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Review and Practical Processes on Rammed Earth Wall Construction

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ABSTRACT
A review of rammed earth wall (REW) construction was carried out in this paper. Rammed earth (RE) has been used for construction in ancient times. The use of REWs in building construction was reduced with the advent the modern construction materials such as concrete, steel, timber, polymers etc. With the increasing effect of green-house effect of which modern buildings and building materials have significant contribution, efforts are on board to revive and re-invent sustainable means of building houses. Among the various options available, REWs is adjudged one of the cheapest means to achieve sustainable buildings especially for the poor and those living in the rural areas. The origin, and types of REWs were reviewed. The codes/documents for REWs, construction techniques, materials, applicable tests, construction processes, stabilisers, cost implication, merits and demerits of REWs were all reviewed in this paper. The paper would be a good source of information on REWs and would also enable further researches on REWs construction aimed at improving its understanding and acceptability.

Keywords: Rammed earth, buildings, sustainability, laterite, *Pise*

1. INTRODUCTION
The use of rammed earth (RE) in construction dates back to centuries in different parts of the world and it is commonly known by the French name *'Pise'*. According to Ciancio and Becket (2014), a lot of historic RE structures exist around the world. Notable among these is the Great Wall of China that dates back to 1500 BC. According to Carnivell et al (2020), RE construction is more advantageous in modern times because of three common inter-connected factors namely, sustainability, bioconstruction and heritage values. Besides these, interest on the use of RE as viable wall system was drawn from its characterization as a sustainable material (Cautius, 2011). Below its sustainable reputation is its ability to function in nearly all climatic zones. Just as it is in different parts of the world, building walls constructed with RE still exist in different parts of Nigeria. With the coming of contemporary means of construction which have generally being accepted, there have been great apathy at reverting back to earth construction with its attendant benefits probably due to ignorance (Okoronkwo et al, 2013) and partly due to lack of knowledge on how to make earthen material durable and appealing aesthetically (Walker and McGregor, 1996; Daniel et al, 2018).

The urgent search into sustainable means of construction which began many decades ago was born out of the fact that buildings consumes 30 – 40% of the world's energy consumption, generates 30 – 40% wastes and 30 – 40% of greenhouse gases released annually (UNEP, Umar and Khamidi, 2012; Nduka and Sotunbo, 2014). The buildings that contribute to this menace were made with one or combination of cement, steel, aluminum and glass as these have largely been produced over many decades and used as building materials. The effect of climate change is world over and there is urgent need to ameliorate the effects through reduction of the causes. In developing countries especially in Nigeria, cement which is among the largest contributor to greenhouse gases is largely produced and used in building construction. RE has many benefits with regard to durability, reusability, thermal insulation (Daniel et al, 2018), cost effectiveness etc and it is wide in use because it houses about 1.5 billion people which comprises about 30% of the world population (Keefe, 2005, Niroumand et al, 2013). With the increasing popularity, it is expected to have housed more people presently. With these benefits, Nigeria and other developing nations need to adopt RE to provide housing to poor mass population within the country and reduce greenhouse emissions. The paper is set to review modern findings with regard to the use and strength of rammed earth walls (REWs), possible ways to improve its strength by additives in order to make the technique more appealing and acceptable.

1.1. Origin of RE

The origin of REWs always dates back to historic China even though the distribution of REWs cut across many parts of the world which may have been due to migration where people from China imported the technology to the other parts of the world. According to Jaquin et al (2008), Warren (1993) observed that the simplest form of construction in the alluvial plains of northern China was RE. This began with nomadic peoples during the Lung-Shan era (2310 – 1810 BC). Initially, the RE was formed by heaping soils in a rhomboid section with the base width increasing in proportion to the height. The developments continued until what constitutes the present method of building RE that involves using two parallel timber boards or steel boards as mould/formwork to form the RE (Yunxiang, 2003). Other foundations of REWs in historic China have been found in places like Erlitou and Longwan in 1900 – 1500 BC (Hong, 2005), Cheng tzu-yai, Shantung (Warren, 1994), dynasty capital, the Anyang city in 1600-1000BC (Houben and Guillaud, 1994), the cities of Linzi and Xiadu in the Warren state periods of (475-221BC) (Shen, 1994).

Elsewhere, REWs were also found to exist around the central Asia, India and the Himalayas. There was also evidence of REWs around the Mediterranean areas from which it spread into the Europe. It is also believed that the European migration to America and Australasia brought RE to areas where it was not in existence before (Jaquin et al, 2008).

The first evidence of REWs in the Himalayas was found around Basgo, Ladakh which was believed to have been constructed before 1357 (Howard, 1995; Jaquin, 2008). Other evidences of RE around the Himalayas region was found at the capital city of Mustang in Nepal, the Lo Manthang, in 1380 (UNITAR, 2006) and at the Western Bhutan (Nock, 1995). Jaquin et al (2008) claimed that there are still evidences of the method still in use today in which case corrugated steel sheets are used in place of wood for formwork. This enables the production of special type of REWs called corrugated REWs.

Evidences of REWs in the Mediterranean was largely connected with the Phoencians settlement. Diggings of Phoenician dwellings points to the use of RE both in North African cities of Carthage, Kerouane and Utique (Houben and Guillaud, 1994) and in Morro de Mequitilla city in Spain (Chazelles, 1993). There is also the report of the use of RE in the ancient French cities of Marseilles, Ruscino, Lyon, and Mouries etc., (Houben and Guillaud, 1994). No wonder, one of the popular names used to describe REWs presently, *the Pise* was coined from French.

In late Medieval Europe, the expansion of Muslim into the Iberia brought the use of RE to the region. When the last Muslim ruler was deposed in 1492, there were many evidences of RE in Spain with improvements such as mixing of fired brick with RE (Gerrard, 2003). The use of RE in Switzerland whose evidence is found in the oldest Swiss RE structure, the Gonzenbach castle near Geneva (Kleespies, 2000) was introduced from from Lyon, France (Jaquin et al, 2008).

In the Americas, RE construction began around 1549 by Jesuit missionaries (Puccioni, 1993; Jaquin et al, 2008). Other evidences of REWs much of which are present in Brazil are found around Goiás and Minas Geras areas (Oliver 1997; Justi-Pisani 2004), the cathedral of Taubaté in São Paulo which was constructed in 1645 (Alvarenga 1993; Pereira 1993; Vinuales 1993) and the Church of Our Lady of the Rosary which was constructed in 1720 (Pecoraro 1993). It was argued by (Easton, 1996) that the first RE in North America used a soil and sea shell mix, compacted in heavy formwork. The structure found in St Augustine, Florida was built in 1556.

Even though not found in the literature we consulted, the history of RE wall cannot be complete without mentioning Africa. Pliny the Elder who was adjudged the first person to put up a documented history of REWs in AD 79 for Western civilization, in Book 35, Chapter 48 of his treatise, 'Natural History' as quoted by (Gramlich, 2013) mentioned Africa and Spain as places where REWs was found in ancient times.

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The authors who are from Africa also have experience of RE buildings. In many parts of Nigeria, RE buildings which were inhabited by our grandparents until towards the 1st decade of 21st century are still in existence but are gradually being phased out. Visible REWs now available in different parts of the country are probably inhabited by those who do not yet have financial strength to erect modern buildings.

1.2. Ancient Iconic RE Construction

Over the years past, RE has been applied in the construction of some of the world ancient and lasting structures. Among these by Owen Geiger (2010) are the Chinese great REW (see figure 1), Kasbah Caid Ali of Morocco (see Figure 2), the Casa Grande RE structure (see Figure 3) and the Church of the Holy Cross in South Carolina (Gramlich, 2013) – see Figure 4.

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Figure 1: The Chinese great REW

Figure 2: Kasbah Caid Ali of Morocco

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Figure 3: Casa Grande RE structure at Casa Grande Ruins National Monument, Coolidge, Arizona, built ca. 1350 (Gramlich, 2013)

Figure 4: The Church of the Holy Cross, made with RE, located near Sumter, South Carolina (Gramlich, 2013)

These are structures that were built so many years ago are still in existing and still strong even under the numerous effects of weather.

1.3 Modern RE Buildings

There are many RE constructions in the modern era. One of such is shown in Figure 5 below.

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Figure 5; Typical RE residence that was built in 1946 (Gramlich, 2013)

2. TYPES OF RE

RE or vernacular architecture as it is often popularly called exist in different types such as RE buildings, Cob, Adobe, Wattle and Daub, Poured earth. The choice of the use of either of the type of wall depends on many factors. According to Niroumand et al (2013), the choice of adobe brick wall (see Figure 6) is largely in connection with prevailing climate and the ability of such walls to be formed in shapes such as vaults, arches and domes, which are impossible to construct with RE. He believed that any climate that can stand half fortnight without rain is convenient for adobe brick wall.

Figure 6: Typical Adobe brick wall

REWs (See Figure 7) on the hand, in juxtaposition to adobe bricks, are built in climates where adobe bricks are practically impossible. Such climates are usually humid and more damp. This involves ramming a mixture of sand, clay and silt into forms, commonly made of lumber, that are positioned and anchored into moist earth. The ramming is done in layers and the forms are removed after few days to allow for curing which continues for some time (Niroumand et al, 2013).

Figure 7: Typical REW

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Another type of RE called the cob (See Figure 8) is adjudged the simplest form of earth buildings. The simplicity lies in the fact that it is made without the use of formwork and with the use of other few tools. It involves heaping together bundles of mire to erect the walls. The cob is usually intermixed with straw content to make it stiffer and stable as the piling goes up.

Figure 8: Typical Cob wall under construction

Wattle and Daub wall (See Figure 9) involve the use of wattle which consists of structure of small plant components woven together to form a rigid frame. Common materials used to create wattle include bamboos, branches of trees, twigs and reeds. The daub consists of a mud mixture with small aggregate that is smeared on the face of the wattle gradually with hand to cover the irregularities made from the wattle. Wattle and daub walls usually have thin sections but are very flexible and are therefore commonly used in seismic zones because they are earthquake-resistant (Niroumand et al, 2013).

Figure 9: Typical Wattle and Daub Wall

The poured earth (See Figure 10) involves pouring a mixture of straw, chalk and soil into forms which when dried and the forms removed presents a brilliant white wall. The colour of such walls makes the quality of lightness to the massive poured earth walls very impressive like reflections from the desert sun (Niroumand et al, 2013).

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Figure 10: Typical Poured Earth Wall

3. REW CODES/STANDARDS

The technique for the construction of REWs would be found common. At present, few countries have developed guidelines for REWs. These countries include Australia, NewZealand, Zimbabwe in Africa, China, Ecuador, Peru, Germany and the United States of America, etc. (Bruce, 2006).

Even though earth used for REWs are readily abundant and cheap, the variation in the quality of earth such as obtainable in bricks and concrete blocks calls for the need of standards of comparison usually called Codes of Practice. In Zimbabwe, the SADC ZW HS 983:2014: Rammed earth structures – Code of practice, recently replaced ZWS 724:2000. The national adoption of Southern African Development Community Cooperation in Standardization's (SADCSTAN) of which Zimbabwe is a member is the code available for the design of REWs. The code is divided into six (6) sections and many subsections.

Section 1 comprises the materials used for RE which include soil, water, mixing and blending, stabilization. Section 2 talks about the formwork that comprises formwork requirements and formwork in use. Section 3 talks about groundworks and this includes: foundations, rising damp protection for walls, and floors. Section 4 deals with superstructure that comprises density, water absorption, weather erosion, compressive strength, and visual test of walls. Section 5 deals with the stability of walls that comprises slenderness, openings and lintels, and bonding. Section 6 deals with details and finishes that comprises fixings and ties, surface treatments, service inserts, walls, floor and health (SADCSTAN TC 1/SC 5/CD SAZS 724).

Bruce (2006) did a comprehensive review of different RE codes available from most of the countries listed above. The areas reviewed among the code include: building systems covered, earthen material requirements, mortars, plasters and renders, reinforcing materials, material properties, testing and quality control, limits of application, wall thickness and aspect ratio, bond beams and diaphragms, bracing walls, openings and lintels/headers, minimum reinforcement, roof overhangs and moisture protection, foundations, tolerances and quality control, engineering design guidelines and applications (limits of application, allowable stresses, flexure and axial loads, design for lateral loads, seismic load considerations). All the standards have near common agreement on the different aspects of RE work. However, New Zealand standards and Australian Earth Building book show far more detail than any other document reviewed whereas some document has no comment for certain aspects of the RE.

4. TESTS REQUIRED FOR REWS

There are many criteria used to ascertain the suitability of soil as RE material. This calls for the conduction of some tests. Qualifying tests for soils include, grading test and plasticity tests (Bryan, 1988; Burroughs, 2008; Hall and Djerbib, 2004a).

In other words, the qualifying tests include the roll test to determine whether the soil is suitable for RE; the drop test or compaction test, used to find the optimum moisture content and to check this during construction; the formwork deformation test, to find how much the formwork to be used will bend when loaded; the compressive strength test used to apply a compressive stress to the wall to ensure that the average compressive strength should not be less than 1.5 N/mm^2 generally, or 2.0 N/mm^2 for walls of height between 3.0 m and 6.0 m at a minimum age of 7 days. If the wall is unmarked at least eight times out of ten, it will have complied; the wall density test to find the dry density of the walls being built; erosion test, to check the erodibility index of the soil, and the render adhesion test to find out the force needed to pull a rendered surface off the wall beneath it (SADCSTAN TC 1/SC 5/CD SAZS 724**).**

Among all these tests, strength criterion tests are very important if the REW would be durable and need further insight. According to Mantidis and Walker (2003), RE possesses three types of mechanical strength viz; compressive strength, shear strength

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and tensile strength. Like concrete, RE is strong in compression but weak in tension and shear especially when it is moist. This mechanical strength is dependent upon the same properties which the strength of soils depends on and these include: void ratio of the soil after ramming, cohesive strength of the present fines content, aggregate strength and moisture content during testing.

The achievement of adequate strength for RE structure begins from the planning stage. The four main particles of subsoil structure which include: clay, silt, sand and gravel, play significant role in the structural integrity of REWs. Thus, important properties of these soils need to be determined and certified before they can be employed in use in REW construction. Gravel is the skeleton that provides underlying structural stability. The gravel, along with the sand, also enhances weathering resistance of exposed surfaces while the clay and silt are the binding agents that hold the material together (Gramlich, 2013). Other necessary tests include: soluble salt content, organic material content, contaminates in the soil such as arsenic or other carcinogens (necessary test where mining or other heavy industry has taken place in the past and the risk of such contaminates abound), color, and organic content test. Table 1 provides summary of typical soil composition requirements for use in RE construction (Gramlich, 2013).

Table 1; Soil Composition Requirements for RE

S/No	Element/Characteristic	Requirement
1.	Gravel and sand	45 – 80% (by mass)
2.	Silt	10 – 30 % (by mass)
3.	Clay	5 – 20 % (by mass)
4	Liquid Limit (LL)	< 45
5.	Plasticity Index (PI)	2 – 30
6.	Linear Shrinkage (LS)	≤ 5%
7.	Soluble Salt	< 2% (by mass)
8.	Organic Matter	< 2% (by mass)
9.	Toxic Carcinogens	< 10 – 20 mg (0.0003 to 0.0007 oz) per kilogram (2lbs) of soil

There are also field tests for use of RE. These tests include: smell test, nibble test (taste test), wash test, cutting test, sedimentation test, ball dropping test, consistency test, cohesion test and pH test (Middleton and Schneider, 1995; Gramlich, 2013).

5. STABILISERS IN RE

It was becoming increasingly popular to use cementing materials to improve performances of RE in terms of durability and shear strength. The substance made from this process came to be known as stabilised rammed earth (sRE) (Ciancio and Boulter, 2012). The common cementing materials used for this purpose are lime and cement. While lime largely reduces the plasticity of the soil, cement on the other hand impacts more strength (Pandey and Rabbani, 2017). If stabilisers would be used, it is also necessary to conduct tests on different contents of the stabilisers such as cement and lime to determine the optimum content that is both economical and safe. This is because there is largely no code that give detailed guidelines or that regulate the design and construction of the material such as is obtainable for concrete, steel and timber. In most handbooks available, as noted in section 3.0, there are suggestions that guide how to determine suitable soils on site and the quantity of cement required to improve the strength of such soils (Ciancio and Boulter, 2012).

We can examine the compressive strength of sRE soil by unconfined compressive strength test. Laboratory test carried out by Ciancio and Boulter, 2012 shows the following results

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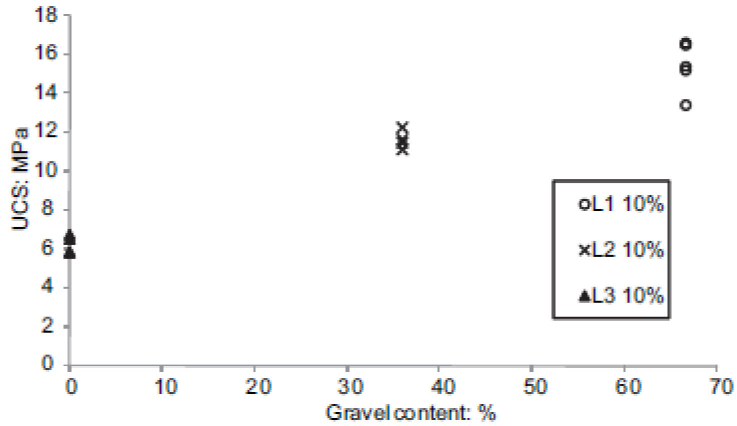

Figure 11; Compressive strength of 10% sRE sample types labelled L1, L2 and L3 (Ciancio and Boulter, 2012)

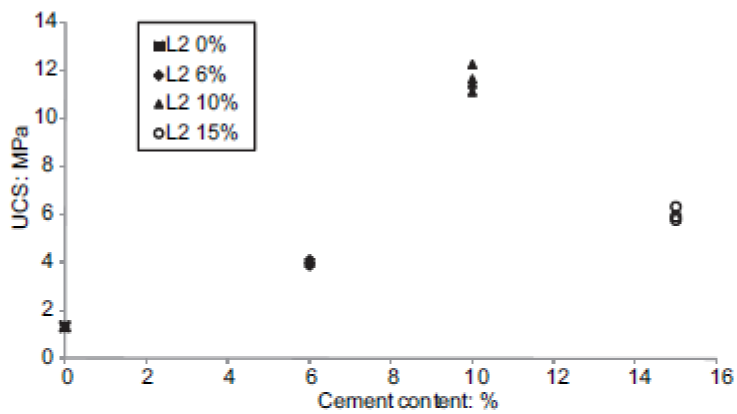

Figure 12; Compressive strength of RE samples improved with varying cement percentages (Ciancio and Boulter, 2012)

We can infer from Figure 12 that even in case of flooding, the 10% cement stabilised RE can guarantee required strength. Where there are cases of near-horizontal rain, often due to high velocity wind, a silicone-based chemical admixture can be used to prevent moisture entrance.

An unpublished research work in the field was done with a lateritic soil from a prominent borrow pit in Awka, Anambra State, Nigeria to ascertain its suitability as RE material.

The material used for the research was red earth collected from Agu Awka in Awka South LGA of Anambra state. Prior to the selection of the Agu Awka soil, three different soil samples were collected from Agu Awka, Nawfia and Ugwuoba that have large deposits of laterite that serve the region. The soils were subjected to sieve analysis. Figure 13 shows the result of the sieve analysis.

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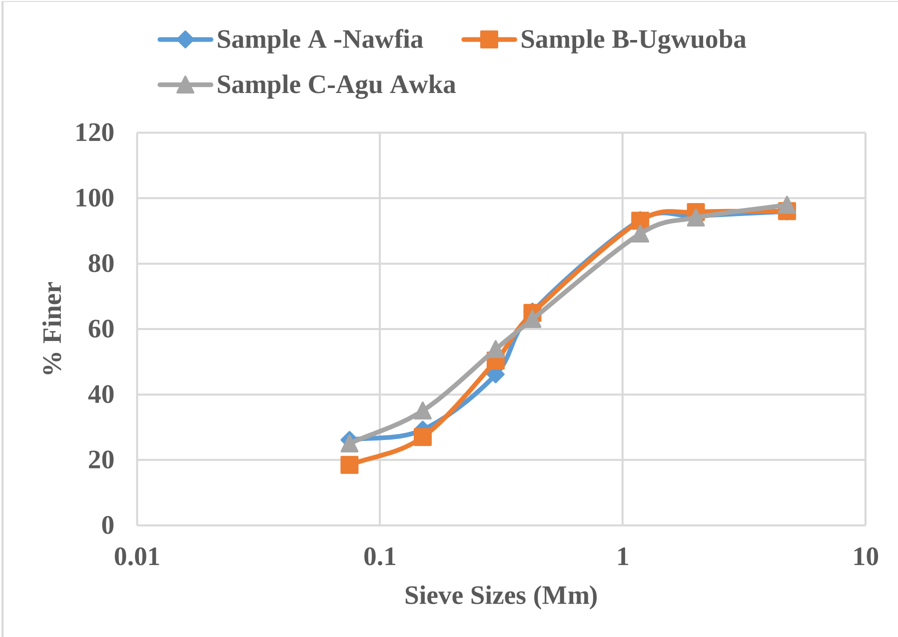

Figure 13; Sieve analysis result of the three samples

From the results, Nawfia soil have fines (26.11%), sand (68.44%) and gravel (5.45%). Ugwuoba soil have fines (18.47%), sand (77.25%) and gravel (4.28%). Agu-Awka soil have fines (25.03%), sand (69.02%) and gravel (5.95%). The three soils have similar range of properties but Agu-Awka soil was preferred due to the percentage of fines which according to Dr Steve Burroughs, should be within 20-25% maximum. He also proposed sand (30-60% maximum) and gravel (3-5% maximum) as being more preferable.

The Agu Awka soil was subjected to other tests such as Atterberg limit tests and compaction tests and the results obtained are tabulated as shown below (Table 2). The results obtained were also found favourable for a natural soil to be used for RE construction.

Table 2; Properties of Agu-Awka soil

S/No	Property	Result
1	Linear Shrinkage (%)	7
2	Maximum Dry Unit Weight (kN/m³) – British Standard Light (BSL)	19.52
3	Optimum Moisture Content (%)	11
4	Liquid Limit (%)	32.5
5	Plastic Limit (%)	22.64
6	Plasticity Index (%)	9.86

Further tests were done to improve the durability and stability of the soil by stabilizing with cement and lime. The cement was of the Dangote 42.5R brand. The lime was bought from a market in Onitsha, Anambra State. Compressive strength tests were conducted at different stabilizer contents to select the most suitable and economical stabilizer ratio. All the tests were done in accordance to BS 1377. Table 3 shows the results of some tests carried out from which was observed significant improvement in the soil compressive strength.

Table 3; Compressive strength of the test results

Lime added (%) of dry mass of soil	Cement added (%) of dry mass of soil	Duration of curing (days)	Average Compressive strength (N/mm²)
2	2	7	1.44
2	4	7	5.78
2	6	7	9.68
2	8	7	19.38

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6. CONSTRUCTION OF RE WALLS

The construction of RE walls just like similar construction works involves planning which consist in the assemblage of materials and procedures to carry out the construction work. The REW is made up of several layers. For each layer, the soil is filled to about 150 mm thick into a formwork and then rammed with either a manual or pneumatic rammer. After ramming, the compacted thickness of each layer should typically be around 80 – 100 mm. The procedure is repeated until the wall is finished (Walker et al; Biu and Morel, 2015).

6.1 Materials for rammed earth

The basic materials used for the erection of REWs include the natural earth, water, formwork, rammers, additives. Among these materials, the ones that require special treatment would be discussed.

6.1.1 Earth

An unstabilised RE is made up of three basic materials of sand, gravel and clay in varying proportions (Easton, 2007; Middleton and Schneider, 1987; Walker, 2002; Ciancio and Boulter, 2012). RE is a natural material, constructed with only a small fraction of the energy input required for other materials to produce structures of similar strength and durability. The base material is usually soil, specifically the inorganic subsoil found beneath the organic topsoil (Gramlich, 2013). Not all soils in any site or region are amenable for RE. This is due to cumulative effects of geology of underlying rock, weathering processes, hydrological and hydro-geological processes that affects the chemical and physical properties of the subsoil from which the RE are usually made. For this reason, the soil must be tested before use to confirm whether it is suitable or not. The most appropriate soil ratio for RE construction contains: 50 to 75 % fine gravel and sand; 15 to 30 % silt (pulverized sand) and 10 to 20 % clay (cohesive particles). This is in agreement with Niroumand et al, (2013) who claimed that the most suitable soil type is the one that has small gravel content, together with suitable sand, silt and clay contents. Clay content is necessary because the durability and water-proofing behaviour of RE depends on it. They recommended values of 15-18% as clay content.

Some literatures advocate the use of stabilizers to improve the soil compressive strength. As much as possible, stabilisers should be avoided so as not to cause pollution and to enable re-use of the soils when demolished. However, this is only possible with optimum soil properties and good building design. In situations where stabilizer must be used to increase compressive strength, small quantities should be used. Other additives may also be used to improve water resistance and reduce shrinkage. Typical stabilizers include cement, bituminous emulsion, lime and adhesion chemicals, more clays, cow-dung, rice husks and ant-beds (Gramlich, 2013).

6.1.2 Formwork

Formwork for RE can range from very simple forms made of wood, and put together with nails, wire or rope, to large manufactured formwork systems which are often used in concrete works (Niroumand et al, 2013). Due to high re-use associated with formwork in RE buildings because the formwork is removed almost immediately after ramming, the formwork should be sufficiently strong, stiff and stable to maintain integrity during the erection, placement and dismantling processes. It should also be lightweight, easy to assemble and disassemble, and durable enough to withstand repeated use on site (Gramlich, 2013).

A good formwork for REWs ought to possess the following desirable properties:

1. It must be more rigid than standard concrete shuttering, because of the high outward pressure of compacted earth;
2. It must be light and easy to dismantle and assemble, so that the work does not become too tiring and time-consuming;
3. It should be of the largest size that can be reasonably handled, so as to reduce the number of turns and;
4. It should permit the wall thickness to be varied.

Formwork for RE are usually made of two systems: the moving system and the static system. In the moving system, the formwork is normally moved horizontally after each section is completed. The length of formwork can range between 150 and 300 cm, the height between 50 and 100 cm. As the ratio of wall thickness to wall height should be between 1: 8 and 1: 12 (the latter requiring good quality control), REWs can be as thin as 300 mm. However, where there is need to compact the soil while standing between the two sides of the formwork, a minimum thickness of 400 mm is recommended. This system it is noted to produce walls with low quality of finished surfaces and can be used when it is proposed to cover the wall with plaster after dismantling formwork; otherwise, the static system should be used.

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In the static system, the formwork is built vertically, a section at a time. More panels are stacked vertically and clipped into place as the wall is built upward. No panels are removed until the section is completed. Thus, the walls are built up vertically in large sections (Gramlich, 2013).

Timber or plywood-based formwork is used in both static and moving formwork systems. Timber or plywood sheathing is combined with either timber or metal strong backs (walers and soldiers) to provide added flexibility for curved forms. With added flexibility comes the price of lower efficiency as timber formwork is generally more labor intensive, as well. Through-bolts are often used in RE construction to limit formwork deflections during compaction. Bolts are placed from 500 mm to 1200 mm apart as needed to limit deflections without hindering compaction. After the formwork is removed, bolt-holes are patched with matching earthen material. If the design aesthetic requires a clean wall without bolt-holes, form deformations are minimized by increasing the stiffness of the formwork with external ties and clamps, as well as external props (Gramlich, 2013).

6.1.3 Rammers

Earth can be rammed with manual or pneumatic rammers. Manual rammers consist of a wooden or steel rod with a heavy wooden or metal striking head. The heavier it is, the better the compaction, though it can easily weaken the user. Pneumatic rammers imitate the manual rammers, but achieve much higher impact frequencies, thus reducing construction time. The main drawback to the use of pneumatic rammers is their high cost.

Presently, there are electric hand-held, vibrating and pneumatically-powered dynamic rammers that make the job faster and produce better compaction ratios (Gramlich, 2013). One of these alternatives is the use of a small vibrating plate, developed at the Kassel College of Technology, Germany. This consists of an electric motor with an eccentric rotating mass that transmits vibrations to the plate, thus causing the machine to move. An automatic switch makes it move back and forth in the formwork to ram the soil, without manual guidance.

6.1.4 Surface Treatment for REWs

The surface of REWs should be properly treated for walls to last long. Immediately after the removal of the forms, broken edges, cracks and holes should be filled and compacted, as the patching material does not bond with partially dried up walls. Outside treatments which could be used during the construction process such as addition of sealants or colours, or other coatings, the walls can be plastered if there is need for it.

At present, the appearance is often considered very attractive and is one of the appeals of RE construction due to the striation effect produced by the successive layers of soils placed in the mould during the ramming process (See Figure 14).

Figure 14: Typical image of layered REW found at Osoyoos Indian Reserve in British Columbia, Canada (Gramlich, 2013)

This striation effect can be enhanced with color additives or by varying soil types. Thus, the walls are often left without plaster or render because of their unique custom finish.

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6.2 Procedure for the Construction of REWs

In the construction of REWs, the first step is to erect the foundation. The foundation can be made of stone, burnt brick or concrete that extends at least 300 mm above the ground level and should be as wide as the REWs. The top surface of the foundation must be horizontal and should be stepped where it is expedient to create step for the foundation. Damp proof course should be introduced between the foundation and the walls especially in moist environments. When the foundation is done, the formwork for the walls is erected on the foundation and should project at least 100 mm for firmness. As noted in section 6.0, the soil is filled to about 150 mm thick into a formwork and thoroughly compacted to a thickness of 80 - 100 mm with a rammer. In some cases, the soil is filled to about 100 mm and then compacted to 60 – 70 mm thick (Figure 15).

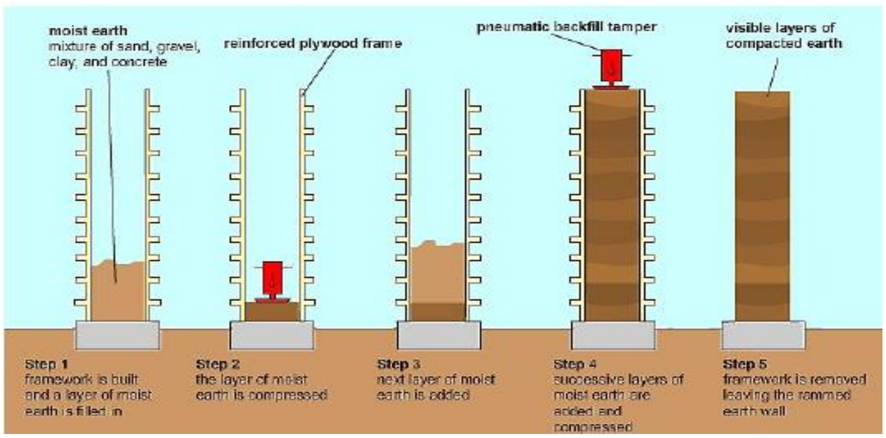

Figure 15: Section views of the compaction process for RE construction (Gramlich, 2013)

Ramming should preferably start from the edge and proceed to the centre of the walls. The person who rams the soil stands on it or on the top edges of the formwork, and strikes the soil systematically, first along the sides and then in the centre. The operation is completed when the sound of each stroke of the rammer changes from a dull to a solid clear sound.

When the formwork is full, it is dismantled and moved (usually horizontally) to the next position, fixing it firmly over a previously completed row. In this way, the walls go up gradually layer-wise and row-wise. For protection against rain, wind and direct sunshine when the formwork is moved, the previous section should be covered with an appropriate material such as grass, leaves, cloth, plastic sheets etc.

During the erection of the walls, there is extreme care to stagger the joints between each row (just as in masonry work) and wall junctions should be made to interlock connecting walls. There should be provisions for reinforcements and wall anchors at building corners and junctions during construction to strengthen them. The reinforcements can be made from rods, scrap metals, strong twigs, rope or split bamboo.

6.3 Openings in REWs

Openings in REWs ought to be well planned so that their sides correspond to the ends of formwork sections and their height in line with the top of the last layer. The ring beam usually substitutes the lintel. Insertion of windows and door frames within the formwork is also possible. Anchors can also be attached, so that the frames are rigidly fixed to the wall. *Pise* saw can be used to create small openings on finished walls.

7. CHALLENGES OF CONSTRUCTING RE

Key challenges of RE construction include but not limited to lack of harmonized International Standards and Regulations. Some countries like Australia, Newzealand and Zimbabwe already have Codes for RE construction. Carnivell et al (2020) provided unified criteria, based on a statistical analysis, for both the production and the quality control of this constructive technique in cases dealing with both samples and walls. Some of their recommendations are as follows:

1. Random compressive strength tests can be used to select best mix strength for REWs.
2. There should be similarity between mixing method, technical system and volume capacity during tests and on actual site work.
3. The soils used in the laboratory tests should be obtained from the batch of the proposed soil to be used for the RE.

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4. The compaction method to be used, including the compactors and even workers to be used during the qualifying laboratory tests should be same or very similar to the one to be adopted on the actual work.
5. Cube samples was recommended for laboratory tests other than cylindrical samples due to their amenability to some non-destructive tests like ultra pulse velocity test and rebound hammer test.
6. There should be proper mixing moisture control test which can be ascertained by testing three soil samples before mixing and after mixing.

Challenges to the use of RE buildings in the United States of America (USA) according to Gramlich (2013) include: politics and special interests of certain industries, common use of lumber in the USA, harsh climate in North America and abundance of natural resources in the state. Included in the list is feeling of its ancient origin. Thus, it is considered an old way of doing things where the definition of industrialization lies more on the use of concrete and steel. In USA, RE is commonly used for constructing slave quarters and farm buildings. Though, not common in USA due to their many preferred alternatives, the technology could be successfully considered in other countries with less preferred alternatives or where preferred alternatives are very costly and non-sustainable.

7.1 Durability of REWs

RE is adjudged a good product with considerable life span (Easton, 2007; Hall and Djerbib, 2004a; Jaquin, 2008). However, when they become susceptible to rainfall and moisture, they can quickly loose their strength and become undurable. To protect them from these adverse natural effects, adequate protection should be provided to them by the use of roof overhangs and proper elevation of the foundation above likely flood levels. Silicone-based, moisture-retarding admixtures have also commonly been used in contemporary RE construction as a means of preserving durability (Ciancio and Boulter, 2012).

Oftentimes, reinforcing bars that have capacity to rust when exposed to adverse whether effects are used in REWs especially at areas prone to cyclone winds. These rods are usually placed at the heart of the RE which generally has a minimum thickness of 300 mm. Thus, there is 150 mm thick protection for the steel from the wall (Ciancio and Boulter, 2012). REW do not burn and are not usually affected by fire.

7.2 Environmental Sustainability and Climatic Implications of the use of REWs

RE would be adjudged an environmentally-sustainable construction material (Bahar et al., 2004; Jayasinghe and Kamaladasa, 2007; Morel et al., 2001; Venkatarama Reddy and Jagadish, 2003, Ciancio and Boulter, 2012) when reinforcement is not used within and cement content used would be little to none. The environmental sustainability which is a measure of the environmental impact of the materials used in the production and construction of buildings uses embodied energy (Boyle, 2005) to measure such impact. Embodied energy comprises the production energy which is the energy used to produce the building materials (Harris, 1999), and the transportation energy which is the energy used to transport the materials to site. It was generally shown that the embodied energy of REWs is smaller than that of steel which implies that REW is more environmentally sustainable than steel in construction (Ciancio and Boulter, 2012).

7.3 Cost consideration of RE

RE is usually adjudged cheap construction technique especially in remote areas. The cost of construction of a house according to Ciancio and Becket (2014) is determined mainly by the cumulative cost of materials used in the construction of the house and the cost of labour force working on the site. The cost effectiveness of REWs lies solely on the use of insitu materials for the purpose and the use of cheap unskilled labour force for the construction. Outside of these, the cost implication could possibly approximate to other conventional means of construction. Considering the additional cost usually involved in transporting and housing work force from developed cities to remote areas to execute conventional building works, RE seems a viable alternative to provide cheap construction technique for remote areas. In agreement with this assertion, a research work by Daniel et al (2018) using adobe bricks which though not RE falls into the category of earthen construction discovered that there is 30% reduction in cost when using adobe bricks over sandcrete hollow blocks in house construction.

7.4 Merits and Demerits of RE Construction

7.4.1 Merits of RE Construction

Special advantages of RE are that it has good impact resistance and durability, low cost and good stability. Carnivell et al (2020), opined that bioconstruction, sustainability, and heritage values also present significant advantage especially for modern

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construction. In addition to these, RE has low environmental impact (Serano et al, 2013; Arrigoni et al, 2017 and Fernandes et al, 2019).

Other major merits include that it forms a solid stable mass which provides strong security to inhabitants and present high acoustic-proof system. They are also good choice as HVAC (heating, ventilating, and Airconditioning systems). It is inherently environmentally suited walls that have a nominal twelve-hour temperature cycle – keeping them cool in the daytime and warm at night. This minimizes the need for artificial air conditioning with its associated costs (Gramlich et al, 2013).

In terms of fire safety, adobe bricks in particular are known to be fireproof with very low energy investment in basic materials.

7.4.2 Demerits of RE Construction

Extra wall thickness is a disadvantage in RE especially for adobe brick walls because of significant reduction between the total building space and the interior spaces available for use. Other demerits include poor insulation and high thermal efficiency (Taylor and Luther, 2004). However, this shortcoming can be provided for at the design stage by orientating the building to maximise cross ventilation and also providing adequate shade. Good solar passive design can also be used to enhance the benefit of the RE (Ciancio and Boulter, 2012).

Other disadvantages include its low to medium resistance to earthquakes, rain, hurricane and insects and its suitability only in hot climates and upland climates.

8. PROSPECTS FOR DEVELOPING COUNTRIES

Most developing countries rely heavily on cement for construction. Nigeria for, instance have a very poorly developed steel production sector. Thus, greater percentage of buildings in Nigeria are made with cement. This is not healthy for the country and countries in similar situation. Even with steel that is more friendly to the environment and used heavily in industrialized nations, the embodied energy is something of worry. Steel is costly and when imported the cost becomes even more. The cost of housing development in developing countries can be reduced by adopting REWs in building construction. Developing nations often have large landmass of non-built-up areas and these can be used to advantage to develop effective RE building solutions that are safe, beautiful, durable, cost-effective, and environmentally friendly. This is especially important for African countries where most soils are amenable for RE and there is mass poverty that many people find it difficult to erect their own houses with the attendant costs.

The growth of this industry can be enhanced by improving the understanding of RE from an engineering view. This would improve, on the long run, the adoption of RE construction in remote areas as well as rural and metropolitan areas. This can be made possible by introducing RE studies in the educational curricula of relevant courses. In this way, there can be leapt from current research on this field that focuses mainly on determining relevant amounts of cement and water for good performance to possibly producing suitable harmonized code for the design of RE (Ciancio and Boulter, 2012).

9. CONCLUSION

The quest to erect sustainable buildings which are cheap, consumes less energy and minimally impact the environment negatively, resurrected the idea of RE structures which was a technology long used before the advent of modern means of building. RE structures were built by our parents without any formal science. Even at present some guidelines are available on how to construct REWs. The origin, materials, strength, and codes for design of REWs etc were reviewed. It was discovered that at present, the acceptability of REWs is still low and there is yet no harmonized code available for RE structures as it is present for concrete, steel, timber and masonry structures. There are many advantages inherent in the use of REWs. It is recommended that more research and awareness need to be done to improve people's understanding of REWs, its acceptability and the production of harmonized Code of Practice to enable its design and construction.

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Conflicts of interests

The authors declare that there are no conflicts of interests.

Data and materials availability

All data associated with this study are present in the paper.

REFERENCES AND NOTES

1. Alvarenga, M. (1993). An architectura de terra no Ciclo do Ouro, em Minas Gerais, Brasil. 7th International Conference of the Study and Conservation of Earthen Architecture, Silves, Portugal 29 - 36.
2. Arrigoni, A.; Beckett, C.; Ciancio, D.; Dotelli, G. (2017). Life cycle analysis of environmental impact vs. durability of stabilised rammed earth. Constr. Build. Mater, 142: 128–136.
3. Bruce, K. (2006). Review of Earthen Building Codes and Standards. Green Building Press, CA 94903 USA (415) 331-7630
4. Bryan, A.J. (1998). Criteria for the suitability of soil for cement stabilization. Building and Environment 23(4): 309–319.
5. Canivell, J. J., Martín-del-Río, J.J.,Falcón, R.M. and Rubio-Bellido, C. (2020). Rammed Earth Construction: A Proposal for a Statistical Quality Control in the Execution Process. Sustainability (MDPI). 12, 2830; doi:10.3390/su12072830
6. Cautius, C.E. (2014). Rammed Earth: Adaptations to Urban Toronto. A thesis presented to the University of Waterloo in fulfilment of the thesis requirement for the degree of Master of Architecture.
7. Chazelles, C. (1993). Savoir-faire indigenes et influences coloniales dans l'architectures de terre antique de l'extreme-occident (Afrique du Nord, Espagne, France Meridionale). 7th International Conference of the Study and Conservation of Earthen Architecture.
8. Ciancio, D. and Boulter, M. (2012). Stabilised rammed earth: a case study in Western Australia. Proceedings of the Institution of Civil Engineers Engineering Sustainability 000 Month, Issue ES000.
9. Ciancio, D.; Jaquin, P. and Walker, P. (2013). Advances on the assessment of soil suitability for rammed earth. Construction and Building Materials, 42: 40–47
10. Ciancio, D. D. and Beckett, C. (2014). Rammed earth: an overview of a sustainable construction Material. University of Western Australia, 6009 Australia. School of Civil and Resource Engineering M051, University of Western Australia, 35 Stirling Highway, Crawley 6009 Western Australia.
11. Daniel, A.A., Benjamin, G.K. and Tali, J.O. (2018). Adopting Stabilized Earth Construction to Address Urban Low-cost Housing Crisis in Jos, Nigeria. J Ergonomics Stud Res 1: 101
12. Easton, D. (1996). The rammed earth house. Chelsea Green Publishing Company: White River Junction.
13. Easton, D. (2007). The Rammed Earth House. Chelsea Green.
14. Fernandes, J.; Peixoto, M.; Mateus, R.; Gervásio, H. (2019). Life cycle analysis of environmental impacts of earthen materials in the Portuguese context: Rammed earth and compressed earth blocks. J. Clean. Prod., 241, 118286.
15. Gerrard, C. (2003). Paisaje y señorío. La casa conventual de Ambel (Zaragoza): arquitectura e historia de las órdenes militares del Temple y del Hospital. Institución Fernando el Católico (CSIC). Zaragoza.
16. Gramlich, A.N. (2013). A Concise History of the use of the Rammed Earth Building Technique Including Information on Methods of Preservation, Repair, and Maintenance.
17. Bahar, R., Benazzoug, M. and Kenai, S. (2004). Performance of compacted cement-stabilised soil.
18. Hall M and Djerbib Y (2004a) Rammed earth sample production: context, recommendations and consistency. Construction and Building 18(??): 281–286.
19. Niroumanda, H. Zainb, M.F.M and Jamil, M. (2013). Various Types of Earth Buildings. 2nd Cyprus International Conference on Educational Research, (CY-ICER 2013)
20. Hong, X. (2005). History-rich province records new discoveries in big relic sites. Xinhua Beijing.
21. Houben, H. and Guillaud, H. (1994). Earthen Architecture: A comprehensive guide. Intermediate Technology Development Group: London, UK.
22. Howard, N. (1995). The fortified places of Zanskar. Recent Research on Ladakh, London
23. Jaquin, P. A. and Augarde, C. and Gerrard, C. M. (2008). A chronological description of the spatial development of rammed earth techniques.', International journal of architectural heritage: conservation, analysis, and restoration., 2(4): 377-400.
24. Jaquin, P.A., Augarde, C.E. and Gerrard, C.M. (2007). Historic rammed earth structures in Spain, construction techniques and a preliminary classification. International Symposium on Earthen Structures, Bangalore, India 327-333.
25. Jaquin, P. (2008). Analysis of Historic Rammed Earth Construction. PhD thesis, School of Engineering, Durham University, UK, see http://www.historicrammedearth.co.uk/.
26. Jayasinghe, C. and Kamaladasa, N. (2007). Compressive strength characteristic of cement stabilised rammed earth walls. Construction and Building Materials 21(??): 1971–1976.
27. Justi-Pisani, M. A. (2004). Taipas: A Arquitetura de Terra. Sinergia 5(1).
28. Kleespies, T. (2000). The history of rammed earth buildings in Switzerland. Terra 2000: 8th International Conference of the Study and Conservation of Earthen Architecture, Torquay, UK 137 – 139.

ISSN 2278–5469 EISSN 2278–5450 I OPEN ACCESS

29. Middleton, G.F. and Schneider, L.M. (1987). Bulletin 5: Earth-Wall Construction, 4th edn. CSIRO, Sydney, Australia.
30. Middleton, G. F., and Schneider, L.M. (1995). Bulletin 5: Earth-Wall Construction, 4th Edition." Bulletin, Division of Building, Construction and Engineering, CSIRO Australia, Australia: CSIRO.
31. Morel, J.C., Mesbah, A., Oggero, M. and Walker, P. (2001). Building houses with local materials: means to drastically reduce the environmental impact of construction. Building and Environment 36(??): 1119–1126.
32. Nduka and Sotunbo (2014). Stakeholders Perception on the Awareness of Green Building Rating Systems and Accruable Benefits in Construction Projects in Nigeria. Journal of Sustainable Development in Africa, 16 (17): 118 -130
33. Nock, D. (1995). The architecture of Bhutan. The Architectural Review 198(1186): 78-81.
34. Oliver, P. (1997). Encyclopaedia of World Architecture. Cambridge University Press: Cambridge, UK.
35. Okoronkwo, D.C., Khatib, J.M., Emekwuru, N. and Hall, R.F. (2013). The Rammed Earth House in Nigeria X CIATTI 2013. Congreso Internacional de Arquitectura de Tierra Cuenca de Campos, Valladolid. PP 27 – 36
36. Owen, G. (2010): Ancient Rammed Earth structures. Accessed at http://www.naturalbuildingblog.com/ancient-rammed-earth-structures/ on 14th February, 2022.
37. Pandey, A. and Rabbani, A. (2017). Stabilization of pavement subgrade soil using lime and cement: Review. International Research Journal of Engineering and Technology (IRJET), Volume 04, Issue 06, pp 5733-5735.
38. Pecoraro, A. (1993). The conservation of the church of Nossa Senhora do Rosario, Embu, Sao Paulo, Brazil. 7th International Conference of the Study and Conservation of Earthen Architecture, Silves, Portugal 278 - 281.
39. Pereira, P. (1993). Negando a tradicao: tebas e a negacao construcos de tapia em Sao Paulo. 7th International Conference of the Study and Conservation of Earthen Architecture, Silves, Portugal, 134-138.
40. Puccioni, S. (1993). O uso da Taipa-de-Pilao em construcoes Luso-Brasileiras. 7th International Conference of the Study and Conservation of Earthen Architecture, Silves, Portugal, 296-298.
41. SADCSTAN. Rammed Earth Structures; Code of Practice THC 03. SADCSTAN TC 1/SC 5/CD SAZS 724; African Organisation for Standardisation: Harare, Zimbabwe, 2014.
42. Serrano, S.; Barreneche, C.; Rincón, L.; Boer, D.; Cabeza, L.F. (2013). Optimization of three new compositions of stabilized rammed earth incorporating PCM: Thermal properties characterization and LCA. Constr. Build. Mater, 47, 872–878.
43. Shen, C. (1994). Early urbanisation in the Eastern Zhou in China (770-221 BC): An archaeological view. Antiquity 68: 754-744.
44. Smith, T. (2006). Rammed earth Great Wall Zhangye. Photograph
45. Umar, U.A. and Khamidi, M.F. (2012). Determination of the Level of Green Building Public Awareness: Application and Strategies. International Conference on Civil, Offshore and Environmental Engineering, Kuala Lumpur Malaysia.
46. UNITAR, (2006). Nomination of the Cultural Landscape of Lo Manthang, Upper Mustang Region, Nepal for the Inscription in World Heritage List. United Nations Institute for Training and Research, Hiroshima, Japan.
47. Venkatarama Reddy, B.V. and Jagadish, K.S. (2003). Embodied energy of common and alternative building materials and technologies. Energy and Buildings 35(2): 129–137.
48. Vinuales, G. (1993). Construcao com terra em Iberoamerica, Herancas e transferencias. 7th International Conference of the Study and Conservation of Earthen Architecture, Silves, Portugal, 148 – 152.
49. Walker, B., McGregor, C. (1996). Building with earth in Scotland: Innovative Design and Sustainability. Edinburgh: Scottish Executive Central Research Unit.
50. . Walker, P. (2002). HB 195: The Australian Earth Building Handbook, 1st edn. Standards Australia International, Sydney, Australia.
51. Yunxiang, B. (2003). On the Early City and the Beginning of the State in Ancient China [Electronic version]. The Humanities Studies, Chinese Academy of Social Sciences. Accessed 28 May 2007. Available from http://bi.cass.cn

ISSN 2278–5469 EISSN 2278–5450 I OPEN ACCESS