

# Engineering Design and Performance Evaluation of a Plastic Waste-Sand Brick Extrusion System for Sustainable Construction Application

Israel Kolawole Adesina

[kolawole4real7799@gmail.com](mailto:kolawole4real7799@gmail.com)

Osun State University

Olayemi .J Adeosun

Federal University of Agriculture

Toyese Friday Oyewusi

Osun State University

Matthew Ayoade Adedeji

Federal Polytechnic Ede

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## Research Article

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# **ENGINEERING DESIGN AND PERFORMANCE EVALUATION OF A PLASTIC WASTE-SAND BRICK EXTRUSION SYSTEM FOR SUSTAINABLE CONSTRUCTION APPLICATION**

**Adesina I. K<sup>1</sup>, Adeosun O. J<sup>2</sup>, Oyewusi T. F<sup>1</sup> and Adededeji M. A<sup>3</sup>**

<sup>1</sup>Department of Agricultural Engineering, Osun State University, Osogbo, Osun State, Nigeria.

<sup>2</sup>Department of Agricultural and Bio-Resource Engineering, Federal University of Agriculture, Abeokuta, Ogun State, Nigeria.

<sup>3</sup>Department of Agricultural and Bio-Environmental Engineering Technology, Federal Polytechnic Ede, Osun State, Nigeria.

Corresponding Email: [kolawole4real7799@gmail.com](mailto:kolawole4real7799@gmail.com), Tel: +234-7068224090

Co-authors Email: [adeosunoj@funaab.edu.ng](mailto:adeosunoj@funaab.edu.ng)

[toyese.oyewusi@gmail.com](mailto:toyese.oyewusi@gmail.com)

[maadededeji@fptb.edu.ng](mailto:maadededeji@fptb.edu.ng)

## **ABSTRACT**

The persistent accumulation of non-biodegradable plastic waste poses critical environmental and public health challenges, particularly in developing countries. This research presents the engineering design, fabrication, and performance evaluation of cost-effective waste plastic-sand brick extrusion system aimed at promoting sustainable construction and decentralized waste recycling. The extruder was developed using standard mechanical design principles, incorporating key components including a hopper, screw shaft, barrel, heating unit, belt drive, and die. Performance evaluation was conducted using a 56 kg mixture of shredded low-density polyethylene and sharp sand under controlled processing conditions (240 °C, 157 rpm). The system achieved a throughput capacity of 224 kg h<sup>-1</sup> with an operational efficiency of 85%, producing 10 bricks within 15 minutes. Mechanical characterisation of the extruded bricks across five mix ratios (70:30, 60:40, 50:50, 40:60, and 30:70 sand-to-plastic) revealed that optimal compressive strengths of 20.25 and 20.94 N/mm<sup>2</sup> were achieved at 50:50 and 40:60 compositions respectively, after 28 days of curing. Additionally, increase in plastic content significantly reduced water absorption (down to 0.6%) and enhanced durability performance.

The developed extrusion system demonstrates strong potential for small to medium scale applications, offering an energy efficient and locally manufacturable solution for converting plastic waste into a value-added construction material (brick). This strategy promotes circular economy principles and sustainable infrastructure development by reducing dependency on traditional cement-based bricks while also mitigating environmental contamination.

**Keywords:** Extruding Machine, Design concept, Waste plastic, Sand, Brick, Compressive strength

### **Nomenclature**

$V_h$  = Volume of hopper

$H$  = height of hopper

$L_h$  = length of the top of the hopper

$l_h$  = length of the base of the hopper

$N_1$  = Speed of electric motor

$N_2$  = Speed of screw shaft (rev/min)

$d_1$  = Diameter of electric motor pulley

$d_2$  = Diameter of shaft pulley

$T$  = Electric motor shaft pulley torque

$\omega$  = Electric motor shaft's angular velocity

$\tau$  = Shear stress

$F$  = Force of extrusion

$L$  = Length of the conveyor shaft

$A$  = The conveyor shaft's cross-sectional area

$r_1$  = The driving pulley's radius

$P$  = Electric motor power

$T_C$  = Centrifugal tension

$T_1$  = Tension in the belt's tight side's

$T_2$  = tension on the belt's loose side's

$T_t$  = Total tension in the belt

$\sigma$  = Belt's maximum allowable tension stress

$R_{SS}$  = The radius of the screw shaft

$M$  = Mass per metre of belt length

$V = \text{Belt's linear velocity}$

$V_{TB} = \text{Volume of the barrel}$

$V_{SS} = \text{Volume occupied by the screw shaft}$

$V_B = \text{Design for the volume of the barrel}$

## 1.0 INTRODUCTION

Metals have been the only means of engineering practice for millennia, but the advent of plastic materials and their growing use have required the creation of various production and shaping procedures for polymers [1].

Waste plastic has been a challenge in waste treatment, particularly in Nigeria, and requires more careful consideration in waste processing. The monomers used to make plastic are derived from fossil fuels; these materials are waterproof and non-biodegradable. Approximately 90% of plastic ends up in municipal waste, which poses problems for waste management. Therefore, a robust plastic waste management solution is essential [2,3]. Owing to the beneficial combination of qualities of plastic waste, which can be altered for a variety of uses, plastic waste may be used to replace cement in brick moulding for specific constructions.

Understanding the fundamentals of raw materials, additives, process control, and product quality is necessary for plastic processing to produce finished goods [4,5]. Material extruded during a compounding or mixing process would be considered a semi-finished product.

Products made from raw materials can be transformed into finished or semi-finished goods via extrusion [6]. The extrusion process involves the pushing of the material through an opening to get a product named an *extrudate* [7,8] Extruders, also known as plastic extrusion machines, are used to make things with a definite cross-sectional profile. Essentially, the extruder with a single screw serves as a volumetric pump.

Feeding, solid conveying, mixing, melting, transferring, and die forming make up the simple extrusion process. These processes are interconnected and take place concurrently. Typically, the extruding device has a die, a heat control unit, a barrel, and a screw. Feeding of the extruder is independent of screw design. The extruder is equipped with heat elements to melt the plastic. In the procedure, an electric heater serves as a source of thermal energy. By insulating the barrel's radial nozzle, which injects molten plastic through the die, it also keeps heat from escaping the system [9,10].

When extrusion technology was first developed in the late 1870s, it completely changed the extruder system by enabling precise regulation of extrusion temperature. Plastic deformation has been successfully decreased as a result of these technologies. Additionally, there has been a simultaneous surge in the production of various thermoplastic polymers. A certain polymer has been the only one that the extruder machine has been able to process. As a result, it is essential to design and construct extruder machines that are capable of processing and incorporating a wide range of polymer types. Extrusion machine production has been successfully improved since 1960. After it, the fundamental design of extruder machines remained the same. According to Crowther [11] and Hyvarinen *et al.* [12], all extruder machines, in theory, follow a specific mechanical process during manufacture. The extruder has changed over time in several ways, with modern engineers paying attention to transforming its traditional form into a modern one. By using the co-rotating and counter-rotating principles, the extruder screw's flight time was extended. For every use, a design was noted. To improve the extruder further, the generated pressure was examined [13]

Noel *et al.*, [14] state that waste plastics are transformed into construction materials using an extruder, which lowers plastic waste, a major contributor to environmental pollution. These days, waste plastics are efficiently transformed into practical building materials like retaining blocks, railway sleepers, roof tiles, bricks, interlocks and paving slabs.

Lamba *et al.* [15] reviewed research studies that produced plastic brick composites by hand rod mixing. Although this artisanal method emphasises a handcrafted approach by manually combining polymer and ceramic components, it has substantial scaling limits. Despite its attention to detail, the hand rod mixing process is ineffective for producing plastic bricks on a big scale. Despite its appealing artistry, large production is not feasible due to its handcrafted nature, which restricts speedy manufacturing and consistent quality.

Abdelkader *et al.* [16] state that it is possible to construct a machine for the extrusion of plastic bricks with careful operation and that it is viable to produce composite bricks using an inexpensive, manually controlled extruder. The strategy addresses the management of plastic waste while providing a viable solution for the construction of affordable housing. Nevertheless, premature melting and extrusion issues resulted from overflowing the hopper. Remelting or screw removal was necessary to remove the melted composite from the pipe, which proved difficult.

However, despite increasing research on plastic-based construction materials (plastic waste-sand bricks), the availability of low-cost extrusion machines capable of producing plastic waste-sand bricks at small and medium scale levels remains limited. Most existing extrusion machines for plastic bricks are either manually operated or designed for industrial-scale production, and these make them unsuitable for decentralized plastic waste recycling in developing countries. Therefore, there is a need to develop an efficient, locally fabricated extrusion system capable of producing plastic waste-sand bricks with adequate mechanical properties.

## **2.0 METHODOLOGY**

### **2.1 The Design Consideration**

The following factors were put into consideration when designing:

- i. The amount of brick to produce per operation
- ii. Availability of construction materials.
- iii. The frame, which serves to support and stabilise the extrusion machine structurally.
- iv. The cylindrical barrel that holds the necessary amount of feedstock, which is a mixture of waste plastic and sand.
- v. The barrel (chamber) was fabricated from galvanised material for several reasons, including
  - a. hardness for abrasion resistance
  - b. toughness to withstand any shock due to load impact.
  - c. High heat absorption
  - d. lower susceptibility to corrosion.
- vi. assembly and maintenance of the machine.

#### **2.1.1 Design assumptions**

The following parameters of the Extrusion machine were also assumed based on recommendations and the expected machine size.

- i. The barrel length,  $L_b = 102\text{cm}$
- ii. External diameter of the barrel,  $d_e = 10.6\text{cm}$
- iii. Barrel thickness =  $b_t = 0.4\text{cm}$
- iv. Diameter of screw winding,  $d_s = 9.5\text{ cm}$

- v. Thread pitch,  $T_p = 3.1\text{cm}$
- vi. Number of band heaters = 3
- vii. Capacity of band heater = 3.5kW

Conceptual designs were developed using design specifications. Safety, temperature, functionality, cost, and manufacturability were all taken into consideration during the design process. The design specifications utilised are highlighted in Table 1.

Table 1: Design specifications adopted in creating conceptual designs.

| S/N | Specifications for design | The basis's                                                                       | Materials and Rate              | Justification                                                                 |
|-----|---------------------------|-----------------------------------------------------------------------------------|---------------------------------|-------------------------------------------------------------------------------|
| 1   | HOPPER                    | The feeding channel                                                               | sheet made of mild steel        | for both strength and weldability.                                            |
| 2   | FRAME                     | Provides rigidity support for the machine and prevents failure caused by fatigue. | An angle bar made of mild steel | The ASTM standard.                                                            |
| 3   | SHAFT                     | High strength, wear-resistant, machinable, and transmission of torque.            | Mild steel                      | Able to withstand both shear force and compressive force.                     |
| 4   | PULLEY                    | ratio of the electric motor's input to output speed to shaft.                     | Cast iron                       | The system's functionality requires the electric motor's speed to be reduced. |
| 5   | Barrel                    | High strength, house of the shaft and for melting and mixing of materials         | Galvanize iron                  | Withstand compressive force.                                                  |
| 6   | V-BELT                    | Transmitting power                                                                | Fibre reinforced rubber         | High torque and low speed operation.                                          |

|   |                   |                                                                                        |                 |                                                  |
|---|-------------------|----------------------------------------------------------------------------------------|-----------------|--------------------------------------------------|
| 7 | MOULD/DIE         | A channel for melted waste plastic and sharp sand to form into a brick                 |                 |                                                  |
| 8 | POWER CONSUMPTION | Determines the energy consumption of the extruding machine and its manufacturing cost. | Low-speed motor | The machine needs a low-speed motor to function. |

## 2.2 THE DESIGN CONCEPT

The design concept is based on the specification highlighted in Table 1 above. An extruding machine for the production of bricks from plastic waste and sharp sand was developed to work on electricity, with the principle of radiation to evenly distribute the heat generated from the band heater to melt the waste plastic and mix it with sharp sand. The isometric and exploded perspectives of the extruding machine design concept are shown in Figures 1 and 2 below.

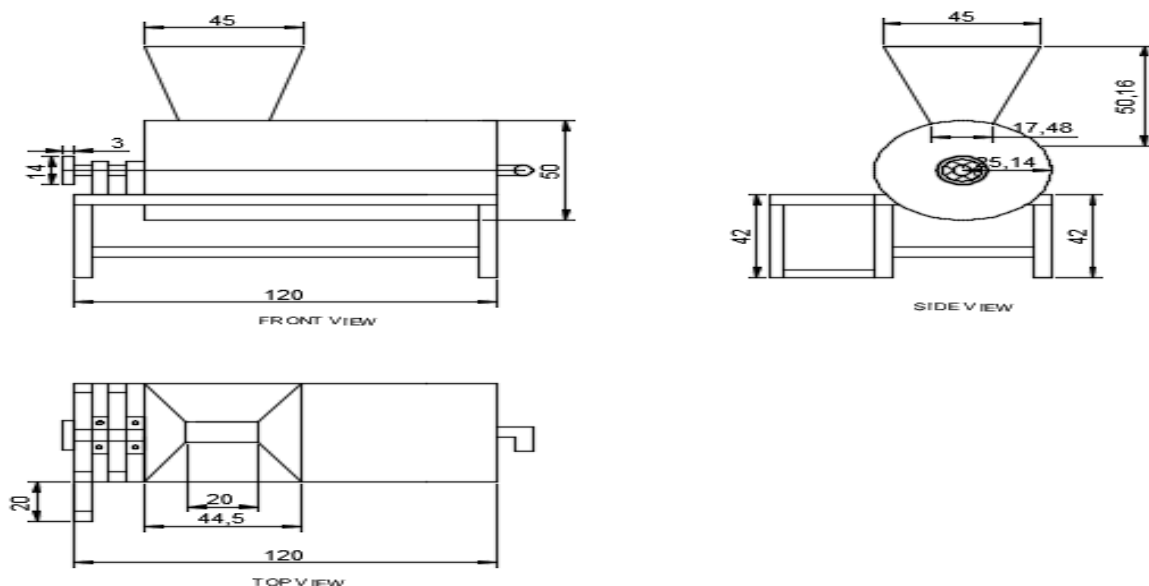


Figure 1: The design concept in an isometric view

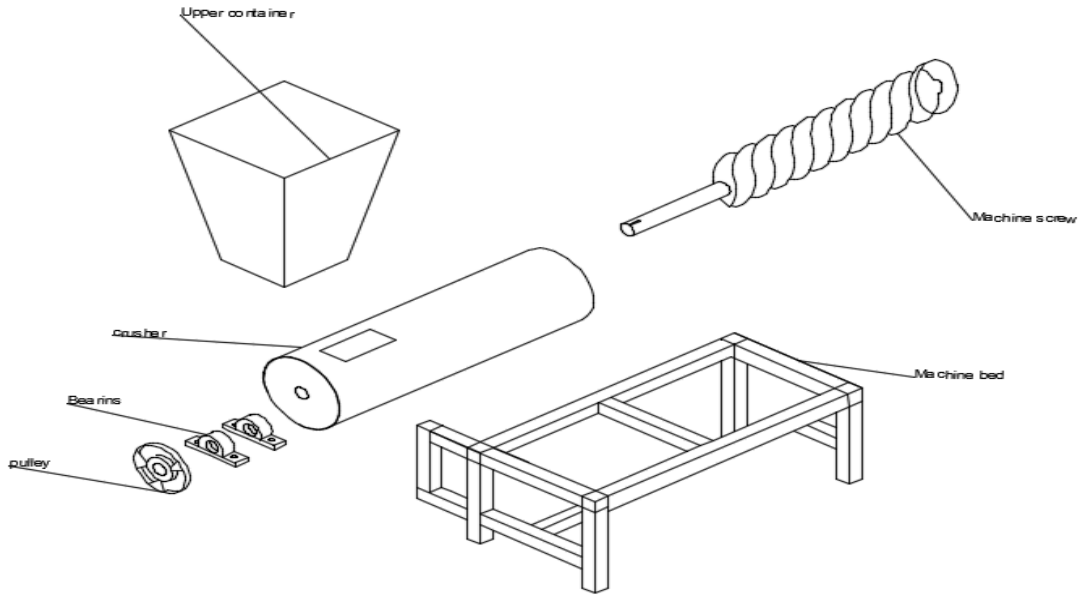


Figure 2: The exploded view of the extruder machine designed

## 2.3 DESIGN ANALYSIS

The analysis of design and calculations was aimed at determining the necessary design parameters. These would assist in the selection of appropriate strength and size of materials for the construction of the various extruder parts.

### 2.3.1 Design for Volume of the Extruder Hopper ( $V_h$ )

The hopper was designed in the form of a pyramid and based on the criterion of the angle of repose, which is the maximum slope at which a heap of any loose or fragmented bulk material will stand without sliding [17,18]. The average repose angle  $\alpha$ , of the feedstock is taken to be  $43^\circ$ , and the hopper has a top length ( $L_h$ ) of 45 cm, a base length ( $I_h$ ) of 20 cm, and a height ( $H$ ) of 50 cm. The hopper is in the form of a frustum of a square-based pyramid, as shown in Figure 3.  $V_h = 179,356 \text{ cm}^3$

$$\text{Volume of hopper } V = \frac{1}{3} \times \pi H (L_h^2 + I_h^2 + L_h \times I_h) \quad (1)$$

Where;

$V_h$  = hopper volume

$H$  = hopper height

$L_h$  = length of the top of the hopper

$l_h$  = length of the hopper at the base

If 90% of the hopper is utilised and 10% is for free space to prevent overloading of hopper, the usage volume of the hopper ( $V_{hf}$ ) is calculated using Equation 2, to be 161,420.4 cm<sup>3</sup>

$$V_{hf} = \text{Calculated volume} \times \% \text{ being utilized} \quad (2)$$

Which means the hopper has a total volume of 179,356 cm<sup>3</sup> with a utilised volume of 161,420.4 cm<sup>3</sup> and a free volume of 17,935.6 cm<sup>3</sup>.

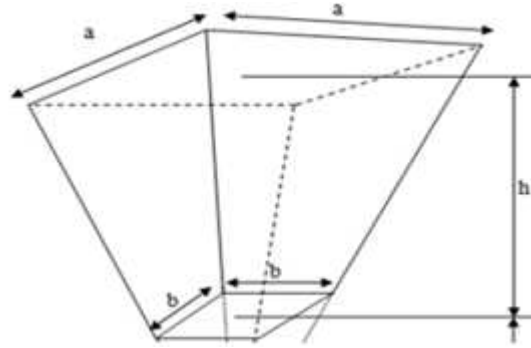


Figure 3. Schematic diagram of hopper

## 2.4 DESIGN FOR THE SCREW

### 2.4.1 Volume Occupied by The Screw Shaft ( $V_{ss}$ )

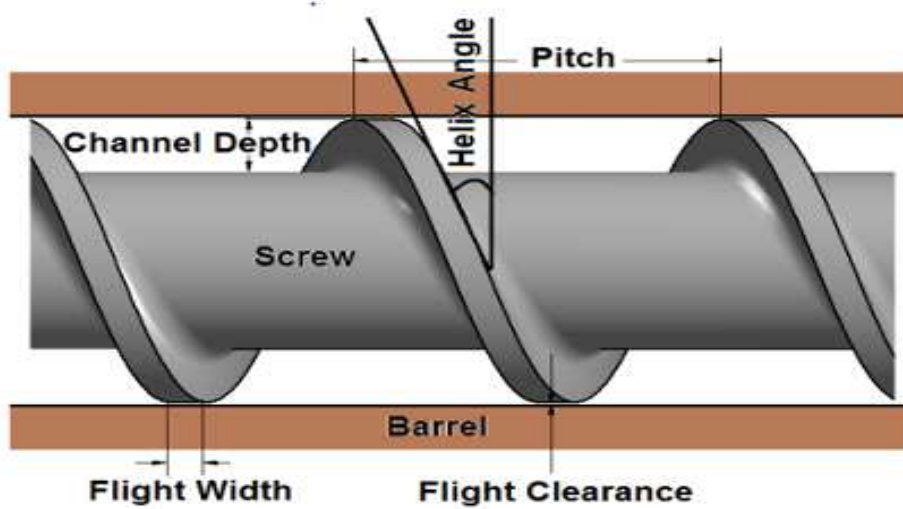


Figure 4: Basic property of plasticising screw [19]

$$V_{ss} = \pi \times r_{ss}^2 \times L_{ss} \quad (3)$$

Where:

$r_{ss}$  is the radius of the screw shaft = 1.5 cm

$L_{ss}$  is the length of the screw shaft = 102 cm

$$V_{ss} = 3.142 \times 1.5^2 \times 102$$

$$V_{ss} = 3.142 \times 2.25 \times 102$$

$$V_{ss} = 721.089 \text{ cm}^3.$$

#### 2.4.2 The Screw Thread's Volume ( $V_{st}$ )

Where the Number of screw ribs ( $n_{st}$ ) = 10 = 5 rev

Length of 1 screw rib ( $L_{st}$ ) = 10 cm

Radius of the screw rib ( $r_{st}$ ) =  $4.75 - 1.5 = 3.25$  cm

Therefore, the volume of the shaft thread is:

$$V_{st} = \pi \times r_{st}^2 \times L_{st} \quad (4)$$

$$V_{st} = 3.142 \times 3.25^2 \times 10$$

$$V_{st} = 3.142 \times 10.563 \times 10$$

$$V_{st} = 331.858 \text{ cm}^3$$

#### 2.4.3 The Screw Volume ( $V_s$ )

$$V_s = V_{ss} + V_{st} \quad (5)$$

$$V_s = 721.089 + 331.858$$

$$V_s = 1052.974 \text{ cm}^3$$

#### 2.4.4 Design of Screw Compression Ratio

The **compression ratio (CR)** of an extruder screw is:

$$CR = \frac{\text{Feed zone channel depth (}h_f\text{)}}{\text{Metering zone channel depth (}h_m\text{)}} \quad (6)$$

For the plastic-to-sand composite, the CR range is assumed to be 2.5:1 to 3:1 [20]

where  $h_f = 9$  mm,  $h_m = 3$  mm

$$CR = \frac{3}{9} = 3 : 1$$

#### 2.4.5 Design of Screw Flight Depth

The flight depth or channel depth is the distance from the root of the screw to the outer diameter (barrel wall). It is usually divided into

- **Feed zone depth ( $h_f$ ):** larger (to accommodate solid material)

$$h_f = 0.08D \text{ to } 0.15D \quad (7)$$

- **Metering zone depth ( $h_m$ ):** smaller (to compress and homogenize melt)

$$h_m = \frac{hf}{CR} \quad (8)$$

Flight Depth from equation (7) above. Taken a mid-range safe value of 0.1

$$h_f = 0.1D = 0.1 \times 102 = 10.2 \text{ mm}$$

Flight Depth from equation (8) above

$$h_m = \frac{10.2}{3} = 3.4 \text{ mm}$$

#### 2.4.6 Screw Feed Zone Length

Feed zone is the section of the screw where the raw material (plastic waste and sand) is introduced and conveyed.

In screw design, the total screw length is divided into three zones: [21,22]

$$L = L_f + L_c + L_m \quad (9)$$

Where:

$L_f$  = Feed zone length

$L_c$  = Compression zone length

$L_m$  = Metering zone length

Total screw length:  $L = 102 \text{ cm}$

Since your material is a plastic + sand composite (high resistance, irregular flow)

$$L_f = 0.45L \quad (10)$$

$$L_f = 0.45 \times 102$$

$$L_f = 46 \text{ cm}$$

#### 2.4.7 Design for the melting zone length

The melting zone (also called the compression zone) is where the plastic softens or melts due to heat and mechanical shear.

$$L_c = L - (L_f + L_m) \quad (11)$$

$$L_c = 102 - (46 + 25) = 31 \text{ cm}$$

## 2.5 DESIGN FOR THERMAL

### 2.5.1 LDPE Melting Temperature

The semi-crystalline thermoplastic known as low-density polyethylene (LDPE) has the following characteristics: Melting temperature  $T_m$ , Processing temperature and extrusion temperature with the value range, 105 – 115°C, 160 – 220°C, and 180 – 200°C, respectively. And 240°C was used to ensure complete melting and proper mixing with sand particles.

$$T_{\text{process}} = 200^\circ\text{C to } 240^\circ\text{C}$$

### 2.5.2 Heat Requirement

$$Q = mc\Delta T + mL \quad (12)$$

Where:

$$m = \text{mass (kg)} = 56\text{kg}$$

$$c = \text{specific heat capacity} = 2.3\text{kJ/kg}$$

$$\Delta T = \text{temperature rise} = T_1 \text{ and } T_2 = 30^\circ\text{C and } 240^\circ\text{C, Therefore, } \Delta T = 210^\circ\text{C}$$

$$L = \text{latent heat of fusion} = 293\text{kJ/kg}$$

From equation (11) above, the total heat required

$$Q = (56 \times 2.3 \times 210) + (56 \times 293) = 43,456\text{kJ}$$

$$Q = 4.35 \times 10^4 \text{ kJ}$$

### 2.5.3 Heat Transfer into the Barrel

$$Q = \frac{kA\Delta T}{t} \quad (13)$$

Where:

$$k = \text{thermal conductivity}$$

$$A = \text{heat transfer area}$$

$$t = \text{time}$$

$$Q = \frac{0.33 \times 0.00817 \times 210}{0.25} = 2.265\text{kJ/h}$$

### 2.5.4 Heater Power

Three (3) band heater was use with power rating of 3.5 kW and the total power is 10.5kW and Energy supplied in 15 minutes (0.25 hr).

$$Q_{\text{input}} = P \times t \quad (14)$$

$$Q_{\text{input}} = 10.5 \times 0.25 = 2.625 \text{ kWh}$$

$$1 \text{ kWh} = 3600 \text{ kJ}$$

$$Q_{\text{input}} = 2.625 \times 3600 = 9450 \text{ kJ}$$

### 2.5.5 Thermal Efficiency

$$\eta = \frac{Q_{\text{useful}}}{Q_{\text{input}}} \times 100 \quad (15)$$

$$\eta = \frac{43456}{9450} \times 100$$

$$\eta = 460\%$$

### 2.6 Extrusion shaft Force

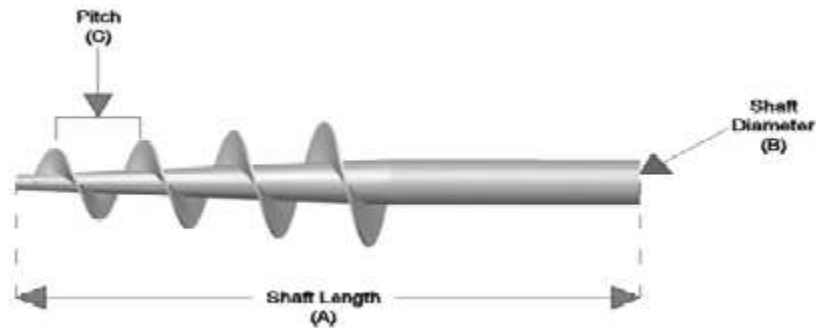


Figure 5: Conveyor Shaft

The shaft shear stress,  $\tau$ , is determined by

$$\tau = \frac{F}{A} \quad (16)$$

$$\text{And, } A = \frac{\pi d^2}{4} \quad (17)$$

If,  $d = 25 \text{ cm} = 0.25 \text{ m}$

$l = 102 \text{ cm} = 1.02 \text{ m}$

Therefore, the conveyor shaft cross-sectional area is:

$$A = \frac{\pi(0.25)^2}{4}$$

$$A = \frac{3.142 \times 0.0625}{4} = 0.0491 \text{ m}^2$$

Assumption: The maximum permissible shear stress,  $\tau$ , to extrude a brick = 40 MPa. based on standard machine design recommendations for mild steel under torsional loading, which typically range from 30 - 60 MPa depending on safety considerations [23,24].

Given:

$$\tau = 40 \text{ MPa} = 40 \times 10^6 \text{ N/m}^2$$

$$F = 40 \times 10^6 \times 0.0491$$

$$F = 1,964,000 \text{ N}$$

$$F = 1.96 \times 10^6 \text{ N (or 1964 kN)}$$

### 2.6.1 Conveyor Shaft Speed

Torque and bending moment are transmitted via the conveyor shaft, according to Khurmi and Gupta [24]. Then the conveyor shaft speed ( $N_2$ ) is determined using equation (18) below.

$$\frac{N_1}{N_2} = \frac{d_2}{d_1} \quad (18)$$

Assumptions:

$$N_1 = 1400 \text{ rev/min}$$

$$d_1 = 10 \text{ cm} = 0.1 \text{ m}$$

$$d_2 = 25 \text{ cm} = 0.25 \text{ m}$$

Therefore, the screw shaft speed;

$$N_2 = \frac{1450 \times 10}{25} = 580 \text{ rev/min}$$

## 2.7 DESIGN FOR THE BARREL

### 2.7.1 Design for Volume of The Barrel ( $V_B$ )

$$\text{Volume of barrel } (V_B) = \pi r^2 L \quad (19)$$

Where;

$$r_b = \text{inner radius of the barrel} = 5.1 \text{ cm}$$

$$L_b = \text{length of the barrel} = 102 \text{ cm}$$

$$V_B = 3.142 \times 5.1^2 \times 102$$

$$V_B = 8335.789 \text{ cm}^3$$

### 2.7.2 Design for Total Volume of the Barrel Used ( $V_{TB}$ )

$$V_{tb} = V_b - V_s \quad (20)$$

$$V_{tb} = 8335.789 - 1052.974$$

$$V_{tb} = 7282.815 \text{ cm}^3$$

## 2.8 POWER OF ELECTRIC MOTOR

The formula for power is Power ( $P$ ) = Torque x Angular Speed [25].

$$P = T\omega \quad (21)$$

$$\text{But } \omega = \frac{2\pi N_1}{60} \quad (22)$$

Where  $\omega$  = Angular Speed,  $T$  = Torsional Stress and  $N_1$  = Speed revolution per minute (1450 rpm).

Therefore,  $\omega = \frac{2\pi N1}{60}$

$$\omega = \frac{2 \times 3.142 \times 1450}{60} = 151.86 \text{ rad/sec.}$$

The angular speed is 151.86 rad/sec

For the electric motor, 1 hp = 746 watts.

$$1 \text{ hp} = 1 \times 746 = 746 \text{ watts}$$

$$P = 746 \text{ watts}$$

The torque transmitted is calculated using equation (21)

$$P = T\omega$$

$$T = \frac{P}{\omega}$$

$$T = \frac{746}{151.86} = 4.912 \text{ N/M}$$

Therefore,

$$T = 5 \text{ N/M}$$

## **2.9 BELT DESIGN**

The machine was equipped with a V-belt drive system that was driven by a 1-horsepower electric motor with a rated speed of 1450 rpm. According to Khurmi and Gupta [24], the basis of the belt drive design is as follows:

- i. The centre-to-centre distance between the pulleys, x
- ii. Belt Length
- iii. The belt cross-sectional area
- iv. Type of belt (V-belt made of reinforced rubber)
- v. The mass of the belt per metre
- vi. Groove angle,  $2\beta$
- vii. Belt tension
- viii. Belt-transmitted power
- ix. Belt-transmitted torque

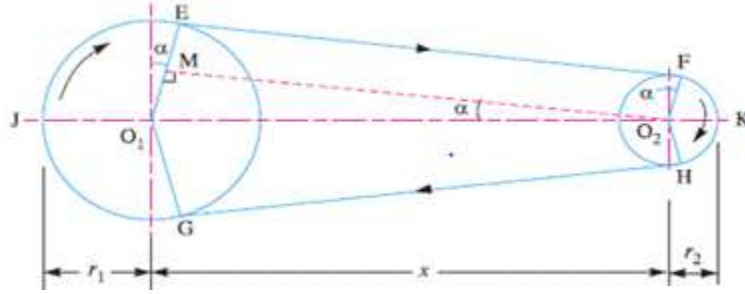


Figure 6: Open Belt Drive [24].

**i. The centre-to-centre distance between the pulleys, x**

Note that the centre distance, x, between the two pulleys is twice the diameter of the larger pulley [26]. Thus, the distance between the centres:

$$X = 2d_2 \quad (23)$$

Where,  $d_2$  is the larger pulley diameter = 25 cm

$$X = 2(25) = 50 \text{ cm}$$

**ii. Belt Length**

$$L = \frac{\pi}{2}(d_1 + d_2) + 2x + \frac{(d_2 - d_1)^2}{4x} \quad (24)$$

Where;

length of the belt (L)

distance between the two pulleys  $X = 50 \text{ cm}$

diameter of the small pulley  $d_1 = 10 \text{ cm}$

diameter of the bigger pulley  $d_2 = 25 \text{ cm}$

$$L = \frac{\pi}{2}(10 + 25) + 2(50) + \frac{(25 - 10)^2}{4(50)} = 156.11 \text{ cm}$$

Therefore,

$$L = 156 \text{ cm}$$

**iii. The belt cross-sectional area**

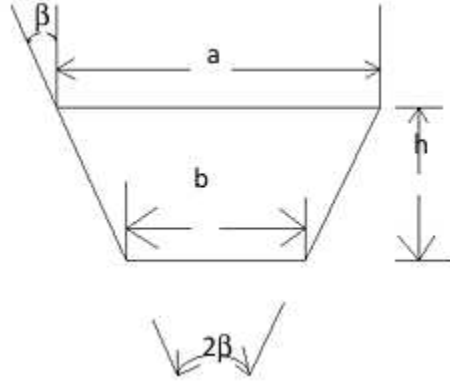


Figure 7: Cross-section of the belt

Area of trapezium,

$$A = \frac{1}{2} (a + b) h \quad (25)$$

Assumption:  $a = 1.2 \text{ cm} = 0.012 \text{ m}$

$$b = 0.6 \text{ cm} = 0.006 \text{ m}$$

$$h = 1.0 \text{ cm} = 0.01 \text{ m}$$

$$A = \frac{1}{2} (0.012 + 0.006) \times 0.01$$

$$A = 9 \times 10^{-5} \text{ m}^2$$

**iv. The mass of the belt per metre**

A double-woven reinforced rubber's density  $d = 1250 \text{ kg/m}^3$  [24]

Therefore, the mass of the belt

$$M = \text{area} \times \text{length} \times \text{density}$$

$$M = 9 \times 10^{-5} \times 1 \times 1250 = 0.113 \text{ kg/m}$$

**v. Groove angle,  $2\beta$**

Using the ratio of trigonometry,

$$\tan \beta = (3/10), \text{ thus } \beta = \tan^{-1} (3/10) = 17^\circ \text{ and } 2\beta = 34^\circ$$

**vi. Angle of contact between each pulley and the belt,  $\alpha$**

In the case of an open belt drive,

$$\sin \alpha = \frac{d_2 - d_1}{2x} \quad (26)$$

$$\sin \alpha = \frac{25 - 10}{100}$$

$$\alpha = 4.7^\circ$$

The lap's angle on the smaller pulley,

$$\theta = 180^\circ - 2\alpha \quad (27)$$

$$\theta = 175.3^\circ = 3.06 \text{ rad}$$

#### vii. Belt tension

Since the belt would continuously run over the pulleys, some centrifugal force is caused, whose effect is to increase the tension on both the tight and slack sides [27,28].

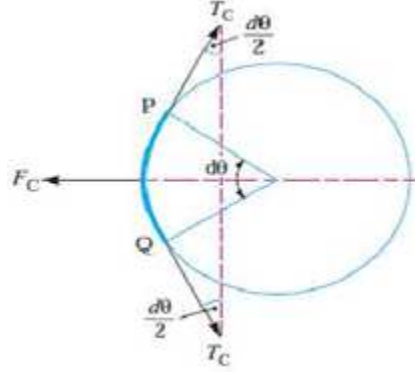


Figure 8: Centrifugal Tension [24].

$$\text{Centrifugal force, } T_C = mv^2 \quad (28)$$

$$\text{But, Belt Velocity, } V = \frac{\pi d_1 N_1}{60} \quad (29)$$

$$V = \frac{\pi \times 0.10 \times 1450}{60} = 7.593 \text{ m/s}$$

Hence, the centrifugal tension of the belt is calculated using Equation (28)

$$T_C = 0.113 \text{ kg/m} \times (7.593)^2 = 6.515 \text{ N}$$

Total tension in the belt,  $T_t$

$$T_t = \sigma \times A \quad (30)$$

Where  $\sigma = 4.0 \text{ MN/m}^2$  for rubber [24].

$$A = 9 \times 10^{-5} \text{ m}^2$$

Therefore, the total tension in the belt:

$$T_t = 4.0 \times 10^6 \times 9 \times 10^{-5} = 360 \text{ N}$$

$$T_t = 360 \text{ N}$$

Belt tight side Tension  $T_1$  [29]

$$T_1 = T_t - T_C \quad (31)$$

$$T_1 = 360 - 6.515$$

$$T_1 = 353.485$$

Relationship between  $T_1$  and  $T_2$  for V- belt

$$2.3 \log (T_1/T_2) = \mu \theta \operatorname{cosec} \beta \quad (32)$$

Where the rubber material's coefficient of friction,  $\mu = 0.2$  [24].

Therefore, tension on the belt's slack side,  $T_2$

$$T_2 = 51.26 \text{ N}$$

**viii. Belt-transmitted power**

The Belt-transmitted power is calculated using Equation (33)

$$P = (T_1 - T_2) V \quad (33)$$

$$P = (353.485 \text{ N} - 51.26) \times 7.593$$

$$P = 2644.072 \text{ Nm/s}$$

Therefore,

$$P = 2.6445 \text{ kW}$$

**ix. Belt-transmitted torque**

The torque transmitted by the driven pulley shaft is calculated using Equation (34) below

$$T = \frac{P \times 60}{2\pi N_2} \quad (34)$$

Where  $N_2$  is the speed of the screw pulley, which is calculated using Equation (35)

$$\frac{N_1}{N_2} = \frac{d_2}{d_1} \quad (35)$$

Where;

$N_1$  = speed of motor pulley, rpm (1450 rpm);

$N_2$  = speed of screw pulley, rpm;

$d_1$  = diameter of motor pulley, cm (10 cm);

$d_2$  = diameter of screw pulley, cm (25 cm).

$$N_2 = \frac{N_1 \times d_1}{d_2} = \frac{1450 \times 10}{25} = 580 \text{ rpm}$$

Therefore, from Equation (34)

$$T = \frac{P \times 60}{2\pi N_2}$$

Where;

$T$  = Belt-transmitted torque in Nm.

$N_2$  = speed of driven pulley, 580 rpm.

$P$  = power transmitted by belt, 2644.072 W.

$$T = \frac{2644.072 \times 60}{2\pi \times 580} = 43.527 \text{ Nm}$$

## 2.10 DESIGN FOR DIE

For the purpose of extrusion of brick, the die is specifically designed for continuous production of bricks instead of batch production.

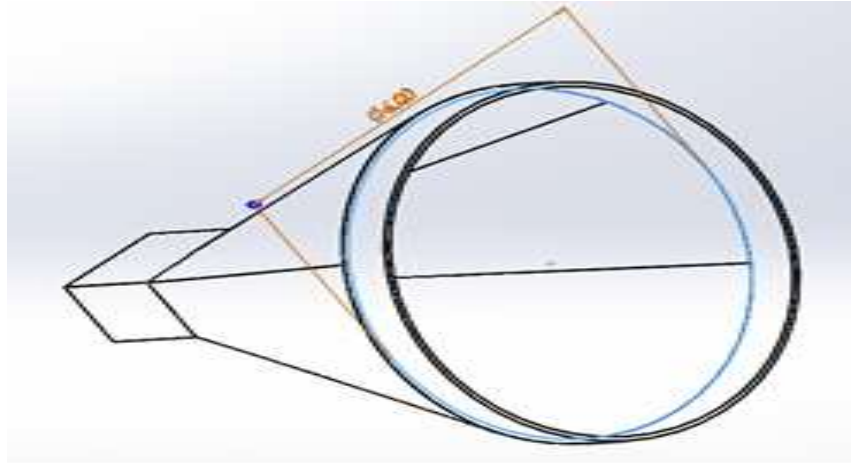


Figure 9: Isometric view of Die

### 2.10.1 Design Considerations

The factors considered for the design of Die

- Final product geometry: Brick size of 120 mm × 110 mm × 40 mm
- Material behaviour: Highly viscous, non-Newtonian plastic–sand mixture
- Flow uniformity: To avoid internal defects such as voids and cracks
- Pressure resistance: Ability to withstand extrusion pressure without deformation
- Thermal stability: Capability to operate at temperatures up to 240°C

#### i. Die Geometry

Die Cross-sectional Area

$$A = b \times h \quad (36)$$

Where;

$$b = 200 \text{ mm (width)}$$

$$h = 100 \text{ mm (height)}$$

$$A = 120 \times 110 = 13,200 \text{ mm}^2$$

#### ii. Equivalent Diameter (for flow analysis)

$$D_e = \frac{4A}{P} \quad (37)$$

When:  $P = 2(b + h)$  (38)

$$P = 2(120 + 110) = 460 \text{ mm}$$

$$D_e = \frac{4 \times 13,200}{460} = 114.8 \text{ mm}$$

iii. **Die Length:** which is very important for Stabilizing flow and Improving surface finish [30,31].

$$L_d = (1 \text{ to } 3) \times D_e \quad (39)$$

$$L_d = 2D_e \quad (40)$$

$$L_d = 2 \times 114.8 = 229.6 \text{ mm}$$

$$L_d = 230 \text{ mm}$$

iv. **Die Pressure**

$$P = \frac{4\tau L_d}{D_e} \quad (41)$$

Where;

$$\tau = 40 \text{ MPa (assumed shear stress)}$$

$$L_d = 0.23 \text{ m}$$

$$D_e = 0.1148 \text{ m}$$

$$P = \frac{4 \times 40,000,000 \times 0.23}{0.1148}$$

$$P = 321 \text{ MPa}$$

## 2.11 Description of The Machine

The extruding machine for the production of plastic waste-sand bricks is a single screw press extruder (see plate 1). It mainly consists of an electric motor, a screw shaft, a barrel, die, a belt, a pulley, hopper, support frame, heating element (Band heater), temperature controller, thermocouple, contactor, and electric motor speed regulator. Through the pulley, the belt transfers power from the electric motor to the screw shaft during operation. The screw shaft rotates and takes the raw material (sharp sand and waste plastic) fed in from the hopper through the barrel, and three heater bands of 3.5kW are attached to the barrel. The barrel is heated up to melt and mixed the materials, and compress it against the die. The opening is what gave the final

product its profile and was designed so that the molten waste plastic-sand evenly flows out to from bricks.

The extruding machine frame and electric motor supports were fabricated from 2 mm angle iron. The electric motor support was welded to the back of the frame such that the centre distance between the motor support and the screw shaft can be adjusted for belt tension. The various desired sizes were marked and cut out using a metal hack saw, and the parts were welded together using an electric welding machine and electrode. The machine's hopper was constructed from a 1 mm-thick steel plate. The shape of the hopper was marked out in the form of a trapezium, and its four ends were welded together to form the described shape of a pyramid. After the fabrication, the barrel was mounted to the top of the frame and bolted with the use of size-16 bolts, and the hopper was welded to the opening of the barrel (chamber), while the electric motor was also bolted to the motor support using size-12 bolts. The belt size needed as calculated was procured and fitted to the machine (see plate 1).



Plate 1: Pictorial view of developed extruder machine

## **2.12 EXPERIMENTAL METHOD**

### **2.12.1 Brick Moulding Process**

The brick moulding process was carried out using the developed single screw extrusion machine. Waste plastic bottles (LDPE) were first collected, cleaned to remove impurities, and mechanically shredded into smaller particles to enhance melting. Sharp sand was sieved to ensure uniform grain size distribution.

The shredded plastic and sand were then mixed in predetermined ratios of 70:30, 60:40, 50:50, 40:60, and 30:70 (sand:plastic by weight). The mixture was fed into the hopper of the extrusion system, where it was conveyed through the barrel by the rotating screw.

The barrel was heated using band heaters to a controlled temperature of approximately 240°C, sufficient to melt the plastic component while allowing it to bind the sand particles. As the material progressed through the screw, it underwent simultaneous heating, and mixing. The molten composite was then forced through a rectangular die, and cut into bricks of dimensions approximately 120 mm × 110 mm × 40 mm, and allowed to cool and solidify under ambient conditions

### **2.12.2 Curing Procedure**

Unlike conventional cement-based bricks, plastic waste-sand bricks do not require hydration curing. Instead, the produced bricks were subjected to ambient cooling and conditioning to achieve dimensional stability and structural integrity.

The conventional cement-based bricks used as the control were cured in potable water at room temperature using a curing tank duration 7, 14, 21 and 28 days, respectively.

### **2.12.3 Compressive Strength Test**

A universal compression testing machine was used to determine the bricks' compressive strength (UTM) in accordance with recognised international standards of ASTM C39 and BS EN 772-1 Methods of test for masonry units [32].

Five samples of plastic waste-sand bricks and a control were produced with five (4) replicates; each brick sample was centrally placed between the compression plates of the testing machine and loaded gradually until failure occurred. The crushing maximum load was recorded.

The formula was used to determine the compressive strength (36) below [32].

$$\sigma_c = \frac{F}{A} \quad (36)$$

Where:

$\sigma_c$  = compressive strength (N/mm<sup>2</sup>)

F = maximum load at failure (N)

A = cross-sectional area of the brick loaded (mm<sup>2</sup>)

### 3.0 RESULTS AND DISCUSSION

#### 3.1 Performance Evaluation

The brick making extrusion machine was tested, and it operated by electrical power supplied at a rating of 240V, 50Hz. An AC induction motor, single phase of 1 Hp or 746 kW was used and its working efficiency was determined with 56000 cm<sup>3</sup> (56 kg) mixture of sharp sand and shredded waste plastic bottle (low-density polyethylene), it was found that the extruder is capable of producing 10 bricks in 15 minutes at a pre-set temperature 240<sup>0</sup>c and at a speed of 157 rpm.

##### 3.1.1 Efficiency of the Machine

Machine efficiency is expressed as the ratio of the percentage weight of brick extrude to the weight of feedstock (mixture of waste plastic and sand) fed into the machine. Its mathematical expression

is seen in Equation (37)

$$\text{Efficiency} = \frac{\text{output quantity}}{\text{input quantity}} \times 100\% \quad (37)$$

Where;

Work input = 56 kg

Work output = 48 kg

$$\text{Efficiency} = \frac{48\text{kg}}{56\text{kg}} \times 100 = 85\%$$

##### 3.1.2 The Extruder Machine throughput (MT)

This is expressed as the ratio of the weight of material input to the time taken to extrude brick. Its mathematical expression is seen in Equation (38).

$$\text{Throughput (kg/h)} = \frac{\text{input quantity (kg)}}{\text{time take to extrude bricks (h)}} \quad (38)$$

Where;

Input quantity = 56 kg

Time to extrude = 15 minute = 0.25 hour

$$\text{Throughput (kg/h)} = \frac{56 \text{ (kg)}}{0.25 \text{ (h)}} = 224 \text{ kg/h.}$$

### 3.2 RESULTS OF THE EXPERIMENT CONDUCTED

Table 2 shows the result of the experiment conducted, which includes compressive strength, percentage of water absorption and water absorption resistance.

**Table 2: Results of the experiment conducted**

| Mixing ratio<br>(%) | Compressive strength<br>N/mm <sup>2</sup> |        | Water absorption capacity<br>(%) |        | Water absorption resistance<br>(%) |        |
|---------------------|-------------------------------------------|--------|----------------------------------|--------|------------------------------------|--------|
|                     | Control                                   | Sample | Control                          | Sample | Control                            | Sample |
| 70:30               | 16.45                                     | 10.29  | 2.0                              | 1.5    | 0.4                                | 1.2    |
| 60:40               | 16.81                                     | 14.22  | 1.4                              | 1.3    | 0.2                                | 2.4    |
| 50:50               | 24.58                                     | 20.25  | 2.0                              | 1.2    | 0.4                                | 3.1    |
| 40:60               | 30.33                                     | 20.94  | 4.0                              | 0.8    | 1.6                                | 6.0    |
| 30:70               | 32.27                                     | 17.37  | 2.0                              | 0.6    | 0.4                                | 7.2    |

#### 3.2.1 Compressive Strength Test

The compressive strength result obtained after 28 days of curing and crushing, for sample 1 at a percentage mix ratio of 70% of sand 30% of plastic, was 10.29 N/mm<sup>2</sup> and control 1 at the same mix ratio gave a compressive strength of 16.45 N/mm<sup>2</sup>. While sample 5 at 30% and 70% plastic is 17.37 N/mm<sup>2</sup> and control 5 gave a compressive strength of 32.27 N/mm<sup>2</sup>. Based on the result from the five controls, the cement-bound bricks show a much higher compressive strength at

40:60 as shown in Fig. 10, than the plastic-bound. For the bricks made from Portland cement, control 5, with 30% sand and 70% cement shows the highest and most suitable compressive strength at 32.27 N/mm<sup>2</sup> which was far above minimum standard recommended, similar to the finds of Praise, *et al.* [33], while for the bricks made from plastics waste, sample 4, gave the best strength of 20.94 N/mm<sup>2</sup>.

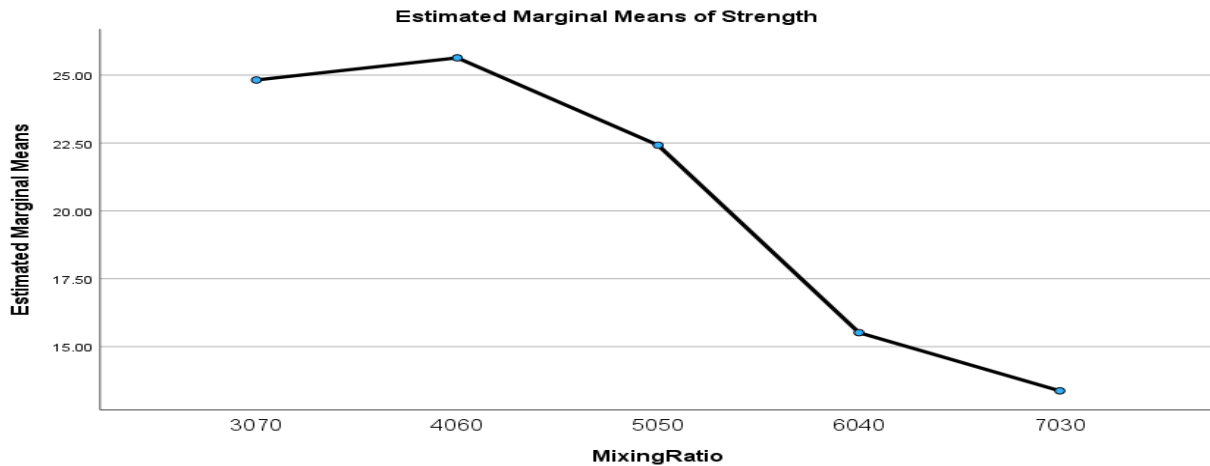


Fig.10: Compressive strength of different mix ratios

### 3.2.3 Water Absorption and Absorption Resistance

Based on the test result for water absorption, it shows that sample 1 absorbed 1.5% water and control 1 2.0%. While sample 5 absorbed 0.6% while, control 5 absorbed 2.0% water (see Table 2), and Figure 11. The results obtained shown the highest levels of water absorption amongst the samples were 30% waste plastic (1.5%), while the lowest was at 70% waste plastic (0.6%). This implies that 70% waste plastic in the mix has the least affinity for water, with an absorption rate of 0.6%. This simply showed that an increase in waste plastic content led to a corresponding decrease in water absorption, which is in line with findings of Omosebi, *et al* [26]. Therefore, the bricks made from sand and waste plastic have better water absorption resistance levels compared to those bricks made from sand and Portland cement, sample 5 has the best water absorption resistance because it has the highest water absorption resistance level of 7.2% (see Fig.12). The higher the waste plastic content the lesser the water absorption and the higher the water absorption resistance of the bricks.

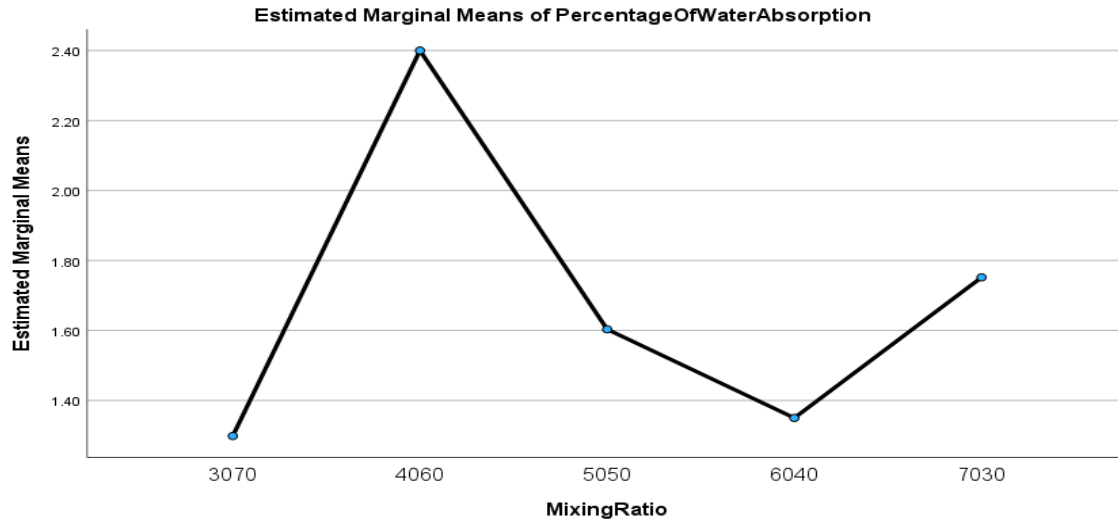


Fig. 11: Percentage of water absorption capacity for different mix ratio

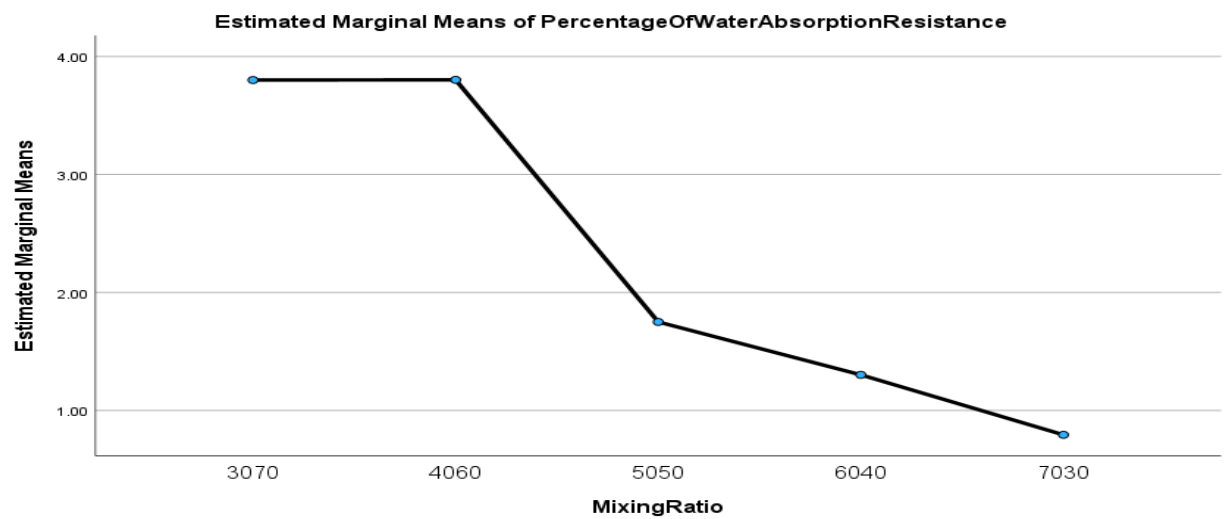


Fig. 12: Percentage of water absorption resistance for different mix ratio

#### 4.0 CONCLUSION

This study presented the design, fabrication, and performance evaluation of a single-screw extrusion system for the production of plastic waste-sand bricks. The developed machine demonstrated satisfactory operational performance, achieving a throughput capacity of 224 kg h<sup>-1</sup> and an efficiency of 85% under controlled conditions (240 °C). The system successfully

produced uniform bricks within a short processing time, confirming its suitability for small to medium scale applications.

Mechanical characterization revealed that the optimal compressive strengths of 20.25 N/mm<sup>2</sup> and 20.94 N/mm<sup>2</sup> were obtained at mix ratios of 50:50 and 40:60 (sand:plastic), respectively, indicating that plastic waste can effectively function as a binding material in composite brick production. Additionally, increased plastic content significantly reduced water absorption, enhancing the durability and moisture resistance of the bricks compared to conventional cement-based counterparts.

The results demonstrate that the developed extrusion system provides a technically viable and economically feasible approach for converting plastic waste into a value-added construction material (Bricks). Its reliance on locally available materials and simple fabrication techniques further supports its adaptability in developing regions. Overall, this technology offers a sustainable alternative for waste management and construction practices, contributing to reduced environmental pollution and decreased dependence on cement-based bricks.

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**Author Contributions:** Conceptualization, I.K.A., O.J.A., T.F.A. and M.A.A.; methodology, I.K.A. and O.J.A.; formal analysis, T.F.A.; data curation, M.A.A.; writing-original draft preparation, I.K.A. and O.J.A.; editing, O.J.A., T.F.A. and M.A.A.; supervision, O.J.A. and T.F.A. All authors have read and agreed to the published version of the manuscript.

## **Declarations**

**Ethics approval** Not applicable

**Ethical responsibilities:** The author has read, understood, and complied as applicable with the statement on “Ethical responsibilities of Authors” as found in the instructions for Authors.

**Consent to participate:** Not applicable

**Clinical trial number:** not applicable

**Conflicts of Interest:** The authors declare no conflicts of interest

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