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Original Research Article

Design and Fabrication of Compressed Earth Block Machine for Low Cost Housing in Nigeria

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ABSTRACT

Bricks/blocks are vital materials for building construction and their quality contributes to the longevity of the structure. This research was aimed at designing and fabricating a locally made manually operated clay stabilized block (CSB) machine. The fabricated machine was made from mild steel materials, and after fabrication, experiments were conducted using laterite sand and 5% cement to produce blocks. The machine is capable of producing blocks with good compressive strength of 3.53 N/mm^2 and initial rate of absorption (IRA) of 1.39 kg/(m^{2}min) at 5% cement stabilization on laterite sand. From the experiments conducted, the machine can be used for good quality block production.

1. INTRODUCTION

The ever- increasing cost of building materials continues to limit the middle- and low-class citizens from owning a house in Nigeria (Abimaje et al., 2014). About 90% of materials required to construct an average home in Nigeria are produced locally but the building cost is still on the increase (Ugochukwua and Chioma, 2015). This reason isn’t farfetched. According to Yakubu and Umar (2015), one of the most expensive materials for building is block. The concrete blocks (mixture of cement, sharp sand and water) are often used for house construction. These blocks are too expensive for low income families (Bichi et al., 2019). In times past, houses in Nigeria were built using clay and bamboo as the major ingredients which were locally available and can be obtained on site (Onyegiri and Ugochukwu, 2016). Due to the local availability of these construction materials, poor people were able to provide themselves with shelter though these buildings were not durable and so required continuous maintenance yearly (Abdullahi, 2006).

When cement came into the market, due to its durability and long- lasting property as building material, it phased out the clay-bamboo houses which constantly required periodic maintenance (Abdullahi, 2005). Any effort geared toward reducing the cost of blocks for construction in Nigeria, would be highly embraced by her low- and middle-class citizens.

Compressed stabilized earth blocks (CSB) are the modern upgrade of the adobe blocks. CSB has a good beneficial building quality such as being fire resistance, bullet proof, durable etc (Buson et al., 2012). the blocks are produced using the CINVA-RAM press. This press can produce cheap blocks from a mixture of clay, sand, water and a small portion of cement in the recommended ratios. Fabricating this machine locally will help reduce cost of importing them, reduce cost of block production in Nigeria and also promote indigenous homemade goods.

The aim of this work is to design and fabricate a locally made clay stabilized block machine which would be used to produce low cost block with minimal water absorption rate and good compressive strength.

2. MATERIALS AND METHODS

2.1. Materials

Locally sourced materials such as mild steel plate, pipes and angle bars for the fabrication of the machine were used for the work. The quantity and dimensions of some materials used to fabricate the machine is summarized in the Table 1. The materials where cut to the specific dimensions required for the design before welding and bolting the welded components to form the complete machine. After the machine fabrication, laterite soil was sourced locally in Benin metropolis. Dangote Ordinary Portland Cement was used as the stabilization agent.

Table 1: Quantity of Steel used for the fabrication of the SCEB machine

S/N	Dimensions (mm)	Quantity	Comment
1	230 × 56	2	Angle bar
2	126 × 64	2	10 mm thickness
3	190 × 44∅	1	2 mm thick pipe
4	254 × 60∅	2	2 mm thick pipe
5	457 × 50∅	2	2 mm thick pipe
6	248 × 20∅	1	Solid bar
7	80 × 12∅	1	Solid bar
8	266 × 32∅	1	Solid bar
9	106 × 32∅	1	Solid bar
10	170 × 32∅	1	Solid bar
11	270 x 152	2	10 mm thickness
12	500 x 320	2	10 mm thickness
13	300 × 38	2	10 mm thickness
14	320 x 152	1	10 mm thickness
15	320 × 43	2	10 mm thickness

2.2. Methods

For reliability of the machine during service/usage, the machine must be able to magnify the force applied to the lever arm of the machine to compress the sand in the mould and also ensure no breakage or tilting of the machine during ejection. To achieve this, some design factors were taken into consideration. Firstly, the machine must not tilt during compaction/compression of the soil cement mixture inside the mould. Secondly, the machine must not tilt during ejection of the block from the mould and finally, the compressive stress at the ram must be less than the ultimate stress of the material to prevent quick failure of the machine. To achieve this, design, the Brown et al. (2014) method was employed.

2.2.1. Forces during compaction

Figure 1 shows the forces acting on the lever arm, length (L_w) required to prevent the machine from tilting during compression, height and weight of the machine after assembly. Equations (1) and (2) represent the horizontal and vertical forces acting on the lever arm. Equation (3) was used to determine L_w.

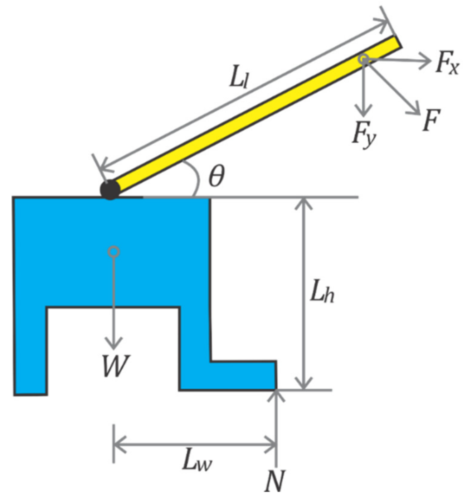

Figure 1: Free body diagram (FBD) for compression stroke

The dimension of the fabricated machine is given as L_w = Length from center of mass to the tip, Weight of machine (W) = 70 kg, Length of lever (L_l) = 1520 mm or 1.52 m and the applied force (F) = 490.5 N
L_h = Height from ground to lever pivot = 513 mm = 0.513 m

$$F_x = F\sin\theta \quad (1)$$
$$F_y = F\cos\theta \quad (2)$$

Analysis for compression: taking clockwise moment as positive, the FBD in Figure 1 was used to develop Equation (3). Substituting Equations (1) and (2) into (3) resulted in Equation (4). Equation (5) was derived by making $L_w$subject of Equation (4).

$$\sum M = 0 = F_x(L_h + L_l\sin\theta) + F_y(L_l\cos\theta - L_w) - WL_w \quad (3)$$
$$0 = F\sin\theta\,(L_h + L_l\sin\theta) + F\cos\theta\,(L_l\cos\theta - L_w) - WL_w \quad (4)$$
$$L_w = \frac{F(\sin\theta L_h + L_l)}{F\cos\theta + W} \quad (5)$$
$$L_w = \frac{(490.5\,(\sin 45)0.513+1.52)}{490.5\cos 45+70} = 0.4305\,m = 430.5\,mm$$

2.2.2. Forces during ejection

Figure 2 present the FBD for the machine during ejection of the block from the mould. Assuming the lever does not slide on pivot and values of W, L_l and F, remain the same as that in Figure 1 with L_d = distance from center of mass to the lever pivot (i.e. 0.172 m) and new height from ground to lever pivot (L_h) during ejection (i.e. 0.191 m). The aim is to compare L_w during compaction and ejection, then fabricate the final length of L_w based on the longest length obtained.

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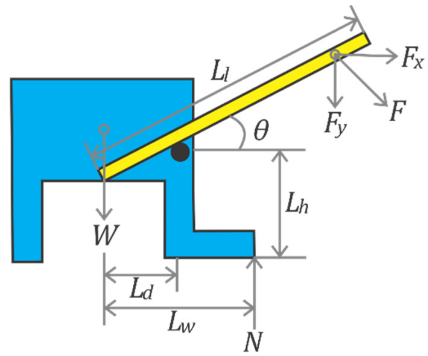

Figure 2: Free body diagram for ejection stroke

Analysis for ejection: taking clockwise moment as positive, the FBD in Figure 2 was used to develop Equation (6). Substituting Equations (1) and (2) into (6) resulted in Equation (7). Equation (8) was derived by making $L_w$subject of Equation (7).

$$\sum M = 0 = F_x(L_h + L_l \sin\theta) + F_y(L_l \cos\theta + L_d - L_w) - WL_w \quad (6)$$
$$0 = F\sin\theta\,(L_h + L_l \sin\theta) + F\cos\theta\,(L_l\cos\theta + L_d - L_w) - WL_w \quad (7)$$
$$L_w = \frac{F((\sin\theta)L_h + L_l + (\cos\theta)L_d)}{F\cos\theta + W} \quad (8)$$
$$L_w = \frac{490.5((\sin 45)0.191 + 1.52 + (\cos 45)0.172)}{490.5\cos 45 + 70} = 0.163\ m = 163\ mm$$

Comparing calculated value of L_w = 430.5 mm for compaction of soil-cement mixture and L_w = 163 mm for ejection of block from mould, the design was done based on the longest length obtained between L_w for compaction and ejection. Therefore, L_w = 430.5 mm was taken as the minimum length to prevent tilting of the machine during usage.

2.2.3. Applied force at the ram carriage and stresses developed on the plate

Figure 3 shows the lever arm and forces (F) acting on the arm. The value of 1791.8 N was obtained by making F the subject from Equation (9).

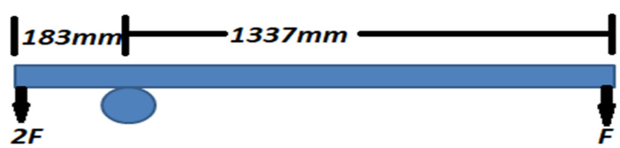

Figure 3: Free body diagram for compression/ejection stroke

$$2F \times 183 = 490.5 \times 1337 \quad (9)$$
$$F = 1791.8N$$

Compressive stress using cross sectional area: the ram plate has a dimension of 270 by 152 by 10 mm presented in Table 1. To get the stress (σ_{y_1}) induced during compression, the value of 1520 mm^2 and 1791.8 N were substituted into Equation (10), to give 1.179 MPa.

Plate thickness = t =10 mm, cross sectional area = A

$$\sigma_{y_1} = \frac{F}{A} \quad (10)$$

$$A = 10\,mm \times 152\,mm$$
$$A = 1520\,mm^2$$
$$\sigma_{y_1} = \frac{F}{A} = \frac{1791.8N}{1520mm^2} = 1.179\,MPa$$

Compressive stress of ram carriage plate: A hole diameter of D = 60 mm was drilled on the ram plate, and to calculate the stress (σ_{y_2}) developed in the hole on the ram during compaction, Equation (11) was applied. Figure 4 shows the sketch for the ram carriage plate. The arrow points to the magnified area affected by the compressive stress impact on the plate. The arrow points to the magnified area affected by the compressive stress impact on the plate. The area was obtained as 942.48 mm^2 and σ_{y_2}=1.901 MPa.

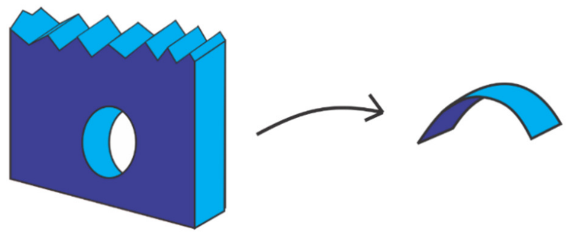

Figure 4: Ram carriage plate

$$\sigma_{y_2} = \frac{F}{A} \qquad (11)$$
$$A = \frac{\pi D}{2}.t = \frac{\pi(60mm)}{2} \times 10mm = 942.48mm^2$$
$$\sigma_{y_2} = \frac{F}{A} = \frac{1791.8N}{942.48mm^2} = 1.901MPa$$
$$S_{y_{steel}} = 370MPa$$

Since $S_{y_{steel}} > \sigma_{y_1} and\ \sigma_{y_2}$, it is safe to assume that the ram carriage plate would not fail under compressive stress.

Stress analysis: the ram carriage plate and pin (shaft) is presented in Figure 5. The lever arm of the machine connects to the ram plate through the pin. As the arm is engaged for compaction or ejection, it lifts the ram bed upward for compression or ejection, therefore producing reactions on the pin as shown in Figure 6.

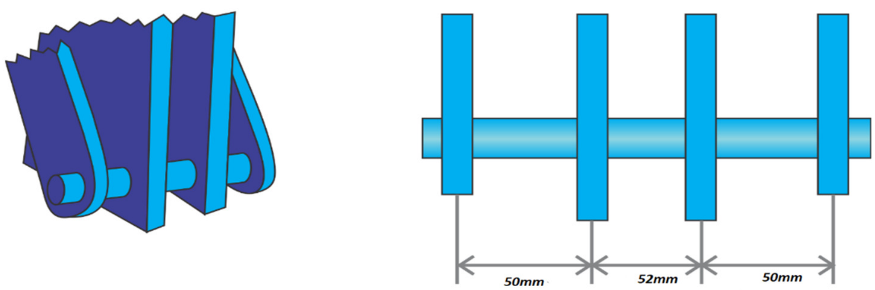

Figure 5: Schematics of the ram carriage plate

The force on each contact point along the pin from the previous analysis was given as 1791.8 N. The free body diagram in Figure 6 showing the forces and reactions on the pin was used to develop the shearing force and bending moment diagram is presented in Figure 7.

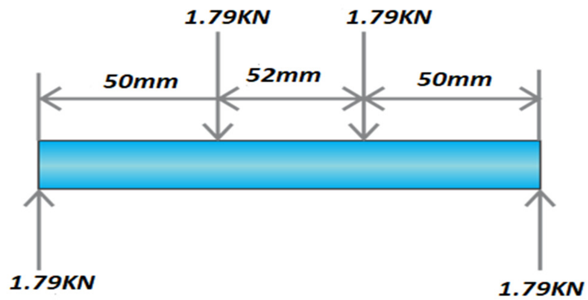

Figure 6: Free body diagram of ram carriage pin

Shearing force and bending moment analysis: Figure 7 present the bending moment and shearing force on the pin. The bending moment (M_c) was analyzed to determine the necessary diameter of the pin to avoid failure due to shear force and bending moment on the shaft.
$S_{y_{steel}}$= 370 MPa and $r = 6.75\ mm$

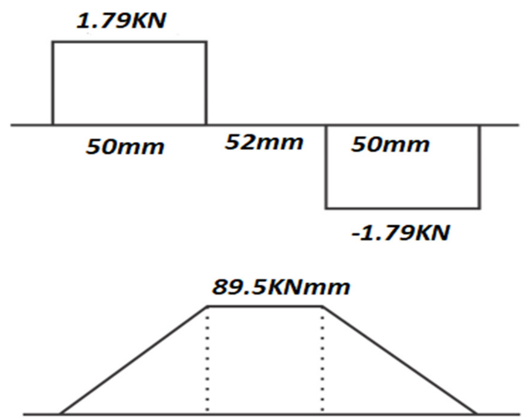

Figure 7: Shear force and bending moment diagrams

$$S_{y_{steel}} = \frac{M_c}{I} = \frac{(89.5Nm)(r)}{\frac{\pi(2r)^4}{64}} \leq S_{y_{steel}} \tag{12}$$

$$S_{y_{steel}} = 370MPa$$

$$\frac{113.95Nm}{r^3} = 370MPa$$

$$r = 6.75mm$$

$$D = 13.5mm$$

2.2.4. Block production process

The soil was sieved first in order to achieve proper gradation of particle size. The sieving operation was important as large soil particles negatively impacts the final compressive strength as well as other properties of the SCEB. After sieving, the soil was mixed with the 5% of Dangote Ordinary Portland Cement by weight. The mixing with the cement was to stabilize the red earth and give it desirable engineering properties. Due to the lack of a mixer, the mixing was done manually by a shovel. After mixing, the soil was fed to the SCEB moulding machine and the lever arm of the machine was engaged and pressed in order to compress the stabilized red soil into a stabilized compressed earth block of dimension 300 mm by 152 mm by 110 mm.

2.2.5. Compressive test and water absorption

The crushing strengths of the blocks were tested using the universal testing machine (Morel et al., 2007). A total of 20 specimens were prepared and crushed at different curing ages of 7, 14, 21 and 28 days. The weight of the air-dried block (W_d) was determined as 12.125 kg and then, the block was immersed such that only 5 mm of its length was in water and it was timed for 60 seconds. The surface of the block was wiped of excess dripping water and weighed thereafter. The weight (W_s) after the process was 12.172kg. The block has an area (A) of 300mm by 152mm. The experimental process was followed according to the BS771 codes (Obonyo et al., 2010). Equation (13) was used to calculate initial rate of absorption (IRA) given as (C). Final value of $IRA = 1.031kg/(m^2\text{min})$
t = 1 min

$$C = \frac{W_s - W_d}{A_s t} \tag{13}$$

$$C = 1.031kg/(m^2\text{min})$$

3. RESULTS AND DISCUSSION

A fully operational stabilized compressed earth brick moulding machine presented in Figure 8 was fabricated and taken to site where the red earth, cement and stone dust were present.

Figure 8: Finished stabilized compressed earth brick moulding machine

The results of the compressive strength against curing ages are presented in Table 2. The results show that the highest average compressive strength of 3.53 N/mm^2 was obtained with 5% cement content at a curing age of 28 days. For clay bricks, it is recommended That the optimum cement content be between the ranges of 5%-10% depending on the percentage clay content present in the sand (Riza, 2010), to produce good clay blocks which is higher than the Nigerian industrial standard of 2.5 to 3.45 N/mm^2 for crushing strength of sandcrete blocks (Nigerian Industrial Standard, 2004). In Table 2, Compressive tests were conducted on the blocks at different ages to indicate the rate of strength gained with time.

Table 2: Compressive strength of blocks

S/N	Compressive strength (N/mm^2)			
	Day 7	Day 14	Day 21	Day 28
1	2.13	2.99	3.02	3.54
2	2.09	2.61	3.09	3.50
3	2.13	2.78	3.02	3.52
4	2.13	2.80	2.90	3.55
5	2.22	2.77	3.00	3.54
Average	2.14	2.79	3.01	3.53

The 28-day compressive strength was determined as 3.53 N/mm^2 with 5% cement stabilization by weight. Initial rate of absorption testing was carried out, and the IRA was determined to be $1.031\ kg/(m^2\text{min})$. According to American Association of Highway and Transportation Officials (AASHTO) guidelines, this value of IRA is well within the stipulated limits of 0.25 – $1.5 kg/(m^2\text{min})$ (Obonyo et al., 2010).
Figure 9 shows the machine in use on site. It was observed that one bag of cement at 5% soil-cement mixture produced about 120 blocks with consistent dimensions of 300 mm by 152 mm by 110 mm.

Figure 9: Practical use of machine on building site

4. CONCLUSION

A mobile SCEBs machine capable of producing blocks with dimension 300 by 152 by 110 mm with a compressive strength of 3.53 N/mm^2 using 5% cement stabilization, has been successfully fabricated locally. The IRA of $1.031\ kg/(m^2\text{min})$ shows that the block has an acceptable water absorption rate. This machine is recommended for low cost clay stabilized blocks production in Nigeria, especially Edo state as it has abundant laterite soil which is vital in the production of CSB.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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