variables were in the quantity of British soil, distilled water and the glycoprotein. The exact quantity of each glycoprotein that was used to prepare a full-size brick is available in Table 4-1 in section 4.3 above.

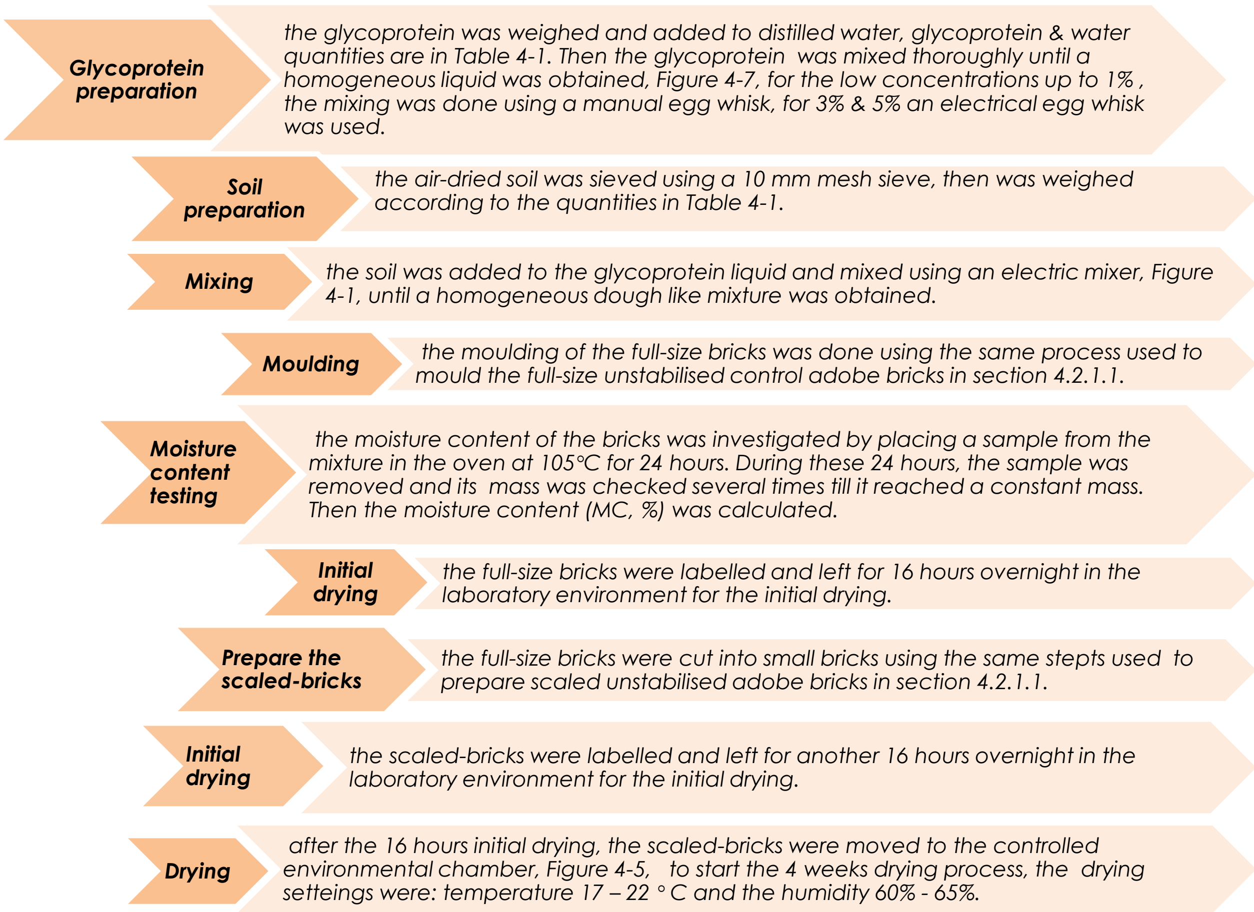



**Figure 4-6:** Preparation steps followed to prepare the stabilised British adobe bricks for the compressive strength test

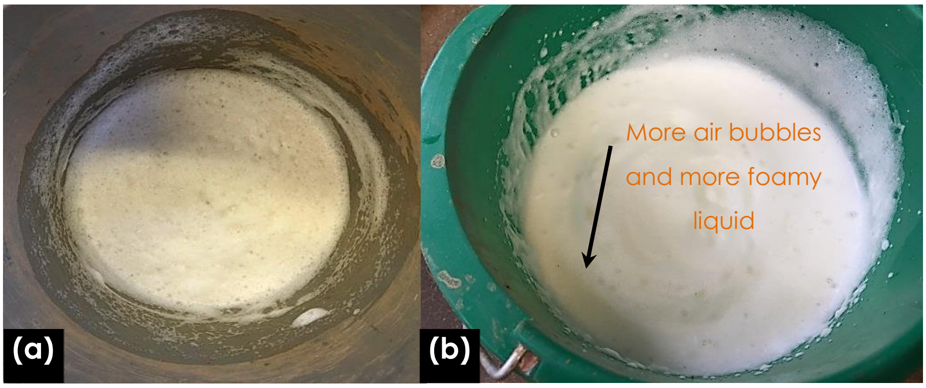



**Figure 4-7:** Samples of how the glycoprotein liquid looks like after mixing in distilled water (in this example the glycoprotein used was Bovine serum albumin), **(a)** low concentration of the bovine serum albumin (only 0.5%) creates less foam and visible bubbles, **(b)** high concentration of the bovine serum albumin (5%) and more air bubbles and foamy liquid is visible

## 4.5 Testing the first hypothesis

### *4.5.1 Phase One: Purpose of the Phase*

The purpose of this phase was to test the lowest possible percentage of glycoprotein that could be used to stabilise the adobe bricks. The first percentage tested was selected based on the results of the investigation that was carried out by Gillman and his colleagues in 1972. They have analysed a mound soil of the *Coptotermes Acinaciformis* termites in Australia. They have found out that the concentration of the glycoprotein in 1 kg of mound's soil was approximately 0.1% (Gillman et al., 1972). As a result, 0.1 by weight % of glycoprotein was the lowest percentage used to stabilise adobe bricks in this study. All the glycoproteins identified as potential stabilisers in section 3.2 (bovine serum albumin, gelatine from cold-water fish skin, mucin from porcine stomach and termite's saliva ingredients) were used to prepare adobe bricks with 0.1% concentration and then the bricks were tested for their unconfined compressive strength.

### 4.5.2 Phase One: The Results

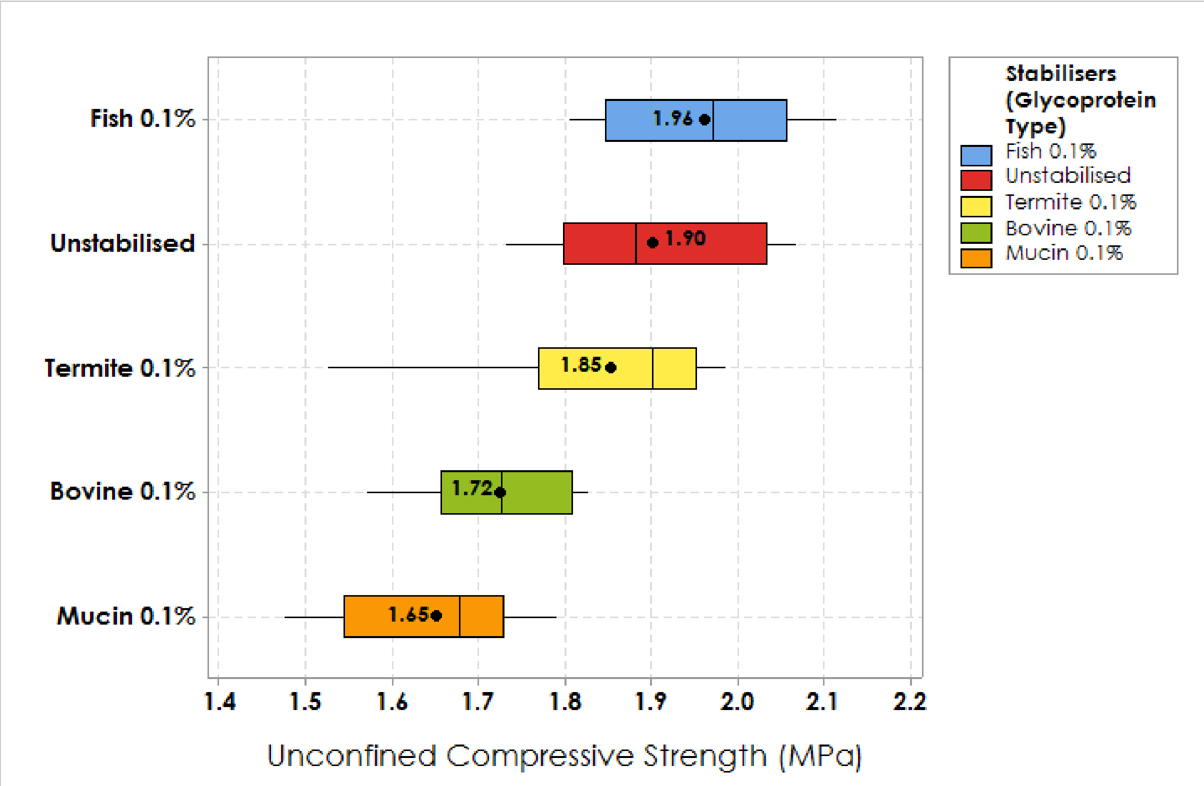



**Figure 4-8:** The effect of adding 0.1% from the glycoproteins on the compressive strength of the British stabilised adobe bricks. *The boxplots represent the inter-quartile range of the data obtained*

Figure 4-8 shows the unconfined compressive strength results of the British glycoprotein stabilised adobe bricks and the British unstabilised bricks which was used as the control sample. The addition of 0.1% of fish gelatine resulted in 3.2% increase in the mean compressive strength of the British adobe bricks. On the other hand, the addition of 0.1% termite's saliva ingredients, bovine serum albumin and mucin resulted in 2.6%, 9.5% and 13.2% reduction in the mean compressive strength of the British adobe bricks respectively.

### 4.5.3 Phase One: Statistical Analysis of the Results

To check the significance difference of the test results, a one-way ANOVA was conducted to compare the effect of the type of the glycoprotein on the compressive strength of the British adobe bricks, Table 4-2. The null hypothesis was that the means of the compressive strength for all the stabilised and unstabilised British adobe bricks come from the same overall population. An analysis of variance showed that the effect of the type of the glycoprotein on the compressive strength was statistically significant, $F$ (4, 25) = 6.169, $p$ = 0.001, Table 4-2. Thus, the differences in the means of the compressive strength among the stabilised and the unstabilised British adobe bricks are significant and thus they are not coming from the same overall population.

**Table 4-2:** One-way ANOVA at 95% confidence interval for unstabilised and 0.1% stabilised British adobe bricks (stabilisers are: Bovine serum albumin, Fish gelatine, Mucin & Termite's saliva ingredients)

| ***Source of Variation*** | ***Sum of Squares (SS)*** | ***Degree of Freedom (df)*** | ***Mean Sum of Squares (MS)*** | ***F*** | ***P-value*** | ***F crit*** |
|---|---|---|---|---|---|---|
| **Between Groups** | 0.393 | 4 | 0.098 | 6.169 | 0.001 | 2.759 |
| **Within Groups** | 0.398 | 25 | 0.016 | | | |
| **Total** | 0.792 | 29 | | | | |

### *4.5.4 Phase One: The Findings*

The above statistical analysis supports the first hypothesis as far as the compressive strength is concerned in this study even though only one glycoprotein has enhanced the compressive strength of the British adobe bricks. Doubling the concentration of the glycoprotein in the adobe bricks will assist in determining the effect of the addition of the glycoproteins on the compressive strength of the British adobe bricks. The next section will cover the results of the second phase (using 0.2 by weight % of glycoprotein).

### *4.5.5 Phase Two: Purpose of the Phase*

The main purpose of this phase was to investigate if there was any effect on the compressive strength of the British adobe bricks due to the increase of the concentration of the glycoprotein to 0.2 by weight %. All the four stabilisers were tested and the results were compared with the compressive strength results of the controlled sample (the unstabilised British adobe bricks).

### 4.5.6 Phase Two: The Results

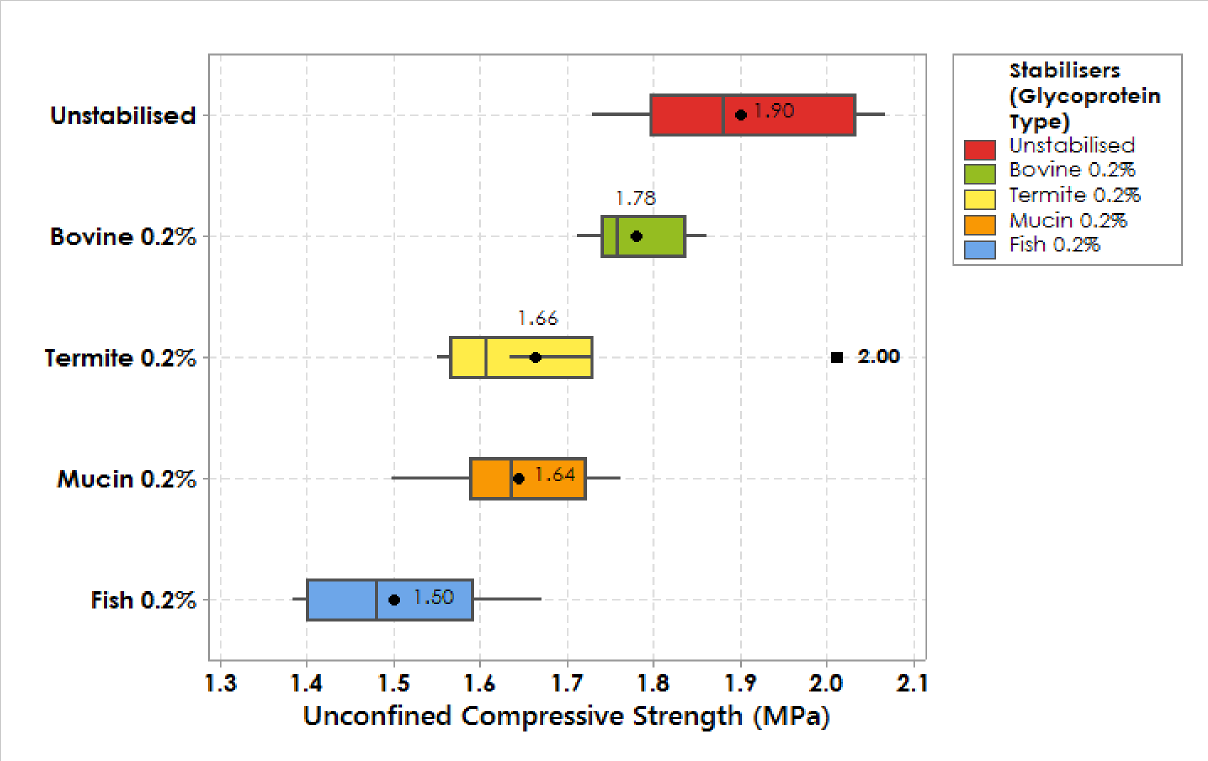



**Figure 4-9:** The effect of adding 0.2% from the glycoproteins on the compressive strength of the British adobe bricks. *The boxplots represent the inter-quartile range of the data obtained*

Figure 4-9 shows the unconfined compressive strength results of the British adobe stabilised and unstabilised bricks. The addition of 0.2 by weight % of glycoprotein reduced the compressive strength for all the stabilised adobe bricks irrespective of the glycoprotein type. The reduction in the compressive strength for the stabilised British adobe bricks was 6.3%, 12.6%, 13.7% and 21.1%, respectively for bovine serum albumin, termite's saliva ingredients, mucin and fish gelatine. For the 0.2% termite's saliva ingredients stabilised adobe bricks the data points for compressive strength were 1.50, 1.60, 1.60, 1.60, 1.60 and 2.00 MPa, this why the 2.00 MPa was an outlier in this sample.

### 4.5.7 Phase Two: Statistical Analysis of the Results

To check the significance difference of the test results, a one-way ANOVA was conducted to compare the effect of the type of the glycoprotein on the compressive strength of the British adobe bricks, Table 4-3. The null hypothesis was that the means of the compressive strength for all the stabilised and unstabilised British adobe bricks come from the same overall population. An analysis of variance showed that the effect of the type of glycoprotein on the compressive strength was statistically significant, $F$ (4, 25) = 9.967, $p$ = 0.000, Table 4-3. Thus, the differences in the means of the compressive strength among the stabilised and the unstabilised British adobe bricks are significant and they are not coming from the same overall population.

**Table 4-3:** One-way ANOVA at 95% confidence interval for unstabilised and 0.2% stabilised British adobe bricks (stabilisers are: Bovine serum albumin, Fish gelatine, Mucin & Termite's saliva ingredients)

| ***Source of Variation*** | ***Sum of Squares (SS)*** | ***Degree of Freedom (df)*** | ***Mean Sum of Squares (MS)*** | ***F*** | ***P-value*** | ***F crit*** |
|---|---|---|---|---|---|---|
| **Between Groups** | 0.551 | 4 | 0.138 | 9.967 | 0.000 | 2.759 |
| **Within Groups** | 0.345 | 25 | 0.014 | | | |
| **Total** | 0.896 | 29 | | | | |

## *4.5.8 Phase Two: The Findings*

From the statistical analysis of phases one and two, the addition of the different glycoproteins influences the compressive strength of the British adobe bricks. All the glycoproteins negatively influence the compressive strength except for the 0.1% fish gelatine. In order to eliminate one of these glycoproteins from further investigations in phase three, a comparison of the results of both phases took place.

### 4.5.9 Phase One and Two: Comparison of the Results

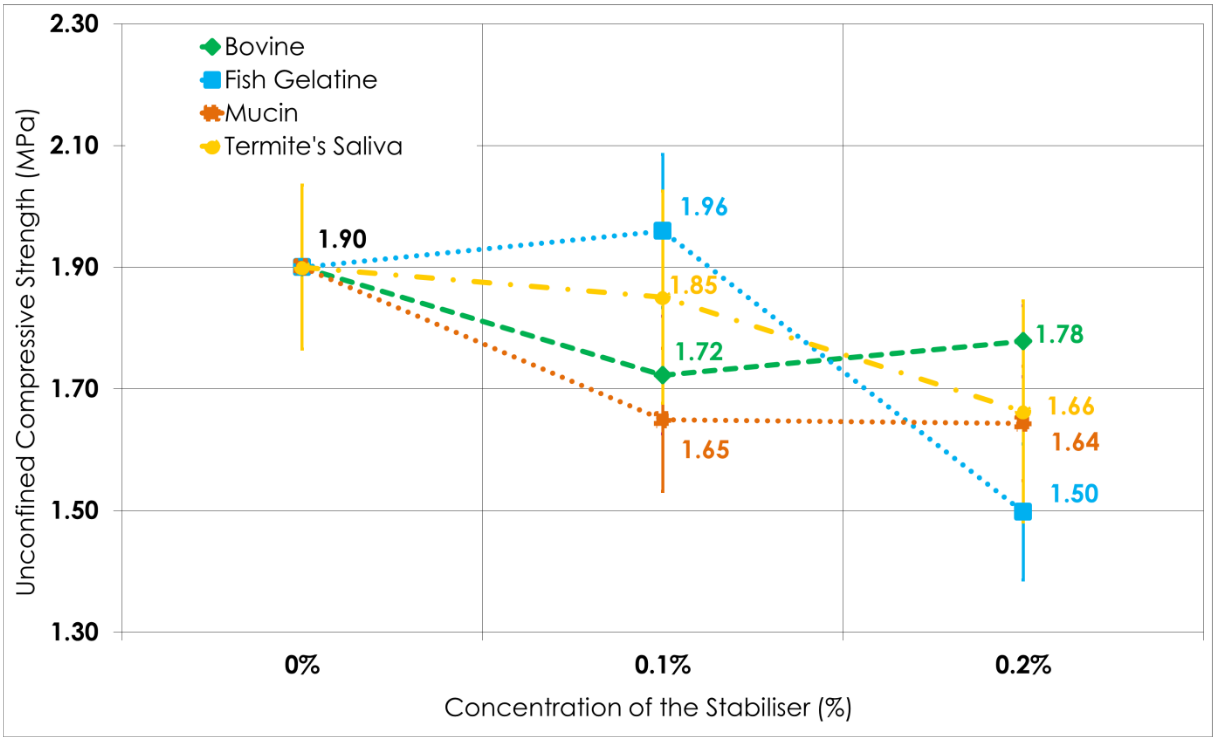



**Figure 4-10:** The unconfined compressive strength of the unstabilised and the stabilised British adobe bricks using different glycoproteins with two concentrations (0.1% & 0.2%). *The error bars represent 95% confidence level for n=6 bricks*

Figure 4-10 shows the effect of the addition of the glycoproteins (bovine serum albumin, gelatine from cold water fish skin, mucin from porcine stomach & termite's saliva ingredients) on the compressive strength of the British adobe bricks using two different concentrations (0.1% & 0.2%) along with the compressive strength of the British unstabilised adobe brick (used as controlled sample). Bovine serum albumin, gelatine from cold water fish skin and termite's saliva ingredients had resulted in different compressive strength when the concentration was changed from 0.1% to 0.2%. Doubling the concentration of the bovine serum albumin has increased the compressive strength of the British adobe bricks from 1.72 MPa to 1.78 MPa. In contrast, doubling the concentration of the fish gelatine has decreased the compressive strength of the British adobe bricks from 1.96 MPa to 1.50 MPa. The increase of the termite's saliva ingredients from 0.1% to 0.2% has resulted in the reduction of the compressive strength from 1.85 MPa to 1.66 MPa. Increasing the concentration of the mucin has no effect on the compressive strength, the compressive strength of the

British adobe bricks was 1.65 MPa for 0.1% concentration and 1.64 MPa for 0.2% concentration.

### 4.5.10 Phase One and Two: Statistical Analysis of the Results

A two-way ANOVA analysis was conducted to determine whether the glycoproteins concentration or the glycoproteins type is more important for enhancing the compressive strength of the British adobe bricks, Table 4-4.

**Table 4-4:** Two-way ANOVA statistics for concentration of the glycoprotein vs. the glycoprotein types (compressive strength of the adobe British bricks), the concentrations are 0.1% & 0.2%, and glycoprotein types are Bovine serum albumin, Fish gelatine, Mucin & Termite's saliva ingredients

| *Source of Variation* | *Sum of Squares (SS)* | *Degree of Freedom (df)* | *Mean Sum of Squares (MS)* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Glycoprotein concentration (%)** | 0.270 | 1 | 0.270 | 18.66 | 0.000 | 4.085 |
| **Glycoprotein types** | 0.094 | 3 | 0.031 | 2.16 | 0.108 | 2.839 |
| **Interaction** | 0.485 | 3 | 0.162 | 11.19 | 0.000 | 2.839 |
| **Within** | 0.579 | 40 | 0.014 | | | |
| **Total** | 1.427 | 47 | | | | |

A two-way analysis of variance was conducted on the influence of two independent variables (glycoprotein concentration, glycoprotein type) on the compressive strength of the British adobe bricks. Glycoprotein concentration included two levels (0.1% and 0.2%) and glycoprotein type consisted of four levels (Bovine serum albumin, Fish gelatine, Mucin and Termite's saliva ingredients). All effects were statistically significant at the 0.05 significance level except for the glycoprotein type factor. The main effect for glycoprotein concentration yielded an F ratio of $F\ (1, 40) = 18.66$, $p < 0.001$, indicating a significant difference between 0.1% glycoprotein (M = 1.80, SD = 0.169), and 0.2% glycoprotein (M = 1.65, SD = 0.148). The main effect for glycoprotein type yielded an F ratio of $F\ (3, 40) = 2.16$, $p > 0.05$, indicating that the effect for glycoprotein type was not significant, bovine serum albumin (M = 1.75, SD = 0.078), fish gelatine (M = 1.73, SD = 0.264), mucin (M = 1.65, SD = 0.097) and termite's saliva ingredients (M = 1.76, SD = 0.189). The interaction effect was significant, $F$ (3, 40) = 11.19, $p < 0.001$.

In addition, the ANOVA results indicate that for the compressive strength, the concentration of the glycoprotein ($F$= 19) is on average dominant over the glycoprotein types ($F$=2). To investigate this in more depth, more glycoprotein concentrations will be tested in phase three.

Furthermore, and based on the above significant interaction between the effect of the type of the glycoproteins and the concentration of these glycoproteins on the compressive strength, Dunnett's multiple comparison test which is a post-hoc test was conducted. Dunnett's multiple comparison test was used to compare the compressive strength of the glycoproteins' stabilised British adobe bricks with different concentrations to the compressive strength of the British unstabilised adobe brick, Figure 4-11. Using this test will provide information on which of the stabilised adobe bricks compressive strength is statistically significant from the compressive strength of the unstabilised British adobe bricks.

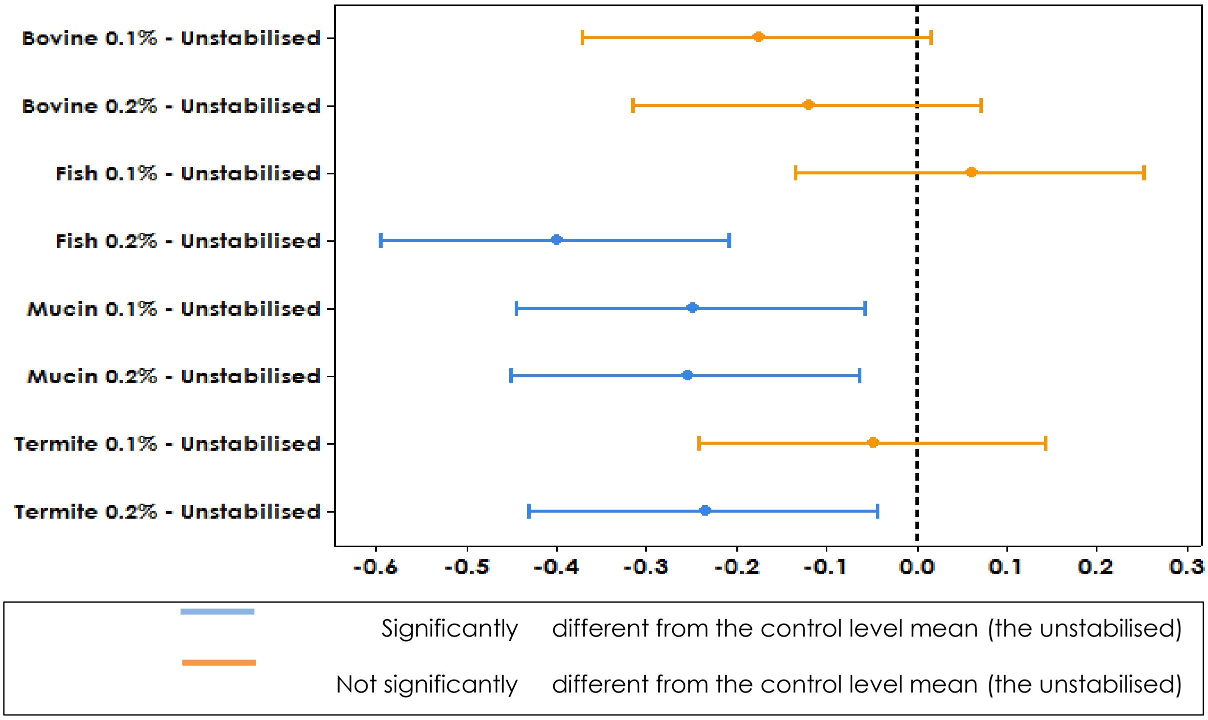



**Figure 4-11:** Dunnett multiple comparisons, the comparison of the means of the different stabilised British adobe bricks compressive strengths from phases one & two to the mean of the unstabilised British adobe brick which was used as the control mean. The test conducted with 95% confident level

The results of the Dunnett multiple comparison show that the means of the compressive strengths of the British adobe bricks which were stabilised using bovine serum albumin (0.1% & 0.2%), fish gelatine 0.1% and termite's saliva ingredients 0.1% are not sigificantly different from the compressive strength of the controlled sample with *p*-values of 0.08, 0.39, 0.95 and 0.98 respectively. In contrast, means of the compressive strengths of the British adobe bricks which were stabilised using fish gelatine 0.2%, mucin (0.1% & 0.2%) and termite's saliva ingredients 0.2% are significantly different from the compressive strength of the controlled sample with *p*-values of 0.000, 0.006, 0.004 and 0.010 respectively.

Further to the above Dunnett multiple comparison test, a one-way ANOVA analysis was conducted on the compressive strength of each glycoprotein type. The one-way ANOVA analysis was used to compare the effect of the increase of the concentration of the glycoprotein on the compressive strength of the British stabilised adobe bricks. The results were divided into four sections based on the glycoprotein types as follows:

a) ***One-way ANOVA statistics for the effect of changing the concentration of the bovine serum albumin from 0.1% to 0.2% on the compressive strength of the British stabilised adobe bricks***

**Table 4-5:** One-way ANOVA statistics for the effect of changing the concentration of the bovine serum albumin from 0.1% to 0.2% on the compressive strength of the British stabilised adobe bricks

| *Source of Variation* | *Degree of Freedom (df)* | *Sum of Squares (SS)* | *Mean Sum of Squares (MS)* | *F* | *P-value* |
|---|---|---|---|---|---|
| **Glycoprotein concentration (%)** | 1 | 0.009 | 0.009 | 1.62 | 0.232 |
| **Error** | 10 | 0.058 | 0.006 | | |
| **Total** | 11 | 0.067 | | | |

Table 4-5, shows that doubling the concentration of the bovine serum albumin from 0.1% to 0.2% has no statistically significant effect on the compressive strength with *p*= 0.232. However, by comparing the compressive strength of the 0.1% with the 0.2% as in the box plot in Figure 4-12, the increase of the bovine serum albumin resulted in the increase of the compressive strength of the British adobe bricks from 1.72 MPa to 1.78 MPa, which is corresponding to 3.5% increase in the compressive strength.

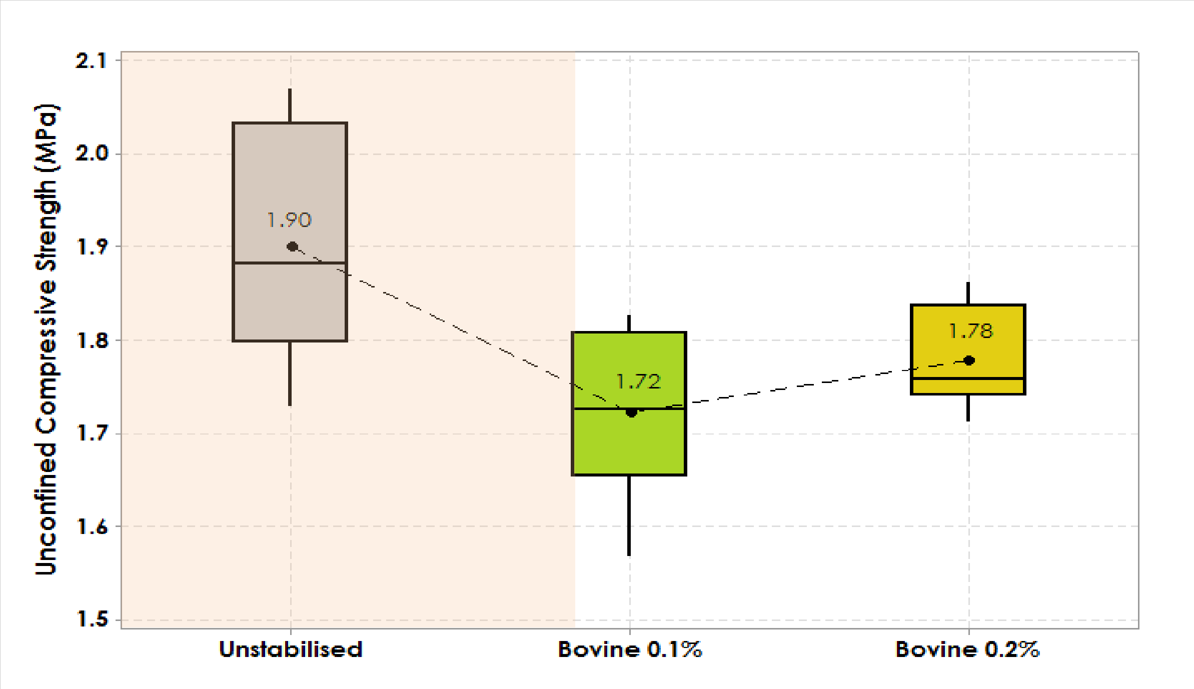



**Figure 4-12:** Box plots represent the inter-quartile range of the unconfined compressive strength data for the unstabilised and bovine 0.1% & 0.2% stabilised British adobe bricks

### *b) One-way ANOVA statistics for the effect of changing the concentration of the fish gelatine from 0.1% to 0.2% on the compressive strength of the British stabilised adobe bricks*

**Table 4-6:** One-way ANOVA statistics for the effect of changing the concentration of the fish gelatine from 0.1% to 0.2% on the compressive strength of the British stabilised adobe bricks

| *Source of Variation* | *Degree of Freedom (df)* | *Sum of Squares (SS)* | *Mean Sum of Squares (MS)* | *F* | *P-value* |
|---|---|---|---|---|---|
| **Glycoprotein concentration (%)** | 1 | 0.640 | 0.640 | 49.66 | 0.000 |
| **Error** | 10 | 0.129 | 0.013 | | |
| **Total** | 11 | 0.769 | | | |

Table 4-6, shows that doubling the concentration of the fish gelatine from 0.1% to 0.2% has a statistically significant effect on the compressive strength of the British stabilised adobe bricks with *p*= 0.000. Furthermore, when comparing the compressive strength of 0.1% with the 0.2% as in Figure 4-13, it is clear that increasing the concentration of the fish gelatine decreased the compressive strength of the British stabilised adobe bricks from 1.96 MPa to 1.50 MPa.

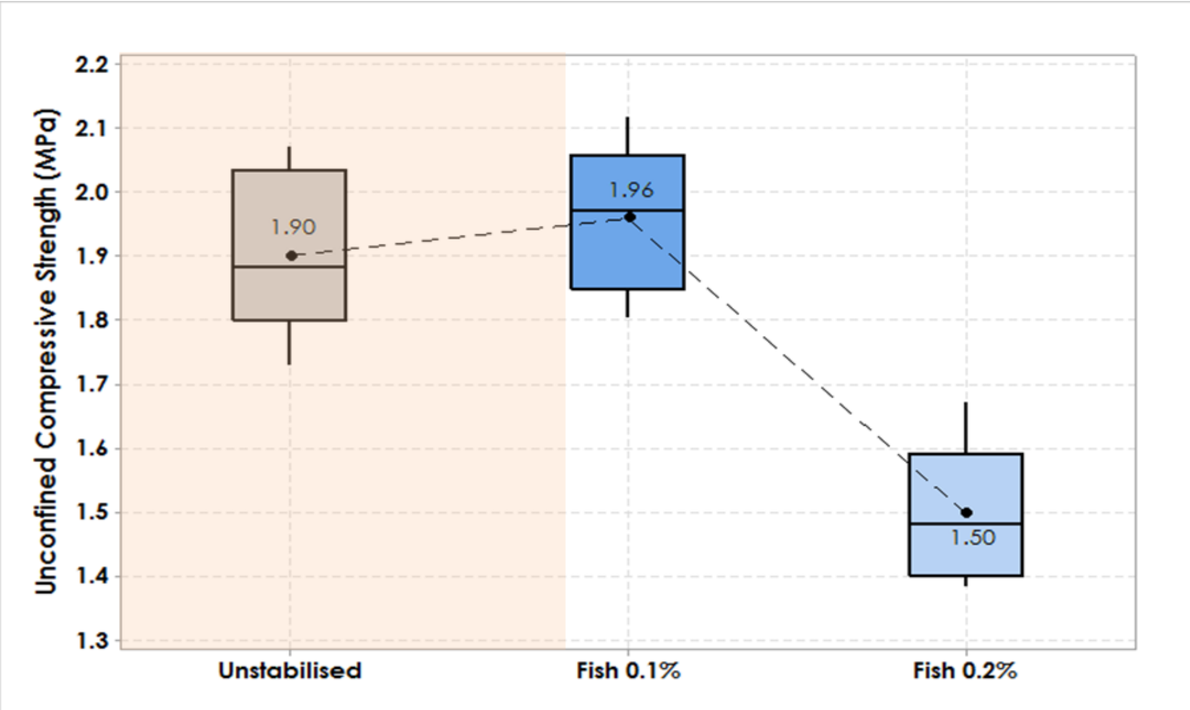



**Figure 4-13:** Box plots represent the inter-quartile range of the unconfined compressive strength data for the unstabilised and fish gelatine stabilised British adobe bricks 0.1% & 0.2%

### c) *One-way ANOVA statistics for the effect of changing the concentration of the mucin from 0.1% to 0.2% on the compressive strength of the British stabilised adobe bricks*

**Table 4-7:** One-way ANOVA statistics for the effect of changing the concentration of the mucin from 0.1% to 0.2% on the compressive strength of the British stabilised adobe bricks

| *Source of Variation* | *Degree of Freedom (df)* | *Sum of Squares (SS)* | *Mean Sum of Squares (MS)* | *F* | *P-value* |
|---|---|---|---|---|---|
| **Glycoprotein concentration (%)** | 1 | 0.000 | 0.000 | 0.01 | 0.920 |
| **Error** | 10 | 0.103 | 0.010 | | |
| **Total** | 11 | 0.103 | | | |

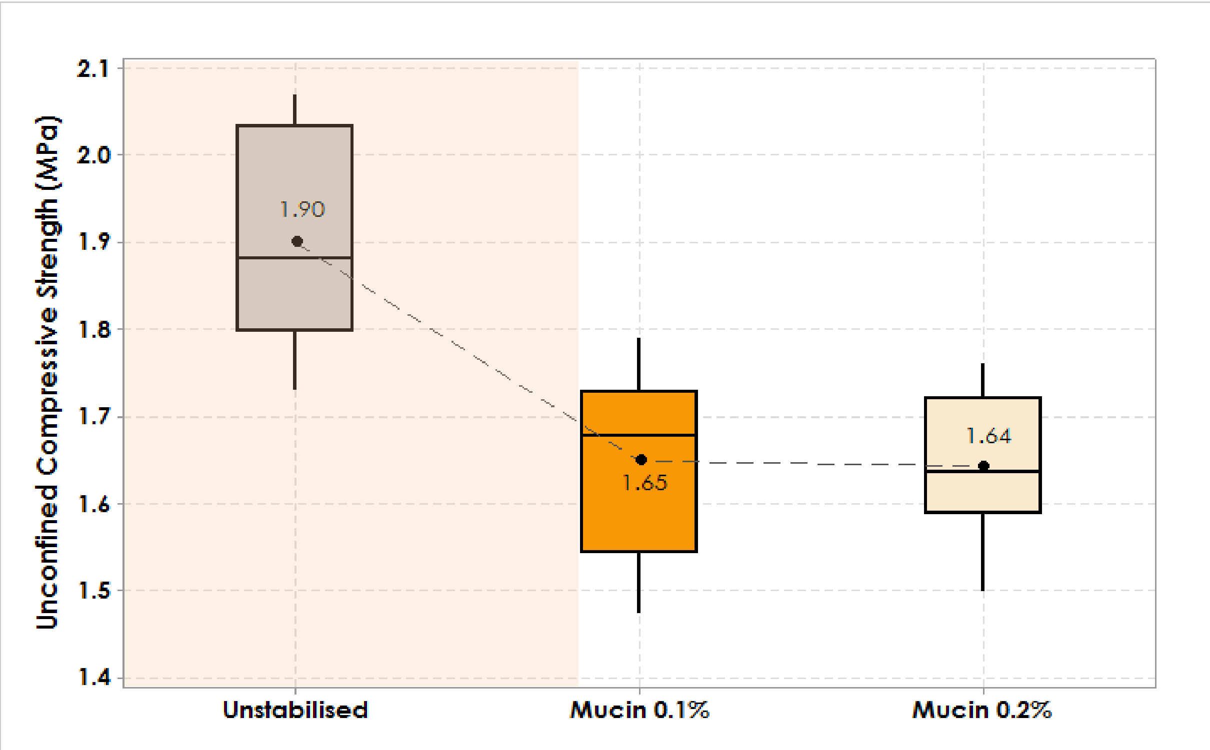



**Figure 4-14:** Box plots represent the inter-quartile range of the unconfined compressive strength data for the unstabilised and mucin stabilised British adobe bricks 0.1% & 0.2%

Table 4-7, shows that doubling the concentration of the mucin from 0.1% to 0.2% has no statistically significant effect on the compressive strength of the British stabilised adobe bricks with $p$= 0.920. In addition, Figure 4-14 confirms the results of the one-way ANOVA test in Table 4-7 and shows that the compressive strength of the mucin stabilised British adobe bricks was 1.65 MPa and then 1.64 MPa for 0.1% and 0.2% respectively.

#### d) One-way ANOVA statistics for the effect of changing the concentration of the termite's saliva ingredients from 0.1% to 0.2% on the compressive strength of the British stabilised adobe bricks

**Table 4-8:** One-way ANOVA statistics for the effect of changing the concentration of the termite's saliva ingredients from 0.1% to 0.2% on the compressive strength of the British stabilised adobe bricks

| ***Source of Variation*** | ***Degree of Freedom (df)*** | ***Sum of Squares (SS)*** | ***Mean Sum of Squares (MS)*** | ***F*** | ***P-value*** |
|---|---|---|---|---|---|
| **Glycoprotein concentration (%)** | 1 | 0.106 | 0.106 | 3.67 | 0.084 |
| **Error** | 10 | 0.289 | 0.029 | | |
| **Total** | 11 | 0.395 | | | |

Table 4-8, shows that doubling the concentration of the termite's saliva ingredients from 0.1% to 0.2% has no statistically significant effect on the compressive strength of the British stabilised adobe bricks with $p$= 0.084. However, the box plot in Figure 4-15 shows that when comparing the compressive strength of the 0.1% and 0.2% stabilised British adobe bricks, the compressive strength is decreasing from being 1.85 MPa to 1.66 MPa as a result of increasing the termite's saliva ingredients. For the 0.2% termite's saliva ingredients stabilised adobe bricks the data points for compressive strength were 1.50, 1.60, 1.60, 1.60, 1.60 and 2.00 MPa, this why the 2.00 MPa was an outlier in this sample.

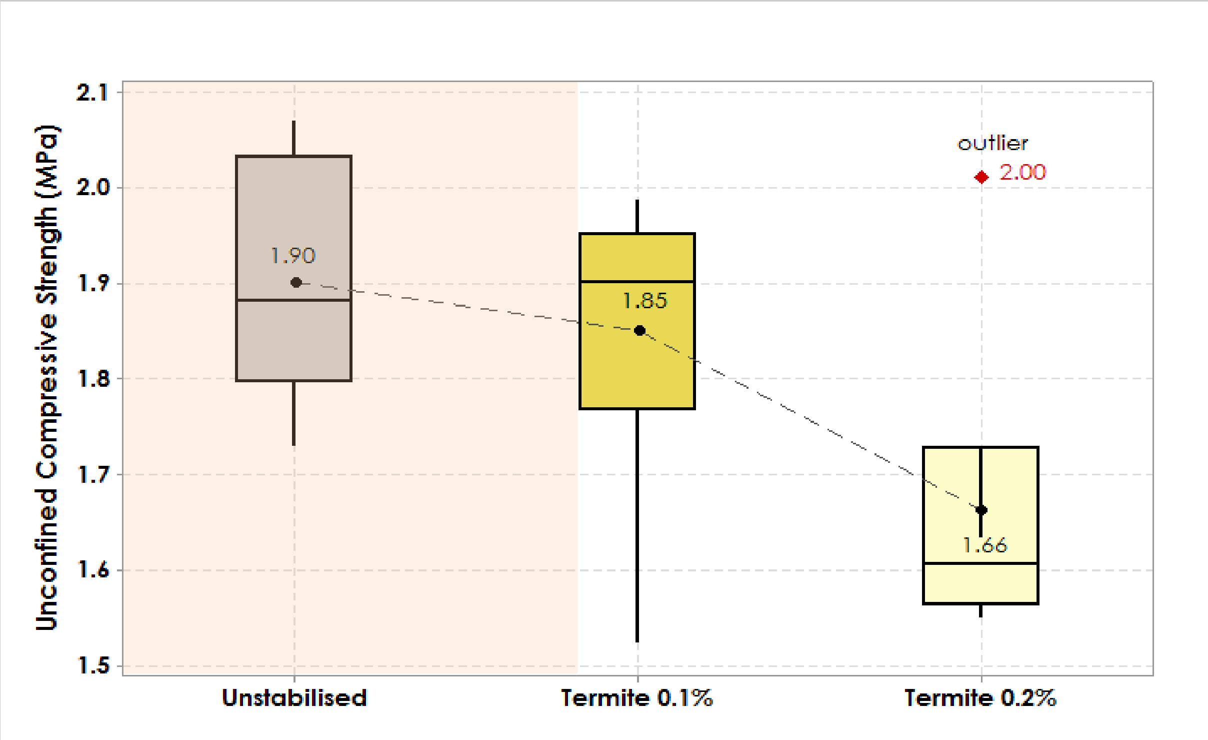



**Figure 4-15:** Box plots represent the inter-quartile range of the unconfined compressive strength data for the unstabilised and termite's saliva ingredients stabilised British adobe bricks 0.1% & 0.2%

### *4.5.11 Phase One and Two: The Findings*

The analysis of phase one and two from the first hypothesis showed that some stabilisers had shown different compressive strengths compared to others. For instance, change the concentration of the bovine serum albumin in the British adobe bricks from 0.1% to 0.2% had resulted in 1.72 MPa and 1.78 MPa. The inclusion of the fish gelatine in the British adobe bricks resulted in 1.96 MPa and 1.50 MPa when the concentration changed from 0.1% to 0.2% respectively. The addition of 0.1% termite's saliva ingredients resulted in 1.85 MPa compared with 1.66 MPa when 0.2% was used. The use of the mucin from the porcine stomach resulted in 1.65 MPa and 1.64 MPa for 0.1% and 0.2% concentrations respectively. This shows that the British adobe bricks made using the mucin as a stabiliser have the same compressive strength irrespective of the change of the mucin concentration in the adobe bricks. Therefore, the mucin from porcine stomach will be eliminated from further investigations in this study. Phase three in the next section will include only bovine serum albumin, fish gelatine and termite's saliva ingredients.

### *4.5.12 Phase Three: Purpose of the Phase*

The purpose of this phase was to test the effect of using higher concentrations of glycoproteins on the compressive strength of the British adobe bricks. Higher concentrations of bovine serum albumin, fish gelatine and termite's saliva ingredients were used to stabilise the British adobe bricks. The higher concentrations used in this phase were 0.3, 0.4 & 0.5 by weight percent glycoprotein. The compressive strength results of the British adobe bricks stabilised using these concentrations was compared with the compressive strength results of the unstabilised British adobe bricks (the controlled sample). At the end of this phase, the stabiliser along with the concentration that had resulted in the best performance in the compressive strength was taken forward to the next phase.

### *4.5.13 The Results for 0.3 by weight % stabiliser*

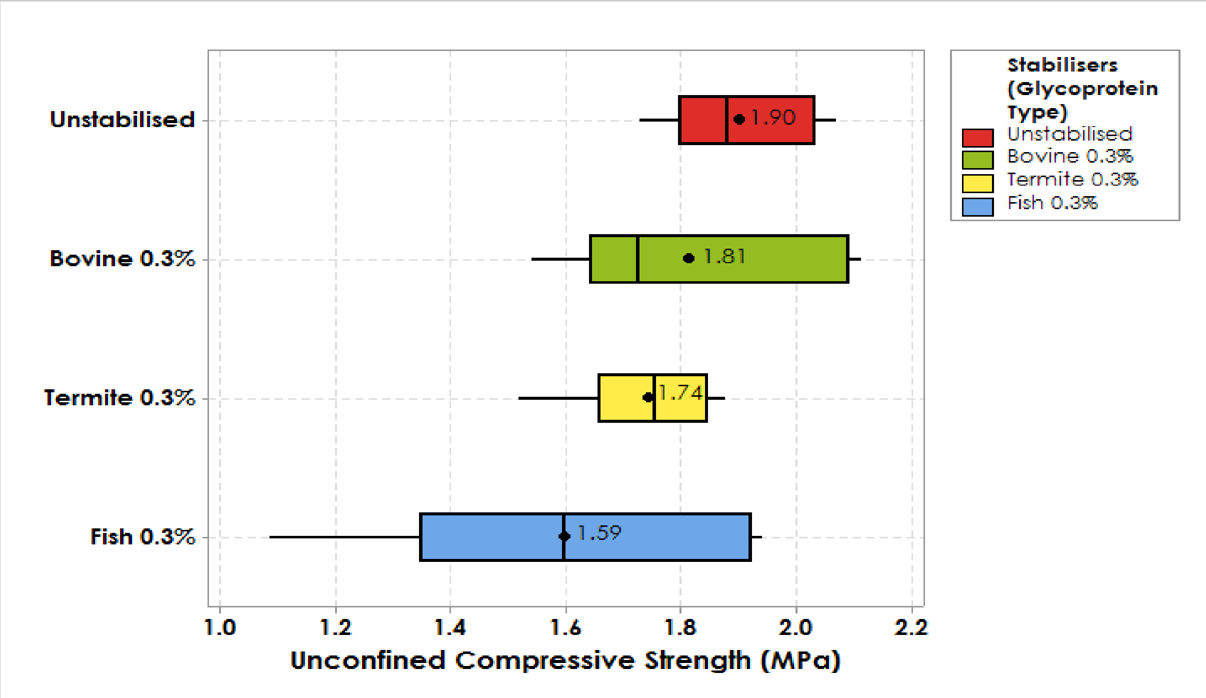



**Figure 4-16:** The effect of adding 0.3% from the glycoproteins on the compressive strength of the British stabilised adobe bricks. *The boxplots represent the inter-quartile range of the data obtained*

Figure 4-16 shows the unconfined compressive strength results for 0.3% British adobe stabilised and unstabilised bricks. By comparing the stabilisers' individual performance on the compressive strength from phase two (0.2% glycoprotein concentration) to this phase (0.3% glycoprotein concentration), it was clear that there is an improvement in the British adobe bricks' compressive strength due to the increase of the glycoprotein concentration. For instance, the compressive strength of the British adobe bricks stabilised using the bovine serum albumin increased from 1.78 MPa to 1.81 MPa corresponding to 1.7% increase in the compressive strength. Furthermore, the use of 0.3% termite's saliva ingredients resulted in a 4.8% increase in the compressive strength (from 1.66 MPa to 1.74 MPa). The addition of 0.3% of the fish gelatine resulted in 6% increase in the compressive strength, and the compressive strength increased from 1.50 MPa to 1.59 MPa when the fish gelatine concentration has increased from 0.2% to 0.3% respectively. However, despite the increase in the compressive strength of the stabilised British adobe bricks based on comparing the individual glycoproteins results, none of the British stabilised adobe bricks' compressive strength was higher than that of the unstabilised British adobe bricks.

### *4.5.14 Statistical Analysis for 0.3 by weight % stabiliser Results*

To check the significance difference of the test results, a one-way ANOVA was conducted to compare the effect of the type of the glycoprotein on the compressive strength of the British adobe bricks, Table 4-9. The null hypothesis was that the means of the compressive strength for all the stabilised and unstabilised British adobe bricks come from the same overall population. An analysis of variance showed that the effect of the type of glycoprotein on the compressive strength was statistically not significant, $F\ (3, 20) = 2.090$, $p = 0.134$, Table 4-9. Thus, the differences in the means of the compressive strength among the stabilised and the unstabilised British adobe bricks are not significant and they are coming from the same overall population.

**Table 4-9:** One-way ANOVA at 95% confidence interval for unstabilised British adobe bricks and 0.3% stabilised British adobe bricks (stabilisers are: Bovine serum albumin, Fish gelatine & Termite's saliva ingredients)

| *Source of Variation* | *Sum of Squares (SS)* | *Degree of Freedom (df)* | *Mean Sum of Squares (MS)* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Between Groups** | 0.300 | 3 | 0.100 | 2.090 | 0.134 | 3.098 |
| **Within Groups** | 0.958 | 20 | 0.048 | | | |
| **Total** | 1.258 | 23 | | | | |

## 4.5.15 The Results for 0.4 by weight % stabiliser

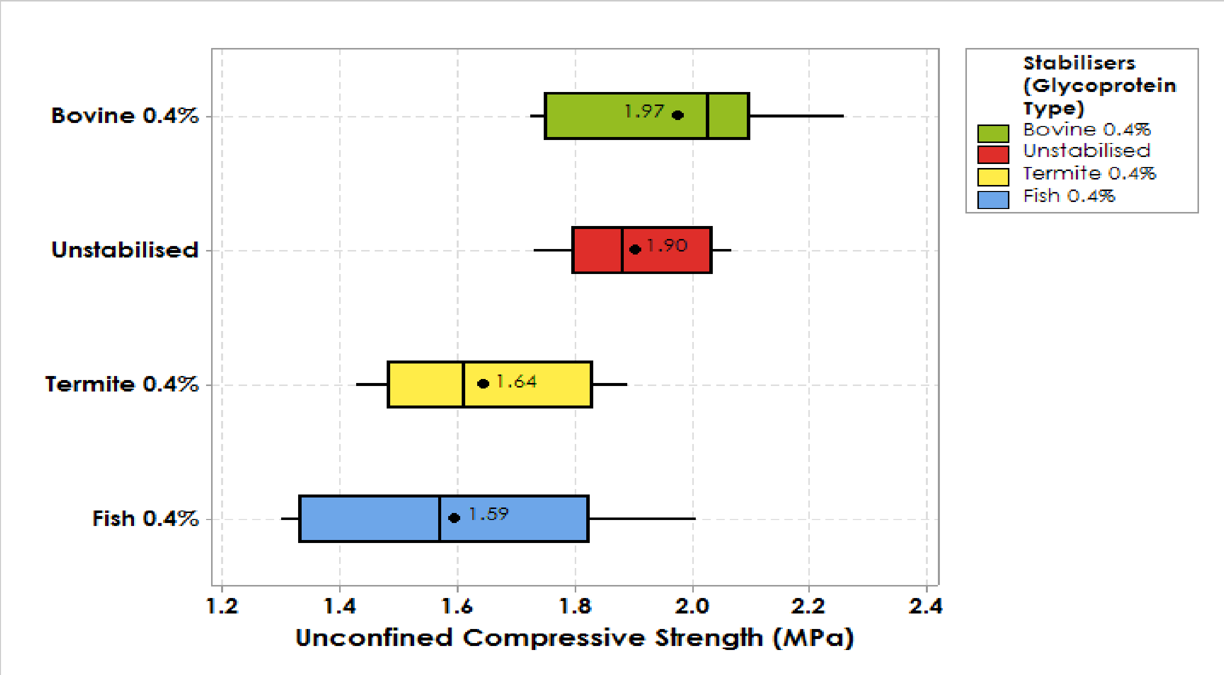



**Figure 4-17:** The effect of adding 0.4% from the glycoproteins on the compressive strength of the British stabilised adobe bricks. *The boxplots represent the inter-quartile range of the data obtained*

Bricks stabilised with 0.4% glycoproteins were produced and tested for their compressive strength. The results of the compressive strength from this concentration were compared to the results from the control sample, the unstabilised British adobe brick.

Figure 4-17 shows the unconfined compressive strength results for the British adobe stabilised and unstabilised bricks. The compressive strength of the bovine stabilised British adobe bricks increased from 1.81 MPa to 1.97 MPa (which was 8.8% increase in the compressive strength) when increasing its concentration from 0.3% to 0.4% respectively. Also, this was the first time during this study the compressive strength of the bovine serum albumin stabilised British adobe brick was higher than the compressive strength of the control sample (the unstabilised British adobe bricks). In total, the addition of 0.4% bovine serum albumin resulted in 3.7% increase in the compressive strength when compared to the compressive strength of the unstabilised British adobe bricks. In contrast, the increase of the termite's saliva ingredients reduced the compressive strength of the British adobe stabilised bricks. The compressive strength of the British adobe bricks decreased from 1.74 MPa when the concentration of the termite's saliva ingredients was 0.3% to 1.64 MPa when the concentration was increased to 0.4%. The increase of the fish gelatine from 0.3% to 0.4% had no effect on the compressive strength of the British adobe bricks. The compressive strength of the fish gelatine British stabilised adobe brick was 1.59 MPa for both concentrations.

### 4.5.16 Statistical Analysis for 0.4 by weight % stabiliser Results

**Table 4-10:** One-way ANOVA at 95% confidence interval for unstabilised British adobe bricks and 0.4% stabilised British adobe bricks (stabilisers are: Bovine serum albumin, Fish gelatine & Termite's saliva ingredients)

| ***Source of Variation*** | ***Sum of Squares (SS)*** | ***Degree of Freedom (df)*** | ***Mean Sum of Squares (MS)*** | ***F*** | ***P-value*** | ***F crit*** |
|---|---|---|---|---|---|---|
| **Between Groups** | 0.639 | 3 | 0.213 | 5.096 | 0.009 | 3.098 |
| **Within Groups** | 0.836 | 20 | 0.042 | | | |
| **Total** | 1.474 | 23 | | | | |

To check the significance difference of the test results, a one-way ANOVA was conducted to compare the effect of the type of the glycoprotein on the compressive strength of the British adobe bricks. The null hypothesis was that the means of the compressive strength for all the stabilised and unstabilised British adobe bricks come from the same overall population, Table 4-10. An analysis of variance showed that the effect of the type of glycoprotein on the compressive strength was statistically significant, $F\ (3, 20) = 5.096$, $p = 0.009$, Table 4-10. Thus, the differences in the means of the compressive strength among the stabilised and the unstabilised British adobe bricks are significant and they are not coming from the same overall population.

### 4.5.17 The Results for 0.5 by weight % stabiliser

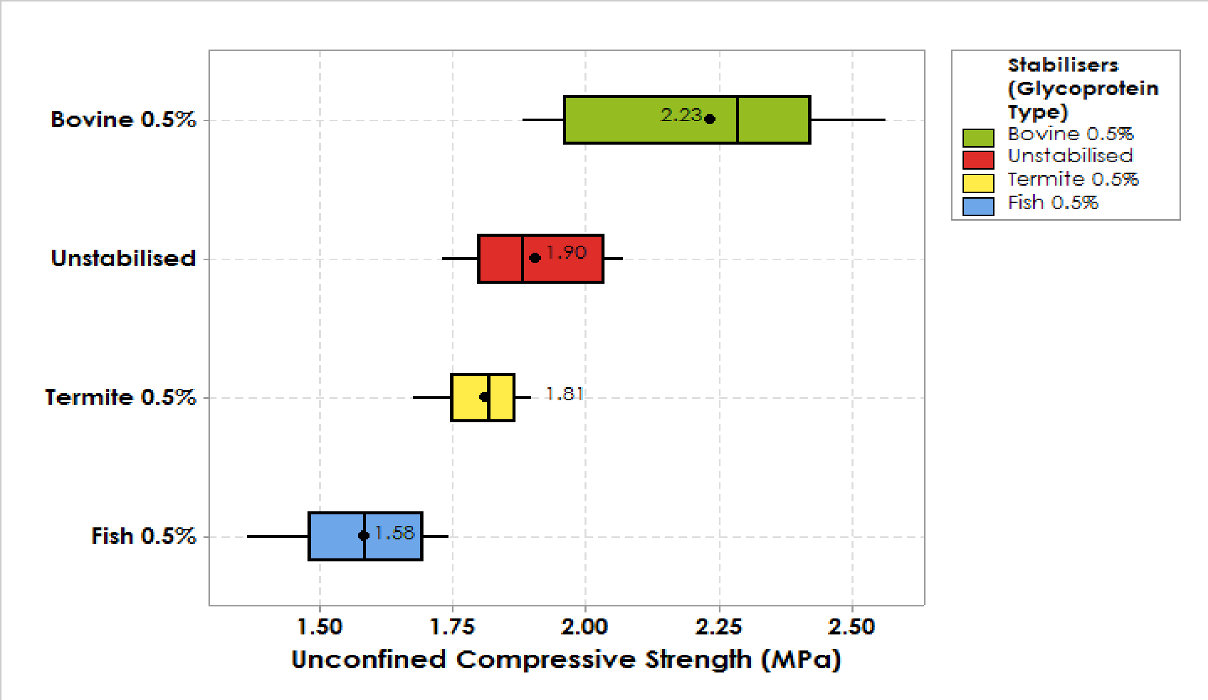



**Figure 4-18:** The effect of adding 0.5% from the glycoproteins on the compressive strength of the British stabilised adobe bricks. *The boxplots represent the inter-quartile range of the data obtained*

Figure 4-18 shows the unconfined compressive strength results for the British adobe stabilised and unstabilised bricks. The compressive strength of the bovine serum albumin stabilised British adobe bricks increased from 1.97 MPa to 2.23 MPa (which is 13.2% increase) when the concentration of the bovine serum albumin in the British adobe bricks increased from 0.4% to 0.5% respectively. In addition, increasing the concentration of the termite's saliva ingredients from 0.4% to 0.5% resulted in increasing the compressive strength of the British adobe brick from 1.64 MPa to 1.81 MPa. In contrast, the increase of the concentration of the fish gelatine did not change the compressive strength of the British adobe bricks. The compressive strength of the British fish gelatine stabilised adobe bricks was constant and below the compressive strength of the unstabilised control sample at 1.60 MPa for 0.3%, 0.4% and 0.5% concentrations. In general, the trend observed in Figure 4-18 is similar to that of Figure 4-17 with the bovine stabilised adobe bricks had the highest compressive strength and the British adobe bricks stabilised using the fish gelatine had the lowest compressive strength.

### 4.5.18 Statistical Analysis for 0.5 by weight % stabiliser Results

**Table 4-11:** One-way ANOVA at 95% confidence interval for unstabilised British adobe bricks and 0.5% stabilised British adobe bricks (stabilisers are: Bovine serum albumin, Fish gelatine & Termite's saliva ingredients)

| *Source of Variation* | *Sum of Squares (SS)* | *Degree of Freedom (df)* | *Mean Sum of Squares (MS)* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Between Groups** | 1.310 | 3 | 0.437 | 16.590 | 0.000 | 3.098 |
| **Within Groups** | 0.526 | 20 | 0.026 | | | |
| **Total** | 1.837 | 23 | | | | |

To check the significance difference of the test results, a one-way ANOVA was conducted to compare the effect of the type of the glycoprotein on the compressive strength of the British adobe bricks. The null hypothesis was that the means of the compressive strength for all the stabilised and unstabilised British adobe bricks come from the same overall population, Table 4-11. An analysis of variance showed that the effect of the type of glycoprotein on the compressive strength was statistically significant, $F$ (3, 20) = 16.590, $p$ = 0.000, Table 4-11. Thus, the differences in the means of the compressive strength among the stabilised and the unstabilised British adobe bricks are significant and they are not coming from the same overall population.

### 4.5.19 Comparison of the Results of Phase Three: 0.3%, 0.4% & 0.5% glycoprotein concentration

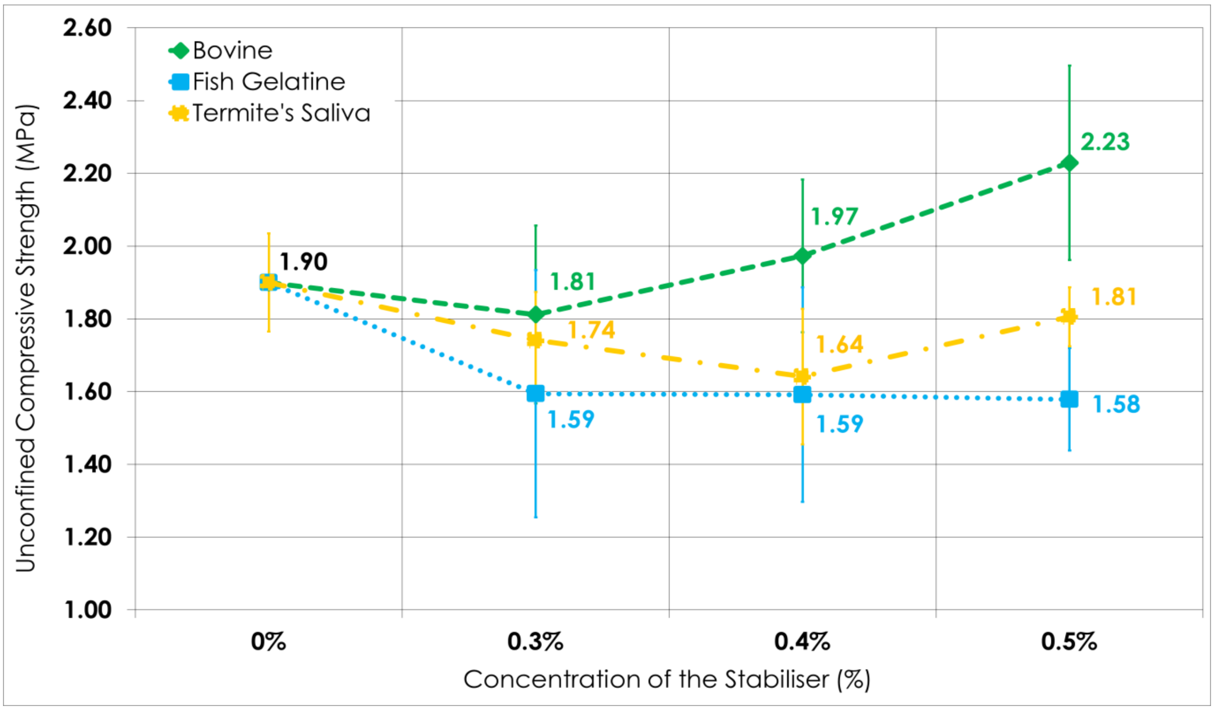



**Figure 4-19:** The unconfined compressive strength for the unstabilised and the stabilised British adobe bricks using different glycoproteins with three concentrations (0.3%, 0.4% & 0.5%). The error bars represent 95% confidence level for n=6 bricks

Figure 4-19 above shows the effect of the addition of the glycoproteins (bovine serum albumin, gelatine from cold water fish skin & termite's saliva ingredients) on the compressive strength of the British adobe bricks using different concentrations (0.3%, 0.4% & 0.5%) compared with the compressive strength of the unstabilised British adobe brick (the control sample). The increase on the compressive strength of the British bovine stabilised adobe bricks is positively correlated with the increase of the concentration of the glycoprotein (the bovine serum albumin) in the bricks' mixture. The compressive strength of the British adobe bricks stabilised with the bovine serum albumin increased from 1.81 MPa to 1.97 MPa and then to 2.23 MPa when the bovine concentration in the adobe brick increased from 0.3% to 0.4% and then to 0.5% respectively. The bricks that were stabilised using 0.5% bovine serum albumin resulted in 17.4% increase in the compressive strength.

The increase of the termite's saliva ingredients concentration in the British adobe bricks resulted in variable compressive strengths. The increase of the termite's saliva ingredient resulted in compressive strength of 1.74 MPa, 1.64 MPa and 1.81 MPa for 0.3%, 0.4% and 0.5% concentrations respectively.

The increase of the fish gelatine decreased the compressive strength of the British adobe bricks when it is compared with the British unstabilised control sample compressive strength. Due to the addition of the fish gelatine there was up to 16.8% reduction in the compressive strength of the British adobe bricks. By far, the inclusion of the fish gelatine as stabiliser for the British adobe bricks resulted in the lowest compressive strength. The compressive strength remained at 1.60 MPa despite the increase of the concentration of the fish gelatine from 0.3% to 0.4% and then to 0.5%.

### *4.5.20 Statistical Analysis for Results of Phase Three: 0.3%, 0.4% & 0.5% glycoprotein concentration*

There were two main factors affecting the compressive strength of the British adobe bricks. These two factors were the glycoproteins' type and the different concentrations of these glycoproteins. The results in section 4.5.19 above showed that both factors affected the compressive strength of the British adobe bricks.

**Table 4-12:** Two-way ANOVA statistics for concentration of the glycoprotein vs. the glycoprotein types (compressive strength of the adobe British bricks), the concentrations are 0.3%, 0.4% & 0.5%, and the glycoprotein types are Bovine serum albumin, Fish gelatine & Termite's saliva ingredients

| ***Source of Variation*** | ***Sum of Squares (SS)*** | ***Degree of Freedom (df)*** | ***Mean Sum of Squares (MS)*** | ***F*** | ***P-value*** |
|---|---|---|---|---|---|
| **Glycoprotein concentration (%)** | 0.258 | 2 | 0.129 | 2.80 | 0.072 |
| **Glycoprotein types** | 1.614 | 2 | 0.807 | 17.52 | 0.000 |
| Interaction | 0.356 | 4 | 0.089 | 1.93 | 0.121 |
| Within | 2.072 | 45 | 0.046 | | |
| Total | 4.300 | 53 | | | |

Table 4-12 shows the results of a two-way analysis of variance which was conducted on the influence of two independent variables (the glycoprotein concentrations, the glycoprotein types) on the unconfined compressive strength of the British adobe bricks. Table 4-12 also shows the combined effect (the interaction) of these two variables on the compressive strength of the British adobe bricks. The glycoprotein concentrations included three levels (0.3, 0.4 and 0.5 by weigh percent concentration) and the glycoprotein types consisted of three levels (bovine serum albumin, fish gelatine and termite's saliva ingredients). All effects were statistically not significant at the 0.05 significance level except for the effect of the glycoprotein type. The main effect for glycoprotein concentrations yielded an *F* ratio of $F\ (2, 45) = 2.80$, $p > 0.05$, indicating that the effect for glycoprotein concentration was not significant, 0.3% glycoprotein (M = 1.72, SD = 0.245), 0.4% glycoprotein (M = 1.74, SD = 0.273) and 0.5% glycoprotein (M = 1.87, SD = 0.321). The main effect for glycoprotein types yielded an F ratio of $F\ (2, 45) = 17.52$, $p < 0.001$, indicating a significant difference between bovine serum albumin (M = 2.00, SD = 0.279), fish gelatine (M = 1.59, SD = 0.244) and termite's saliva ingredients (M = 1.73, SD = 0.143). The interaction effect between the glycoprotein concentrations and the glycoprotein types on the compressive strength of the British adobe bricks was not significant, $F\ (4, 45) = 1.93$, $p > 0.05$. This ANOVA analysis shows that there is no interaction but there is main effect which is the glycoprotein type. Changing the glycoprotein type from bovine serum albumin to fish gelatine or termite's saliva ingredients has more effect on the compressive strength comparing with the effect of the concentrations of these glycoproteins.

## 4.5.21 The First Hypothesis: Comparison of the results alone and in the light of the dry density

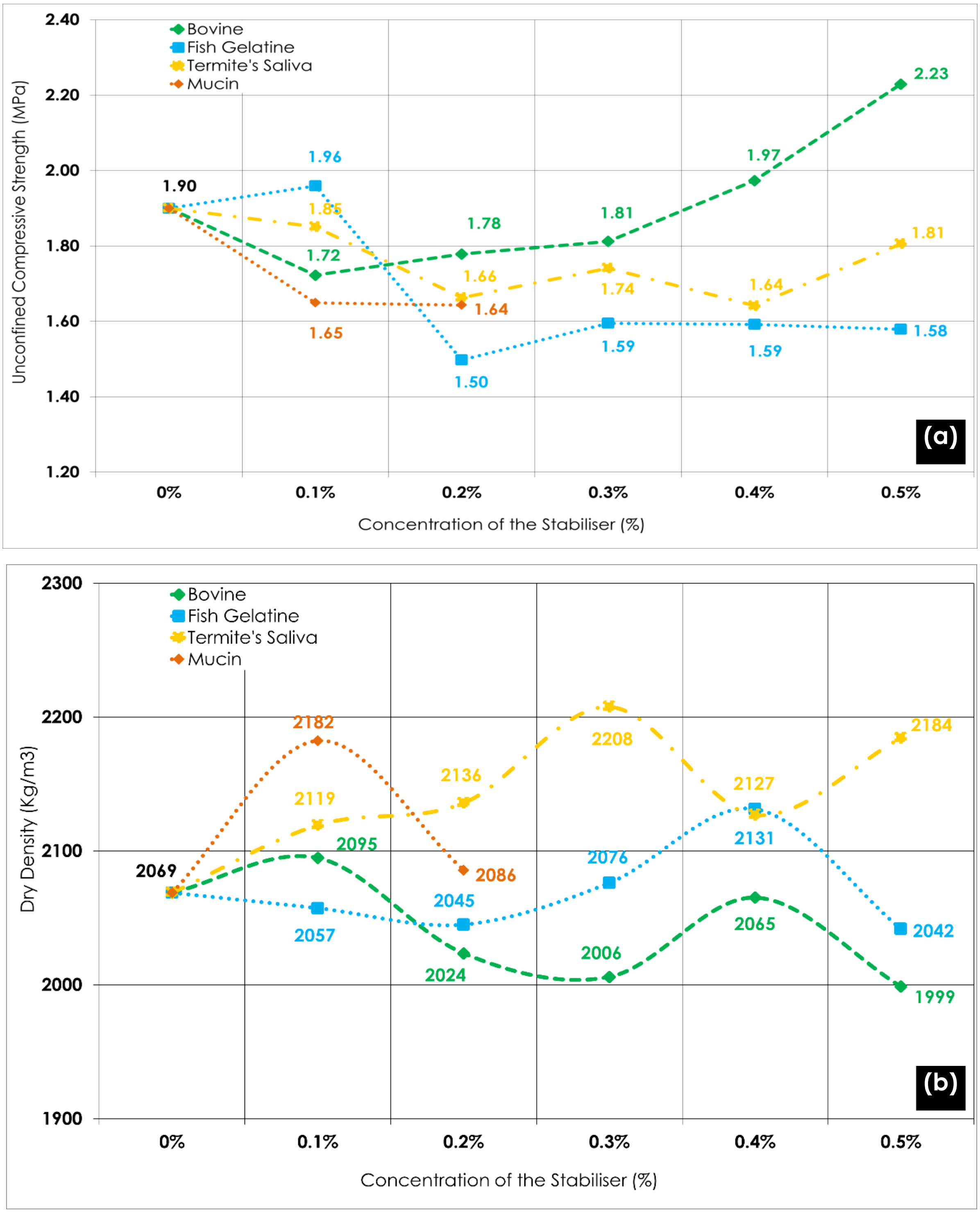



**Figure 4-20: (a)**The unconfined compressive strength of the unstabilised and the stabilised British adobe bricks using different glycoproteins with all the concentrations (0.1%, 0.2%, 0.3%, 0.4% &0.5%), **(b)** The dry density of the unstabilised and the stabilised British adobe bricks using different glycoproteins with all the concentrations (0.1%, 0.2%, 0.3%, 0.4% &0.5%)

The first hypothesis in this study was that the addition of the glycoprotein to the British adobe bricks will have an effect on the adobe brick's durability and strength. Figure 4-20 (a), shows that the addition of the different glycoproteins, bovine serum albumin, fish gelatine, mucin & termite's saliva ingredients, has affected the compressive strength of the British adobe bricks. There was a difference on the magnitude of the effect between the different glycoproteins and their concentrations on the adobe bricks. For instance, concentrations (0.1%, 0.2% & 0.3%) of bovine serum albumin reduced the compressive strength of the British adobe bricks. The compressive strength of the British adobe bricks decreased from 1.90 MPa (the compressive strength of the unstabilised British adobe bricks) to 1.72 MPa when using 0.1% of bovine serum albumin as a stabiliser. Then the compressive strength of the bovine stabilised adobe bricks increased progressively from 1.72 MPa to 1.78 MPa and then reach 1.81 MPa as a result of the increase of the concentration of the bovine serum albumin from 0.1% to 0.2% and then to 0.3% respectively. Despite the increase in the compressive strength as a direct result of the increase of the bovine serum albumin concentration on the bricks, the compressive strength of the bovine serum albumin stabilised British adobe bricks at 0.3% concentration was still lower than that of the control unstabilised adobe bricks. A significant and noticeable increase in the compressive strength was achieved when higher concentrations (0.4% and 0.5%) of the bovine serum albumin were used to stabilise the British adobe bricks. The compressive strength of the British adobe bricks increased from 1.90 MPa (compressive strength of the unstabilised British adobe bricks) to 1.97 MPa when using 0.4% bovine serum albumin and then to 2.23 MPa when 0.5% bovine serum albumin was used in the stabilisation.

On the other hand, stabilising the adobe bricks using 0.1% of the gelatine from cold water fish skin resulted in an increase on the compressive strength. The compressive strength of the British adobe bricks increased from 1.90 MPa to 1.96 MPa. The compressive strength of the British adobe bricks dropped from 1.90 MPa (for the unstabilised control sample) to 1.50 MPa when stabilised with 0.2% fish gelatine. Further increase in the concentration of the fish gelatine to 0.3% resulted in increasing the compressive strength of the adobe bricks from 1.50 MPa to 1.59 MPa which was still below the compressive strength of the unstabilised British adobe bricks. The addition of more fish gelatine (0.4% and 0.5%) did not increase the compressive strength of the adobe bricks and the bricks' compressive strength remained constant at 1.59 MPa.

Moreover, the termite's saliva ingredients had an inconsistent effect on the compressive strength of the British adobe bricks. As has been mentioned before in section 3.2.4, this stabiliser was a mixture of the ingredients of the termite's glycoprotein that was available in the saliva and it was used by the termites as the cementing adhesive during their mound construction. The addition of 0.1% of the termite's saliva ingredients to the British adobe bricks reduced the compressive strength from 1.90 MPa to 1.85 MPa. By increasing the concentration of the termite's saliva ingredients on the British adobe bricks to 0.2%, the compressive strength decreased to 1.66 MPa. Adding more termites' saliva ingredients to the adobe bricks to reach 0.3% concentration increased the compressive strength of the adobe bricks to reach 1.74 MPa. However, increasing the concentration of the termite's saliva ingredients to 0.4% resulted in the decrease of the compressive strength of the adobe bricks to 1.64 MPa. A further increase in the concentration of the termite's saliva ingredients in the British adobe bricks resulted in a compressive strength of 1.81 MPa. The compressive strength of this British stabilised adobe brick was still below the compressive strength of the unstabilised British adobe bricks.

Finally, the addition of 0.1% mucin to the adobe bricks reduced the compressive strength from 1.90 MPa to 1.65 MPa. Further increase of the mucin concentration in the bricks up to 0.2% resulted in the same compressive strength achieved when using 0.1% mucin concentration.

Figure 4-20 (b), shows the dry density of the unstabilised and all the stabilised adobe bricks with different glycoproteins and their concentrations. From Figure 4-20 (b), the bricks stabilised using bovine serum albumin for all the concentrations had lower density than that of the unstabilised adobe bricks except of 0.1% concentration. However, this glycoprotein for higher concentrations above 0.3% resulted in increasing the compressive strength of the bricks compared with the unstabilised adobe bricks. The highest compressive strength was 2.23 MPa which was achieved when 0.5% bovine serum albumin was used and this concentration resulted in the lowest dry density achieved (1999 kg/m$^3$).

For the adobe bricks stabilised using fish gelatine, the highest increase in the compressive strength was achieved when 0.1% fish gelatine was used, but at this concentration the dry density was not the highest achieved using this stabiliser. The highest dry density achieved for this stabiliser was when 0.4% fish gelatine was used, 2131 kg/m$^3$. At this concentration, the dry density was higher than the dry density of the unstabilised adobe bricks, however, the compressive strength was lower.

The trend of the dry density of the adobe bricks stabilised using the termite's saliva ingredients followed that of the compressive strength. For instance, when the compressive strength was increased, the dry density was high and the vice versa.

For the adobe bricks stabilised using mucin from porcine stomach, both concentrations used in this study resulted in adobe bricks with dry density higher than the dry density of the unstabilised adobe bricks. However, regardless of the high dry density, both concentrations resulted in compressive strength which was lower than the compressive strength of the unstabilised adobe bricks.

The results above have supported the part that was concerned about the compressive strength from the first hypothesis of this study. The glycoprotein has an effect on the compressive strength of the adobe bricks. The addition of some glycoproteins to the British adobe bricks enhanced the compressive strength of the bricks. By comparing and contrasting the above results from different glycoproteins with their different concentrations, the bovine serum albumin has proved to increase the compressive strength of the British adobe bricks on concentrations as low as 0.4% and 0.5%.

In order to find out if the effect on the compressive strength of the British adobe bricks is coming from the type of the glycoproteins or from the different concentrations of these glycoproteins, further statistical analysis is conducted in the following section.

### *4.5.22 The First Hypothesis: Statistical Analysis of the Results*

There were two main factors affecting the compressive strength of the British adobe bricks. These two factors were the glycoproteins' type and the different concentrations of these glycoproteins.

**Table 4-13:** Two-way ANOVA statistics for concentration of the glycoprotein vs. the glycoprotein types (compressive strength of the adobe British bricks), the concentrations are 0.1%, 0.2% 0.3%, 0.4% & 0.5%, and the glycoprotein types are, Bovine serum albumin, gelatine from cold water fish skin & termite's saliva ingredients

| ***Source of Variation*** | ***Sum of Squares (SS)*** | ***Degree of Freedom (df)*** | ***Mean Sum of Squares (MS)*** | ***F*** | ***P-value*** |
|---|---|---|---|---|---|
| **Glycoprotein concentration (%)** | 0.631 | 4 | 0.158 | 4.63 | 0.002 |
| **Glycoprotein types** | 1.021 | 2 | 0.511 | 15.01 | 0.000 |
| Interaction | 1.358 | 8 | 0.170 | 4.99 | 0.000 |
| Within | 2.552 | 75 | 0.034 | | |
| Total | 5.561 | 89 | | | |

Table 4-13 shows the results of a two-way analysis of variance which was conducted on the influence of two independent variables (the glycoprotein concentrations, the glycoprotein types) on the unconfined compressive strength of the British adobe bricks. Table 4-13 also shows the combined effect (the interaction) of these two variables on the compressive strength of the British adobe bricks. The glycoprotein concentrations included five levels (0.1, 0.2, 0.3, 0.4 and 0.5 by weigh percent concentration) and the glycoprotein types consisted of three levels (bovine serum albumin, fish gelatine and termite's saliva ingredients). All effects were statistically significant at the 0.05 significance level. The main effect for glycoprotein concentrations yielded an *F* ratio of $F$ (4, 75) = 4.63, $p < 0.001$, indicating that the effect for glycoprotein concentration was significant, 0.1% glycoprotein (M = 1.83, SD = 0.153), 0.2% glycoprotein (M = 1.65, SD = 0.165), 0.3% glycoprotein (M = 1.72, SD = 0.245), 0.4% glycoprotein (M = 1.74, SD = 0.273) and 0.5% glycoprotein (M = 1.87, SD = 0.321). The main effect for glycoprotein types yielded an F ratio of $F$ (2, 75) = 15.01, $p < 0.001$, indicating a significant difference between bovine serum albumin (M = 1.90, SD = 0.253), fish gelatine (M = 1.64, SD = 0.254) and termite's saliva ingredients (M = 1.74, SD = 0.160). The interaction effect between the glycoprotein concentrations and the glycoprotein types on the compressive strength of the British adobe bricks was also significant, $F$ (8, 75) = 4.99, $p < 0.001$. This ANOVA analysis confirms that there is an interaction between the glycoprotein type and concentration on the compressive strength of the British adobe bricks. In addition, the ANOVA results indicate that for the compressive strength, the glycoprotein types (*F*= 15) is on the average dominant over the concentration of the glycoprotein (*F*=5).

Furthermore, and based on the above significant interaction between the effect of the type of the glycoproteins and the concentration of these glycoproteins on the compressive strength, Dunnett's multiple comparison test which is a post-hoc test was conducted. Dunnett's multiple comparison test was used to compare each glycoprotein's concentration (0.1%, 0.2%, 0.3%, 0.4% & 0.5%) mean compressive strength to the mean compressive strength of the British unstabilised adobe brick. The purpose of this comparison was to find out which glycoproteins and concentration are statistically significantly from the control unstabilised, Figure 4-21. The results from this test will help to identify if the compressive strength of the British adobe bricks stabilised with higher concentrations of bovine serum albumin are statistically significant from that came from the unstabilised control sample. It would also help in identifying the glycoprotein and the concentration that will be taken for further testing in the next sections.

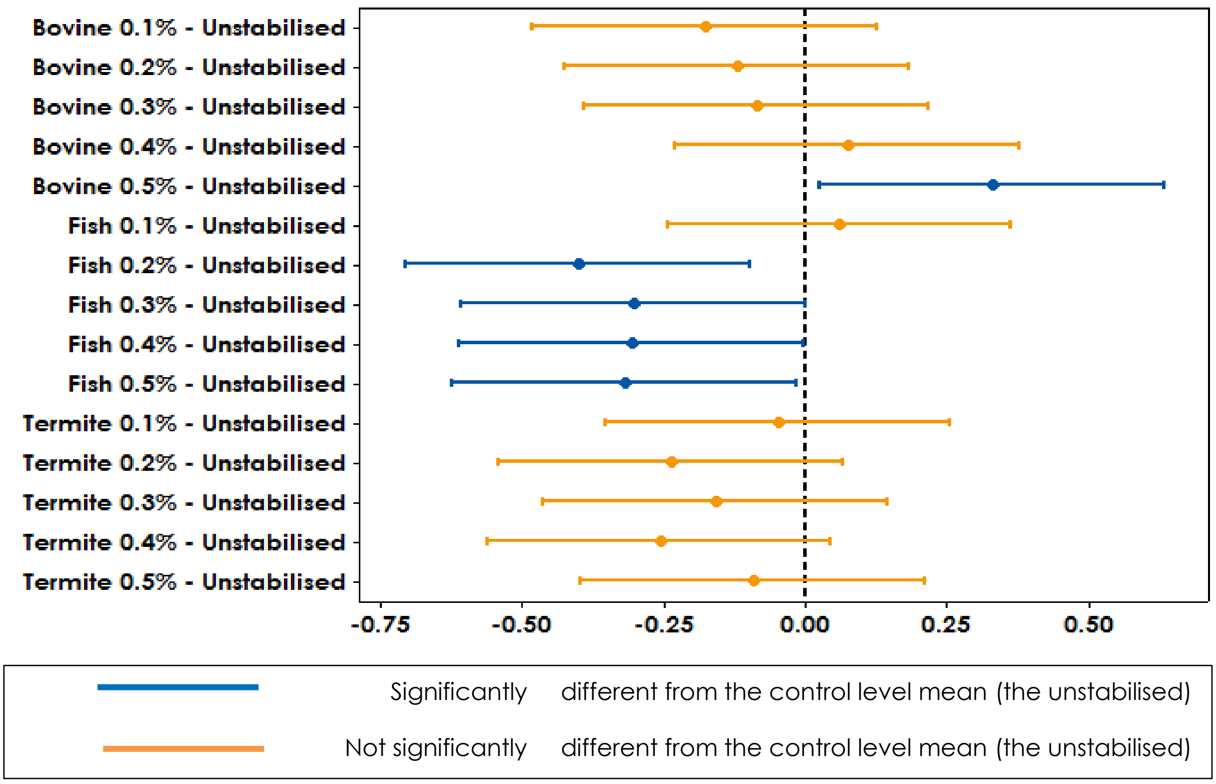



**Figure 4-21:** Dunnett multiple comparisons, the comparison of the means of the different stabilised British adobe bricks compressive strengths from the first hypothesis to the mean of the unstabilised British adobe brick which was used as the control mean. The test conducted with 95% confident level

Figure 4-21 above shows that the mean compressive strength of the British adobe bricks stabilised using 0.5% bovine serum albumin is statistically significant and higher than that of the British unstabilised control bricks. The mean compressive strengths of the 0.4% bovine and 0.1% fish gelatine stabilised British adobe bricks are higher than the mean compressive strength of the unstabilised British adobe bricks but are not statistically significant from it. The British adobe bricks stabilised with 0.2%, 0.3%, 0.4% and 0.5% fish gelatine resulted in mean compressive strengths which are statistically significant from the mean compressive strength of the control unstabilised adobe bricks but lower than it. All the rest of the mean compressive strengths (0.1%, 0.2% and 0.3% bovine serum albumin, and 0.1%, 0.2%, 0.3%, 0.4% and 0.5% termite's saliva ingredients) are lower and statistically not significant from the mean compressive strength of the British unstabilised adobe bricks.

### 4.5.23 The First Hypothesis: The Findings

Based on the series of the unconfined compressive strength tests conducted in this section, the results obtained supported the study first hypothesis regarding the part that was concerned with the compressive strength. The hypothesis was that the addition of the glycoprotein to the British adobe bricks will enhance the bricks' unconfined compressive strength and increase their erosion resistant to the wind-driven rain. The following points could be drawn based on the results from this section:

- The addition of 0.1% concentration of all the glycoproteins introduced in this study except the fish gelatine, resulted in the reduction of the unconfined compressive strength of the British adobe bricks.
- The increase of the concentration of the glycoprotein in the adobe bricks to 0.2% and 0.3% resulted in different compressive strength patterns, but the overall trend was that all the compressive strengths were lower than that of the British unstabilised adobe bricks.
- When the concentration of the glycoprotein in the adobe bricks reached 0.4% and 0.5%, the British adobe bricks stabilised using bovine serum albumin were the only bricks had a compressive strength that was higher than that of the unstabilised adobe bricks.
- Statistical analysis showed that both the glycoprotein type and the glycoprotein concentration have statistically significant effect on the unconfined compressive strength of the British adobe bricks. Both factors have

a combined effect on the compressive strength of the adobe bricks which could not be ignored.

From the above series of tests, the inclusion of 0.5% bovine serum albumin as a stabiliser for the British adobe bricks resulted in 16% increase in the unconfined compressive strength. As a consequence of this, bovine serum albumin will be taken as the potential stabiliser for further investigations in the upcoming sections. The bovine serum albumin with 0.5% concentration is the only glycoprotein that will be tested in the second hypothesis of this study.

## 4.6 Preparation of the unstabilised Sudanese adobe bricks

The unstabilised adobe bricks were prepared with a mixture of soil, sand and distilled water. According to Bengtsson and Whitaker, 1986 in (Danso, 2015), the combined percentage of clay and silt in a soil that is considered suitable for adobe brick making is between 20% and 50%. From the wet sieve test results of the Sudanese soil in section 3.3.5.2, the total percentage of the finer particles (the clay and the silt) which are responsible of the cohesiveness and the plasticity of the soil was 65%. This percentage was higher than the upper limit in the range recommended by Bengtsson and Whitaker above. In addition, the percentage of the sand and gravel together for adobe brick production recommended by Bengtsson and Whitaker, 1986 in (Danso, 2015) was between 50 and 80%. The Sudanese soil particle size distribution determination test in section 3.3.5.2 has revealed that the percentage of the sand and gravel combined was only 35%. This percentage of the sand and gravel was below the lower limit recommended by Bengtsson and Whitaker. As a result, the Sudanese soil lacks the coarse particles and has higher finer particles, which will result in less workable mixture when water is added to prepare the adobe bricks. Consequently, the soil needed modification before it was used to prepare the adobe bricks. The modification was done by adding 40% by weight natural sand. By doing this particle size modification, the Sudanese soil consisted of 39% clay and silt, and 61% sand and gravel, and it was inside the recommended range addressed by Bengtsson and Whitaker for the soil suitable for adobe bricks production.

The soil was sieved using a 10 mm mesh sieve. For each unconfined compressive strength test, six scaled bricks were used. These six scaled bricks were cut from two full-size bricks. These two full-size bricks were made from different mixtures but with the same composition to ensure replicability and reproducibility of the bricks. The quantity of the soil needed to prepare a full-size brick was mixed with the recommended quantity of the natural sand in the dry state. The measured known quantity of distilled water was added to the soil-sand mixture. The quantities of the soil, sand and water used to prepare a full-size brick are in Table 4-14.

**Table 4-14:** Quantities and percentages of the Sudanese soil, natural sand and distilled water used to prepare a full-size unstabilised Sundanese adobe brick

| | Sudanese soil | Natural sand | Distilled water |
|---|---|---|---|
| **Quantities** | **3315 (g)** | **2210 (g)** | **1463 (ml)** |
| **Percentages** | **60 (%)** | **40 (%)** | **26.5 (%)** |

The quantities of soil, sand and distilled water for one full-size brick from Table 4-14 were mixed using the same electrical drill mixer (EZR22, twin paddle mega mixer) used to prepare the British unstabilised adobe bricks in section 4.3(Figure 4-1). The soil-sand and water were mixed until a homogenous mixture was obtained and the mixture was ready for moulding. The moulding was done using a wooden mould, Figure 4-22, which was wetted with water and dusted using sand prior to the moulding. This dusting process helped in the removal of the mould at the end of the moulding process.

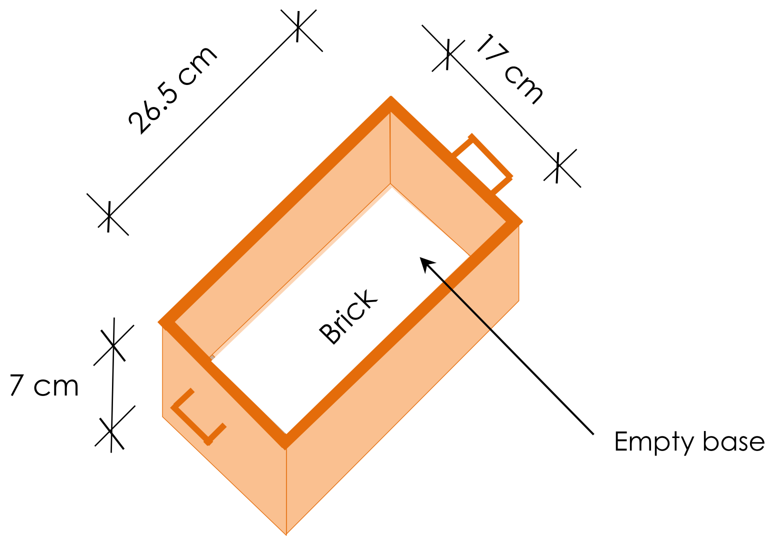



**Figure 4-22:** Wooden mould used to prepare the Sudanese full-size adobe bricks

The moulding was done in layers and each layer has enough pressure along the surface and the attention was paid to the edges and the corners of the brick to ensure a regular shape later. This pressure was applied by hand along using the 5 kg metal weight used to prepare the British bricks in section 8.2.1 (Figure 4-2). After moulding the brick, the extra mud was removed using a scrapper and the top of the brick was smoothed using wetted hands and then levelled, Figure 4-23. The final step on preparing the bricks was the wooden mould removal. Then the bricks were left in the laboratory environment overnight (for 16 hours) for the initial drying to take place. After these 16 hours, the bricks were settled and ready to be cut into small bricks.

**Figure 4-23:** The levelled smoothed Sudanese adobe brick after scraping the excess mud and before removing the wooden mould

Each brick was cut into eight small bricks using the linear scale of 1:2 (1:8 volumetric scale), Figure 4-24 .

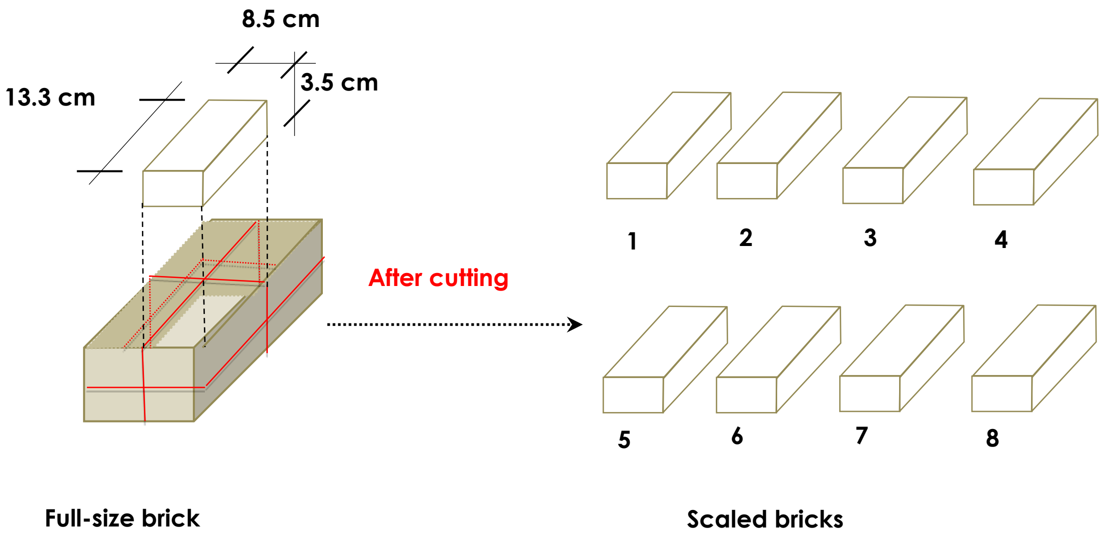



**Figure 4-24:** Cutting the Sudanese adobe full-size brick to prepare scaled-bricks using the segmented blade "snap-off blade" utility knife, in Figure 4-3, after the initial overnight drying in the laboratory, with the dimensions of the final scaled-brick

The small bricks were smoothed on all the surfaces to ensure their flatness and evenness using a flat wooden pieces and water. The scaled-bricks left for another 16 hours overnight for initial drying. The next day the bricks were labelled and moved to dry for 28 days in the controlled environmental chamber, Figure 4-5. The drying settings were representative of the settings of temperature and humidity in summer in Khartoum, Sudan. The temperature was set between 37.2 – 41.2 ° C and the humidity between 30% - 34% (El Sayed et al., 2000). During the drying process, the bricks were turned frequently to ensure an even drying.

## 4.7 Preparation of the stabilised Sudanese adobe bricks

As it has been mentioned before in the findings of the first hypothesis in section 4.5.23, only bovine serum albumin with 0.5% concentration will be used to prepare the Sudanese stabilised adobe bricks. The quantities used to prepare the full-size Sudanese bovine stabilised adobe bricks are in Table 4-15.

**Table 4-15:** Quantities and percentages of Sudanese soil, natural sand, bovine serum albumin and distilled water used to prepare a full-size 0.5% bovine serum albumin stabilised Sundanese adobe brick

| | Sudanese soil | Natural sand | Bovine serum albumin | Distilled water |
|---|---|---|---|---|
| **Quantities** | **3315 (g)** | **2210 (g)** | **28 (g)** | **1463 (ml)** |
| **Percentages** | **60 (%)** | **40 (%)** | **0.5 (%)** | **26.5 (%)** |

To prepare the 0.5% bovine serum albumin stabilised Sudanese adobe bricks, the following steps were used, Figure 4-25 below.

| | |
|---|---|
| **Bovine serum albumin preparation** | *the bovine serum albumin was weighed and added to distilled water following the quantities in* Table 4-15 *. Then the glycoprotein was mixed thoroughly until reach a homogeneous liquid. The mixing was done using a manual egg whisk.* |
| **Soil preparation** | *the soil was sieved using a 10 mm mesh sieve, then was weighed according to the quantities in* Table 4-15. |
| **The dry mixing** | *the soil was added to the natural sand following the quantities identified in* Table 4-15 *and they were mixed thourly to obtain a well graded soil.* |
| **The wet mixing** | *the soil-sand mixture was added to the bovine serum albumin liquid and mixed using an electric mixer until reach a homogeneous like a dough mixture.* |
| **Moulding** | *the moulding was done using the same process used to mould the unstabilised control bricks in section (4.2.3.1). See the full-size bricks in* Figure 4-23 above. |
| **Moisture content testing** | *The moisture content of the bricks was investigated by placing a sample from the mixture in the oven at 105°C for 24 hours. During these 24 hours, the sample was removed and its mass was checked several times till it reached a constant mass. Then the moisture content (MC, %) was calculated* |
| **Initial drying (Full-size bricks )** | *the full-size bricks were labelled and left for 16 hours (overnight) for initial drying in the laboratory environment.* |
| **Prepare the scaled-bricks** | *the full-size bricks were cut into small bricks following the same stepts used to prepare scaled unstabilised adobe bricks in section (4.2.3.1). See the scalled bricks in* Figure 4-26. below. |
| **Initial drying (scaled bricks)** | *the scalled bricks were labelled and left for 16 hours (overnight) for initial drying in the laboratory environment.* |
| **Drying** | *after the 16 hours of the initial drying, the bricks were moved to the controlled environmental chamber to start the 4 weeks drying process, the drying setteings were: temperature 37.2 – 41.2 ° C and the humidity 30% - 34%, in* Figure 4-25 below. |

**Figure 4-25:** Stabilised Sudanese adobe bricks preparation steps for compressive strength test

**Figure 4-26:** 0.5% Sudanese bovine adobe stabilised scaled bricks drying in the controlled environmental chamber

The following sections will address the compressive strength test results of the adobe bricks prepared using the Sudanese soil to test the second hypothesis in this study.

## 4.8 Testing the second hypothesis

In order to test this second hypothesis, unstabilised and stabilised Sudanese adobe bricks were made following the preparation steps mentioned in sections 4.6 and 4.7 above. The stabilised Sudanese adobe bricks were made using only 0.5% bovine serum albumin. The bovine serum albumin with 0.5% concentration was the stabiliser which has resulted in 16% increase in the compressive strength for the British stabilised adobe bricks. This 16% increase in the compressive strength was the highest strength achieved during investigating the first hypothesis in the previous section. Due to that, the bovine serum albumin with 0.5% concentration was the focus of the second hypothesis tests.

### *4.8.1 The Second Hypothesis: The Results*

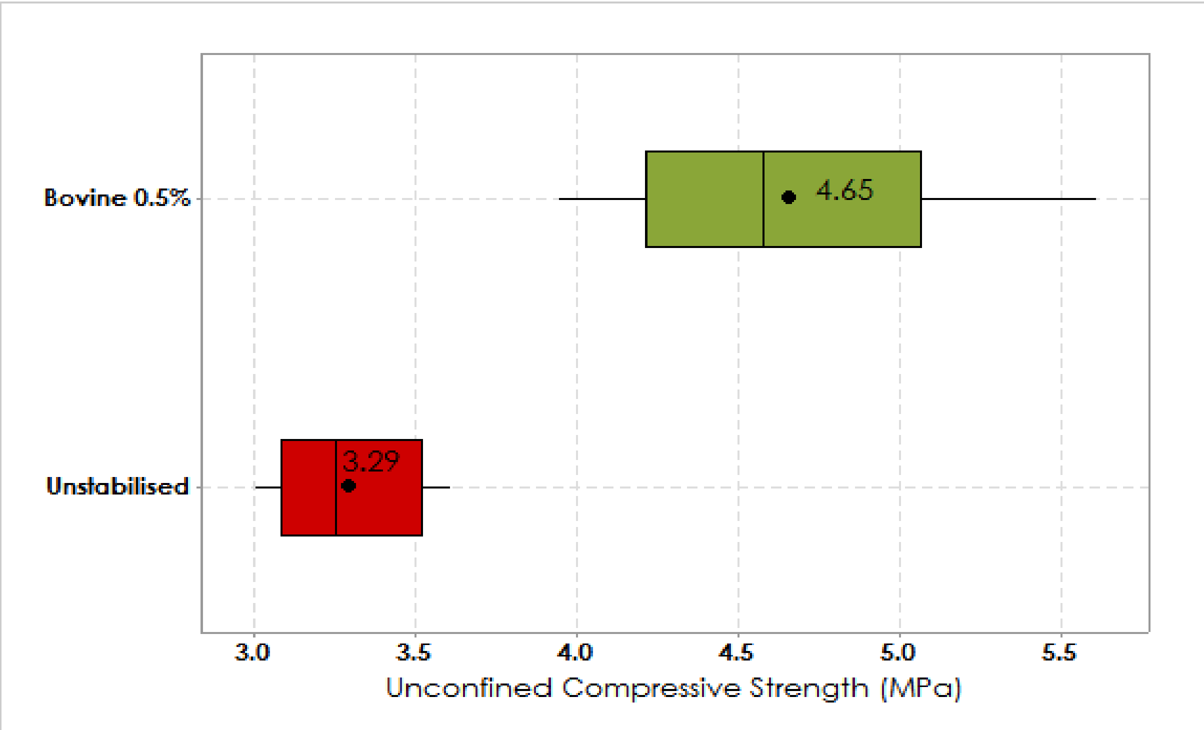



**Figure 4-27:** The compressive strength of the Sudanese unstabilised and 0.5% bovine serum albumin stabilised adobe bricks. *The boxplots represent the inter-quartile range of the data obtained*

Figure 4-27 shows the compressive strength results of the Sudanese adobe bricks unstabilised control sample and the 0.5% bovine serum albumin stabilised adobe bricks. The addition of the 0.5% bovine serum albumin to the Sudanese adobe bricks resulted in 41.34% increase in the compressive strength compared with the unstabilised Sudanese control adobe bricks' compressive strength. The compressive strength has increased from 3.29 MPa for the Sudanese unstabilised adobe bricks to 4.65 MPa after the addition of the 0.5% bovine serum albumin to stabilise the Sudanese adobe bricks.

### *4.8.2 The Second Hypothesis: Statistical Analysis of the Results*

To check the significance difference of the test results, a one-way ANOVA was conducted to compare the effect of the addition of the bovine serum albumin on the compressive strength of the Sudanese adobe bricks, Table 4-16. The null hypothesis was that the means of the compressive strength for the bovine stabilised and unstabilised Sudanese adobe bricks come from the same overall population. An analysis of variance showed that the effect of the addition of the bovine serum albumin on the compressive strength of the Sudanese adobe bricks was statistically significant, $F(1, 10) = 27.775$, $p = 0.000$, Table 4-16. Thus, the differences in the means of the compressive strength among the bovine stabilised and the unstabilised Sudanese adobe bricks are significant and they are not coming from the same overall population.

**Table 4-16:** One-way ANOVA at 95% confidence interval for the unstabilised Sudanese adobe bricks and 0.5% bovine serum albumin stabilised Sudanese adobe bricks

| ***Source of Variation*** | ***Sum of Squares (SS)*** | ***Degree of Freedom (df)*** | ***Mean Sum of Squares (MS)*** | ***F*** | ***P-value*** | ***F crit*** |
|---|---|---|---|---|---|---|
| **Between Groups** | 5.568 | 1 | 5.568 | 27.775 | 0.000 | 4.965 |
| **Within Groups** | 2.005 | 10 | 0.200 | | | |
| **Total** | 7.572 | 11 | | | | |

### *4.8.3 The Second Hypothesis: The Findings*

The findings of this section of the study based on the series of the unconfined compressive strength tests conducted and the observations made during the tests in general could be summarised in the following points:

- The addition of the natural sand to modify the Sudanese soil has great impact on the workability of the soil and this was experienced during the preparations of the soil mixture of the unstabilised adobe bricks.
- The addition of the 0.5% bovine serum albumin resulted in a jelly like dough which was elastic and sticky during moulding but when smoothed with a touch of water the final brick surface was shiny and looked like a polished laminated surface which was a very interesting observation. This phenomenon was not noticed when moulding and preparing the Sudanese unstabilised adobe bricks.
- During the mixing of the soil using the electrical mixer, despite using the same quantity of distilled water for preparing the unstabilised and the stabilised Sudanese adobe bricks, it was noticed that the bovine soil mixture was very slurry at the beginning of the mixing but by continuing the mixing, the mixture turned into a workable dough. This was unique for the 0.5% bovine stabilised Sudanese adobe bricks.
- The cutting of the full-size brick into the scaled bricks was much easier for the unstabilised Sudanese adobe bricks compared with the 0.5% bovine Sudanese stabilised adobe bricks.
- The addition of the 0.5% bovine serum albumin to the Sudanese adobe bricks has increased the compressive strength of the bricks. The compressive strength has increased from 3.29 MPa for the unstabilised to 4.65 MPa for the stabilised adobe bricks (which is 41.34% increase in the compressive strength).
- The tests in this section have supported the part that was concerned about the compressive strength from the second hypothesis of this study. The glycoprotein, which is the bovine serum albumin, has enhanced the compressive strength of the Sudanese adobe bricks.

## 4.9 Testing the Third Hypothesis

As has been mentioned before in section 4.1.3, only one glycoprotein will be used with higher concentrations as a potential stabiliser for the adobe bricks in testing this third hypothesis. The selection of the glycoprotein was based on the results of testing the first hypothesis in section 4.5 above. The glycoprotein which has resulted in the highest compressive strength will be investigated in this hypothesis. From the analysis of the results of the first hypothesis in section 4.5 bovine serum albumin was the glycoprotein that resulted in the highest compressive strength (16% increase in the compressive strength) when used to stabilise the British adobe bricks. Therefore, bovine serum albumin was the only glycoprotein that was used to test the third hypothesis in this study.

The third hypothesis was that the addition of higher concentrations of glycoprotein to the adobe bricks will continue to enhance the unconfined compressive strength of the bricks. The unconfined compressive strength results from this step will be compared with the unconfined compressive strength of the unstabilised adobe bricks (the control sample). This step of the laboratory tests has two phases based on the soil types. The stabilised adobe bricks were made using the British and the Sudanese soils.

### *4.9.1 Phase One: The British Soil*

For the British soil, three concentrations of the bovine serum albumin were used in stabilising the British adobe bricks. These concentrations were 1, 3 & 5 by weight percent. The preparations of the stabilised British adobe bricks and the results will be discussed in the coming sections.

#### 4.9.1.1 Preparation of the 1% bovine serum albumin stabilised British adobe bricks

The 1% bovine serum albumin stabilised British adobe bricks were made using the same steps used to prepare the stabilised British adobe bricks in Figure 4-6 in section 4.4. The quantities used to prepare the 1% bovine serum albumin stabilised British adobe bricks are in Table 4-17.

**Table 4-17:** Quantities and percentages of the British soil, bovine serum albumin and distilled water used to prepare a full-size 1% bovine serum albumin stabilised British adobe brick

| | British soil (g) | Bovine serum albumin (g) | Distilled water (ml) |
|---|---|---|---|
| **Quantities** | **3000** | **30** | **690 (23%)** |

During the preparation of the bricks, it was observed the same phenomenon that was mentioned before for the Sudanese adobe bricks stabilised using 0.5% bovine serum albumin (in section 4.8.3). The mixture was in a jelly like dough which was elastic and sticky during moulding but when smoothed with a touch of water the final brick surface was shiny and looked like a polished laminated surface, Figure 4-28. For the British stabilised bricks, this was the first time to notice such observation during the preparation of the bricks.  In addition, after the initial drying of the full-size bricks, they were very hard and cutting them into small bricks was not an easy process. This was unusual and it was linked to the increase of the bovine serum albumin concentration per brick.

#### 4.9.1.2 *Preparation of the 3% & 5% bovine serum albumin stabilised British adobe* bricks

The 3% and 5% bovine serum albumin stabilised British adobe bricks were made using the same steps used to prepare the stabilised British adobe bricks in Figure 4-6 in section 4.4. However, there were two key different steps in the preparation of the bricks for these two bovine serum concentrations compared with all the previous bovine concentrations used in this study. The first step was related to the preparation of the glycoprotein liquid. Due to the immense quantities of the bovine serum albumin used in stabilising these two types of British adobe stabilised bricks, an electrical egg whisk was used to obtain a homogenous bovine serum albumin liquid instead of the manual whisking. The second step was related to the moulding of the bricks. During the production of the bricks for both stabilisation concentrations (3% & 5%), it was observed that the brick did not stand its shape after the immediate removal of the mould. As a result, the decision was made to produce scaled bricks instead of preparing a full-size brick and cut into small bricks. The bricks were made using a small mould, Figure 4-28 , and they were left in the mould for 16 hours (overnight) to harden and to keep their final shape. When the mould was removed, the bricks were labelled and then moved to the drying chamber for the final drying process (see Figure 4-29). The quantities used to prepare each four scaled bricks are in Table 4-18 below.

**Table 4-18:** Quantities and percentages of British soil, bovine serum albumin and distilled water used to prepare four scaled 3% & 5% bovine serum albumin stabilised British adobe brick

| | British soil (g) | Bovine serum albumin (g) | Distilled water (ml) |
|---|---|---|---|
| **Quantities for 3%** | **1500** | **45** | **360 (24%)** |
| **Quantities for 5%** | **1500** | **75** | **330 (22%)** |

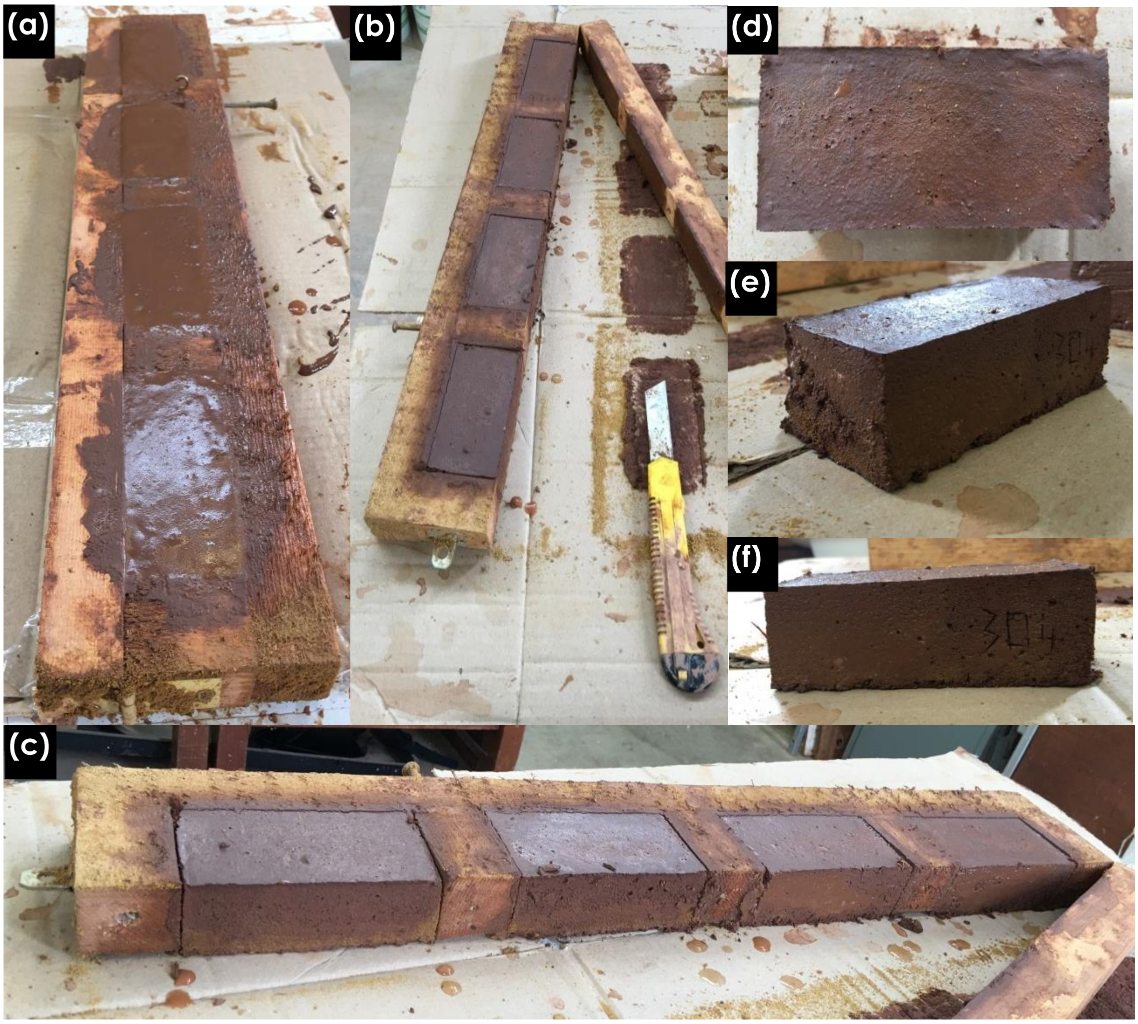



**Figure 4-28:** 3% & 5% bovine stabilised British adobe bricks, **(a)** the bricks immediately after moulding, notice the glossiness on the surface of the bricks, **(b) & (c)** the stabilised bricks after they were left for 16 hours inside the mould for the initial drying in the laboratory and before remove them from the wooden mould. **(d), (e) & (f)** the brick after it was removed from the mould (the brick age: only one-day old)

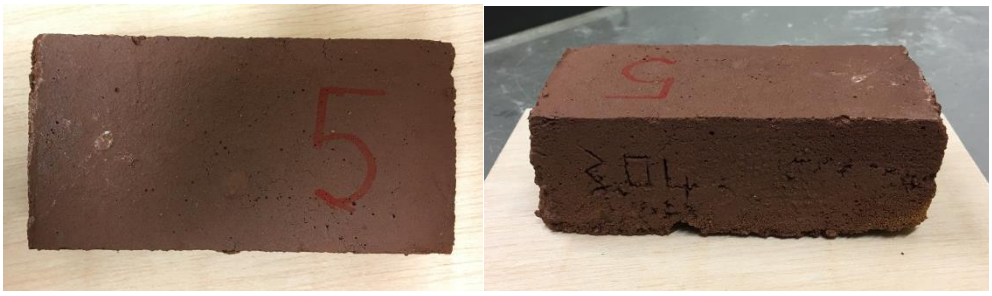


**Figure 4-29:** The 3% bovine stabilised British adobe bricks after complete the full drying period (the brick age: 28 days old)

### *4.9.2 Phase One: The Results*

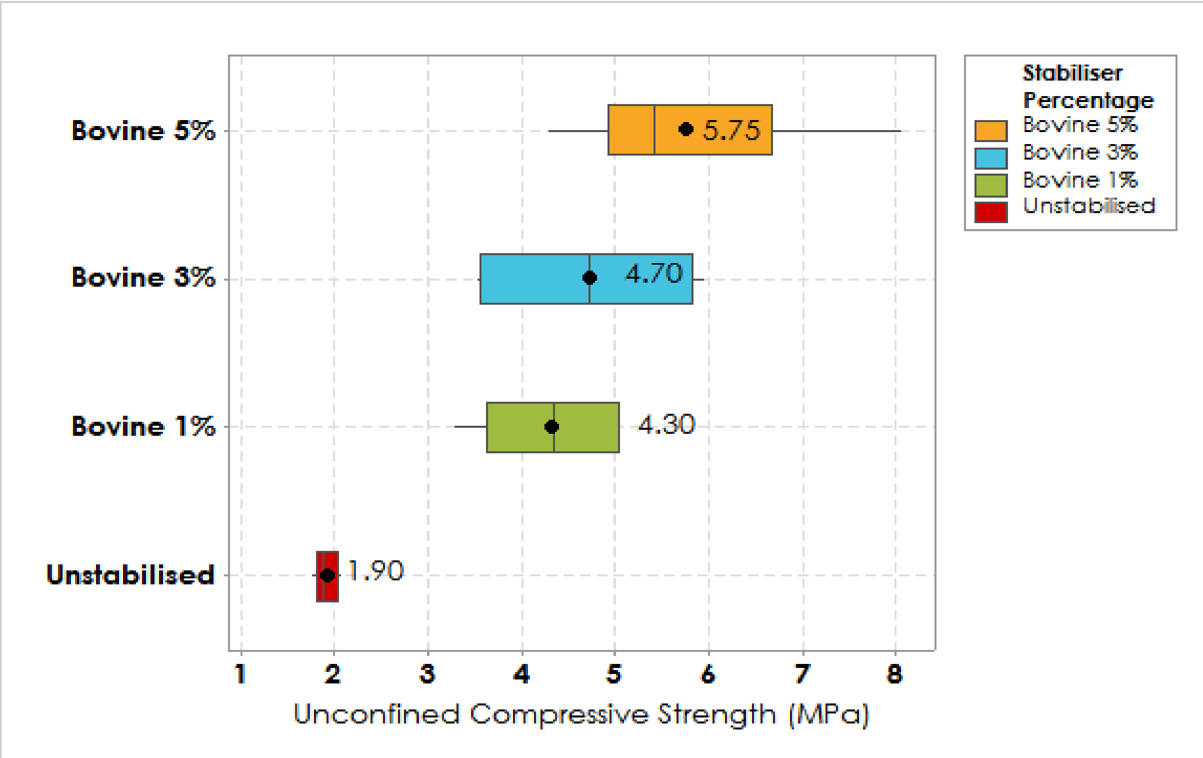



**Figure 4-30:** The effect of increasing the concentration of the bovine serum albumin (1%, 3% & 5%) on the compressive strength of the British stabilised adobe bricks. *The boxplots represent the inter-quartile range of the data obtained*

Figure 4-30 shows the unconfined compressive strength results of the unstabilised and the bovine stabilised British adobe bricks with three different concentrations (1%, 3% & 5%). The use of 1% bovine serum albumin to stabilise the British adobe bricks resulted in 126.3% increase in the compressive strength. The compressive strength incresed from 1.90 MPa for unstabilised British adobe brick to 4.30 MPa when stabilised with 1% bovine serum albumin. Furthermore,147.4% increase in the compressive strength was achieved when 3 by weight percent of bovine serum albumin was used in stabilisng the British adobe bricks. The compressive strength of the British adobe bricks increased from 1.90 MPa for the unstabilised adobe bricks to 4.70 MPa for 3% bovine stabilised adobe bricks. In addition, reaching 5% concentration of bovine serum albumin in the British adobe bricks resulted in 202.6% increase in the compressive strength of the bricks. The compressive strength of the British adobe bricks has risen from 1.90 MPa when unstabilised to 5.75 MPa when it was stabilised using 5% bovine serum albumin. From the results in Figure 4-30 above, it was clear that there is a strong positive correlation between the concentration of the bovine serum albumin in the British adobe bricks and their compressive strength. In this phase, the increase of the bovine serum albumin in the British adobe bricks consistently resulted in the increase of the compressive strength of the bricks and thus, has enhanced the quality of the British adobe bricks.

### 4.9.3 Phase One: Statistical Analysis of the Results

To check the significance difference of the test results, a one-way ANOVA was conducted to compare the effect of changing the concentration of the bovine serum albumin on the compressive strength of the British adobe bricks. The null hypothesis was that the means of the compressive strength for all the bovine stabilised British adobe bricks with the different concentrations and unstabilised British adobe bricks come from the same overall population, Table 4-19. An analysis of variance showed that the effect of the concentration of the bovine serum albumin on the compressive strength was statistically significant, $F$ (3, 20) = 18.935, $p$ = 0.000, Table 4-19. Thus, the differences in the means of the compressive strength among the bovine stabilised and the unstabilised British adobe bricks are significant and they are not coming from the same overall population.

**Table 4-19:** One-way ANOVA at 95% confidence interval for the unstabilised British adobe bricks and 1%, 3% & 5% bovine serum albumin stabilised British adobe bricks

| *Source of Variation* | *Sum of Squares (SS)* | *Degree of Freedom (df)* | *Mean Sum of Squares (MS)* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Between Groups** | 47.647 | 3 | 15.882 | 18.935 | 0.000 | 3.098 |
| **Within Groups** | 16.776 | 20 | 0.839 | | | |
| **Total** | 64.423 | 23 | | | | |

### 4.9.4 *Phase Two: The Sudanese Soil*

Due to the limited available quantities of the Sudanese soil in this study, only one concentration of the bovine serum albumin was tested in this third hypothesis. This concentration was the highest concentration tested for the British adobe bricks which was 5 by weigh percent. The preparation of the Stabilised Sudanese adobe bricks and the results will be discussed in the following sections.

#### 4.9.4.1 Preparation of the 5% bovine serum albumin stabilised Sudanese adobe bricks

The full-size 5% bovine stabilised Sudanese brick was made from a mixture of Sudanese soil, natural sand (to modify the properties of the soil as mentioned before in section 4.6), bovine serum albumin and distilled water. The quantities used to prepare a full-size brick were as in Table 4-20 below.

**Table 4-20:** Quantities and percentages of the Sudanese soil, natural sand, bovine serum albumin and distilled water used to prepare a full-size 5% bovine serum albumin stabilised Sundanese adobe brick

| | Sudanese soil | Natural sand | Bovine serum albumin | Distilled water |
|---|---|---|---|---|
| **Quantities** | **1660 (g)** | **1105 (g)** | **138 (g)** | **830 (ml)** |
| **Percentages** | **60 (%)** | **40 (%)** | **5 (%)** | **30 (%)** |

The 5% bovine serum albumin stabilised Sudanese adobe bricks were made using the same steps used to prepare the stabilised Sudanese adobe bricks in Figure 4-25 in section 4.7, using the quantities in Table 4-20. The only difference was in the preparation of the bovine serum liquid where an electrical egg whisk was used instead of the manual one due to the high concentration of bovine used (5%).

Figure 4-31below shows a full-size 5% bovine stabilised adobe brick after the 16 hours (overnight) initial drying and before cutting into scaled bricks, and the scaled bricks after they have been prepared, labelled and ready for the 28 days drying period in the controlled chamber.

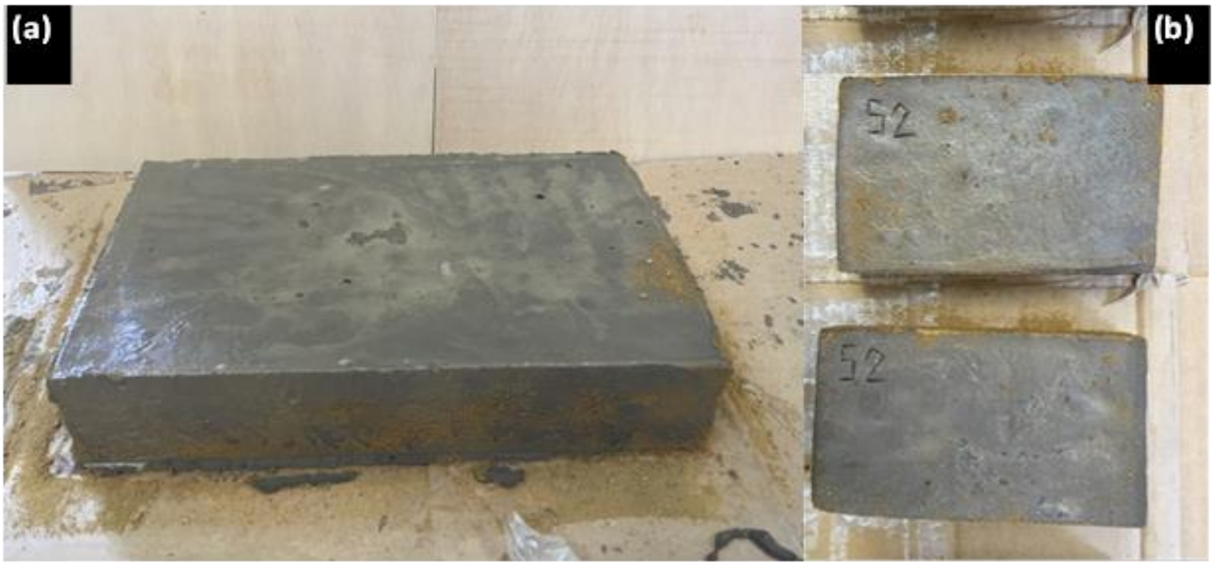



**Figure 4-31:** 5% Bovine stabilised Sudanese adobe bricks, **(a)** Full-size brick before cutting into scaled bricks, **(b)** Scaled bricks produced from cutting the full-size brick, this photo of the scaled bricks was taken just after the bricks finished the 16 hours of the initial drying in the laboratory environment

### *4.9.5 Phase Two: The Results*

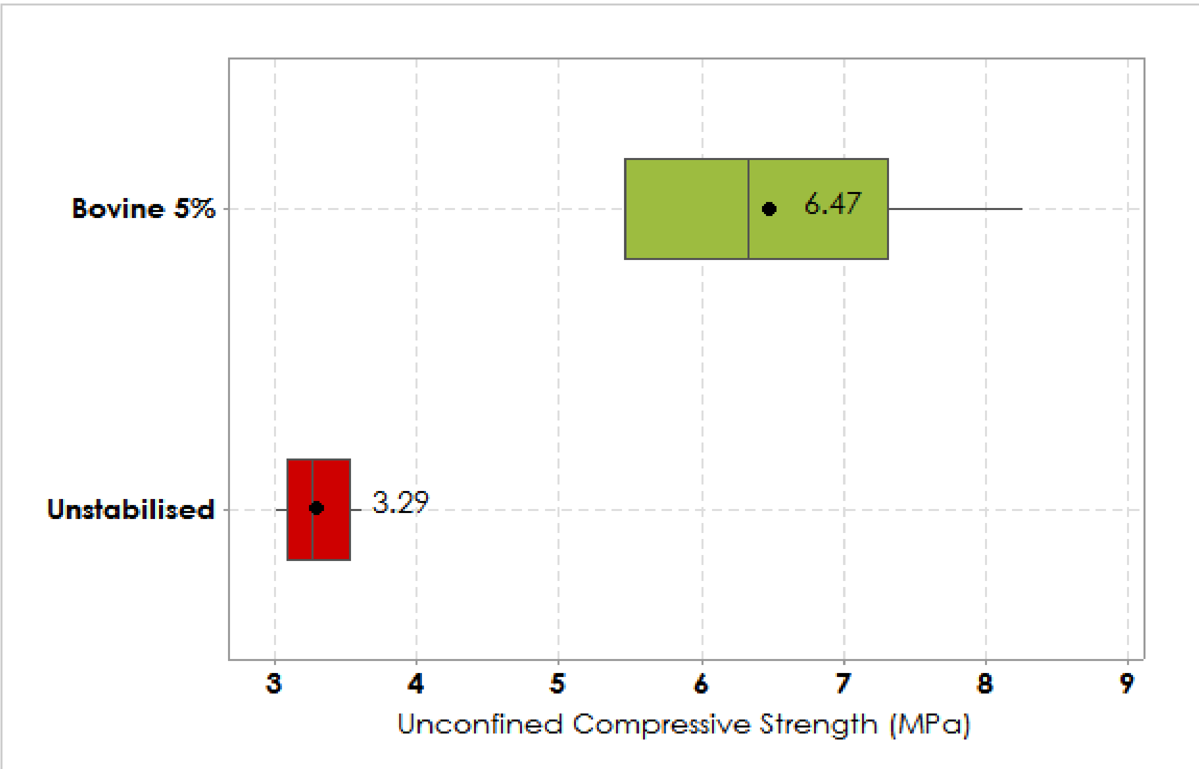



**Figure 4-32:** The compressive strength of the Sudanese unstabilised and 5% bovine serum albumin stabilised adobe bricks. *The boxplots represent the inter-quartile range of the data obtained*

Figure 4-32 shows the compressive strength results of the Sudanese unstabilised adobe bricks (the control sample) and the 5% bovine serum albumin stabilised adobe bricks. The addition of the 5% bovine serum albumin to the Sudanese adobe bricks resulted in 96.7% increase in the compressive strength compared with the unstabilised Sudanese control adobe brick compressive strength. The compressive strength increased from 3.29 MPa for the Sudanese unstabilised adobe bricks to 6.47 MPa after the addition of the 5% bovine serum albumin to the Sudanese adobe bricks.

### *4.9.6 Phase Two: Statistical Analysis of the Results*

To check the significance difference of the test results, a one-way ANOVA was conducted to compare the effect of the addition of the 5% bovine serum albumin on the compressive strength of the Sudanese adobe bricks. The null hypothesis was that the means of the compressive strength for the 5% bovine stabilised Sudanese adobe bricks and unstabilised Sudanese adobe bricks come from the same overall population, Table 4-21. An analysis of variance showed that the effect of the addition of the bovine serum albumin on the compressive strength was statistically significant, $F$ (1, 10) = 49.858, $p$ = 0.000, Table 4-21. Thus, the differences in the means of the compressive strength among the 5% bovine stabilised and the unstabilised Sudanese adobe bricks are significant and they are not coming from the same overall population.

**Table 4-21:** One-way ANOVA at 95% confidence interval for the unstabilised Sudanese adobe bricks and 5% bovine serum albumin stabilised Sudanese adobe bricks

| ***Source of Variation*** | ***Sum of Squares (SS)*** | ***Degree of Freedom (df)*** | ***Mean Sum of Squares (MS)*** | ***F*** | ***P-value*** | ***F crit*** |
|---|---|---|---|---|---|---|
| **Between Groups** | 30.390 | 1 | 30.390 | 49.858 | 0.000 | 4.965 |
| **Within Groups** | 6.095 | 10 | 0.610 | | | |
| **Total** | 36.485 | 11 | | | | |

### 4.9.7 The Third Hypothesis: The Findings

The findings of this section of the study based on the series of the unconfined compressive strength tests conducted on both soils, the British and the Sudanese, and the observations made during the preparations of the bricks and the tests in general could be summarised in the following points:

- The increase of the bovine serum albumin concentration in both soils has resulted in jelly like mixtures which were sticky and did not maintain shape if the wooden mould immediately was removed after moulding. As a result, the mixture had to stay in the mould for 16 hours (overnight) to start the initial drying which resulted in preserving the brick shapes. It was also noticed that the surface of the bricks was glossy immediately after the moulding was finished, Figure 4-28.
- It was observed that for the British bovine stabilised bricks, cutting the full-size brick into small bricks after the initial drying was not an easy procedure and has resulted in distorted scaled bricks. Due to that, the scaled bricks used for testing the compressive strength were made using a small wooden mould and by doing this there was no need for cutting the full-size bricks. For the scaled bricks to take constant shape, the bricks were left for 16 hours in the scaled-wooden mould to settle and then the mould was removed and the scaled bricks were labelled and moved to the controlled environmental chamber for the final drying period (28 days).
- In contrast, the Sudanese bovine stabilised bricks were made using the full-size mould then were left for 16 hours for the initial drying before they were cut into small bricks. It was observed that cutting the Sudanese soil into small bricks was easy and manageable compared with the bovine stabilised British bricks. It was thought that the lack of the coarse particles (the gravel) in the Sudanese soil might be the factor behind the easy cutting process. The percentage of the gravel in the British soil was 38% and in the Sudanese soil was only 5.50%, see section 3.1.3.5.2.
- It was observed that by increasing the concentration of the bovine serum albumin, it was not easy to mix it with the distilled water using the simple manual egg whisk to obtain a homogenous bovine liquid (the liquid after the mixing was in a foam form more than a liquid form). To achieve a homogenous bovine

liquid, the use of an electrical egg whisk resulted in a well-mixed bovine liquid with a defined foamy surface, Figure 4-7.

- The increase of the bovine serum albumin concentration in the British adobe bricks resulted in more defined bricks shape with darker brown colour and right angles when they were compared with the unstabilised British adobe bricks.
- The increase of the bovine serum albumin concentration in the Sudanese adobe bricks resulted in more defined bricks' shape with darker greyish colour and right angles when they were compared with the unstabilised Sudanese adobe bricks.
- There was a positive correlation between the increase of the concentration of the bovine serum albumin per brick and the compressive strength of the brick. This was particularly noticed for the British adobe bricks because more than one concentration was used, 1%, 3% & 5%.
- The statistical analysis test conducted on both soils' bricks confirmed that the mean compressive strength of the 5% bovine serum albumin bricks was statistically significant from the mean compressive strength of the unstabilised adobe bricks.
- When using 5% of bovine serum albumin to stabilise the British adobe bricks, there was 202.6% increase in the compressive strength of the British adobe bricks compared with the unstabilised British adobe bricks. The use of 5% bovine serum albumin to stabilise the Sudanese adobe bricks resulted in 97% increase in the compressive strength compared with the unstabilised Sudanese adobe bricks.
- The use of higher concentrations of bovine serum albumin have resulted in noticeable improvement in the adobe bricks compressive strength and hence enhanced the bricks overall performance and strength.
- As a result of the compressive strength tests on both soils in this section, the tests' results support the third hypothesis in this study.

## 4.10 Unconfined compressive strength results: Overall Summary

This section is intended to summarise the results of the unconfined compressive strength in four different groups without referring to the previous three hypotheses. These groups are as follow:

1. Summarise all the British adobe stabilised bricks results, compare them to each other and to the results of the unstabilised British adobe bricks.
2. Summarise all the Sudanese adobe stabilised bricks results, compare them to each other and to the results of the unstabilised Sudanese adobe bricks.
3. Compare the compressive strength results of the British stabilised adobe bricks to the compressive strength results of Sudanese stabilised adobe bricks.
4. Summaries the main effects on the compressive strength for both the British and the Sudanese adobe bricks.

### *4.10.1 British adobe stabilised bricks unconfined compressive strength: Summary of the Results*

Figure 4-33 below shows the percentage of the increase in the unconfined compressive strength of the British adobe bricks stabilised with different glycoproteins and their different concentrations. The glycoproteins that were used as stabilisers for the British adobe bricks were Bovine serum albumin, Fish gelatine from cold water fish skin, Mucin from porcine stomach and Termite's saliva ingredients. All of these stabilisers were used to test the first hypothesis in this study. From Figure 4-33, the use of the mucin from the porcine stomach resulted in 13% and 14% reduction in the compressive strength of the British adobe bricks for 0.1 and 0.2 by weight percent concentrations respectively. Due to the constant and negative effect of the addition of the mucin on the compressive strength of the British adobe bricks, mucin was eliminated from further investigations in hypotheses two and three in this study.

The use of different concentrations of the termite's saliva ingredients to stabilise the British adobe bricks resulted in decreasing the compressive strength of the adobe bricks. There was no defined pattern for this reduction and there was no correlation between the concentration of the stabiliser and the compressive strength of the British adobe bricks. For instance, the addition of 0.1% and 0.5% of the termite's saliva ingredients resulted in 3% and 5% reduction in the compressive strength respectively. Furthermore, the addition of 0.3% from the Termite's saliva ingredients to the British adobe bricks resulted in 8% reduction in the compressive strength when it was compared with the unstabilised British adobe bricks. Using 0.2% and 0.4% of the termite's saliva ingredients resulted in the highest reduction achieved using this stabiliser, and they have resulted in 13% and 14% reduction respectively.

The glycoprotein that resulted in the lowest compressive strength ever achieved during these tests was the fish gelatine from the cold-water fish skin. The addition of 0.2% of the fish gelatine to the British adobe bricks resulted in 21% reduction in the compressive strength. The inclusion of lower concentration of the fish gelatine in the British adobe bricks (0.1%) improved the compressive strength of the adobe brick and resulted in 3% increase. In contrast, higher concentrations of the fish gelatine (0.3%, 0.4% & 0.5%) have not improved the compressive strength of the British adobe bricks. In fact, the compressive strength of the British adobe bricks decreased and remained stable irrespective of the increase of the fish gelatine concentration. For example, the use of 0.3%, 0.4% and 0.5% of the fish gelatine resulted in 16%, 16% and 17% reduction in the compressive strength respectively.

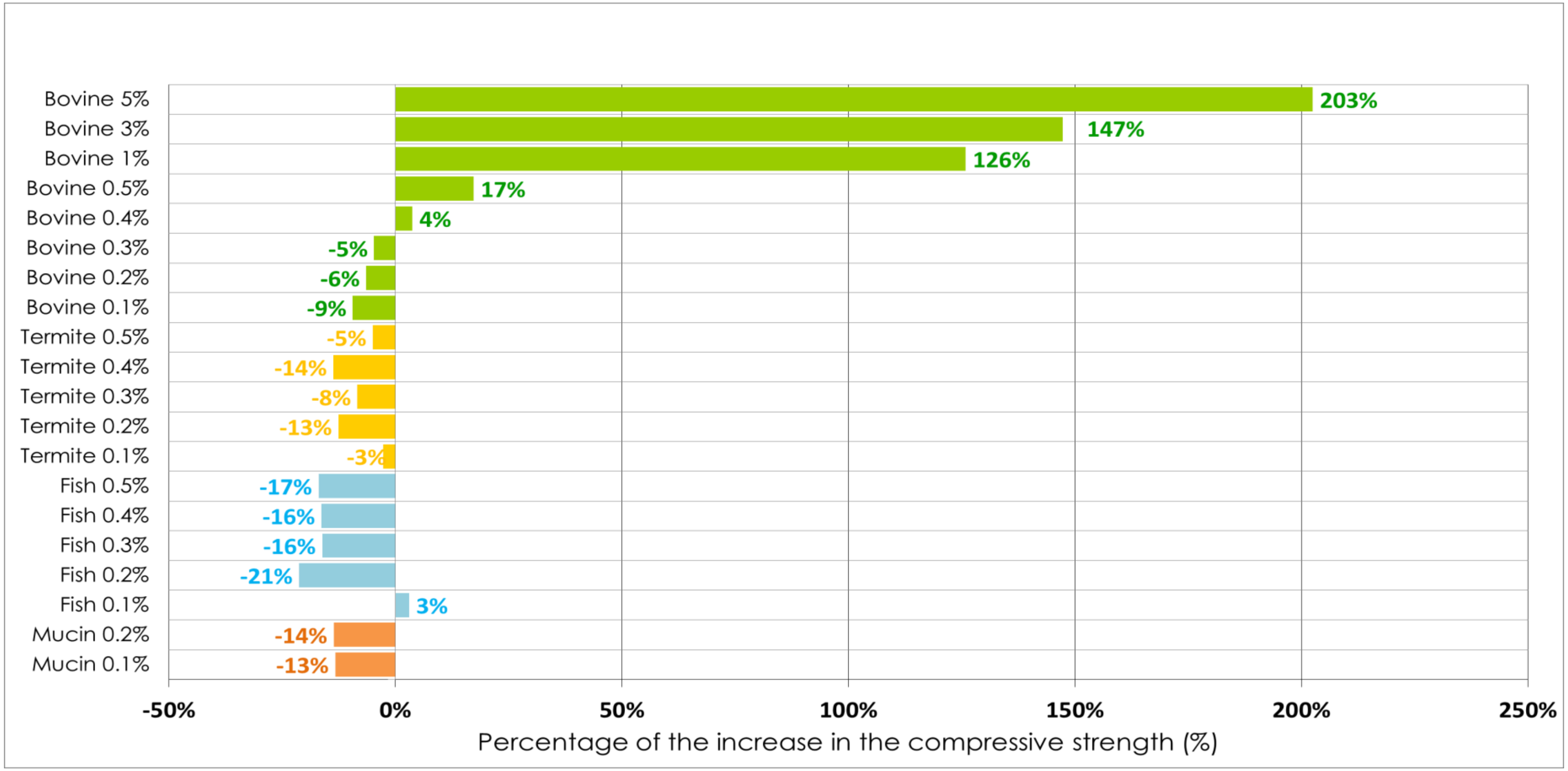



**Figure 4-33:** The effect of the addition of the different stabilisers and their concentrations on the unconfined compressive strength of the British adobe bricks. The percentages of the increase in the compressive strength were calculated using the compressive strength of the unstabilised British adobe bricks as the reference. The stabilisers are: Bovine serum albumin, Termite's saliva ingredients, Fish gelatine from cold water fish skin and Mucin from porcine stomach.

Bovine serum albumin was the glycoprotein which resulted in the highest increase in the compressive strength for the British adobe bricks in this study. The use of 5% bovine serum albumin resulted in over 200% increase in the compressive strength of the British adobe bricks. There were 147% and 126% increase in the compressive strength of the British adobe bricks due to the use of 3% and 1% of bovine serum albumin respectively. Furthermore, the inclusion of lower percentages of the bovine serum albumin (0.5% and 0.4%) in the British adobe bricks also increased the compressive strength of the bricks. There was 17% increase in the compressive strength when 0.5% bovine serum albumin was used and 4% increase in the compressive strength as a result of adding 0.4% of the bovine serum albumin. In contrast, the addition of concentrations lower than 0.4% of the bovine serum albumin resulted in the reduction of the compressive strength of the British adobe bricks. For instance, the use of 0.3% bovine serum albumin led to 5% reduction in the compressive strength. Similarly, the addition of only 0.2% and 0.1% of the bovine serum albumin resulted in 6% and 9% reduction in the compressive strength of the British adobe bricks.

### 4.10.2 Sudanese adobe stabilised bricks unconfined compressive strength: Summary of the Results

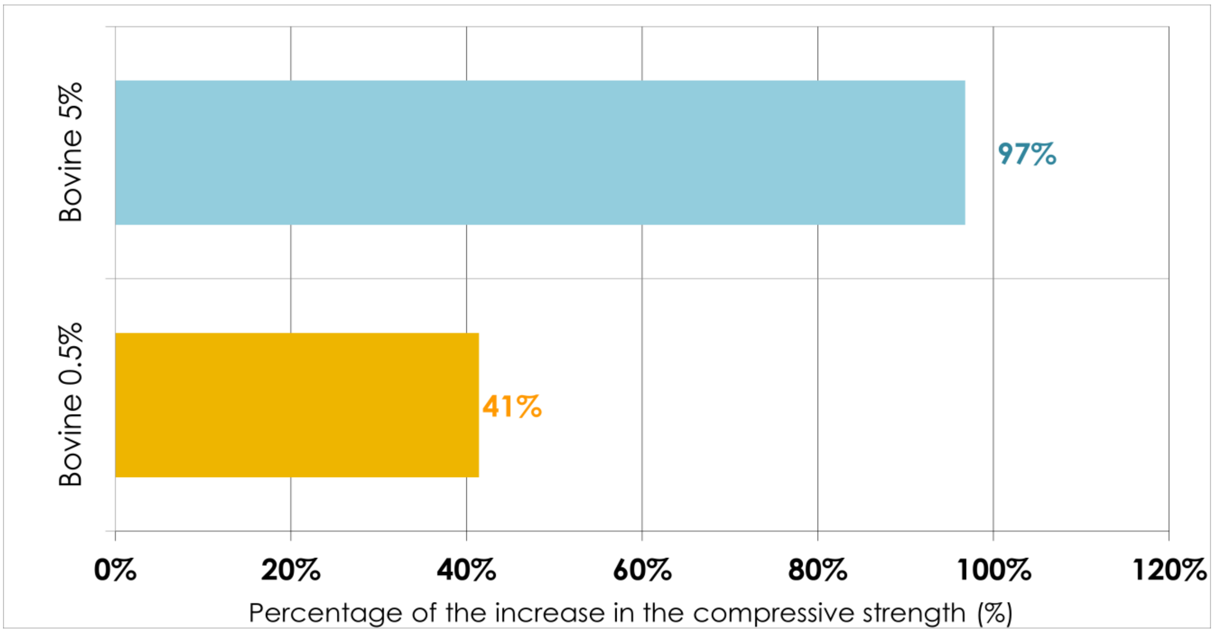



**Figure 4-34:** The effect of the addition of the bovine serum albumin on the unconfined compressive strength of the Sudanese adobe bricks. The percentages of the increase in the compressive strength were calculated using the compressive strength of the unstabilised Sudanese adobe bricks as the reference.

Figure 4-34 above shows the percentage of the increase in the unconfined compressive strength of the Sudanese adobe bricks stabilised with two different percentages of the bovine serum albumin. From Figure 4-34, the addition of 0.5% of the bovine serum albumin resulted in 41% increase in the compressive strength. Furthermore, the inclusion of 5% of bovine serum albumin in the Sudanese adobe bricks led to 97% increase in the compressive strength. In general, the use of bovine serum albumin as stabiliser for the Sudanese adobe bricks has enhanced the strength of the bricks and led to better quality of bricks.

### *4.10.3 Comparison of the Results: The British and the Sudanese stabilised adobe bricks compressive strength*

Figure 4-35 shows the increase in the compressive strength for the British and the Sudanese adobe bricks after they were stabilised using the 0.5% and 5% bovine serum albumin. The Sudanese adobe bricks showed 43% increase in the compressive strength as a result of the inclusion of the 0.5% bovine serum albumin compared to an increase of 16% for the British adobe bricks.

The addition of 5% bovine serum albumin resulted in 200% increase in the compressive strength of the British adobe bricks compared with 97% increase in the compressive strength of the Sudanese adobe bricks.

The British adobe bricks showed 159% increase in the compressive strength when the concentration of the bovine serum albumin was increased from 0.5% to 5% compared to an increase of 38% for the Sudanese adobe bricks.

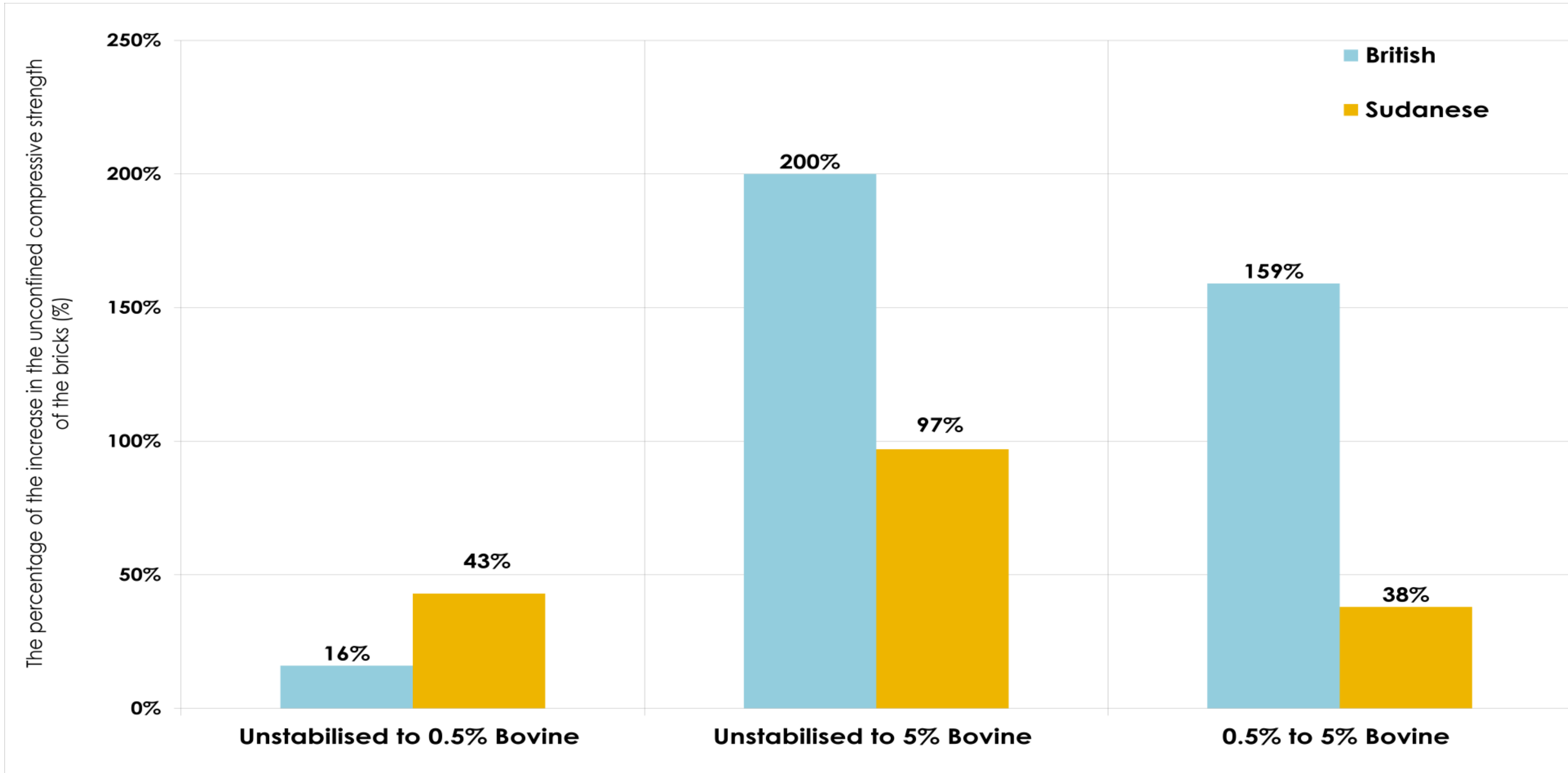



**Figure 4-35:** The increase in the unconfined compressive strength due to the addition of 0.5% & 5% bovine serum albumin for the two soils: **the British** and **the Sudanese** soils. The percentages of the increase in the compressive strength were calculated using the compressive strength of the unstabilised British adobe bricks for the bovine stabilised British adobe bricks and the unstabilised Sudanese adobe bricks for the bovine stabilised Sudanese adobe bricks as the reference. The graph also shows the percentage of the increase in the compressive strength when the bovine serum albumin concentration has been increased from 0.5% to 5% for both soils.

### 4.10.4 Statistical Analysis: The British and the Sudanese stabilised adobe bricks compressive strength Results

From the results in the previous section (4.10.3) it was clear that the two soils were reacting differently for the same concentration of the bovine serum albumin. Figure 4-35 in section 4.10.3 above, showed that the increase in the compressive strength for the two soils was not solely dependent on the soil type, nor dependent on the bovine serum albumin concentration. Hence this was the case, it was thought is better to find out which one of these two factors (soil type and the glycoprotein concentration) has more effect on the compressive strength. In addition, finding out if these two factors have a combined effect (an interaction) on the compressive strength of the adobe brick is crucial. In order to investigate this, a two-way ANOVA analysis was conducted to compare the main effects of the bovine serum albumin concentration and the soil types and the interaction effect between bovine serum albumin concentration and the soil types on the compressive strength of the adobe bricks, Table 4-22 below.

**Table 4-22:** Two-way ANOVA statistics for concentration of the bovine serum albumin vs. the soil types (compressive strength of the adobe bricks), the concentrations are: 0.5% & 5%, and the soil types are: the British and the Sudanese soils

| ***Source of Variation*** | ***Sum of Squares (SS)*** | ***Degree of Freedom (df)*** | ***Mean Sum of Squares (MS)*** | ***F*** | ***P-value*** |
|---|---|---|---|---|---|
| **Bovine concentration (%)** | 42.777 | 1 | 42.777 | 53.02 | 0.000 |
| **Soil types** | 14.832 | 1 | 14.832 | 18.38 | 0.000 |
| Interaction | 4.332 | 1 | 4.332 | 5.37 | 0.031 |
| Within | 16.136 | 20 | 0.807 | | |
| Total | 78.077 | 23 | | | |

A two-way analysis of variance was conducted on the influence of two independent variables (the bovine serum albumin concentration, soil types) on the unconfined compressive strength of the adobe bricks. Bovine serum albumin included two levels (0.5 and 5 by weigh percent concentration) and soil types consisted of two levels (British soil and Sudanese soil). All effects were statistically significant at the 0.05

significance level. The main effect for bovine serum albumin concentration yielded an $F$ ratio of $F$ (1, 20) = 53.02, $p < 0.001$, indicating a significant difference between 0.5% bovine serum albumin concentration (M = 3.44, SD = 1.336) and 5% bovine serum albumin concentration (M = 6.11, SD = 1.193). The main effect for soil types yielded an $F$ ratio of $F$ (1, 20) = 18.38, $p < 0.001$, indicating that the effect for soil type was significant, British soil (M = 3.99, SD = 2.040) and Sudanese soil (M = 5.56, SD = 1.260). The interaction effect was significant, $F$ (1, 20) = 5.37, $p < 0.001$.

In addition, the ANOVA results confirmed that for the compressive strength, the bovine serum albumin concentration ($F$= 53.02) is on the average dominant over the soil types ($F$=18.38).

# 5. Accelerated Erosion Test Results

## 5.1 Accelerated Erosion Test

The accelerated erosion test was performed on all bricks in accordance with Bulletin 5 (Earth wall construction), the Australian earth building handbook and the New Zealand Materials and workmanship for earth buildings [Building Code Compliance Document E2 (AS2)], (Middleton, 1987, NZS4298, 1998, Walker and International, 2002). This chapter investigates the effect of the addition of the glycoprotein on the erosion resistance of the adobe bricks made using both the British and the Sudanese soils. It will include the preparation of the unstabilised and the stabilised bricks as well as the results of the bricks' erosion resistance. Based on the structure of the experimental tests in section 4.1, this erosion section will be divided into four parts as follows:

**Table 5-1:** The four parts of the erosion tests based on the structure of the experimental tests

<table>
<tr><th>Hypotheses</th><th>Phases</th><th>Tests</th></tr>
<tr><td rowspan="3">Testing the first hypothesis (British soil)</td><td>Phase one</td><td>0.1% Glycoprotein</td></tr>
<tr><td>Phase two</td><td>0.2% Glycoprotein</td></tr>
<tr><td>Phase four</td><td>0.5% Bovine serum albumin</td></tr>
<tr><td>Testing the second hypothesis (Sudanese soil)</td><td colspan="2">Test the effect of adding 0.5% Bovine serum albumin on the erosion resistance</td></tr>
</table>

## 5.2 Preparation of the unstabilised British adobe bricks

The unstabilised adobe bricks were made by following the steps described in section 4.3 using full-size bricks.

## 5.3 Preparation of the stabilised British adobe bricks

The stabilised British adobe bricks were made by following the steps described in section 4.4 using full-size bricks. The quantities used to prepare the bricks are in Table 4-1 in section 4.3.

## 5.4 Preparations of the adobe bricks prior to the erosion test.

Prior to conduct the erosion test, all the bricks were measured for their length, width and height (three measurements were taken for each parameter and then the average was calculated). Furthermore, masses of the bricks were recorded. In addition, another new parameter which named as erosion depth correction factor (d) was introduced which it was noticed to affect the erosion depth measurements during conducting the preliminary experiments. As mentioned before in section 4.3, every effort was made to ensure that the upper face of each brick was even and flat. However, after the 28 days of the drying, the bricks shrunk in size due to the evaporation of the water from the pores. It was observed that this shrinkage had affected the upper surface of the brick where the water jet struck the brick surface during the erosion test. As a result, the upper surface of the brick was bent exactly in the centre where the erosion spray jet operates, Figure 5-1

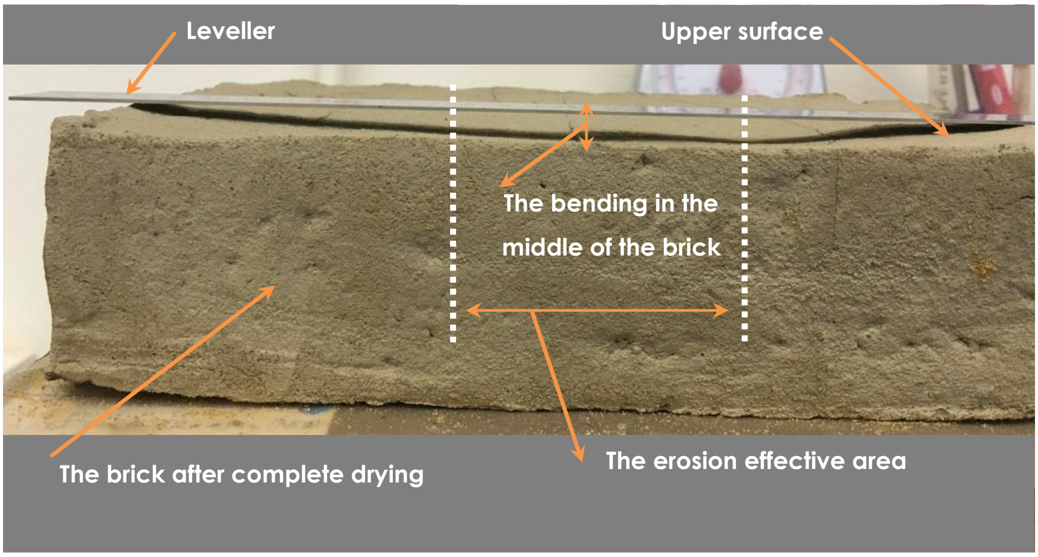
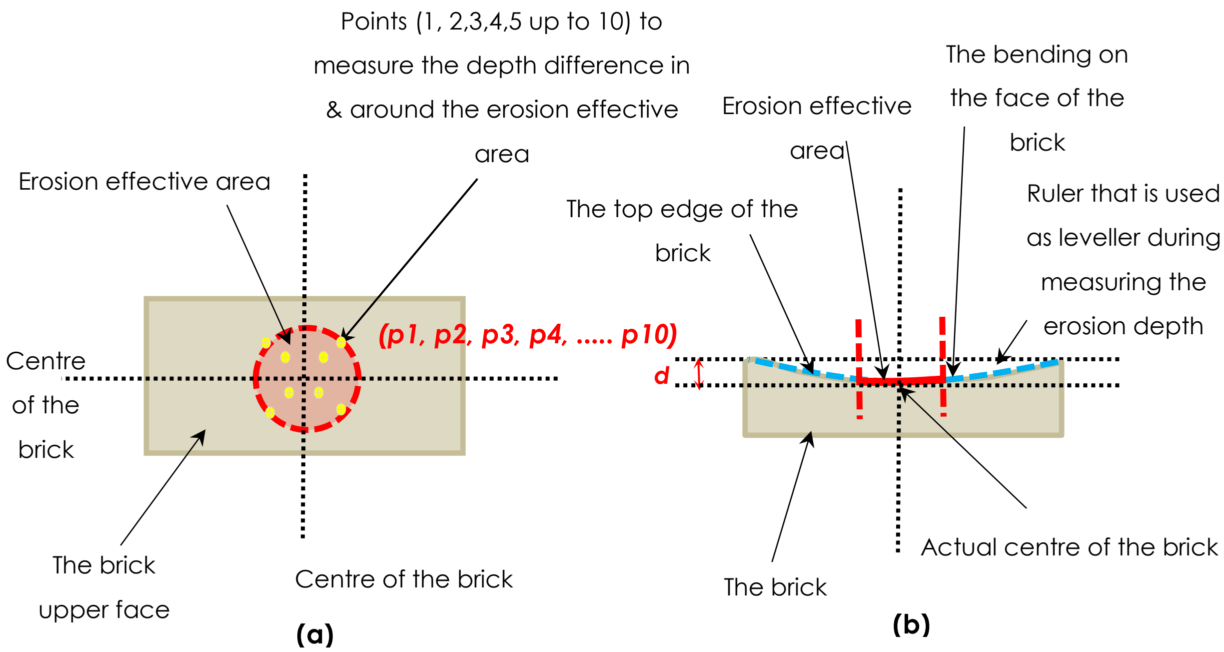



**Figure 5-1:** The brick with a leveller on the upper surface showing the bending in the middle of the brick where the erosion testing will take place after the drying period was complete

It was noticed that this bending will result in increasing the erosion depth measurements. To avoid any misleading measurements a correction factor was introduced. The correction factor (*d*) was calculated according to the erosion effective area on the face of the brick (the area in the centre of the brick face where the spray jet hits during the erosion test). This area was a circular in shape in the middle of the brick upper surface, Figure 5-2. The diameter of the circle was 8 cm. The measurements for calculating (*d*) were conducted using the 10 mm metal flat ended rod that was used to measure the erosion depth during the test. Ten different measurements were taken. Two measurements in the centre of the circle and the rest of the measurements were in eight different points inside and along the circle line, Figure 5-2. The correction factor (*d*) was calculated as the average of these ten points. This (*d*) was used to correct the original depth of the erosion measured during the test. This correction factor was used in all erosion test results for all the unstabilised and the stabilised bricks of both soils types.

This correction factor was preferred to be used over the use of an electrical sander to level the surface of the brick. In some previous research on adobe bricks, an electrical sander was used to smooth and level the face of the bricks under investigation. For example, (Illampas et al., 2014) used a sander to smooth their bricks. They used the sander to prepare bricks for compressive strength test and not for erosion test. It was thought that using an electrical sander to smooth and level the face of a brick for the erosion test will affect the measurements and the overall results of the erosion test. The contact of the sander with the brick surface will break the surface by introducing holes and small cracks which will result in a face which is so vulnerable to erosion by water and thus will lead to inaccurate results.




$$d = \frac{p1 + p2 + p3 + p4 + p5 + p6 + p7 + p8 + p9 + p10}{10}$$

***Actual erosion depth = Original erosion depth from the erosion test - d***

**Figure 5-2:** The erosion depth correction factor (*d*) calculations, **(a)** the face of the brick showing the erosion effective area in the centre of the upper face of the brick with the ten points used to calculate the correction factor (*d*), **(b)** the side of the brick showing the bending on the upper surface of the brick due to the shrinking during the drying process along with the erosion effective area in the middle and the erosion correction factor (*d*)

## 5.5 Conducting the erosion test

All the bricks were sprayed for one hour in 15 minutes intervals according to the accelerated erosion test standard mentioned in section 3.3.4. For the erosion test in this study, the top face of the brick was chosen for testing the resistance of the brick to erosion. However, it is well documented that the brick's erosion resistance differs from top face to bottom face and to the side face of the brick (Heathcote, 2002). (Heathcote, 2002)reported that the erosion on the side face of a brick could be significantly higher than on the usual tested face, which is generally either the top or the bottom face. In an ideal situation, the test is preferred to be conducted on the side face of the brick which in the reality is the face that faces the rain. However, in this study, the side face was not chosen due to its small area which was smaller than the erosion equipment which was available for the test.

The spray was aimed at the top face of the brick, Figure 5-3. Then the spray was stopped and the erosion depth was measured using a 10 mm flat ended metal rod. All the measurements were in mm. The spray jet resulted in 9 pits in and around the centre of the upper face of the brick, Figure 5-3.

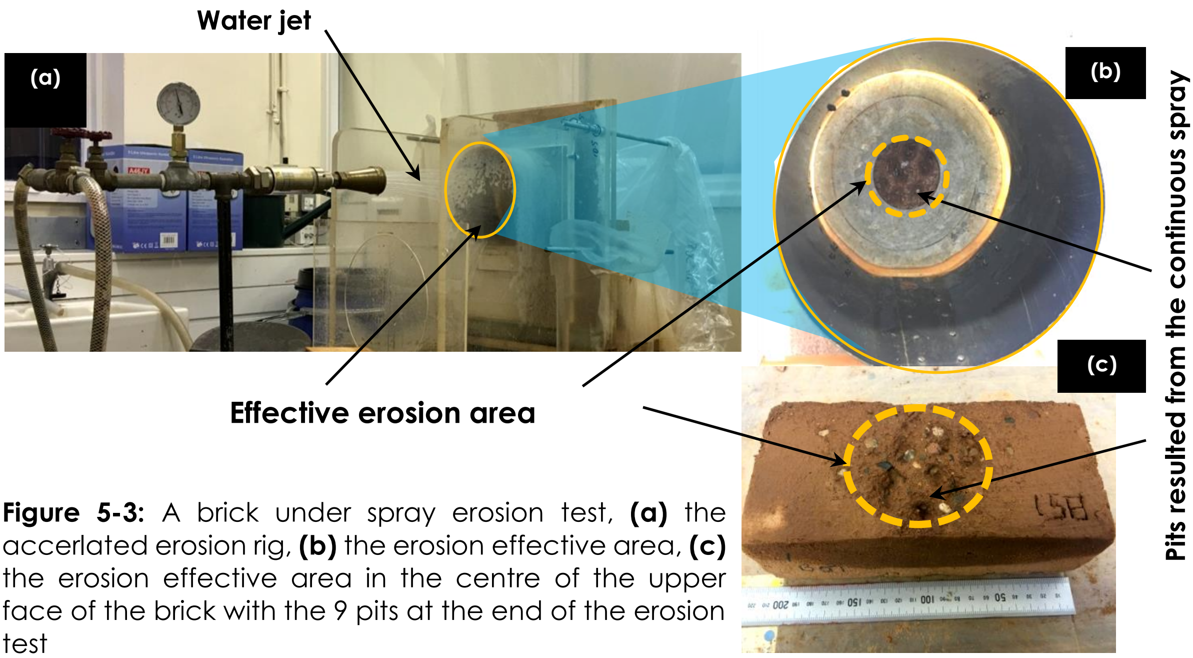



**Figure 5-3:** A brick under spray erosion test, **(a)** the accerlated erosion rig, **(b)** the erosion effective area, **(c)** the erosion effective area in the centre of the upper face of the brick with the 9 pits at the end of the erosion test

## 5.6 Testing the First Hypothesis:

### *5.6.1 Phase One: Purpose of the Phase*

As has been mentioned before in section 4.5.1, the purpose of this phase was to test the lowest possible percentage of glycoprotein that could be used to stabilise the adobe bricks. The first percentage tested was selected based on the results of the investigation that was carried out by Gillman and his colleagues in 1972. They analysed the mound soil of the Coptotermes Acinaciformis termites in Australia. They found that the concentration of the glycoprotein in 1 kg of the mound's soil was approximately 0.1% (Gillman et al. 1972). As a result, 0.1 by weight % of glycoprotein was the lowest percentage used to stabilise British adobe bricks in this study. All the glycoproteins identified as potential stabilisers in section 3.2 before (bovine serum albumin, gelatine from cold-water fish skin, mucin from porcine stomach and termite's saliva ingredients) were used to prepare adobe bricks with 0.1% concentration and then the bricks were tested for their erosion resistance. The erosion results of the 0.1% British stabilised adobe bricks were compared with the results of the unstabilised British adobe bricks, the control sample. The results were presented as erosion rate (D) in mm/min, which is the maximum erosion depth achieved in one hour in mm divided by 60 minutes.

### *5.6.2 Phase One: The Results*

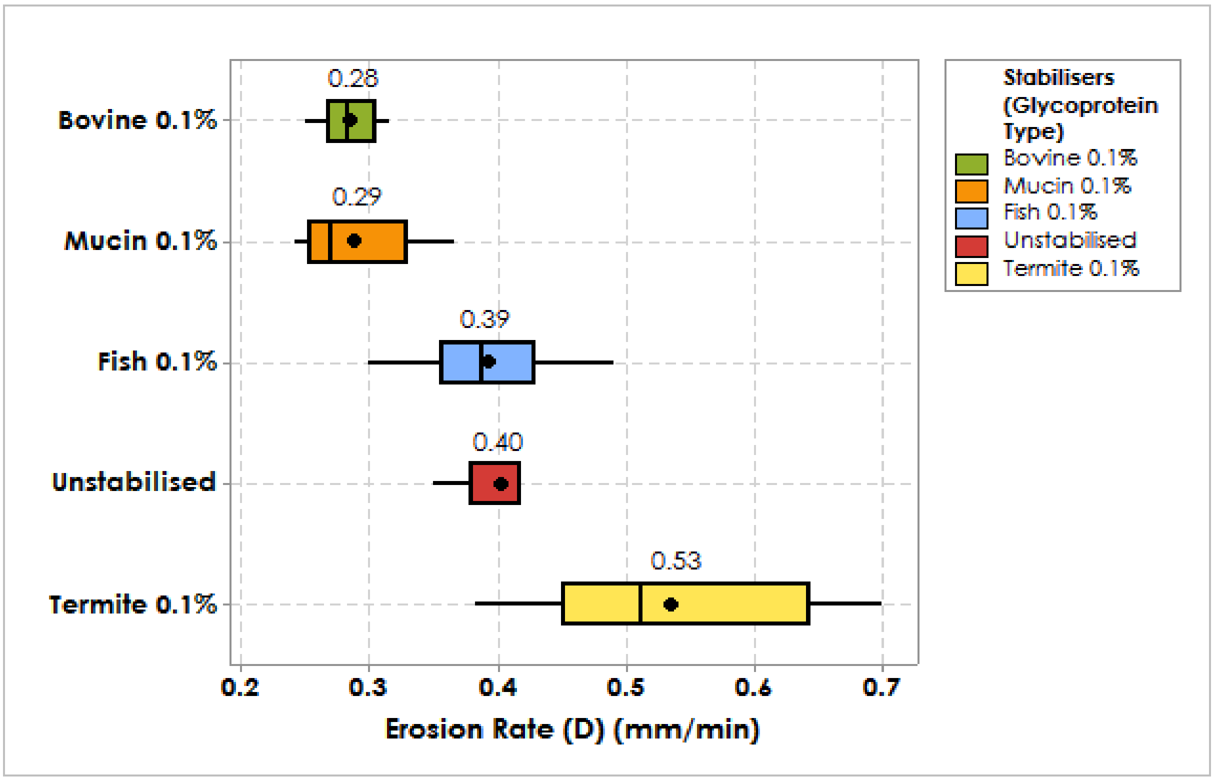



**Figure 5-4:** The effect of the adding 0.1% from the glycoproteins on the erosion resistance of the British adobe bricks. The boxplots represent the inter-quartile range of the data obtained. *(there was an outlier in the unstabilised data, however, neither the presence (0.42 mm/min) nor absence (0.40 mm/min) of it would change the graph).*

Figure 5-4 shows the results for the erosion rate (D) of the British adobe stabilised and unstabilised bricks. The addition of 0.1 by weight % of bovine serum albumin reduced the erosion rate compared with the unstabilised British adobe bricks. The erosion rate decreased from 0.40 mm/min to 0.28 mm/min when bovine serum albumin was used to stabilise the British adobe bricks. Furthermore, the erosion rate reduced from 0.40 mm/min to 0.29 mm/min as a result of the addition of 0.1% mucin. In contrast, the addition of 0.1% fish gelatine has no change over the erosion rate. However, the use of 0.1% of the termite's saliva ingredients resulted in increasing the erosion rate of the British adobe bricks from 0.40 mm/min for the unstabilised British adobe bricks to 0.53

mm/min when 0.1% of the termite's saliva ingredients was used. Figure 5-5 below shows how the bricks upper face looks after the erosion test was finished and the bricks were completely dried out. It was noticed that the bricks which were stabilised using 0.1% termite's saliva ingredients ended up having one big hole in the erosion effective area when they were compared to other bricks. In fact, the usual 9 pits resulted from the erosion test came together to create this one big hole when the termite's saliva ingredients was used to stabilise the British adobe bricks. The mucin stabilised British adobe bricks had the most defined erosion pits at the end of the test. Although the surface of the final eroded bricks for the unstabilised and the 0.1% bovine and fish gelatine stabilised adobe bricks look to some extent similar, there was difference in the degree of the erosion.

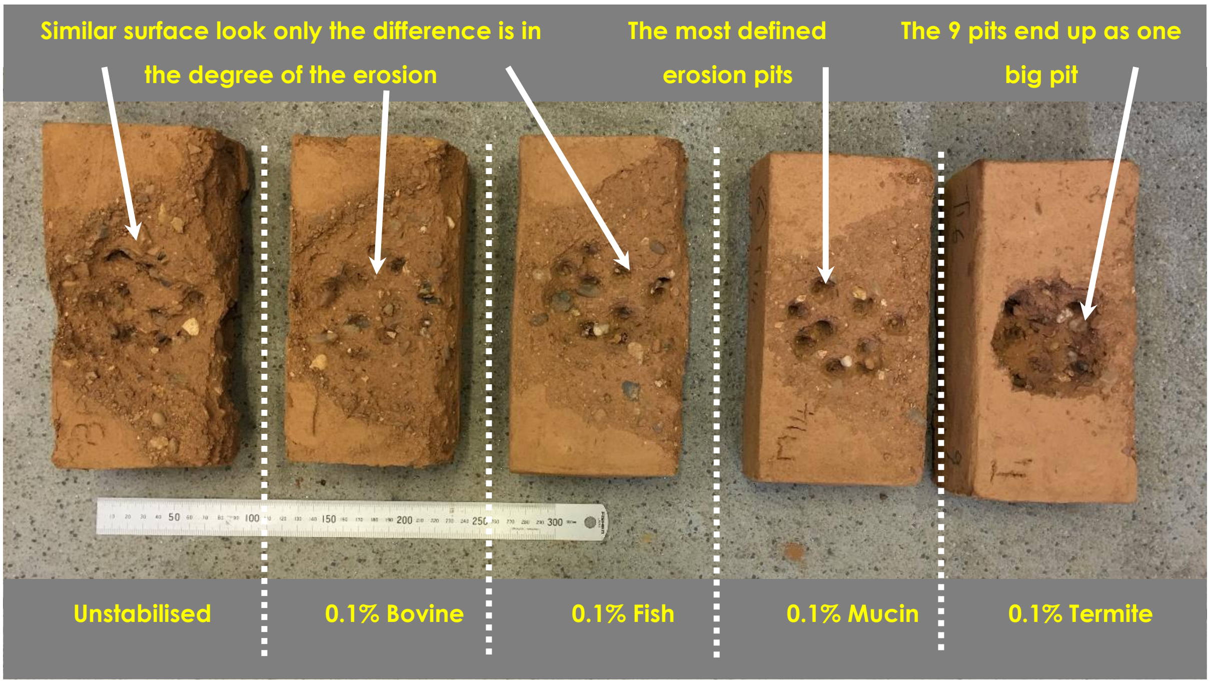



**Figure 5-5**: Unstabilised and 0.1% stabilised British adobe bricks' upper face after the accelerated erosion test has finished and the bricks fully dried out. The difference in the degree of the erosion between the bricks was linked to the use of different types of stabilisers, glycoproteins.

## *5.6.3 Phase One: Statistical Analysis*

To check the significance difference of the test results, a one-way ANOVA test was conducted to compare the effect of the type of the glycoprotein on the erosion rate (D) of the British adobe bricks, Table 5-2. The null hypothesis was that the means of the erosion rate (D) for all the stabilised and unstabilised British adobe bricks come from the same overall population. An analysis of variance showed that the effect of the type of the glycoprotein on the erosion rate (D) was statistically significant, $F\ (4, 25) = 14.572$, $p = 0.000$, Table 5-2. Thus, the differences in the means of the erosion rate (D) among the stabilised and the unstabilised British adobe bricks are significant and they are not coming from the same overall population.

**Table 5-2:** One-way ANOVA at 95% confidence interval to compare the effect of the type of the glycoprotein on the erosion rate (D) of the British adobe bricks for 0.1% stabilisers (stabilisers groups are: Unstabilised, Bovine serum albumin, Fish gelatine, Mucin & Termite's saliva ingredients)

| ***Source of Variation*** | ***Sum of Squares (SS)*** | ***Degree of Freedom (df)*** | ***Mean Sum of Squares (MS)*** | ***F*** | ***P-value*** | ***F crit*** |
|---|---|---|---|---|---|---|
| **Between Groups** | 0.260 | 4 | 0.065 | 14.572 | 0.000 | 2.759 |
| **Within Groups** | 0.112 | 25 | 0.004 | | | |
| **Total** | 0.372 | 29 | | | | |

### 5.6.4 Phase Two: Purpose of the Phase

Based on the results from phase one and the improvement of the erosion rate as a direct result of the addition of some of the glycoproteins, it was decided to investigate the reduction of the erosion rate of the British adobe bricks due to the increase of the concentration of the glycoprotein to 0.2 by weight %. All the four stabilisers were tested and the results were compared with the erosion rate results of the controlled sample (the unstabilised British adobe bricks).

### *5.6.5 Phase Two: The Results*

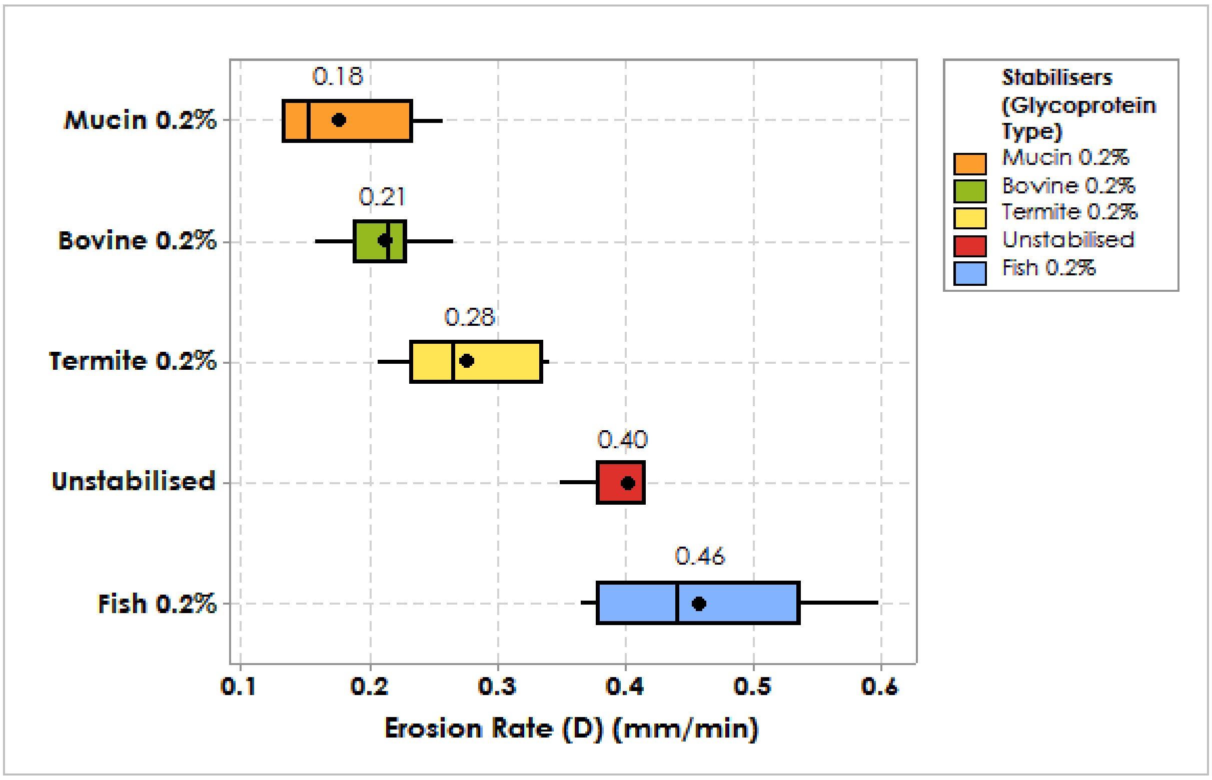



**Figure 5-6:** The effect of the adding 0.2% from the glycoproteins on the erosion resistance of the British adobe bricks. The boxplots represent the inter-quartile range of the data obtained. *(there was an outlier in the unstabilised data, however, neither the presence (0.42 mm/min) nor absence (0.40 mm/min) of it would change the graph).*

Figure 5-6 shows the erosion rate (D) results for the British adobe stabilised and unstabilised bricks. The addition of 0.2 by weight % of mucin resulted in the least erosion rate compared with all the other stabilisers. The inclusion of the mucin reduced the erosion rate from 0.40 mm/min for the unstabilised British adobe bricks to 0.18 mm/min. Furthermore, both bovine serum albumin and termite's saliva ingredients improved the erosion resistance of the British adobe bricks compared with the unstabilised British adobe brick. The erosion rate reduced from 0.40 mm/min to 0.21 mm/min and 0.28 mm/min for unstabilised, 0.2% bovine stabilised and 0.2% termite's saliva stabilised British adobe bricks respectively. However, the use of 0.2% of the fish gelatine resulted in increasing the erosion rate of the British adobe bricks. The erosion rate increased from 0.40 mm/min for the unstabilised British adobe bricks to 0.46 mm/min when 0.2% of the fish gelatine was used.  From Figure 5-7 below, it is clear that the mucin stabilised bricks have the least eroded surface compared with all other bricks' surfaces. The 0.2%

bovine serum albumin stabilised bricks upper surface no longer looks similar to that of the unstabilised and the 0.2% fish stabilised bricks. This means the addition of more bovine serum albumin enhanced the surface of the British adobe bricks make it more resistant to erosion. The eroded surface of the unstabilised and 0.2% fish stabilised adobe bricks look similar with difference in the degree of the erosion. The surface of the 0.2% termite's saliva ingredients stabilised adobe bricks less eroded than the surface of the 0.1% termite's stabilised adobe brick in Figure 5-5.

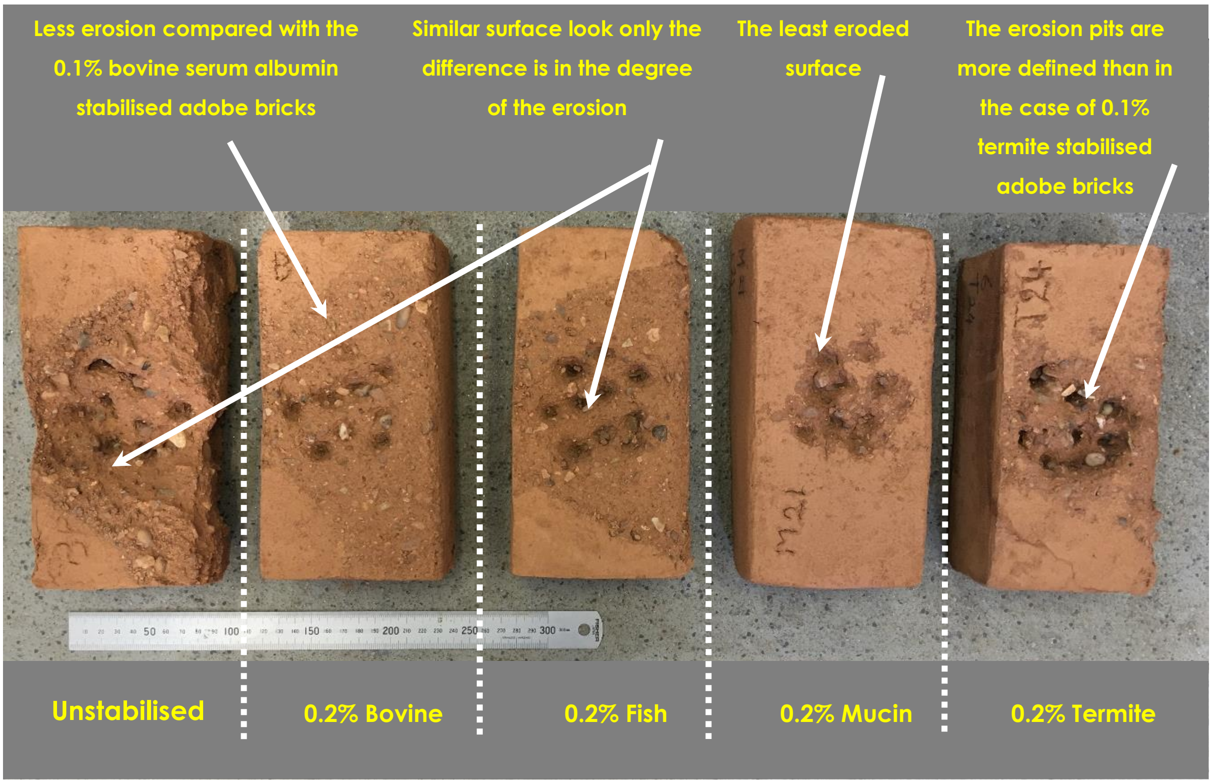



**Figure 5-7:** Unstabilised and 0.2% stabilised British adobe bricks after the accelerated erosion test has finished and the bricks fully dried out. The difference in the degree of the erosion between the bricks was linked to the use of different types of stabilisers, glycoproteins.

## 5.6.6 Phase Two: Statistical Analysis

**Table 5-3:** One-way ANOVA at 95% confidence interval to compare the effect of the type of the glycoprotein on the erosion rate (D) of the British adobe bricks for 0.2% stabilisers (stabilisers groups are: Unstabilised, Bovine serum albumin, Fish gelatine, Mucin &Termite's saliva ingredients)

| *Source of Variation* | *Sum of Squares (SS)* | *Degree of Freedom (df)* | *Mean Sum of Squares (MS)* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Between Groups** | 0.378 | 4 | 0.095 | 26.233 | 0.000 | 2.759 |
| **Within Groups** | 0.090 | 25 | 0.004 | | | |
| **Total** | 0.469 | 29 | | | | |

To check the significance difference of the test results, a one-way ANOVA test was conducted to compare the effect of the type of the glycoprotein on the erosion rate (D) of the British adobe bricks, Table 5-3. The null hypothesis was that the means of the erosion rate (D) for all the stabilised and unstabilised British adobe bricks come from the same overall population. An analysis of variance showed that the effect of the type of the glycoprotein on the erosion rate (D) was statistically significant, $F$ (4, 25) = 26.233, $p$ = 0.000, Table 5-3. Thus, the differences in the means of the erosion rate (D) among the stabilised and the unstabilised British adobe bricks are significant and they are not coming from the same overall population.

## 5.6.7 Comparison of the bricks' erosion resistance throughout the test one-hour period for both glycoprotein concentrations (0.1% & 0.2%)

As has been mentioned before in section 3.3.4, the erosion test was conducted in 15 minutes intervals and after each 15 minutes the test was stopped and the pits depth was measured using a 10 mm diameter flat-ended metal rod. The maximum erosion depth in one hour is divided by 60 to give the rate of erosion ($D$) in mm per min. Looking at the erosion rate for each 15 minutes and compare it across all the stabilised and the unstabilised bricks gives a glimpse of how these stabilisers behave overtime. As it has been mentioned before in 3.3.4, one hour of this test is equivalent to 85 years of wind-driven rain in Sydney where this test was developed (Heathcote, 2002). According to this, every 15 minutes of the erosion test could be used as an indication of ≈ 21 years of erosion in Sydney (in nature). By comparing the erosion rate based on the 15 minutes intervals, it can tell how these stabilised bricks are eroded overtime. From Figure 5-8 below, for the first 15 minutes during the erosion test, the 0.2% fish gelatine stabilised British adobe bricks has the highest erosion rate with 0.66 mm/ min compared with all the other stabilised British adobe bricks and the unstabilised ones. Also, the 0.1% fish gelatine stabilised British adobe bricks has high erosion rate, 0.48 mm/min, compared with all other stabilised British adobe bricks and the unstabilised adobe bricks. All the other stabilised British adobe bricks (0.1% & 0.2% bovine serum albumin, 0.1% & 0.2% mucin and 0.1% & 0.2% termite's saliva ingredients) have lower erosion rate compared with the erosion rate of the unstabilised. For instance, the addition of 0.1% & 0.2% bovine serum albumin, 0.1% & 0.2% mucin, 0.1% & 0.2% termite's saliva ingredients, resulted in 0.44 mm/min, 0.33 mm/min, 0.33 mm/min, 0.17 mm/min, 0.34 mm/min and 0.32 mm/min respectively.

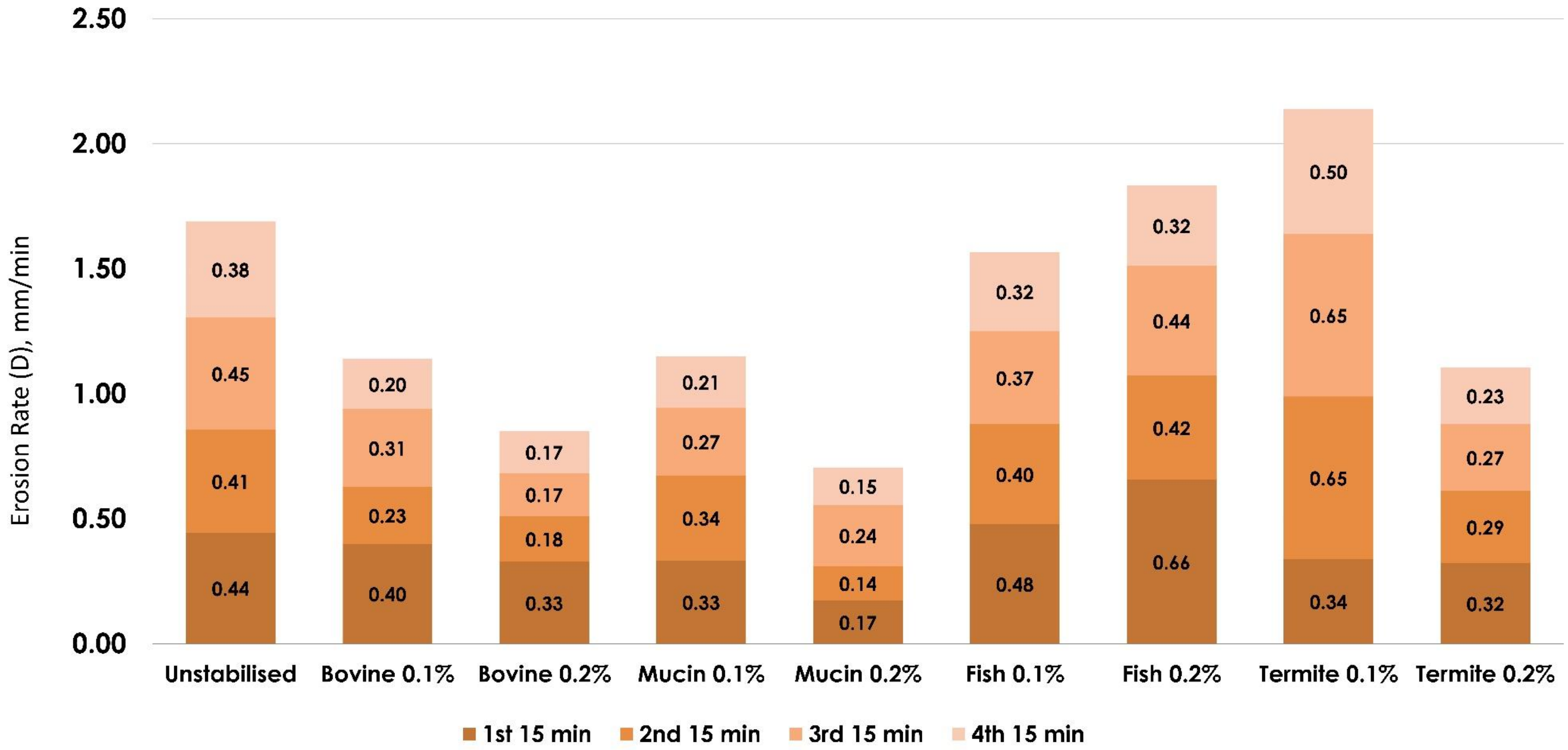



**Figure 5-8:** The rate of the erosion (D) for the unstabilised and all stabilised British adobe bricks throughout the one-hour test period. The one hour has been divided into 15th intervals and each data point for each 15th interval is the average of 6 data points. The data is in mm/min for each 15 minute intervals.

In the second 15 minutes intervals, the bricks which were stabilised using 0.1% termite's saliva ingredients had the highest erosion rate (0.65 mm/min) compared with all the other stabilised adobe bricks and the unstabilised ones. The 0.1% fish gelatine stabilised and the 0.2% fish gelatine stabilised resulted in erosion rate similar to the unstabilised British adobe bricks erosion rate which was 0.41 mm/min. The bricks stabilised using 0.1% mucin resulted in 0.34 mm/min erosion rate which was lower than the erosion rate of the unstabilised adobe bricks. The 0.2% termite's saliva ingredient stabilised adobe bricks had 0.29 mm/min erosion rate which was also lower than the erosion rate of the unstabilised adobe bricks. The lowest erosion rates were achieved by using 0.1% & 0.2% bovine serum albumin and the 0.2% mucin, with 0.23 mm/min, 0.18 mm/min and 0.14 mm/min respectively.

After the third 15 minutes of the test, the adobe bricks stabilised using 0.1% termite's saliva ingredients still had the highest erosion rate with 0.65 mm/min. The unstabilised and 0.2% fish gelatine stabilised adobe bricks had the same erosion rate, 0.44 mm/min which was lower than the 0.1% termite's saliva ingredients, but higher than all the other stabilised adobe bricks. The adobe bricks stabilised using 0.1% fish gelatine and 0.1% bovine serum albumin resulted in 0.37 mm/min and 0.31 mm/min erosion rate respectively. In addition, 0.1% mucin and 0.2% termite's saliva ingredients stabilised adobe bricks have the same erosion rate which was 0.27 mm/min. The lowest erosion rates were achieved by using 0.2% mucin and 0.2% bovine serum albumin with 0.24 mm/min and 0.17 mm/min respectively.

In the last 15 minutes of the erosion test, the 0.1% termite's saliva ingredients stabilised adobe bricks still have the highest erosion rate among all the other stabilised adobe bricks and the unstabilised with 0.50 mm/min. All the other stabilised adobe bricks have erosion rate lower than the unstabilised adobe bricks with 0.38 mm/min. For instance, the adobe bricks stabilised using 0.1% & 0.2% fish gelatine have 0.32 mm/min erosion rate. The 0.2% termite's saliva ingredients, 0.1% mucin and 0.1% bovine serum albumin stabilised adobe bricks resulted in 0.23 mm/min, 0.21 mm/min and 0.20 mm/min erosion rate. The lowest erosion rate achieved due to the use of 0.2% bovine serum albumin and 0.2% mucin with 0.17 mm/min and 0.15 mm/min respectively.

The above comparison shows that, some stabilisers started the erosion process with a rate lower than the unstabilised adobe bricks such as the bricks made from the termite's saliva ingredients, but in the long run of the life of the brick they eroded more frequently and they end up eroded deeper than the unstabilised adobe bricks. In addition, other stabilisers started the erosion process similar to that of the unstabilised bricks, but with time they ended with either same progress as the unstabilised or more eroded such as when fish gelatine was used. In contrast, some stabilisers starting looks similar or lower than the unstabilised adobe bricks, but end with lower erosion rate such as the bovine serum albumin and the mucin. In general, mucin has proved to be the best stabiliser from erosion resistance point of view for the British adobe bricks.

### *5.6.8 Comparison of the bricks' erosion resistance for 0.1% & 0.2%: Statistical Analysis*

A two-way ANOVA analysis was conducted to compare the main effects of the glycoprotein concentrations and the glycoprotein types and the interaction effect between them on the erosion rate of the adobe bricks, Table 5-4.

**Table 5-4:** Two-way ANOVA statistics for concentration of the glycoprotein vs. the glycoprotein types (erosion rate of the adobe British bricks), the concentrations are 0.1% & 0.2%, and the glycoprotein types are Bovine serum albumin, Fish gelatine, Mucin & Termite's saliva ingredients

| ***Source of Variation*** | ***Sum of Squares (SS)*** | ***Degree of Freedom (df)*** | ***Mean Sum of Squares (MS)*** | ***F*** | ***P-value*** |
|---|---|---|---|---|---|
| **Glycoprotein concentration (%)** | 0.106 | 1 | 0.105 | 24.85 | 0.000 |
| **Glycoprotein types** | 0.371 | 3 | 0.124 | 29.18 | 0.000 |
| Interaction | 0.161 | 3 | 0.054 | 12.63 | 0.000 |
| Within | 0.170 | 40 | 0.004 | | |
| Total | 0.807 | 47 | | | |

A two-way analysis of variance was conducted on the influence of two independent variables (the glycoprotein concentrations, the glycoprotein types) on the erosion rate of the British adobe bricks. The glycoprotein concentrations included two levels (0.1, and 0.2 by weigh percent glycoprotein) and the glycoprotein types consisted of four levels (bovine serum albumin, fish gelatine, mucin and termite's saliva ingredients). All effects were statistically significant at the 0.05 significance level. The main effect for glycoprotein concentrations yielded an *F* ratio of $F$ (1, 40) = 24.85, $p$ < .001, indicating a significant difference between 0.1% glycoprotein (M = 0.37, SD = 0.123),) and 0.2% glycoprotein (M = 0.28, SD = 0.125). The main effect for glycoprotein types yielded an F ratio of $F$ (3, 40) = 29.18, $p$ < .001, indicating a significant difference between bovine serum albumin (M = 0.25, SD = 0.047), fish gelatine (M = 0.43, SD = 0.081), mucin (M= 0.23, SD= 0.075) and termite's saliva ingredients (M = 0.41, SD = 0.159). The interaction effect between the glycoprotein concentrations and the glycoprotein types on the erosion rate of the British adobe bricks was also significant, $F$ (3, 40) = 12.63, < .001.

This ANOVA analysis shows that there is a significant interaction along significant main effects. However, by comparing the $F$ values for both the glycoprotein concentration and the glycoprotein type, the glycoprotein type with $F$= 29.18 has higher effect on the erosion rate of the bricks compared with $F$= 24.85 for the glycoprotein concentration. This means that changing the glycoprotein type from bovine serum albumin to fish gelatine, mucin or termite's saliva ingredients has more effect on the erosion rate compared with the effect of the concentrations of these glycoproteins.

Furthermore, and based on the above significant interaction between the effect of the type of the glycoproteins and the concentration of these glycoproteins on the erosion rate, Dunnett's correction test which is a post-hoc test was conducted. Dunnett's correction test was used to compare the erosion rate of the glycoproteins' stabilised British adobe bricks with different concentrations to the erosion rate of the British unstabilised adobe brick, Figure 5-9. Using this test will provide information on which of the stabilised adobe bricks erosion rate is statistically significant from the erosion rate of the unstabilised British adobe bricks.

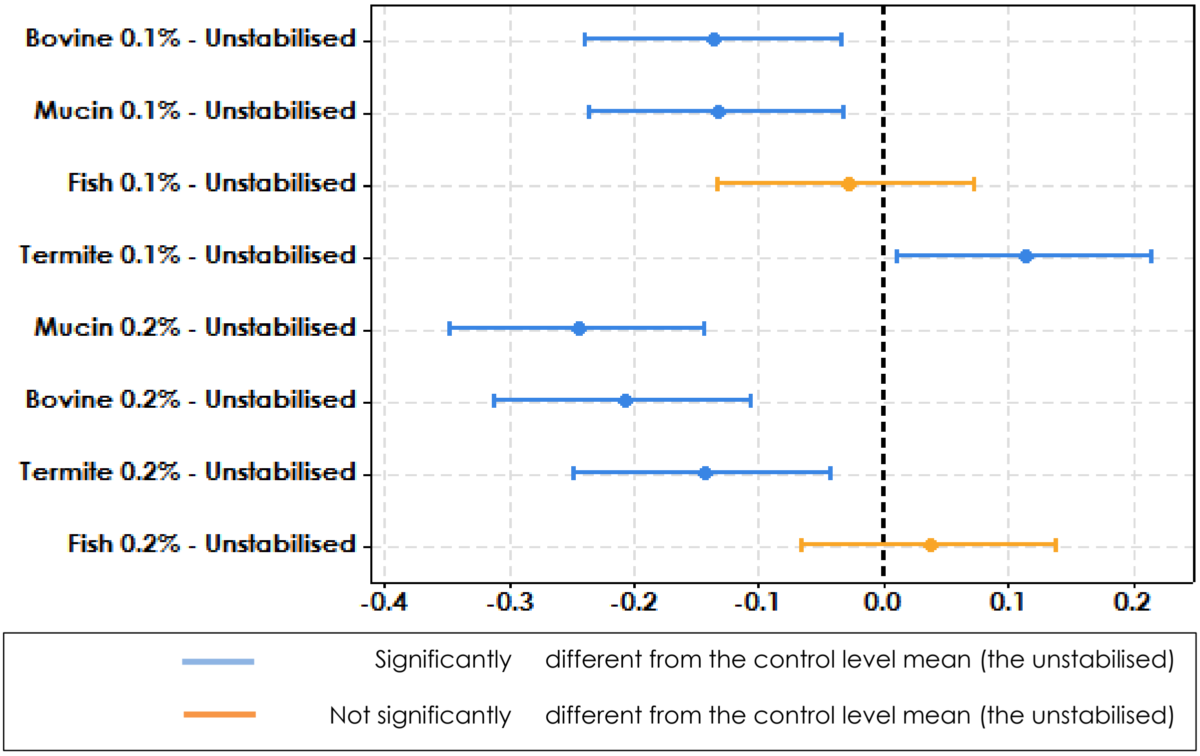



**Figure 5-9**: Dunnett multiple comparisons with a control, the control mean is the unstabilised British adobe bricks erosion rate, the other stabilisers are: bovine serum albumin (0.1% & 0.2%), gelatine from the cold-water fish skin (0.1% & 0.2%), mucin from porcine stomach (0.1% & 0.2%) and the termite's saliva ingredients (0.1% & 0.2%). The test conducted with 95% confident level

The results of the Dunnett multiple comparison shows that the overall means of the erosion rate of the British adobe bricks stabilised with the fish gelatine was not statistically significant from the mean of erosion rate of the unstabilised British adobe brick with $p$ = 0.953 and 0.896 for 0.1% and 0.2% fish gelatine stabilised adobe bricks respectively. The British adobe bricks stabilised using 0.1% of termite's saliva ingredients has erosion rate higher than the erosion rate of the unstabilised controlled adobe bricks and statistically significant from it with $p$ = 0.025. In contrast, all other stabilised British adobe bricks' erosion rate was statistically significant from the unstabilised bricks erosion rate with p = 0.004, 0.000, 0.005, 0.000 and 0.002 for bovine serum albumin 0.1% & 0.2%, mucin 0.1% & 0.2%, and 0.2% termite's saliva ingredients respectively. In addition, the erosion rate of the aforementioned stabilisers was lower than the erosion rate of the unstabilised British adobe bricks which means they enhanced the British adobe brick surface resistance to erosion.

## 5.6.9 Phase Four: Purpose of the Phase

This phase in the design of the experimental tests in section 4.1 follow the results of phase three of the unconfined compressive strength results. Based on the results of the unconfined compressive strength in section 4.5.12, bovine serum albumin with 0.5% concentration will be used as the stabiliser for the British adobe bricks in this phase. British adobe bricks stabilised using 0.5% bovine serum albumin resulted in the highest compressive strength in phase three in section 4.5.12. In this phase the erosion rate of the British adobe bricks stabilised using 0.5% bovine serum albumin will be tested and the results will be compared to that of the unstabilised British adobe bricks.

## 5.6.10 Phase Four: The Results

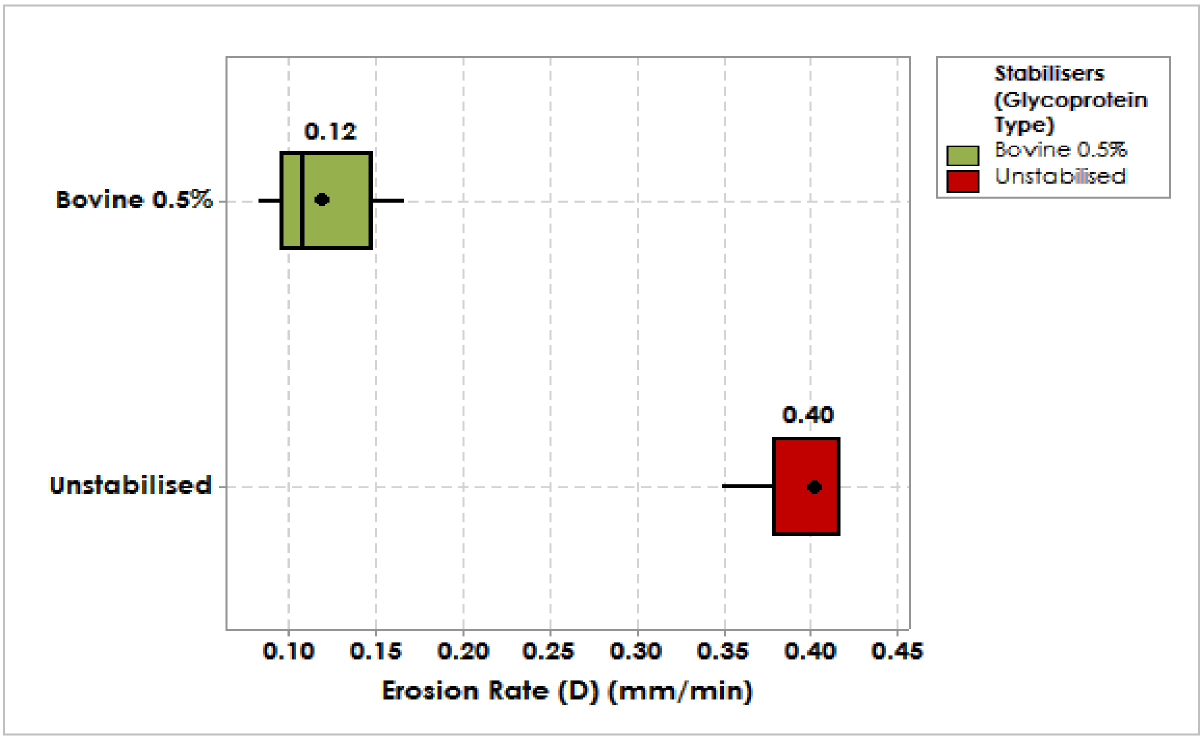



**Figure 5-10**: The effect of the addition of 0.5% bovine serum albumin on the erosion rate of the British adobe bricks. *The boxplots represent the inter-quartile range of the data obtained. (there was an outlier in the unstabilised data, however, neither the presence (0.42 mm/min) nor absence (0.40 mm/min) of it would change the graph).*

Figure 5-10 above shows the effect of adding 0.5% bovine serum albumin on the erosion rate of the British adobe bricks. The addition of the bovine serum albumin to the British adobe brick resulted in reducing the erosion rate from 0.40 mm/min to 0.12 mm/min which is 70% reduction in the erosion rate.

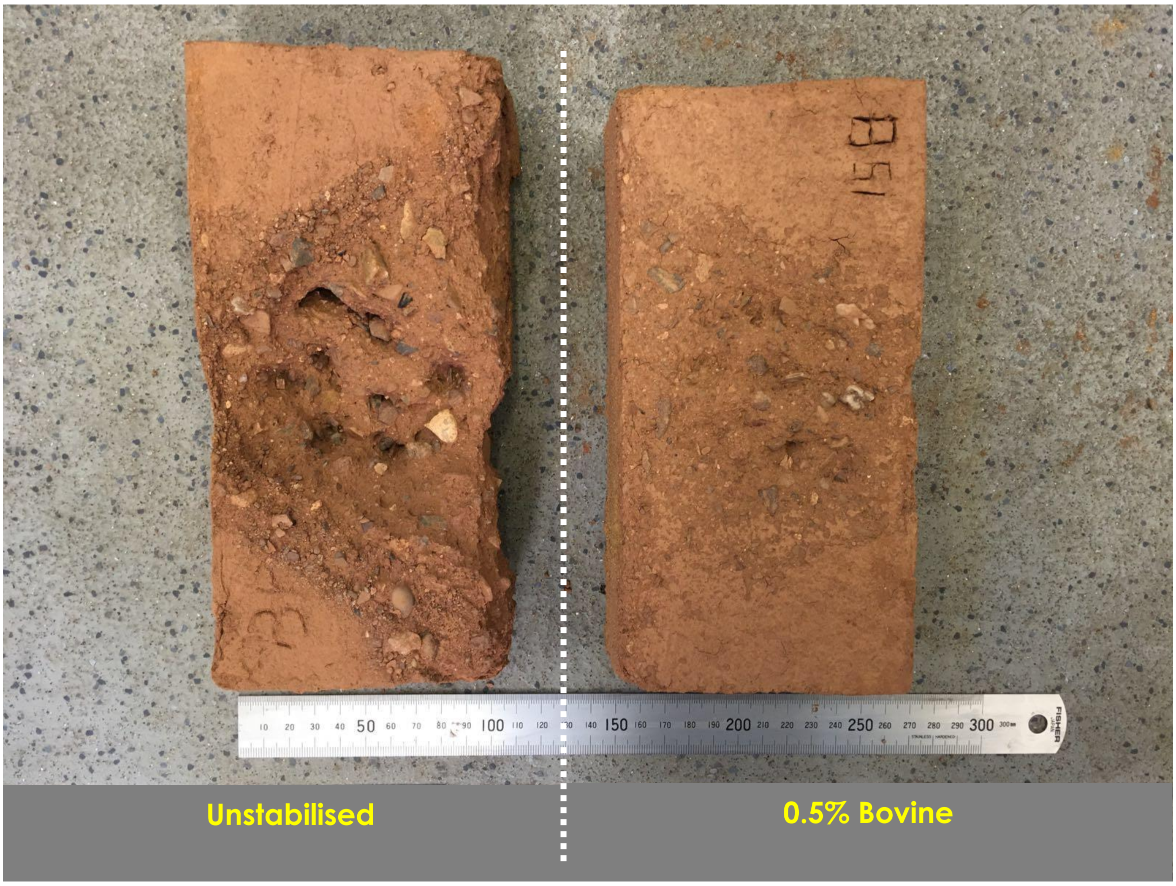



**Figure 5-11:** Unstabilised and 0.5% bovine serum albumin stabilised British adobe bricks after the accelerated erosion test has finished and the bricks were fully dried out

Figure 5-11 above shows the improvement on the upper face of the British adobe bricks as a result of using 0.5% bovine serum albumin in the stabilisation process. The erosion has been reduced on the surface of the 0.5% bovine serum albumin stabilised British adobe bricks compared with the surface of the unstabilised British adobe bricks.

### 5.6.11 Phase Four: Statistical Analysis

**Table 5-5:** One-way ANOVA at 95% confidence interval for the erosion rate of the unstabilised British adobe bricks and 0.5% bovine serum albumin stabilised British adobe brick

| *Source of Variation* | *Sum of Squares (SS)* | *Degree of Freedom (df)* | *Mean Sum of Squares (MS)* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Between Groups** | 0.278 | 1 | 0.278 | 134.044 | 0.000 | 4.965 |
| **Within Groups** | 0.021 | 10 | 0.002 | | | |
| **Total** | 0.298 | 11 | | | | |

To check the significance difference of the test results, a one-way ANOVA was conducted to compare the effect of the type of the glycoprotein on the erosion rate of the British adobe bricks. The null hypothesis was that the means of the erosion rate for all the stabilised and unstabilised British adobe bricks come from the same overall population, Table 5-5. An analysis of variance showed that the effect of the addition of the glycoprotein on the erosion rate was statistically significant, $F\ (1,\ 10) = 134.044$, $p = 0.000$, Table 5-5. Thus, the differences in the means of the erosion rate among the stabilised and the unstabilised British adobe bricks are significant and they are not coming from the same overall population.

### 5.6.12 The First Hypothesis: The Summary

From the series of the accelerated erosion tests conducted in this section, the following points could be summarised:

- These series of tests have supported the first hypothesis on this study and in general, the addition of some of the glycoproteins has improved the erosion resistance of the British adobe bricks.
- The use of only 0.1% and 0.2% of mucin in the stabilisation of the British adobe bricks resulted in 31% and 57% reduction in the erosion rate respectively. This indicates that significant improvement in the erosion resistant could be achieved with adding low percentages of mucin.
- The use of 0.1%, 0.2% and 0.5% of bovine serum albumin in the stabilisation of the British adobe bricks resulted in 33%, 50% and 70% reduction in the erosion rate respectively.

- The use of 0.1% termite's saliva ingredients in the stabilisation of the British adobe brick resulted in 26% increase in the erosion rate. However, increasing the concentration of the termite's saliva ingredients to 0.2% resulted in 33% reduction in the erosion rate.
- The use of 0.1% fish gelatine to stabilise the British adobe bricks resulted in 7% reduction in the erosion rate. On the other hand, the use of more fish gelatine, 0.2%, resulted in 10% increase in the erosion rate of the British adobe bricks.

## 5.7 Preparation of the unstabilised Sudanese adobe bricks

The unstabilised adobe bricks were made following the same steps followed before to prepare the unstabilised Sudanese adobe bricks for the compressive strength in section 4.6. The only difference was that full-size bricks were used for the erosion test instead of the scaled bricks for the compressive strength, Figure 5-12.

## 5.8 Preparation of the 0.5% bovine serum albumin stabilised Sudanese adobe bricks

The 0.5% bovine serum albumin stabilised Sudanese adobe bricks were made following the same steps used to prepare the Sudanese stabilised adobe bricks for the compressive strength test in section 4.7. The only difference was that the full-size bricks were used for the erosion test instead of the scaled-bricks, Figure 5-12 below.

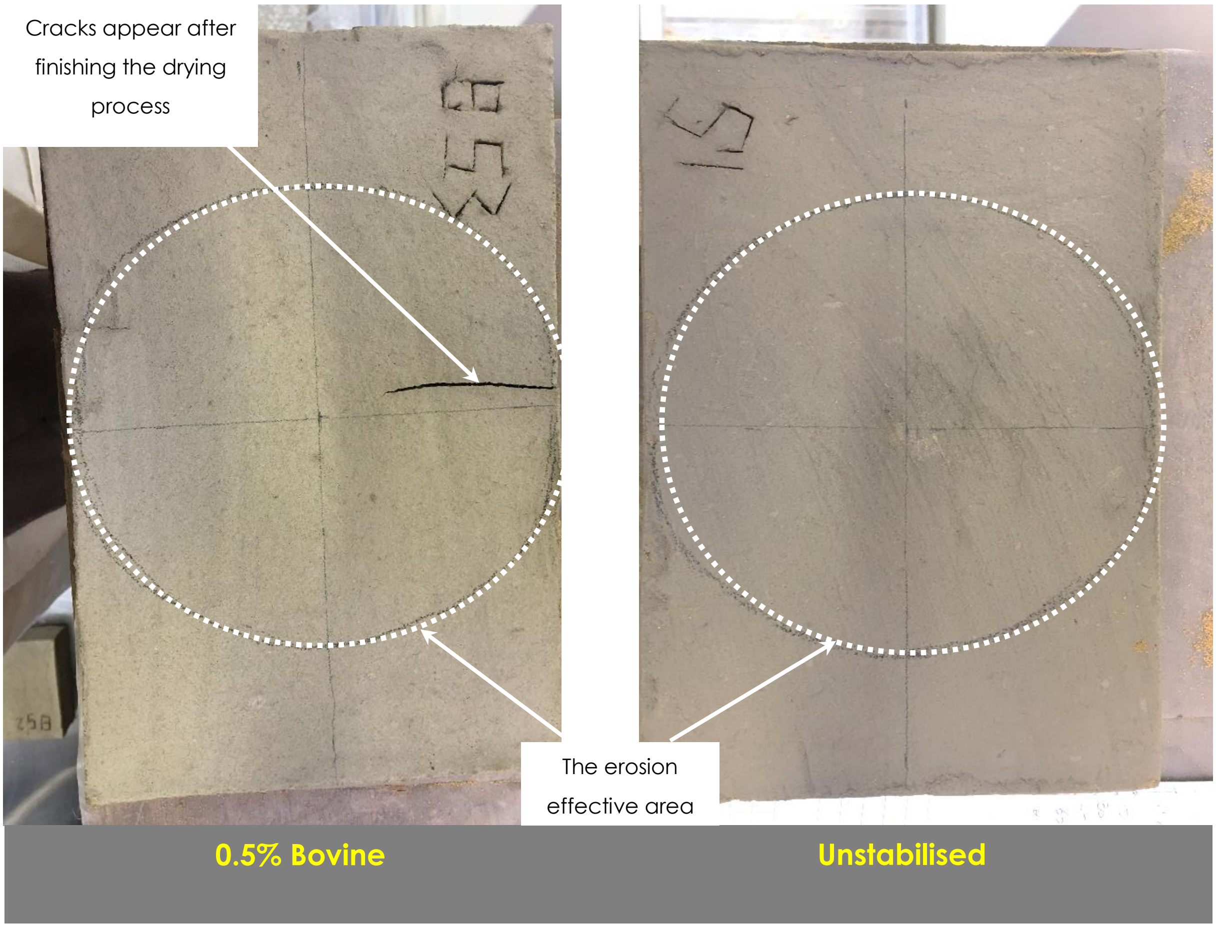



**Figure 5-12:** The Sudanese 0.5% bovine serum albumin stabilised adobe bricks & the unstabilised Sudanese adobe bricks after 28 days of drying and before the erosion test. It was observed that there were cracks along the surface of the dried 0.5% bovine stabilised Sudanese bricks, these kinds of cracks were not observed on the surface of the unstabilised Sudanese adobe bricks

The preparations of the adobe bricks prior to the erosion test was made following the same process mentioned before in section 5.4. The erosion test was conducted as mention in section 5.5 before.

## 5.9 Testing the Second Hypothesis:

The second hypothesis is related to test the effect of adding 0.5% bovine serum albumin to the Sudanese adobe bricks on the erosion rate.

## 5.9.1 The Second Hypothesis: The Results

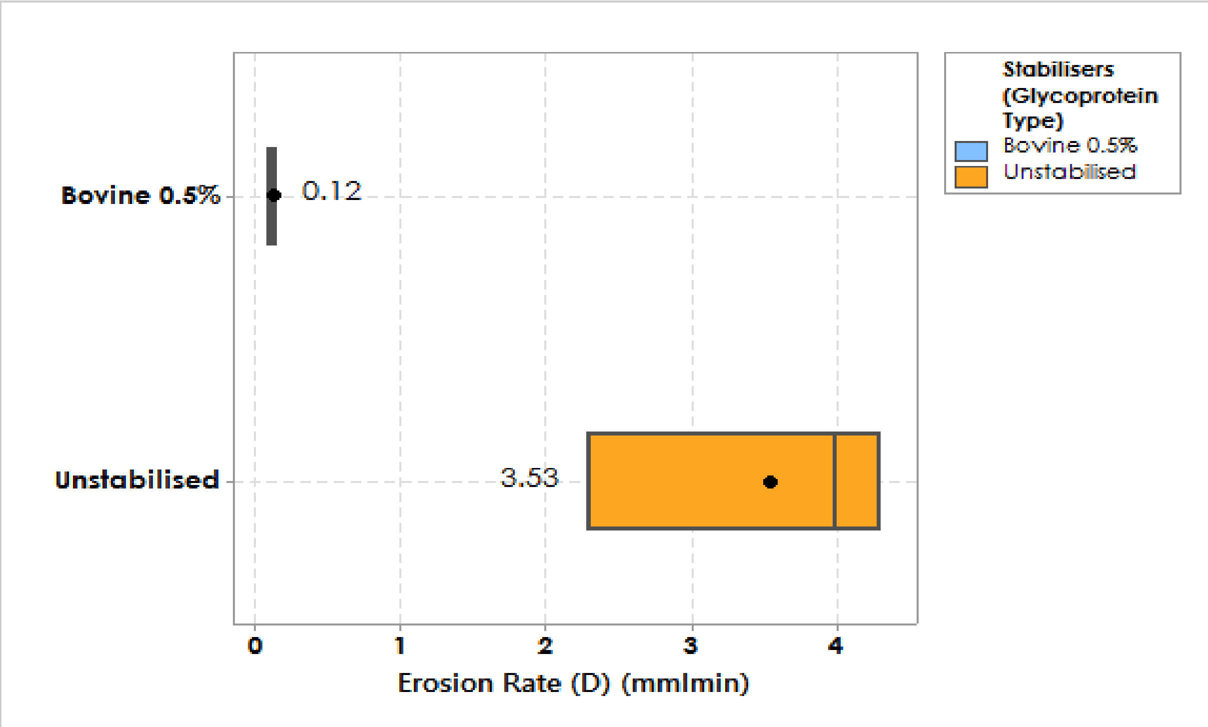



**Figure 5-13:** The effect of the addition of 0.5% bovine serum albumin on the erosion rate of the Sudanese adobe bricks. *The boxplots represent the inter-quartile range of the data obtained*

Figure 5-13 shows the effect of adding 0.5% bovine serum albumin on the erosion rate of the Sudanese adobe bricks. The addition of the bovine serum albumin to the Sudanese adobe brick resulted in reducing the erosion rate from 3.53 mm/min to 0.12 mm/min which is 96.6%. In fact, all the Sudanese unstabilised specimens were completely eroded in an average of 20 minutes during the erosion test, Figure 5-14. None of the unstabilised Sudanese adobe bricks stood the full one hour of the erosion test.

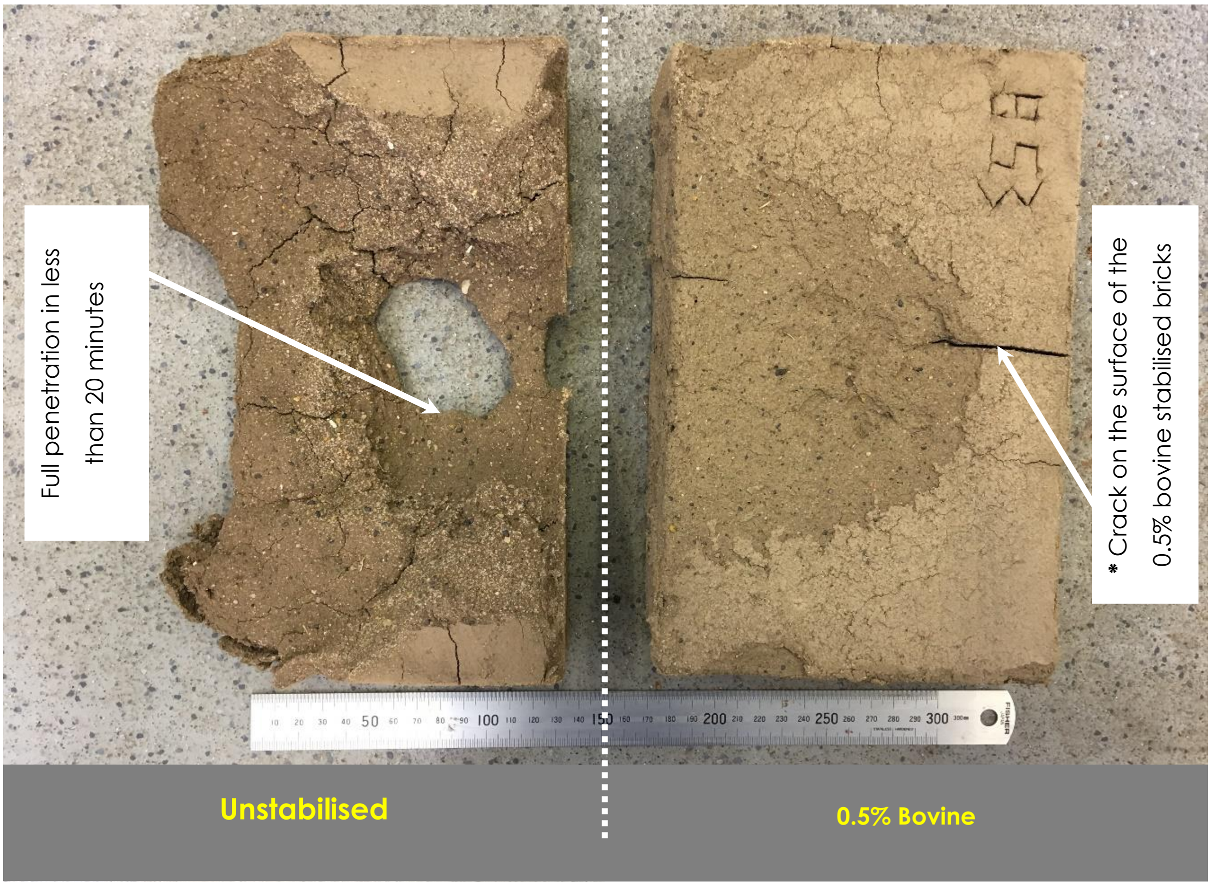



**Figure 5-14:** Unstabilised and 0.5% bovine serum albumin stabilised Sudanese adobe bricks after the accelerated erosion test has finished and the bricks fully dried out. * The crack on the surface of the 0.5% bovine serum albumin stabilised Sudanese adobe brick was present before the erosion test was conducted, Figure 5-12 above, and it was anticipated that this crack will affect the erosion rate for the stabilised brick by allowing more water to penetrate inside the brick.

Figure 5-14 above shows the improvement on the surface of the Sudanese adobe bricks after the erosion test was conducted as a result of using 0.5% bovine serum albumin in the stabilisation process. The erosion has been reduced significantly on the surface of the 0.5% bovine serum albumin stabilised Sudanese adobe bricks compared with the unstabilised Sudanese adobe bricks.

## 5.9.2 The Second Hypothesis: Statistical Analysis

**Table 5-6:** One-way ANOVA at 95% confidence interval for the erosion rate of the unstabilised Sudanese adobe bricks and 0.5% bovine serum albumin stabilised Sudanese adobe brick

| *Source of Variation* | *Sum of Squares (SS)* | *Degree of Freedom (df)* | *Mean Sum of Squares (MS)* | *F* | *P-value* | *F crit* |
|---|---|---|---|---|---|---|
| **Between Groups** | 17.454 | 1 | 17.454 | 29.995 | 0.005 | 7.709 |
| **Within Groups** | 2.328 | 4 | 0.582 | | | |
| **Total** | 19.781 | 5 | | | | |

To check the significance difference of the test results, a one-way ANOVA was conducted to compare the effect of the type of the glycoprotein on the erosion rate of the Sudanese adobe bricks. The null hypothesis was that the means of the erosion rate for all the stabilised and unstabilised Sudanese adobe bricks come from the same overall population, Table 5-6. An analysis of variance showed that the effect of the type of glycoprotein on the erosion rate was statistically significant, $F(1, 4) = 29.995$, $p = 0.005$, Table 5-6. Thus, the differences in the means of the erosion rate among the stabilised and the unstabilised Sudanese adobe bricks are significant and they are not coming from the same overall population.

## 5.9.3 The Second Hypothesis: The Summary

The addition of the 0.5% bovine serum albumin improved the erosion resistance of the Sudanese adobe bricks. The test results support the second hypothesis of this study regarding the erosion resistance of the adobe bricks. As has been mentioned before, 97% reduction in the erosion rate was achieved as a result of using 0.5% bovine serum albumin as stabilising agent for the Sudanese adobe bricks. In addition, the observed cracks shown before in Figure 5-12 on the surface of the 0.5% bovine serum albumin stabilised Sudanese adobe bricks did not affect the erosion rate and did not lead to the collapse of the bricks during the erosion test as it was anticipated when firstly observed. The unstabilised Sudanese adobe bricks which have not had any cracks on the surface did not stand the test and the bricks were fully penetrated in less than an hour.

## 5.10 Accelerated erosion results: Overall Summary

This section will summarise the accelerated erosion results in four different groups without referring to the previous hypotheses. These groups are as follow:

1. Summarise all the British adobe stabilised bricks results, compare them to each other and to the unstabilised British adobe bricks.
2. Summarise all the Sudanese adobe stabilised bricks results, compare them to each other and to the unstabilised Sudanese adobe bricks.
3. Comparison of the British and the Sudanese erosion rate results: 0.5% bovine serum albumin stabilised adobe bricks
4. Statistical analysis of the British and the Sudanese erosion rate results: 0.5% bovine serum albumin stabilised adobe bricks

### *5.10.1 British stabilised adobe bricks erosion rate: The Results*

Figure 5-16 below shows the percentage of the reduction in the erosion rate of the British adobe bricks stabilised with different glycoproteins and different concentrations. The glycoproteins that were used as stabilisers for the British adobe bricks were Bovine serum albumin, Fish gelatine from cold water fish skin, Mucin from porcine stomach and Termite's saliva ingredients. From Figure 5-16, the use of 0.1% of the termite's saliva ingredients resulted in 27% increase in the erosion rate. However, increasing the concentration of the termite's saliva ingredients to 0.2% resulted in 35% reduction in the erosion rate of the British adobe bricks. The use of 0.1% of fish gelatine enhanced the bricks erosion resistance and resulted in 7% reduction in the erosion rate. In contrast, the use of more fish gelatine led to the deterioration of the bricks from erosion perspective. The bricks have 9% increases in the erosion rate as a result of increasing the fish gelatine concentration to 0.2%. The use of the mucin improved the erosion rate of the British bricks. For instance, the use of 0.1% and 0.2% of mucin resulted in 32% and 58% reduction in the erosion rate of the British adobe bricks respectively. The use of bovine serum albumin also improved the British adobe bricks' resistance to the erosion. The use of 0.1%, 0.2% and 0.5% resulted in 33%, 50% and 70% reduction in the erosion rate. By comparing the best glycoproteins which they are the mucin and the bovine serum albumin, the use of the mucin resulted in more resistant bricks compared with the bovine serum albumin stabilised bricks for the same concentration. Thus, it is easy to conclude that mucin could be considered as the best stabiliser from erosion resistance point of view when it is used with low concentration compared with all other glycoproteins.

Furthermore, a simple water penetration test was conducted on some of the 5% bovine serum albumin stabilised British adobe scaled bricks which were originally prepared for compressive strength test. Water was splashed over the upper surface of the brick. The brick was left with the water on its surface for 15 minutes and then the water was wiped away. The brick does not show penetration of water from the surface. This indicates that the bovine serum albumin might have sealed the surface of the brick making it water impervious.

### 5.10.2 Sudanese stabilised adobe bricks erosion rate: The Results

As it has been mentioned before, the addition of only 0.5% bovine serum albumin has a significant effect on the erosion resistance of the Sudanese adobe bricks. The inclusion of 0.5% bovine serum albumin resulted in 97% reduction in the erosion rate of the Sudanese adobe bricks, Figure 5-13.

### 5.10.3 Comparison of the British and the Sudanese erosion rate results: 0.5% bovine serum albumin stabilised adobe bricks

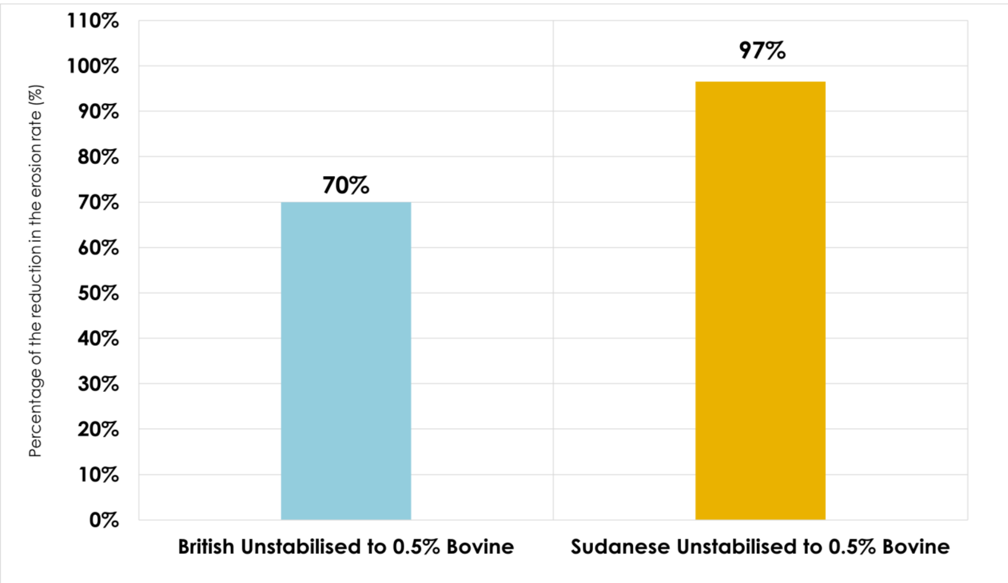



**Figure 5-15:** The reduction in the erosion rate due to the addition of 0.5% bovine serum albumin for the two soils: the British and the Sudanese soils. The percentages of the reduction in the erosion rate was calculated using the erosion rate of the unstabilised British adobe bricks for the bovine stabilised British adobe bricks and the unstabilised Sudanese adobe bricks for the bovine stabilised Sudanese adobe bricks as the reference.

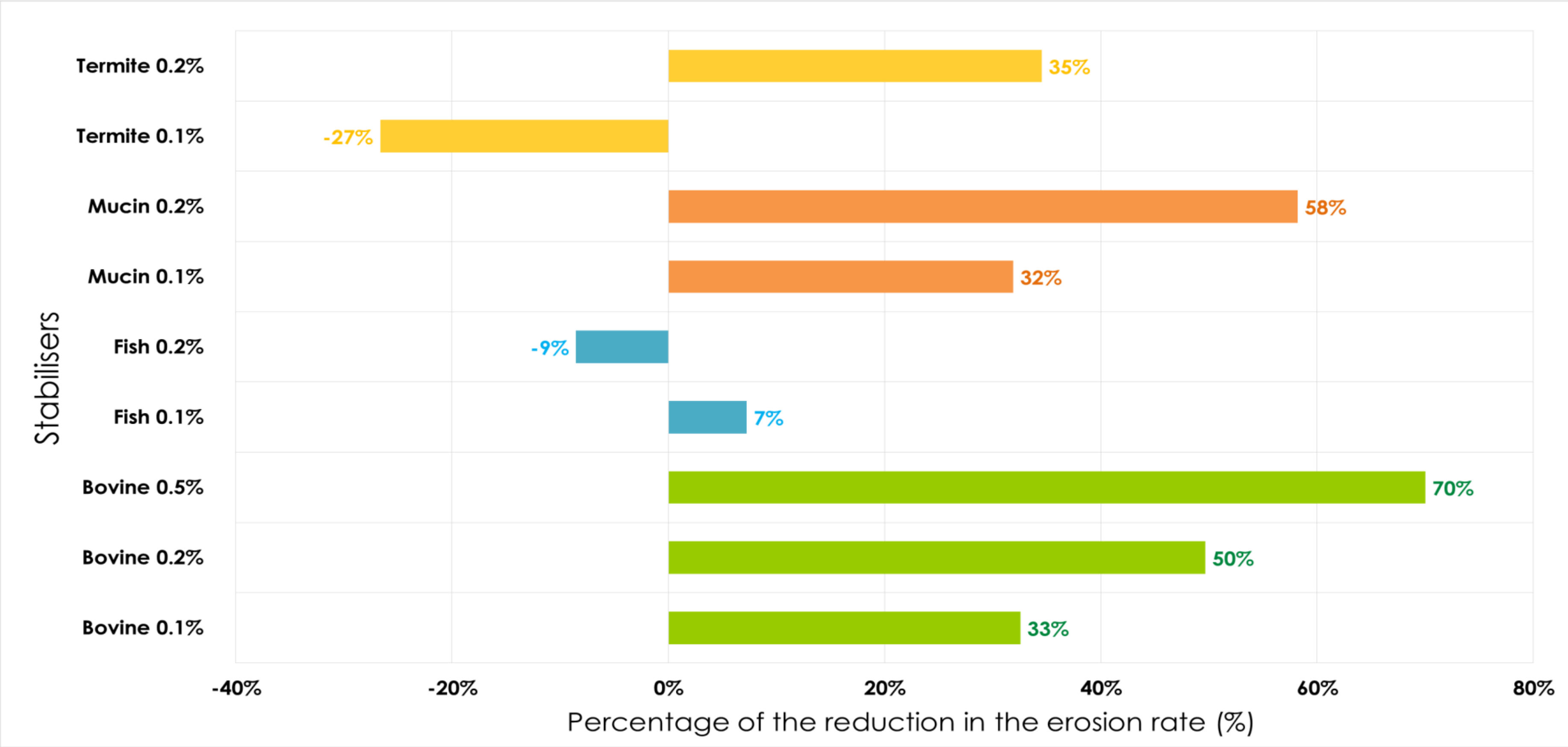



**Figure 5-16:** The effect of the addition of the different stabilisers and their concentrations on the erosion rate of the British adobe bricks. The percentages of the reduction in the erosion rate were calculated using the erosion rate of the unstabilised British adobe bricks as the reference. The stabilisers are: Bovine serum albumin, Fish gelatine from cold water fish skin, Mucin from porcine stomach and Termite's saliva ingredients.

Figure 5-15 above shows the reduction in the erosion rate for the British and the Sudanese adobe bricks after they were stabilised using 0.5% bovine serum albumin. From the graph, the Sudanese adobe bricks have 97% reduction in the erosion rate as a result of the inclusion of the 0.5% bovine serum albumin. This reduction in the Sudanese adobe bricks was higher than the reduction in the erosion rate of the British adobe bricks due to the inclusion of the same concentration of the bovine serum albumin which was 0.5%. The British adobe bricks have only 70% reduction in the erosion rate. Furthermore, it implies that the British soil might need more bovine serum albumin to reach the same reduction in erosion rate achieved by the Sudanese soil.

### *5.10.4 Statistical Analysis of the British and the Sudanese erosion rate results: 0.5% bovine serum albumin stabilised adobe bricks*

A two-way ANOVA analysis was conducted to compare the main effects of the bovine concentrations and the soil types and the interaction effect between them on the erosion rate of the adobe bricks, Table 5-7.

**Table 5-7:** Two-way ANOVA statistics for concentration of the bovine serum albumin vs. the soil types (erosion rate of the adobe bricks), the concentrations are 0.0% & 0.5%, and the soil types are the British soil and the Sudanese soil

| *Source of Variation* | *Sum of Squares (SS)* | *Degree of Freedom (df)* | *Mean Sum of Squares (MS)* | *F* | *P-value* |
|---|---|---|---|---|---|
| **Bovine concentration (%)** | 13.803 | 1 | 13.8033 | 82.29 | 0.000 |
| **Soil types** | 9.705 | 1 | 9.7050 | 57.86 | 0.000 |
| Interaction | 9.653 | 1 | 9.6531 | 57.55 | 0.000 |
| Within | 2.348 | 14 | 0.1677 | | |
| Total | 29.784 | 17 | | | |

A two-way analysis of variance was conducted on the influence of two independent variables (the bovine serum albumin concentrations, the soil types) on the erosion rate of the adobe bricks. The bovine serum albumin concentrations included two levels (0.0, and 0.5 by weigh percent concentration) and the soil types consisted of two levels (the British and the Sudanese soil). All effects were statistically significant at the

0.05 significance level. The main effect for bovine serum albumin concentrations yielded an *F* ratio of $F\ (1,\ 14) = 82.29$, $p < 0.001$, indicating a significant difference between 0.0% bovine serum albumin (M =1.459, SD = 1.647), and 0.5% bovine serum albumin (M = 0.119, SD = 0.026). The main effect for soil types yielded an F ratio of $F\ (1,\ 14) = 57.86$, $p < 0.001$, indicating a significant difference between the British soil (M = 0.270, SD = 0.165) and the Sudanese soil (M = 1.828, SD = 1.989). The interaction effect between the bovine serum albumin concentrations and the soil types on the erosion rate of the adobe bricks was also significant, $F\ (1,\ 14) = 57.55$, $p < .001$.

This ANOVA analysis shows that there is a significant interaction along significant main effects. However, by comparing the *F* values for both the bovine serum albumin concentration and the soil type, the bovine serum albumin concentration with $F= 82.29$ has higher effect on the erosion rate of the bricks compared with $F= 57.86$ for the soil types. This means that changing the bovine serum albumin concentration from 0.0% to 0.5% has more effect on the erosion rate compared with the effect of the soil types.

# 6. Discussion

## 6.1 Introduction

This study investigated the effect of the addition of bio-inspired stabilisers on the compressive strength and the erosion resistance of adobe bricks made using two different soils. The following will be discussed:

1. The ability of the different clay minerals available in the two soils used to prepare the adobe bricks to adsorb the different types of the glycoproteins used in this study.
2. The unconfined compressive strength test results will be discussed and compared with those available in literature.
3. The accelerated erosion test results will be discussed and compared with those available in literature.

## 6.2 Unconfined compressive strength and erosion resistance of the British & the Sudanese adobe bricks

To analyse the results of the compressive strength and the erosion resistance of the British and the Sudanese soil, the following soil comparison is important, Table 6-1. The difference in the characteristics between the two soils will assist in understanding the adsorption behaviour of the clay minerals to the glycoprotein. It will also shed a light on how the difference on the particle size distribution affected the compressive strength and the erosion resistance results.

**Table 6-1:** Comparison of some of the characteristics between the British and the Sudanese soils

| British soil | Sudanese soil |
|---|---|
| **Particle size distribution:**<br>• Clay: 5.3%<br>• Silt: 18.7%<br>• Sand: 38%<br>• Gravel: 38% | **Particle size distribution:**<br>• Clay: 7.5%*<br>• Silt: 31.5%*<br>• Sand: 51.4%*<br>• Gravel: 9.6%* |
| **X-ray Diffraction results for clay minerology in 100% clay:**<br>• Smectite: 32% (swelling)<br>• Kaolinite: 3% (non-swelling)<br>• Chlorite: 11% (non-swelling)<br>• Illite: 54% (non-swelling) | **X-ray Diffraction results for clay minerology in 100% clay:**<br>• Smectite: 63% (swelling)<br>• Kaolinite: 14% (non-swelling)<br>• Chlorite: 13% (non-swelling)<br>• Illite: 10% (non-swelling) |
| **% of clay minerals in 5.3%:**<br>• Smectite: 1.7% (swelling)<br>• Kaolinite: 0.2% (non-swelling)<br>• Chlorite: 0.6% (non-swelling)<br>• Illite: 2.9% (non-swelling) | **% of clay minerals in 7.5%:**<br>• Smectite: 4.7% (swelling)<br>• Kaolinite: 1.1% (non-swelling)<br>• Chlorite: 1% (non-swelling)<br>• Illite: 0.8% (non-swelling) |

| British soil | Sudanese soil |
|---|---|
| **General soil characteristics:**<br>• Less clay minerals<br>• Less swelling clay minerals (1.7%)<br>• More non-clay minerals (3.6%)<br>• Less silt<br>• Less sand<br>• More gravel | **General soil characteristics:**<br>• More clay minerals<br>• More swelling clay minerals (4.7%)<br>• Less non-swelling clay minerals (2.8%)<br>• More silt<br>• More sand<br>• Less gravel |

[*] This is the adjusted percentages for the Sudanese soil after modifying the soil particle size distribution for brick making, section 4.6.

### *6.2.1 Bovine serum albumin stabilised British adobe bricks compressive strength and erosion resistance: Analysis of the Results*

The bovine serum albumin is considered as a large globular protein (Enomoto et al., 2008), and the most studied protein over the years (Tai, 2004). It is also classified as a soft protein. Bovine serum albumin is considered as a large protein with molecular size of 68 kDa (Yu et al., 2013). In order to analyse and discuss the results of the bovine serum albumin stabilised British adobe bricks, the results analysis will be divided into two groups. The first group will include low concentrations of the bovine serum albumin used in stabilising the British adobe bricks which are: 0.1%, 0.2% and 0.3%. The second group will include high concentrations of the bovine serum albumin used in stabilising the British adobe bricks (0.4%, 0.5%, 1%, 3% and 5%).

## 1. Low concentrations of the bovine serum albumin: 0.1%, 0.2% & 0.3%

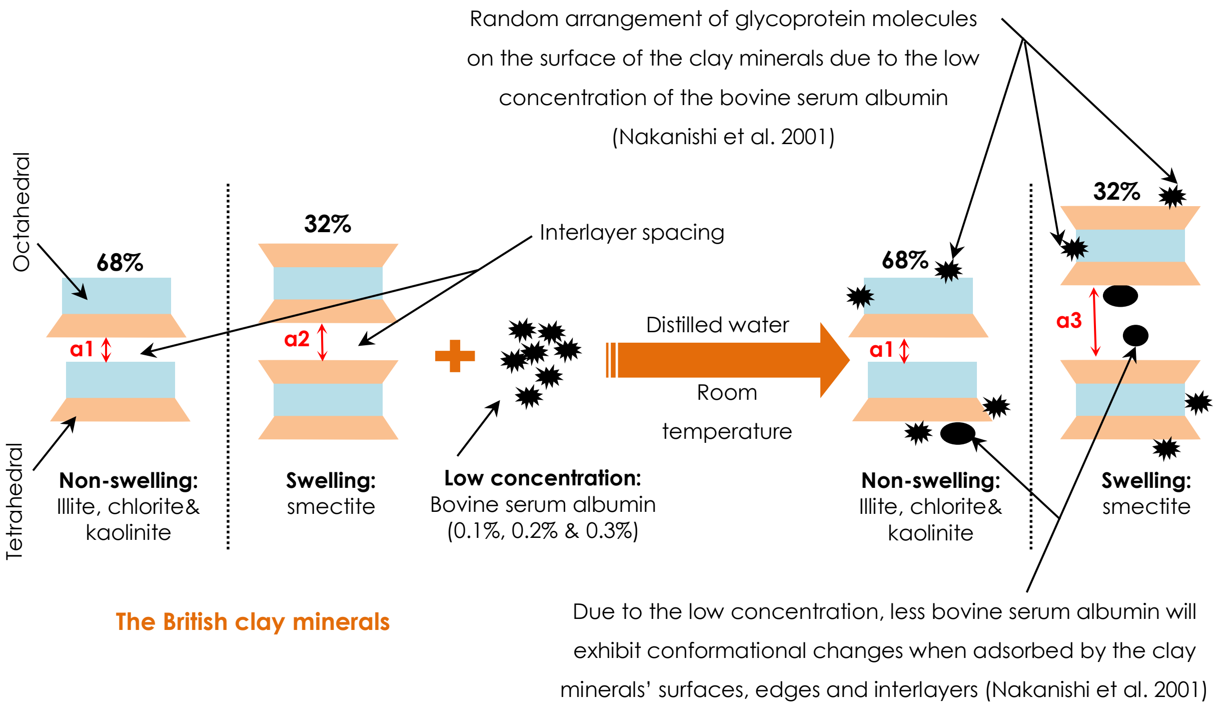



**Figure 6-1:** Conceptual illustration of the adsorption of the bovine serum albumin by the clay minerals of the British adobe bricks for low concentrations (0.1%, 0.2% & 0.3%)

Figure 6-1, shows the conceptual illustration of the adsorption of low concentrations (0.1%, 0.2% & 0.3%) of the bovine serum albumin by the clay minerals in the British adobe bricks. Due to the low concentration of the bovine serum albumin, most of the adsorption will be through the external surfaces and the edges of both clay minerals (the swelling and the non-swelling). Furthermore, less bovine serum albumin will exhibit conformational changes upon adsorption. In addition, the high percentage of the non-swelling clay minerals in the British soil (68%) compared with the swelling clay minerals (32%) will encourage more surface and edges adsorption to take place. On the other hand, and despite the low percentage of the swelling clay minerals in the British soil, this clay minerals exhibit very high specific surface area (40622 $m^2/g$) compared with the specific surface area of the non-swelling clay minerals of 8350 $m^2/g$. This high specific surface area will result in the increase of the external surface area available for the adsorption of the bovine serum albumin by the clay minerals.

From the compressive strength results of the British adobe bricks in Figure 4-33 in section 4.10.1 and in Table 6-2, the compressive strength of the low concentrations of the bovine serum albumin (0.1%, 0.2% & 0.3%) was lower than that of the unstabilised British adobe bricks.

**Table 6-2:** Unconfined compressive strength of the unstabilised and 0.1%, 0.2% & 0.3% Bovine serum albumin stabilised British adobe bricks

| Stabiliser | Unconfined compressive strength (MPa) |
|---|---|
| Unstabilised | 1.90 |
| **0.1%** Bovine serum albumin | 1.72 |
| **0.2%** Bovine serum albumin | 1.78 |
| **0.3%** Bovine serum albumin | 1.81 |

When the adobe bricks were unstabilised, the only source of the cohesiveness in the soil was the natural clay. It was thought by introducing the bovine serum albumin to the British soil as a stabiliser; it will result in the increase of the cohesion of the soil and hence increase the compressive strength of the adobe bricks. On the contrary, the addition of the bovine serum albumin with low concentration to the British adobe bricks decreased the compressive strength, Figure 4-33 in section 4.10.1 and in Table 6-2 above. In fact, due to the low concentration of the bovine serum albumin, its adsorption would predominantly be by the surfaces and the edges of the swelling and the non-swelling clay minerals, and very low percentage will be adsorbed by the interlayers of the swelling clay minerals. As a direct result of the bovine serum albumin low concentration, instead of it acts as an enhancement to the soil structural integrity, it will act as a barrier between the clay minerals themselves and the clay minerals and other soil particles, Figure 6-2. As a result, the bovine serum albumin will reduce the cohesive properties of the natural clay and will weaken the bond between the clay minerals, Figure 6-2. It was thought this would be the reason behind the decrease in the compressive strength of the British adobe bricks due to the addition of the low concentrations of the bovine serum albumin compared with the compressive strength of the British unstabilised adobe bricks.

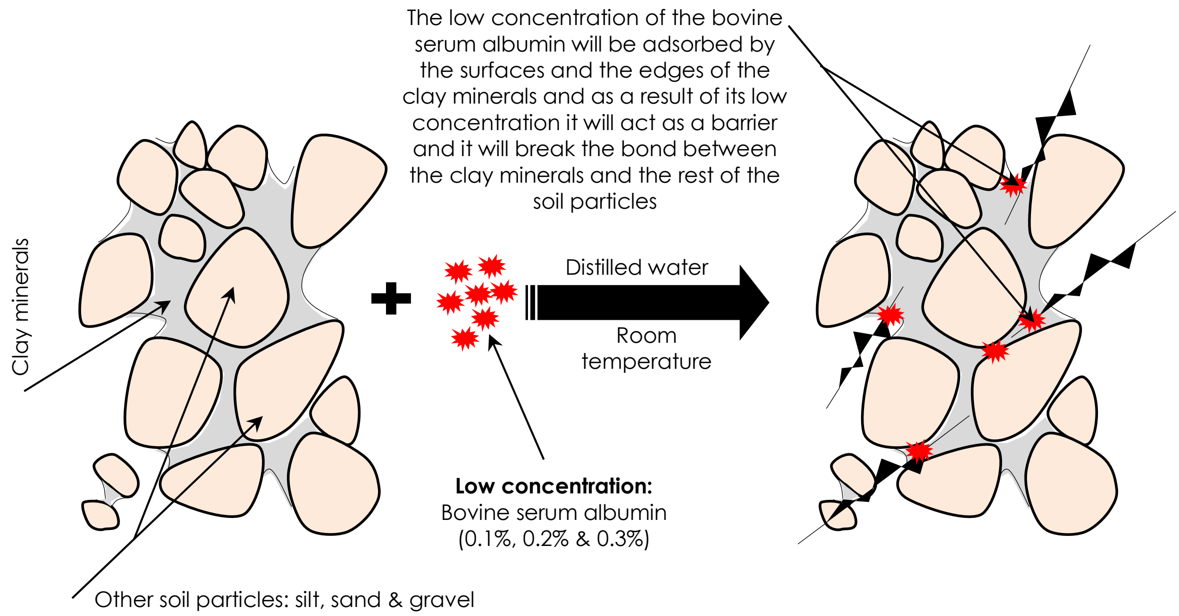



**Figure 6-2:** Conceptual illustration for the effect of the addition of low concentrations of bovine serum albumin (0.1%, 0.2% & 0.3%) on the British soil structural integrity

On the other hand, by comparing the compressive strength of the British adobe bricks made using the low concentrations of the bovine serum albumin (0.1%, 0.2% & 0.3%) to each other, it was clear that the increase in the compressive strength was positively correlated with the increase in the concentration of the bovine serum albumin. The availability of more bovine serum albumin resulted in more of it to be adsorbed by the surfaces, edges of the clay minerals and in particular by the interlayers of the swelling clay minerals. It was thought that the conformational changes on the bovine serum albumin upon the adsorption by the interlayers of the swelling clay minerals could be the reason behind the increase in the compressive strength exhibited by the adobe bricks due to the increase in the bovine serum albumin concentration. Due to the adsorption of the bovine serum albumin by the interlayers of the swelling minerals, it will exhibit structural changes which will result in an irreversible adsorption process. Thus, the characteristics of the swelling clay minerals will be changed and this has resulted in increasing the structural integrity of the adobe bricks whereby the bovine serum albumin will enhance the cohesiveness of the British adobe bricks.

From the erosion rate results of the British adobe bricks in Figure 5-16 in section 5.10.1, and in Table 6-3 below, the erosion rate decreases with the increase of the concentration bovine serum albumin on the adobe bricks.

**Table 6-3:** Erosion rate of the unstabilised and 0.1% & 0.2% Bovine serum albumin stabilised British adobe bricks

| Stabiliser | Erosion Rate, D (mm/min) |
|---|---|
| Unstabilised | 0.40 |
| **0.1%** Bovine serum albumin | 0.28 |
| **0.2%** Bovine serum albumin | 0.21 |

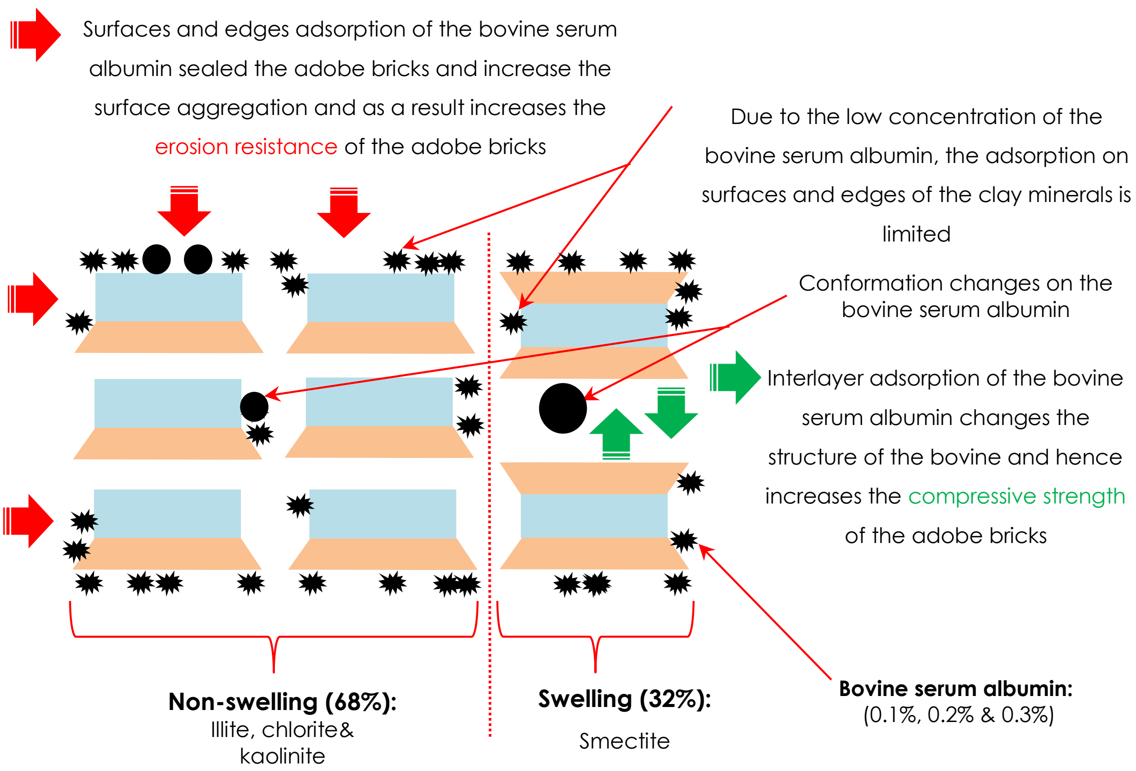



**Figure 6-3:** Conceptual illustration of the adsorption mechanisms of the low concentrations of bovine serum albumin, 0.1%, 0.2% & 0.3%, by the clay minerals of the British adobe bricks and how these mechanisms affect the adobe bricks' compressive strength and erosion resistance

As has been mentioned before when discussing the compressive strength results, most of the bovine serum albumin will be adsorbed into the surfaces and the edges of the swelling and non-swelling clay minerals and thus will result in sealing the clay minerals and increase the surface aggregation. This why it was thought, adding only low concentrations of the bovine serum albumin (0.1% & 0.2%) has improved the adobe bricks resistance to the erosion.

Figure 6-3 shows and summaries the adsorption mechanisms of the low concentrations of the bovine serum albumin (0.1%, 0.2% & 0.3%) by the clay minerals of the British adobe bricks and how these mechanisms may affect the adobe bricks' compressive strength and erosion resistance.

## 2. High concentrations of the bovine serum albumin: 0.4%, 0.5%, 1%, 3% & 5%

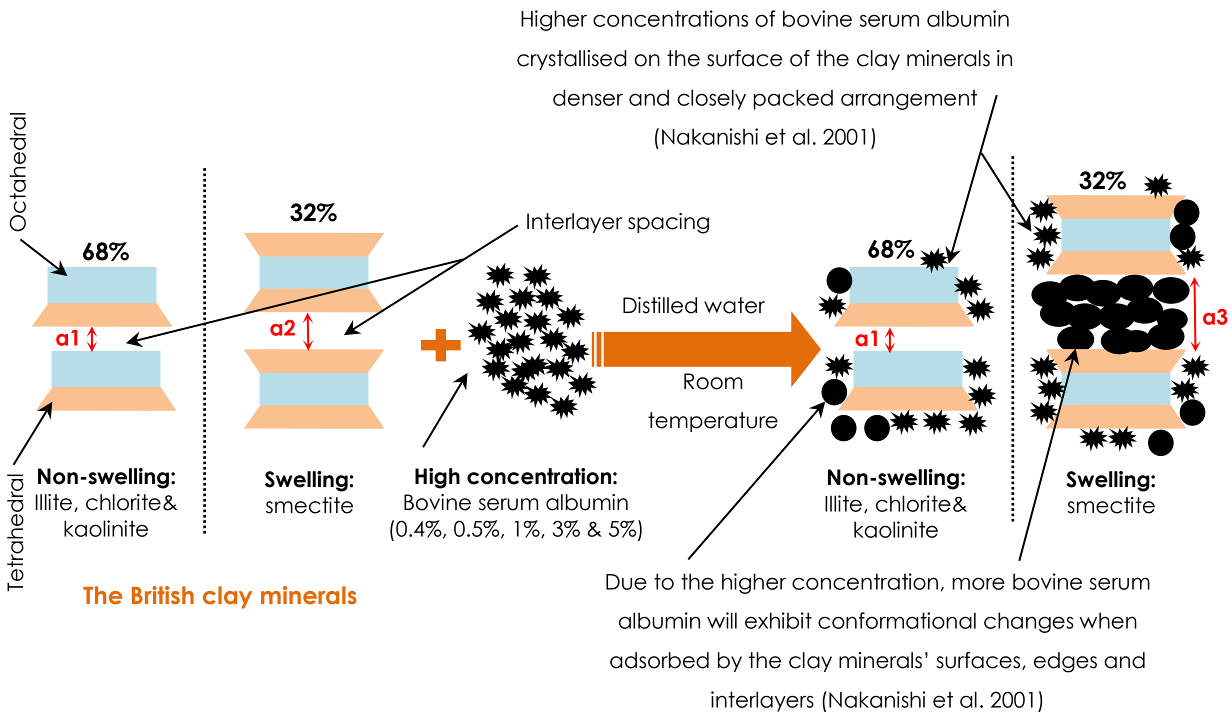



**Figure 6-4:** Conceptual illustration of the adsorption of the bovine serum albumin by the clay minerals of the British adobe bricks for high concentrations (0.4%, 0.5%, 1%, 3% & 5%)

Figure 6-4 shows the conceptual illustration of the adsorption of high concentrations (0.4%, 0.5%, 1%, 3% & 5%) of the bovine serum albumin by the clay minerals of the British adobe bricks. The availability of more bovine serum albumin in the adobe bricks increases the adsorption of the bovine serum albumin by the swelling and the non-swelling clay minerals. The increase of the concentration of the bovine serum albumin from 0.4% up to 5% resulted in the increase of the adsorbed bovine by the surfaces and edges of the non-swelling clay minerals and the surfaces and interlayers of the swelling clay minerals. Therefore, the increase of the concentration of the bovine serum albumin will result in the increase of the cohesiveness and the structural integrity of the soil. The bovine serum albumin will act as an additional cementing agent to cement the particles in the soil along with the natural clay, Figure 6-5.

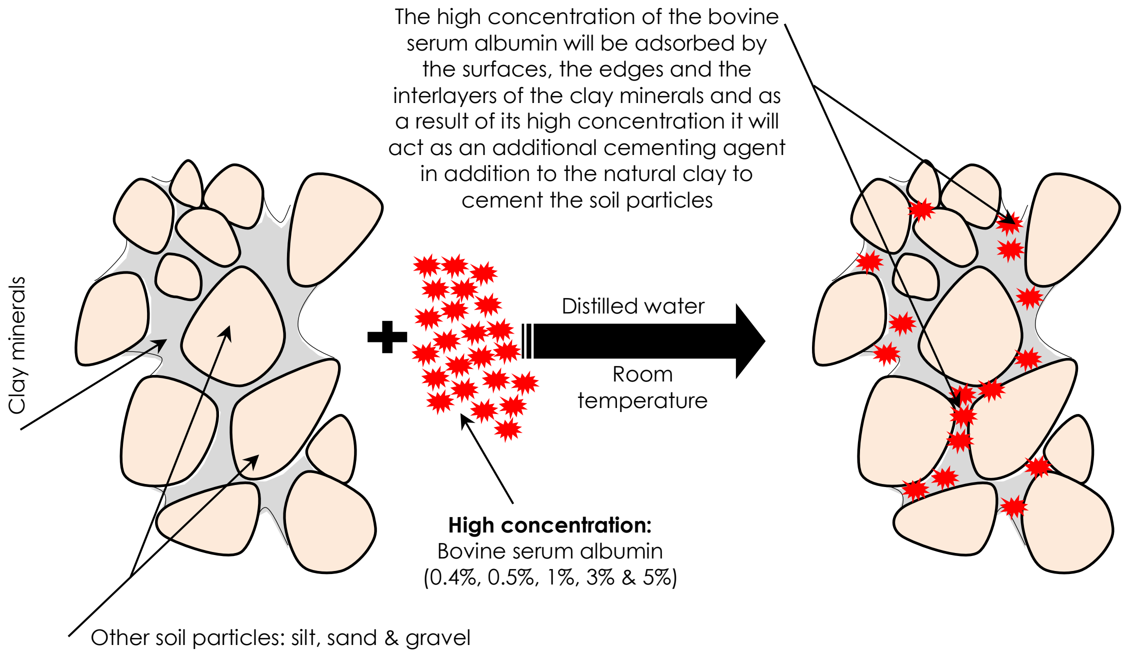



**Figure 6-5:** Conceptual illustration for the effect of the addition of high concentrations of bovine serum albumin (0.4%, 0.5%, 1%, 3% & 5%) on the British soil structural integrity

In addition, more bovine serum albumin will exhibit conformational changes to fill the interlayer of the swelling clay minerals. This will lead to seal and pack the clay minerals and also enhance the aggregation of the surface of the adobe bricks.

It was thought that all the above points together could explain the compressive strength results of the British adobe bricks when higher concentrations of the bovine serum albumin were used, Figure 4-33 in section 4.10.1 and in Table 6-4 below. The results show positive correlation between the increase of the concentration of the bovine serum albumin in the British adobe bricks and the bricks' compressive strength.

**Table 6-4:** Unconfined compressive strength of the unstabilised and 0.4%, 0.5%, 1%, 3% & 5% Bovine serum albumin stabilised British adobe bricks

| Stabiliser | Unconfined compressive strength (MPa) |
|---|---|
| Unstabilised | 1.90 |
| **0.4%** Bovine serum albumin | 1.97 |
| **0.5%** Bovine serum albumin | 2.23 |
| **1%** Bovine serum albumin | 4.30 |
| **3%** Bovine serum albumin | 4.70 |
| **5%** Bovine serum albumin | 5.75 |

In addition, the same points support the results of the British adobe bricks erosion resistance in Figure 5-16 in section 5.10.1 and in Table 6-5 below for the 0.5% bovine stabilised British adobe bricks.

**Table 6-5:** Erosion rate of the unstabilised and 0.5% Bovine serum albumin stabilised British adobe bricks

| Stabiliser | Erosion Rate, D (mm/min) |
|---|---|
| Unstabilised | 0.40 |
| **0.5%** Bovine serum albumin | 0.12 |

The increase of the concentration of the bovine serum albumin in the British adobe bricks resulted in the adsorption of the bovine serum albumin first by the surface of both clay minerals (the swelling and the non-swelling clay minerals). This was thought to be resulted in the increase of the aggregation on the clay surfaces which will result in protecting the adobe bricks' surface against erosion.

Figure 6-6 below shows and summaries the adsorption mechanisms of the high concentrations of the bovine serum albumin (0.4%, 0.5%, 1%, 3% & 5%) by the clay minerals of the British adobe bricks and how these mechanisms affect the adobe bricks compressive strength and erosion resistance.

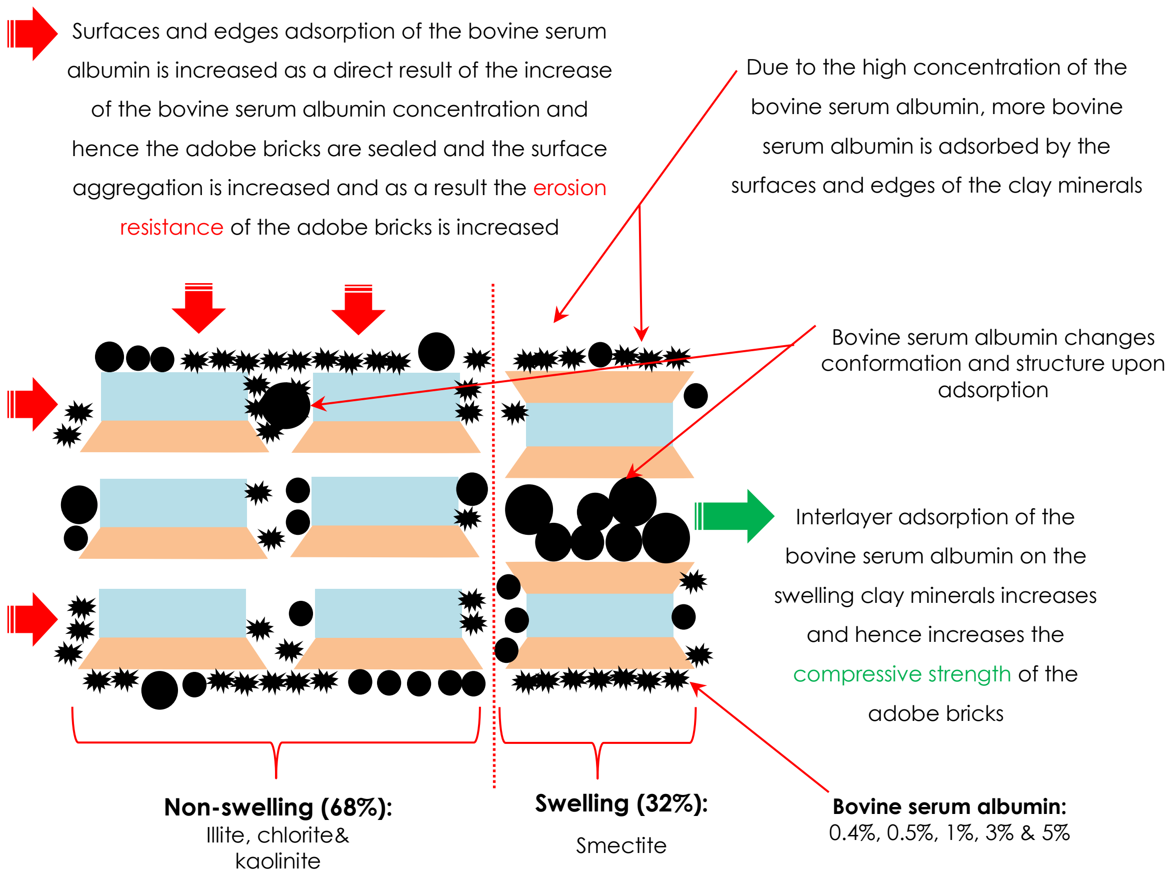



**Figure 6-6:** Conceptual illustration of the adsorption mechanisms of the high concentrations of bovine serum albumin, 0.4%, 0.5%, 1%, 3% & 5%, by the clay minerals of the British adobe bricks and how these mechanisms affect the adobe bricks compressive strength and erosion resistance

### *6.2.2 Bovine serum albumin stabilised Sudanese adobe bricks compressive strength and erosion resistance: Analysis of the Results*

As has been mentioned before in section 3.2.2.1, the Sudanese soil consists of 63% swelling clay minerals and 37% of non-swelling clay minerals. This indicates that more surface area would be available for the bovine serum albumin adsorption as a direct result of the high specific surface area of the swelling clay minerals (203099 $m^2/g$) compared with the total specific surface area of the non-swelling clay minerals collectively (6176 $m^2/g$). In addition, more bovine serum albumin adsorption will occur by the interlayers of the swelling clay minerals.

From the compressive strength results of the Sudanese adobe brick in section 4.8.1 and 4.9.5 and in Table 6-6 for 0.5% and 5% bovine serum albumin concentrations respectively, the increase in the compressive strength of the adobe bricks is positively correlated with the increase in the concentration of the bovine serum albumin.

**Table 6-6:** Unconfined compressive strength of the unstabilised and 0.5% & 5% Bovine serum albumin stabilised Sudanese adobe bricks

| Stabiliser | Unconfined compressive strength (MPa) |
|---|---|
| Unstabilised | 3.29 |
| **0.5%** Bovine serum albumin | 4.65 |
| **5%** Bovine serum albumin | 6.47 |

The increase availability of the swelling clay minerals in the Sudanese soil will allow more bovine serum albumin to be adsorbed into the interlayers of the clay minerals upon hydration. The bovine serum albumin will face conformational changes and its adsorption will be irreversible. This will increase the cohesion and the aggregation of the soil and hence increase the soil structural integrity. It was thought these factors maybe the reason behind the increase in the compressive strength of the Sudanese adobe bricks as a direct result of the inclusion of the bovine serum albumin.

From the erosion rate results in Figure 5-13 in section 5.9.1 and in Table 6-7, the addition of 0.5% bovine serum albumin to the Sudanese adobe bricks resulted in a significant reduction in the erosion rate.

**Table 6-7:** Erosion rate of the unstabilised and 0.5% Bovine serum albumin stabilised Sudanese adobe bricks

| Stabiliser | Erosion Rate, D (mm/min) |
|---|---|
| Unstabilised | 3.53 |
| **0.5%** Bovine serum albumin | 0.12 |

The high percentage of the swelling clay minerals in the Sudanese soil (63%) was the reason behind the high erosion rate of the unstabilised Sudanese adobe bricks. As has been mentioned before in section 5.9.1, that all the Sudanese unstabilised specimens were completely eroded in an average of 20 minutes during the erosion test. This quick erosion behaviour of the unstabilised adobe bricks proves the high vulnerability of the Sudanese soil to the water. However, the inclusion of only 0.5% of the bovine serum albumin resulted in 96.6% reduction in the erosion rate. This significant reduction in the erosion rate of the Sudanese adobe bricks could be explained by the following points:

- The high percentage of the swelling clay minerals which characterised with very small particle size and very high specific surface area resulted in more surfaces and edges available for the bovine serum albumin adsorption.
- The availability of the non-swelling clay minerals 37% increase to the total available surfaces and edges for bovine serum albumin adsorption.
- The bovine serum albumin adsorbed through the surfaces and edges of both clay minerals change its conformation upon adsorption and this adsorption process is an irreversible process.
- Due to the conformational changes on the bovine serum and the irreversibility of the adsorption process, the bovine serum albumin will result in sealing the clay minerals and might also result in changing the physical and chemical properties of the clay minerals such as the sensitivity of the swelling clay minerals to the water.
- As a result, the clay minerals will be water resistance and the water molecules will no longer have a free access to the interlayers of the minerals as the case with the unstabilised Sudanese adobe bricks, Figure 3-33 in section 3.2.2.1.
- Also, the adsorption of the bovine serum albumin by the two types of the clay minerals will result in cementing the soil particles together in a way better than when the clay was the only binder (e.g. in the case of the unstabilised Sudanese adobe bricks).

### 6.2.3 *Mucin stabilised British adobe bricks compressive strength and erosion resistance: Analysis of the Results*

Mucin is a large, extracellular glycoprotein with molecular size ranging between 500 - 50 000 kDa (Bansil and Turner, 2006). With this large molecular size, the mucin is far larger than the bovine serum albumin with molecular size of 68 kDa (Yu et al., 2013). As it has been noted before that the molecular size of the glycoprotein is considered as one of the important factors when it comes to the adsorption of the glycoprotein into the interlayers of the swelling clay minerals (Yu et al., 2013). As in Figure 3-33 in section 3.2.2.1, the interlayer space in the swelling clay minerals expand and increase from (a1) to (a3) upon hydration allowing the glycoproteins to access the interlayers of the clay mineral. Furthermore, the final interlayer spacing after the hydration (a3) is the one relevant to the adsorption of the glycoprotein. This means if the glycoprotein size is bigger than the final size (a3), it will not access the interlayer and all of its adsorption will be on the surfaces and the edges of the clay minerals. (Ralla et al., 2010) investigated the adsorption of different proteins with different molecular sizes by the montmorillonite clay minerals. They compared the adsorption of ovalbumin (43.5 – 45 kDa), trypsinogen (23.9 kDa), human serum albumin (66.4 kDa) and alkaline phosphatase (130 kDa) by the montmorillonite. They found that the alkaline phosphatase which was the largest protein in their investigation has the lowest adsorption capacity compared with all other proteins. This was due to that the alkaline phosphatase hydrodynamic diameter was bigger than the average pore diameter of the montmorillonite clay minerals and hence it has a limited access to the interlayer of the clay mineral. In addition, the second largest protein in their investigation was the human serum albumin and also it witnessed a lower adsorption capacity compared to all other smaller proteins which implies a size effect on the adsorption (Ralla et al., 2010). When compared the molecular size of the mucin (500 - 50 000 kDa), bovine serum albumin (68 kDa), alkaline phosphatase (130 kDa) and human serum albumin (66.4 kDa), it is clear that the mucin is far larger than all these proteins and hence it was thought this will result in all of its adsorption to be restricted and limited to the surfaces and edges of the clay minerals.

Based on the above point, the results of the addition of the mucin with the two different concentrations (0.1% & 0.2%) on the compressive strength and the erosion resistance of the British adobe bricks could be explained. If all the mucin is adsorbed only by the surfaces and the edges of both clay minerals, the swelling and the non-swelling, then none of the mucin will be in the interlayers of the swelling clay minerals. This might support the theory that the increase in the compressive strength in general is related to the amount of the glycoprotein adsorbed by the interlayers of the swelling clay minerals. On the other hand, the low concentration of the mucin (0.1% & 0.2%) will affect the structural integrity of the soil by acting as barrier between the clay minerals themselves and the clay minerals and the other soil particles (silt, sand and gravel) similar to what happened in the case of the lower concentrations of the bovine serum albumin in Figure 6-2 in section 6.2.1. This could explain the decrease in the compressive strength of the British adobe bricks upon the addition of the mucin as stabiliser compared with that of the unstabilised adobe bricks, Table 6-8 below.

In contrast, the adsorption of all of the mucin by the surfaces and the edges of the swelling and non-swelling clay minerals will result in sealing the clay minerals and hence increase the surface aggregation which will result in increasing the erosion resistance of the stabilised British adobe brick, Figure 6-7 and Table 6-9.

**Table 6-8:** Unconfined compressive strength of the unstabilised and 0.1% & 0.2% Mucin stabilised British adobe bricks

| Stabiliser | Unconfined compressive strength (MPa) |
|---|---|
| Unstabilised | 1.90 |
| **0.1%** Mucin | 1.65 |
| **0.2%** Mucin | 1.64 |

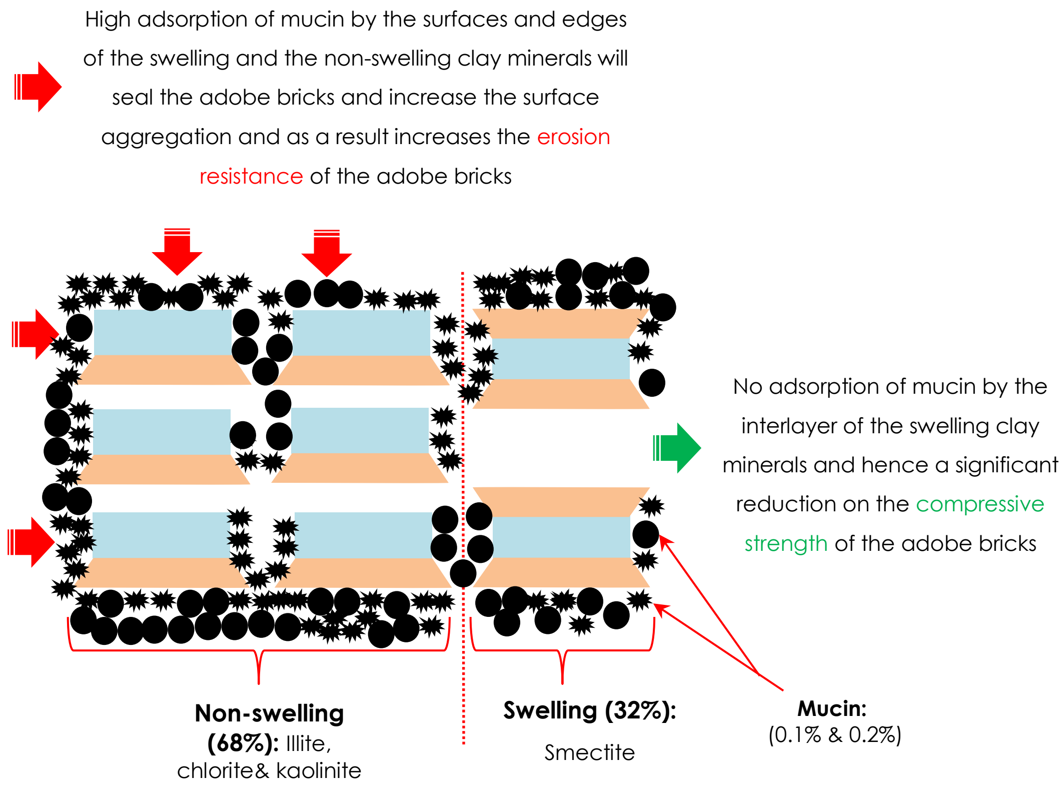



**Figure 6-7:** Conceptual illustration of the adsorption mechanisms of the mucin 0.1% & 0.2% by the clay minerals of the British adobe bricks and how these mechanisms affect the adobe bricks' compressive strength and erosion resistance

**Table 6-9:** Erosion rate of the unstabilised and 0.1% & 0.2% Mucin stabilised British adobe bricks

| Stabiliser | Erosion Rate, D (mm/min) |
|---|---|
| Unstabilised | 0.40 |
| **0.1%** Mucin | 0.29 |
| **0.2%** Mucin | 0.18 |

### *6.2.4 Fish gelatine stabilised British adobe bricks compressive strength and erosion resistance: Analysis of the Results*

The gelatine from cold-water fish skin has a molecular weight of ~ 60 kDa (Karimi et al., 2013). The use of fish gelatine with clay is not new. The fish gelatine has been combined with clay minerals to create gelatine-nanoclay composite films which of most importance in the packaging industries (Bae et al., 2009). However, the use of gelatine sourced from warm water fish skin was preferable in creating the gelatine-nanoclay composite films because of the gelling forming properties of this type of gelatine which makes the casting technique achievable (Bae et al., 2009). The gelling temperature of the warm water fish skin gelatine which is between 21– 22 °C makes it easy to work with this gelatine compared with the gelatine extracted from the cold-water fish skin. The cold-water fish skin gelatine has a very low gelling temperature which is between 4 – 8 °C. In addition, the warm water fish skin gelatine has a higher melting temperature (28 – 29 °C) when it is compared with that of the cold-water fish skin gelatine (14 – 16 °C) (Haug and Draget, 2009).

As has been mentioned before in section 3.2.7, using gelatine as stabiliser in earth construction is not new and different types of animal products were used in earth construction. They were mainly used to stabilise the wall render and they were rarely used to stabilise the walls themselves (Houben and Guillaud, 1994). Animal glues prepared from horns, bones, hooves and hides were the main source for the stabilisers (Houben and Guillaud, 1994). These animal glues are gelatine. These mammalian gelatines are different from the cold-water fish skin gelatine in their gelling and melting temperatures. The gelling temperature for the mammalian gelatine is between 26 – 27° C. and the melting temperature is between 33 – 34° C. These high gelling and melting temperature of the mammalian gelatine were thought to be the reason behind the success of using these gelatines as stabilisers in earth construction.

The gelling of the gelatine in general is affected by the amount of amino acids available in the gelatine structure. The gelatine from the cold-water fish skin has considered as poor gelling agent because it contains low amount of amino acids compared with the mammalian and the warm fish gelatine (Haug and Draget, 2009). There are two kinds of amino acids that are responsible of the difference between the mammalian, warm fish gelatine and the cold-water fish gelatine properties. The cold-water fish gelatine contains less proline and hydroxyproline (Haug et al., 2004, Gareis and Schrieber, 2007, Haug and Draget, 2009). The decrease in these amino acids affects the formation of the gelling network (Ledward 1986) in (Gómez-Guillén et al., 2011). In addition, the proline and hydroxyproline enhance the rigidity of the gel (Djabourov et al., 1988). As a result, the decrease of these amino acids resulted in lowering the gelling and the melting temperature of the gelatine. This means in order for the cold-water fish skin gelatine in the bricks to gel and harden the drying temperature should be between 4 - 8° C. Also, for the bricks to sustain this gelling effect, the temperature should not exceed 14 °C, where above this temperature in the availability of water the gel will change into liquid.

The gelling network is achieved when the gelatine reaches an equilibrium state that is characterised by a three-dimensional structure. To achieve very strong gelling network, the cooling process should be very slow because rapid cooling results in very poor gelling network (Gareis and Schrieber, 2007). Furthermore, drying affects the amount of the water available for the gelling to continue taking place. When gelatine is used in a high-solid system (for example, in this case the mud mixture for the bricks) and the water is little, the gelatine will not or very slowly be capable of forming and stabilising the three-dimensional structure of the gelling network. The gelling in this case is affected by the temperature and also might be inhabited by the other components of the system, for example the soil particles (Gareis and Schrieber, 2007). As a result, higher concentrations of the cold-water fish skin gelatine is needed to form a continuous network along with slow cooling process (Haug et al., 2004). The gelling temperature of cold fish gelatines highly affected by the gelatine concentration in the system compared with the melting temperature (Haug et al., 2004). The increase of the concentration will shorten the distance between the gelatine molecules in the system and thus lead to the formation of junction zones and so gel network (Haug et al., 2004).

One of the oldest characteristics of gelatine which has been known for more than 8000 years is its surface adhesion. The binding properties of gelatine depend on both adhesion and cohesion. Cohesion is related to the interaction between the gelatine molecules in the system. On the other hand, adhesion is connected with the interaction between the gelatine molecules and other components in the system. To fully cover a surface and to ensure the binding of its particles to each other, gelatine concentration is considered as a key. By using high concentration of gelatine, the adhesion forces starts to build-up and results in gel formation upon cooling (Gareis and Schrieber, 2007). Permanent gels could be formed by further reduction in temperature, and this will have a viscoelastic behaviour giving the system the nature of a solid material (Gareis and Schrieber, 2007).

Another important factor affecting the strength of the gelatine is the pH of the medium. If the pH of the medium is corresponding to the pI of the gelatine (the isoelectric point) then the gelatine has neutral charge. More compact and stiffer gels can be formed by adjusting the pH of the gelatine close to its isoelectric point, where the protein chains will be more neutral and thus the gelatine polymers are closer to each other (Jamilah and Harvinder, 2002, See et al., 2010). However, if the pH is higher than the pI the gelatine will be negatively charged and if it is lower than the pI, then the gelatine is positively charged. All types of the gelatine are negatively charged if the pH of the medium is above 9, and positively charged for pH below 5 (Gareis and Schrieber, 2007), Figure 6-8.

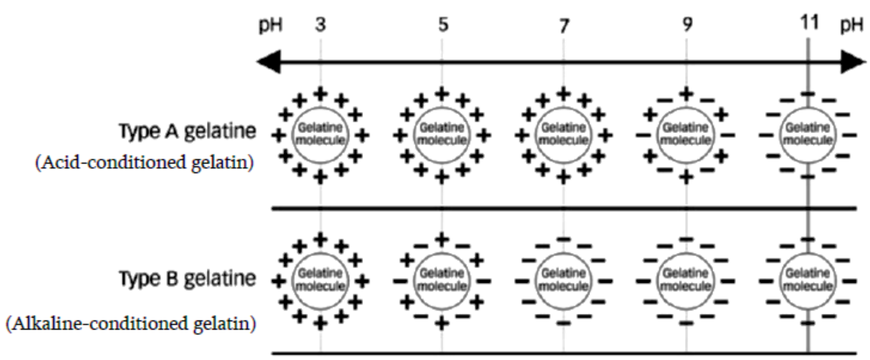



**Figure 6-8:** Charge distribution pattern of type A and B gelatines in aqueous solutions of different pH. *Adopted from (Gareis and Schrieber 2007)*

However, in this study the use of different concentrations of the gelatine from the cold-water fish skin to stabilise the British adobe bricks resulted in the reduction of the bricks' compressive strength except for the lowest concentration (0.1%) which increased the compressive strength. However, based on the Dunnett multiple comparison analysis in Figure 4-11 in section 4.5.10, the results of 0.1% fish gelatine concentration was not statisticaly significant form the compressive strength results of the unstabilised British adobe bricks and hence this result will not be included in this discussion. The inclusion of 0.1% fish gelatine resulted in no change in the erosion rate. However, the addition of more fish gelatine (0.2%) increased the erosion rate, Table 6-10.

**Table 6-10:** The unconfined compressive strength for the unstabilised and 0.1%, 0.2%, 0.3%, 0.4% & 0.5% fish gelatine British adobe bricks and the erosion rate of the unstabilised and 0.1% & 0.2% fish gelatine stabilised British adobe bricks

| Stabiliser | Unconfined compressive strength (MPa) | Erosion Rate, D (mm/min) |
|---|---|---|
| Unstabilised | 1.90 | 0.40 |
| **0.1%** Fish gelatine | 1.96 | 0.39 |
| **0.2%** Fish gelatine | 1.50 | 0.46 |
| **0.3%** Fish gelatine | 1.59 | - |
| **0.4%** Fish gelatine | 1.59 | - |
| **0.5%** Fish gelatine | 1.58 | - |

To discuss the results of the fish gelatine British stabilised adobe bricks in Table 6-10 above, the mixing and the drying environments these bricks were exposed to should be highlighted. As has been mentioned before in section 4.4, all the unstabilised and the stabilised British adobe bricks were made in the laboratory environment. All the British adobe unstabilised and stabilised bricks were dried for 28 days in a controlled environmental chamber. The temperature was set between 17 – 22 °C and the humidity between 60% - 65% inside the drying chamber. Based on these preparations and drying temperatures which are higher than the gelling temperature for the cold-water fish gelation (4 -8 °C), it is easy to confirm that the gelatine from the cold-water fish skin will remain liquid in the presence of water at the room temperature. In addition, during the drying process and the evaporation of the water, the gelatine might just has returned back to its original powder state. As a result, the cold-water fish skin gelatine would never engage in any adhesion/ cohesion activities in the soil. It was thought due to dysfunctionality of the fish gelatine and not been able to gel in order to glue the soil particles together, its availability in the soil matrix of the adobe bricks lead to the breaking of the binding forces between the clay minerals together and the clay minerals and other soil particles. This will affect both the compressive strength and the erosion resistance of the British adobe bricks.

Based on these facts regarding the gelling properties of the cold-water fish skin gelatine, there was no gluing effect achieved from using this gelatine under the experiment settings. However, some adjustment in future experiments should be made if this gelatine will be recommended as stabiliser in order to achieve more durable stabilised bricks:

- Ensure to use high concentrations of this gelatine to make sure to cover all the surface of the system where the particles needed to be affixed and glued.
- The drying temperature should be between 4 - 8 °C and never increase above 13°C.
- The cooling should be very slow process and rapid cooling should be avoided.
- The availability of water as the medium for the reaction to continue and as a control for the gelling effect, should be available as long as possible to ensure the continuation of the gelling and the gluing effect.

### 6.2.5 Termite's saliva ingredients stabilised British adobe bricks compressive strength and erosion resistance: Analysis of the Results

As has been mentioned before in section 3.2.4, the termite's saliva ingredients used in this study was a mixture of the ingredients of the termite's saliva glycoprotein which was extracted from the investigation conducted on the soil mound of *Coptotermes Acinaciformis* termites in Australia by Gillman and his colleagues (Gillman et al. 1972). The mixture was consisted of one amino sugar (5.2% of the total glycoprotein), six monosaccharides of the hemicellulose group (42.2% of the total glycoprotein), eight amino acids (52.3% of the total glycoprotein) and sialic acid (0.27% of the total glycoprotein).

These chemicals were added to distilled water and mixed in the room temperature until a homogenous mix was obtained and then the soil was added. However, due to the availability of many chemicals involved in the preparation of the adobe bricks made using this termite's saliva ingredients stabiliser, the results of the compressive strength and the erosion resistance were diverse and no general pattern was observed compared to other stabilisers results. It is believed that a lot of different chemical reactions were taken place between the chemicals themselves and between the chemicals and the soil constituents in the availability of water as a medium.

It is known for sure that the monosaccharide and/or polysaccharides have the ability to interact with the clay. The availability of the polysaccharides in the soil lead to the creation of a bond between the soil aggregates, so it affects the structural stability of the soil in general and the erodibility of the soil in particular (Ahmed and Hussain, 2008). This aggregation is attributed to the cementing effect due to the interaction between the clay minerals and the polysaccharides (Tan, 2011). The polysaccharides reduce the swelling and wetting in the soil by changing the clay surface with respect to adsorption of water and by doing this they increase the cementing effect (Tan, 2011). The clay minerals have the ability to absorb the monosaccharide as well as the polysaccharides which result in the aggregation and the structural stability of the soil particles (Lima et al., 2009). In addition, the polysaccharides are strongly hydrophilic and as a result it will enhance the water holding capacity of the soil (Lima et al., 2009). (Chenu and Guerif, 1991) investigated the effect of the addition of a fungal polysaccharide (scleroglucan) in the strength, aggregation and stabilisation of two types of clay minerals, kaolinite and montmorillonite. They concluded that this polysaccharide has increased the strength, aggregation and stabilisation properties of both clay minerals by the formation of inter-particular bridges and also due to the formation of a gel network. In addition, (Chang et al., 2015) have tested the effect of the addition of Xanthan gum (a polysaccharide used as a food additive and rheology modifier) in the mechanical properties and durability of different types of soils. They found out that the addition of this polysaccharide has improved the soil mechanical properties and durability by coating the soil grains, creating connection bridges between particles that are not in direct contact and also by a direct interaction between the Xanthan gum and the electrically charged fine particles of the soil (clay minerals). They also suggested that the electro-static and hydrogen bonding could not be happening between the sand particles because the sand carries no electrical charges. On the other, hand, other research in termite mound soils also showed the significant relationship between the stability of the aggregate, resistant to erosion and the sugar content of the mound soil (Contour-Ansel et al., 2000) have investigated this in depth in two termites mound soils belong to two different termite species from Senegal. They have concluded that monosaccharide and/or polysaccharides make the soil structure more stable.

It is also well known that the clay minerals have the ability to adsorb the amino acids in nature (Lambert, 2008). It is believed that the clay minerals played an important role in the prebiotic chemistry and the origin of life on earth (Zaia and Zaia, 2006). The clay minerals have served as primitive vessels for amino acids and other biological polymers (Yu et al., 2013). It is also suggested that the clay minerals might play a central role in the formation of proteins and nucleic acid (Hashizume, 2012). The adsorption of amino acids by clay minerals has been addressed and investigated in several previous studies (Greenland et al., 1965, Friebele et al., 1980, Dashman and Stotzky, 1982, Hedges and Hare, 1987, Wang and Lee, 1993). However, in all these studies there were no mention to the effect of the adsorption of the amino acids on the mechanical strength of the clay. Instead some research has addressed the effect of the Extracellular Polymeric Substances (EPS) on stabilizing the soil sediments. EPS are comprised of a range of organic molecules, including polysaccharides, proteins, nucleic acids and lipid. They also could be referred to the complex compound of these organic molecules such as glycoproteins, peptidoglycans, and glycolipids. The availability of the EPS in soil decreases erosion rates of both cohesive and non-cohesive sediment. However, from the definition of the EPS above there were no mention to the amino acids as part of the EPS, instead proteins were mentioned. It is known that amino acids are the building block of proteins (Clerici et al., 2016). However, the synthesis of the protein is a complex process which includes many steps and it has two production methods, cell-based (in vivo) and cell-free (in vitro) (Biyani et al., 2012).

As a result, it is unlikely that the simple mixture of amino acids in this study would lead to the production of the protein. Therefore, the effect of the addition of the termite's saliva ingredients on the compressive strength and the erosion resistance of the British adobe bricks will only be highlighted from monosaccharides point of view.

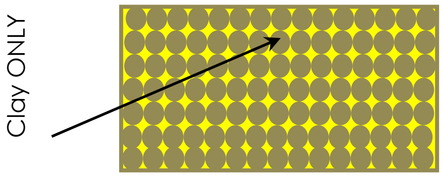
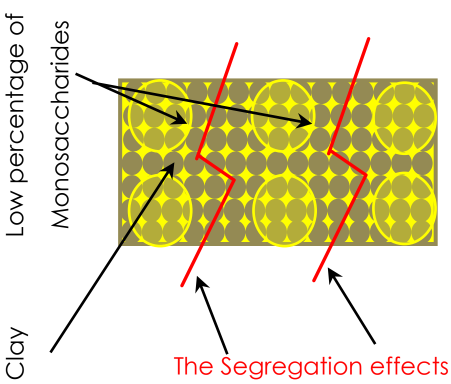
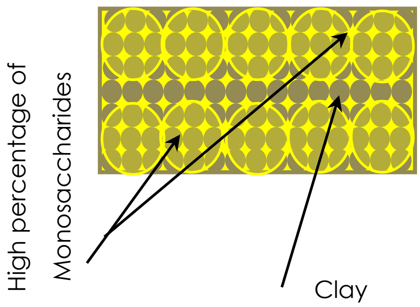
**Table 6-11:** The unconfined compressive strength for the unstabilised and 0.1%, 0.2%, 0.3%, 0.4% & 0.5% termite's saliva ingredients British adobe bricks and the erosion rate of the unstabilised and 0.1% & 0.2% termite's saliva ingredients stabilised British adobe bricks

| Stabiliser | Unconfined compressive strength (MPa) | Erosion Rate, D (mm/min) |
|---|---|---|
| Unstabilised | 1.90 | 0.40 |
| **0.1%** termite's saliva ingredients | 1.85 | 0.53 |
| **0.2%** termite's saliva ingredients | 1.66 | 0.28 |
| **0.3%** termite's saliva ingredients | 1.74 | - |
| **0.4%** termite's saliva ingredients | 1.64 | - |
| **0.5%** termite's saliva ingredients | 1.81 | - |

From Table 6-11 above, the trend of the compressive strength of the stabilised adobe bricks does not follow the previous mentioned points regarding the improve of the strength of the soil with the increase of the monosaccharides quantities in it. However, these inconsistent results were expected based on the high number of chemicals involved in the adobe mixture. In fact, the compressive strength results suggested that a chemical reaction might be taken place between the amino acids and the monosaccharide. This means the effect of the amino acids could not be ignored. However, the compressive strength results could not be discussed any further because the chemical reaction between the soil, distilled water, amino acids and monosaccharides and the final product from this reaction is not known.

The erosion rate of the termite's saliva ingredients stabilised adobe bricks started by being higher than the erosion rate of the British unstabilised bricks when the concentration of the termite's saliva ingredients was 0.1%. When the concentration of the stabiliser increased to 0.2% in the adobe bricks, the erosion rate reduced below the erosion rate of the British unstabilised bricks. It was though these results could be explained by the following theory, Table 6-12.

**Table 6-12:** The suggested theory for the erosion rate of the termite's saliva ingredients stabilised British adobe bricks

| Adobe Brick surface | Suggested theory for erosion rate |
|---|---|
|   | **1. The unstabilised brick:** The stabiliser is the natural clay ONLY |
|   | **2. 0.1% termite's saliva ingredients:** The stabilisers are the natural clay and the sugars, however due to the low concentration of the sugar, the sugar will play a role in breaking the solidity of the soil matrix. Due to its low concentration, the available sugar was only enough to hardly start the electro-static and hydrogen bonding with the clay but it was not enough to create the bridges between the sand particles. As a result, it was suggested that the sugar was leading to the segregation of the soil matrix instead of the gluing effect which results in a very vulnerable surface for erosion. |
|   | **3. 0.2% termite's saliva ingredients:** The stabilisers are the natural clay and the sugars. When the sugar concentration was increased, more sugar was available to start the electro-static and hydrogen bonding with the clay along with creating the bridges between the sand particles. As a result, more gluing effect and durable surface was achieved that was more resistance to erosion compared with both unstabilised and 0.1% termite stabilised adobe bricks. |

## 6.3 The Unconfined Compressive Strength of the Stabilised Adobe Bricks

In this section, the compressive strength of the best stabiliser will be the only one to be compared with compressive strength from the literature. For the British and the Sudanese stabilised adobe bricks, the bovine serum albumin will be the stabiliser to be discussed. The concentration range of the bovine serum albumin that will be covered in this section is between 0.5 and 5% for the stabilised adobe bricks. The 0.4% bovine serum albumin stabilised British adobe bricks is excluded from this discussion even though the compressive strength was higher than that of the unstabilised British adobe bricks because the results were not significant as it was reported in section 4.5.22.

**Table 6-13:** Comparison of the compressive strength of the adobe bricks stabilised using bovine serum albumin in this study with cement & lime stabilised earth bricks of previous studies and other popular building materials

| Stabiliser \ Percentage | 0.5 – 3% | 5% | 6 – 12% | Earth technique | Test unit | Reference |
|---|---|---|---|---|---|---|
| **Fired clay brick** | 5-20 (London Stock bricks)<br>15–30 (Fletton)<br>90 (Solid wirecut)<br>40 (Perforated wirecut) | | | - | MPa | (Domone and Illston, 2010, Association, 2013) |
| **Concrete bricks** | 7-40 | | | - | MPa | (Association, 2013) |
| **Hollow Concrete blocks** | 3.6- 22.5 | | | - | MPa | (Association, 2013) |
| **Unfired clay brick** | 1-2 | | | - | MPa | (Houben and Guillaud, 1994, Danso, 2016) |
| **Bovine serum albumin** | **2.23-4.70** | **5.75-6.47** | **-** | **Adobe** | **MPa** | **-** |
| **Cement** | - | 5 | 10%: 13 | Stabilised soil block masonry units | MPa | (Gavigan et al., 2012) |
| | - | 1.79 | - | Compressed earth blocks | MPa | (Arumala and Gondal, 2007) |
| | - | 1.03 | 7%: 1.31<br>10%: 2.00 | Adobe | MPa | (Alam et al., 2015) |
| | - | 4%: 2.5 | 6%: 3.5<br>8%: 4<br>10%: 4.5 | Cement-stabilised cylinders | MPa | (Bahar et al., 2004) |
| | 2.5%: 1.03 | 1.53 | 7.5%: 2.84 | Compressed stabilized earth blocks | MPa | (Waziri and Lawan, 2013) |
| | - | 3.9-5.5 | 10%: 6-8 | Adobe | MPa | (Vilane, 2010) |
| | 3%: 5 | - | 6%: 6.5<br>9%: 9 | Unfired clay bricks | MPa | (Miqueleiz et al., 2012) |

| Stabiliser / Percentage | 0.5 – 3% | 5% | 6 – 12% | Earth technique | Test unit | Reference |
|---|---|---|---|---|---|---|
| **Lime** | - | 0.62 | 7%: 0.79<br>10%: 1.29 | Adobe | MPa | (Alam et al., 2015) |
| | - | 4%: 3.20 | 6%: 3.28<br>10%: 3.52 | Adobe | MPa | (Millogo et al., 2008) |
| | - | - | 10%: 2.51<br>12%: 2.71 | Adobe | MPa | (Bharath et al., 2014) |
| | 3%: 4.8 | - | 6%: 7<br>9%: 8 | Unfired clay bricks | MPa | (Miqueleiz et al. 2012) |
| | - | 4%: 0.8-5 | - | - | MPa | (Bell, 1996) |
| | - | - | 10%: 3.5 | Adobe | MPa | (Millogo et al., 2008) |

Table 6-13 above shows the comparison of the compressive strength of the adobe bricks stabilised using bovine serum albumin in this study with cement & lime stabilised earth bricks from previous studies and some other popular building materials. As it has been mentioned before, the 5% was selected as the highest concentration of bovine serum albumin used in this study. This concentration was chosen because it represents the lowest concentration recommended in cement stabilisation and usually blocks stabilised with cement concentration lower than 5% are often too friable for easy handling (Walker, 1995). Table 6-13 also shows the compressive strength of some earth units stabilised using 10% of cement and lime even though in this study 10% was not used as one of the investigated percentages for the bovine serum albumin. The 10% was covered in this comparison because it represents the highest cement concentration that could be used and the cement stabilisation could be still considered economical (Walker, 1995). Table 6-13 shows that from the studies compared for the cement stabilisation, two studies only used cement concentrations lower than 5%. Using only 0.5% bovine serum albumin resulted in compressive strength highest than that achieved using 2.5% cement. Furthermore, this 2.5% cement stabilised earth units were not adobe bricks but they were compressed units. So, this compressive strength for this 2.5% cement stabilised earth units was achieved as a result of both stabilisation and compaction effort. The other study shows that when 3%

cement was used in stabilising earth units the compressive strength was similar of that achieved when 3% of bovine serum albumin was used.

For 5% concentration, the compressive strength of the adobe bricks stabilised using bovine serum albumin in this study was higher than the compressive strength of all the studies reviewed using 5% cement as stabiliser. The compressive strength of 5% bovine serum albumin stabilised adobe bricks was also compared to the compressive strength of earth units stabilised using between 6% to 10% cement. From the compressive strength data in Table 6-13, it is clear that the compressive strength of the 5% bovine serum albumin stabilised adobe bricks in most studies was higher than that of the earth units stabilised using higher concentrations of cement. It is worth mentioning that in this study the bovine serum albumin was not achieved the saturation adsorption curve. This means that there is a room to investigate higher concentrations of the bovine serum albumin in future research and the data then could be compared with that of the cement.

For the lime, only one study from the studies covered in this comparison used lime concentration lower than 5%. The compressive strength of the 3% lime stabilised earth unit was in the range achieved for 3% bovine serum albumin stabilised adobe bricks.

For lime concentrations between 4% and 5%, the compressive strength was in the range between 0.62 to 5 MPa. However, using 5% of bovine serum albumin to stabilise adobe bricks resulted in compressive strength of 6.47 MPa which was higher than the compressive strength achieved using lime as stabiliser.

In this study, the highest concentration used was 5%, however the compressive strength of the 5% bovine serum albumin stabilised adobe bricks was higher than all the compressive strength of the earth units stabilised using higher concentrations of lime (6%-12%) in the studies took place in the comparison in Table 6-13 except for only one study whereby using 6% and 9% lime yielded compressive strength of 7 and 8 MPa respectively.

When comparing the compressive strength of the 5% bovine serum albumin stabilised adobe bricks in this study with the compressive strength of the London Stock bricks (fired clay brick), Table 6-13, its strength fall in the lower band of the compressive strength recommended for this kind of fired clay bricks. However, the compressive strength of the 5% bovine serum albumin in this study is lower than the compressive strength recommended for other types of fired clay bricks included in this comparison, Table 6-13. This was expected bearing in mind that these adobe bricks in this study are not compressed and they are only air-dried.

In addition, the compressive strength of the 5% bovine serum albumin stabilised adobe bricks is lower than the recommended compressive strength for the concrete bricks, Table 6-13. Furthermore, the compressive strength of the 5% bovine serum albumin stabilised adobe bricks is higher than the lower recommended compressive strength for the concrete hollow blocks, Table 6-13. In construction of houses in the UK, the concrete blocks are usually used in the internal walls (Bloodworth et al., 2001), therefore, this adobe bio-inspired bricks could have a wide market to substitute the reliance on these concrete blocks in the future.

Finally, the compressive strength of the bovine serum albumin stabilised adobe bricks with concentrations between 0.5% to 5% from this study is higher than the recommended compressive strength for the unfired clay brick which is between 1 and 2 MPa, Table 6-13.

## 6.4 The Erosion Resistance of the Stabilised Adobe Bricks

In this section only the stabilisers that resulted in a continuous improvement in the adobe erosion rate will be addressed and discussed. The increase in the concentration of the bovine serum albumin and the mucin from porcine stomach in the adobe bricks led to continuous reduction in the erosion rate of these bricks. The erosion rate of these two stabilisers will be compared with the erosion rate from other studies in the literature, Table 6-14.

**Table 6-14:** Comparison of the erosion rate of the adobe bricks stabilised using bovine serum albumin and mucin from porcine stomach in this study with erosion rate of earth bricks of previous studies

| Earth technique | Stabiliser | Percentage (%) | Erosion Rate, D (mm/min) | Reference |
|---|---|---|---|---|
| **Adobe** | **Bovine serum albumin** | **0.1 – 0.5** | **0.28 – 0.12** | **-** |
| **Adobe** | **Mucin from porcine stomach** | **0.1 – 0.2** | **0.29 – 0.18** | **-** |
| **Compressed earth bricks** | Cement | 7% | 0.008 - 0.013 | (Obonyo et al., 2010) |

| Earth technique | Stabiliser | Percentage (%) | Erosion Rate, D (mm/min) | Reference |
|---|---|---|---|---|
| **Compressed earth bricks** | Cement + lime | 4.68% cement, 6.70% lime | 0.375 - 0.333 | (Obonyo et al., 2010) |
| **Compressed earth bricks** | Cement + lime + fluid (Aeonian brick stabilizer) | 4.66% cement, 4.66% lime, 2.26% fluid | 0.416 - 0.50 | (Obonyo et al., 2010) |
| **Compressed earth bricks** | Cement + fibre (coconut husks) | 4.96% cement, 0.94% fibre | 0.667 - 0.917 | (Obonyo et al., 2010) |
| **Factory produced interlocking bricks** | - | - | 0 - 0.003 | (Obonyo et al., 2010) |
| **Compressed soil blocks** | Bagasse | 0.25 – 1 | 0.65 – 1.50 | (Danso et al., 2015) |
| **Compressed soil blocks** | Coconut | 0.25 – 1 | 0.60 – 1.30 | (Danso et al., 2015) |
| **Compressed soil blocks** | Oil Palm | 0.25 – 1 | 0.63 – 1.40 | (Danso et al., 2015) |

Table 6-14 above shows the results of the erosion rate of the adobe bricks stabilised by bovine serum albumin and mucin from the porcine stomach in this study and other studies available from the literature. From Table 6-14, the erosion rate of both the bovine serum albumin and the mucin adobe stabilised bricks in this study were lower than all the bricks investigated by Obonyo and his colleagues except for the bricks stabilised with 7% cement and their benchmark brick (the factory produced interlocking bricks). In (Obonyo et al., 2010) all the bricks were manufactured by undergoing a compaction pressure which was achieved using a manually-operated device. The compaction pressure will enhance the surface integrity of the bricks by bringing the soil particles closer to each other and increasing the density of the bricks. In this study, all the adobe bricks were manually produced without any specialized well-known compaction devices, section 4.3 and 4.6. In addition, in this study the highest concentration of a stabiliser used for the erosion rate test was 0.5% which is lower than all the concentrations of the different stabilisers used by Obonyo and his colleagues.

Furthermore, the erosion rate of both the bovine serum albumin and the mucin adobe stabilised bricks in this study was lower than all the bricks investigated by Danso and his colleagues. Danso and his colleagues produced their bricks by subjected them to a 10 MPa pressure using a block making machine (Danso et al., 2015). As it has been mentioned earlier, this pressure during production will enhance the bricks density and hence enhance the bricks' overall quality.

In general, the compressed stabilised earth units are well known for their strength and durability. They have gained these better qualities as function of using a stabiliser such as cement, lime and ect., along with being subjected to a constant manual or mechanical pressure during their production. In contrast, adobe bricks are lower in the mechanical and physical properties when they are compared with compressed stabilised earth units. This is attributed to the absence of the constant manual or mechanical pressure effort during production which results in low density bricks and hence low-quality bricks. In addition, the high moulding moisture content of the adobe bricks during the production usually results in the appearance of surface micro-cracks upon drying. These micro-cracks add to the vulnerability of the surface of the adobe bricks to the erosion by the wind-driven rain. For all the above-mentioned points, compressed stabilised earth units all the time are expected to result in less erosion rate when they exposed to erosion tests compared with the adobe bricks. Furthermore, the highest concentration of bovine serum albumin used in this study was 0.5% and the highest for the mucin was 0.2%. Nevertheless, in erosion resistance, the adobe stabilised bricks in this study were performed better than most of the compressed earth units from the literature.

# 7. Conclusions & Recommendations for future work

## 7.1 Introduction

Termite mounds were the inspiration behind this research. The high mechanical strength and the erosion resistance of the termite mounds were the incentives behind investigating these magnificent constructions. The construction technique termite uses to construct its mounds was studied as part of this study. The intention behind studying the termite construction technique was to investigate the biological adhesive the termite incorporates during the construction process to cement the subsoil particles together. One key study revealed that the biological adhesive used by the termite to cement the soil was glycoprotein. By approaching the termite engineering ideas using biomimicry as scientific approach, the glycoprotein which is a biological component that plays vital roles and widely abundant in nature was studied in more depth. Three glycoproteins were then selected to be tested as potential stabilisers in earth construction. The fourth stabiliser was a mixture of the ingredients of the glycoprotein used by termites during the construction of the mounds. The aim of this study was to enhance the strength and the durability of adobe bricks by introducing these bio-inspired stabilisers. This aim has been successfully fulfilled, though further research is recommended to investigate more types and sources of stabilisers and other earth construction techniques.

The main conclusion is that, bovine serum albumin which is a glycoprotein derived from cows' blood and considered as a by-product of the beef industry, has proved its potential to be used as stabiliser in earth construction.

The conclusions are presented based on the findings of the experimental work which is directly linked to the objectives of this study.

## 7.2 Conclusions

### 7.2.1 Glycoproteins

Animal glycoproteins could be used as stabiliser in adobe bricks. However, the selection of the glycoprotein is governed by two main factors:

- The molecular size of the glycoprotein

In general, the molecular size plays an important role in the adsorption of the glycoprotein by the clay minerals. The general rule is that the size of the glycoprotein should not exceed the interlayer spacing of the clay mineral. From the experimental work in this study, it was concluded that the compressive strength is governed by the amount of the glycoprotein adsorbed by the interlayers of the clay minerals.

- Source of the glycoprotein and its function in the animal body

The source of the glycoprotein is referred to the organ where the glycoprotein is extracted from. The location of the glycoprotein inside the animal body will show the function and the role of the glycoprotein. This is important because for example, the same glycoprotein can be secreted in two different organs and functioning completely two different functions. Based on the function of the glycoprotein, its adhesive properties will change. This adhesive property is important when it comes to use the glycoprotein as stabiliser in the earth construction.

It is also important to know if the glycoprotein is gelatine. Gelatines are affected by their melting and gelling temperatures. This is important to be known beforehand because it will affect the selection of the drying settings. It will also affect the treatment of the bricks during the drying process such as for example; the decision could be to sprinkle the bricks with water during the drying process in order to allow the gelling to harden.

Another important factor is the concentration of the glycoprotein in the bricks. For example, when bovine serum albumin was used to stabilise the adobe bricks in this study, the adobe bricks' compressive strength and erosion resistance were improved with the increase of the concentration of the bovine serum albumin in the bricks.

### 7.2.2 Soils

In general, knowing the type of the clay minerals in the soil is important when it comes to the adsorption of the glycoprotein. The whole stabilisation process depends on the clay minerals available in the soil. Swelling and non-swelling clay minerals adsorb the glycoprotein differently. The site of the adsorption on the clay minerals affects the total adsorption and hence the strength and the durability of the final product. Both types of clay minerals play an important role in the erosion resistance of the bricks. However, it was thought that the glycoprotein concentration in the bricks along with the quantity of the swelling clay minerals both play a vital role in the compressive strength of the unit. This indicates that a soil with high percentage of smectite clay minerals which is one of the swelling clay minerals, will have better results in compressive strength and also in erosion resistance. This is a very interesting finding, since soils with high percentage of smectite are not desired in construction in general.

### 7.2.3 Bovine serum albumin

In this study bovine serum albumin was the best stabiliser and when it was used with concentrations above 4 by weight percent, it resulted in significant improvements in compressive strength and erosion rate for both the British and the Sudanese soils. The concluding points for the use of the bovine serum albumin as stabiliser in this study are as follow:

- 0.5% concentration of bovine serum albumin resulted in a 41% increase in the compressive strength of the Sudanese adobe bricks compared with 17% increase for the British adobe bricks.
- 5% concentration of bovine serum albumin resulted in 202% increase in the compressive strength of the British adobe bricks compared with 97% increase for the Sudanese adobe bricks.
- For the erosion resistance, the use of very low concentrations of the bovine serum albumin resulted in significant improvement in the bricks durability.
- The use of 0.1% concentration of the bovine serum albumin resulted in 30% reduction in the erosion rate of the British adobe bricks.
- The use of 0.2% concentration of the bovine serum albumin resulted in 48% reduction in the erosion rate of the British adobe bricks.

- The use of 0.5% concentration of the bovine serum albumin resulted in 97% reduction in the erosion rate of the Sudanese adobe bricks compared with 70% reduction for the British adobe bricks.
- It worth mentioning that this 97% improvement in the erosion rate of the Sudanese adobe bricks is considered outstanding because the Sudanese soil is predominantly composed of smectite clay minerals which is an expansive clay. This is considered as one of the most problematic soils when it comes to construction. The high sensitivity of this soil to water makes it swells in contact with water and shrinks upon drying. However, it is thought that the bovine serum albumin has the ability to change this soil swelling properties and thus gives it the potential to be used in the construction.
- Furthermore, a simple water penetration test was conducted on some of the 5% bovine serum albumin stabilised British adobe scaled bricks which were originally prepared for compressive strength test. Water was splashed over the upper surface of the brick. The brick was left with the water on its surface for 15 minutes and then the water was wiped away. The brick does not show penetration of water from the surface. This indicates that the bovine serum albumin might have sealed the surface of the brick making it water impervious.

### 7.2.4 Mucin from porcine stomach

From the use of the mucin from the porcine stomach to stabilise the British adobe bricks, the following points could be concluded:

- The use of low percentages of mucin from porcine stomach (0.1% & 0.2%) deteriorated the compressive strength of the British adobe bricks.
- However, the use of the same low concentrations has improved the erosion resistance of the British adobe bricks. The use of 0.1% and 0.2% of mucin resulted in 28% and 55% reduction in the erosion rate of the British adobe bricks respectively.
- Due to the above two points, the mucin is recommended to be used in the render of the walls instead of being used as an additive in the brick mixture.

### 7.2.5 Cold water fish skin gelatine

The use of gelatine from cold water fish skin in stabilising earth wall is not recommended. In this study, most of the concentrations of the gelatine used resulted in reducing the compressive strength and the erosion resistance of the British adobe bricks. This mainly was attributed to the gelling properties for this type of gelatine. However, some adjustment in future experiments should be made if this gelatine will be recommended as stabiliser in order to achieve more durable stabilised bricks:

- Gelatine concentrations higher than the concentrations used in this study should be used. This means concentrations higher than 0.5% which was the highest concentration used for this stabiliser in this study. By increasing the concentration of the gelatine in the brick, the gelatine will cover all the surface of the brick and hence will glue the soil particles.
- The above concentration point should be accompanied by managing the drying process. The drying temperature should be between 4 - 8 °C and never exceed 13°C.
- During the drying process, the bricks could be sprinkled with water in order to allow the gelling to harden.

### *7.2.6 Termite's saliva ingredients*

It is well documented in the literature that the termite saliva glycoprotein is the secret behind its very strong mounds (Gillman et al., 1972, Pariyarath, 2014). As it has been mentioned before in section 3.2.4, this stabiliser was not the true termite glycoprotein but instead it was a mixture of the ingredients of the glycoprotein. As a result of the inconsistent compressive strength and erosion rate results from this study, this mixture of chemicals is not recommended to be used as stabiliser in earth construction.

## 7.3 Recommendations for future research

Based on the findings of this study, the following recommendations for future research are proposed:

### *7.3.1 Soils*

It is recommended that more types of soils especially soils which contain more expansive clay minerals to be stabilised with bovine serum albumin and tested. In addition, it is recommended to test soils with different particle size distributions to understand the effect of the particle sizes in the glycoprotein adsorption and hence the strength and the durability of the bricks.

### 7.3.2 Glycoproteins

Glycoproteins in nature are sourced from animals and plants. It is recommended to investigate new sources of glycoprotein from the animals to be used as stabilisers in earth construction. Furthermore, plants' glycoproteins are worth investigating. In addition, it is recommended to test crude glycoproteins instead of pure ones. If the crude glycoproteins give results similar to the pure one, then there is no need to use purified form of glycoprotein in earth construction.

### 7.3.3 Concentrations

More concentrations of bovine serum albumin are recommended to be tested. This will help with understanding the adsorption saturation curve for the bovine serum albumin. This saturation curve will establish the highest recommended concentration for the bovine serum albumin which results in the highest compressive strength and lower erosion rate possible.

### 7.3.4 Internal mechanism

Investigating the internal mechanism of the adsorption of the glycoprotein by the clay minerals with the use of advanced instrument such as CT scan, Scanning Electron Microscope and Computerised Optical Microscope is highly recommended. This is very important to fully understand how the adsorption of the glycoprotein by the clay minerals change the clay mechanical and physical properties.

### 7.3.5 Earth construction techniques

In this study only adobe was investigated as a construction technique. It was chosen because of its simplicity and easy fabrication which not involves any sophisticated equipment. However, it is recommended to test the glycoprotein as potential stabiliser using other earth construction techniques such as compressed earth blocks and rammed earth.

### 7.3.6 Strength tests

In this study only dry unconfined compressive strength was tested. However, it is worth investigating and testing these adobe bricks under wet compressive strength and understand how they perform. In addition, other strength tests such as tensile strength test, and flexural test (modulus of rupture, or bending strength test) are worth investigating.

### 7.3.7 Durability tests

In this study only accelerated erosion test was used. Even this test was only used for low concentrations up to 0.5 by weigh percent. Bricks with higher concentrations of bovine serum albumin is highly recommended to be tested for their erosion resistance. Other durability tests such as the wire brush test and drip test could be investigated.

### 7.3.8 Experimental settings

During the preparations of the glycoproteins in this study, room temperature distilled water was used. It is recommended to investigate how the heating of the glycoprotein water mixture will affect the compressive strength and the erosion resistance of the bricks. In addition, different mixing timing is recommended to be tested and understand its effect on the compressive strength and the erosion resistance of the bricks. The mixing timing will represent the contact time between the protein and the clay minerals which the literature highlight to have an effect on the total adsorption. Also, it is recommended to test the effect of changing the dielectric constant of the medium where the clay minerals and the glycoprotein are present for example by adding some solvents such as alcohols and test how this will affect the strength and the durability of the bricks. The pH of the medium is a very important factor affecting the adsorption of the glycoprotein by the clay minerals. For a maximum adsorption of glycoprotein by the clay minerals to take place, the general rule is to bring the pH of the medium closer to the isoelectric point of the glycoprotein. By doing this the adsorption of the glycoprotein by the clay minerals will increase and hence the strength and the durability of the bricks will improve. This is an interesting experimental setting that could be tested to understand its effect on the strength and the durability of the bricks.

### 7.3.9 Other tests

It was thought that since the incorporation of the bovine serum albumin in the expansive soil affected the ability of this type of soil to swell when in contact with water, it worth investigating the potential of using of this glycoprotein in wider scale. This means to the investigate the use of this glycoprotein to stabilise soils under highways and roads and in building structures (under buildings foundations). In addition, it is recommended to test the potential of the use of this glycoprotein to stabilise soils in and around flood zones.

It is highly recommended to investigate the thermal performance of this bovine serum albumin stabilised adobe bricks. It is also recommended to test the long-term performance of these adobe bricks. In addition, it worth investigating the air quality inside spaces build using these adobe bricks to trace if there are any toxic gases released from using these bricks which could have potential health effects on the users in the future.

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