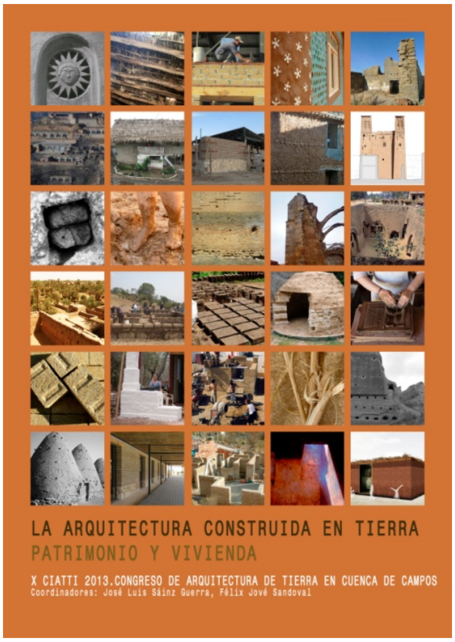

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THE RAMMED EARTH HOUSE IN NIGERIA

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PALABRAS CLAVE: rammed earth, earth building, sustainability, lime, stabilisation.

1. Introduction

The Earth is the oldest material available to man for the construction of shelter. The first builders of earth structures were termites[1]. They made masticated earth into durable structures to house their colonies. Then followed birds and beavers. Mud brick houses dating from 8000 to 6000 BC have been discovered in the Russian Turkrstan. Earth was used as a building material in all ancient cultures. Not only for homes, but for religious buildings as well. The 4000 year old Great Wall of China was originally built from rammed earth[2].

However, owing to ignorance and other factors, prejudice against Earth building is still wide spread in Nigeria[3]. Nigerians have been found to difficulty accepting that natural building materials such as Earth need not be processed and that in many cases the excavation for foundation provides a material that can be used directly in building. Olotuah[4] reports that a 40% cost saving is made when local building materials are used over conventional ones. This report investigates the advantage of using lime in the stabilisation process of earth found in Nigeria to provide structurally sound rammed earth structures.

Figure 1. Northern Nigerian Buildings.[7]

1.1. Rammed Earth

As public awareness grows regarding the importance of environmentally responsible building methods rammed earth is gaining much deserved recognition.

Rammed Earth has been found to be used in all continents of the world. Earth is extracted from the ground and constructed in layers inside removable shuttering to produce monolithic walls that are strong and durable. After compaction the formwork is removed to a new position, upwards to the next layer or sideways to extend the wall. Because earth is an abundant resource, rammed Earth buildings are very economical, costing very little in technology and requiring semiskilled labour.

As a material that is similar to compressed adobe or unfired clay masonry in physical composition, rammed earth is a structural process that will always prove stronger than blocks as there are no mortar joints and the material is compacted in place[5]. The finished material is however similar to masonry in that there are a series of semi-cold joints between layers and within each league the density varies from highly compacted at or near the top to less densely packed below the top of the lift[5].

1.2. Rammed Earth in Nigeria

Though Nigeria is experiencing rapid urbanisation[4], the use of earth building is still considered rural and archaic. Nigeria lies at the extreme inner corner of the gulf of guinea in West Africa[6]. It is divided broadly into the Northern, Western and Eastern regions. Most ancient houses in Nigeria were made from one form of earth building or the other. Earth building architecture was most developed in the Hausa speaking north with houses made into various shapes and sizes (Fig 1). The south and west had a similar basic architecture that saw most houses constructed spherically (Fig 2). Earth houses in the ancient north were more commonly made from Rammed earth while southern historic houses were made from cob or compressed earth blocks. The eastern part of Nigeria had its own unique architecture (Fig 3).

Due to rural-urban drift, most cities have developed and are characterised by building with conventional materials like sandcrete blocks and concrete. The use and development of rammed earth buildings in Nigeria suffered a blow as soon as modern building materials became available. There are very many reasons for this among which are social stigma, deterioration rate and poor construction techniques. Other reasons are the fact that earth building in Nigeria was labour intensive and involved a lot of drudger[4].

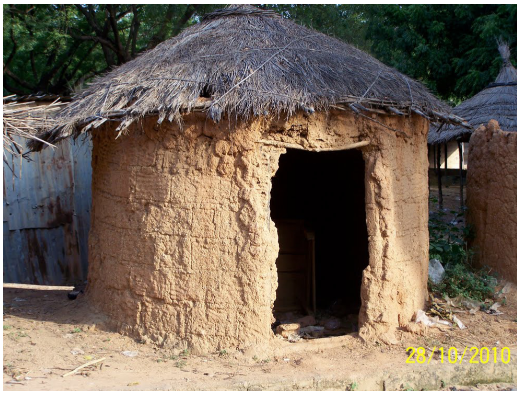

Figure 2. Southern Nigerian Compressed Earth Block Building.[7]

Figure 3. An Eastern Nigerian Cob building.[8]

At a time where conservation is a very important factor in construction, there is a need for builders in Nigeria to consider going back to the age old practice of building with earth. Not in the ways that it was carried out in the past, but with recourse to the increasing result of research that has transformed rammed earth into a modern building material as seen in Fig 4.

1.3. Composition

The composition of rammed earth is basic but can be greatly varied from site to site. Various soil combinations can be identified by grading the soil. The main constituents of soil are Clay, silt, sand and gravel. In its simplest form earth is the product of the erosion of rocks from the earth's crust. This erosion occurs usually due to mechanical grinding of rock as a result of the movement of wind and water. The thermal expansion and contraction of rock that occurs during freezing and thawing cycles also accounts for soil formation[10]. Other actions responsible can include organic interactions through the roots of plants and chemical reactions due to water.

Any design to create desired compressive strength in rammed earth should be based on actual tests. Theoretical prediction is unreliable. Tests that can be carried out include:

(1) Density and chemistry tests.
(2) Compressive strength tests
(3) Moisture exposure tests
(4) Bond strength tests
(5) Absorptivity tests
(6) Erosion and wear resistance tests

The strength of rammed Earth material is largely dependent on the quality of the mix. Usually increase in the fraction of binder material would result in strength gain[11]. But this also gives rise to other problems like drying shrinkage and expansion.

2. Stabilisation

2.1. Lime Stabilisation

Lime has been used in building techniques for over 5,000 years[12]. Archaeological evidence shows it to have been in existence for this time frame due to its resilience, durability, and water resistant qualities[13].

Lime is one of the older materials produced by man and remains a most useful material. Earlier uses have been in chemical, metallurgical and building industries Surprisingly enough, the published knowledge on such an old and widespread material is not as large as could be expected, and some process relations are not well documented[14]. This fact stresses the necessity to analyse some empirical knowledge established almost as 'universal truth' at basic level.

Figure 4. Rammed Earth Wall Building.[9]

The Romans used lime extensively in their building programme in Britain, and refined its application into mortars and plasters, which remained the principal surface finish for buildings until the nineteenth century, when cements took over this function[15]. The use of lime as a building material is currently undergoing a revival of interest. New applications are being found especially among those who favour a more natural approach to construction.

Soil stabilisation occurs when lime is added to a reactive soil to generate long-term strength gain through a pozzolanic reaction. This reaction produces stable calcium silicate hydrates and calcium aluminate hydrates as the calcium from the lime reacts with the aluminates and silicates solubilised from the clay. The full-term pozzolanic reaction can continue for a very long period of time, even decades -- as long as enough lime is present and the pH remain high (above 10)[16]. As a result, lime treatment can produce high and long-lasting strength gains. The key to pozzolanic reactivity and stabilisation is a reactive soil, a good mix design protocol, and reliable construction practice[17].

In order to produce lime, limestone is calcinated by supplying heat. The dissociation reaction of the carbonates contained in limestone is promoted by the heat absorbed by the limestone in a kiln, which implies three aspects: chemical, energetic and process control. Dissociation begins when limestone reaches the calcination temperature at the limestone surface, with a well-defined reaction interface moving to the centre of the limestone stone, forming a growing shell of quick lime around the unreacted core. To increase the reaction velocity, in order to reach a sufficient rate of production, it is necessary to increase the surface temperature of the stone over the calcinations temperature[14].This process is carried out in kilns.

In cement mortars and gypsum plasters, calcium hydroxide is often added to improve plasticity and water retention. However, the carbonation capability of calcium hydroxide allows for its use as the main binder in lime–sand mortars and plasters, since the precipitation of carbonate crystals results in hardening and strength development. High-Calcium lime mortar is mainly applied in the conservation of historic buildings, as its properties are more compatible with those of old materials. Among these properties, the higher permeability of lime-bonded in relation to cement ones not only suits historical applications, but can also provide a "breathable" inorganic coating for indoor rendering, thereby reducing moisture and fungus problems[18].

The material is utilized either in the form of "dry" hydrated lime (industrialized powder) or as lime putty (slaked with excess water). The properties and performance of mortars and plasters differ significantly depending largely on the physical features of the calcium hydroxide used. Particle's characteristics as size distribution, shape and surface area have major influence on rheological properties, water retention and carbonation kinetics. Aged putties, for instance, are known to possess small particle size, a predominant plate-like portlandite morphology and large surface area. Consequently, these present high plasticity and water retention values undergo fast carbonation and provide early strength development[18].

Different deterioration factors can affect the durability of any earthen structure. Some of the most important ones could be included in the following main groups:

i) Wet and dry cycles;
ii) Rain exposure and related leaching;
iii) Freezing and thawing cycles;

iv) Exposure to pollutants (such as SO_2); and
v) Sun's rays.

The extent to which rammed earth is affected by these deterioration factors is a function of its properties, which depend, in turn, on several issues, such as the kind and characteristics of the binder and the aggregate, the binder/ aggregate ratio, the amount of mixing water, the mortar's permeability, the water absorption capacity through capillarity, water intake, the presence of admixtures and the curing conditions.

When calcium oxide from lime or cement is added to a soft soil, hydration reactions occur, immediately forming calcium hydroxide. Immediately, Ca^{2+} ions preferentially displace monovalent cat-ions at the negatively charged sites on the clay mineral. These cat-ion exchange processes displace Na^+ and K^+ ions into the pore water. The replacement of the monovalent ions by Ca^{2+} ions induces changes in the soil system and soil properties on a timescale of minutes to hours. The increased concentration of Ca^{2+} ions coagulates the clay particles and transforms the plastic soil to a more granular soil character[19]. The rapid ion exchange is known as soil improvement or modification[20–22].

Lime, in one form or another, has been used to modify the properties of fine grained deposits. Treatment of soils with lime has brought many beneficial effects, such as improvements in the plasticity characteristics and strength behaviour with time. It is well established that the use of lime in fine-grained soils makes the system less sensitive to changes in stress and other environmental factors[23–25]. Many engineers have realized this advantage all over the world and hence, in many situations, lime is used to improve soil characteristics in civil engineering applications[26].

Lime stabilisation is not difficult to carry out. After proper mix design and testing is performed, in-place mixing is usually used to add the appropriate amount of lime to soil, mixed to an appropriate depth. Pulverization and mixing is used to thoroughly combine the lime and soil. For maximum development of strength and durability, proper compaction is necessary.

Some of the identified advantages include[27–30]:

a) Fast Setting
Hydraulic lime mortar is fast setting so it can be used on-site just as efficiently as modern mortars.

b) No Shrinkage
Shrinkage cracks are virtually eliminated due to the mortar's hydraulic setting characteristics.

c) Breathable
It lets walls breathe by absorbing and evaporating moisture from surrounding masonry. This also helps protect the masonry because less moisture means less risk of salt and frost damage.

d) Elasticity
It has a low modulus of elasticity. This means it is extremely flexible and allows for movement and thermal expansion.

e) Adaptable
The mix can be engineered to suit different types of masonry and degrees of weather exposure. Hydraulic lime mortar can set underwater, therefore an excellent mortar for masonry in extreme conditions.

f) Workable
Mixed correctly, hydraulic lime mortar is a beautiful material to use. With the correct technique, even a novice's repointing can look clean and tidy, totally professional.

g) Sympathetic
It is softer than modern cement, stones and bricks are reclaimed more easily if buildings are dismantled.

h) Environmental
It is more eco-friendly, the manufacture of hydraulic lime produces less carbon dioxide than ordinary limes. Furthermore, it re-absorbs carbon dioxide thus lowering its carbon footprint even further.

i) Appearance
It has an attractive traditional gritty texture, pale in colour. Just like lime putty mortar in appearance, in fact, they are practically indistinguishable".

3. Methodology

The following section describes the techniques used for soil selection, grading, mixing, blending and stabilisation. Also described in this section is the production of rammed earth cubes and the test methodologies for measuring their engineering properties.

3.1. Materials

Materials used for the procedure include Earth and Lime. All experiments were carried out in the University of Wolverhampton Construction and Infrastructure laboratory.

The earth material compressed to produce rammed earth for this research has been put together by blending three component sub-soils of known origin and properties. The components of rammed earth materials are comparable to those of concrete. The inert aggregate fraction is represented by granular soils (sand and gravel), the binder fraction is represented by cohesive soil (clay) and water is used to activate the lot.

The process of incorporating these ingredients to form a sub-soil is simple and consists of the basic steps outlined below. The particle-size distribution of each component soil was determined in accordance with British Standard 1377:1990.

3.2. Material Preparation

After the sample selection process, two of the soil components (Sand and gravel) were oven-dried at a temperature of 105^{o}C. The clay was cut into short pieces and air dried until completely dried. The clay was then pulverized into a coarse powder using direct mechanical energy. The sub-soils were then mixed together using an electronic paddle mixer. This ensured an even mix of the sand, gravel and clay. The soil was mixed in batches of 10kg (dry mass) such that a 523 mix recipe required 5kg sand, 2kg clay and 3kg gravel and was used as the standard mix for the entire procedure.

Cube samples measuring 50x50x50mm were produced in batches, each containing five cubes.

The amount of lime added was calculated as a mass proportion of the total amount of dry soil. For example, for 10kg of dry soil, an addition of 1kg of lime would equal 10% addition. In this example, the total mass of dry components for the mix becomes 11kg. The optimum moisture content (OMC) was always calculated as a percentage of the total mass of the dry components. This means that in an unstabilised soil with a dry mass of 10kg, if the optimum moisture content is 8%, then 800g of water must be added to the mix. If the soil then has 10% lime added to it, then 880g of water must be added to achieve the same optimum moisture content value of 8%.

3.3. Specimen Preparation

The laboratory based production of rammed earth samples should be a reflection of the onsite constriction technique used in making rammed earth walls. This has the effect of providing results that are meaningful, useful and applicable to real life building situations. There are factors that are considered as important in relation to sample production and these include the level of compaction and total input energy. A manual hand rammer was used for the dynamic compaction of the soil in order to replicate field rammed earth production. For each of the rammed earth mix recipes produced, the optimum moisture content was found to be a value ranging from between 7% and 9% moisture in relation to the dry mass of the soil. The optimum moisture content for each of the soils was determined in accordance with British Standard BS 1377 using the established proctor 'light' compaction method. NZS 4298 states that for rammed earth production, the moisture content should not fall below 3% of the optimum moisture content or rise above 5% of it. This standard was continually monitored by using the gravimetric method of moisture content determination.

The 523 mix was moistened to 8% moisture content and placed inside a mould. It was then compacted in two separate layers. The number of blows that ensures even compaction was soon observed to be 36 blows. The rammer was a 4kg stainless steel solid cube tube with edges that ensure proper compaction at the cube corners. The mould used was a standard 50x50x50mm mould used in normal concrete cube making. The inside of the cube mould was painted with form oil to ensure ease of removal of the cubes.

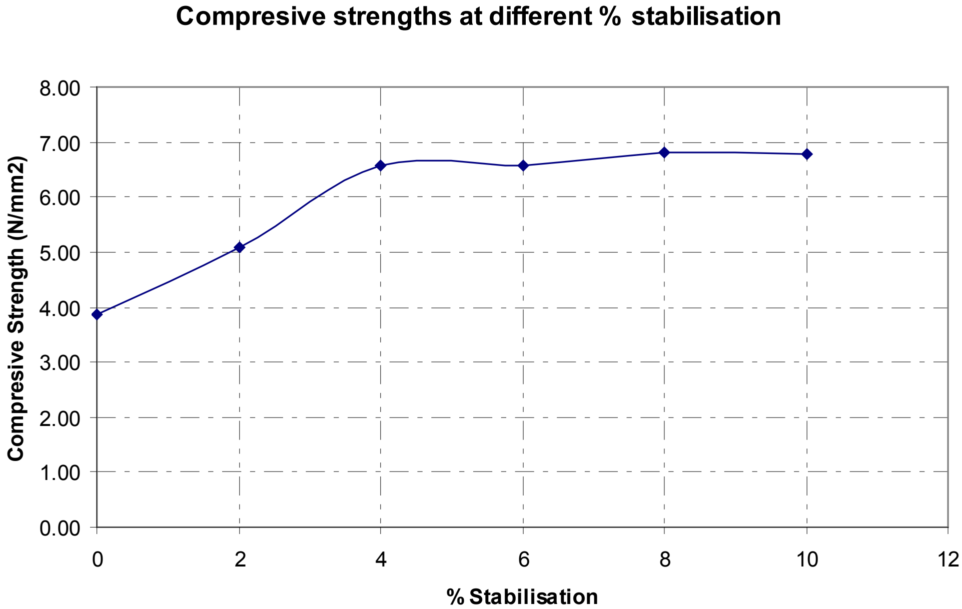

Figure 5. Comparison between the 28-day f'cu for different degrees of stabilisation with lime

3.4. Compressive Test Procedure

Compressive strength testing was carried out to determine the 28th day compressive strength of various mixes. The apparatus used for this was the 'Controls Sercomp 7' compression machine. A specimen was placed between the load platens of the test machine. The applied load rate was set at 50N/s. This ensured that failure of the sample occurred at a time typically between 30 and 90 seconds after the beginning of the test. This method is consistent with standard test procedure for conventional masonry materials such as concrete and mortar. A minimum of five rammed earth cube samples was required for compressive strength testing in order to give a good representative value for a particular soil type. The machine provided values for the load at failure, and the corresponding stress.

4. Results

The unconfined compressive strength (f'_{cu}) is calculated using the formula below consistent with Standards New Zealand 4298.

$$f'_{cu} = \left(1 - 1.5\frac{X_s}{X_a}\right)X_l \quad (1)$$

Where:
X_s = Standard deviation of the data series (for the 5 cube samples)
X_a = Mean average of the data series (for the 5 cube samples)
X_l = The lowest result from the series.

This is preferred to using the average of the compressive strengths obtained because it provides a more representative value as it takes into account the highest and lowest values and the deviation between them.

4.1. Performance of Lime as a Stabiliser

The main reason for carrying out this study is to compare rammed earth to conventional masonry materials to be used in the Nigerian construction industry. Compressive testing was carried out on samples of rammed earth that did not contain any stabilisers and also on samples that contained varying degree of stabilisers (from 2% to 10%).

Testing was carried out using the Controls Sercomp 7 compressive test machine. Figure 5 shows a chat of the results obtained.

It can be observed from the chat that 0% stabilisation (samples that were unstabilised) had a compressive strength of 3.86N/mm^2. A fractional input of lime as a stabiliser produces perceived strength increase. An addition of 2% (by mass) of stabilisers (lime) produced an increase of 32% in compressive strength (from 3.86 to 5.10N/mm^2). Further increase produced an even larger increase in strength as 4% stabilisation resulted in over 70% compressive strength increase from an unstabilised state. It also resulted in a 29% increase from a 2% stabilised state. The results further showed that there was no real appreciable increase when the degree of stabilisation was notched up. 6% stabilisation resulted in no perceived increase in compressive strength. A further increase was noted when the same soil samples was stabilised by 8% as the compressive strength property recorded a 76% increase from the unstabilised state. However this was a mere 3.5% increase in strength from the recorded 4% stabilised state. At 10% stabilisation, the same rammed earth sample was noted to have its compressive strength raised by just over 75% from 3.86N/mm^2 to 6.78N/mm^2.

5. Conclusion

While traditional mud houses are regarded generally as peasant dwellings in Nigeria, it should be noted that the cost savings that rammed earth construction offers is not only financial or economical but hugely environmental. The emission that is often associated with cement production is largely avoided when rammed earth is used on a large-scale. When rammed earth is used as it is found, it possesses the basic strength required of any building material. However, it is evident that stabilisation with lime highlights the strength and improves the chances that rammed earth can find further application.

It should be noted also that the strengths recorded are only 28day strengths. Under the right conditions, lime stabilised rammed earth will continue to gain strength over time. Rammed earth would thus fulfil the structural requirement of the Nigerian construction industry.

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