Geotechnical Characterisation of lateritic soils from south-western Nigeria as materials for cost effective and energy efficient building bricks

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Abstract

Lateritic soils which have been described as highly weathered tropical or sub-tropical residual soils, were studied with an attempt to establish its suitability or otherwise as sustainable material in building bricks and housing development that will meet the present challenge of sustaining the environment without costing too much and maintaining a high standard of strength, durability and aesthetics. Index properties of the tested lateritic soils revealed them as mostly well-graded, comprising both cohesive (silt and clay) and cohesionless (sand and gravel) soil fraction. The geotechnical analyses on the studied lateritic soil revealed a strong compressive strength with a relatively sound dry density which could guarantee a good durability in resulting bricks made from these soil materials.

Further test on the strength and durability of the compressed earth bricks (CEBs) made from these lateritic soils revealed a brick with compressive strength ranging between 6.33 and 15.57 MPa which are considered to be good strength coupled with its sound durability strength established over a period more than one year under a complete cycle of weather and seasonal conditions.

In conclusion, lateritic soils from the study area were found to be suitable as materials for bricks (CEB) with good compressive and durability strength which qualifies them sustainable and cost effective materials for low-cost housing development.

Keywords: Lateritic soil, compressed earth bricks, suitability, energy efficient, geotechnical characterisation and durability.

Introduction

Countries around the world are facing major challenges relating to providing shelter in expanding urban areas. This problem seems more prevalent in the Developing World, e.g. West-Africa and it is often aggravated by exponential population growth, rural to urban migration, low Gross Domestic Products (GDP) and more importantly, the high cost and scarcity of building materials. United Nations Habitat report (2011) affirmed that high cost of building materials were responsible for unaffordable housing especially in Africa and was attributed to the failure of governments to recognise the use of local earth materials in building constructions. Governments rather focus on conventional building materials stipulated in the national regulations and codes with little innovation when it comes to alternative building material. The demand for more sophisticated housing infrastructure which requires large volumes of building materials in the form of raw materials and other natural resources that are limited and non-eco-friendly are on the rise (Morel et al. 2001; Jiménez Delgado and Guerrero 2007; Bachar et al. 2014; Oyelami and Van Rooy 2016). If this trend would continue, natural resources will be totally depleted which may lead to environmental degradation. This concern brings to the fore the need to look elsewhere and find better alternatives rather than depleting conventional building materials. There is an urgent need to explore innovative technologies in building construction which requires lesser dependence on imported building materials and promoting the use of locally available materials while maintaining the best of standard practices without compromise to quality and aesthetics. The growing environmental concerns have led to the discovery and appreciation of the unique qualities of earth materials. The use of earth material in construction works, will not lead to depletion of resources, increased pollution (water, air, soil), waste generation and biological changes (Bachar *et.al.*, 2015)

Researchers have proposed tropical soils as a sustainable resource to be utilised in the construction of housing around the world (Houben and Guillaud 1994; Rigassi 1995; Arumala 2007; Oti et al. 2009b; Oti et al. 2009a; Das et al. 2010; Deboucha and Hashim 2011; Goodary et al. 2012; Villamizar et al. 2012; Bachar et al. 2014; Taallah et al. 2014). Laterite as a typical tropical soil that could fill the gap between a housing deficit and provision of modest housing for the growing populations in Africa. In achieving this, an in-depth understanding of the suitability of lateritic soil must be established with the aim of creating awareness of its important use and building confidence in its efficacy in brick making and housing development.

Therefore, this paper looks critically at the geotechnical properties of lateritic soil which make it suitable as a material for brick manufacturing with a focus on the influence of geology on its structure, texture and mineralogy. This should give a better picture of the various properties of lateritic soils derived from different parent materials in their use for compressed earth bricks.

The use of naturally available tropical soils to produce Compressed Earth Bricks (CEBs) that are economical and fire resistant has been well researched (Bahar et al. 2004; Horpibulsuk et al. 2005; Jiménez Delgado and Guerrero 2007; Kasthurba et al. 2007; Kasthurba et al. 2008; Das et al. 2010; Deboucha and Hashim 2011; Muntohar 2011; Reddy 2012; Bachar et al. 2014; Nagaraj et al. 2014). Most of these papers are mainly centred on the strength, durability and important use of tropical soils. In the present study the focus is on the geological significance of lateritic soils related to their parent materials and the influence thereof on their suitability or otherwise for use in the production of compressed earth bricks.

In order to preserve and sustain the environment the use of environmentally friendly building materials, commonly referred to as green building materials must be encouraged and promoted in order to realise the concept of sustainable building. Compressed earth bricks, as building material entirely satisfies the requirements of sustainable building.

For a proper understanding, the word 'lateritic soil' is used here to describe "*the highly weathered tropical or sub-tropical residual soil with varying proportions of particle sizes ranging from clay size to gravel, usually coated with sesquioxide rich concretions with colours varying from liver brown to rusty red and 'laterite' would be regarded as fitting exactly the definition but in the case of laterites, non-residual (transported) soils are often also included"* (Oyelami and Van Rooy 2016).

The Study Area

It is very important to understand the geomorphology of an area when dealing with tropical soils, that is, the relationship between the geology and topography of the area. Different authors have established that landform influences the formation and characteristics of soils, especially lateritic soils (e.g. Adeyemi, 2003; Bourman and Ollier, 2003; Mcfarlane, 1990; Ola, 1978).

The study area covers the towns of Osogbo (OS) and Ado-Ekiti (ADK) in Osun and Ekiti States respectively in Nigeria. Ado township and its environs are referred to as ADK and Osogbo and its environs as OS. The physical settings of the areas and geology are shown in Figures 1 and 2.

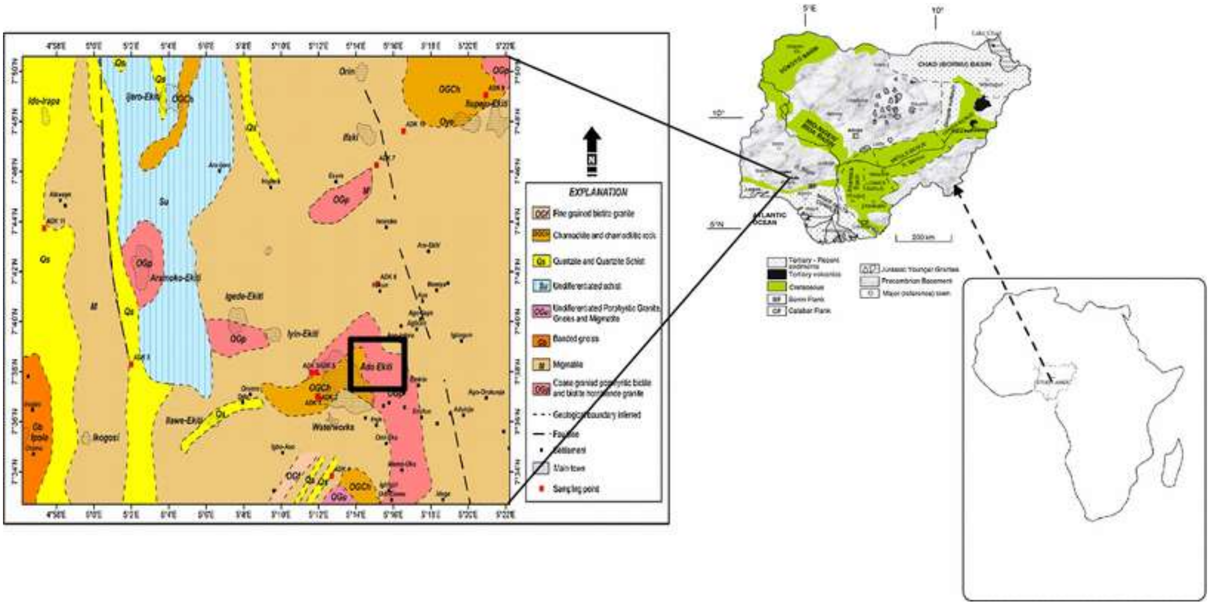

Fig. 1. Geological map Ado-Ekiti. *Inset outline of map of Africa and generalised geological map of Nigeria* (modified after Nigerian Geological Survey Agency 2008)

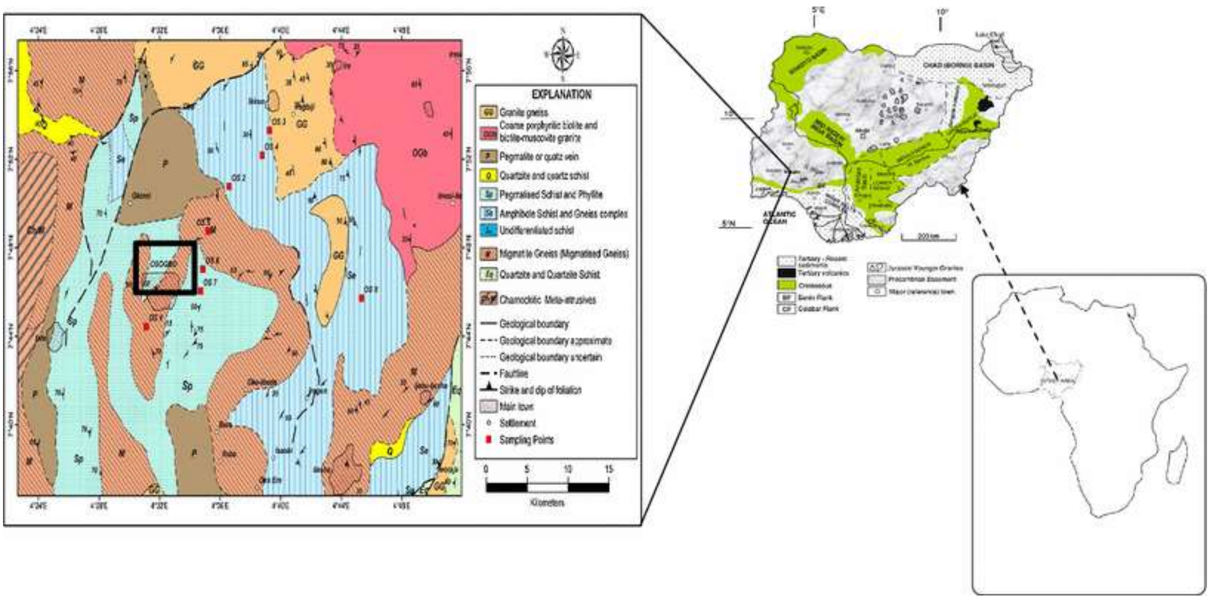

Fig. 2. Geological map of Osogbo. *Inset outline of map of Africa and generalised geological map of Nigeria* (modified after Nigerian Geological Survey Agency 2009)

The topography of the area can be described as undulating with both study areas characterised by hills and valleys. The elevated platforms are the high-rise outcrops. The altitude of sampling points within ADK ranges between 406 and 582m while that of OS is between 342 and 395m. Ekiti State (ADK) has the highest elevation points because the whole state is located at a high altitude above the sea level, and the name Ekiti means "hill" which can be translated to "mountainous region". The areas underlain by basement show a dendritic drainage pattern influenced by structural control. The study area falls within the tropical climatic zone with well-defined rainy (wet) and dry seasons. The rainy season occurs between March/April to September/October and November/December to February for the Harmattan or dry season. The total annual rainfall ranges between 1500 and 2500 mm with peaks in June and October. The mean annual temperature is about 28^0 with 3^0 annual variability and relative humidity of 90% average throughout the year (Gbadegesin and Nwagwu 1990).

Geology of the study areas

Ado-Ekiti and its environs are mostly underlain by Precambrian crystalline rocks of igneous and metamorphic origin. Prominent lithologies include; charnockites, porphyritic granite, fine to medium grained granite, migmatite, banded gneiss, quartzite and schist (Fig. 1). Migmatite and gneiss occur as migmatite-gneiss, granite gneiss and banded gneiss. The age of the migmatite gneiss complex is between 2.0 – 3.0 Ga. (Dada, 1998; Rahaman et.al., 1988 and Talabi 2013). The granites occur as later intrusions within the migmatite–gneiss–quartzite complex and are of Pan-African (600±150 Ma) age (Okonkwo and Folorunso, 2012; Oyinloye, 1998; Talabi, 2013). It was, however, noticed that weathering is more pronounced in the porphyritic granite than in the fine-medium grained granite. Charnockites occur within the study area as intrusive rocks emplaced during the Pan-African orogeny and are massive greenish to dark-grey with medium-coarse grained texture. The charnockites around Ekiti occur along the margin of the older granite bodies (Afolagboye et al., 2015; Rahaman, 1976; Talabi, 2013). The mineralogy of rocks within this area provides a clue to the strength and texture of the resultant soils. It is for instance expected that quartzite will produce soils that are medium to coarse grained in texture with good strength properties while rocks like schist and migmatites with high mica and feldspar content are expected to breakdown into fine grained soils with a higher clay content.

Osogbo lies within the Precambrian Basement Complex of south-western Nigeria that forms part of the Pan-African Mobile and Ilesha/Iwo schist belts east of the West African Craton. Lithologies within this area include; migmatite/gneiss, pegmatites and metasediments predominantly amphibolites, quartz schist, amphibole schist and pegmatite schists (Fig. 2). Low temperature regional metamorphism coupled with hydrothermal alteration were responsible for the development of the varieties of schist in the area (Adepelumi et al., 2008; Elueze and Kehinde-Philips, 1993; Kehinde-Phillips and Tietz, 1995; Tijani and Onodera, 2009). Another rock type also present within this region is quartzite, associated with quartzite ridges that form part of the Ilesha schist belts, with surficial soils characterized by strongly weathered residual profiles forming lateritic soils as a result of chemical weathering of the parent rock material.

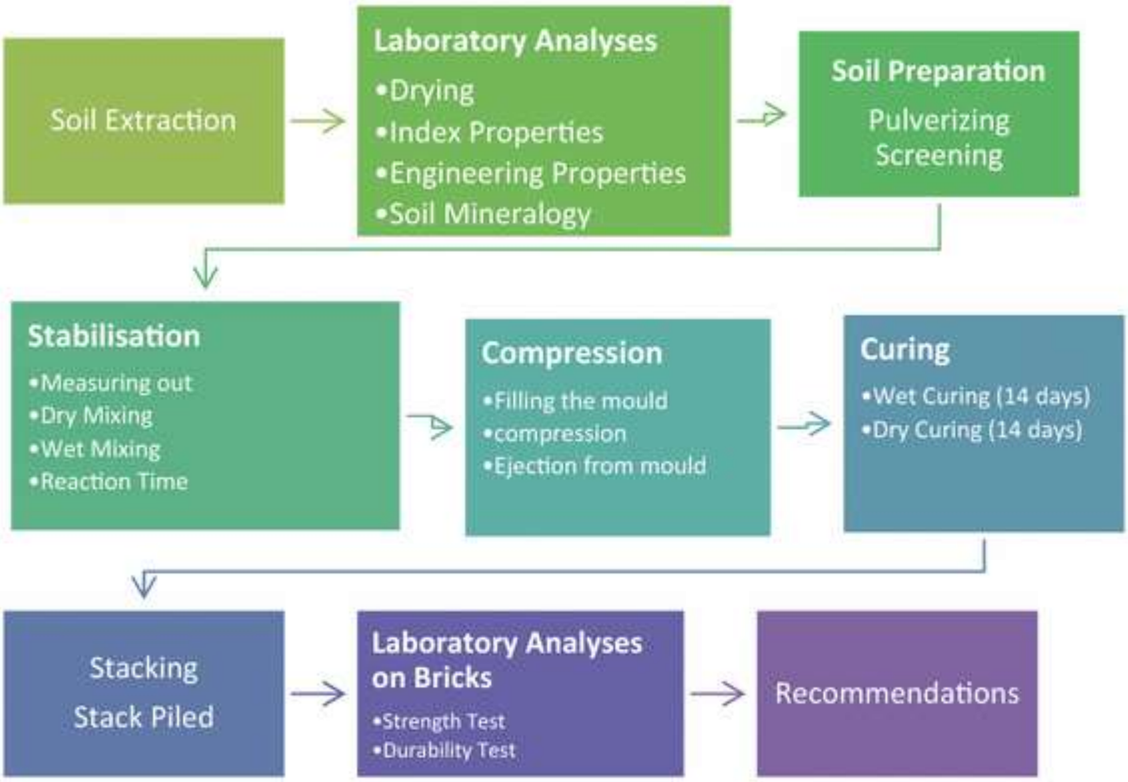

Fig 3 Flowchart of the methodology adopted in the present study

Methodology

Lateritic soil samples were collected from existing borrow pits that have previously been used for road construction material and are presently used as a source for brick and building construction material. A detailed flowchart of the methodology used during this study is presented in Figure 3. A total of 25 disturbed soil samples were collected at 19 locations in and around Osogbo (sample reference OS) and Ado Ekiti (sample reference ADK). The samples were typically taken from between 2 and 10 m depths. Soil samples within the Schist belts (Osogbo) tend to have variable physical properties over short distances and this necessitated taking two different soil samples based on changes in colour within a specific location. Based on already established standards for earth buildings (Centre for Development of Industry CDI; African Regional Organization for Standardization ARSO, 1998 and Standards Australia and Walker, HB 195, 2002), a number of in-situ tests were also carried out on the soil at each borrow pit which included a visual description to estimate the relative proportions of the various grain sizes and differentiate lateritic soil from top soil based on colour, smell test to differentiate organic soil from other types of soil (organic soils smells musty) and a touch test.

The samples were air dried by atmospheric exposure for about three weeks prior to laboratory testing. Laboratory testing can be grouped into soil classification tests, geotechnical tests, mineralogical tests and brick durability testing. The classification tests include specific gravity, grain size distribution analysis, and Atterberg limits. Geotechnical tests include compaction tests (California Bearing Ratio - CBR) and direct shear tests. All tests were carried out according to the British Standard, BS 1377 (1990) procedures with small modifications where necessary. Compaction tests were carried out on the soil at different levels of cement addition, starting from 0% up to 10% cement addition to the soil samples by mass. This was done to determine the response of the soil at different cement contents and the effect on the optimum moisture content at which maximum density can be achieved. Each soil sample was compacted using the so-called West Africa method in order to avoid over-compaction (Gidigasu, 1976, Adeyemi and Oyeyemi, 2000). CBR was determined at different cement contents to establish if there is any significant effect on the bearing capacity of the soil and also on the strength of CEB's. The response of the soil to soaking was also assessed by determining the CBR of soaked soil samples.
The suitability of lateritic soil for brick making typically forms an important part of the assessment of different lateritic soils from different localities. The soil samples were first mixed based on location and not on sampling points followed by soil screening and pulverising after which 50 kg was measured out. Portland limestone cement (42.5R grade) was used as stabilizer for the brick making and 5% (2.5 kg) cement was then added to the soils based on the results of the different tests mentioned above. The soil and cement were properly mixed in the dry state to form a homogenous mass after which water was added according to the optimum moisture content derived from the compaction tests. In order to ascertain the proper water content a drop test was carried out on the mixture before transferring it into the mould. The soil-cement-water mixture was transferred into a manual CIRAM (QR 40) low pressure (2 – 4 MPa) hand press mould and pressed about 3 times before removing the damp brick from the mould. The brick was then transferred immediately to a curing section where it was moisture cured for 14 days before being exposed to air and sunlight for another 14 days. This procedure was repeated for all the samples from the 15 locations producing an average of 6 bricks per location. The pictorial description of the processes involved is given in Fig. 4 which illustrates the step by step procedure. After 28 days of combined moisture and air curing, the dry bricks were subjected to dry compressive strength tests according to the Standards Australia and Walker, (2002) specification for earth buildings. Durability tests were carried out by exposing the bricks to natural weather conditions. The bricks were stacked in a wall without any mortar and left in an open field exposed to wind, rain and extreme heat. Physical responses of the bricks were assessed quarterly for one year and the results are shown in Fig. 5.
Multivariate regression analyses and linear correlation, involving the correlation coefficient, T-test and F-test were used to establish the relationships between various variables and determine their rate of dependence on each other. Pearson's correlation coefficient between variables ranges between positive (+1) and negative (-1) unity where a correlation of +1 signifies a strong direct relationship between two variables while a correlation of -1 signifies that a variable is inversely related to the other (Davis 2002). T-test and F-test were carried out at both 0.05 (95%) and 0.1(90%) level of significance, at 95% and 90% confidence intervals.
The study adopts a linear regression equation to evaluate the effect of X_1, X_2-----X_k on dependant variable Y. (Unless otherwise stated, our dependant variable Y is the brick strength, while X_1…. are the variable parameters in terms of the index and engineering parameters in this case). Population regression equation for the (PRF) is stated as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \text{---------------------} + \beta_k X_k + \mu \text{ ---------} \qquad \text{Eq. 1}$$

Since this research only cover a certain part of the whole population from where representative sample were taken and conclusion drawn based on the analyses carried out on the samples, generalisation can be made based on these conclusions. Therefore, the sample regression function (SRF) is as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \text{---------------------} + \beta_k X_k + e \text{ ----------------} \qquad \text{Eq. 2}$$

(Where μ is the population mean and e is the error factor)

The T-test and F-test for all samples were computed using SPSS software which gives a T-test and F-test at a 95% confidence interval, the results were again tested at 90% confidence interval as well, this implies that any result less than 0.05 for 95% confidence interval and 0.1 for 90% confidence interval are significant while anyone greater than 0.05 and 0.1 respectively are not significant.

Fig 4: Pictorial description of processes involved in brick making. (starting from soil screening, stabilizer, mixing, compression, curing, stack piling and use)

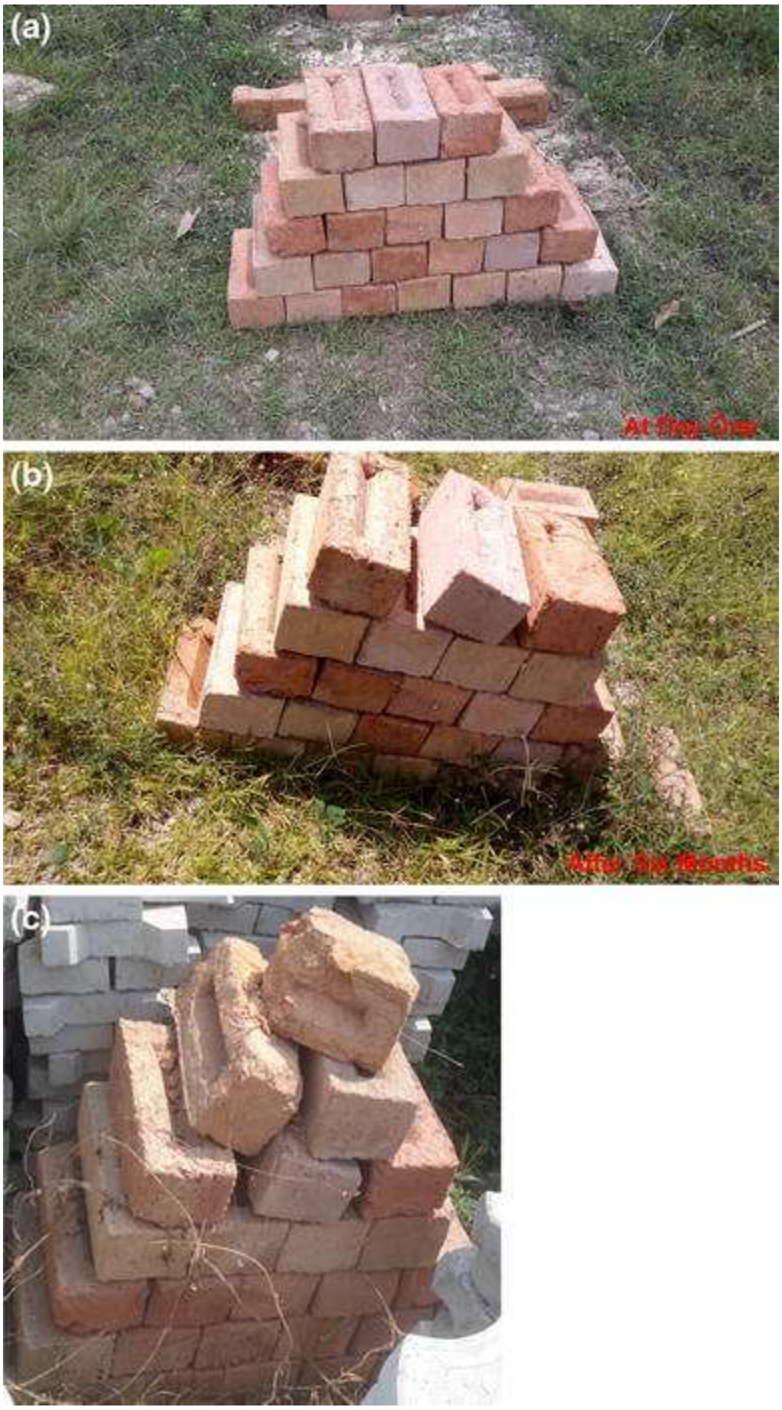

Fig 5: Compressed earth bricks made from different lateritic soils. A) Bricks after 28-day curing, exposed to test for its durability against intense weather, erosion and wind. B) After six months of exposure to intense weather, rainfall and wind (A&B after Oyelami and Van Rooy 2016) C) After One year of exposure to intense weather.

Results and Discussions

Index Properties

The results of the index properties are presented in Table 1and 2 with the corresponding specific gravities. The soils were classified according to the AASHTO and Unified (USC) systems which show the ADK soils to be predominantly clayey sand (SC) and the OS samples falling mainly into the silty sand (SM) group.

Soils from the study areas are all well graded, which implies that they would be expected to have good compaction characteristics with low porosity and low permeability (Goodary et al. 2012). The grain size

Table 1 Index Properties of the Soil (ADK)

	Specific Gravity	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Amount of Fines (%)	Amount of Coarse (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Linear Shrinkage (%)	AASHTO Classification	USCS
ADK 1	2.63	26.4	36.84	28.49	7.99	36.48	63.24	32.4	17.1	15.3	1	A-6	SC
ADK 2	2.71	25.64	36.14	29.73	8	37.73	61.78	26.01	12.8	13.21	0.8	A-6	SC
ADK 3	2.65	18.87	37.37	26.91	10.22	37.13	56.24	55.04	23.9	31.14	0.9	A-7-6	SC
ADK 4	2.25	37.69	44.89	11.71	2.77	14.48	82.58	37.33	22.2	15.13	1	A-2-6	SM
ADK 5	2.72	20.76	36.89	39.35	3	42.35	57.65	46.2	18	28.2	0.9	A-7-6	SC
ADK 6	2.64	1.2	70.5	22	5	27	71.7	33.96	16.1	17.86	1.1	A-2-6	SM
ADK 7	2.87	8.71	43	36.51	11.49	48	51.71	32.17	19.32	12.85	1	A-6	SC
ADK 8	2.64	21.2	44.42	34.66	0	34.66	65.62	40.17	17.6	22.57	1.1	A-6	SC
ADK 9	2.89	12.06	43.38	34.41	10	44.41	55.44	38.56	21.4	17.16	0.9	A-6	SC
ADK 10	2.9	4.14	46.16	35.65	13.89	49.54	50.3	31.56	18.17	13.39	0.8	A-6	SC
ADK 11	2.85	20.5	40.78	33.58	5.24	38.82	61.28	32.1	16.6	15.5	0.9	A-6	SM

Table 2 Index Properties of the Soil (OS)

Index Properties	Specific Gravity	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Amount of Fines	Amount of Coarse	Liquid Limit	Plastic Limit	Plasticity Index	Linear Shrinkage	AASHTO Classification	USCS
OS 1A	2.72	38.39	47.11	14.49	0	14.49	85.5	40.18	13.6	26.58	0.9	A-2-6	SM
OS 1B	2.64	7.5	44.32	24.19	24.06	48.25	51.82	42.56	18.2	24.36	1.2	A-7-6	SC
OS 2A	2.72	3.81	55.47	23.7	16.4	40.1	59.28	51.82	35.2	16.62	1.1	A-7-5	SM
OS 2B	2.62	25.96	43.54	26.16	2.54	28.7	69.5	44.56	32.5	12.06	1	A-2-7	SC
OS 3A	2.54	7.76	46.24	43	0	43	54	44.94	29.9	15.04	1.2	A-7-6	SM
OS 3B	2.62	37.93	47.03	14.74	0	14.74	84.96	42.7	30.4	12.3	0.9	A-2-7	SM
OS 4A	2.71	17.23	34.13	28.93	19.31	48.24	51.36	51.16	16.6	34.56	1.3	A-7-6	SC
OS 4B	2.56	2.07	53.89	21.78	22.26	44.04	55.96	43.92	19.8	24.12	1.2	A-7-6	SC
OS 5A	2.8	13.98	46.72	28.61	7.49	36.1	60.7	35.63	17.5	18.13	1.2	A-6	SC
OS 5B	2.76	23.54	41.89	25.14	7.24	32.38	65.43	38.6	33.7	4.9	1.1	A-2-4	SC
OS 6A	2.25	6.24	48.88	30.92	12.74	43.66	55.12	53.76	29.2	24.56	1.3	A-7-6	SC
OS 7A	2.74	31.42	41.1	23.51	0	23.51	72.52	47.53	21.9	25.63	1.2	A-2-7	SM
OS 7B	2.5	12.16	39.95	29.52	17.7	47.22	52.11	36.26	17.4	18.86	0.9	A-6	SC
OS 8	2.7	8.71	43	36.51	11.49	48	51.71	40.79	18.1	22.69	1.2	A-7-6	SC

SC-Clayey Sand, SM- Silty Sand

distribution, compaction characteristics, porosity and permeability are all very relevant in the making of compressed earth bricks as the compressive strength is achieved mainly by compaction. The amount of fines (which corresponds to particle sizes from >0.002mm to 0.06mm) ranges generally between 14.48 - 49.54% with an average of 37.3% for ADK lateritic soils while that of OS is 36.6% (Figs. 6a & b). According to the literature this can be considered suitable for construction (Houben and Guillaud 1994; Rigassi 1995; Jiménez Delgado and Guerrero 2007; Adeyemi and Wahab 2008; Oyediran and Okosun 2013; Giorgis et al. 2014; Adeyemi et al. 2015). The coarse particle (which corresponds to sand and gravel particle sizes, 0.06mm to 20mm) contents ranged between 50.3 - 85.5% with the individual averages at 61.6% and 62.1% for the ADK and OS lateritic soils respectively. These results are typical of soils derived from rocks that are mostly felsic in origin and the soils from both sample areas reflect the mineralogical and textural characteristics of the parent rock. (Adeyemi and Oyeyemi, 2000 and Millogo et al., 2008).

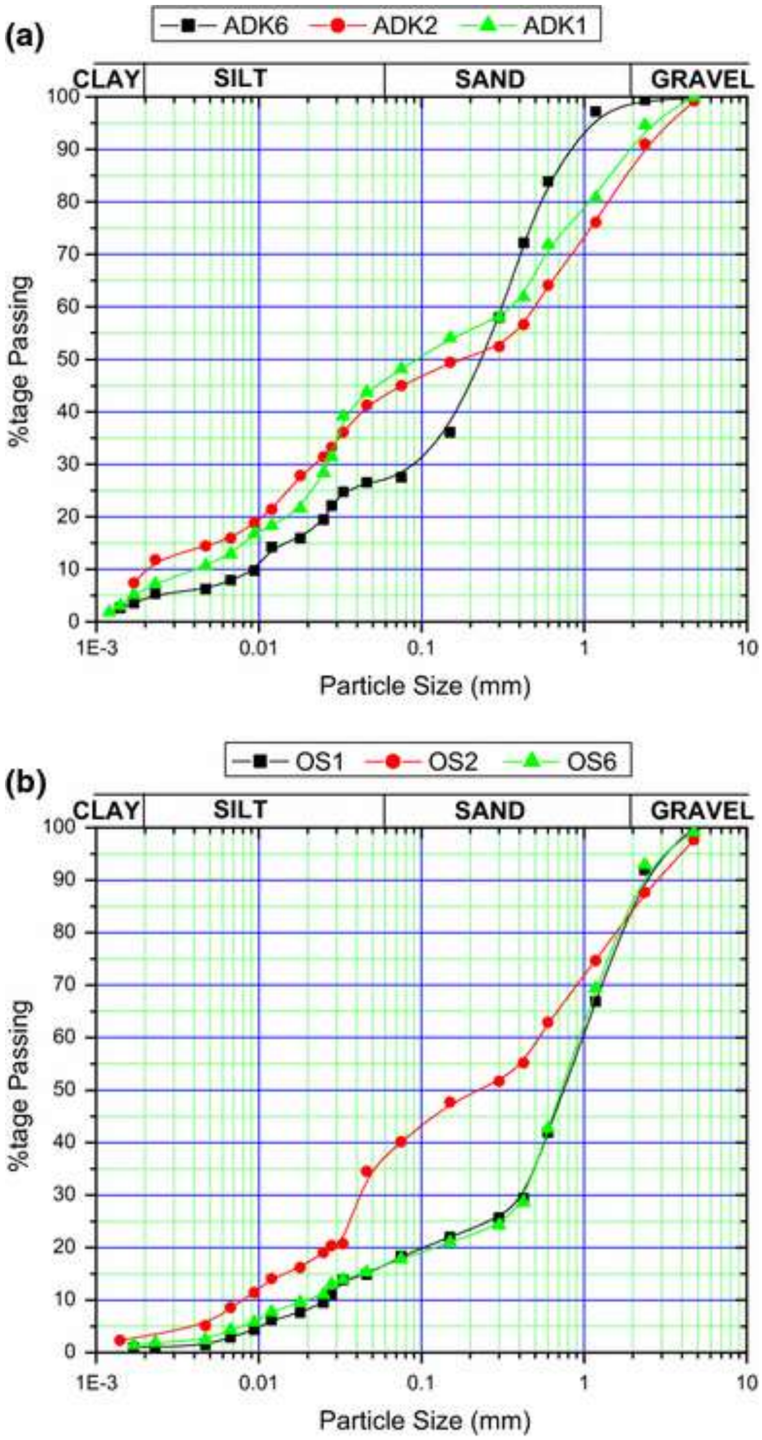

Fig. 6a & b Grain size distribution of representative samples from both locations.

Building standards and published sources agree on the need for a minimum clay content in soil material used as construction material (Centre for Development of Industry CDI; African Regional Organization for Standardization (ARSO, 1998), The United States Office of Internal Affairs handbook for building homes of earth, (Wolfskill et al., 1970), The Australian Earth Building Handbook, (Standards Australia and Walker, HB 195, 2002); Houben and Guillaud, (1994); Delgado and Guerrero, 2007). The general consensus is a maximum grain size of 20 mm with slight variation in the recommended maximum clay content. Houben and Guillaud, (1994) recommended a maximum clay content of about 23% , (Rigassi, 1995) recommended between 6 - 30% clay, 10 - 25% silt, 25 - 80% sand and 0 - 40% gravel and other recommendations cited in Delgado and Guerrero, (2007) falling within the range of 5 - 40% clay,10 - 30% silt and 25 - 80% sand and fine gravel. It is clear from the above that there is still no agreement between the different standards and that recommended grain sizes are listed according to the soil properties occurring in various regions. Goodary et al., (2012) recommended a well graded soil with a sizable amount of fines which will assist with handling on demoulding and add cohesion in bricks: however, they caution against excessive clay as well, which may lead to certain negative behaviour in these bricks. Judging from the aforementioned, all the soils considered during this study are suitable for use as materials in CEB.

The effect of grain size distribution is reflected on the brick strength (Table 6), It was found that lateritic soils derived from the schist belt region (OS) tend to give higher brick strengths due to the specific particle size distribution (higher amount of fines), amount of stabiliser added i.e. 5% and more importantly, the load at compression (compaction pressure) (Adam and Agib 2001; Oyelami and Van Rooy 2016). Based on the fact that a low pressure manual mould was used, the load at compression depended partly on the effort of the human operator. It is not possible to apply a consistent load to all the bricks and this obviously influences the density of the bricks which is directly related to the strength of the bricks.

In conclusion it is clear that a well graded soil, which depends on the parent rock, is better suited to sound brick production than poorly graded soils.

A multivariate regression analysis with the soil index properties (particle size, liquid limit and plasticity index) as independent variables and brick strength as the dependent variable, shows that the index properties of soils have a significant influence on brick strength. The F-test has a value of 2.569 (0.070 significance level) at the 90% level of confidence (Table 4). A correlation matrix showing the linear relationship between individual parameters is presented in Table 7. The T-test reveals a very strong influence of plasticity index on the brick strength at 95% confidence level.

Consistency of soil and its impact on strength of bricks

The index test results show the following ranges of consistency of the samples from both localities: liquid limit ranges between 26.0 and 55.0%, plastic limit between 12.8 and 35.2% while plasticity index ranged from 4.9 to 34.56% (Tables 1a & b). The Plasticity chart in Figure 7 show that most of the soils from both localities are inorganic clays with medium plasticity. These soils are therefore considered suitable for earth building as it is generally accepted that soils for earth building usually fall within the inorganic clay of medium plasticity as well as inorganic silts of low and medium compressibility in the Casagrande chart (Delgado and Guerrero, 2007). The importance of compressibility is stressed in Rigassi (1995), as a parameter that defines the maximum capacity of a soil to be compressed at a particular compaction energy and moisture content. This again stresses the importance of a certain amount of fine particles (clays and silts) in any particular soil to be used as material in the production of CEBs. It is suggested that up to 35% fines may be suitable for soils in CEB production and to prevent overuse of stabiliser, a minimum amount of about 10% fines may be required in these soils. A high clay content will not be acceptable due to high expected shrinkage in CEB's produced from such soils. Although stabilisation with lime has been suggested for soils with more than 35% clay, it may not be economical (Houben and Guillaud 1994; Oyelami and Van Rooy 2016). The soil index properties were found to have a significant influence on brick strength at a 10% level of significance as estimated through the F-test while the plasticity index was found significant at 5% which reflects a strong influence on the strength of bricks (Table 4).

The specific gravity of the lateritic soils from the two locations fall within a range of about 2.25 – 2.9 with an average specific gravity of 2.71 for ADK and 2.6 for OS samples. This is due to the influence of the sesquioxides present, especially Iron (Fe) bearing oxides, and it therefore confirms that most of them are lateritic soils.

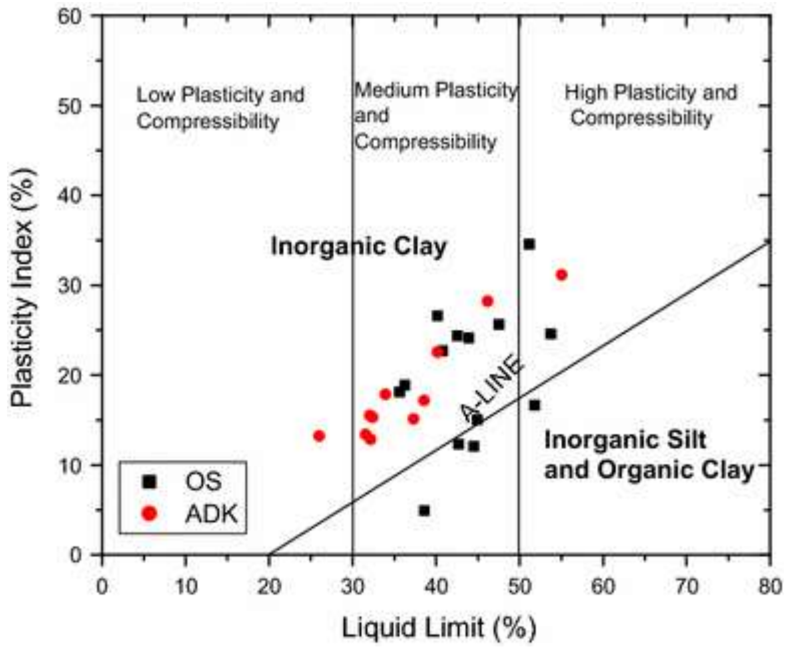

Fig. 7 Plasticity chart of soil samples from the study area

Engineering Properties of Soil.

The engineering properties of the lateritic soils investigated during this study are summarised in Table 3. The tables show the different geotechnical tests carried out on the soils, and include compaction testing, California Bearing Ratio and the shear strength parameters (shear strength of soil, τ., cohesion, c and angle of internal friction, φ). Results from these three tests are discussed below:

Compaction Test

Compaction tests were executed on soil samples with cement contents of 0%, 5% and 10% at West-African level of compaction. The results show corresponding optimum moisture content ranges of 12 – 23%, 12.4 – 23% and 13 - 24% with maximum dry densities of 1476 – 1910 kg/m^3, 1580 – 1930 kg/m^3 and 1630 - 1970 kg/m^3 respectively. The optimum moisture results do not reflect much effect when increasing the cement content. The presence of cement when water is added to the soil to reach maximum dry density at the optimum moisture content seems to have no effect on the role water plays to mobilise soil grains to move to a denser packing. These water contents are useful to determine the amount of water to add when producing CEB's. Addition of cement, however, increases the maximum dry density of the soil which is important in CEB quality and durability as higher MDD signifies denser packing of grains, lower permeability and higher strength. There are no specified standards for compaction requirements of soils for CEB but there is a prescribed maximum density for the brick after compression. The compaction characteristics of a soil used for CEB manufacture gives a good idea of the OMC and MDD that dictates the water content needed in order to achieve a maximum density in the bricks. Schroeder, (2012) suggested that OMC with a defined compaction energy helps in identifying the maximum weight of a soil per volume. Delgado and Guerrero, (2007) recommended a water content verification test using a *"drop test"* in which a handful of moist soil is squeezed into a ball and dropped from a height of about 1m and interpreting the moisture level by describing the shape at impact. They also recommended a maximum density of 2 300 kg/m^3 for CEBs. Compaction test results of soils with 5% cement have been found to be significant at 95% confidence limit, which implies that 5% cement starts to influence the strength of CEBs. It is therefore recommended that 5% cement addition is sufficient to achieve the required compressive strength in CEBs, but the soil properties must also be taken into account. Statistical evaluation show a 95% significance of the MDD at both 0 and 5% cement, which further established the significance of the compaction characteristics of a soil in the overall strength of the bricks produced.

Table 3 **Summary Table of the Engineering Properties of the Soil at Different Cement Content (ADK)**

	Engineering Properties	ADK 1	ADK 2	ADK 3	ADK 4	ADK 5	ADK 6	ADK 7	ADK 8
CBR at 0% Cement (%)	Unsoaked	34.15	15.63	22.47	22.40	14.88	50.30	17.56	31.25
	Soaked	10.64	7.96	8.33	10.57	6.62	13.99	6.70	11.68
	Reduction (%)	68.85	49.05	62.91	52.82	55.50	72.19	61.86	62.62
	Soaked MC	15.1	26.1	22.6	22.2	22.1	20.1	25.4	23.2
	Increase in MC	25.8	13.5	16.3	19.6	17.7	14.3	12.6	24.6
CBR at 5% Cement (%)	Unsoaked	37.35	24.63	30.36	25.97	17.34	54.91	22.77	45.76
	Soaked	11.46	12.35	10.49	11.61	7.74	15.33	8.41	15.03
	Reduction (%)	69.32	49.85	65.44	55.30	55.36	72.09	63.07	67.15
	Soaked MC	15.7	26.6	23.8	22.7	23.4	21.4	27.1	24.1
	Increase in MC	26.8	13.6	19.0	18.4	21.6	19.0	17.8	28.0
CBR at 10% Cement (%)	Unsoaked	46.88	46.21	35.42	56.70	21.35	53.27	31.62	45.46
	Soaked	14.43	10.19	10.12	14.96	9.08	15.10	10.86	14.14
	Reduction (%)	69.21	77.94	71.43	73.62	57.49	71.65	65.65	68.90
	Soaked MC	15.8	27.3	24.0	23.4	23.8	22.7	27.7	23.3
	Increase in MC	21.6	13.8	17.8	12.5	21.2	20.6	15.3	21.4
Compaction at 0% Cement	OMC (%)	12	23	19.4	18.6	18.8	17.6	22.6	18.6
	MDD (kg/m^3)	1910	1565	1820.04	1865.15	1680	1895	1640	1890
Compaction at 5% Cement	OMC (%)	12.4	23.4	20	19.2	19.2	18	23	18.8
	MDD (kg/m^3)	1930	1580.22	1840	1880	1720	1920.15	1650	1910
Compaction at 10% Cement	OMC (%)	13	24	20.4	20.8	19.6	18.8	24	19.2
	MDD (kg/m^3)	1970.06	1630	1890	1905	1750	1950	1690.02	1930
Shear Strength	C (kPa)	29	80	35	110	34	150	120	144
	φ (^{o})	40	41	42	38	40	24	38	36
	τ (kPa)	63.30	115.54	71.81	141.94	68.30	168.20	151.94	173.70

Table 4 Regression Analysis between Index Properties and Brick Strength

Variables	Coefficient	t - statistic	Significance
(Constant)	-32.955	-1.025	0.317
Amount of Fines (X1)	0.384	1.246	0.227
Amount of Coarse (X2)	0.391	1.232	0.232
Liquid Limit (X3)	0.012	0.145	0.886
Plasticity Index (X4)	0.200**	2.335	0.030
	R = 0.583	**R^2 =0.339**	**F = 2.569 (0.070)***

Note: * significant at 10% and ** significant at 5%. Dependant variable: Brick Strength

California Bearing Ratio (CBR)

The CBR was determined at the maximum dry density (MDD) and OMC on samples with cement content of 0%, 5% and 10% and for both unsoaked and soaked conditions. Soaking was carried out to predict the response/behaviour of soil to moisture under soaking condition. A summary of the results (Table 3) shows a reduction in strength due to soaking and an improvement in the resistance of soil to applied load due to increase in cement content. Unsoaked CBR values for soils with 0%, 5% and 10% cement content are between 15 to 50, 17 to 62 and 21 to 66 respectively, while the soaked CBR values falls between 7 to 14, 8 to 20 and 9 to 25 respectively.

Soils from OS performed better with added cement than the soils from ADK, probably due to the OS soils containing more silty sand (SC). It has been stated that the addition of cement to coarser grained soils tends to increase the CBR values of the soil (Basha et al. 2005; Goodary et al. 2012), this is because fine particles tends to fill up voids within sands and silts. It seems that the CBR value can be used to determine soil suitability for CEB's and may assist with predicting the required cement content, the likely response of bricks to increasing moisture content especially in a water logged environment and the response of the soil to stabilisation. The reduction in strength with an increase in moisture content may also indicate the response of the soil to water ingress and the related effect on the soil strength. This is because of the presence of fine particles in lateritic soils which swells in contact with water thereby reducing their strength. In this way it may be possible to predict the optimum amount of stabiliser that will produce the best resistance to water ingress of the bricks. Although multivariate regression does not show a significant level of influence between CBR values and brick strength (Table 5), this does not take away from the usefulness of the CBR value to get an idea of the characteristics of a soil used in brick making (Table 4).

Shear Strength Characteristics

The shear strength refers to the maximum resistance a soil could offer to shear stress before failure and is an important mechanical property of soil which controls it's stability under load. Shear strength is dependent on the structure/nature of soil, inter-particle frictional resistance, force of attraction (cohesion) and fluid pressure within its pores (González de Vallejo and Ferrer 2011). The strength parameters from the tested soils from ADK (Table 3) show cohesion values between 29 and 150 kPa and from the OS site the cohesion falls between 46 and 114 kPa. Corresponding internal friction angles for both sites fall between 24^o and 42^o while the shear strengths range from 63.3 to 173.0kPa and 69.1 to 148.3kPa for ADK and OS respectively. A critical look at the results reflects the impact of the percentage of fines on the cohesion and can be explained by the parent rock mineralogy. Minerals present include the following in the order of abundance, kaolinite, quartz, muscovite, goethite, heamatite, microcline, anatase and rutile. Oxides include among others, SiO_2, Al_2O_3, Fe_2O_3. The presence of coarse, low-friction, platy minerals around the Osogbo axis may be responsible for the slightly lower cohesion observed from the results as presented in Table 3 with an attendant effect on the shear strength of the lateritic soils. Adequate attention has not been given to the role of strength parameters of soil materials (i.e. c and φ) in the strength and durability of earth bricks. The results of this present study have been able to indicate the significance of these parameters on the strength of bricks. This is established by the result of the t-test carried out, which shows that cohesion of soil is significant at 95% level of confidence while angle of internal friction was found to be significant at 90% confidence level (table 5. The role of shear strength in brick making cannot be overemphasised, it forms one of the basic parameters necessary for the choice of soil material in brick making. Judging from the result of shear strength, materials from both locations possess a good strength for durable and strong bricks. This reflects the role of clay as a binding agent in the material and sand-sized material as an indispensable constituent as well. An adequate mix of coarse and fine material is more important in soil selection for brick making than in other construction materials: this is because fine materials plays an initial role in the binding process and aid the compaction properties of a soil, coarse particles are responsible for the long term durability of the brick and they react easily with cement to form a lasting cohesion (Muntohar 2011). The combination of clay and sand naturally complement each other by occupying void spaces present in the sand with clay/finer materials leading to a reduction in permeability and water absorption, a more densely packed soil and greater shear strength. Al-Jabri and Shoukry, (2014) stressed the importance of particle size distribution in both flow and hardened state of cement as well as its importance in strength and durability. The strength of soils, especially lateritic tropical soil, is equally dependent on their mineralogy and composition, this is evident in the present study by comparing the results from both locations.

Table 5 Regression Analysis between Engineering Properties and Brick Strength

Variables	Coefficient	t - statistic	Significance
(Constant)	-19.966	-1.157	0.331
CBR@0% (X1)	0.094	1.638	0.200
CBR@5% (X2)	0.002	0.030	0.978
CBR@10% (X3)	-0.056	-1.046	0.373
0% OMC (X4)	6.228	1.596	0.209
0% MDD (X5)	-0.239**	-4.169	0.025
5% OMC (X6)	-10.755	-2.035	0.135
5% MDD (X7)	0.203**	4.723	0.018
10% OMC (X8)	4.664*	2.490	0.088
10% MDD (X9)	0.044	0.934	0.419
C (X10)	-0.042**	-4.201	0.025
φ (X11)	0.209*	2.984	0.058
	R = 0.990	**R^2 =0.979**	**F = 13.013 (0.029)****

Note: * significant at 10% and ** significant at 5%. Dependant variable: Brick Strength

Table 6 Dry Compressive Strength on Bricks

Sample No	Weight (kg)	Density (g/cm^3)	Load(@failure) (KN)	Strength (MPa)	% cement	Drop Test
ADK 1a	7.94	1.72	50.7	12.07	5	Smashed
ADK 1b	8.04	1.74	55.5	13.21	5	Smashed
ADK 2a	6.42	1.4	26.6	6.33	5	Smashed
ADK 2b	6.47	1.39	30.3	7.21	5	Smashed
ADK 3a	7.69	1.66	48.3	11.5	5	Slightly smashed
ADK 3b	7.27	1.57	43.2	10.29	5	Slightly smashed
ADK 4a	7.41	1.6	36.3	8.64	5	Slightly smashed
ADK 4b	7.61	1.65	40.4	9.62	5	Slightly smashed
ADK 5a	7.20	1.56	65.4	15.57	10	Not smashed
ADK 5b	7.32	1.58	53.6	12.76	10	Not smashed
ADK 6a	7.21	1.56	29.9	7.12	5	Smashed
ADK 6b	7.80	1.69	32	7.62	5	Smashed
ADK 7a	6.63	1.44	23	5.48	5	Not smashed
ADK 7b	6.40	1.39	22.4	5.33	5	Not smashed
ADK 8a	6.74	1.46	26.9	6.4	5	Not smashed
ADK 8b	6.87	1.49	33	7.86	5	Not smashed
OS 1a	8.56	1.85	54.4	12.95	5	Smashed
OS 1b	8.34	1.81	61.5	14.64	5	Smashed
OS 2a	7.27	1.57	42.8	10.19	5	Not smashed
OS 2b	7.08	1.53	44	10.48	5	Not smashed
OS 3a	7.17	1.55	30.1	7.17	5	Not smashed
OS 3b	7.12	1.54	36.3	8.64	5	Not smashed
OS 4a	7.02	1.52	50	11.9	10	Not smashed
OS 4b	6.91	1.5	43.2	10.29	10	Not smashed
OS 5a	7.25	1.57	34.2	8.14	5	Not smashed
OS 5b	7.15	1.55	27.3	6.54	5	Not smashed
OS 6a	7.14	1.55	35.4	8.43	5	Not smashed
OS 6b	7.07	1.53	39	9.29	5	Not smashed
OS 7a	7.39	1.6	56.7	13.5	10	Not smashed
OS 7b	7.39	1.6	47.3	11.26	10	Not smashed

Table 7 **Correlation Matrix for Index Properties**

		BS	Fines	Coarse	LL	PI
BS	Pearson Correlation	1	0.131	-0.107	0.267	0.533**
	Sig. (2-tailed)		0.534	0.609	0.197	0.006
	N	25	25	25	25	25
Fines	Pearson Correlation	0.131	1	-.989**	0.026	0.171
	Sig. (2-tailed)	0.534		0.000	0.903	0.414
	N	25	25	25	25	25
Coarse	Pearson Correlation	-0.107	-0.989**	1	-0.084	-0.193
	Sig. (2-tailed)	0.609	0.000		0.689	0.356
	N	25	25	25	25	25
LL	Pearson Correlation	0.267	0.026	-0.084	1	0.600**
	Sig. (2-tailed)	0.197	0.903	0.689		0.002
	N	25	25	25	25	25
PI	Pearson Correlation	0.533**	0.171	-0.193	0.600**	1
	Sig. (2-tailed)	0.006	0.414	0.356	0.002	
	N	25	25	25	25	25

**. Correlation is significant at the 0.01 level (2-tailed).

Compressive Strength of Bricks

The compressive strength of bricks were tested after air and moisture curing for 28 days. The results were presented in Table 6. It shows a significantly high strength with a least compressive strength of 5.33MPa and highest of about 15.33. This is considered very good for an earth brick without firing. This is suitable for the required compressive strength in CEBs for low rise or bungalow residential buildings, single-storey building based on the recommended value of 2.8 and 5.2 MN/m^2 for precast concrete blocks and load bearing fired clay bricks, respectively (BS 771-3, 1990). Compressive strength of bricks is a function of many factors which include, grading characteristics of the soil, method/kind of stabilisation, energy of compression and mineralogy of soil. The good compressive strength observed in this case is attributed to the following characteristics; the well graded nature of the soil with an adequate mix of fine and coarse particles, a good shear strength characteristics of the soil and the presence of a considerable amount of quartz, goethite and heamatite in the soil material. (Table 7)

Conclusions

Generally speaking, the influence of the engineering properties discussed in this paper is significant at the 95% confidence level. This implies that their role is important in controlling the strength and durability of earth bricks. There is also a strong linear relationships between all the variables. Based on these, it is recommended that the basic soil engineering tests (compaction, CBR and shear strength) should be performed on soils used in brick making with the aim of developing standards for suitability of materials in brick making.

The following are the more significant conclusions drawn from this study:

1. The importance of parent rock on the grain size characteristics of residual lateritic soils has been established. Products of rocks from the study area are well graded lateritic soils with good compaction characteristics, low porosity and permeability which make them excellent material in brick making.
2. Based on the index properties of the lateritic soils, it is suggested that about 35% maximum fines content could be suitable for soils used for CEB production. In order to prevent excessive waste of stabiliser/binder, a minimum of about 10% fines may be required for these soils. Again, the type of soil and the geographic location may play a significant role in their index properties and the above recommendation is based on results from the present study.
3. For a well graded lateritic soil, a 5% cement addition as binder may be suitable to achieve the required compressive strength in CEBs for low rise residential buildings or bungalows, and this percentage of binder may still give a suitable compressive strength required for a single storey building based on the recommended value of 2.8 and 5.2 MN/m^2 for precast concrete blocks and load bearing fired clay bricks respectively.
4. Specific gravity of tropical soils may serve as an important clue of their strength and durability since specific gravity is influenced mainly by the types of minerals and oxides present in these soils.
5. Compaction parameters in terms of OMC and MDD proved relevant in predicting the amount of water required in achieving the maximum density of the bricks with low porosity and permeability. Compaction characteristics of lateritic soils for CEB manufacture also serve as a pointer to what is expected in the process of compression, i.e. the handleability of bricks in the mould and the ease of extruding bricks after compression.
6. CBR values are also relevant in predicting the required cement content that will produce the best resistance to load. Equally, it could predict the response of bricks to increasing moisture content especially in a water logged environment. The reduction in strength due to soaking will also indicate the response of bricks to increasing moisture and the related effect on the brick strength.
7. Shear strength of lateritic soils are the reflection the parent rock mineralogy which plays a critical role in the expected strength and durability of bricks. It is dependent on the grain size distribution of the soil in terms of the relative percentages of fine and coarse materials. An adequate mix of these has been recommended for bricks of good quality. Shear strength parameters (c and φ) were equally found to be important in achieving best strength quality and durability of bricks. It emphasises the important role of clay materials as binding agents and sand as indispensable constituents in achieving long lasting strength and quality of CEB.

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