DEVELOPMENT OF A TWO-STOREY MODEL ECO-HOUSE FROM RAMMED EARTH

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ABSTRACT

The use of conventional building materials is facing two main challenges of excessive cost and large-scale depletion of the sources thus creating environmental problems. These challenges demand that alternative building materials be explored that are not only affordable but are also environmentally friendly. In this regard and inspired by the global need for sustainable development, earth(soil) is re-emerging as the grand eco-material for building construction due to its availability, environmental/cultural appropriateness, structural adequacy, familiarity to the local people, "breathability", health benefits, amongst others. This paper presents results of experimental work in Kenya aimed at utilizing earth in formal housing constructions with a view to alleviating the severe housing shortage in the country. Studies were conducted on structural performance of various types and blends of earth material, from which a suitable blend was selected and used to construct a model two-storey rammed earth building. The model house had load-bearing walls of rammed earth, and a hollow-pot reinforced concrete slab containing light-weight stabilized soil blocks. The rammed earth two-storey model house was tested for vertical load resistance using sacks of sand. Results obtained from this study indicate that certain blends of local earth materials had higher stabilized block strengths than the standard dressed stones which are normally used in construction in Kenya. Further, the model eco-house was able to resist applied vertical loading with minimal deflections within the standard requirements. The model house has been in use as an office building for over four years with negligible deterioration in terms of material erosion or cracking or deflections.

KEYWORDS

Earth in construction, earth structures, rammed earth, sustainable construction.

INTRODUCTION

About nine (9) million Kenyans are in need of proper housing, with the capital city of Nairobi with a population of three million having about 60% of its residents leaving in slums [1]. Accordingly, the provision of shelter is a key item on the national agenda, and solutions are currently being sought not only in reducing the cost of construction but also ensuring environmental preservation and enhancement of the social fabric in line with global trends towards sustainable development. Thus, the focus and mission of ongoing research and development activities is geared towards complementing government efforts in shelter provision by availing sustainable eco-materials and eco-technology for all, viz, materials/technologies that are environmentally friendly, locally based, culturally acceptable, affordable, structurally sound and durable. Earth-based materials are proving to be the grand eco-materials of this century (Venkatarama et al. 2010; Graham et al. 2001; Martins et al. 2015; Oyawa 2004).

The work herein presents results of studies on structural performance of various types of earth-based wall panels, culminating in the construction of full scale prototype two-storey house from rammed earth. **Rammed earth** construction is an ancient technique that is under revival as mankind seeks sustainable building materials and natural building methods (Voral *et al.* 2014; Windstorm *et al.* 2013). The technique emphasizes on use of local natural raw materials such as earth, cowdung, lime or gravel to build walls or structures. The objectives of this study were to determine appropriate material mix ratios for the construction of stable earth-based structural element, evaluate the impact of compaction methods on strength of earth-based structural element, determine the structural performance of wall panels made of varying types of blocks and jointing mortar, and to evaluate the stability and durability of model eco-structures made of earth-based material.

EXPERIMENTAL WORK

Experimental work involved material property tests on constituent materials e.g. soils, river sand, and quarry dust, employing standard test methods stipulated in Kenya/British codes. Further tests were on various types of compressed earth blocks (CEB), testing of wall panels of various sizes and of different materials, and finally constructing and testing a full scale 2-storey rammed earth house. Hence, tests undertaken may be classified as standard material property tests, compressed earth block (CEB) tests, wall panel tests, and stability/durability tests on full-scale prototype rammed earth structures.

Compressed earth block (CEB) tests were conducted to determine suitable mix ratios for the construction of model eco-structure. Standard compressed earth blocks (CEB) of size 290x140x120mm high were prepared by mixing soil or stabilized soil at optimum moisture content, and then compressing by a standard press block machine (Fig. 1). The main variables in these tests included the type of soil (Murram-MS or red clay soil-RCS or black cotton soil-BCS), the extent of stabilization by cement or lime or quarry dust, and the mode of compaction. The aim of tests on compaction method was to compare the strength of blocks produced using only the standard press block machine (designated CM blocks) and those produced by using hand compaction on 2 layers with the final flat topping being achieved using the press block (designated HC+CM) as listed in Table 1.

(a) CEB preparation using press block (b) testing of CEB in compression

Figure 1 Block making and block testing

Table 1 Mix ratios to investigate the effect of hand compaction on eco-block strength

Mix series	Mix designation	Description
Black Cotton Soil (BCS) series	BCS-63S-6C	BCS with 63% sand and 6% cement
	BCS-63S-4L-2C	BCS with 63% sand, 4% cement of lime and 2% cement
	BC-4L-2C	BCS with 4% cement of lime and 2% cement
Red Coffee Soil (RCS) series	RCS-63S-6C	RCS with 63% sand and 6% cement
	RCS-63S-4L-2C	RCS with 63% sand, 4% cement of lime and 2% cement
	RCS-4L-2C	RCS with 4% cement of lime and 2% cement
Murram Soil (MS) series	MS-20S-6C	MS with 20% sand and 6% cement
	MS-20S-4L-2C	MS with 20% sand, 4% cement of lime and 2% cement
	MS-4L-2C	MS with 4% cement of lime and 2% cement

The compressed earth block specimens were covered and left to cure until the time of testing. Compressive test on CEB was conducted by placing each block between the platens of a Universal Testing Machine, and gradually compressing until failure while recording the failure strength. Each test result was an average of at least three block specimens.

Wall panels tests involved preparing walls of size 1200mm length by 700mm high by 140mm thick on a thick steel plate, lifting the arrangement onto a testing frame and testing under compressive load regime while monitoring loads, displacements and strains. The wall panel tests were conducted to determine the effect of jointing mortar on CEB wall panel strength, and also to compare the behavior of CEB wall panels vis-à-vis stone wall panels. The variables were the type of block material for the wall, and the type of jointing mortar i.e. conventional mortar of sand and cement in a ratio of 1:4 (Wall CS1:4), conventional mortar of sand and cement ratio 1:16 (Wall CS1:16) having similar strength to the stabilized blocks, and eco-mortar of the same materials as block i.e. cement, quarry dust, quarry chips and murram in a ratio of 1:4:4:8 (Block mix BM 1:4:4:8). Table 2 gives typical details of the walls tested with the aim of evaluating the effect of jointing mortar, where the compressive strength test for mortar was done on 100x100x100mm cubes using universal testing machine at the age of 7 days. Mortar strength results reveal that replacing river sand with a blend of quarry dust, quarry chips and murram has positive effect on strength i.e. the strength of BM 1:4:4:8 mortar is higher than the strength of CS1:16 mortar.

To determine the effect of block type on wall strength, wall panels made of stabilized soil blocks, unstabilized soil blocks and standard dressed stone blocks, were prepared on the testing frame, cured and tested under compressive load regime (Figs. 2 and 3). For all the wall panels, the proportion of mortar mix was 1:3 (cement:sand). The CEB wall panels had a dimension of 1000 x 520 x 140 mm while the conventional stone wall panels had a dimension of 1000 x 520 x 150mm.

(a) Conventional dressed stones used in construction

(b) Wall panels under curing environment

Figure 2 Conventional dressed stones and wall panels

Table 2(a) Material properties (Compressive strength of eco-block and mortar types)

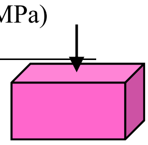
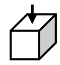
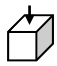
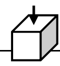
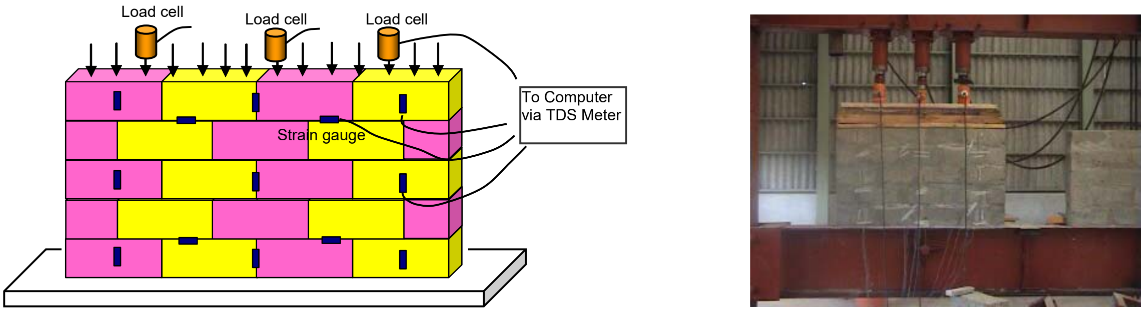
Specimen designation	Description	Percentage of cement in mix (%)	Avg. Compressive strength (MPa)	
Eco-Block (MurQDndarQDnbi 6% cem)	Eco-block of mix ratio 1:4:4:8 of cement: quarry chips: quarry dust: murram	5.9	4.1	
	Jointing mortar			
Jointing mortar CS1:4	Mix ratio of 1:4 of cement: sand mortar	20.0	4.3	
Jointing mortar CS1:16	Mix ratio of 1:16 of cement: sand mortar	5.9	0.7	
Jointing mortar Block mix BM 1:4:8:8	Mix ratio of 1:4:4:8 of cement: quarry dust: quarry chips: murram mortar	5.9	1.1	

Table 2(b) Description of wall panels (Effect of mortar series)

Wall specimen designation	Description of jointing mortar used for wall
Wall CS1:4	Mix ratio of 1:4 of cement: sand mortar
Wall CS1:16	Mix ratio of 1:16 of cement: sand mortar
Wall BM 1:4:8:8	Mix ratio of 1:4:4:8 of cement: quarry chips: quarry dust: murram mortar

During compressive test on each wall panel, timber planks were placed on the top of the wall followed by load cells to measure the load applied. Timber planks were used to distribute the load over the wall. The electric resistance strain gauges were pasted at several locations of wall vertically and horizontally; some on the blocks while others on mortar. The load cells and the strain gauges were connected to TDS 302 strain meter, which was connected to a computer. The load was applied through hydraulic jacks, mounted at several locations on top of the wall. The experimental set up is as shown in Fig. 3.



(a) Schematic representation (b) Photo

Figure 3 Experimental set up for tests on wall panels

Tests on full-scale prototype rammed earth eco-structures were geared towards assessing the stability and durability of the prototype single storey and 2-storey rammed earth buildings. The constructed two-storey structure was subjected to 1.6 time the anticipated live loads by placing sand bags on the slab and measuring deflections. The rammed earth building was further subjected to prevailing weather conditions over several years so as to assess the impacts of weather. Further, a rammed earth single storey building made stabilized with materials **other than** standard Portland cement has been constructed as is undergoing evaluation under the effects of prevailing weather conditions.

RESULTS AND DISCUSSION

Material Properties

Table 3 gives basic material properties that include **bulk densities, water absorption, fineness modulus and silt content**. It is observed that river sand has the highest bulk densities while quarry dust from dressed stone plant (QDNbi) has the lowest bulk density, which is even lower than that of murram soil. The values obtained compare well with the results reported by Ilangovan *et al.* (2008) and Mulu *et al.* (1998). Murram has the highest silt content, highest water absorption and highest fineness modulus, and hence a good "candidate" for blending with other coarser materials. BS 882:1973 specifies maximum silt content of 15% in crushed stone sand and 3% in natural or crushed gravel sand, hence murram soil which has a silt content of 14% does not meet the minimum requirements for silt content according to British standard BS 882:1973. One of the roles of laterite in this study was to modify the quarry dust material to be used for masonry block manufacture.

Table 3 Basic material properties

PHYSICAL PROPERTIES		RIVER SAND	QDNbi	QDNdar	MURRAM
Specific density		2.6	2.63	_	_
Bulk density	Loose condition	1405	1354	950	1162
(kg/m^3)	Dense condition	1547	1496	1050	1294
Water absorption in %		1.3	2.0	6.5	6.8
Silt content %		2.7	5.5	12.5	14.0
Fineness modulus		2.27	4.46	1.78	5.46

Shrinkage of various soil mixes was also determined by preparing saturated mixes in boxes of size 40x40x600mm, and leaving the mixes to dry out. Shrinkage measurement and crack observation was done after 3 days. Table 4 shows respectively the type of mixture, the number of cracks, amount of shrinkage, and shrinkage patterns. The table reveals that black cotton soil and red coffee soil have the highest shrinkage and number of cracks, while murram soil did not present any crack. It was also observed that as sand and quarry dust are added to the soil mix, the amount of shrinkage reduced considerably.

Table 4 Linear shrinkage and cracking of soil mixes

Blocks label	Number of cracks of large width	Linear shrinkage Ls (mm)	Shrinkage pattern
RCS (Red coffee soil)	5	30	
RCS-20QD (RCS blended with quarry dust)	1	13	
BCS (Black cotton soil)	3	33	
BCS-20QD (BCS blended with quarry dust)	1	26	
MS (Murram soil)	0	12	
MS-20S (Murrum blended with sand)	0	8	

Effect of Material Type and Mix Ratio on CEB Strength

The effects of material type and mix ratios on strength of CEB are given in Figs. 4 and 5. Results obtained for CEB are compared to conventional building stones that are used to construct load bearing walls in Kenya as presented in Fig 4. A glance at Fig. 4 confirms that novel eco-blocks consisting of a blend of murram (Murr) and other materials such as quarry dust from building stone dressing plant (QDndar), pumice dust from volcanic eruption (Pum) and quarry dust obtained from aggregate crushing plant (QDnbi) have comparable or higher strengths than the minimum strength required for stabilized blocks of 2.5 N/mm^2, and further still, these eco-blocks have comparable or higher strengths than conventional dressed stone blocks used in Kenya. Eco-block, which is stabilized by 10% cement and made from a blend of murram and pumice dust i.e. MurrPum, has the highest strength, which is higher than the strongest stone block, thus affirming the great potential of eco-blocks as alternative environmentally friendly materials for construction in the 21st century.

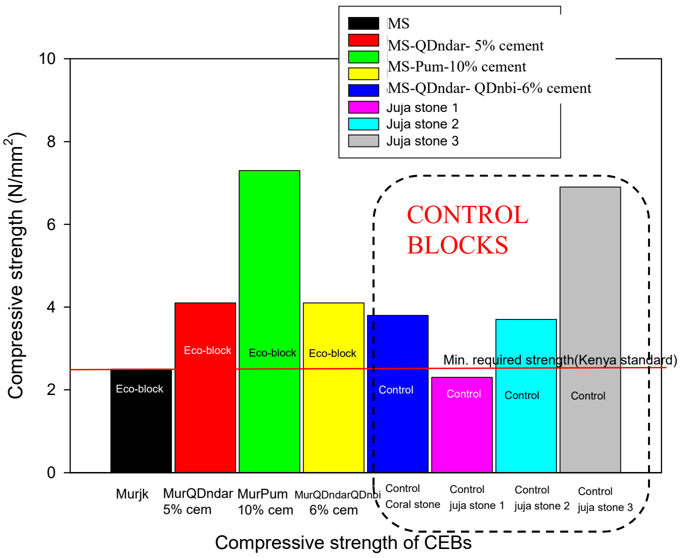


Figure 4 Comparison of CEB with conventional dressed building stones

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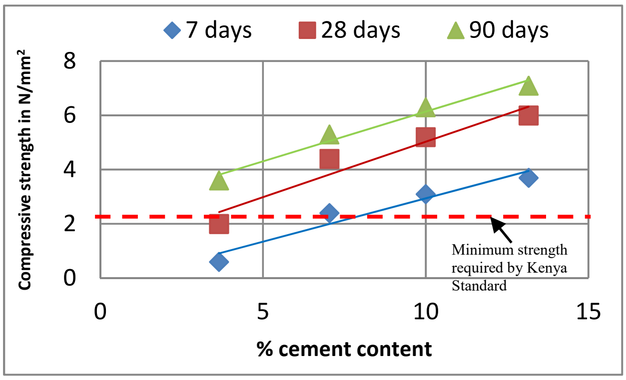
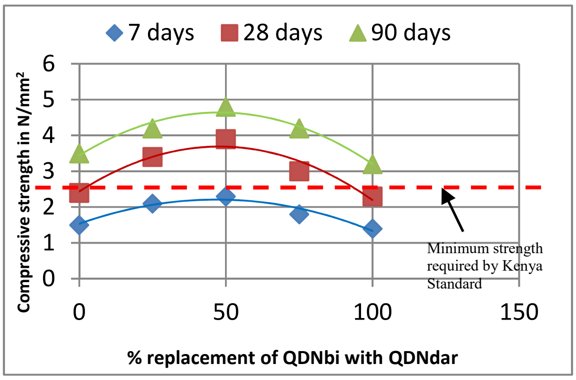
The study also sought to determine the variation of compressive strength of CEB with increasing cement content, and the effect of replacement of QDnbi with QDNdar on CEB strength. Constituent materials for the CEB were cement, murram soil, quarry dust from stone dressing quarries (QDNdar) and Quarry dust from aggregate crushing plant (QDNbi). The amount of quarry dust from dressed building stone quarry (QDNdar) was varied as a replacement of the content of quarry dust from aggregate crushing plant (QDNbi). Results obtained are shown in Fig. 5 where it is clearly observed that CEB strength increases linearly with increased cement content and with age of curing. It also observed that an optimum of 50% replacement of QDNbi by QDNdar is desirable. Generally, masonry blocks containing a blend of alternative materials Murr, QDNbi and QDNdar have better performance in terms of strength and water absorption.



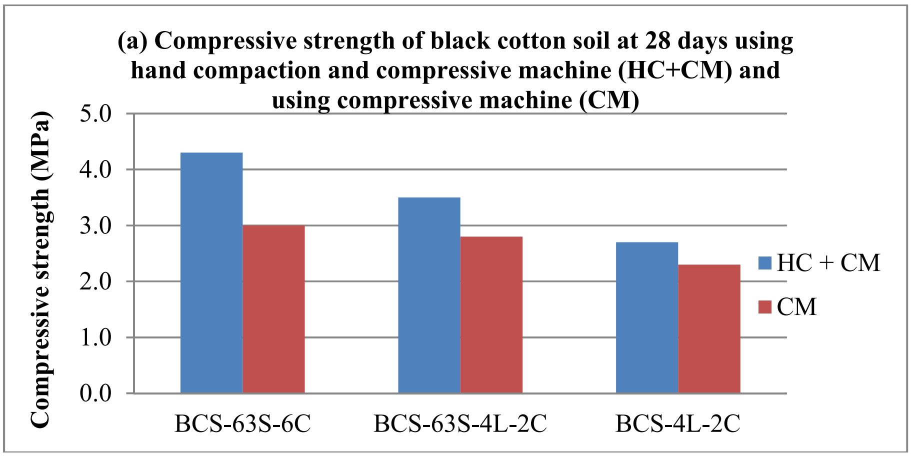


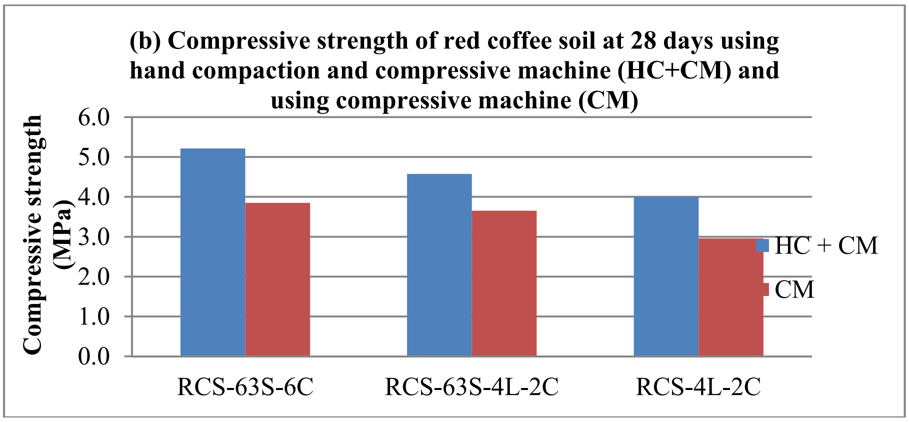
(a) Effect of cement content (b) Effect of QDndar as a replacement of QDnbi

Figure 5 Variation of compressive strength of CEB with cement content, and QDndar content

Effect of Hand Compaction on Compressive Strength of Eco-blocks

As presented in Fig. 6, hand compaction (HC+CM) produced blocks of increased compressive strength as compared to machine compaction (CM). The maximum impact is for mixes with 6% cement where for black cotton soil serie, the compressive strength of blocks increased from 3.01 MPa for machine compaction to 4.3Mpa for hand compaction, for red coffee soil series strength of blocks increased from 3.9 MPa for machine compaction to 5.2 MPa for hand compaction, and for murram soil series the compressive strength of blocks increased from 4.4 MPa to 6.2 Mpa for murram soil. The results confirm what Fetra *et al.* (2011) determined i.e. the density of the compressed earth block is consistently related to its compressive strength and compactive force applied during production.





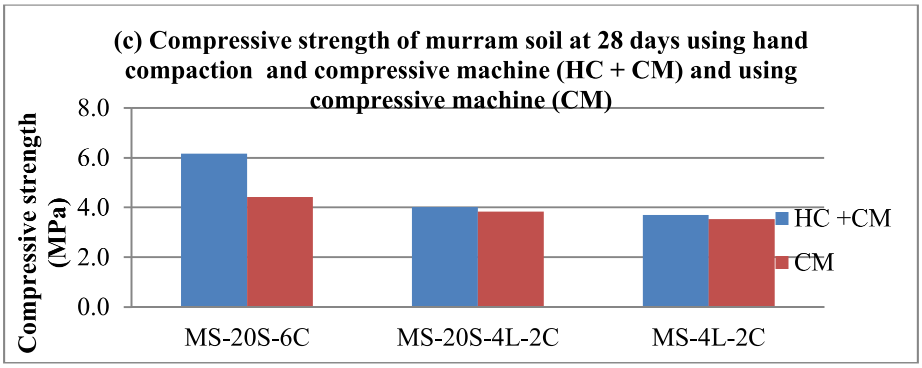


Figure 6 Effect of hand compaction on compressive strength of different types of block at 28 days

Effect of jointing mortar on strength and strain distribution of wall panels

Fig. 7 clearly demonstrates that wall BM 1:4:4:8 jointed in weak mortar similar to the block mix gives the highest ultimate load compared to the other wall panels. In fact, wall CS 1:4 jointed with the strongest cement-sand mortar has the lowest ultimate load. This indeed is an important result as it goes against expectations. It would seem that the homogeneity of the wall panel is of utmost importance with regard to strength and structural performance of walls. Thus, a wall panel made of blocks and jointing mortar that are similar in strength and characteristics has much better performance than a wall made of jointing mortar whose strength is much higher than the blocks. From economic point of view, it would seem prudent to use jointing mortar of similar strength and characteristics as the block. Accordingly, the higher the block strength, the higher the mortar strength required and vice versa.

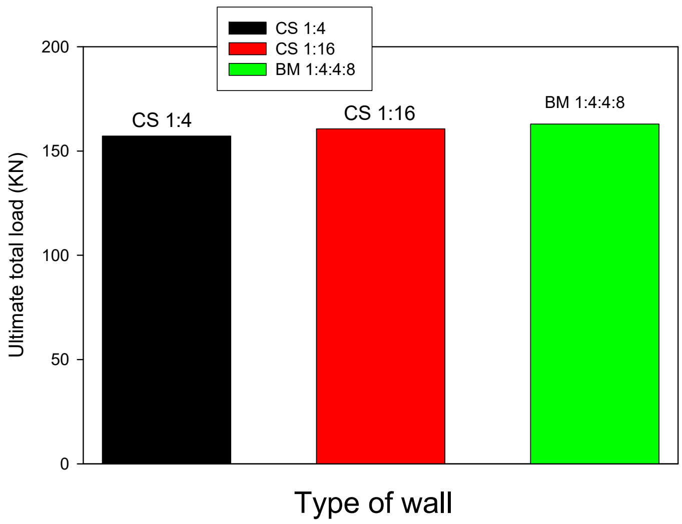


Fig. 11 Ultimate load for wall types

Figure 7 Ultimate load for wall types

Effect of Block Type on Wall Panel Flexibility and Strength

Figures8 represents the maximum stress supported by each wall before failure. It is determined that the stress in the wall types are 1.0411N/mm^2, 1.0643N/mm^2 and 0.9517 N/mm^2 respectively for wall made of unstabilized soil block, wall made of stabilized soil block, and wall made of stone block respectively. This result shows that the compressive strength of stabilized compressed earth blocks is higher than the compressive strength of stone blocks wall used in this works. Moreover, Fig. 8 reveals that strength of the wall is lower than the compressive strength of the unit blocks used for masonry. From these observations it may be inferred that the compressive strength of a blocks unit is not a direct measurement of the compressive strength of the masonry. This was confirmed by Hendry *et al.* (2004) who determined that the compressive strength of masonry varies roughly as the square root of the nominal unit crushing strength and as the third or fourth root of the mortar cube strength.

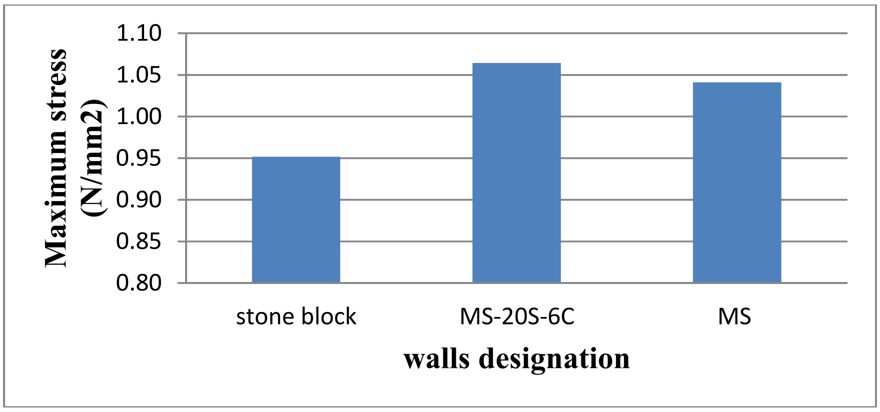


Figure 8 Maximum stress in the walls

The structural adequacy of masonry walls depends upon a number of factors such as quality of masonry units and mortars, methods of bonding, unsupported height of walls hence the strength of masonry is affected by the strength of the blocks, the water/cement ratio and the bond between the masonry unit and the motar. The respective strength of blocks was 2.9 MPa, 4.4MPa and 2.1 MPa respectively for unstabilised soil block, stabilised block and the conventional stone block from Ndarugu quarry. According to Gichuhi (2011), Quarry stone has a compressive strength of between 2 to 5 N/mm2 depending on the type of stone which varies from region to region. It was noted that the strength of conventional stone block used in this work is less than the 2.5 MPa strength of stabilised block required by the KS-02-107:1993. Mortar has a function to bond the bricks or blocks together so that they will resist the loads applied to the wall by giving strength and durability.

Stability and Durability of Full-scale Prototype Single and Two-storey Rammed Earth Buildings

Further to experimental work on structural components of a building structure, actual construction of model eco-structures was undertaken by constructing single and two storey buildings of load-bearing rammed earth wall (Figs 10 and 11). The construction of model full-scale structures was based on test results from material property tests, CEB tests and wall panel tests as illustrated in Figure 9.

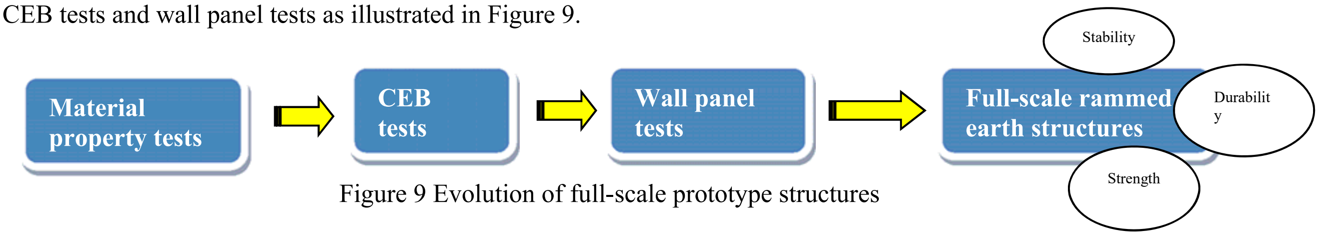


Figure 9 Evolution of full-scale prototype structures

Prior to normal use as a structure, the two-storey model eco-structure with load bearing rammed earth wall was subjected load testing by applying to 1.6 times the anticipated live loads by use of sand bags (see Fig. 11b). Floor displacements were measured using a survey staff. Results observed demonstrate that the two-storey structure was

able to resist applied loading without any visible damage, and the measured floor displacements were minimal and within acceptable levels.
After load testing, the constructed prototype eco-structures have been subjected to prevailing weather conditions and normal use load. To-date these structures have performed satisfactorily both under the weather and normal use loading. Work by Bui et al. (2009) on the durability of different types of stabilised and unstabilised rammed earth walls involved constructing and exposing rammed earth walls for 20 years to natural weathering in a wet continental climate. Results obtained in this study confirm the structural adequacy and stability of rammed earth walls since it was observed that none of the walls had shown complete collapse.

Generally, earth-based construction is seen to be the grand eco-material of this century owing to low embodied energy, low carbon dioxide emissions, very low pollution impacts, and good thermal comfort, amongst other reasons (Pacheco-Torgal et al. 2012). However, the use of ordinary Portland cement for soil stabilization increases embodied energy, and hence further studies are required to evaluate alternative stabilizers that are eco-friendly such as lime, gypsum, and industrial waste products.

(a) Ramming process of earth wall (b) Model single storey rammed earth building

Figure 10 Constructing single storey rammed earth eco-building

(b) Rammed earth building under test loads (b) Completed structure under use as office block

Figure 11 Construction and testing of a model two-storey building from rammed earth

CONCLUSIONS

The work presented herein demonstrates that eco-blocks made of stabilized murram soil and quarry dust have comparable or higher strength than conventional dressed stone blocks used in Kenya. It is further determined that the use of jointing mortar of similar characteristics to the block produces wall panels of higher strength and structural characteristics than blocks jointed in higher strength mortar. This is attributable to homogeneity of the wall panel made of similar jointing mortar. This is therefore a potential saving in masonry construction because, the cement content in the mortar is only 5.9% as compared to the conventional mortar with cement content of 20%.

Results of the study also vividly demonstrate the viability of constructing eco-buildings in Kenya employing local sustainable construction materials. Constructed full-scale prototype single storey building and two-storey building of rammed earth load-bearing wall were found to perform satisfactorily under applied loads and prevailing weather conditions.

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