Development of a Mixing and Moulding Unit for Mini Foam Batch Production Plant

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Abstract

This study focuses on the development of a mixing and mould system for the production of flexible polyurethane foam. Foam is a vital material used in every home and the demand rate of this valuable product has increased over the years. It was estimated to be seven million metric tons, with an average growth rate of 5%. Considering this factor, there is a need for improvement in the manufacturing process of foams. This research aims at developing a standard mixing and moulding unit of a mini foam (petroleum-based) batch production plant**.** The major components of the machine include the electric motor, which is the prime mover of the machine, a mixing tank, baffles, hopper through which the reagents are poured into the mixing tank, ball valve, and the mould. The result showed that the machine produced a high-quality foam with a moulded foam density of about 0.03g/cm^3 although this value was dependent on the foam formulation.

Keywords: Design, mould unit, mould foam density, petroleum-based, mini foam

1. Introduction

The current population of Nigeria based on the latest United Nations World Population Estimation is roughly 187,896,647 as of September 2016, this implies that Nigeria population is equivalent to 2.48% of the total world population and is estimated to double that figure by the year 2050 (Worldometer, 2016). Nigeria population has an average growth rate of about 2.6% resulting in an increased in the demand for flexible polyurethane foam in an average home. There is hardly any home where polyurethane foam is not used, whether in flexible or rigid form, thus mechanization of the production polyurethane foam will be a welcome development. Furthermore, most small-scale producers of foam have issues with their product because in most cases the mixing of the raw materials is done mechanically with stirrer driven by an electric motor, but turned manually into the mould, hence, there is time wastage before pouring which can affect the foam formed. The research is aimed at developing the mixing and moulding Unit for a Foam Batch Production Plant, integrating them into a single unit, hence to reduce human (operator) effort, processing time as well as the cost of production using suitable engineering materials without compromising the efficiency of the machine. The major objective of this study is the development of mixing and molding system for easy production of foam. The sub-objectives include to: Study already existing batch production plants and look at ways of possible improvement; design and construct the molding and mixing unit using a ball valve as the connector, and other locally sourced materials; assemble the various component of the batch production plant into a single machine and conduct a performance test on the developed machine.

2. Literature Review

Polyurethanes are one the most important class of special polymer, though this term is not derived from polymerizing methane monomers, nor are they the polymers containing primarily urethane group. Possibly the most important class of polymeric foams are polyurethane foams (PUFs), as their low density and thermal conductivity combined with their interesting mechanical properties make them excellent thermal and sound insulators, as well as structural and comfort materials (Nuno et al., 2018). Ideally, a typical polyurethane may contain in addition to the urethane linkages, aliphatic and aromatic hydrocarbons, esters, ether and other groups (Michael, 2013). The chemistry of urethanes makes use of reactions of organic isocyanates with compounds containing active hydrogen. When poly-functional isocyanates and intermediates containing at least two active hydrogens per mole are reacted at proper ratios, polymer result that can produce foams, elastomers, coatings, adhesives, and sealants are formed (Suleman et al., 2014). Flexible polyurethane foam formation is an intricate process employing two reactions which occurs together: urethane formation, which produces a covalent polymer network, and CO_2 blowing, which secondarily forms polyurea (Lee et al., 2004). In water-blown flexible polyurethane foams, two active hydrogen-containing compounds are involved, water and polyol. The reaction between isocyanate and the polyol is called the gelling reaction. Usually, the polyol and isocyanate used are polyfunctional, and this reaction leads to cross-linked polymers. Over 90% of the foam volume is the carbon dioxide generated from the reaction of an isocyanate with water (Lee et al., 2004).

Foams are formed by a collection of minute bubbles formed on the surface of a liquid by agitation or shaking, a colloid in which particles of a gas are dispersed throughout a liquid. Foaming is a straightforward process of generating bubbles and stabilizing them within a polymeric matrix. Foams are materials, and foaming is a process. Both terms involve the presence of a gas phase encapsulated by a spherical shell dense phase. When gas is encapsulated in dense materials, interesting products are formed, in this material, either there is a hollow space surrounded by solid, or gaseous voids are dispersed in the solid (Lee et al., 2004). Bubble formation, in general, is a consequence of unstable phenomena or a way to dissipate a “disturbance” to resume a stable state. When a system is excited into an unstable state, a means of stabilizing the foam formed must be done to retain the form product (Mills, 2007). Soluble foaming or physical foaming which involves the physical variation of the polymer state and reactive foaming or chemical foaming, which is dependent solely on chemical reaction are the two major methods of making foams. Soluble or physical foaming which is the major focus of this project involves blowing an agent into the polymer by mixing within a chamber, taking advantage of the gas vapourization while reducing pressure (Nasir, 2009).

Foams can be classified into; solid foams and liquid foam depending on their application, or on the medium (liquid or solid) in which gas is dispersed. The major focus of this design was on solid polymeric foams, that is, polymer foams, in this case, tiny gas bubbles are trapped in the polymer melt phase in other to produce light-weight materials without sacrificing mechanical and physical properties of the polymer. The trapped-in gas bubbles are formed by means of blowing agents which are either physical or chemical agent. The chemical agent takes part in the reaction as part of the reacting compounds, giving off chemicals in the process, while physical agents are gases which do not take part in the reaction. Shau-Tang et al., (2007) shows the gaseous bubbles in the dense matrix as presented in Figure 1, while Figure 2 represent the foaming process.

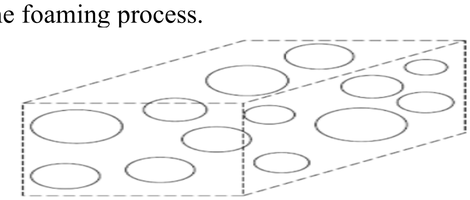


Fig.1 Gaseous bubbles in a dense matrix

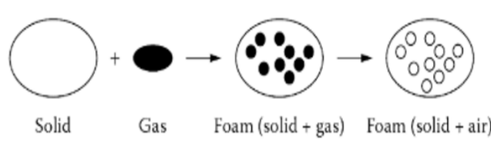


Fig.2 Foaming Process

Considering the increased demand for flexible polyurethane foam in every average Nigerian home because of increase in her population, hence the need to make the production rate higher and more efficient became necessary, thus this research work. The continuous growth of the usage of Polyurethane foams requires that designers and manufacturers investigate the appropriate factors that affect their production and full usage to exploit their full potential (Oppon et al., 2015).

3. Methods

3.1 Materials
Mild steel was used for the construction of the machine. Mild steel plates, Angle bar, and C-channels were obtained locally from steel markets within Warri, Delta State. The machine was fabricated using the arc welding method at the mechanical workshop section.

3.2. Material Selection
ASTM A36 Mild/Low Carbon steel
ASTM A36 is one of the most commonly used mild and hot-rolled steels. It has excellent welding properties and is suitable for grinding, punching, drilling, tapping and machining processes. Yield strength of ASTM A36 is less than that of cold roll C1018, thus enabling ASTM A36 to bend more readily than C1018. Normally, larger diameters in ASTM A36 are not produced since C1018 hot roll rounds are used (Azom ,2012). ASTM A36 is usually available in the following forms:

(i) Rectangle bar (ii) Square bar (iii) Circular rod (iv) Steel shapes such as channels, angles, Beams and I-Beams.

3.3 Machine Description
The mini foam production plant units in this design are to produce a 40cm x 30cm x 30cm sized of polyurethane foam. The machine has two parts, the mixing unit and the mould. The mixing unit is made up of the mixing tank where the different chemicals are mixed by a stirrer coupled to an electric motor. The mixed chemicals are then poured from mixing tank, through the bottom of the tank, using a large diameter ball valve, putting cost into consideration. Fig. 3 shows an overview of the design, with different part or components well highlighted.

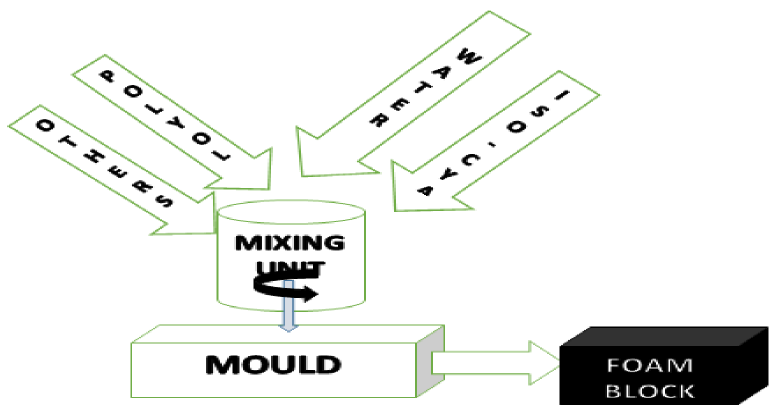


Fig. 3 Overview of the Design

3.4 Design Consideration
To achieve the aim of this research, the following design considerations were embarked on:

i. Sourcing for materials that make up the complete machines locally.
ii. Ensuring that the component that makes up the machine are cheap, affordable, easy to operate and maintain.
iii. Selection of standard materials capable of withstanding additional weight.
iv. Ensuring that the foam chemicals are good enough to react with the machine material.
v. The power ratings of the electric motor to be used is precise and accurate.
vi. Ensuring the design of easy process of transferring the mixed polyurethane raw material from the mixing tank to the mould.

3.5. Design Requirement
The mini foam production plant is made up of the following components: Polyurethane raw material mixing tank, electric motor, shaft, impeller, frame, bolts, mould and electrical control board.

3.6. Functional Analysis of the Design

The design process and architecture of the system is presented in Figure 4 showing the functional process of the machine. The raw materials are fed into the system for mixing and moulding to form solid foam products

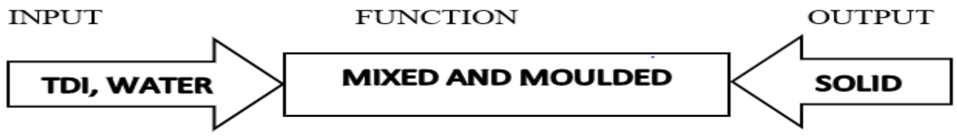


Fig.4 Functional Analysis of the Design

4. Data Collection

4.1 Estimation of Foam Volume and Density

$$V = Lbh \quad (1)$$

Using a standard foam formulation for each component of foam per 100 grams of polyol as shown in Table 1. The density of foam component is presented in Table 2.

Table 1. Foam Formulation for Density Calculation (Michael, 2013)]

Raw material	**Grams per one gram of polyol**
Polyol	100
Water	4
TDI	52.1
Silicone oil	1.2
Amine	0.13
Stannous octoate	0.24
Methylene chloride (an auxiliary blowing agent	4.8
Total mass	162.47

Using the above formulation for flexible foams, for every gram of polyol used, a total of 1.6247 grams of foam components will be mixed.

Table 2. Density of Foam Components [Michael (2013)]

Raw material	**Density (g/cm^3)**
Polyol	1.1
Water	1
TDI	1.2
Silicone oil	0.93
Amine	1.02
Stannous octoate	1.251
Methylene chloride (an auxiliary blowing agent	1.36266

Therefore, for a gram of polyol, the following volume of foam constituents can be computed as shown in Table 3.

Table 3. Calculated Volume of Foam Components

Raw material	**V (cm^3)**
Polyol	0.9091
Water	0.04
TDI	0.4342
Silicone oil	0.0129
Amine	0.00275
Stannous octoate	0.001985
Methylene chloride (an auxiliary blowing agent	0.036183
Total	1.437188

The approximate density of constituent before mixing should be,

$$\rho = \frac{M}{V} \tag{2}$$

4.2 Design of Frame

The dimension of the frame was selected based on the following design considerations:

i. Maximum breadth of mould the machine can accommodate 54cm
ii. Maximum height of mould the machine can accommodate 60cm

From the consideration, dimension of the frame used is 30cm x 60cm x110cm
Frame material: A36 Mild/Low Carbon steel, angle bar
Angle bar size: 35mm X 35mm X 3mm

4.2.1 Assumed Load on Frame Top

The approximate Weight on the frame top (load-bearing support) was further computed and the load on frame top is presented in Figure 5.

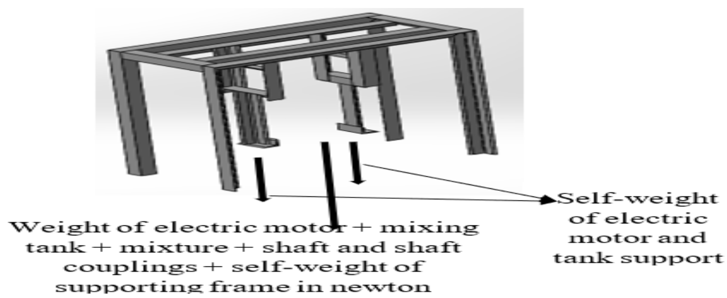


Fig.5 Load on Frame Top

Load of Mixing Tank Size

Material: 3mm thick, AISI A36 sheet metal with the dimension as shown in Figure 6 while the load action on frame is presented in Figures 7 and 8. Figure 9 represent the bending moment and shear force diagram for the setup while Figure 10 represent the cross section of the angle iron.

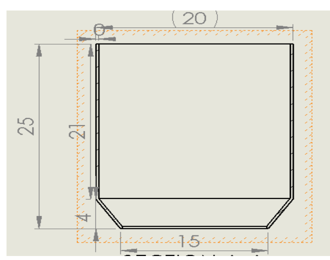


Fig.6 Mixing Tank Geometry

$$V_{container} = volume\ of\ top\ cyliderof\ mixing\ tank + volume\ of\ conic\ frustrum \tag{3}$$

4.2.2 Load Estimation of Mixture

$$V_{mixture} = \frac{\pi T^2(z-4)}{4} + \frac{\pi T^2 h_o}{3*4} - \frac{\pi D_m^2 (h_o-4)}{3*4} \tag{4}$$

where,
T = internal diameter of top cylinder,
z = mixture level,
t = plate thickness, and
h_o = calculated height of completed cone = 10cm

Weight of Supporting Frame Member Based on Angle Iron Dimension and Density
For the top of the frame

$$W_{frame\ top} = cross\ section\ area\ of\ angle\ iron * lenght * density * 9.81 \tag{5}$$

Support for Mixing Tank and Motor

$$W_{frame\ top} = cross\ sectional\ area\ of\ angle\ iron * lenght * density * 9.81 \quad (6)$$

Bending Moment on Top of the Frame

Assumptions;

i. The loads on the top frame are concentrated at the centroid of the frame
ii. The load is distributed equally among the load-bearing beams elements of the frame, at their mid-mid-span.

Therefore, the total force acting on each supporting frame including their self-weight and the weight of the motor, assumed to be 60N, is;

$P = 30 + 16.3 + 129 + 51.311 + 60 = 286.611N$

Therefore, for each beam,

$p = \frac{288.61}{2} = 143.31N$

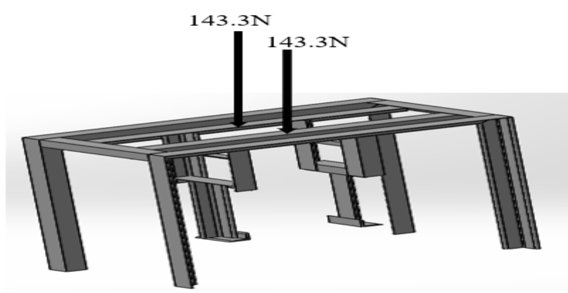


Fig.7 Load acting on Frame

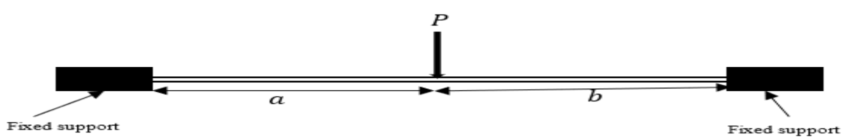
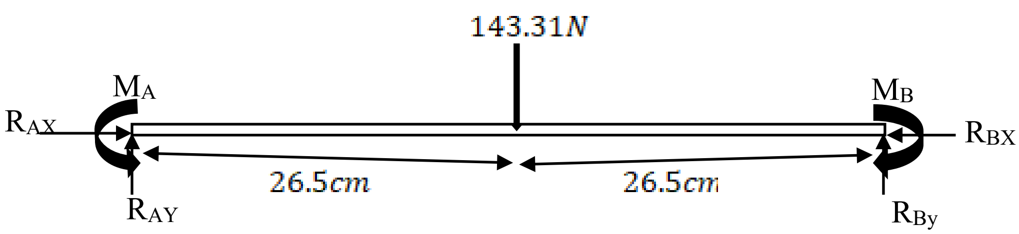


Fig.8 Load **acting on Frame**



$$R_A + R_B = P = 143.31N \quad (7)$$

Since P is assumed to be located at the mid span of the angle iron, $R_{Ay} = R_{By}$

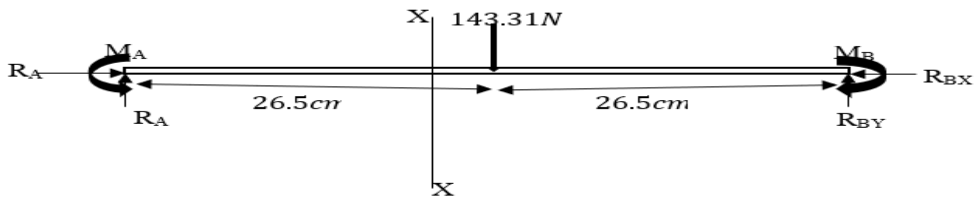
$2R_A = 143.31$

$R_{Ay} = \frac{143.31}{2} = 71.655N$

Also, $R_B = 71.655N$

$R_{AX} = R_{BX} = 0$, (with the assumption that there is no horizontal load)

Also, since P is located at the mid-span, $M_A = M_B$



The bending moment at any point of x distance from the fixed ends is;

$$M = \frac{P(4x - l)}{8} \tag{8}$$

Therefore,

$$M_A = \frac{P(4(0) - l)}{8} = -\frac{Pl}{8} = -\frac{143.31 * 53}{8 * 10^2} = -9.4945Nm$$

Also, $M_B = -9.494Nm$

At the mid-span,

$$M = \frac{P\left(4\left(\frac{L}{2}\right) - L\right)}{8} = \frac{PL}{8} = \frac{143.31 * 53}{8 * 100} = 9.494Nm$$

Shear Force and Bending Moment Diagram

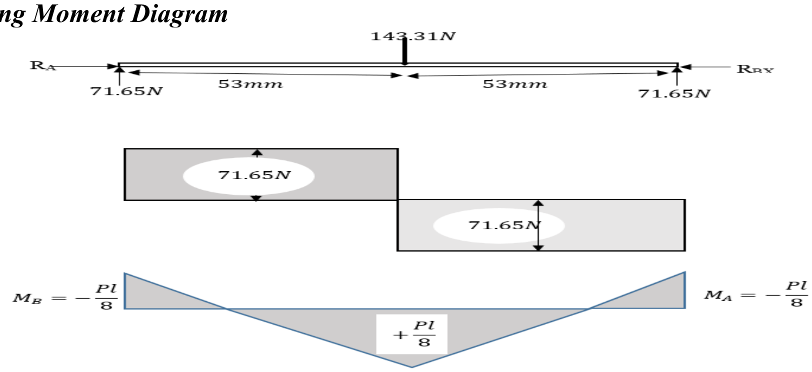


Fig.9 Bending Moment and Shear Force Diagram

Designing for frame safety, maximum bending stress of the beam is given by,

$$\sigma_{max} = \frac{M y_c}{I} \tag{9}$$

Where,

M = Resisting moment

I_Z = moment of inertial of the beam about the natural axis

y_c = maximum vertical distance from the natural axis

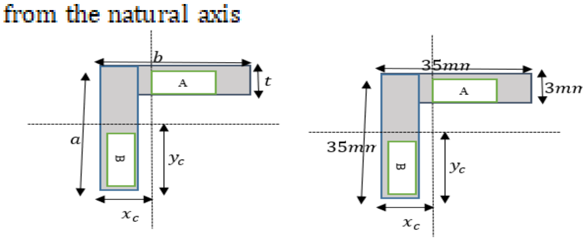


Fig.10 Cross Section of Angle Iron

$$Ay_c = \sum_{i=1}^{n} yA = A_A * y_A + A_B * y_B \tag{10}$$

Also,

$$I = \frac{(t y_c^3 + b(a - y_c)^3 - (b - t)(a - y_c - t)^3}{3} \tag{11}$$

Motor Selection

A single-phase high speed 220 volts AC motor of 1hp, 2800rpm was selected because of its high speed and its availability.

4.2.3 Mixing Tank

For the optimum result of mechanically stirred tanks or agitators, mixing systems must be designed following the under-listed steps:

i. Process mixing requirements, such as blending quality, drop sizes, degree of solids suspension, mass transfer rates, etc., must be defined
ii. A suitable impeller type must then be selected based on the type of fluid system and mixing requirements.
iii. The overall mixing system can then be designed, which involves determining the appropriate number of impellers, sizing the impeller, determining mixer speed, and estimating energy requirements.
iv. Other components, such as baffles, must also be specified based on desired flow patterns.
v. One must design the mechanical components, such as shaft diameter, impeller blade thickness, baffles and supports, bearings, seals, etc. (Paul *et al.,* 2004).

Fig. 11 shows the standard geometry of mixing tanks.

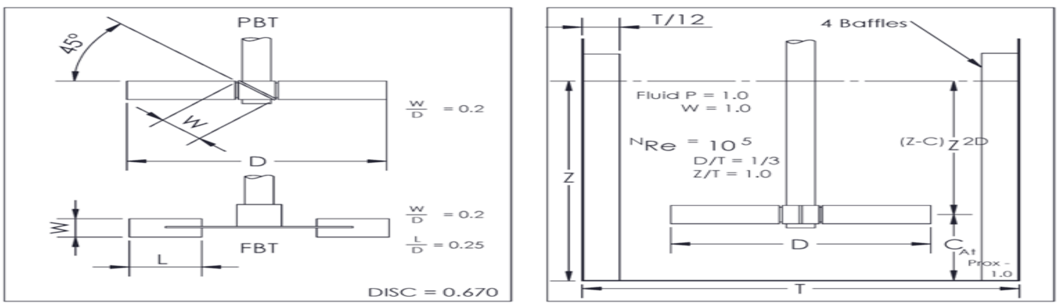


Fig.11 Standard geometry of Mixing Tanks

Power Required to Drive the Impeller

The power consumed by the impeller during mixing can be obtained by multiplying pumping, Q, and head, H, and is given by Equation (12). Power is dependent on fluid density, viscosity, impeller diameter, etc.
Dimensionally,

$$P = f\left[\frac{\rho N D^2}{\mu}, \frac{N^2 D}{g}, \frac{T}{D}, \frac{W}{D}, \frac{H}{D}, \ e.t.c\right] \quad (12)$$

where,

$$\frac{P g_c}{\rho N^3 D^5} = power\ number, P_o \quad (13)$$

$$\frac{DN^2}{g} = froude\ number \quad (14)$$

$$\frac{\rho N D^2}{\mu} = reynold\ number, Re \quad (15)$$

Froude number is usually important only in a situation where gross vortexing exists and this can be neglected if Re is less than 300. For higher Reynolds number, the vortexing effect can be eliminated by using baffles or by off-centre vortexing.

Shaft Design for Strength

$$T_{Q(max)} = \frac{P_m}{2\pi N} \quad (16)$$

$$M_{max} = \sum_{i=1}^{n} \frac{0.48 L_i F_{Hi}}{N D_i} \quad (17)$$

Also,

$$d_s = \left[\frac{16\sqrt{T_{max}{}^2 + M_{max}{}^2}}{\pi \sigma_s}\right]^{1/3} \quad (18)$$

$$d_s = \left[\frac{16(M_{max} + (\sqrt{T_{max}{}^2 + M_{max}{}^2})}{\pi \sigma_t}\right]^{1/3} \quad (19)$$

where,

$d_s = minimum\ shaft\ diameter$, $\sigma_s = allowable\ shear\ stress$, $\sigma_t = allowable\ tensile\ stress$

$$W_{b\ pitched} = \sqrt{\frac{0.084 D^3 P_i}{N}} \qquad (20)$$

Where,
$p_i = power\ drawn\ by\ the\ impeller, which\ is\ a\ fraction\ of\ the\ motor\ power\ after\ lost$

Selection of Bolt for the Mixing Tank Assembly

$$P = \frac{\pi d_c^2 \sigma_t}{4} n \qquad (21)$$

where,
$d_c = root\ or\ core\ diameter\ of\ bolt,$
$\sigma_t = permissible\ tensile\ strengtht, and\ n = 4\ is\ the\ number\ of\ bolts$

Fig. 12 shows the dimensioned view of the mixing tank and Fig. 13 shows the isometric view of the machine.

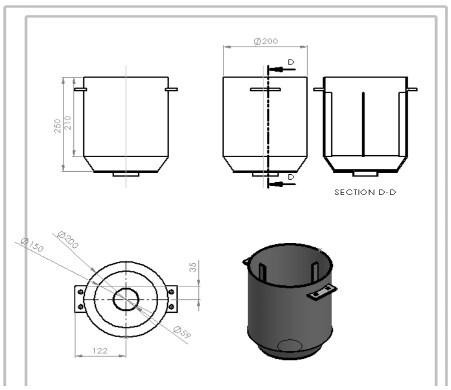


Fig12. Dimensioned View of Mixing Tank

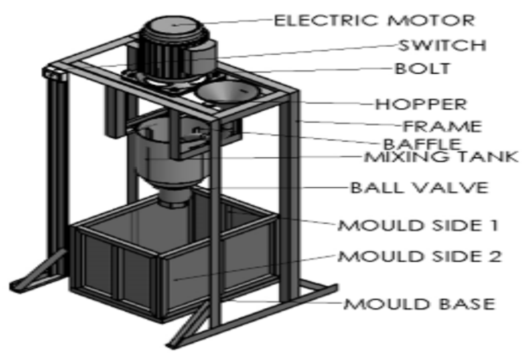


Fig 13. Isometric View of the Machine

Fig.14. Is a representation of the chemical foam constituents while Fig.15 shows the fabricated machine.

Fig 14. The chemical foam constituents

Fig. 15 Fabricated Machine

5. Results and Discussion

5.1 Numerical Results

The fabricated machine was evaluated for performance. The chemical composition of used samples is shown in Table 4.

Table 4. Chemical Composition of the Test carried out

Chemicals	Exp. 1 (mls) (Good)	Exp. 2 (mls) (Good)
Polyol	500	1000
TDI	230	450
Methyl Chloride	30	60
Silicon Oil	15	26
Stannous Octoate	3	5
Amine	1.5	3
Water	20	45
Calcium Trioxocarbonate ($CaCO_3$)	25mg	50mg

5.2 Graphical Results

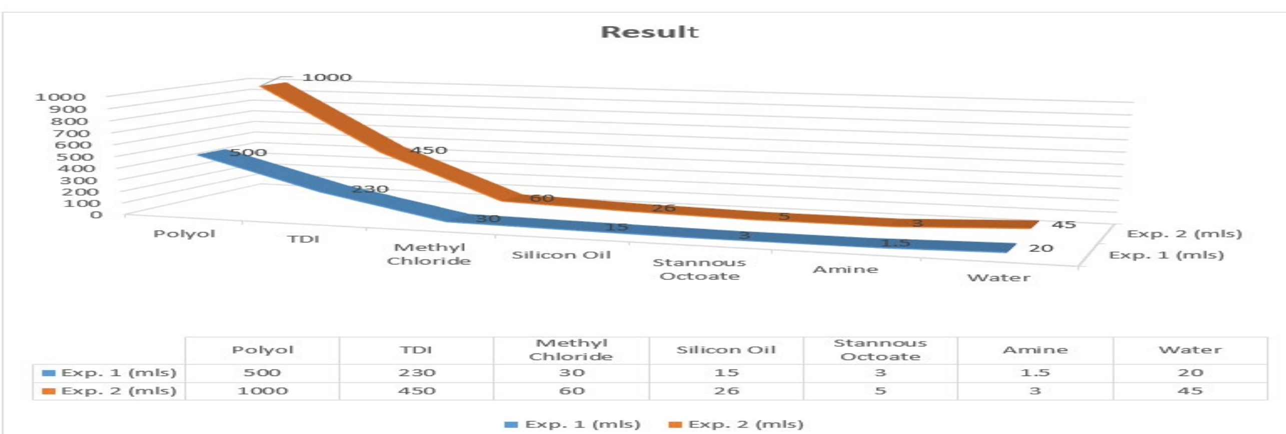


Fig 16. The graph of foam constituents against quantity

Fig. 17 Performance Evaluation of the Machine

The estimated density of the foam produced was excluding waste material was evaluated as;
Experiment 1
Mass of product = 454.2g
Volume of product = 13291.2cm^3
Density = 0.034g/cm^3

Experiment 2
Mass of product= 767.7g
Volume of product = 25474.8cm^3
Density = 0.0301g/cm^3

The fabricated machine was tested on two different occasions using the foam formulation as shown in Table 4. The graph of foam constituent against quantity produced is presented in Figure 16. Detailed diagram showing the test procedure of the developed machine is presented in Figure 17. The agitation process was quite effective with a mixing speed of about 5secs. The result from the test formulation was the flexible foam of density of about 0.03g/cm^3.

6. Conclusion

An efficient batch foaming machine mixing and moulding unit was designed and fabricated. Small scale tests were performed on the completed setup and the machine was observed to be very efficient with a mixing time of about 5secs per set. The fabricated mini foam production plant would be able to meet all basic need of foam users in homes, hospitals, hostels and other facilities. Development of larger setup is strongly recommended for future research. This would make foam production cheap and high-quality products can be available at an affordable rate. Young people can venture into the business of production of quality foams.

Acknowledgement

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