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Biomimicry in Construction: Glycoprotein-stabilised Adobe Bricks for Enhanced Compressive Strength Inspired by Termites Mounds

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Abstract

Earth is a green building material with very low embodied energy and almost zero greenhouse gas emissions. However, it lacks strength and durability when used without stabilisation. By incorporating responsibly sourced stabilisers, it is possible to enhance the strength of this material. In this study, adobe bricks stabilised using bio-inspired stabilisers were investigated. This research was inspired by the high strength and durability of termite mounds, exploring the stabiliser behind such robust natural constructions. Termites build their mounds by incorporating a glycoprotein from their saliva to cement the sub-soil particles together. Biomimicry has been employed to investigate the potential use of the termites' construction stabiliser in adobe bricks. Three glycoproteins from meat and fish industry waste were identified as potential stabilisers in adobe bricks. Bovine serum albumin (BSA) from cows' blood, mucin from the porcine stomach, and gelatine from cold-water fish skin were the three stabilisers used in this study. Two soils were used to prepare adobe bricks for testing. The primary soil used in this study was from Devon in the United Kingdom (UK). The second soil was obtained from the Mayo neighbourhood in Khartoum, Sudan, and used only 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. The main conclusion of this study is that BSA has proven its potential to be used as a stabiliser in earth construction. Using 0.5% BSA resulted in a 17% and 41% increase in the unconfined compressive strength of the British and Sudanese adobe bricks, respectively. In addition, using 5% BSA resulted in a 203% and 97% increase in the unconfined compressive strength of the British and Sudanese adobe bricks, respectively. The compressive strength of BSA-stabilised adobe bricks is higher than that of earth bricks stabilised using 5% cement and 5% lime reported in the literature. Furthermore, the compressive strength of the 5% BSA-stabilised adobe bricks is higher than the lower recommended compressive strength for the hollow concrete blocks in the UK. Hence, these BSA-stabilised adobe bricks could substitute hollow concrete blocks to construct internal walls. The other stabilisers tested did not significantly improve the unconfined compressive strength of the adobe bricks. The study underscores the value of biomimicry and proposes glycoproteins as viable natural stabilisers in earth construction, with further recommendations for in-depth research to optimise application methods and formulations.

Keywords: Adobe bricks, Biomimicry, Bovine serum albumin, Clay minerals, Compressive strength, Glycoproteins, Sustainable construction, Termites' mounds, Waste management.

1. Introduction

The construction industry and building operations significantly contribute to global carbon dioxide (CO_2) emissions, global warming, and the overall climate change phenomenon [1, 2]. For instance, their contribution to global CO_2 emissions rose from 38% (13.1 gigatons of energy-related CO_2 emissions) in 2015 to 13.4 gigatons of CO_2 in 2019 [1]. This increase continued until the impact of the COVID-19 pandemic in 2020 [1]. The share of building materials and products manufacturing in the global CO_2 emissions in 2018 was 11% [3]. The production of concrete, steel, aluminium and bricks is responsible for most global building materials' CO_2 emissions [4]. Globally, an annual 1.5 billion manually moulded clay bricks are produced and fired in kilns using coal to fuel the firing process [5]. This amount of bricks contributes to 20% of the world's CO_2 emissions [5]. Most of these bricks (90%) are produced in China, India, Pakistan, Vietnam, and Bangladesh [5]. As a result, these manually operated production kilns contribute massively to global air pollution, CO_2 emissions, and climate change. By 2060, global material use will be doubled and a third of this rise will be attributed to materials related to the building and construction sector [6]. The recognition and understanding of the size of the problem with an immediate and fast reaction in the construction sector is inevitable. Using more sustainable building materials with low greenhouse gases emissions in the construction sector is crucial.

In 2019, the UK became the first major economy to commit and set a legally binding target for Net Zero Carbon (NZC) emissions by 2050. In addition, in 2020, the UK Green Building Council (UKGBC) announced the launch of the Net Zero Whole Life Carbon Roadmap project for the UK's built environment. This roadmap aims to establish a shared vision and agreed-upon actions to achieve net-zero carbon emissions in the construction industry and its related fields in the UK, aligning with the 2050 Carbon Neutral plan [7]. In general, this roadmap targets the reduction of the carbon intensity of building materials, improvement of material efficiency, promotion of the reuse and circularity of building materials, reconsideration of building material choices such as transitioning to lower-emission materials, and reduction of demand for new buildings and materials (achieved through the change of use of existing non-domestic buildings) among other targets and policies [8].

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Generally, the UK's building and construction industry is responsible for 25% of the total greenhouse gas emissions [8]. The predominant architectural feature in both rural and urban areas of the UK is the widespread use of fired clay bricks [9]. The vast majority of the old buildings in the UK were constructed with fired clay bricks, which are still in high demand [9]. In 2007, the total production of fired clay bricks in the UK reached 6 million tonnes, equivalent to 2.5 billion bricks [10]. The UK requires between 225,000 to 275,000 or more homes per year to accommodate its population growth [11]. Fired clay bricks are extensively used in the construction of various structures in the UK, including residential, commercial, educational, healthcare, retail, and industrial buildings [12]. Remarkably, 75% of housing projects in the UK involve the use of bricks [13]. Fired clay bricks are renowned for their high-quality performance as a building material, often lasting for hundreds of years with minimal maintenance work [13]. However, these desirable qualities are achieved through the drying and firing of kilns at very high temperatures ranging from 900 °C to 1250 °C [14]. The firing and drying processes of clay bricks result in the direct emission of numerous greenhouse gases. For instance, the fired clay bricks industry emits one million tonnes of CO_2 annually [10]. Furthermore, 19% of the total CO_2 emitted by electricity consumption in the UK each year (166,000 tonnes of CO_2) is attributed to the fired clay bricks industry [10]. On the other hand, fuel consumption in the fired clay bricks industry accounts for 82% of the CO_2 emissions [10].

In developing countries, such as Sudan, earth (mud) construction techniques are popular and widely used in both urban and rural areas [15]. Earth remains a primary and popular building material in Sudan [16], constituting approximately 80% and 90% of construction in urban and rural areas, respectively [15]. Mud is preferred due to the high cost of alternative building materials. Local options are limited to a minimal list, including red brick, mud, cement blocks, stone blocks, corrugated iron sheets, and cement. In Sudan, cob and adobe are the most popular earth-construction techniques for walls [15]. Unstabilised adobe bricks are commonly used in wall construction. Houses constructed with unstabilised adobe bricks require regular annual maintenance before the rainy season [15]. However, without annual maintenance, the lifespan of these buildings is limited to 10 to 15 years [17, 18]. Moreover, infrequent maintenance exposes inhabitants to the risk of injury or loss of life due to partial or complete collapse. Unfortunately, the high cost of maintenance, when compared to individuals' incomes, leaves most earthen houses in a critical state.

Earth is considered the first available choice for building materials for humans and it is usage dates back to the existence of humans on planet Earth [19-21]. Today, roughly one-third of the world's population lives in houses made either totally or partially from mud [22, 23], with 50% of this population residing in rural and urban areas in developing countries [19]. However, in developed countries, the story of earthen heritage is different. For instance, in the UK, earth construction techniques ceased with the Industrial Revolution about 250 and 100 years ago [24]. After the Industrial Revolution, new building materials such as concrete, steel and red brick dominated the market. People favoured these new construction methods and materials over the traditional earth construction techniques, mainly due to the high-quality performance of the new materials. Consequently, many earth buildings were abandoned and neglected, left without maintenance and exposed to the severe damp weather of the UK [24]. Only in the past 40 years in the UK have people started to recognise the importance and value of earthen buildings. As a result, more earthen buildings have been acknowledged as heritage that should be preserved and conserved [24].

Therefore, one way to decrease carbon dioxide emissions related to the firing of clay brick, a significant contributor to the UK's CO_2 emissions, is to return to the roots of the raw material (mud) and revive the traditional method of using it. This involves reintroducing air-dried earth bricks and other earth techniques as construction materials. On the other hand, in developing countries such as Sudan, enhancing the quality of earth-building materials and techniques is crucial, as it would play a vital role in the sustainable development of the construction industry. Overall, mud could be one of the elements contributing to the delivery of sustainable housing in both developed and developing countries. Therefore, introducing an environmentally friendly stabilising process to improve the quality of mud as a building material is unavoidable.

1.1. Earth as a building material

Earth, as a building material, offers numerous advantages over industrial and conventional building materials [15, 23, 25-28], including the following:

- Soil is abundant, accessible, sustainable, and reusable [29] building material.
- Soil is a low-energy green building material compared to red bricks and concrete blocks [29-31].
- Soil requires basic equipment during construction, making it well-suited for DIY construction.
- Soil is suitable as a construction material for building various elements like walls, roofs, and floors.
- Soil is fire-resistant and cleans indoor air by absorbing pollutants [23].
- Soil has high thermal capacity, maintaining and balancing thermal performance [31].

Despite the mentioned advantages, earth has three main disadvantages when compared with industrially available building materials in today's market, as follows [23]:

- The quality of earth as a building material cannot be controlled or standardised [30], unlike many industrialised building materials such as concrete. Different soils lead to different earth compositions and potentially varying end-product quality.
- As a building material, earth shrinks during the drying process, producing cracks [28] that affect the material's overall strength.
- Earth does not resist water, so protecting its surfaces against rain is essential.

The mentioned drawbacks highlight earth's limited durability as a building material in its natural state [31, 32]. This lack of durability is its main drawback. To address this, stabilisation techniques were introduced [33, 34], with historical roots dating back to ancient Greece [35]. Scientific stabilisation, as known today, began in the 1920s [15]. It involves modifying the properties of the soil-water-air system [19], bonding soil particles to increase strength and stiffness, enhance durability, improve workability, and limit water absorption [32, 36]. Over 130 materials have been tested as stabilisers (Lal 1995 in [37]), including widely used ones like cement, lime, gypsum, straw, and animal dung. Cement improves durability but is expensive and environmentally harmful, contributing significantly to the global CO_2 emissions [15, 33]. Cheaper, natural and sustainable stabilisers like straw and animal dung result in a product that lacks durability and require maintenance [15].

It is worth mentioning that certain types of animal products have been extracted and utilised in earth construction. Historically, these products were primarily employed as stabilisers in rendering walls and were seldom used to stabilise wall bricks/blocks [19]. Animal glues, derived from horns, bones, hooves, and hides, served as the source for the stabilisers used in rendering earth walls [19]. These animal glues are collagen glycoproteins, commonly known as gelatine. Hence, the use of gelatine as a stabiliser in earth construction is not a new concept.

1.2. Termites and their mounds

Termites are among various organisms, such as ants and worms, that inhabit the soil [38]. There are approximately 3000 species of termites, varying in their living spaces and dietary habits [38-40]. Some dwell in wood, while others reside in earthen nests [38, 41]. Generally, termites are found in tropical and subtropical regions [41], and their presence depends largely on the local temperature and rainfall [38]. The group of termites living in earthen nests constructs magnificent pieces of architecture known as termite mounds, considered the tallest non-human structures on earth [42]. These mounds vary in shape and size among different species and locations, with heights reaching up to 9 meters and diameters of 20 to 30 meters at the base [38, 41]. Termites build durable and rigid structures [40, 43-45] that withstand decades of violent climatic conditions in rainforests of Africa and South America, sclerophyll forests, savannahs, and woodlands of Australia [38, 46], where the rainfall rate is around 1200 mm per year [46]. In constructing these mounds, termites use sub-soil collected from various depths [39, 40, 43, 44, 47-49] and bind the soil pellets together with their saliva [45, 48, 50-53]. Despite differences in soil [49, 53] and climate, termite earth nests endure for many years with consistent construction quality. The compressive strength and bending strength of termite mounds are in the range of 5.1 ± 0.3 and 1.3 MPa respectively, falling within the range required for adobe bricks [41]. Unstabilised adobe bricks typically have compressive strength ranging between 1-2 MPa [19, 54]. Termite mound soil exhibits higher compressive resistance compared to crude bricks from different soil types [41], and it rivals the strength of cement-stabilised bricks [41]. Due to its strength, termite mound material has been utilised as a surface for tennis courts in some African village schools [45]. Moreover, termite mound soil has been employed in Australia, Zimbabwe, Mozambique, and America for constructing sports courts, earth houses, floors, footpaths, stoves, plaster walls, traps, lining water tanks, and amending soil [43, 55].

1.3. Magical termites' stabiliser: The chemistry of the bio-adhesive

In 1972 a researcher and his colleagues from the Department of Chemistry at James Cook University of North Queensland in Australia investigated the soil mound of the Australian termite *Coptotermes Acinaciformis*. They observed that the exterior wall of this termite's mound was exceptionally hard and resistant to water compared to the surrounding soil. To understand the adhesive used by these termites during mound construction, they conducted experiments using soil from around the mound as a control sample for comparison. The research team discovered differences in composition between the mound soil and the control soil. Two components were present in the mound soil but absent in the control sample. The first component was a mixture of polysaccharides from the hemicellulose group, derived from the termites' faeces and representing their incompletely digested diet (plants). The second component, believed to be the adhesive used by termites to cement and glue soil particles together for mound construction, was identified as a glycoprotein. The researchers suggested that this glycoprotein might be the secret chemical behind the strength and erosion resistance of the exterior walls of the termite mounds, possibly secreted by the termites themselves [56].

1.4. Glycoprotein: Definition and interaction with clay minerals

''Glycoproteins can be simply defined as proteins which have carbohydrate covalently attached to their peptide portion''[57, 58]. They are abundant in animal tissues, plants, and microorganisms. In nature polysaccharides, glycoproteins and proteins are the three defined types of biological polymers used to form adhesive gels [59]. Clay minerals have the ability to adsorb organic polymers such as amino acids, proteins, and glycoproteins in natural environments [60, 61]. The adsorption and binding of these organic polymers have various applications, including enzyme immobilization, protein fractionation, adsorption of protein in the wine and poultry industry, genetic information storage, bio-sensing, bio-nanocomposites, bio-functional materials, soil chemistry, drug delivery, and the Earth's biochemical evolution and origin of life [60, 62-65]. It has been observed that positively and negatively charged proteins/glycoproteins aggregate at the edges of clay minerals [66]. The process of protein adsorption on clay minerals involves three steps: [67] initial adsorption at the edges, (2) subsequent intercalation, and (3) eventual adsorption of a weakly bound fraction onto the clay mineral-protein complex formed in the preceding steps [68].

Two main factors generally affect the adsorption process of these organic polymers by clay minerals. The first factor is the type of the clay minerals available for the adsorption of the organic polymers [60]. Clay properties such as surface area, cation exchange capacity, charge density and degree of swelling influence the amount of the organic polymers adsorbed [60]. For instance, the montmorillonite clay minerals (swelling clay minerals) adsorbs 2.0 ± 0.09 g/g of human serum albumin (a glycoprotein) compared to 0.8 ± 0.08 g/g by kaolinite clay minerals (non-swelling clay minerals) for the same glycoprotein [69].

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 adsorption sites on the clay minerals [60]. For example, the montmorillonite clay minerals (swelling clay minerals) adsorb 0.16g/g [70], and 2.0 ± 0.09g/g [69] of bovine serum albumin and human serum albumin respectively.

However, 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 [60, 65]. Eight important parameters affect the adsorption of glycoprotein by clay minerals, as outlined in Table 1:

Table 1: 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 swelling and non-swelling clay minerals in the soil	The molecular size of the protein
The adsorption sites on the clay minerals	Classification of the protein and conformational changes upon adsorption
The specific surface area of the clay minerals	The concentration of the protein
The charges on the clay minerals (pH related)	The charges on the protein (pH related)

1.4.1. Parameters affect the clay minerals to adsorb the glycoproteins

Understanding the quantity of swelling and non-swelling clay minerals in the soil is crucial. Swelling clay minerals, such as smectite and montmorillonite, exhibit swelling through hydration and shrinking through dehydration. This swelling leads the mineral to expand as a result of increasing the repulsive forces between its interlayers. In contrast, non-swelling clay minerals like kaolinite, chlorite, and illite undergo negligible expansion when in contact with water, maintaining constant spacing between their interlayers [71]. In addition, adsorption sites on clay minerals play a significant role in glycoprotein adsorption. Clay minerals differ in their adsorption sites for proteins. For example, non-swelling clay minerals have adsorption sites only on the external surface and edges. In contrast, proteins can be absorbed by the interlayers, external surfaces, and edges of swelling clay minerals, with smectite (swelling clay mineral) exhibiting higher adsorption capacity than kaolinite and illite (non-swelling clay minerals) [60]. Furthermore, particle size is crucial as it influences the surface area of clay minerals. Smaller particle sizes result in larger surface areas and corresponding surface forces [72]. Specific surface area, defined as the surface area per unit mass of soil [72], affects the amount of glycoprotein adsorbed by clay minerals [60]. For example, smectite has a high specific surface area (800 m^2/g) compared to kaolinite with a specific surface area ranging between 5 – 40 m^2/g [73].

1.4.2. The molecular size of the protein

The molecular size of proteins/glycoproteins directly relates to clay interlayer adsorption. If the size of a protein exceeds 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 adsorption primarily to the external surfaces and edges [60].

1.4.3. Classification of the protein and conformational changes upon adsorption

There are two types of proteins, hard proteins and soft proteins. Hard proteins, with high internal stability, are adsorbed without changing their structural conformation on solid surfaces [64, 74]. The amount of adsorbed hard protein on hydrophilic surfaces is usually small unless there is an electrostatic attraction [74]. Soft proteins, with low internal stability, change their conformation and structure upon adsorption to adapt to the surface [64, 74]. Soft proteins can even be adsorbed on electrostatically repelling surfaces [74].

1.4.4. The concentration of the protein

The adsorption of soft protein is governed, among other factors, by the protein concentration in the medium. The higher the protein concentration, the greater the protein adsorbed, which means the adsorption of the protein has a saturation curve. Lower protein concentrations cause minimal structural changes during adsorption, while higher concentrations induce conformational changes in two steps. The first step involves the rapid adsorption of the protein upon contact with the surface without changing its conformation. The second step is slower, during which the total amount of adsorbed protein on the surface increases as the protein undergoes conformational and structure changes to adapt to the surface [74]. Due to these conformational changes, protein adsorption becomes irreversible, even at room temperature [74]. On the other hand, even if the protein undergoes no structural changes during adsorption, the process could still be irreversible. In addition, in the case of higher protein concentrations, the protein tends to favour surface crystallisation. Consequently, the protein crystallised on the surface may result in a more closely packed arrangement than the randomly deposited one occurring at a low bulk concentration [74].

1.4.5. Surface charge of the clay minerals and the protein/ glycoprotein

The pH of the solution (the medium) where the clay minerals and the glycoprotein present is the most crucial external factor in the adsorption process. The pH impacts the surface charge of the clay minerals and the ionisation degree of the protein molecules [75]. Depending on the solution's pH, proteins can be negative, neutral, or positively charged. Below the protein's isoelectric point (pI), its net molecular charge is positive; at the pI, it's neutral, minimizing repulsive forces. Above the pI, it becomes negative [60]. Solution pH also affects clay mineral surface charges. When the pH of the solution is below that of the pI of the protein, clay has a positive charge; at the pI, it's neutral; above the pI, it's negative. This influences adsorption mechanisms. For instance, when pH is below the pI, both glycoprotein and clay have positive charges, facilitating the adsorption through cation exchange. Positive charges decrease with the increase of the pH of the solution until the pI of the protein is reached, minimizing electrostatic repulsion between the clay surface and the glycoprotein, enhancing adsorption. Maximum adsorption occurs at the protein's pI. Above the pI, both are negatively charged, increasing electrostatic repulsion, reducing adsorption [60]. pH thus critically influences glycoprotein-clay interactions, impacting adsorption levels.

1.5. Biomimicry approach

Biomimicry derived 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 serves as a model, mentor, and measure [76, 77]. Biomimicry takes and studies nature's models and then emulates or takes inspiration from these forms, processes, systems, and strategies to solve human problems sustainably [76, 77]. As a mentor by observing, learning, and valuing nature [76, 77]. On the other hand, biomimicry takes nature as a measure by uses an ecological standard to judge the sustainability of innovations. This approach acknowledges that after 3.8 billion years of evolution, nature has determined what works, what is appropriate, and what lasts [76, 77]. These ideas from nature are mimicked and implemented in many fields, such as engineering, architectural design, computer modelling and general design [42].

2. Aim of the study

The study presented in this paper aims to enhance the strength of adobe bricks by introducing bio-inspired stabilisers, such as typical glycoproteins and collagen glycoproteins. Despite the historical use of gelatine in earth construction, employing pure typical glycoproteins and collagen glycoproteins (gelatines) to produce stabilised adobe bricks and in earth construction, in general, represents a novel and innovative approach.

Three different glycoproteins, all by-products of the meat or fish industries with limited use in the food industry, were selected and used to stabilise adobe bricks. Biomimicry serves as an approach to study termite mounds and mimic the termite stabilisation process in stabilising adobe bricks. The bio-inspired stabilised adobe bricks underwent compressive strength testing, and the results were compared with literature findings.

3. Methodology and materials

3.1. Soil selection

For this study, two types of soil samples were selected and prepared, Figure 1. One of the soils was from Devon in the UK. The Devon soil was the primary soil used in this study due to its availability and low cost. Devon was chosen because it is the centre of earthen buildings in Southern England [78]. In addition, Devon contains more earth buildings than any other county in the UK [79], indicating the soil's suitability for earthen construction. Herein, the Devon soil is referred to as "British Soil (BS)".

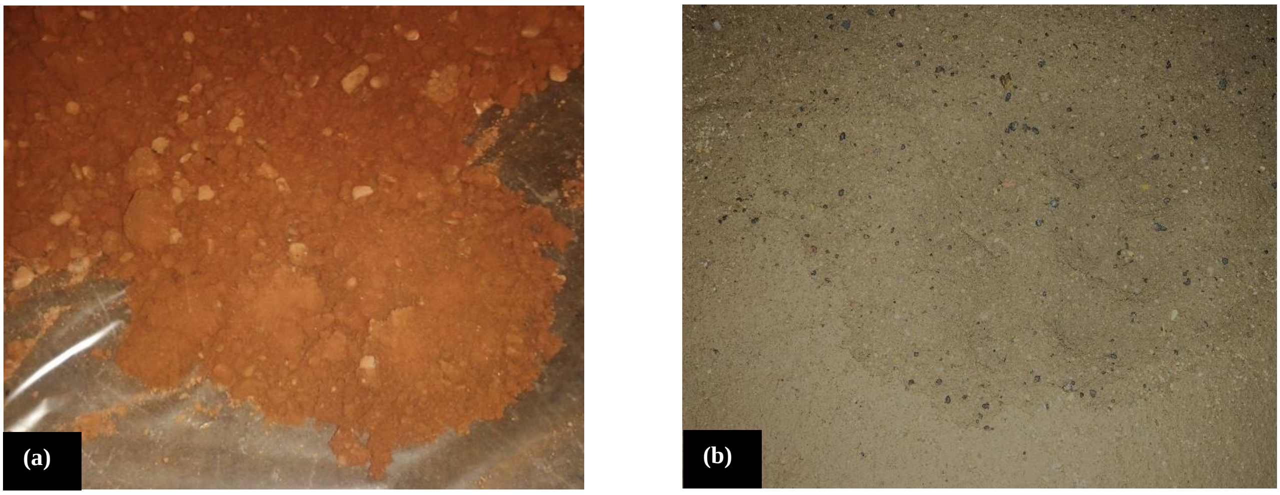


Figure 1: Raw soils, **(a)** BS from Devon, **(b)** SS from Khartoum

The second type of soil was from the Mayo neighbourhood, Khartoum, Sudan. This neighbourhood is one of Khartoum's largest and most highly populated squatter settlements. Moreover, most houses there were built using earth construction techniques, making the soil of this neighbourhood ideal for testing. This soil was used in key tests only. Herein, the Mayo neighbourhood soil is referred to as "Sudanese Soil (SS)".

3.2. Soil preparation

Achieving an initial moisture content is a crucial step in preparing earthen bricks. The initial moisture content helps control the amount of water needed to achieve a workable mixture when preparing the bricks. To achieve this, British Soil (BS) was air-dried at room temperature for two weeks. The drying process involved spreading the soil on the laboratory floor and turning it over every two days to ensure even drying. After two weeks, the soil was ground using a heavy metal roller to eliminate large clumps. The roller was applied multiple times until all large clumps were crushed. Subsequently, the soil was sieved using a 10 mm mesh to remove larger particles and other materials that might be present, such as tree leaves and roots. The soil was then transferred to an airtight plastic barrel to retain its moisture content. The Sudanese Soil (SS) was delivered in a plastic sack inside a small airtight plastic barrel. The soil was air-dried in Sudan before delivery and was kept in its original plastic barrel to preserve its moisture content. As the soil was finely grained, it did not undergo grinding processes and was only sieved using a 10 mm mesh immediately before the preparation of the bricks.

3.3. Soil classification tests

Several classification tests were conducted on the two soils to identify their properties and suitability for adobe brick production. Moisture content, liquid limit, plastic limit, particle density (specific gravity), particle size distribution (wet sieving and sedimentation), and pH were the tests used to classify the two soils in this study. These tests except the pH analysis were performed following the British Standard (BS 1377-2: 1990). The pH analysis was conducted in accordance with the analysis of agricultural materials - Ministry of Agriculture, Fisheries and Food in Great Britain [80].The results are presented in Table 2 & Figure 2.

Table 2: Properties of both soil samples

Soil type	**Natural moisture content (*w*) %**	**Liquid limit (*w*L) %**	**Plastic limit (*w*p) %**	**Plasticity index (*IP*) %**	**Particle density (*ps*) mg/m3**	**Particle size distribution (wet sieving and sedimentation)**				**pH**
						Clay **(<0.002mm)** (%)	Silt **(0.002–0.06 mm)** (%)	Sand **(0.06 –2 mm)** (%)	Gravel **(2–20 mm)** (%)	
BS	1.43	37.00	19.40	17.60	2.71	5.30	18.70	38.00	38.00	7.78
SS	2.53	48.00	21.70	26.30	2.69	12.50	52.50	29.50	5.50	8.50

The acceptable liquid limit for adobe brick production is between 31% and 50%, and the acceptable plasticity index is between 16% and 33% [19]. Based on the results of the liquid limit and the plasticity index in Table 2 above, both soils fall within the zone suitable for adobe brickmaking. The percentage of clay in both soils is above the minimum limit suitable for adobe brickmaking, which is 5% [19], Figure 2. Therefore, both soils are suitable for adobe brickmaking based on the clay percentage. The results of particle size distribution align with the findings on the plasticity of both soils. Moreover, the total percentage of the finer particles, clay and silt, which contribute to the soil's cohesiveness and plasticity, is higher in SS (65%) than in BS (24%). This higher percentage of silt and clay in SS explains the elevated results of the liquid and plastic limits and the plasticity index compared to BS. According to [81] in [82], the percentage of clay and silt in soil suitable for adobe brick production is between 20 and 50%. Therefore, the BS clay and silt percentage of 24% falls within this suitable range. However, the SS clay and silt percentage of 65% exceeds the maximum limit. The percentage of sand and gravel for adobe brick production is between 50 and 80% [83] in [54]. The BS sand and gravel percentage is 76%, within limits, but the SS sand and gravel percentage is below the minimum at only 35%. Consequently, the SS lacks coarse particles and has a higher proportion of fine particles. This abundance of fine particles would result in a less workable mixture, making it sticky when water is added to prepare the adobe bricks. Therefore, the SS was modified before being used for adobe brick making. The modification involved introducing coarse particles (natural sand) to reach roughly 40% by weight. This addition of 40% sand resulted in soil suitable for adobe brick making, with 39% clay and silt and 61% sand and gravel, Figure 2.

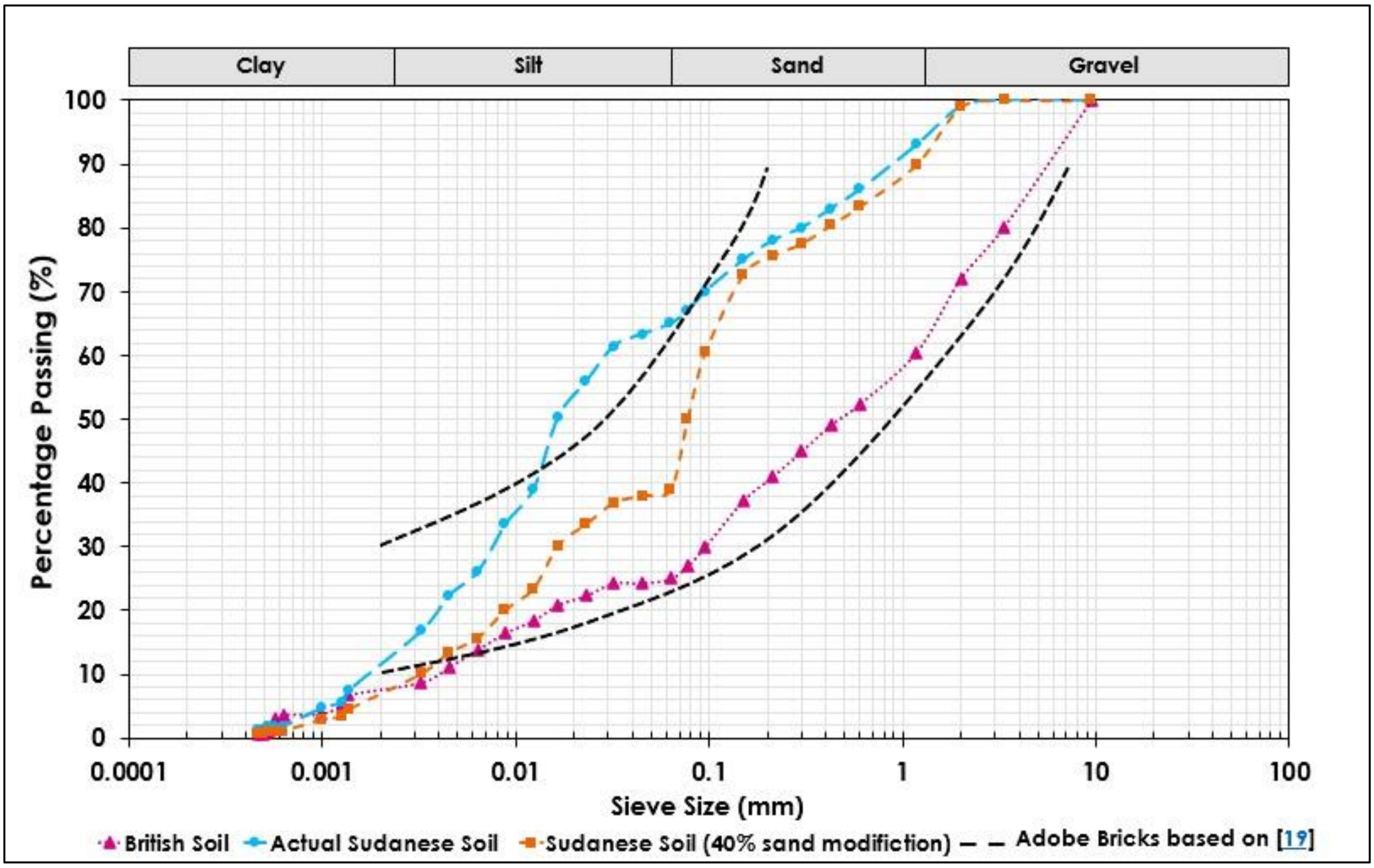


Figure 2: Particle size distribution using the wet sieving method and sedimentation test (Hydrometer method) for the British, actual Sudanese, and modified Sudanese soils, along with the recommended range for particle size distribution of soils for adobe bricks from [19], (clay <0.002 mm, silt 0.002–0.06 mm, sand 0.06–2 mm, fine gravel 2–6 mm, medium gravel 6-20 mm)

An X-ray diffraction (XRD) analysis was conducted for clay mineralogy, comprising two types: a clay mineral analysis and a whole rock analysis. The whole rock analysis reveals which minerals are present in the sample, but its ability to identify clay minerals is limited. Therefore, a clay mineral analysis is typically necessary for the clear identification of clay minerals. Both types of XRD analyses were performed for soil characterisation in this study.

For clay mineral analysis 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 the identification of clays using clay aggregate mounts can be found in [84]. To identify the clay mineral species in the samples, the oriented mounts were analysed using XRD after four preparation steps: (a) air dried, (b) after glycolation with ethylene glycol, (c) after heat treatment at 400ºC, and (d) after heat treatment at 550ºC, as shown in Figure 3 and Figure 4.

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 0.25º, and the measurements were carried out between 3 and 40º 2Theta, at a step size of 0.017º and a time per step of 100s.

For the whole rock analysis, 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 used for the clay mineral analysis. Measurements were carried out using the same settings except the measurement range was between 3 and 120º 2Theta. The measured XRD patterns were evaluated for phase identification with the Highscore Plus software (Panalytical) in combination with the PDF-4 database from the International Centre for Diffraction Data. The mineral proportions were calculated with the Rietveld refinement method [85], using the BGMN software [86]. 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 patterns were minimised in a least-squares minimisation calculation by adjusting structural parameters and the scale factor, as shown in Figure 5 and Table 3.

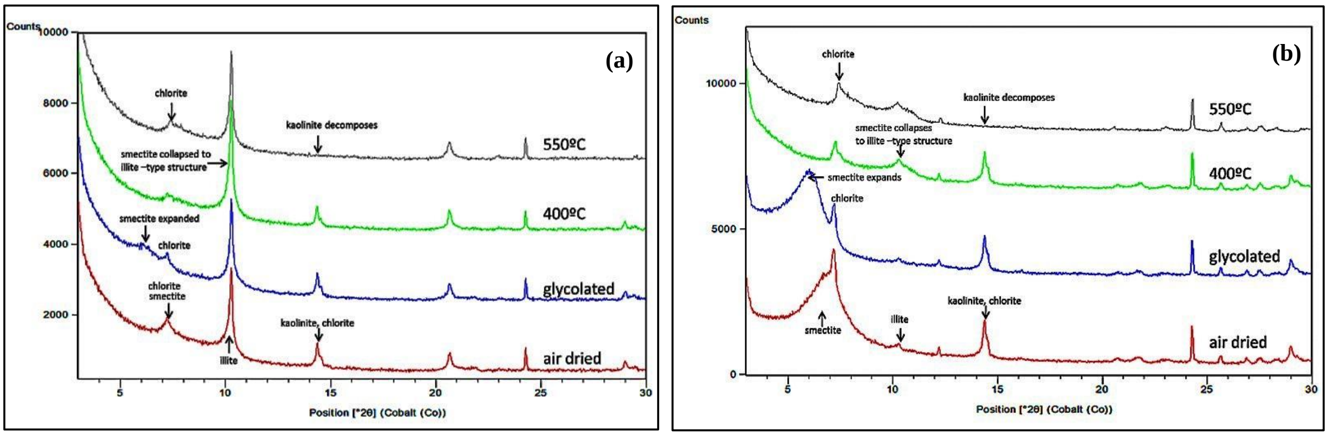
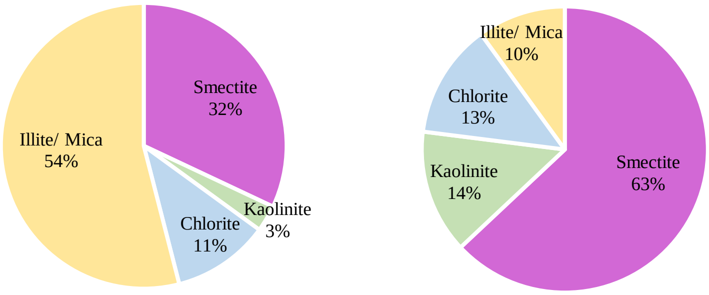


Figure 3: Clay mineral analysis, XRD pattern of clay size fraction of soils after various treatments **(a)** BS, **(b)** SS, *Indicative changes to clay minerals are shown*



(a) **(b)**

Figure 4: Proportions of the clay minerals in **(a)** BS, **(b)** SS

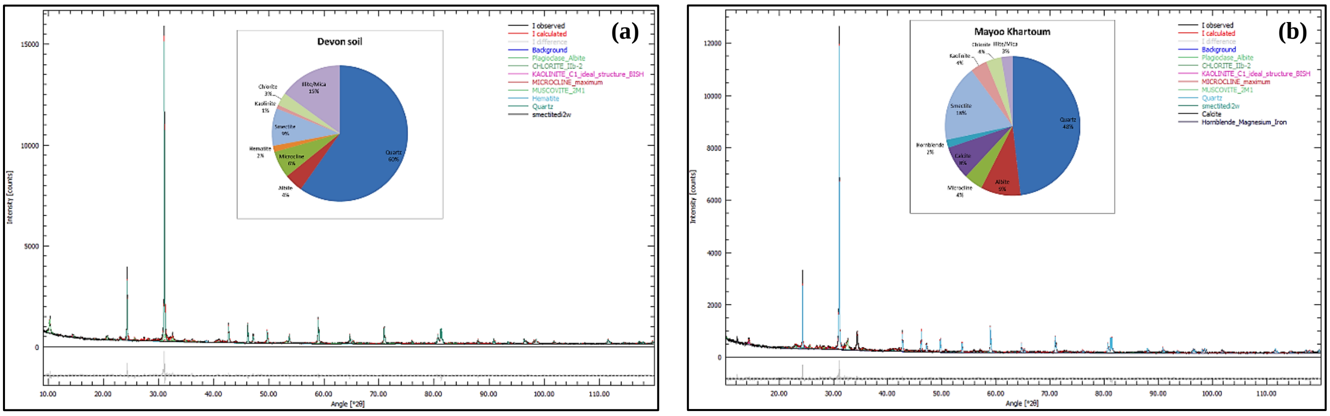


Figure 5: Phase quantification of soils, **(a)** BS, *measured and calculated patterns are in very good agreement (R_{wp}=7.63%, R_{exp}=5.98%, χ^2=1.28)*, **(b)** SS, *measured and calculated patterns show a very good agreement (R_{wp}=7.42%, R_{exp}=6.17%, χ^2=1.20)*

Table 3: Mineral quantification of the soils using the Rietveld Method (in weight%)

Minerals type	BS		SS	
	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*

Table 3 shows that the major phase in both soils is quartz and other non-clay minerals have proportions below 25 wt%. The clay minerals in both soils include smectite, illite, kaolinite, and chlorite. Smectite is the major clay mineral in SS (18 wt%), known for its ability to incorporate variable amounts of water and exhibit plastic properties as its structure expands with water addition. In contrast, BS has less smectite (9 wt%) but higher amounts of the less expandable illite (15 wt%). The red-brown colour of BS is attributed to small amounts of hematite (1.5 wt%).

From the comparison of the proportions of clay minerals in both soils in Figure 4 above, it is evident that the two soils differ in their clay mineralogy. The SS has double the quantity of the smectite clay mineral compared to BS. In addition, SS has lower quantities of less expandable clay minerals (illite, kaolinite, and chlorite). In contrast, BS has a high percentage of less expandable clay minerals. Therefore, the difference in clay mineralogy between these two soils will impact the adobe bricks made using them and how these soils will respond to the stabilisers. Furthermore, the difference in clay mineralogy between the two soils will affect the strength and durability of the adobe bricks produced.

3.4. Stabilisers selection

Three different stabilisers have been selected based on the criteria outlined in Figure 6 below.

A stabiliser is:

1. A ready made glycoprotein
2. Sourced from the Animal Kingdom
3. A by-product
4. Not widely used in food industry & readily available

Figure 6: selection criteria for the stabilisers

Table 4: Stabilisers type, source of origin & availability

No	Stabiliser	Type	Source of origin	Availability
1	Mucin	Glycoprotein Type I[1]: By-product of the meat industry	Porcine	Readily available in the market
2	Serum albumin	Glycoprotein Type I [1]: By-product of the meat industry	Bovine	Readily available in the market
3	Gelatine	Glycoprotein Type III[2]: By-product of the fish industry	Fish	Readily available in the market

[1]*Typical glycoproteins,* [2] *Collagens glycoproteins [87]*

These stabilisers were chosen to explore a range of biological adhesive gels (glycoproteins) found in nature, which could be sourced readily from the animal kingdom. It's important to note that all the stabilisers listed in Table 4 & Figure 7 are by-products of the meat or fish industries, with limited applications in human food processing.

(a) (b) (c)

Figure 7: (a) Porcine mucin, *Description: Very fine yellowish powder, Type: Type II, Composition: Bound sialic acid, ~1%, Storage temperature: 2-8°C* **(b)** Bovine Serum Albumin (BSA), *Description: Yellowish colour medium size flakes, Assay: ≥ 96% (agarose gel electrophoresis), Form: Lyophilised powder, Storage temperature: 2-8°C* **(c)** Gelatine from cold water fish skin, *Description: Light yellow colour fine flakes, Storage temperature: Room temperature.* All stabilisers were purchased from Sigma–Aldrich, United Kingdom

As termites use their saliva to cement soil particles during the mound construction [88], mucin is considered as the primary glycoprotein in their saliva. In general, mucin is the main constituent and the key component of mucus [89]. Therefore, the mucin was chosen to substitute the termites' saliva glycoprotein. The mucin was sourced from the porcine stomach (a by-product of the pig industry).

Bovine serum albumin (BSA), derived from cow's blood, is a by-product of the beef industry. Animal blood, which contains valuable proteins, is often discarded as waste, contributing to environmental pollution. However, disposing of animal blood in a well-organised and environmentally friendly manner is complex and costly. Extracting valuable proteins from the blood is essential to reduce pollution and generate more profit from blood waste [90, 91]. Concerns about using blood proteins in the food industry are considerable, stemming from religious, cultural, and ethical beliefs, as well as worries about contamination and toxicity [90]. Moreover, some consumers have experienced allergic reactions to food products containing BSA [91]. Due to these concerns, the utilisation of animal blood proteins in the food industry is limited [90].

Skin and bones are usually discarded as waste in the fish industry. However, [92] and [93] have suggested extracting gelatine from them, which would offer environmental benefits (waste management) as well as economic benefits. Originally intended for use in the food industry, recent studies have identified fish collagen and gelatine as potential allergens, regardless of the fish species [94]. Consequently, the use of fish collagen and gelatine in the food industry has been restricted. Gelatines from other animals, such as cows and pigs, were not selected due to their high demand in the food and various other industries.

3.5. Structure of the tests

Different concentrations of glycoproteins were tested in this study. The unconfined compressive strength results for these concentrations were compared with those obtained from an unstabilised sample (the control sample). Concentrations as low as 0.1 by weight % were tested. The lowest glycoprotein concentration used in this study was 0.1%, selected based on the findings of a research study published in 1972 [56]. This research paper is the only study that references the availability of glycoprotein in termite mounds and considers it to be the adhesive responsible for the strength and erosion resistance of their exterior walls. According to this research which was conducted on the mound of *Coptotermes Acinaciformis* termite in Australia, the glycoprotein concentration in 1 kg of mound soil was 0.1% (0.1% by weight of soil) [56]. The maximum glycoprotein concentration tested in this study (the cap) was 5%. This concentration of 5% was used as the maximum because it corresponds to the lowest effective concentration used for cement in adobe bricks stabilisation, as reported in [95]. The tested glycoprotein concentrations for both soils are presented in Table 5.

Table 5: Glycoproteins' concentrations tested for both soils

Test	Glycoprotein	Glycoprotein concentrations tested in BS (by weight %)	Glycoprotein concentrations tested in SS (by weight %)
Unconfined Compressive Strength	Porcine mucin	0.1%, 0.2%*	NA***
	Fish gelatine	0.1%, 0.2%, 0.3%, 0.4%, 0.5%**	NA***
	Bovine serum albumin (BSA)	0.1%, 0.2%, 0.3%, 0.4%, 0.5%, 1%, 3%, 5%	0.5%, 5%

***** *The tests in this study were divided into different phases. Phase (a) involved testing 0.1% glycoproteins, while phase (b) tested 0.2% glycoproteins. However, by the end of phase (b), the glycoprotein that resulted in the lowest unconfined compressive strength in phases (a) & (b) was eliminated and excluded from further investigations.* ****** *In phase (c), glycoprotein concentrations of 0.3%, 0.4%, and 0.5% by weight were tested. By the end of this phase, the glycoprotein that resulted in the highest unconfined compressive strength was identified for further investigations.* ******* *Due to the limited available quantities of SS, only the glycoprotein that resulted in a high unconfined compressive strength in the BS was tested.*

3.6. Termite mound biomimicking

3.6.1. Preliminary experiments

In this study, preliminary experiments were conducted to investigate the effect of moisture content during mixing on the strength and erosion properties of bricks. Determining the mixing moisture content is vital in preparing adobe bricks, as it affects workability, density, compressive strength, and erosion resistance. The goal was to determine the moisture content range that yields maximum compressive strength and minimum erosion depth. This identified range will be used to prepare the controlled bricks (unstabilised bricks). A key consideration in moulded adobe brick production is ensuring sufficient mixing moisture for easy mixing, moulding and, removal from the mould [78]. Correct moisture content results in minimal or no slump during production, ensuring the brick retains its proper shape, as slump can adversely affect the final shape of the brick.

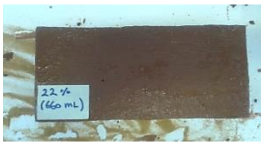
Despite the wide use of famous concrete workability tests such as the slump and flow tests [96] to determine the water content of adobe bricks in earth construction [97, 98], it's evident that concrete and earth possess distinct properties. Therefore, in this study, the author refrained from using concrete workability tests and adhered to fundamental earth construction principles to determine the optimum moisture content for adobe bricks. The optimum water content is that which facilitates easy mixing, moulding, and results in controlled brick shape [78].

Different bricks were made using varying moisture contents. These bricks were prepared solely with sieved soil and distilled water, moulded by hand without any compacting effort. Moisture content determination was conducted only for the unstabilised British adobe bricks. However, due to the limited quantity of SS, similar intensive tests for mixing moisture content were not feasible. The optimum moisture content for the unstabilised Sudanese adobe bricks was determined by using water above 21.7% (representing the plastic limit of the SS as shown in Table 2 in Section 3.3) during mixing and gradually increasing it until achieving easy mixing, moulding, and removal from the mould. The achieved mixing moisture content (26.5%) was then used to prepare all Sudanese unstabilised specimens.

For the BS, moisture content above the plastic limit (19.4% as shown in Table 2 in Section 3.3) was tested, Table 6. Using a 21% moisture content resulted in a manageable mixture during moulding, but the bricks sagged during mould removal. Increasing the water content to 22%, 23%, and 24% had a positive impact on mixing, moulding, and mould removal. The resulting bricks had straight edges and flat top surfaces. However, increasing the water content to 25% made the mixture too moist and sticky, leading to slumping and irregular edges after mould removal. Further tests were conducted with higher water contents of 30% and 33%, resulting in overly moist and slurry-like mixtures that were difficult to mould and resulted in distorted bricks without flat surfaces or straight edges.

These experiments clearly demonstrated a strong correlation between workability and moisture content. Workability decreases with either very low or very high moisture content. Excess moisture content reduces the stiffness of the soil and results in very weak adobe bricks [99]. It also increases shrinkage on the brick surface during the drying process [100]. While various sources suggest different optimal moisture content for adobe bricks, such as around 30% [78] and 16 to 20% [99], the tests conducted indicated that for this soil from Devon, the optimal moisture content falls within the range of 22% to 24%.

Table 6: The various mixing moisture contents tested during the study aimed to determine the optimal moisture content for producing the unstabilised British adobe bricks

Moisture content (%)	Density (kg/m^3)	The mixture	The adobe brick
21%	**2137**		
22%	**2101**		
23%	**2034**		
24%	**2029**		
25%	**1993**		
30%	**1813**		
33%	**1705**		

For each type of soil used in adobe brick preparation, there exists an optimal moisture content that yields maximum dry density and consequently maximum strength [101] in [102]. There is a significant correlation between the water content used during moulding and the final dry density. The range of workable moisture contents (22%, 23%, & 24%) mentioned above has been examined for its impact on the bricks' density, compressive strength, and erosion resistance, refer to Figure 8.

When water is added to the soil during mixing, it occupies and fills the intergranular voids within the soil [103]. During the subsequent drying process, this water evaporates from these intergranular voids. This evaporation process causes the bricks to shrink and increases the porosity of the soil [103]. Porosity, also known as voids ratio, refers to the volume of voids in the soil expressed as a percentage of the total volume [19]. This porosity exhibits a positive relationship with the moulding water content. Therefore, an increase in the moulding water content results in more shrinkage and porosity, leading to a lower dry density [103]. The inverse relationship between moisture content and dry density becomes apparent when comparing the dry densities across the range of potential moisture contents (22%, 23%, & 24%). Even a slight change in water content significantly impacts the density of the brick, as illustrated in Figure 8.

Compressive strength test is considered the most widely used and accepted method for assessing the strength and quality of wall units (bricks/blocks) [104-106]. The ease of applying the compressive strength test, especially when compared to other tests like resistance to abrasion and flexural tests, along with the potential improvement of other properties when higher compressive strength is achieved, are the factors contributing to the widespread acceptance of compressive strength as a reliable measure to determine the quality of bricks/blocks [107]. Compressive strength, however, is not considered a replacement for durability tests but can be viewed as a control measure for durability [31].

The graph in Figure 8 also shows that the maximum unconfined compressive strength was achieved when the moisture content was 23%, whereas the lowest compressive strength was obtained at 22% moisture content. In the preparation of the adobe bricks in these preliminary experiments, techniques known for increasing density, such as the use of a manual compressive machine and mechanical means (tampers), were not employed. Consequently, the densification required to increase compressive strength was not achieved in this test series. As a result, despite the high density of the bricks made with 22% moisture content compared to others (as shown in Figure 8), their compressive strength was the lowest. The likely reason for this low strength is that the mixture used for these bricks (22% water content) lacked sufficient water for the binder reaction to occur. The binder, in this case, was solely the natural clay minerals present. Sufficient water is necessary for the clay to bind the soil particles together effectively. Clay is commonly used as a stabiliser in earth construction [78], but for the binding reaction to occur in adobe techniques, ample water is essential; otherwise, the binder will not function, and strength will not improve. In other earth techniques relying on compaction and densification, the optimum moisture content is defined as the water content necessary to achieve a percentage of maximum compaction [108], with very low moisture content resulting in high compressive strength.

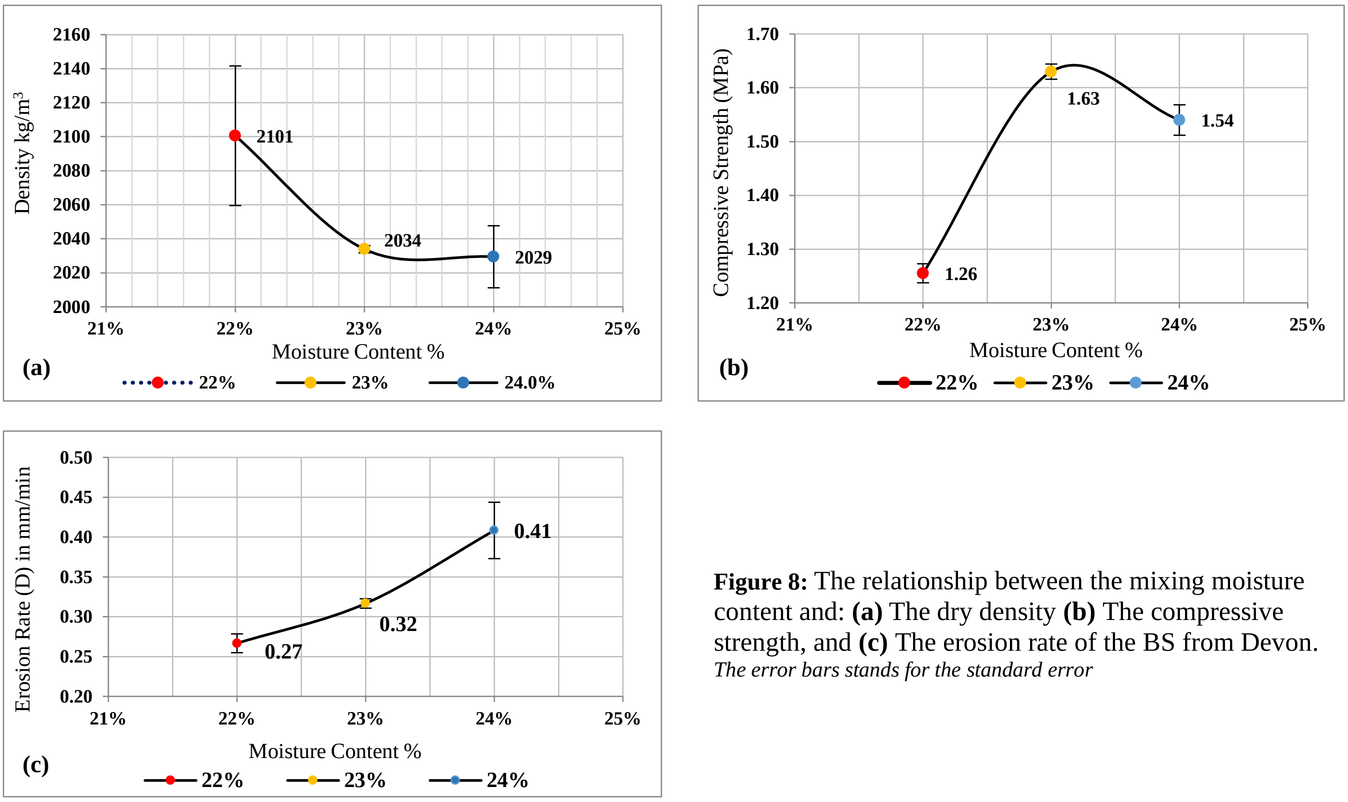


Figure 8: The relationship between the mixing moisture content and: **(a)** The dry density **(b)** The compressive strength, and **(c)** The erosion rate of the BS from Devon. *The error bars stands for the standard error*

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

In earth buildings, the primary cause of functional deterioration over time is physical durability, which results from wind-driven rain and leads to surface erosion of the material [31]. There are three general types of durability tests in earth construction: indirect, accelerated, and simulation tests [31]. In these preliminary experiments, the accelerated erosion test developed by the Commonwealth Experimental Building Station in Australia, commonly referred to as Bulletin 5 [31, 109], was used to determine the relationship between erosion rate and moisture content in this study. This test is also included in other earth building handbooks and codes [78, 110].

From the graph in Figure 8, 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 0.41 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 a decrease in the erosion resistance of the adobe bricks. The increase in water content fills the pores between the soil particles. However, upon the evaporation of this water, the remaining air pockets decrease surface aggregation, leaving 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 BS from Devon. This range of moisture content has resulted in the best workable mixture during the moulding process. Additionally, 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. However, for the stabilised adobe bricks, the mixing moisture content will be around this moisture content range, depending on the basic principle of easy mixing, moulding, and removing from the mould.

3.6.2. Material preparation and recipe making

Both soils (BS & SS) were sieved using a 10 mm mesh sieve. Room-temperature distilled water was employed in the sample preparation process. Unstabilised control samples were used for both soils (BS & SS), and their unconfined compressive strength was compared to that of the stabilised samples. For stabilised samples, glycoprotein concentrations of up to 1% were mixed at room temperature with distilled water using a manual egg whisk until a homogeneous liquid was obtained. However, for higher glycoprotein concentrations (3% & 5%), an electrical egg whisk was used to obtain the glycoprotein liquid. The quantities of glycoproteins, distilled water, and soils used to prepare one full-size adobe brick for both soils are detailed in Table 7.

Table 7: Unstabilised and glycoprotein stabilised adobe bricks mixing proportions used to prepare one full-size adobe brick for both soils

Glycoprotein percentage to the dry soil (%)	Type of glycoprotein	Quantity of glycoprotein (g)	Quantity of distilled water (mL)	Quantity of soil (g)
0% (BS)	N/A (Unstabilised)	0	708 (23.6%)	3000
0% (SS)	N/A (Unstabilised)	0	1463 (26.5 %)	5525
0.1% (BS)	BSA	3	732 (24.4%)	2997
	Fish gelatine	3	747 (24.9%)	2997
	Mucin	3	741 (24.7%)	2997
0.2% (BS)	BSA	6	750 (25%)	2994
	Fish gelatine	6	768 (25.6%)	2994
	Mucin	6	831 (27.7%)	2994
0.3% (BS)	BSA	9	825 (27.5%)	2991
	Fish gelatine	9	774 (25.8%)	2991
0.4% (BS)	BSA	12	765 (25.5%)	2988
	Fish gelatine	12	837 (27.9%)	2988
0.5% (BS)	BSA	15	750 (25%)	2985
	Fish gelatine	15	804 (26.8%)	2985
0.5% (SS)	BSA	28	1463 (26.5 %)	5497
1% (BS)	BSA	30	720 (24%)	2970
3% (BS)	BSA	90	699 (23.3%)	2910
5% (BS)	BS A	150	660 (22%)	2850
5% (SS)	BSA	138	830 (30%)	2765

3.6.3. Sample preparation

This study utilised a linear scale of 1:2 (1:8 volumetric scale) to prepare scaled bricks for testing their unconfined compressive strength, Figure 9. Scaled bricks were produced by cutting full-size bricks using a segmented or 'snap-off blade' utility knife. Six scaled bricks were used for each compressive strength test. Full-size bricks were prepared from a distinct mixture of the same composition to enable repeatability testing. Two different sizes of wooden moulds were employed for full-size brick preparation, representing the sizes of adobe bricks in the origin soils (United Kingdom and Sudan). For the BS, the mould was based on the dimensions of small-scale mass-produced earth bricks in the UK (21cm X 10.3cm X 6.5cm) [111], Figure 10. For the SS, the mould dimensions were selected to mirror traditional adobe bricks produced in Sudan (26.5cm X 17cm X 7cm) [18], Figure 10.

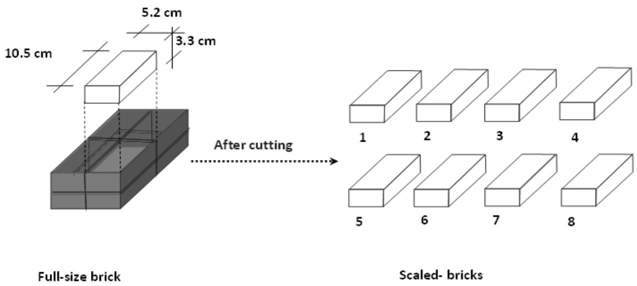


Figure 9: Cutting full-size brick to prepare scaled-bricks using the linear scale of 1:2 (1:8 volumetric scale)

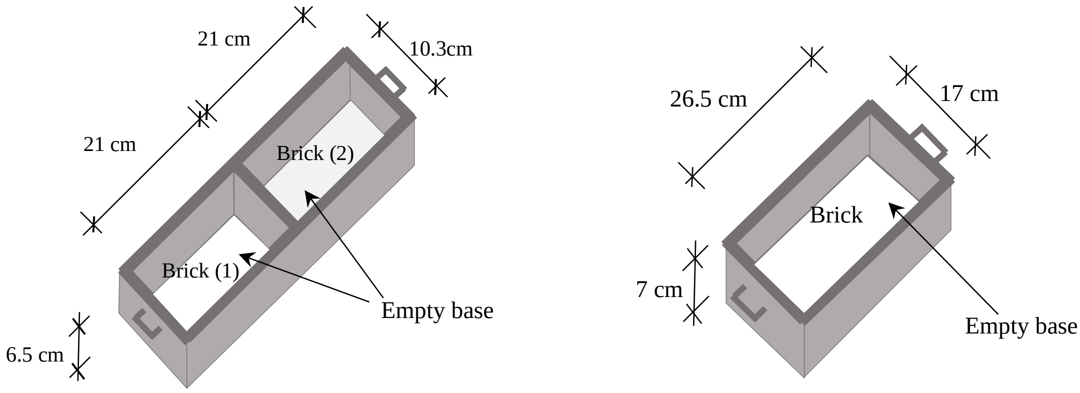


Figure 10: Wooden mould used to prepare: **(a)** Full-size British adobe bricks, **(b)** Full-size Sudanese adobe bricks

The unstabilised control samples were prepared using only soil and distilled water. Initially, the soil was sieved through a 10 mm mesh sieve, weighed, and then added to a measured quantity of distilled water, as shown in Table 7. Next, a homogeneous mixture suitable for moulding was obtained using an electric drill mixer (EZR22, twin-paddle mega mixer). Before moulding, the wooden mould was moistened with water and dusted with sand to facilitate easy removal at the end of the process. The geometry of a brick plays a crucial role in determining its compressive strength. The interaction between the brick's surface and the machine's steel plates creates confinement [106], which, in turn, delays the brick's failure during testing by restricting its lateral expansion, consequently boosting compressive strength [106]. As a result, and to control the geometry of the bricks during moulding, the following steps were crucial:

- *Moulding was done in layers (between three to four layers). This helped ensure smooth and levelled bottom and top surfaces of the brick. Additionally, all the brick's corners would be filled with mud, and air pockets are reduced.*
- *Sufficient pressure was applied to each layer along the surface, by hand and using a 5 kg metal weight. This step was important for controlling the density of the bricks under investigation. The decision was made to use this weight to mimic the hand pressure usually applied when moulding traditional adobe bricks. Furthermore, using this weight controlled the amount of compaction the adobe bricks experienced during production, ensuring the reproducibility of the bricks.*
- *Attention was given to the edges and the corners as they affect the overall shape of the final bricks.*
- *After moulding, excess mud was removed using a scraper.*
- *The top of the brick was smoothed using wet hands and then levelled, Figure 11. Levelling and smoothing the top of the brick would play an important role in reducing the confinement created by the interaction between the bricks' surface and the compression machine's steel plates.*
- *Then the mould was removed, and the top level of the brick was levelled again. This was important because when removing the mould sometimes the brick moved and minor bending happened. This is quite noticeable in the adobe bricks produced in the traditional way.*

The bricks were left at room temperature inside the laboratory for 16 hours (overnight) for initial drying. In the morning, the bricks were dry enough to be cut into small bricks using a segmented blade 'snap-off blade' utility knife, Figure 11. The same steps used to prepare the unstabilised control samples were employed to prepare the stabilised samples. However, the only difference was that the glycoprotein was added to the distilled water and whisked until a homogenous glycoprotein liquid, Figure 12, was obtained before adding the weighed soil.

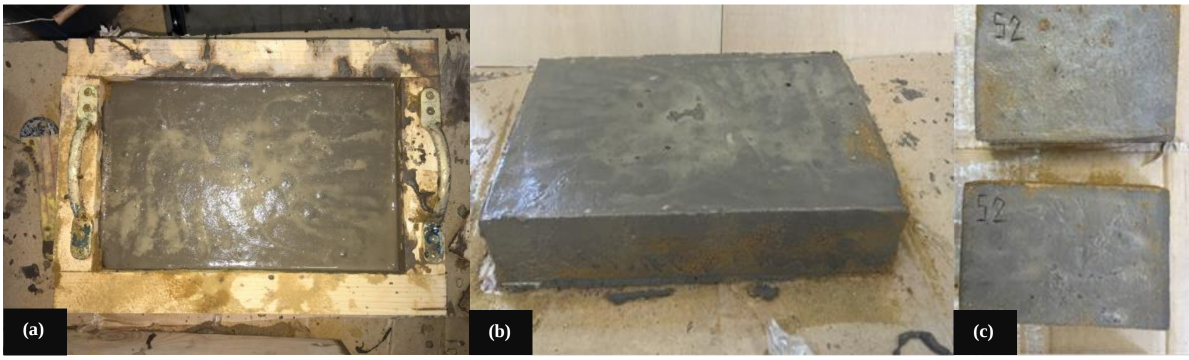


Figure 11: (a) The levelled smoothed stabilised Sudanese adobe brick after scraping the excess mud and before removing the wooden mould, **(b)** Full-size stabilised Sudanese brick before cutting into scaled-bricks, **(c)** Stabilised Sudanese scaled-bricks produced from cutting a full-size brick

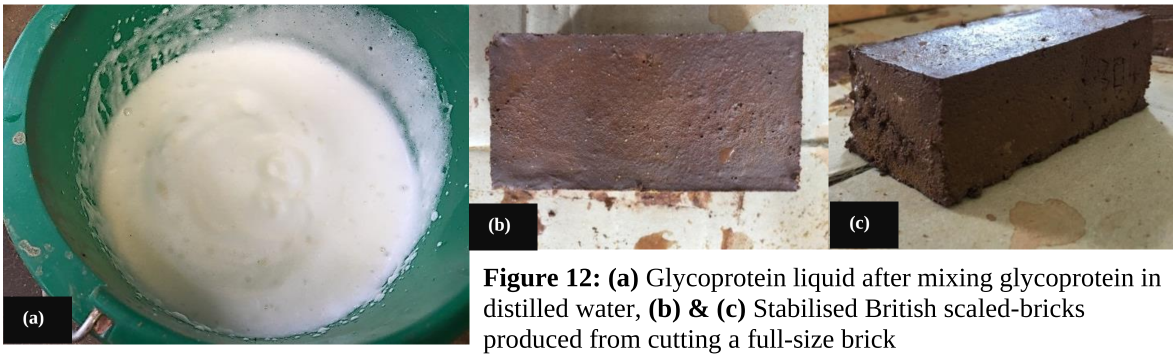


Figure 12: (a) Glycoprotein liquid after mixing glycoprotein in distilled water, **(b) & (c)** Stabilised British scaled-bricks produced from cutting a full-size brick

The scaled bricks were left at room temperature inside the laboratory for another 16 hours for initial drying. After the initial drying, the bricks were labelled and moved to dry for 28 days in a controlled environmental chamber. The drying settings were based on soils' origin which represents the temperature and humidity in summer in both countries. The difference in drying settings between the two soils was crucial to evaluate how they would react with the stabilisers under their origin environmental conditions. On the other hand, termites have succeeded in constructing very strong and durable mounds regardless of the soil type, environmental conditions, and location. Perhaps, in this study, by testing the stabilisers on different soils under different environmental conditions, a better understanding of these stabilisers and their effect on mechanical performance could be achieved. For the BS adobe bricks, the temperature was set between 17- 22 °C, and the humidity between 60% - 65%, representing the temperature and humidity of Reading town in the summer [112]. The SS adobe bricks drying temperature was set between 37.2 - 41.2 °C, and the humidity between 30% - 34%, based on the settings of temperature and humidity in the summer in Khartoum, Sudan [113]. The bricks were turned frequently during drying to ensure an even drying process.

3.7. Testing

3.7.1. Compressive strength test

Bricks/blocks serve as essential components in constructing walls, arches, vaults, and columns, primarily experiencing compressive stress and low tensile stress, often negligible [114]. The compressive strength test is a method used to evaluate a material's ability to withstand compressive loads, providing insights into its mechanical properties. Compressive strength is widely acknowledged as a crucial parameter for assessing material quality [104, 115]. In this study, compressive strength was employed to gauge the bricks' resistance to applied compression loads. The test was conducted in accordance with Bulletin 5 (Earth Wall Construction) and the Australian Earth Building Handbook [78, 109], using an Instron 4206 test machine. Continuous load was applied to the bricks without shock until failure at a rate of 2.5 mm/min [109]. Typically, the surfaces of the brick under testing must be flat and parallel to ensure an even distribution of the load [104]. The test continued until brick failure, with the failure load (maximum load the brick can withstand) recorded. The compressive strength was then calculated using the maximum applied loading and the cross-sectional area of the brick face under compression [78].

3.7.2. The geometrical correction of the compressive strength test

The geometry of a brick plays a crucial role in determining its compressive strength. The interaction between the brick's surface and the machine's steel plates creates confinement, which, in turn, delays the brick's failure during testing by restricting its lateral expansion, consequently boosting compressive strength [106]. This confinement primarily occurs on the top and bottom surfaces of the brick under testing. To mitigate the impact of this confinement, the investigated brick is typically placed between two plywood pieces (4 mm to 6 mm thick) [78], Figure 13. The influence of geometry on compressive strength is particularly significant for adobe bricks, given their manual production and inherent variations in geometry and dimensional stability [104].

To standardise compressive strength results and to minimise the geometry effect, a geometrical correction factor is applied, resulting in the unconfined compressive strength [104]. This correction factor accounts for the effect of the aspect ratio of the unit under testing, where the aspect ratio is defined as the ratio between a specimen's thickness and height (height/thickness) [106, 116]. In addition, these correction factors are the same factors applied to fired bricks, known as Krefeld's correction factors [104, 106], as shown in Table 8. These aspect correction factors were derived using linear interpolation and were applied to each specimen's confined compressive strength to convert it to unconfined compressive strength, Table 9.

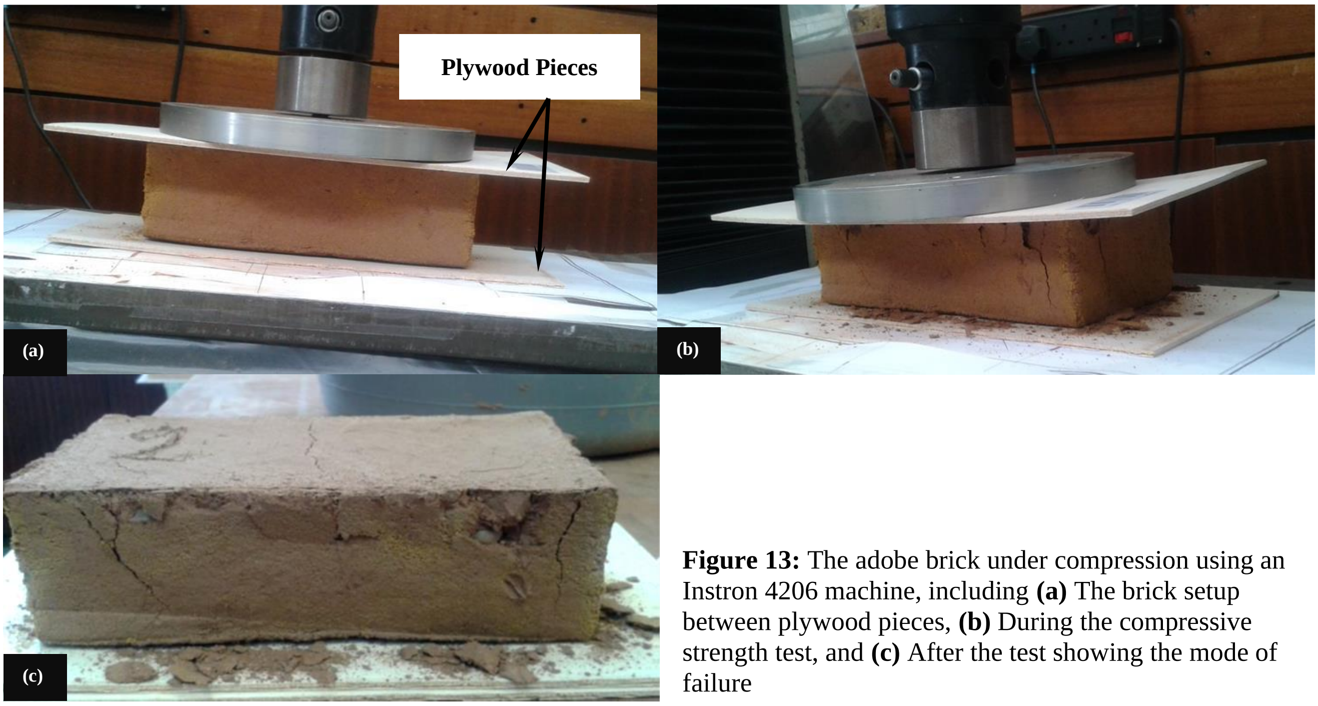


Figure 13: The adobe brick under compression using an Instron 4206 machine, including **(a)** The brick setup between plywood pieces, **(b)** During the compressive strength test, and **(c)** After the test showing the mode of failure

Table 8: Aspect ratio correction factors [109]

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

Table 9: An example of using Krefeld's geometrical correction factor to convert the confined compressive strength of adobe bricks into unconfined compressive strength*

Specimen	**Length (mm)**	**Width (mm)**	**Height (mm)**	**Net area of the specimen surface (mm^2)**	**Maximum load at failure (N)**	**Compressive strength (MPa)**	**Aspect ratio = height/ width**	**Correction factor (Ka)**	**Unconfined compressive strength (MPa) (After adjustment**	**Average (MPa)**
1	101	50	34	5050	15020	3.0	0.68	0.59	1.8	1.78
2	98	50	34	4900	14160	2.9	0.68	0.59	1.7	
3	105	51	30	5355	16710	3.1	0.59	0.56	1.8	
4	101	48	33	4848	15170	3.1	0.69	0.59	1.9	
5	103	49	32	5047	15820	3.1	0.65	0.58	1.8	
6	104	49	33	5096	15120	3.0	0.67	0.59	1.8	

** The data shown in this table are derived from this research study.*

4. Results and discussion

The results in this section will be discussed in light of the parameters influencing the ability of different clay minerals to adsorb glycoproteins, as outlined in Table 1. The hypothesis in this study was that *'the increase in unconfined compressive strength of adobe bricks is correlated with the clay minerals' ability to adsorb glycoproteins within the interlayers'*. It's important to note that glycoprotein adsorption by other sites on clay minerals may enhance various brick qualities beyond compressive strength. The extent of glycoprotein adsorption by clay minerals' interlayers is primarily influenced by the quantity of swelling clay minerals in the soil, the molecular size of the glycoprotein, and the glycoprotein's concentration.

4.1. Unconfined compressive strength of the BS: The results

5.

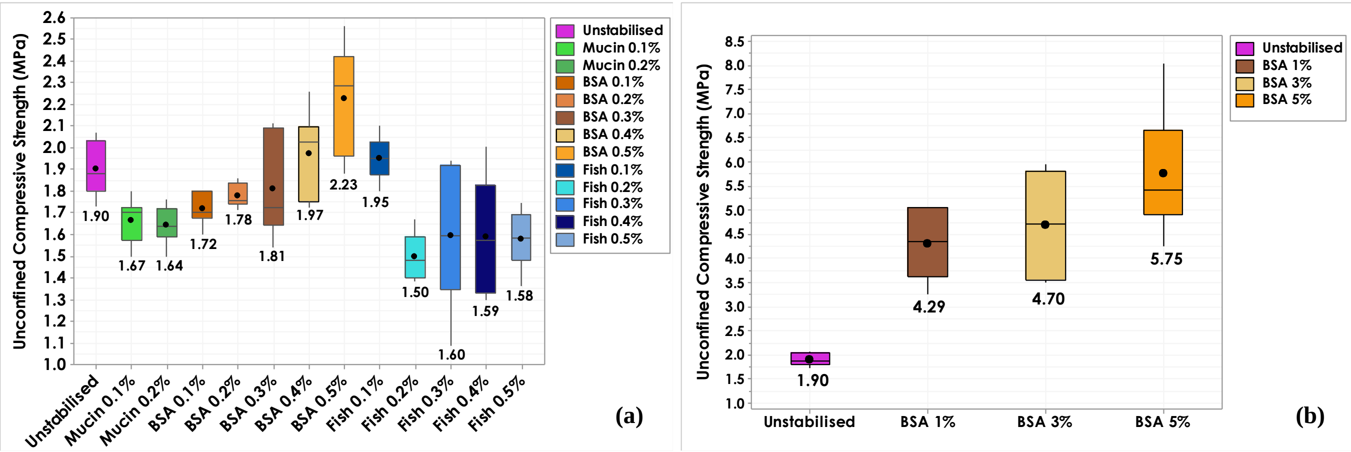


Figure 14: Unconfined compressive strength comparison between unstabilised British adobe bricks and **(a)** Lower concentrations (0.1%-0.5%) of different stabilisers used for stabilising British adobe bricks, **(b)** Higher concentrations (1%, 3%, & 5%) of BSA used for stabilising British adobe bricks. *The boxplots represent the inter-quartile range of the data obtained*

The results in Figure 14 show that adding 0.1% mucin led to a noteworthy 13.2% reduction in the mean unconfined compressive strength of British adobe bricks. Increasing the mucin concentration to 0.2% further decreased the unconfined compressive strength, resulting in a 13.7% reduction. On the other hand, the addition of 0.1%, 0.2%, & 0.3% BSA resulted in a 9.5%, 6.3%, and 4.7% reduction in the mean unconfined compressive strength of the British adobe bricks. In contrast, using BSA concentrations of 0.4% and 0.5% resulted in 3.7% and 17.4% increase in the mean unconfined compressive strength of the British adobe bricks respectively. Moreover, incorporating 0.1% cold-water fish skin gelatine led to a 3.2% increase in the average compressive strength of the British adobe bricks. Conversely, adding 0.2%, 0.3%, 0.4%, and 0.5% of cold-water fish skin gelatine resulted in reductions of 21.1%, 16.3%, 16.3%, and 16.8% in the mean compressive strength of the British adobe bricks, respectively. Furthermore, the addition of 1%, 3%, & 5% BSA resulted in a 125.8%, 147.4%, and 202.6% increase in the mean unconfined compressive strength of the British adobe bricks.

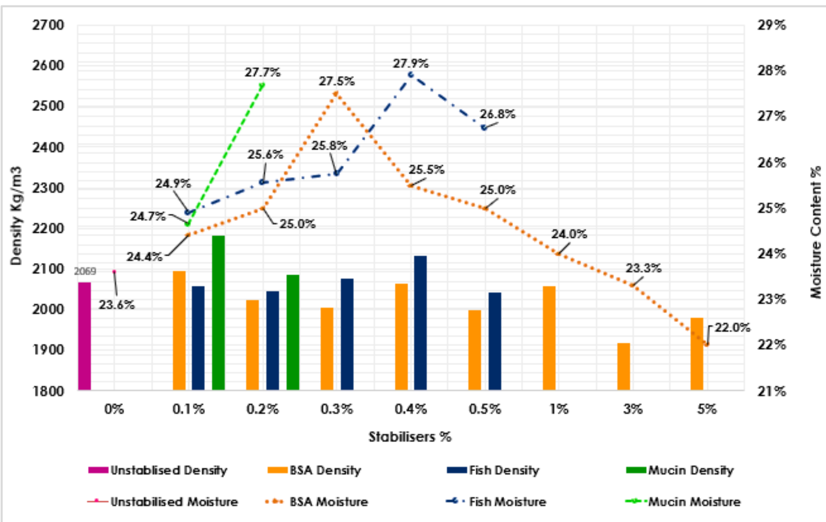


Figure 15: The relationship between the dry density and the moisture content for the unstabilised and all the stabilised British adobe bricks using the different percentages of the stabilisers

The results presented in Figure 15 demonstrate that the dry density of BSA-stabilised British adobe bricks varies between 2095 Kg/m³ and 1919 Kg/m³ across all used percentages (0.1% - 5%). Increasing the BSA concentration has led to a decrease in the dry density of the bricks. Moreover, higher BSA percentages have reduced the required moisture content to achieve a workable mixture. Particularly, the moisture content for higher BSA concentrations (3% and 5%) was lower than that of unstabilised British adobe bricks, with the least moisture content likely used when employing the highest BSA percentage (5%).
Furthermore, the dry density of cold-water fish skin gelatine-stabilised British adobe bricks ranged from 2131 Kg/m³ to 2042 Kg/m³ for the tested percentages (0.1% - 0.5%). However, increasing the cold-water fish skin gelatine percentage resulted in an increased moisture content requirement to achieve a workable mixture. Across all cold-water fish skin gelatine percentages used, the moisture content needed for workable mixtures exceeded that of unstabilised British adobe bricks.
Additionally, the dry density of porcine mucin-stabilised British adobe bricks ranged from 2086 Kg/m³ to 2182 Kg/m³ for the tested percentages (0.1% and 0.2%). Figure 15 indicates that increasing the porcine mucin percentage from 0.1% to 0.2% necessitated more moisture content to reach a workable mixture.
Comparing the moisture content requirements for workable mixtures between the three stabilisers revealed a sharp increase in moisture content with an increase in porcine mucin concentration from 0.1% to 0.2%. Both porcine mucin and cold-water fish skin gelatine showed a positive correlation between their percentages and the required moisture content for workable mixtures. Furthermore, BSA exhibited a positive correlation with increasing percentages up to 0.3%, beyond which a negative correlation was observed between stabiliser percentages and required moisture content for workable mixtures.

5.1. Unconfined compressive strength of the SS: The results

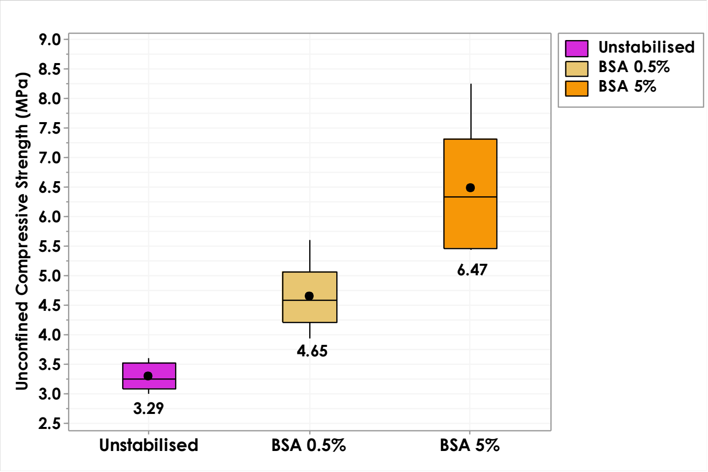


Figure 16: The unconfined compressive strength of the unstabilised and BSA stabilised Sudanese adobe bricks
The boxplots represent the inter-quartile range of the data obtained

From the results in Figure 16 above, adding 0.5% BSA to the Sudanese adobe bricks has resulted in a 41.3% increase in the mean unconfined compressive strength of the Sudanese adobe bricks. On the other hand, a further increase in the concentration of BSA (5%) has resulted in a 97% increase in the mean unconfined compressive strength of the Sudanese adobe bricks.

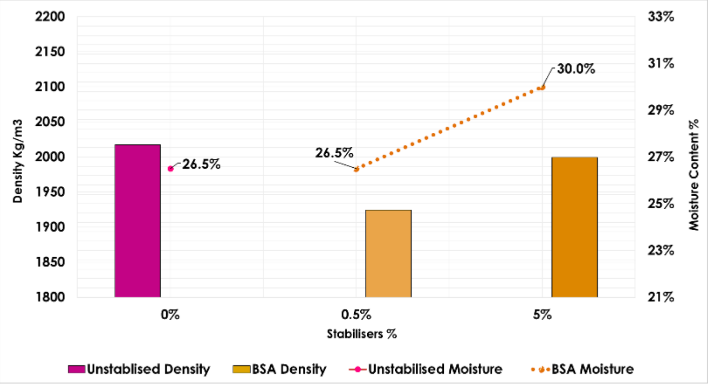


Figure 17: The relationship between the dry density and the moisture content for the unstabilised and the BSA-stabilised Sudanese adobe bricks

The results depicted in Figure 17 above reveal that the dry density of BSA-stabilised Sudanese adobe bricks ranges between 1999 Kg/m³ and 1924 Kg/m³ for the percentages used in this study (0.5% and 5%). In comparison, the density for both percentages was lower than that of unstabilised Sudanese adobe bricks (2018 Kg/m³). Furthermore, employing a low percentage of BSA (0.5%) resulted in using the same amount of water content needed to achieve a workable mixture for the unstabilised Sudanese adobe bricks. Conversely, a sharp increase in moisture content was observed when the BSA concentration was increased to 5%.

5.2. Discussion of the results

By comparing the compressive strength of the British adobe bricks made using different concentrations of BSA (0.1%, 0.2%, 0.3%, 0.4%, 0.5%, 1%, 3%, & 5%) to each other, it became clear that the increase in compressive strength was positively correlated with the increase in the concentration of BSA. The availability of more BSA resulted in more of it being adsorbed by the surfaces, edges of the clay minerals, and, in particular, by the interlayers of the swelling clay minerals. It was hypothesised that the conformational changes in BSA upon adsorption by the interlayers of the swelling clay minerals could be the reason behind the increase in compressive strength exhibited by the adobe bricks due to the increase in BSA concentration. Due to the adsorption of BSA by the interlayers of the swelling minerals, it undergoes structural changes, resulting in an irreversible adsorption process. Thus, the characteristics of the swelling clay minerals are altered, increasing the adobe bricks' structural integrity, whereby BSA enhances the cohesiveness of the British adobe bricks. Table 11 and Figure 18 below provide a detailed discussion of the unconfined compressive strength results of BSA-stabilised British adobe bricks, the mucin stabilised British adobe bricks, and the BSA-stabilised Sudanese adobe bricks.

Furthermore, in this study, utilising various concentrations of cold-water fish skin gelatine to stabilise the British adobe bricks reduced the compressive strength of the bricks, except for the lowest concentration (0.1%), which led to an increase in the compressive strength. However, the Dunnett multiple comparison analysis in Table 10 indicates that the results of 0.1% cold-water fish skin gelatine were not statistically significant compared to the unstabilised British adobe bricks. Hence, this result will not be included in this discussion.

Table 10: Dunnett multiple comparisons, comparing the different stabilised British adobe bricks' unconfined compressive strengths to the mean of the unstabilised British adobe brick used as the control means. The test was conducted with a 95% confident level. Means not labelled with the letter A are significantly different from the control level mean

Factor	N	Mean	Grouping
Unstabilised (control)	6	1.9000	A
Bovine 0.5%	6	2.2280	
Bovine 0.4%	6	1.9733	A
Fish 0.1%	6	1.9500	A
Bovine 0.3%	6	1.8117	A
Bovine 0.2%	6	1.7767	A
Bovine 0.1%	6	1.7167	A
Mucin 0.1%	6	1.6667	A
Mucin 0.2%	6	1.6433	A
Fish 0.3%	6	1.5950	
Fish 0.4%	6	1.5930	
Fish 0.5%	6	1.5783	
Fish 0.2%	6	1.4967	

The gelatine extracted from cold-water fish skin has a molecular weight of approximately 60 kDa [117]. In addition, this type of gelatine exhibits a very low gelling temperature (4 – 8 ºC) and melting temperature (14 – 16 ºC) [118]. Generally, the gelling process is influenced by the quantity of amino acids present in the gelatine structure. Cold-water fish skin gelatine is considered a poor gelling agent due to its lower amino acid content compared to mammalian and warm-water fish gelatine [118]. The reduction in amino acids affects the formation of the gelling network [119], resulting in a decrease in the gelatine's gelling and melting temperatures. Consequently, for the cold-water fish skin gelatine in the bricks to undergo gelling and hardening, the drying temperature should be maintained between 4 - 8° C. Furthermore, to sustain this gelling effect, the temperature should not exceed 14 °C, as temperatures beyond this range, in the presence of water, would cause the gel to revert to a liquid state.
The formation of the gelling network occurs when the gelatine reaches an equilibrium state, characterised by a three-dimensional structure. However, the cooling process should be extended to achieve a strong gelling network, as rapid cooling results in a very poor gelling network [120]. Furthermore, the drying process impacts the available water for continued gelling. The formation and stabilisation of the three-dimensional structure of the gelling network in a high-solid system are only achieved in the presence of sufficient water. The drying temperature and other system components, such as soil particles, can influence gelling formation [120]. Therefore, higher concentrations of cold-water fish skin gelatine are essential for forming a continuous network along with a slow cooling process [121]. The gelatine concentration significantly affects the gelling temperature of cold-water fish skin

gelatines, while it has a minimal effect on the melting temperature [121]. Increasing the concentration shortens the distance between gelatine molecules in the system, forming junction zones and the gel network [121].

One of the oldest characteristics of gelatine, 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 ensure the binding of its particles to each other, gelatine concentration is considered key. Using a high gelatine concentration results in the build-up of adhesion forces, forming a gel upon cooling [120]. Permanent gels could be formed by further temperature reduction, exhibiting viscoelastic behaviour and giving the system the characteristics of a solid material [120].

To discuss the results of the fish gelatine British stabilised adobe bricks, it is essential to highlight the mixing and drying environments of these bricks. Section 3.6.3 emphasises that these bricks were made in a 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 was maintained between 60% - 65% inside the drying chamber. Considering the drying temperature settings that were higher than the gelling temperature for cold-water fish gelatine (4 -8 °C), it can be confirmed that the gelatine from cold-water fish skin would remain liquid in the presence of water at room temperature. In addition, during the drying process and the evaporation of water, the gelatine might return to its original powder state. Consequently, the cold-water fish skin gelatine would never engage in any adhesion/cohesion activities in the soil. Therefore, an assumption has been made based on the inability of cold-water fish gelatine to form a gel network to glue the soil particles together. The assumption is that the availability of gelatine in the adobe bricks' soil matrix will break the binding forces between the clay minerals and other soil particles, affecting the compressive strength of the British adobe bricks.

5.3. BSA-stabilised adobe bricks VS other construction materials

For a 5% concentration of BSA, the compressive strength of the adobe bricks in this study ranged between 5.75 and 6.47 MPa. This surpassed the compressive strength of 5% cement-stabilised earth bricks (1.03 - 5.5 MPa) [36, 122-125]. Similarly, compared to 4% and 5% lime-stabilised earth bricks with compressive strength ranging from 0.62 to 5 MPa [124, 126, 127], the 5% BSA-stabilised adobe bricks showed superior performance.

When comparing the compressive strength of the 5% BSA-stabilised adobe bricks (5.75 - 6.47 MPa) to London Stock bricks (fired clay bricks) with strengths ranging from 5 to 20 MPa [128], it falls within the lower band of the recommended compressive strength for this type of fired clay bricks. However, the compressive strength of the 5% BSA-stabilised adobe bricks surpasses the lower recommended compressive strength for hollow concrete blocks (3.6 - 22.5 MPa) [129]. Considering that concrete blocks are commonly used in the construction of internal walls in the UK [9], these adobe bio-inspired bricks could potentially find a substantial market to replace conventional concrete blocks in the future.

Table 11: Discussion of the parameters affecting the adsorption of different glycoproteins by the BS & SS

Type of the Bricks	Parameters affecting the adsorption						Remarks
	The molecular size of the glycoprotein	Quantity of swelling & non-swelling clay minerals	Adsorption sites on the clay minerals	The specific surface area of the clay minerals	The concentration of the protein	Classification of the protein & conformational changes upon adsorption	
1. BSA-stabilised British adobe bricks	• The molecular size of the glycoprotein is considered one of the crucial factors influencing the adsorption of the glycoprotein into the interlayers of swelling clay minerals [60]. • BSA is considered a large globular protein [130] and has been extensively studied over the years [131]. • It is also classified as a soft protein with a molecular size of 68 kDa [60]. • Based on [132] investigations, the molecular size of BSA is smaller than the average pore diameter of the smectite clay mineral. • The Stokes Radius (*Rs*)* for BSA is 3.6 nm [133], and the average interlayer spacing of hydrated smectite clay minerals ranges between 4 nm to 10 nm [68, 134]. • Thus, BSA could be adsorbed by the interlayers of the mineral.	• The BS contains 32% of swelling (smectite) clay minerals, whereas non-swelling (illite, chlorite, and kaolinite) clay minerals make up 68%. • The smectite plays a vital role in the adsorption of glycoprotein, impacting the compressive strength when its interlayers can adsorb it.	• In lower concentrations (0.1%, 0.2%, & 0.3%) of BSA, most adsorption will occur through the external surfaces and edges of both clay minerals (the swelling and the non-swelling). • In higher concentrations of BSA (0.4%, 0.5%, 1%, 3%, & 5%), there is an increased adsorption on the surfaces and edges of the non-swelling clay minerals, as well as on the surfaces, edges, and interlayers of the swelling clay minerals.	• Despite the low percentage of smectite swelling clay minerals (32%) in the BS, these clay minerals exhibit a very high specific surface area (800 m^2/g) compared with the specific surface area of non-swelling clay minerals ranging between (illite: 10-100 m^2/g, chlorite: 10-55 m^2/g, kaolinite: 5-40 m^2/g) [72, 73, 135]. • This high specific surface area increases the external surface area available for BSA and mucin adsorption by the BS. • The SS has a high percentage of smectite swelling clay minerals (63%), and with its very high specific surface area, it increases the external surface area, edges, and interlayers available for adsorption of BSA by the SS. • The low percentage of non-swelling clay minerals (37%) in the SS, along with their low specific surface areas, contributes to the external surfaces and edges available for BSA adsorption by the SS. • In addition, smectite exhibits a higher adsorption capacity than illite, chlorite, and kaolinite (non-swelling clay minerals) [60], which also affects the adsorption of BSA by both the BS and SS.	• In natural soil, clay functions as a binding agent among various soil particles such as silt, sand, and gravel. Therefore, at low concentrations of BSA, a greater amount of moisture content is required to achieve a workable mixture. Conversely, at higher concentrations of BSA, less moisture content is needed since the binder is no longer solely the clay. • At low concentrations of BSA (0.1%, 0.2%, & 0.3%), its adsorption will predominantly occur on the surfaces and edges of both swelling and non-swelling clay minerals, with a minimal percentage adsorbed by the interlayers of the swelling clay minerals. • The low concentrations of BSA may impact the structural integrity of the soil by forming a barrier between the clay minerals themselves and between the clay minerals and other soil particles. • This barrier could explain the decrease in the compressive strength of the British adobe bricks when low concentrations of BSA are added as a stabiliser, compared to the unstabilised adobe bricks. • Increasing the concentration of BSA from 0.4% to 5% will increase the amount of BSA crystallised on the surface of the clay minerals in a denser and closely packed arrangement [74]. • This increase in concentration will also improve the cohesiveness and structural integrity of the soil. • BSA, acting as an additional cementing agent, will contribute to cementing the particles in the soil, working in conjunction with the natural clay.	• Due to the low concentrations (0.1%, 0.2%, & 0.3%), a smaller amount of BSA will undergo conformational changes when adsorbed by the clay minerals' surfaces, edges, and interlayers. • However, at higher concentrations of BSA (0.4%-5%), a higher amount of BSA is adsorbed, leading to conformational changes on the interlayers, surfaces, and edges of the swelling clay minerals, as well as on the surfaces and edges of the non-swelling clay minerals [74]. • Consequently, BSA undergoes conformational changes, and its adsorption becomes irreversible. • This process leads to the sealing and packing of clay minerals, enhancing the aggregation on the surface of the adobe bricks by improving cohesion, aggregation, and structural integrity of the soil.	• Higher concentrations of BSA (3% and 5%) resulted in a jelly-like dough that was elastic and sticky during moulding. • However, when smoothed and levelled with a touch of water, the final brick surface appeared shiny and resembled a polished laminated surface, which was a very interesting observation. • After 28 days of drying, the surface of the brick became matte and resembled a normal brick. • It was also noticeable that these higher concentrations of BSA (3% and 5%) resulted in more defined brick shapes with a darker brown colour and sharper right angles compared to the unstabilised British adobe bricks.

2. Mucin stabilised British adobe bricks	• Mucin, characterized as a large extracellular glycoprotein, exhibits a molecular size ranging between 500 and 50000 kDa [136]. • The pore size of mucin could reach 211 nm [137, 138]. • Given its substantial molecular and pore size, mucin significantly exceeds the average interlayer spacing of hydrated smectite clay minerals, which ranges between 4 nm to 10 nm [68, 134]. • Consequently, it is anticipated that mucin will not undergo adsorption within the interlayers of the smectite clay minerals. • Instead, mucin adsorption will be confined to the mineral's surface and edges.	• In the case of mucin, due to its large size, the difference in percentages between swelling and non-swelling clay minerals in the BS was thought to have no effect, as the adsorption would primarily occur externally.	• Since the size of mucin exceeds the average interlayer spacing of hydrated smectite clay minerals, the adsorption sites on all clay minerals (smectite, illite, chlorite, and kaolinite) will be limited to their external surfaces and edges.		• In natural soil, clay functions as a binding agent among various soil particles such as silt, sand, and gravel. Therefore, at low concentrations of mucin, a greater amount of moisture content is required to achieve a workable mixture. • As clay binds together different soil particles, the addition of low concentrations of mucin (0.1% & 0.2%) affects the soil's structural integrity by acting as a barrier between clay minerals themselves and between clay minerals and other soil particles. • This barrier could explain the decrease in compressive strength observed in British adobe bricks when mucin is added as a stabilizer, compared to unstabilised adobe bricks.	• Due to the low concentration, less mucin will undergo conformational changes when adsorbed by the clay minerals' surfaces and edges.	• This stabiliser was in the form of a very fine powder, and when mixed with water, it had the most distinct and unpleasant odour compared to the other stabilisers. • None of the other stabilisers had an odour after being mixed with the soil.
3. BSA-stabilised Sudanese adobe bricks	*For more details on this point, refer to the section above on the molecular size of the glycoprotein in BSA-stabilised British adobe bricks.*	• More swelling (smectite) clay minerals (63%) compared with the non-swelling (illite, chlorite, and kaolinite) clay minerals (37%) in the SS. • The smectite plays a vital role in the adsorption of the glycoprotein, hence the compressive strength when its interlayers can adsorb it. •	• High concentrations (0.5% & 5%) of BSA will be adsorbed by the surfaces and edges of the non-swelling clay minerals (37%) and the surfaces, edges, and interlayers of the swelling clay minerals (63%) in the SS.		• The increase in BSA concentration from 0.5% to 5% resulted in a higher amount of BSA crystallizing on the surface of the clay minerals in a denser and closely packed arrangement [74]. • This will also enhance the cohesiveness and structural integrity of the soil, with BSA serving as an additional cementing agent alongside the natural clay. • The increase in the concentration of BSA from 0.5% to 5%, coupled with the high percentages of swelling clay minerals (63%) compared to non-swelling clay minerals (37%), and the capability of BSA to be adsorbed by the interlayers of the swelling clay minerals, has collectively led to a sharp increase in the moisture content required to achieve a workable mixture when 5% BSA-stabilised Sudanese adobe bricks were produced.	*For more details on this point, refer to the section above on the classification of the protein and conformational changes upon adsorption in BSA-stabilised British adobe bricks (for higher concentrations of BSA).*	• The addition of 0.5% BSA resulted in a jelly-like dough that was elastic and sticky during moulding. • However, when smoothed and levelled with a touch of water, the final brick surface appeared shiny and resembled a polished laminated surface, which was a very interesting observation. • This phenomenon was not noticed when moulding and preparing the Sudanese unstabilised adobe bricks. • It was also noticeable that higher concentrations of BSA (5%) resulted in more defined brick shapes with a darker greyish colour and sharper right angles compared to the unstabilised Sudanese adobe bricks.

**Rs is defined as the radius of a smooth sphere that would have the actual frictional coefficient of the protein. This definition is more intuitive, enabling one to envision a tangible sphere that closely matches the size of the protein or is slightly larger in the case of an elongated protein with bound water [133].*

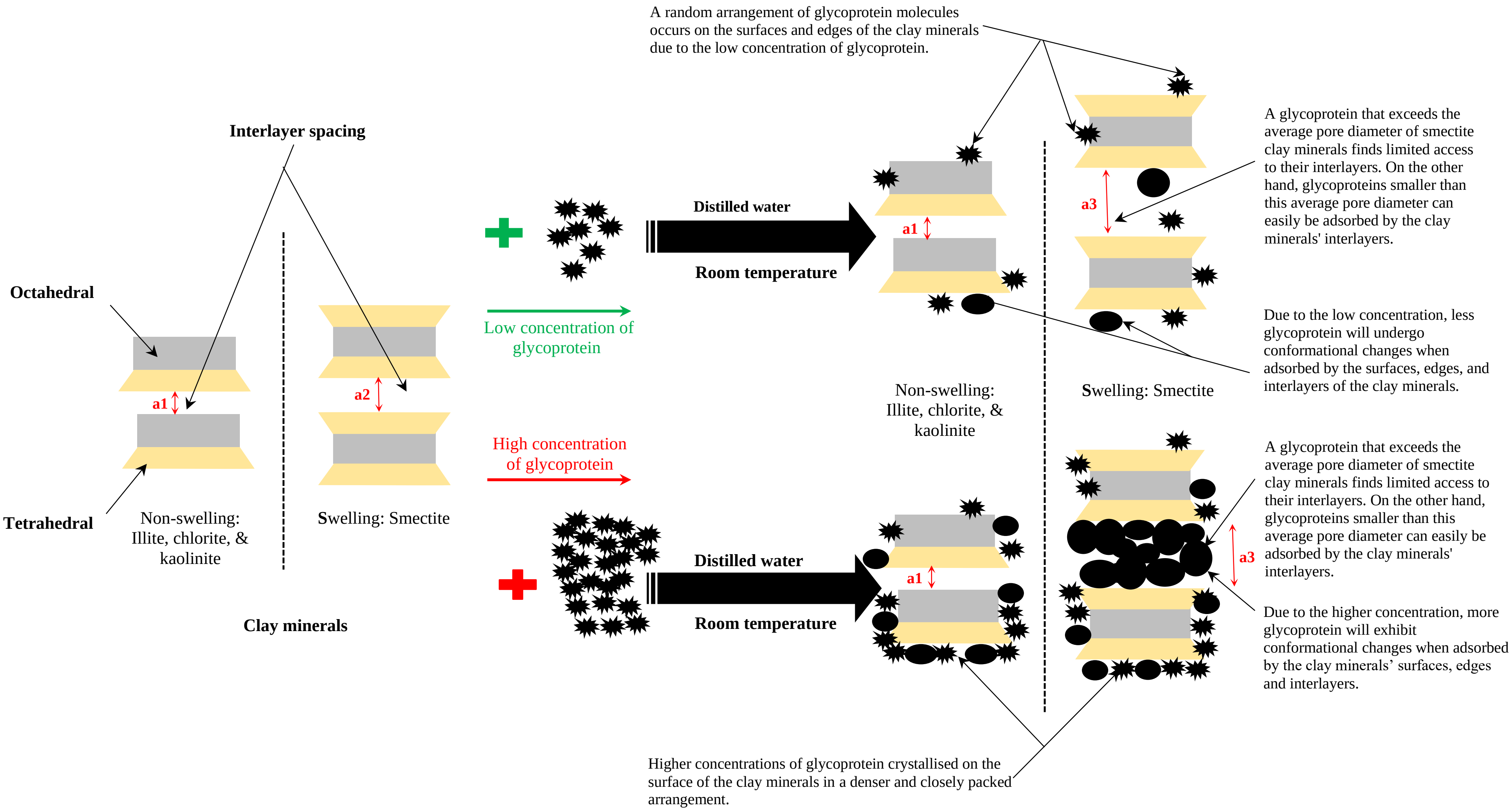


Figure 18: Conceptual illustration depicting the adsorption of high and low concentrations of glycoproteins by various clay minerals (non-swelling and swelling)

6. Conclusion

In conclusion, this study has demonstrated that bio-inspired stabilisers, particularly bovine serum albumin (BSA), can significantly enhance the compressive strength of adobe bricks. The incorporation of glycoproteins such as BSA has proven more effective than traditional stabilisers like cement and lime, with a notable increase in strength of both British and Sudanese adobe bricks. This marks an innovative stride in sustainable building practices, offering an eco-friendlier alternative that mimics the resilience found in termite mounds. The study also sheds light on the importance of molecular size and the type of soil clay minerals for optimal adsorption and effectiveness of glycoproteins as stabilisers. In detail, the conclusions of this study could be presented based on the findings of the experimental work as follows:

- ***Glycoprotein molecular size****:* The molecular size of the glycoprotein is crucial in its adsorption by clay minerals. The general rule is that the glycoprotein size should not exceed the interlayer spacing of the clay mineral. The experimental results demonstrate that the amount of glycoprotein adsorbed by the clay mineral interlayers directly influences the compressive strength properties of adobe bricks.
- ***Glycoprotein source and function:*** The source and function of the glycoprotein, referring to the animal organ from which it is extracted, are critical. This information indicates the glycoprotein's role in the animal body and its adhesive properties. These adhesive properties become significant when using glycoprotein stabilisers in earth construction.
- ***Gelatine glycoproteins properties:*** Properties such as melting and gelling temperatures of gelatine glycoproteins will impact the selection of drying settings for earth bricks. These properties also influence the treatment of bricks during the drying process. For instance, bricks should be sprinkled with water throughout the drying period to facilitate the formation and hardening of the gelling network.
- ***Glycoprotein concentration:*** The concentration of glycoprotein is a significant factor in enhancing the compressive strength of adobe bricks. For example, in this study, the use of BSA to stabilise adobe bricks resulted in improved compressive strength with an increase in the concentration of BSA in the bricks.
- ***Soil clay minerals type****:* The type of soil clay minerals is crucial in glycoprotein adsorption. The entire stabilisation process depends on the clay minerals present in the soil. Swelling and non-swelling clay minerals exhibit different glycoprotein adsorption patterns. The adsorption sites on clay minerals impact total adsorption and, consequently, the strength of the final product. Based on this study, it is suggested that glycoprotein concentration and the quantity of swelling clay minerals play a vital role in compressive strength. Therefore, soils with a high percentage of smectite clay minerals, one of the swelling clay minerals, show better results in compressive strength. This finding is noteworthy, as soils with a high percentage of smectite are not typically preferred in construction.

Furthermore, engineering and environmental benefits were achieved through the use of BSA. Its application has resulted in a decrease in the density of the bricks, and increasing its concentrations has reduced the amount of mixing water needed to achieve workable mixtures in soils primarily composed of non-swelling clay minerals. These advantages are highly sought-after in the construction sector overall and particularly in sustainable construction practices. However, engineering benefits were achieved in soils dominated by swelling clay minerals as higher concentrations of BSA have decreased the dry density of the bricks. In contrast, environmental benefits, such as the use of a lower amount of mixing water when preparing the adobe bricks, were not attained.

Future research should further explore the long-term performance of these materials to solidify their application in earth construction, with the ultimate goal of developing materials that are both environmentally friendly and structurally robust. This approach could revolutionise the construction industry, aligning with the principles of biomimicry and sustainability, and potentially leading to new horizons in the field of eco-construction and material science.

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