A review of the use of lateritic soils in the construction/development of sustainable housing in Africa: A Geological Perspective

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Highlights

• Appraisal of the previous work in the use of tropical soils in low cost, energy efficient housing development.

• It established CEBs as sustainable building materials for a sustainable environment.

• Identification of lateritic soils as suitable material in the production of CEBs.

• Established the importance of parent rock material (its type and mineralogy) in strength and durability of CEBs.

• Discouraging the common practice of firing clay bricks for the sake of sustainable environment.

Abstract

Lateritic soils have been described as highly weathered tropical or sub-tropical residual soils with varying proportions of particle sizes ranging from clay size to gravel, usually coated with sesquioxide rich concretions. It is sometimes referred to as brick earth based on its use. The use of laterite and lateritic soils have been found to promote the realization of decent housing and bridging the housing deficit, especially in Africa.

The author has attempted to review available information on the recent trends in building bricks and housing development with the aim of identifying a suitable soil material that will meet the present challenge of sustaining the environment without costing too much and maintaining a high standard of strength, durability and aesthetics. A critical review of laterite and lateritic soils from a geological point of view indicated these soils to be one of the best natural materials used in the production of compressed earth bricks. Lateritic soils are mostly well graded, comprising both cohesive (silt and clay) and cohesionless (sands and gravels) soil fraction, it contains sesquioxides and clay minerals which are very useful in the natural binding process as well as in the presence of most chemical binders.

Compressed earth bricks are mainly composed of raw earth materials (soil) with their cohesion due principally to the clay fraction present in both humid and dry states. CEB's promote building in a 'sustainable' way and offers a good prospect to using our resources in an efficient manner while creating dwellings that improve human health, well-being and preserving a better environment, with an affordable and natural alternative.

Keywords:

Sustainable building; Compressed earth bricks; Laterite; Lateritic soils; Sesquioxides

1 Introduction

Earth has proven to be man's best friend, companion and solution to most of his problems. Humans live on the earth, food is produced from the earth and earth seems to be the only friendly habitat for safe living.

Earth within the above context refers to soil which is un-cemented mineral grains, usually formed by weathering of rocks and includes organic matter and water.

Growing environmental concerns have led to the realization and appreciation of the usefulness of natural earth material to many environmental and construction problems facing humankind. The use of earth material, if managed correctly, does not lead to the same scale of depletion of resources, increase in pollution and waste generation or biological changes as compared to conventional building materials. (Bachar et al., 2014)

In order to preserve and sustain the environment, the use of environmental friendly building materials, commonly referred to as green building materials must be encouraged to promote the idea of sustainable building. One such green building material that meets the standards of achieving sustainable housing developments is compressed earth bricks.

Sustainable building was defined by Sergio (2008) as structures that are designed, built, renovated or operated in a resource-efficient manner. It is designed generally for the well-being of the environment as well as the occupants, using resources (energy, water, and other construction materials) in a more effective way. This should lead to a reduction of environmental impacts without compromising standards and aesthetics.

The building industry has been reported to cause increased levels of pollution during the extraction, processing and transportation of raw materials. For instance in the United Kingdom, it has been reported that dwelling and household usage accounts for 50% of all energy consumed and about 8% (350 PJ per year) is used to manufacture and transport building materials. (Adalberth K., 1996 in Morel et al., 2001). Waziri et al., (2013) compared energy consumed as well as the amount of carbon emissions between Compressed Earth Bricks (CEB) and other conventional bricks. CEB was reported to generate about 22 kg CO_2/tonne with concrete blocks producing, 143 kg CO_2/tonne, burnt clay bricks, about 200 kg of carbon dioxide (CO_2) per tonne and perforated concrete blocks 280 - 375 kg CO_2 per tonne. This implies that CEB uses about 10% of the input energy compared to the production of burnt clay and concrete masonry units. Earth bricks have numerous advantages both for man and the environment. With the present global concern about the environment and its sustainability, attention is beginning to shift to energy efficient and environmentally friendly construction materials. Based on this fact, earth construction remains the best and the most effective way of addressing the housing deficit and simultaneously reduce the environmental impact of building construction, as well as reducing the housing energy needs.

According to UN Habitat Report, (2011), *"much more can be done in Africa to reduce the cost and increase accessibility of building materials whilst harnessing their ability to contribute to local economies and provide employment opportunities. Increasing affordable housing supply must equally be achieved in a way that is environmentally sustainable and does not affect local, international, and continent's ecosystems and natural resources in adverse manner"*.

Earth bricks, especially compressed earth bricks, are naturally available, economically viable, environmentally friendly and above all energy efficient to produce. It is an ideal material for sustainable construction, but despite the environmental advantages and cost benefits, it is frequently regarded as a building material for the underprivileged and often considered as second class building material for low income earners. This perception and non-acceptance by some governments are due to the inappropriate use by the so-called poor people. Low income communities use earth materials in its simplest, natural form without any improvement. This has led to low acceptability amongst most social groups and resulted in earth materials not being widely recognized by authorities in many countries. Standard building codes and regulations for the use of these natural materials have therefore not been fully developed. With the recent trend in reviving the use of sustainable materials in construction, coupled with the research work in this regard and the aggressive promotion of this style of construction by international organizations (e.g. UN, UNIDO, WHO, CRATerre-EAG,) earth material is now more acceptable for use in the realization of decent housing, especially in Africa. This is with an aim of bridging the housing deficit that exists in the world and this new trend and aesthetically pleasing architecture utilising earth materials are now acceptable as a viable construction material in modern housing developments. It is now realised that the past negative perception is not necessarily about the material, but rather, how it is being used by different levels of society. Figure 1 shows a poorly constructed earth building and the new faces of modern earth construction, (compressed earth and fired bricks).

2 Definition of Compressed Earth Blocks/Bricks (CEBs)

Stulz et al., (1993) defined compressed earth blocks (CEBs) as *“masonry elements, which are small in size with regular and verified characteristics obtained by the static or dynamic compression of earth in a humid state followed by immediate demoulding”.*

Compressed earth bricks are mainly composed of earth materials (soil) with their cohesion due principally to the clay fraction present in both humid and dry states. Earth strength characteristics and cohesion could however be enhanced by the addition of a stabilizer.

The final feature of CEBs are dependent on the kind/quality of raw materials utilised (e.g. the kind of stabilizer, soil) and on the steps and expertise in executing various stages of manufacturing i.e. the preparation of materials, addition and mixing of stabilizers and compaction or compression up to curing stage.

In this paper, the term “Compressed Earth Bricks” would be adopted implying the commonly used terms “Compressed Earth Blocks” or “Compressed Stabilised Earth Blocks”.

Laterite or lateritic soil remains one of the best natural materials to be used in compressed earth bricks, because, it is generally well graded soil that combines both cohesive (silt and clay) and the cohesionless (sands and gravels) parts of a soil. It contains sesquioxides and clay minerals which are very useful in the natural binding process as well as in the presence of most chemical binders. Characteristics of laterites and its constituents are discussed in the subsequent sections.

Figure 1: Different faces of earth bricks in building construction. (A&B) Ebira Farm Settlement in Nigeria, (C&D) Departments of Economics and Geography (fired bricks), University of Pretoria, (E) Catholic Mission House in Nigeria (CEB).

3 Lateritic Soils

The term ‘Laterite’ appeared in academic literature over a century ago. Buchanan (1807) first used this term to denote a building material in the mountainous region of Malabar, India (Maignien R., 1966). The term ‘Laterite’ could mean brick earth in some local dialects but the name 'latérite' got its meaning from a Latin word *later*, meaning 'brick' and so relating solely to the use of these soils in block making (Prescott and Pendleton, 1952 in Gidigasu, 1974). There have been so many arguments, criticism and learned discussion on the definitions of “laterite” and “lateritic soils” by different authors and workers giving different definitions in terms of its physical nature, chemistry, origin and morphology (Buchanan, 1807; Babington, 1821; Benza, 1836; Clark, 1838; Newbold, 1844 and 1846; Prescott and Pendleton (1952) cited in Maignien, 1966). Gidigasu (1972) described laterites as; “*all the reddish, tropically weathered residual and non-residual soils including laterite rocks*”.

Pendelton and Sharasuvana (1946); (cited in Gidigasu, 1974) defined "laterite" as "*soils in which a laterite horizon is found, and* "laterite soils" *as those in which there is an immature laterite horizon from which a true laterite horizon will develop if appropriate conditions prevail long enough"*. By implication, a lateritic soil could then be described as that which has an underdeveloped laterite horizon capable of becoming true laterite given the appropriate conditions and sufficient time. Schellmann, (1986) (in Giorgis et al., 2014) attempted to re-define laterite, by proposing a new definition and classification based on rock chemistry; basically on the Si/(Al + Fe) ratio in comparison to the chemical composition of the underlying parent rock. This was widely accepted, but later criticised strongly by several authors *e.g.,* Bourman and Ollier, (2002 and 2003); Schellmann, (2003), where Bourman and Ollier proposed that the term ''laterite'' should have been abandoned.
Considering the difficulty and varying opinions as to the term 'laterite' and 'lateritic soil', the term lateritic soil is defined in this paper strictly based on field observations and purpose of this research. Therefore 'lateritic soil' is used to describe the highly weathered tropical or sub-tropical residual soil, which is well-graded and usually coated with sesquioxide rich concretions. The colour may vary from liver brown to rusty red. Based on this, a 'laterite' could therefore be regarded as fitting exactly the definition although non-residual (transported) soils are often included.
High moisture content and temperature cause intense chemical weathering that produces well developed residual soils (González de Vallejo and Ferrer, 2011). Their geotechnical behaviour is controlled by mineralogical composition, micro-fabric and geochemical environmental conditions. Where high iron (Fe) and aluminium (Al) content are present, laterites are formed and when drainage is poor, black cotton soils may develop, which have high smectite clay content. Alternate wet (rainy) and dry seasons favours the formation of lateritic soils, as leaching of the parent rock takes place in the rainy season while during the dry season, capillary action transports solutions of leached ions to the surface from where it evaporates with the salts left behind to be washed down the following wet season. Thus the whole zone is progressively depleted of the more mobile elements like Na, K, Ca etc.. Olanipekun, (2000) observed that the high proportion of Fe^{3+} oxides in laterites signifies a left-over accumulation as a result of removal of silica and alkalis. The process of laterisation around south-western Nigeria was observed by Emofurieta, & Salami, (1993) while studying the geochemical dispersion patterns associated with the laterisation process at Ile-Ife. It was reported that the soils derived from the melanocratic bands in gneiss bedrock are SiO_2 rich, compared to soils derived from the leucocratic bands. Based on their average SiO_2/Al_2O_3 + Fe_2O_3 ratios, the soils derived from the melanocratic bands are lateritic whilst the leucocratic derivatives were described as non laterite. In the authors opinion, based on the earlier definition of lateritic soil, those leucocratic derivatives could still be described as lateritic soils, as they could also reach a matured stage of laterisation given favourable conditions over time. (See Figure 2).

Figure 2: An exposed lateritic profile with a varying degree of laterization due to mineralogy.

Chemical weathering progresses more rapidly in warm than in cool climates and provided there is good drainage, it is more prevalent in wet than dry climates. (Mitchell and Soga, 2005). This explains the more pronounced laterisation processes observed in the tropics compared to arid regions and also, the formation of laterites in the south-western region of Nigeria compared to the black cotton soils of the north-eastern part of the country. The parent rock material was found to have a significant impact on the formation of laterite (Thorne et al., 2012 and Ko, 2014). A recent finding by Giorgis et al., (2014) utilises Rare Earth Element (REE) patterns measured in a set of laterite horizons, which closely match that of the underlying basement rocks. It was reported that, the shape of the chondrite normalized REE patterns of all lateritic horizons is virtually the same, thus implying a direct origin of the sequence from the underlying bedrock. Laterites are mostly residual soils formed directly or almost directly on the parent rock making it possible for laterite/lateritic soils to retain some of the characteristics of the parent rocks. Little (1969) cited in Gidigasu, (1974) gave a simple model of the degree of decomposition of rocks. It shows a progressive weathering upwards with different horizons having a different degree of weathering. Figure 3 shows a similar profile observed around south-western Nigeria.

Kasthurba et al., (2007) reported a downward softening of material as a result of decline in sesquioxide cementation and increase in the amount of clay filled pore spaces. This brings about lateritic profiles which are characterized by accumulation of sesquioxides in the upper horizons and kaolinitization at lower levels.

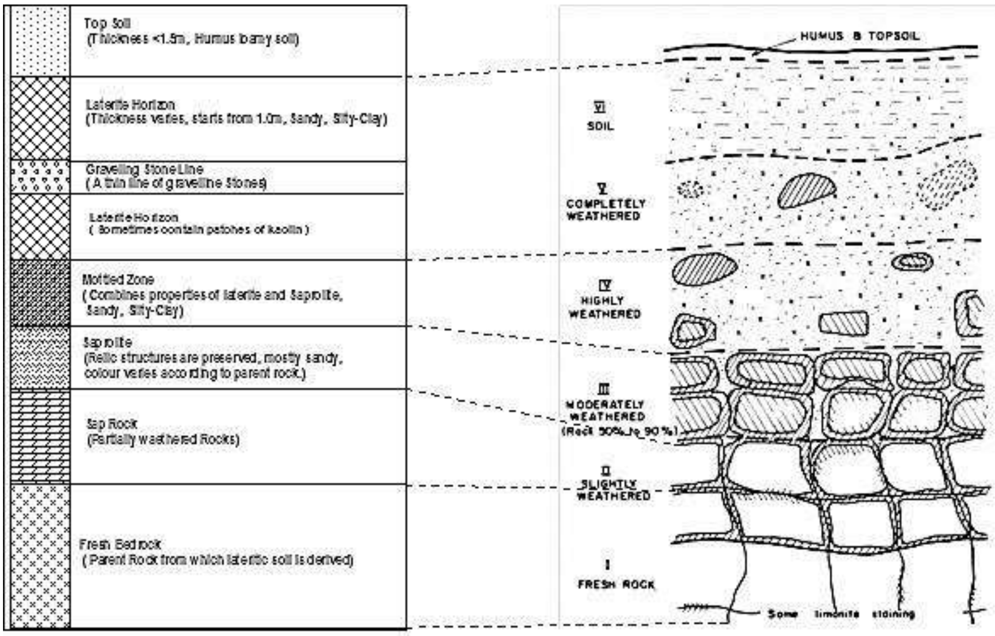

Figure 3: (I) Lateritic soil profile as observed in the field; and (II) Definition (Morphological) of degree of decomposition of rocks. (Modified after Little, 1969).

3.1 Composition of Laterite

Laterite is composed of both cohesionless and cohesive soils. This forms the basis of laterites being referred to as C-φ (C-Phi) soils. The cohesionless portion consist of gravel, sand and silts while the cohesive portion includes fine particles usually in silt and clay sizes. Lateritic soils behave in a unique way with some laterites changing volume when exposed to humidity variations while others are not affected. Hence, some components are referred to as stable *i.e* gravel and sand, while silt and clay are referred to as unstable. Stability in this sense is based on their ability to withstand variations in terms of moisture without a significant change in its properties, which is of course fundamental in materials for building construction. Rigassi, (1995) described the properties of each of these components of lateritic soil as follows:

a) Gravels; composed of fragments of rock of varying hardness, whose size fall between 2 - 20 mm with stable mechanical properties when it comes in contact with water.

b) Sands; composed of mineral particles, with size ranging between 0.06 - 2 mm. Stable, though lacks cohesion when dry, it has an appreciable degree of internal friction, which means, it offers a great resistance (i.e. mechanical) to intra-particle movement. It is normally characterised by apparent cohesion when wet due to the surface tension of the water present in the void spaces.

c) Silts; consist of grain particles ranging from 0.002 to 0.06 mm; cohesion is low when dry and it offers lower resistance to intra-particle movement than sands. Silts are characterized by cohesion in wet condition and susceptible to swell and shrinkage on exposure to varying levels of humidity, leading to appreciable change in volume. In the dry state, they have very poor cohesion and therefore cannot be used independently as main material for building.

d) Clays; the finest of the particle sizes in lateritic soil, generally smaller than 0.002mm. Their characteristics differ completely from the larger sized particles in that they consist mainly of microscopic clay minerals which include: kaolinite, illite and montmorillonite. Clay particles are usually coated in a thin-film of absorbed water molecules and since they are microscopic, they tend to be very light in comparison to surface tension forces acting on the film of absorbed water. Clays unlike gravel and sand, are not stable and quite sensitive to varying humidity. Due to strong attraction of clay to water, its volume increases due to increase in moisture content as a result of thick films of absorbed water (Mitchell and Soga, 2005). On the other hand; as clay dries out, shrinkage cracks may appear in the clay mass with a reduction in strength. The cracks also form pathways for water during subsequent wetting up events. This creates a major problem when clay is being used independently as a building construction material. Thus, a combination of the stable constituents *i.e* gravel and sand with silt and clay forms good soil material for construction purposes. Lateritic soils appear to be best suited in this regard because it is made up of all these different particle sizes in varying proportions (well-graded).

3.2 Shear Strength of Lateritic Soils

Shear strength is dependent on factors such as the nature of the soil, its structure, bonds and degree of deformation particularly in terms of stress and fluid pressures in the pore spaces. (González de Vallejo and Ferrer, 2011). Millogo et al., (2008) listed the following geotechnical properties of laterites in Burkina Faso: maximum dry density (MDD) of 21.7 kN/m^3 at an optimum moisture content (OMC) of 6.6% with 43% CBR at 95% of MDD. They went further to describe the stress-strain curves of the soils, which show a ductile type of rupture mechanism with a well-defined plastic phase. The samples were described as nearly flexible with its tensile and compressive strengths given as 0.09 and 1.26 MPa, respectively. In general, compressive strengths of soils fall within the range 0.5–1.5 MPa. The above laterite possesses excellent engineering properties and it may be suitable for different engineering construction works.

It is generally assumed by most authors and researchers that clays almost always negatively influence geotechnical properties of soils. This invariably means that the lower the clay content, the better the soil for engineering uses. This assumption should obviously be evaluated in context as the engineering properties of soil not only depend on the shear strength characteristics, but also on index properties. A careful evaluation must therefore be made based on the purpose and specific function of the clay fraction in the soil. For instance, in the building industry, some countries (e.g. South Africa) prefer the use of fired clay bricks as the clay properties are enhanced during firing to improve the durability and strength parameters. The firing process has however been widely criticised because of its negative impact on the environment (Shehu Waziri et al., 2013). Adding lime as a stabilizer has been found to positively influence the geotechnical properties of lateritic soils from south-western Nigeria (Oyediran and Okosun, 2013). The Unconfined Compressive Strength (UCS) of the soils increased with the addition of about 6% lime, which results in more than 100% increase in the UCS of the soils. Other index properties of the soils were also appreciably improved by the addition of lime.

The geotechnical properties of soils used in construction can therefore be improved significantly by stabilisation. This could be achieved either by physical stabilisation when a more suitable soil is mixed with a less suitable one, mechanical stabilisation in the form of compaction, compression or consolidation and chemical stabilisation in form of addition of lime or cement.

4 Strength of CEBs

The compressive strength of compressed earth bricks depends on soil type, type and amount of stabiliser and the compaction pressure used in compressing the brick according to Adam and Agib (2001). In addition to this, strength and durability of CEBs, depend on parent rock material, grain size characteristics, soil mineralogy and method/duration of curing. Maximum strengths (usually described in MN/m^2 or MPa) are derived using a proper mix of suitable materials coupled with adequate compression/compaction and curing. Generally, typical wet compressive strengths of CEBs are less than 4 MPa (Adam and Agib, 2001). Arumala, (2007) recommended soil constituting of 8% sand and 87% clay with 5% ordinary Portland cement for producing compressed earth bricks. Based on the knowledge of clay mineralogy, this recommendation may not be suitable for durable bricks because the very high clay content may cause shrinkage and cracking of the brick. The effect of this can be seen in the behaviour of bricks when exposed to climatic conditions after three months (Figure 4). The poor response to climatic conditions was due to the effect of high clay content present in the soil.

Figure 4: Response of CEBs made from clayey soil to climatic conditions, after three months (After Arumala, 2007)

Aguy, (2011) discussed the engineering characteristics of CEB and found that the performance of clay bricks in terms of their flexural and compressive strength was greatly improved by mixing clay with sand and improved even more by the addition of lime and RHA (Rice Husk Ash). He observed that clay–sand mixed specimens absorb less water compared to the stabilized clay specimens (

Table 1). His work confirms that a stabilized clay–sand mix is more resistant and impermeable to moisture/water than stabilized clay specimens. Invariably, this goes further to prove that well graded soil, like lateritic soils, are more durable than only cohesive soils. The compressive strength of clay seems higher than that of clay-sand mixture in the dry state, but when wet, the clay-sand mix has the best strength properties. The implication is that there are no correlation between compressive strength and durability. A brick may have a very high compressive strength but it may not stand the test of time in terms of climatic/weather conditions and moisture changes. This is illustrated in Figure 4 (Arumala, 2007). In comparison, Plate 1 shows the response of bricks made with adequately graded mixtures to extreme weather conditions.

It is therefore pertinent to note that, in selecting soils for building materials, durability is very important and this should be carefully studied without compromising the minimum standard for compressive strength as well. This can be achieved by properly selecting soil materials preferably well graded with an adequate particle size mix.

In as much as clay is very important in soil materials for brick making, especially because of its cohesive properties that serves as binder for the soil, extreme care must be taken to avoid too high clay content because of possible volume change under variable moisture conditions. In the same vein, curing had been found to improve the compressive strength of CEBs with a maximum improvement in compressive strength of the cement stabilized soil achieved after curing for about 28 days (Bahar et al., 2004) (Figure 5).

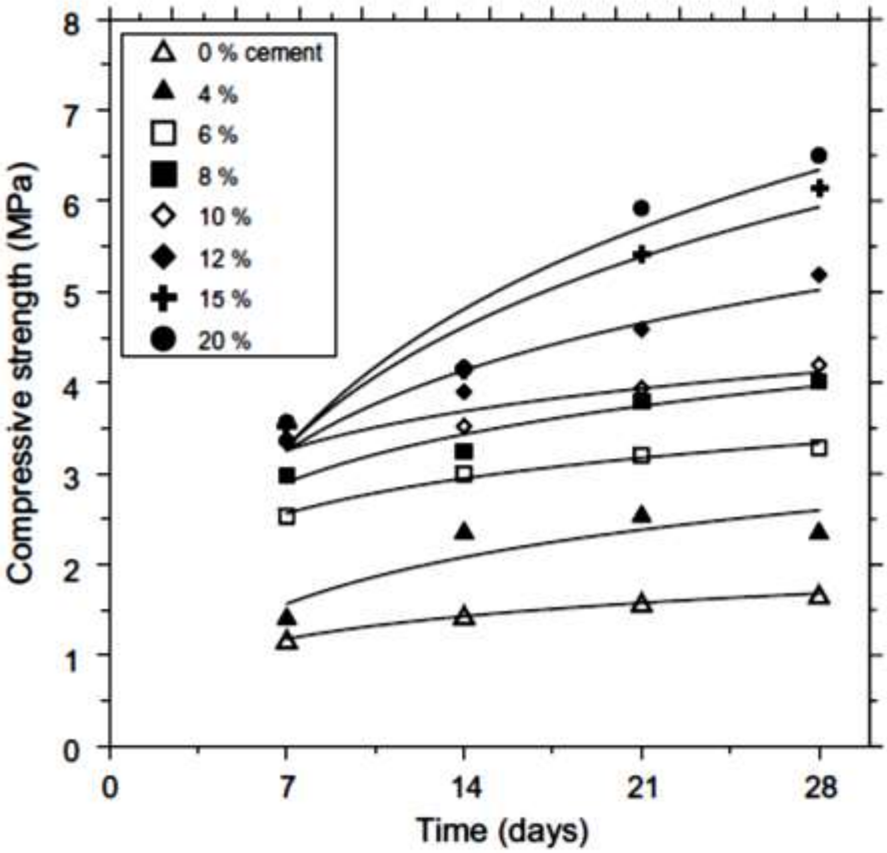

Figure 5: Effect of Curing on Compressive Strength of CEBs (After Bahar *et.al.* 2004).

Table 1: Compressive Strength and Loss of Strength observed in CEBs. (After Aguy, 2011)

Compressive strength (MPa) and strength loss (%).

Lime:RHA ratio	Dry		Wet		Strength loss	
	Clay	Clay-sand	Clay	Clay-sand	Clay	Clay-sand
0	13.3	11.2	-	-	-	-
1:3	16.7	14.9	10.4	12.0	38	20
1:2	18.1	17.7	11.8	15.1	35	15
1:1	20.7	18.6	15.5	16.1	25	13
2:1	17.3	16.6	14.8	15.2	15	9
3:1	15.4	13.0	13.8	12.4	11	5

5 Stabilization of CEB's and Stabilizers

Building with earth bricks usually involves making a choice between using the available soil as it is and adapting the project to the available soil quality (building standard requirements may be compromised but saving cost) or importing suitable soils for the project or modifying the available local soil to suit the requirements with an obvious cost implication. Modifying the available soil seems the best option as this will save costs and improve the material to the required standards. Stabilization is therefore a very important aspect. Stabilization has been described as a means of modifying the properties of a soil, water and air system with the aim of obtaining long lasting properties (Houben and Guillaud, 1994). Different materials, ranging from natural to synthetic fibres, have been used in stabilizing soil materials for building construction. Most often, these materials are used in combination with either cement or lime to improve the soil properties. Some of these fibre materials include rice husk ash (RHA), peat, marl, coal ash, cassava peels and a host of others. Many researchers have studied the response and effect of the addition of these materials in improving the strength characteristics and durability of compressed earth bricks (Ola, 1989; Moore, 1987 in Attoh-Okine, 1995; Osula, 1996; Bell, 1996; Bahar et al., 2004; Venkatarama Reddy and Gupta, 2008; Billong et al., 2009; Al-Amoudi et al., 2010; Villamizar et al., 2012; Al-Jabri and Shoukry, 2014; and Cong et al., 2014). Their findings generally indicate a positive improvement in strength properties and durability of CEBs, which depend largely on the method and type of stabilization. Stabilization can therefore improve the compressive strength and durability of CEBs to suit any required purpose, but this will be subject to cost and time constraints. Durability requirements of Saudi calcareous marl soils were studied by Al-Amoudi et al., (2010) who found that the durability of the marl soils improved satisfactorily by adding 5% or 7% lime. It was however concluded that, cement stabilization provided better results, with less material losses than for lime-stabilized marl.

6 Types of Stabilization

Three methods of Stabilization have been identified in Engineering Geology and are equally relevant to building technology:

i. **Mechanical Stabilization:** This according to Lemougna et al., (2011) involves compacting the soil with the aim of improving its resistance to shearing, compressibility, permeability and porosity. This altogether leads to changes in density. The processes of mechanical stabilization are compaction and consolidation.

ii. **Physical Stabilization:** This process acts on soil texture. It is achieved by mixing different types of soil and introduction of natural or synthetic fibres from cereal plants, animals and minerals into the soil. Physical stabilization may also utilize other forms of curing which include; air cure, heat treatment, moisture curing, freezing *etc.*

iii. **Chemical Stabilization:** This involves acting on the physico-chemical properties of the soil by the addition of chemicals. This is the most widely used method in compressed earth bricks as well as in building construction generally.

The effects of cement and lime, being popular stabilisers, are discussed in more detail below.

6.1 Cement

Ordinary Portland cement hydrates with the addition of water. Bachar et al., (2015) noted that soils are mostly influenced by the hydration of cement in reaction with water which forms complex carbohydrates and this is responsible for hardening of the soil.

Chemical reactions during hydration

Mamlouk and Zaniewski, (1999) described details of the hydration process as follows:

“Tri-calcium aluminate + gypsum + water → *ettringite + heat*

$C_3A + 3C\underline{S}H_2 + 26H \rightarrow C_6AS_3H_{32},\ \Delta H = 207cal/g$ ***Equation 1***

Tri-calcium silicate + water → *calcium silicate hydrate + lime + heat*

$2C_3S + 6H \rightarrow C_3\underline{S}_2H_3 + 3CH,\ \Delta H = 120\ cal/g$ ***Equation 2***

Tri-calcium aluminate + ettringite + water → *mono-sulphate aluminate hydrate*

$2C_3A + 3\ C_6A\underline{S}_3H_{32} + 22H \rightarrow 3C_4ASH_{18},$ ***Equation 3***

Di-calcium silicates + water → *calcium silicate hydrate + lime*

$C_2S + 4H \rightarrow C_3\underline{S}_2H_3 + CH,\ \Delta H = 62\ cal/g$ ***Equation 4***

Ferrite + gypsum + water → *ettringite + ferric aluminum hydroxide + lime*

$C_4AF + 3C\underline{S}H_2 + 3H \rightarrow C_6(A,F)\underline{S}_3H_{32} + (A,F)H_3 + CH$ ***Equation 5***

Ferrite + ettringite + lime + water → *garnets*

$C_4AF + C_6(A,F)\underline{S}_3H_{32} + 2CH + 23H \rightarrow 3C_4(A,F)\underline{S}H_{18} + (A,F)H_3$ *”* ***Equation 6***

CSH is produced in the reaction shown in Eq. 2 which contributes to the initial cohesion and strength of material. CSH shown in Eq. 4 contributes more towards lasting strength of the cement paste. Although this particular reaction proceeds slowly, it is responsible for the long-term strength in a Portland cement mix/stabilisation. This is the reason why bricks made with cement should be moisture cured for a certain number of days. In Eq. 5 lime is produced, which is responsible for the added strength in cement stabilization through a pozzolanic reaction.

In summary, the cement-water hydration reaction can simple be expressed as:

$$\boldsymbol{Cement + H_2O \longrightarrow CSH + Ca(OH)_2} \qquad \textit{\textbf{Equation 7}}$$

Based on the reactions above, one could conclude that cement stabilization is well suited to lateritic soils because of the presence of iron oxides that react with cement as a result of pozzolanic reactions. However, sulphates should be avoided because of the presence of mono-sulphate aluminate hydrate that are only stable in a sulphate deficient solution. With addition of sulphate, their crystal size increases as they resort back to ettringite, which is about double the size of mono-sulphate and this volume increase is often responsible for cracking when cemented material is exposed to sulphate attack (Equation 3).

Research by the Nigerian Building and Road Research Institute (NBRRI) has shown that the addition of 4% cement to soil improves the cohesive nature of the soil resulting in good quality bricks (Olotuah, 2002). They also noted that lime is more expensive than cement in some countries such as Nigeria. Ouhadi et al., (2014) identified two sources (CAH & CSH) responsible for strength development when cement is used as the stabilizing agent compared to soil stabilized with lime. Trials on stabilization of soil using cement dates back to 1917 and, since then, it has gained a wide acceptance and usage in different engineering applications all over the world. Recently, various authors reported on the use of cement in construction works with earth materials and the improvement of engineering properties of these soils as well as lower water absorption (Walker, 1995; Bahar et al., 2004; Horpibulsuk et al., 2010; Goodary et al., 2012; Cong et al., 2014; and Khemissa and Mahamedi, 2014).

6.2 Lime

Five basic reactions are involved in lime stabilization as highlighted by Houben and Guillaud, (1994), namely:

Water Absorption: quicklime undergoes an exothermic hydration reaction in the presence of water or moist soil. Findings have shown that about 300 kcal of energy is released for every kg of quicklime added.

Cation exchange: addition of lime to a moistened soil causes an influx of calcium ions to the soil and leads to cation exchange whereby calcium ions replace the exchangeable cations (sodium, magnesium, potassium *etc.*) in the soil compounds.

Flocculation and aggregation: due to cation exchange and increase in the quantity of electrolytes in the pore water, flocculation and accretion occurs. This occur especially with clay particles.

Carbonation: lime reacts with carbon dioxide from the air to form carbonated cements.

Pozzolanic reaction: The dissolution of clay minerals in an alkaline environment produced by lime and recombination of silica and alumina in clay together with calcium to form complex aluminium and calcium silicates is mainly responsible for the strength of the material, by cementing the grains together. This is the most important reaction involved in lime stabilisation.

The following reactions take place between soil and lime according to Attoh-Okine, (1995):

i. $Ca(OH)_2 \longrightarrow Ca^{2+} + 2(OH)^-$ *Equation 8*

ii. $Ca^{2+} + 2(OH)^- + SiO_2 \longrightarrow CSH$ *Equation 9*

iii. $Ca^{2+} + 2(OH)^- + Al_2O_3 \longrightarrow CAH$ *Equation 10*

Where SiO_2 is Silica Clay, Al_2O_3 is Alumina Clay, C is CaO, S is SiO_2 and A is Al_2O_3

Combination of rice husk ash (RHA) with lime and/or cement have been shown to improve the shear strength and geotechnical properties of soils (Muntohar, 2011). He recommended a ratio of 1:1 as the optimum quantity of lime and RHA that will produce the highest strength in terms of lime and RHA addition. The chemical composition of RHA and lime are given in Table 2.

Table 2: Chemical Composition of Additives (After Muntohar, 2011)

Chemical composition of the additives.

Constituents	RHA (%)	Lime (%)
SiO_2	89.08	0.00
Al_2O_3	1.75	0.13
Fe_2O_3	0.78	0.08
CaO	1.29	59.03
MgO	0.64	0.25
Na_2O	0.85	0.05
K_2O	1.38	0.03
MnO	0.14	0.04
SO_3	0.01	0.02
P_2O_5	0.61	0.00
H_2O	1.33	0.04
Loss on ignition	2.05	40.33

It was observed by Bell, (1996) that some of the significant engineering properties of clays were appreciably improved with lime addition. However, their mixture properties vary and are dependent on the character/properties of the clay, i.e. the type, length of curing, method and quality of construction. An increase in the percentage of lime in the binder was found to increase the compressive strength of the final products and lead to a decrease in water absorption and apparent density (Billong *et.al.,* 2009).

7 Economy of Stabilization

Before deciding on the method of stabilization, the following should be considered:

i. The properties of the soil will, to a large extent, determine the quantity and quality (type) of stabilizer to be added. For cost efficiency, soils should be carefully chosen, as well graded soils will perform better. For instance, clayey soils will require more added cement than sandy soils. Previous literature recommended the use of lime for any material containing >35% clay (Houben and Guillaud, 1994). Lime as stated earlier is more expensive than cement, judging from the situation in Nigeria (Olotuah, 2002).

ii. When choosing a method of stabilization, the purpose and type of the project is important. The required strength of the bricks will determine the stabilization method as the method directly affects the strength, e.g. for a single storey building a compressive strength of about 1-4 MPa may be adequate but for a multiple storey building more than double the strength may be necessary.

iii. The time involved in the stabilization process and available funds are also critical factors. A decision has to be taken either to minimize cost by spending more time (on curing and stabilization) in producing bricks or to save time by spending more on stabilization additives. It has been found that different stabilizers take different lengths of time to attain maximum strength (Osula, 1996).
iv. In order to minimize the cost of maintaining a project, the choice of material, choice of stabilization and durability are of paramount importance. These factors help in minimizing the future expenses on maintenance.

8 Curing of CEB's

Curing is a form of mechanical stabilization necessary for bricks. A certain period of time is necessary for any cementitious material to achieve a maximum strength. This implies that moisture is retained in such material for a minimum of three to seven days after which they are exposed to air for further curing. Lime stabilization may require a longer moisture curing time. Sudden withdrawal of moisture from soil materials could lead to desiccation cracking and shrinkage.

Figure 6: A Curing Process of CEB. (After, Adam and Agib, 2011)

According to Adam and Agib, (2001) different methods are employed in ensuring a proper curing procedure and may include preventing drying out by using plastic bags, grass, leaves *etc*. as cover (Figure 6). They stated that various soils and different types of stabilizer require different curing times. Cement stabilized bricks will for instance, need a curing time of at least three weeks, while lime requires a minimum of four weeks to attain a maximum strength. Bahar et al., (2004) on the performance of compacted cement-stabilized soil, noticed rapid shrinkage during the first four days after moulding in both cement-stabilised soil and un-stabilised specimens where after the shrinkage starts to decrease. Hence, they recommended curing for the first four days after moulding, as this would reduce drying shrinkage and cracking. They reported that the shrinkage of cement-stabilised soil after 25 days was about 20% compared to 44% for the unstabilised soil bricks. Figure 7 below shows the variation of shrinkage with time for bricks with different added cement contents. It was also shown that the addition of sand reduces shrinkage as sand particles limit the shrinkage movement. The reduction in shrinkage level was given as 29% and 64% for 10% and 15% of sand content respectively. Deboucha and Hashim, (2011) reported that increasing curing periods improved the compressive strength and decreased the water absorption capacity of bricks.

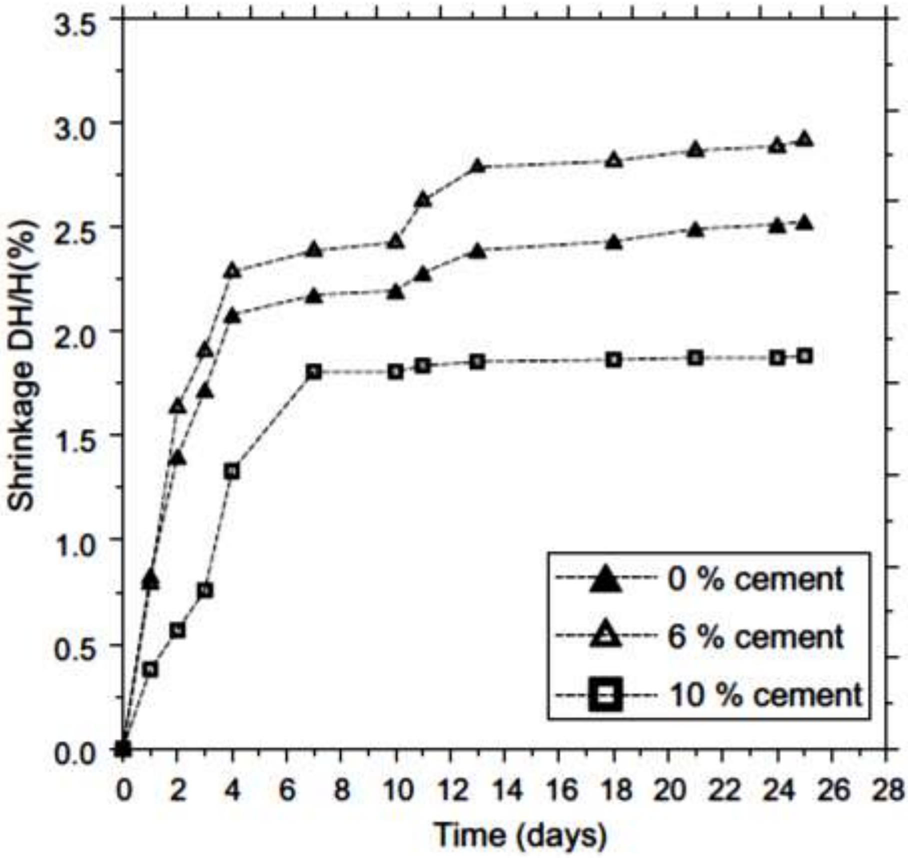

Figure 7: The Effect of Cement Content on the Development of Shrinkage. (After, Bahar *et.al.* 2004).

9 Advantages of Compressed Earth Bricks

Numerous authors have discussed the advantages of compressed earth bricks with some of the notable works being: Houben, Riggasi, (1995); Adam and Agib (2001); Kasthurba *et.al.* *(*2007 and 2008); Meriani, (2008); Lemougna *et.al.* (2011); Al-Jabri and Shoukry, (2014). In all these papers, the benefits of compressed earth bricks to the end user and to the environment at large are highlighted. CEBs are described as materials for sustainable building construction supporting a sustainable environment. Building in a 'sustainable' way offers an opportunity to utilize our resources in an efficient manner while creating habitats that improve quality of human health and well-being as well as preserving a better environment, with an affordable and natural alternative. Some of the more important benefits are described below.

9.1 Cost Efficiency

Madeador, (1994) in (Olotuah, 2002) reported that there was at least 40% cost saving when using natural building materials compared to conventional manufactured materials in identical buildings. This figure is based on findings of an experiment by the Nigerian Building and Road Research Institute (NBRRI) in collaboration with the Federal Housing Authority (FHA). He also noted that, due to the cost of cement compared to lime, the use of cement in Nigeria is more economical than using lime. Affordable housing, as defined by the UN Habitat, can therefore be achieved by using compressed earth bricks. Affordable housing is defined as "*that which is adequate in quality, location and does not cost so much that it prevents its occupants or owners from meeting other basic living costs or threatens their enjoyment of basic human rights"* (Majale *et.al.*, 2011). Table 3 shows the findings of the United Nations Human Settlement Program (UN Habitat) on the cost efficiency of compressed earth bricks. The work was carried out in Sudan, hence, the cost implication was given in the Sudanese currency (SGD).

Compressed earth bricks are cost efficient in many ways. Firstly, the raw materials are readily available in large quantities in most regions, particularly in the tropical regions. Winnowing distance is greatly reduced or eliminated totally with the availability of these materials on site. CEBs measure up to present-day building material requirements as it presents a technological alternative to imported or produced materials. The wide range of cheap presses and production units presently available in the market has made it more accessible to people from all levels of society. These presses range from manually operated to mechanical presses which are easily moved from one place to another and makes for very flexible use from small/medium scale to large-scale or even industrial applications. In addition, CEBs come in natural bright colours (purplish red to orange red) and are resistant to weathering, making them aesthetically pleasing and saves costs of painting and mortar rendering. Construction with CEBs also reduces the costs of heating and cooling due to their low thermal conductivity and high thermal capacity.

Table 3: A Comparative Cost Analysis between Burnt Bricks and CEBs. (UN- Habitat, 2011)

Cost component	Burned Brick	Stabilized Soil Blocks	Cost Difference in SGD
Materials	22,155	17,020	5,135
Labour	12,267	11,162	1,105
Total Cost of Construction	**34,422**	**28,182**	**6,240**

Estimated materials and labour cost inputs in SGD.

Source: UN-Habitat

Exchange rate as at 2011, 1USD ≈ 3SDG

9.2 Material Efficiency

Compressed earth bricks are material efficient and 30% less water is used in the production of CEBs compared to what is used in other conventional building material production. CEBs are produced from a generally sustainable resource, namely earth material (lateritic soil). These materials are recyclable, produce very little harmful air emissions, have zero or low toxicity, are durable and readily available. Generally, these materials can be regarded as green building materials, which are suitable for use in most parts of a building, e.g. foundations and walls up to roof level of any building.

9.3 Energy efficiency

Meriani Sergio., (2008) stated that energy efficient buildings should be properly sized with energy-efficient heating/cooling systems coupled with a thermally efficient building interior and electric usage for lighting, equipment and appliances should be minimised. CEBs have proven to be excellent housing construction material in cold climates due to its efficient thermal properties moderating internal temperatures in extreme outdoor temperature environments. An investigation by Bachar *et.al.* (2015) on thermal conductivity of stabilized earth concrete, concluded that densely packed CEBs have a higher thermal conductivity than other conventional materials in building construction. The production of CEBs require about 1% of the energy input compared to a similar volume of concrete. The energy required to manufacture 1 m^3 of earth (soil) bricks is about 36 MJ (10 kWh), compared to about 3000 MJ (833 kWh) that is needed to manufacture the same quantity of concrete (UN Habitat, Technical Note No. 12 cited in Adam, 2001). Compressed earth bricks are fire resistant, fired clay bricks are stronger in terms of compressive strength and are sound proof, hence, privacy is guaranteed.

9.4 Environmental Friendly

As stated earlier in the introduction, the World is moving towards a global green environment approacht and construction materials are also required to promote a sustainable environment.

Numerous benefits, both environmental and ecological, are accruable from the use of earth materials especially in the residential building construction industry. Lemougna et al., (2011) highlighted some of the salient benefits of building with earth materials. These include a drastically reduced amount of cement which in turn reduces the amount of carbon dioxide (CO_2) emitted and the total energy used in construction activities. Radhi, (2009) concludes that the largest contribution to carbon emissions emanates from power generation, transportation, industrial activities and building constructions. The production of a ton of cement generates around 0.55 tons of CO_2 and the burning of carbon-fuel produces another 0.4 tons of CO_2 (Davidovit, 1991 in Lemougna et al., 2011). The production and consumption of cement therefore contribute hugely to global warming.

It is therefore important to reduce the consumption of excessive volumes of cement through the promotion and use of environmentally friendly earth materials that utilises minimal quantities of cement.

10 Conclusions

Judging from the available literature and from the field observations by the authors, the following conclusions can be drawn:

- Compressed earth bricks have proven to be sustainable building materials for a sustainable environment.
- Lateritic soils are well suitable with minimal stabilization as durable materials in the production of compressed earth bricks. Lateritic soils are readily available especially in the tropics and sub-tropical regions and possess adequate grading characteristics required for the production of durable CEBs. Other types of soil may be used but will need more added stabilizer or mixing.
- Strength and durability of CEBs depend on the parent rock material, which determines the mineralogy, grading characteristics and type of soil derived. These parameters will also determine the amount and type of stabilizer, compaction pressure in moulding of bricks, method and duration of curing.
- Finally, for the sake of the environment, firing of clay bricks should be discouraged as much as possible since adequate stabilization methods could be employed in achieving any required strength of bricks for various construction purposes. Equally, the use of fibers have proven efficient in improving strength and durability of bricks.
- The final product and whether only stabilization or additional firing of earth materials are needed will depend on the geology of the soil, including the mineralogy, weathering mode and stage as well as the climatic region.

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Appendix

Plate 1: Compressed earth bricks made from different lateritic soils. A) Bricks after 28-day curing, exposed to test for its durability against intense weather, erosion and wind. B) After six months of exposure to intense weather, rainfall and wind.