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ENHANCING THE PERFORMANCE OF WALLS BUILT WITH LATERITE-CEMENT BRICKS: A CONCEPTUAL DESIGN AND SPECIFICATIONS WRITING APPROACH

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The long term performance characteristics of buildings built with laterite-cement bricks to satisfy functional requirement of walls is desirable, particularly where walls are not rendered externally or not plastered internally. The paper aims to address performance enhancing issues arising from conceptual design solutions including component mixture selection to enhance better performance of laterite-cement bricks. The methodology adopted used a building surveying procedure to assess selected two failed housing schemes whose main load bearing walls failed as a result of poor component mixture specifications including selected buildings with identifiable conceptual design flaws within the study area. The development of the appropriate domain of mixture combinations to enhance better performance was developed using the Mixture Method developed by Scheffe to be able to select component mixture proportions for meeting prescribed requirements for both strength and durability. This study is applicable to the hydraulically compressed M7-Twin Hydraform machine exerting a compactive force of 10 MN/m^2. The study has shown that eliminating conceptual design flaws and component mixture selections within a cement content of 8-20 percent would enhance better performance of walls built with laterite-cement bricks

Keywords: conceptual design, laterite-cement bricks, mixture design, specified requirements

INTRODUCTION

One of the basic functional requirements of walls is strength and stability, (Ejeh and Adedeji, 1998). The wall is regarded as a continuous thin and vertical structure. It can also be regarded as a slender member because of its high ratio of the length to the thickness and must be stable when used to provide partitions for the interior of a building or as shelter against wind, rain and/or extreme seasonal weathers, (Hendry et al., 1987). Walls are so described according to structural requirements as load bearing or non-load bearing walls especially when they are used as partitions and the requirements for its design are covered by many design codes such as the BS 5628: Part 1 (2005). They could also be made to satisfy other

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requirements such as thermal resistance. They exist based on different materials among which are: sandcrete, laterite-cement and clay bricks/blocks. They are also available in sizes to meet architectural or structural requirements.

The walling material described here is made from lateritic material which can be described as a class of pedogenics where the cementing materials are the sesquioxide contents which should normally constitute not less than 50 percent of the mineralogical composition (Gidigasu, 1976). Tests on the mineralogical composition are carried out using the X-ray fluorescence test for the compounds. This class of material for walls also has very good thermal properties, impact, including shock and earthquake resistance (Hydraform, 2014). The material considered here is referred to as dry jointed or interlocking, requiring no bedding or jointing. They are normally preferred to be left unrendered externally and unplastered internally and should still be required to meet basic functional requirements of strength and stability including meeting durability requirements. Laterite as a material for building bricks is different from expansive clay with shrink-swell characteristics (Amadi et al, 2011). It has been used right from the pre-historic days and it is still becoming as popular especially because of the improvement in the mechanical stabilization process. Today, improvements have been made in developing uniaxial compression machines for mechanical stabilization of this laterite-cement bricks (Hydraform, 2014; NBRRI, 2014; Cinva Ram, 1999; Guetalla at al, 2015) with compactive effort ranging between 5-15MN/m2. The most common method of stabilization apart from mechanical stabilization is cement. The mineralogical compounds in laterite soils interact with fluids and determine other characteristics such as plasticity, swelling, hydraulic behavior and compressive strengths (Amadi et al, 2011).

In sourcing for laterites from burrow pits, the properties of the laterite soil could vary according to depth (Alao and Jimoh, 2017). Plasticity of a soil still remains a very important index in the selection of laterite sample for use in both Civil Engineering works and in the production of Building bricks. Plasticity of a soil is usually measured by indices such as Plastic Limit, Liquid Limit, Plasticity Index and Shrinkage limit. Typical test procedure is covered in BS 1377 (2016). Another method of providing standard basis for comparing laterite deposits include the Unified Soil Classification System (USCS) and the American Association of State Highways and Transport Officials (AASHTO). Unlike in other types of bricks, two types of bonds exist in laterite-cement bricks. They are: "plastic bonds" and "cement bonds". The bonding characteristics are therefore influenced by the sesquioxides content, cement content and compactive effort (Alao and Jimoh, 2017; Alao and Jimoh, 2018; Guetalla et al, 2015). Apart from cement as a binder, lime can also be added especially where Plasticity index are in excess of 20 percent to allow for flocculation of the particles because excess clay (Singh, 2006; Hydraform, 2014; Olutoge et al. 2018). Addition of pozzolanic materials however are intended to reduce cement cost.

In spite of advances in the manufacturing and availability of hydraulically compressed compaction machines for laterite-cement bricks, production of bricks meeting specified requirements still represents a challenge mainly as a result of component mixture selection. Similarly, certain conceptual design flaws which has led to a partial collapse of laterite-cement brick walls including concepts that created maintenance concerns also presents a challenge that need to be addressed. The paper seeks to address these performance enhancing issues arising from conceptual design, and develop limits on the component mixture selection to enhance better performance of laterite-cement bricks in order to avert the ugly trends.

LITERATURE REVIEW

Conceptual approach to design of laterite-cement brick walls

Safe and efficient load bearing and non-load bearing walls can be built using laterite-cement bricks as compressive strength achievable can be as much as four (4) times in excess of the minimum strength of the conventional sandcrete blocks, (NIS, 2004; Hydraform, 2014; Alao and Jimoh, 2017) at just 8% cement content. Compressive strength achievable can be as much as 8N/mm2. This has also made it possible to use the material to construct buildings up to 2-storey without structural frames (Hydraform, 2014). Blockwall design procedure are similarly well established using the mathematically derived procedure of structural mechanics and are as well documented in several codes of practice for design of walls such as BS 5628: Part I (2005). The principle of conceptual design would translate (Fraser, 1981; Hsu and Liu, 2000; Mola, Mola and Pellegrini, 2011) to: Intuitive reasoning to allocate and maximize space for functionality, aesthetics and efficiency of a building. Details that would also impede durability concerns should normally be taken into consideration such as avoiding water retention on walls thereby causing dark patches.

i) Permit development of adequate resistance to lateral forces in certain or foreseeable directions exposed to strong wind loads. This is particularly evident at vulnerable gable ends and therefore, a code of practice should not be a substitute for care and vigilance.
ii) Avoid torsional effects and therefore avoiding undesirable stress distributions to ensure robustness of the building.
iii) Redirecting load paths for optimal structural efficiency.

Laterite-cement brick walls design process should therefore be guided by both theoretical and practical considerations. In essence, it has to satisfy the limit state principles of ultimate and serviceability, remembering that a wall is a slender member which must both satisfy strength and stability requirements. Similarly, it must also avoid constructability problems and conceptual design flaws which could pose durability concerns. This would produce a balanced design. The main aim of a design ultimately is to function throughout the intended life without excessive deflection, cracking as well as without eventual collapse.

When brickwork is loaded in uniform compression, failure occurs by development of tension cracks parallel to the axis of loading (Ejeh and Adedeji, 1998; Hendry et al, 1987). It is also good to note that the strength of brickwork is usually smaller than the compressive strength of individual brick approximately, it is equal to the square of the nominal brick crushing strength for which it was built, (Hendry et al, 1987).

The building surveying procedure

This essentially represents a report on the general condition of a building. A general practice procedure outlined by the Nigerian Institute of Building (NIOB) requiring expert knowledge of building inspection, identification of building defects, defects diagnosis, determining the causes and proposing appropriate remedies with the sole aim of restoring the economic value of the building. It could also be prepared for the purpose of purchasing a house to establish the condition and value of a property which may also be used as a document for a loan. The process as outlined (NIOB, 2002) include:

i) Carry out reconnaissance survey of the building
ii) Carry out detailed inspection to identify defects, determine causes and propose appropriate remedies
iii) Prepare schedule of repairs, improvements, possible conversion, alteration and renovation
iv) Prepare schedule of dilapidation and negotiating on behalf of the client and manage its execution
v) Prepare a report on the general condition of the building

Among additional responsibilities include

i) undertaking investigations into works with historical buildings, including its preservation and restoration
ii) undertaking investigations into works associated with preservation of buildings and its amenities
iii) assessing, negotiating and implementing improvement grants

Where expert knowledge is required for specialist diagnosis or input, it should be sought for and a supplementary report should normally accompany the building surveying report. In all of these, the report should accompany an estimate of the cost of the repairs.

Inspection of the structure should include both the visible exposed and inaccessible parts of a building and should all be carried out. It is however, advisable to adopt a logical sequence when surveying a property to minimize the risk of omission (Seeley, 1985).

Developing a procedure for component mixture proportioning for laterite-cement bricks

In developing a domain of component mixture proportions and responses which will enable component mixture selection to be obtained to satisfy specification requirements for a laterite deposit, several methods can be employed. These include:

i) Use of trial mixes using absolute volume method
ii) Use of mixture experimental design methods which use factorial designs approach such as the Taguchi's Mixture method, Scheffe's Mixture method and the Response Surface Methodology

The Scheffe's experimental design method discussed here was used to select points within a triangular simplex for a three component mixture described in Figure 1. It is particularly unique to produce mixtures at maximum compacted absolute volume equal to unity. In this case, laterite, cement and water. It can enable an empirical model to be fitted for each response of interest, particularly strength. Further refinements of the empirical models can be carried out by modifying a model after removing all insignificant terms in a model. A resulting final model now forms the response prediction equation. This should satisfy the condition that at least 95 percent of the results are expected to fall within the normal distribution curve. This could then form a basis for a quality control procedure and acceptance criteria process.

This methodology of fitting a polynomial can be used to define an experimental region or domain. The vertices of the triangle as shown in Figure 1 represent numerically, the three actual variable component mixtures (Montgomery, 2001). The vertices represent P1 equal 8%, P2 equal 14% and P3 equal 20% cement contents respectively or more precisely, ratio 1:12.5, 1:7.14 and 1:5 representing the ratio of cement to laterite mix. The first part represents the component part, water, the second part represents cement while the third part represents laterite. Similarly, the pseudo components at the vertices are represented by P1 equal (1, 0, 0), P2 equal (0, 1, 0) and P3 equal (0, 0, 1)

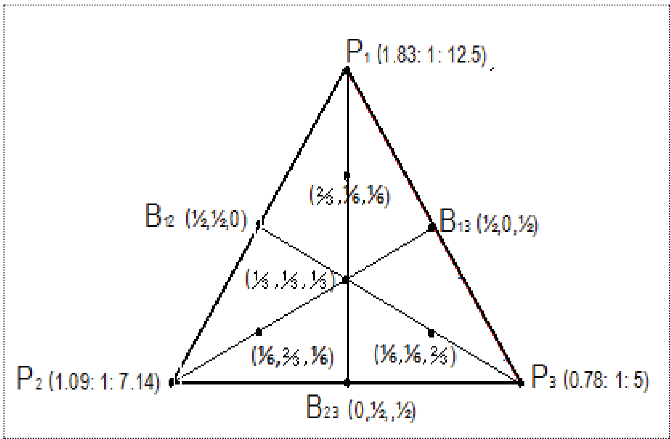

Figure 1: An augmented [3, 2] Simplex lattice

In order to satisfy the requirement of this Scheffe's mixture approach, the component materials are estimated in absolute volume using equation (1) which is fixed and constrained to be summed equal to unity.

$$\frac{water}{\rho_{water} \times 1000} + \frac{cement}{\rho_{cement} \times 1000} + \frac{laterite}{\rho_{laterite} \times 1000} = 1 \qquad (1)$$

$where: \rho = specific\ gravity$

This represents a pre-condition for using this method of solution procedure (Simons et al, 1999; Montgomery, 2001). The components materials in this particular case are water, cement and laterite. The equality constraint of equation (1) estimated in absolute volume is therefore represented in equation (2), (Montgomery, 2001) as:

$$\sum_{i=1}^{n} x_i = 1 \qquad (2)$$

and $\quad x_i \geq 0$

The standard form for the response prediction for water, cement and laterite mixture is represented by the second order-quadratic polynomial expressed as, (Montgomery, 2001):

$$y = \sum_{i=1}^{p} \beta_i x_i + \sum \sum_{i<j}^{p} \beta_{ij}\, x_i x_j \qquad (3)$$

$where$: $\quad x_1 = water, x_2 = cement, x_3 = laterite$

The expressions x_1x_2, x_1x_3, x_2x_3 are the interaction terms while the expressions b_{12}, b_{13}, b_{23} represent coefficients of the interaction terms of water, cement and laterite respectively.

A transformation between pseudo and actual components is required for estimating the component proportions for all other design points in the interior of the [3, 2] Simplex lattice in the factor space. This is made possible because of the inverse relationship that exists between the vertices and the interior points as described by Onuamah (2015), Onwuka et al. (2011) and Alao & Jimoh (2018). These enable making predictions and explore the full properties within the Simplex.

The augmented [3, 2] Simplex lattice shown in Figure 1 consists of ten runs consisting of pure blend, binary blends, axial blends and the centroid, (Montgomery, 2001). This procedure is also implementable using Design Expert Software (Design Expert, 2000). However, the transformation procedure was implemented to keep the mixtures at a full absolute compacted volume.

MATERIALS AND METHODOLOGY

The Mandate 2003 and Harmony Estate housing schemes were studied, both built within Ilorin, Kwara State, Nigeria. The two housing schemes were built using laterite-cement bricks sourced within Ilorin environs. The two housing schemes were evaluated using the methodology of Building Surveying procedure outlined by the Nigerian Institute of Building to assess the condition of the buildings. In a similar manner, two other buildings within the study area built with the same walling material were also surveyed with a satisfactory performance in terms of the quality of the laterite-cement walling materials used but exhibiting certain conceptual design flaws. In all of these cases, the bricks were produced using the M7-Twin Hydraform brick moulding machine capable of exerting a compactive force of 10MN/m2. Samples from burrow pits of the two housing schemes were evaluated to determine the suitability of the deposit to provide answers for such a colossal failure of the two housing schemes. The methodology also tried to establish lack of quality control measures that was inherent in such a failed multi million naira projects. This scenario, which has become a case of sanctions, liabilities and litigations as at the time of this survey. Table 1 shows the methodology adopted to enhance the performance of laterite cement brick walls

Table 1: The survey method

Develop component materials selection process	Determine suitability of laterite deposit
	Develop component selection procedure for development of specifications writing
	Develop limits or bounds to mitigate against poor mixture combinations
Identifying conceptual design flaws	Identify defects and its diagnosis arising from conceptual design flaws
	Suggest remedial measures

Geotechnical and mineralogical properties of samples

The physical, geotechnical and mineralogical properties of the laterite sample were obtained and tested in accordance with BS 1377 (2016). These properties include: Liquid limit (LL), 49%; Plastic limit (PL), 30.6%; Plasticity Index (PI), 18.4%. Other properties include: Specific gravity of (SG), 2.64; Linear shrinkage (LS), 10.1% and Maximum dry density (MDD) of the deposit was 1821kg/m3. Soil classification: A-2-7. The mineralogical properties include Fe2O3, 18.01% and Sesquioxide content of 42.21%. These indices showed that the properties conform with requirement for moulding laterite-cement bricks since PI ≤ 20% and SL≤ 15%.

Properties of brick samples

The factored brick samples were produced, cured and tested at 7 and 28 days to obtain compressive strengths and other mechanical properties using a Testometric Universal Testing Machine Model FS300CT. The testing plan described by ASTM C 170-90 was used. The cement type used here can be termed as Portland Limestone Cement Table 2 shows the design matrix considered for this investigation.

The augmented [3,2] simplex in Figure 1 was used to produce the design matrix in Table 2 for developing specifications writing, specific for the laterite deposit used for the housing scheme. It consists of a 3-component mixture. Additional design points were also selected within the interior of the simplex which enables the possibility of detecting curvatures, (Simon et al., 1999; Montgomery, 2000). In a similar manner, the centre point was replicated in order to obtain statistical significance for model fitting for predicting responses of interest.

Table 2: Design matrix with mixing water at Optimum Moisture Content using an augmented [3, 2] Simplex lattice by weight

S/No.	Coordinate Points		Pseudo component ratios for selected design points			Actual components ratios			Actual component mixes, kg/m^3		
			X_1	X_2	X_3	x_1 Water	x_2 Cement	x_3 Laterite	x_1 Water	x_2 Cement	x_3 Laterite
(1)	(2)		(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1		P_1	1	0	0	1.83	1.00	12.50	265.75	145.33	1816.63
2	VERTICES	P_2	0	1	0	1.09	1.00	7.14	264.69	243.32	1737.29
3		P_3	0	0	1	0.78	1.00	5.00	261.26	334.06	1670.30
4		B_{12}	½	½	0	1.46	1.00	9.82	265.66	181.90	1786.22
5	BINARY	B_{13}	½	0	½	1.31	1.00	8.75	265.45	202.25	1769.70
6		B_{23}	0	½	½	0.94	1.00	6.07	263.55	281.44	1708.35
7		C_1	⅙	⅔	⅙	1.16	1.00	7.68	265.03	227.79	1749.40
8	CONTROL	C_2	⅔	⅙	⅙	1.53	1.00	10.36	265.71	173.11	1793.44
9		C_3	⅙	⅙	⅔	1.01	1.00	6.61	264.22	260.80	1723.88
10	CENTROID	O	⅓	⅓	⅓	1.24	1.00	8.21	265.28	214.37	1760.00

**The highlighted are the upper and the lower limits on the domains of constituent proportions*

Building surveying process

Two housing units consisting of 350 units each was surveyed. The building survey methodology adopted a logical sequence as required to minimize the risk of omission. Including general description, roof, openings (roofs and doors), fittings, external and internal walls, drainages, ceilings and foundations. This survey however, laid emphasis on the laterite-cement brick walling material. The clear distinction between the magnitude of serious defects and those of lesser consequences however led to conclusions leading to imposition of sanctions, liabilities and invoking legal implications as at the time of this study. This is particularly evident where little remedial actions are least possible to restore the fabrics of the building to a useful state. Jambol (2012), advocated that these punitive measures arising from fraud and outright disregard for quality control would stem such a menace. This phenomenon poses a threat to sustainability in the use of laterite-cement bricks as a walling material for building construction. Appendices A and B show some level of defects and conceptual design flaws. Three basic conceptual design flaws were inherent from two identifiable buildings also within the study area and are as shown in Appendix B. They are:

i) Inability to keep out water running down on walls
ii) Inability to insulate wall from preventing condensation on wall
iii) Collapse of gable end of wall through high wind pressure as a result of absence of lateral stability
iv) Unstable wall

ANALYSIS OF RESULTS

The mixture combinations shown in the design matrix of Table 2 was used to produce bricks using cement and laterite with water requirement at optimum moisture content. This produced responses of interest, compressive strength at 7 and 28 days using the second-order polynomial expression in Equation 3. The domain as highlighted in Table 2 can produce reasonable result. It can be used for building constraints on the lowest and upper bounds on the proportions to yield 1m3 of compacted volume. The limits are represented in absolute volumes and by dividing the proportions of the quantities by their respective unit weight for lowest and upper limits of water (1000 kg/m3) which gives 0.261 and 0.266. Likewise for cement, by dividing the proportions by the unit weight of cement (3150 kg/m3) gives 0.046 and 0.106 and for laterite, by dividing the proportions by the unit weight of laterite (2640 kg/m3) gives 0.633 and 0.688. This is summarized and represented in equation (4).

$$\left.\begin{aligned} 0.261 \leq x_1 \leq 0.266 \\ 0.046 \leq x_2 \leq 0.106 \\ 0.633 \leq x_3 \leq 0.688 \end{aligned}\right\} \qquad (4)$$

This domain of mixture proportioning would invariably prevent a reversal of stabilization associated with moisture intrusion within the stabilized laterite-cement bricks, although blending of laterite with silica sand would reduce this effect (Heathcote, 2002). Selection of constituent materials represents what is appropriate for production of bricks for these housing units.

The response prediction yields an inverse relationship for strength at 28-day, 7-day respectively as depicted in equations (5) and (6)

$$\frac{1}{fc_{28}} = -3.54724 * x_1 + 0.10341 * x_2 + 1.53865 * x_3 \qquad (5)$$

$$\frac{1}{fc_7} = -4.13545 * x_1 + 0.21151 * x_2 + 1.79349 * x_3 \qquad (6)$$

$$where: \qquad x_1 = water, x_2 = cement, x_3 = laterite$$

In each case, the minimum compressive strength ranges between 8 and 18N/mm2 within the domain selected. The test results are shown in Appendix C. The compressive strength values are well above the minimum requirement of 2.8N/mm2 in accordance with NIS (2004), SANS (2008) for load bearing brickwork design. The limits shown in Equation (4) will also produce durable bricks (Guetalla et al., 2006). In likewise manner, a perfect linear relationship for response prediction for quantity of laterite based on ratio of laterite:cement can be obtained using a simple regression analysis at 95% confidence interval. The response in column (11) against cement, the variable in column (10) of Table 1 can be carried out. The merit of this method is that component mixtures can be estimated at 1m3. The resulting predictive response for laterite quantity is presented in equation (7).

$$Laterite\ quantity = 1927 - 0.7767 * x_2 \qquad (7)$$

$$where: \qquad x_2 = cement,$$

Stability concerns of the main load carrying member

The building survey report carried out has shown that the main load carrying structural member, which is the wall, has failed completely. When a structure cannot perform its main functional requirement, then it is deemed to have failed. Contrary, the conceptual design flaws which can be avoided to enhance the performance and safety of the walls built with laterite-cement bricks as shown in the surveyed structures in Appendix B.1 (a) – (c).

DISCUSSION AND CONCLUSIONS

The study identified that despite the availability of hydraulically compressed brick moulding machines, component mixture selection specific for a laterite deposit can adversely affect the quality of the brick produced. The development of specification writing is suggested to accompany contract documents so as to stem the menace of poor performance. This will avoid the scenarios experienced in the two housing schemes surveyed. Component mixture proportioning, if adequately given attention is fundamental for producing bricks capable of meeting specified requirement of strength and durability. In using the second-order quadratic polynomial design in Table 2, indices which can serve as guides in the form keeping within specified boundaries can be achieved particularly using this innovative compression machine. Elimination of conceptual design flaws would enhance the performance of laterite-cement brick walls and avoid scenarios shown in Appendices A and B.

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APPENDIX A: FAILURE ARISING FROM COMPONENT MIXTURE PROPORTIONING

A.1(a): Total failure of load bearing walls and all fabrics of the building

A.1(b): Total failure of load bearing including sinking floor

A.1(c): External walls plastered and all roofing sheets replaced

A.1(d): Visible cracks on walls including spalling and eroding wall by rain

A.1(e): Collapse of external walls and internal partitions

A.1(f): Part of external walls replaced with sandcrete blocks

APPENDIX B: FAILURE ARISING FROM CONCEPTUAL DESIGN

B.1(a): The gable end shown with a pointer collapsed and re-built by introducing vertical pier in the walls

B.1(b): The vertical wall shown with a pointer has dark patches as a result of undrained water from the cladding

B.1(c): The vertical wall shown with a pointer has caved-in. Could have been prevented if lintel was introduced at window level

APPENDIX C: MIXTURE PROPORTIONS (PER M^3) AND RESPONSES- RUN ORDER

Std Order	Run Order	Block	Component 1 A:Water m^3	Component 2 B:Cement m^3	Component 3 C:Laterite m^3	Response 1 fc 7 N/mm^2	Response 2 fc 28 N/mm^2
4	1	Block 1	0.266	0.058	0.677	6.09	8.406
6	2	Block 1	0.264	0.089	0.647	11.079	14.445
1	3	Block 1	0.266	0.046	0.688	7.627	8.4
7	4	Block 1	0.265	0.072	0.663	10.558	11.976
11	5	Block 1	0.265	0.068	0.667	8.22299	10.551
10	6	Block 1	0.265	0.068	0.667	10.349	10.359
3	7	Block 1	0.261	0.106	0.633	12.508	16.653
5	8	Block 1	0.265	0.064	0.67	8.792	10.432
9	9	Block 1	0.264	0.083	0.653	10.959	12.991
14	10	Block 1	0.265	0.068	0.667	8.47996	10.8807
12	11	Block 1	0.265	0.068	0.667	8.22299	10.551
2	12	Block 1	0.265	0.077	0.658	9.884	13.249
13	13	Block 1	0.265	0.068	0.667	8.73693	11.2104
8	14	Block 1	0.266	0.055	0.679	8.337	10.452