Development of a Laboratory-Scale Steam Boiler for Polyurethane (Foam) Waste Recycling Machine

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Abstract. *In this paper, a laboratory scale (small) Steam Boiler was designed and developed for small scale polyurethane recycling machine. A small sized polyurethane machine was developed for the recycling of polyurethane foams to reduce wastes in the polyurethane production industries and also to reuse old discarded foams after their useful lives. It has been observed from studies carried out in many foam manufacturing industries that the polyurethane foam wastes generated from various plants operations are enormous. Also, polyurethane (foam) products are everywhere in our homes, industries and automobiles and are always discarded after their useful lives. These wastes needed to be recycled always in other for them not to get back into our ecosystems thereby polluting our environment because polyurethane foams are non-biodegradables and can remain in the environment for a very long time. However, only few companies with strong financial capabilities are able to embark on this venture because of the high costs of machineries and large quantities of chemicals involved. The high costs of machineries and chemicals also deter cottage industries from participating in the recycling of old and discarded polyurethane foams. Therefore, there is need to develop small scale polyurethane foam wastes recycling machine to reduce costs of machineries and chemicals involved in the recycling thereby allowing more participation in the recycling process. The boiler is used to generate high temperature steam for curing and better bonding of the shredded foams. The heating chamber of the machine consists of the steam boiler, pressure hose to enable passage of steam from the steam boiler into the molding box. the total volume of the boiler is 2.5 Litres. The outlet steam temperature is 135 0C and 25 psi pressure. The heat rate is 1.52 kJ/s. The recycled foams were able to cure and bonded better with the addition of steam compared to without the steam. The percentage difference in I.F.D, Resilience, Tensile Stress and percent elongation are +0.56, -2.00, +85.45, and +68.39 respectively.*

Keywords

Biodegradable, Molding box, Orthopedic foam, Polyurethane foams, Recycling machine, Steam boiler.

1. Introduction

Polyurethanes are polymers with carbamate groups (-NHCO2) as their internal structure, were first developed in 1937 by Friedrich Bayer, a chemist of German origin, was the first to produce prototypes as a replacement for rubber.

Polyurethanes have many useful applications in homes, offices, automobiles, aircraft designing, upholstery works, and also, in use in thermal insulation, coatings and adhesives, plastics (solid and athletic apparels), packaging of electronic appliances as well as sound proofing of power generating sets and several other uses in our environment. Waste generated from the production and everyday uses of these products are enormous. The disposal of the used product is an environmental concern because of their polymeric nature and they are non-biodegradable [1]. It is however necessary to find ways of minimizing and reuse the waste generated during production of polyurethanes and their reuse after their useful lives such that they don't find their ways into our ecosystems thereby destroying our ecosystems, so the waste generated from their production be recycled to minimize waste. The good news is that polyurethane foams can be recycled in various ways like other plastics, in order to remove them from the environment and convert them to other useful products. These recycling can be done either mechanically by utilizing a compression mold or chemically, by the use of chemical reagents that will eventually result to fusing together of the shredded foams. Attempts had always been made to reuse polyurethane wastes from industries, households, and other sources through physical, chemical and combination of different recycling methods [2, 3, 4, 5, 6]. Other means of safe disposal of polyurethanes are landfills and exporting [7, 8].

The recycling or recovery of polyurethane wastes can be categorized into three; Mechanical recycling (i.e. material recycling) which is the treatment of the wastes; chemical recycling which involves chemical treatment that can be used to produce feedstock chemicals; and energy recovery which include waste-to-energy processes, this process is complete or partial oxidation of the polyurethane materials thereby producing heat and power and/or gaseous fuels, oils for the purpose of electricity generation and chars besides other byproducts such as ashes that must be disposed of. Mechanical recycling involves three steps of regrinding or powder incorporation; Compression molding involving molding polyurethanes particles at high temperatures and pressures enough to generate the shear forces for the particles to flow together, without using additional binders [9, 10, 11, 12, 13, 14]. Recycling of polyurethanes foams are necessary for but not limited to the following reasons (1) recovery and reuse of the waste generated during production operations, (2) testing and sample testing of materials in polyurethane industries (3) keeping the environment from pollution due to non-biodegradable products and (4) reuse of old and discarded foams to achieve various bye products including very high-density foam for orthopedic application. These polyurethane products are prevented from entering into the ecosystem, either through burning (ozone layer depletion) or disposal on land and waterways, thereby converting these polyurethane foam wastes into wealth and achieving clean environment (achieving United Nation's SDGs 6 and 13). Individuals and cottage industries should be able to partake in the recycling of polyurethane foams, but the industrial recycling plants are way out of their purchasing capacities. The products of recycled polyurethane foams are in high demand in hospitals especially orthopedics because of its good properties including high densities and hardness especially as it helps to relieve pain and aches.

It has been observed from studies carried out in the foam manufacturing industries that the polyurethane foam wastes generated from various plants operations are enormous. Also, polyurethane (foam) products are everywhere in our homes, industries and automobiles and are always discarded after their useful lives. These wastes needed to be recycled always in other for them not to get back into our ecosystems thereby polluting our environment because polyurethane foams are non-biodegradables and can remain in the environment for a very long time. However, the recycling of wastes foams in polyurethane industries are done on large scale which makes it very expensive to be carried out and only few companies with strong financial background are embarking on this venture because of the high costs of machineries and large quantities of chemicals involved. The high costs of machineries and chemicals also deter cottage industries from participating in the recycling of old and discarded polyurethane foams. Therefore, there is need to develop small scale polyurethane foam wastes recycling machine to reduce costs of machineries and chemicals involved in the recycling thereby allowing more participation in the recycling process. This will reduce wastes that will be released back to the environment. Also, many polyurethane foam industries cannot perform pre-recycling operation tests on small test samples before performing them on industrial scales because there are no small machines to achieve this there by wasting resources and time thus making recycling very expensive. The objective of this paper is to design and develop a small steam boiler for a laboratory size polyurethane foam recycling machine (already developed [11]) that will recycle polyurethane wastes by mechanical method.

2. Methodology

The major components of the polyurethane recycling machine are: The shredder, the Mixer, the Mold, the screw presser, and the steam boiler. The different components parts were designed, and developed locally. The shredder is already designed and developed [10] to shear and shred the waste polyurethane foams that will be recycled while the mixer, designed and developed [11] is to mix the foam crumbs with the chemical (binder) for bonding. The mold receives the mixture from the mixing chamber and the vertical screw press presses the mixture [14]. The machine is tested for integrity and compliance with the objectives of the work.

2.1. Material Selection Process

The proper material selection for the effective operation of the machine that will maintain a balance between cost, availability, mechanical properties, processing and environment concerns is necessary.

1) The Boiler Cylinder

The boiler cylinder is shown in Fig. 1, Fig. 2 and Fig. 3. It is a vessel that will be used to produce steam to be supplied to the mixing chamber. The selection criteria considered for the engineering materials such as aluminum and stainless steel, but taking into consideration cost, availability, rigidity, temperature resistance, pressure resistance, fatigue strength, fracture toughness, weldability, corrosion resistance and other properties, stainless steel cylinder was considered. This component is majorly to produce steam at a temperature of 135 0C and 25 psi. A stainless steel cylindrical can of thickness 2.5 mm was selected, which was of the desired volume for this project. Four holes were bored on the top of the cylinder for boiler accessories and these accessories, temperature gauge, pressure gauge, water inlet and steam discharge outlet fittings were fitted on the cylinder. A water level gauge was also installed at the side of the boiler. The entire boiler was then mounted on a fabricated burner stand.

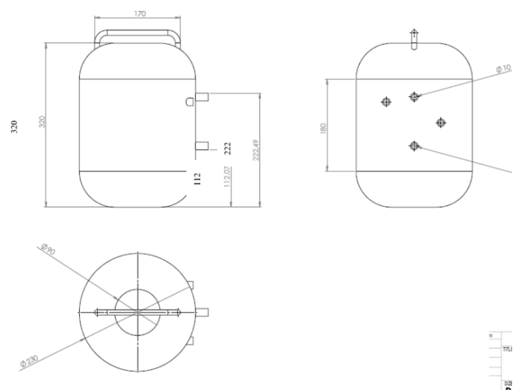


Fig. 1: CAD view of the steam boiler.

2) The heating device

The heating device for the boiler comprised of the burner, the housing, the fire brick and burner stand. It is shown in Fig. 4 and Fig. 5 below. A circular burner of external diameter 155 mm and internal diameter of 80 mm was enclosed by metal sheet of thickness 1.5 mm and

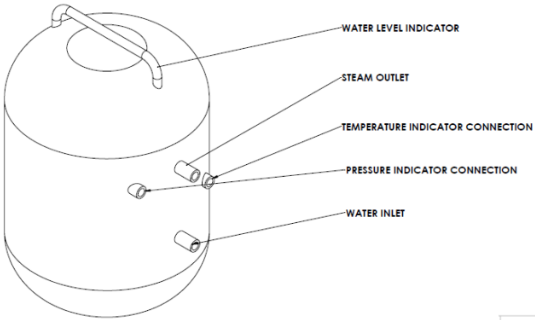


Fig. 2: CAD model of Boiler.

Fig. 3: Fabrication model of Boiler.

folded into a length 455 mm, breadth 330 mm and height 240 mm which is supported by four angular bar of height 490 mm at each corner. The enclosed area surrounding the burner was insulated by 6 fire bricks, each of length 225 mm, breadth 60 mm and height 120 mm.

The Burner housing: This device houses the burner and the fire brick with curved edges for proper sitting and accommodation of the boiler cylinder. Many engineering materials were considered during selection process, these include mild steel, high speed steel, galvanized steel and stainless steel but after considering cost, availability, formability, rigidity, temperature resistance, fatigue strength, fracture toughness, weldability, corrosion resistance, wear and other properties a mild steel plate was considered for the housing of the burner.

The Fire Bricks: These are thermal insulators. They are blocks of refractory materials used to line the burner housing. These were made of refractory materials primarily to withstand high temperature with low thermal conductivity for heat conservation and greater energy efficiency for effective heating.

Burner Frame and Stand: The burner frame and stand, shown in Fig. 4 and Fig. 5, is a heat producing component that houses the burner and the fire bricks. It is insulated with silica fire brick to prevent heat loss during boiling process and it also serves as stand for both the boiler and the burner by raising and supporting the boiler and the burner above the ground level.

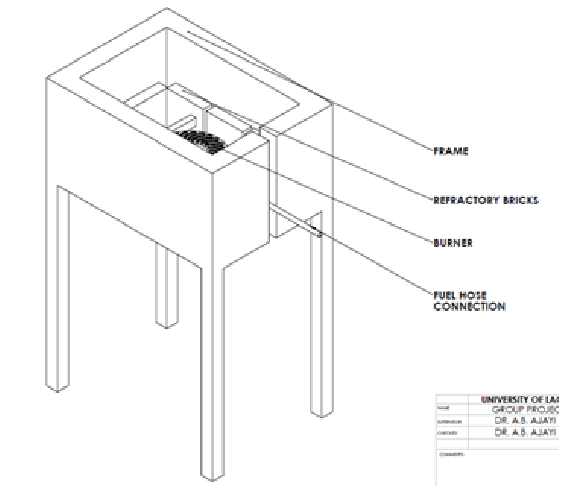


Fig. 4: CAD model of burner stand.

3) Pressure and Temperature Gauges

These were selected according to need (what we intend) to read in the steam boiler for safety and accuracy before discharge into the mold.

Fig. 5: Fabrication model of burner stand.

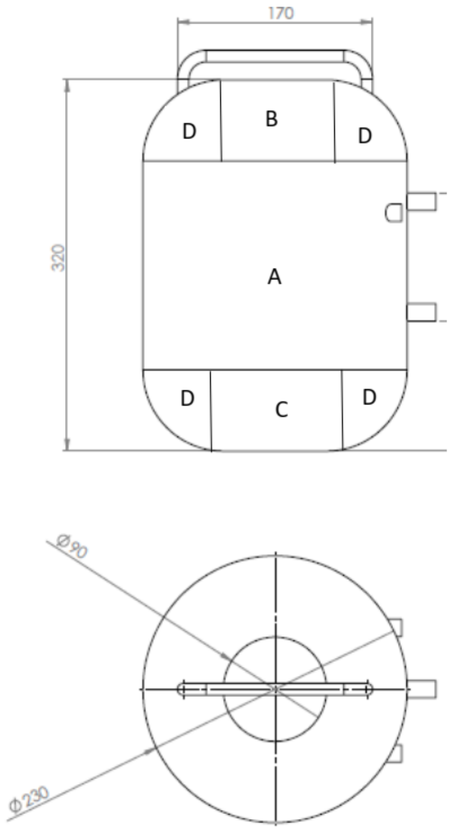


Fig. 6: Sections of the Cylinder.

2.2. Design Calculation and Analysis

1) Design calculation of steam boiler

Boiler Volume: The boiler is assumed to be a right circular cylinder. The height and diameter are 230 mm and 320 mm respectively. The volume of the cylinder can be estimated graphically and mathematically by dividing the cylinder into appropriate sections as shown in Fig. 6 and calculating the volumes of each section and adding them together. Sections A, B and C are assumed to be perfect cylinders and sections D are assumed to be a quadrant of a sphere.

The total volume =volume of A + volume of B + volume of C + 4 x (volume of D) (1)
$= \pi$ x $[0.18$ x $0.115^2 + 2(0.070$ x $0.045^2) + 4(4/3$ x $0.07^3)]$
$= 0.0141148066\ m^3$
= 14.12 litres

2) Boiler heat rate

The boiler heating rate is proportional to the rate at which the water within the boiler rises. Below are the parameters of water to be used in the boiler for the recycling.
Parameters:
Initial Temperature of Water = 27.9 ^{0}C
Final Temperature = 137 ^{0}C
Volume of water admitted into the boiler, V = 10 litres = 0.01 m3
Density of Water, ρ= 997 kg/m3 at 27.9 ^{0}C
Specific Heat Capacity of Water, C = 4186 J/kg ^{0}C
Time = 50mins = 3000 s
Boiler Heat Input Rate:
Mass of water added = ρV = 0.01 X 997 = 9.97 kg (3)
Temperature difference, ΔT= 109.1 ^{0}C (4)
Boiler heat gain, Q = mCΔT (5)

= 9.97 X 109.1 X 4186
= 4,553 kJ (6)
Boiler Heat Rate = $\frac{BoilerHeatGain}{Timetaken}$ (7)
Boiler Heat Rate = (4,553)/3,000 = 1.52 kJ/s (8)
The boiler heat input rate is 1.52 KJ/s or 1.52kW (9)
Boiler steam discharge rate: 2.5 liters of steam is discharged for approximately 90 seconds into the steam box.

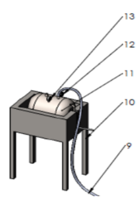
Quantity of water required for single heating = 2.5L
Time taken to discharge = 90 seconds

Steam discharge rate= $\frac{litersofsteamdischarged}{timetakentodischarge}$ (10)
=2.5/90 (11)

=0.028 l/s (12)

2.3. Experimental Set-up/Description of Machine Operation

Fig. 7 shows the complete machine assembly with the machine parts labeled. The design and construction of the machines, that is, the shredder, the mixer, the mold and the screw press were done in batches. The last of the batches is the boiler. Old and waste foams were loaded into the shredder to be shredded into small crumbs at the rate of 10 kg per hour. The shredded crumbs are then loaded into the mixing chamber of the mixing machine. The chamber has a capacity of 6 kg but only 3 kg of crumbs were loaded at a time to allow for enough room for mixing. Thereafter, electric powered motor was used to mix the crumbs while the pre-polymer binder was added gradually until homogeneity of the mixture (pre-polymer and crumbs) was attained, this took about 10 minutes to be achieved. While the mixing process is ongoing, the steam boiler was powered on for the steam to be ready by the time the homogeneous mixing has been achieved. After achieving homogeneous mixing, the molding box is transferred under the mixing drum on a travelling rail constructed for the purpose after which the underneath portion of the mixing drum is opened to discharge the mixture while the stirring blade continues to stir. The molding box is then returned back to the compression section of the machine where the vertical screw was used to compress the mixture. In the compression section, the screw presser, designed and developed [14], and the ram were suspended above the molding box to allow easy movement of the molding box, immediately the molding box is returned from under the mixer, the screw presser was quickly lowered to compress the mixed crumbs to the desired height to ensure expected density is achieved. To ensure rapid curing of this mixed crumbs after compression the steam generated from the boiler is discharged at a temperature of 135 0C and pressure of 25 psi through a pressure hose of diameter 20 mm connected to the steam boiler and attached to the molding box. The screw presser for compression was held in place for about 20 minutes before and the steaming before the presser is lifted from the mold. Then, the final product is allowed to cool before removal.



9	Steam Hose	1	Standard	Rubber
10	Boiler Frame	1	Constructed	Carbon Steel
11	BOiler	1	Constructed	Carbon steel
12	Pressure Indicator	1	Standard	Alloy Sensing Element
13	Temperature Indicator	1	Standard	Alloy Sensing Element

Fig. 7: The Laboratory Scale Assembly.

Fig. 8: Sample of the recycled product.

Fig. 8a is the molding box with the mixing chamber and steam boiler at the background. Fig. 8b a sample of the recycle foam produced by the steam cuing of the waste foams.

3. Results and Discussions

3.1. Results

Results of the experiments performed with the polyurethane recycling machine are presented in this section. Three samples were used for the testing of the machine. Table 1 shows the material constituents of Samples 1 to 3 of the recycled polyurethane foams.

3.2. Discussions of Results

Fig. 9 is the graph of mass of sample products with and without steam. The samples were weighed immediately after they were made and also weighed after drying for 3 days. It is clearly seen from the graph that there is significant change in the mass of the product when weighed instantly and after 3 days of drying. This change in mass was due to mass of steam used for curing.

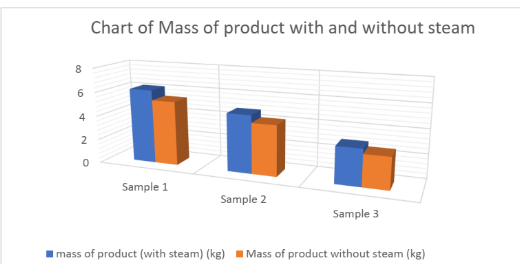


Fig. 9: Mass of product with and without steam.

Fig. 10 illustrates the effect of different masses of materials on the densities of product. For sample 1, 3 kg of crumbs was loaded into the mixing drum with 2.4 kg of chemicals, this produced the sample with the highest density of 226.7 kg/m3 as it was compressed to height of 0.0762 m. The chemical for sample 2 was reduced to 1.2 kg from 2.4 while maintaining the same 3 kg crumbs and same height of compression of 0.0762 m but a lower density sample was produced. Sample 3 was produced with crumbs reduced to 1.5 kg but same mass of chemical 1.2 kg and height of 0.0762 m as samples 1 and 2, this sample of the product with the lowest density. It was observed that the more the chemicals utilized for the mixture, the denser the product becomes as illustrated in sample 1 compared to sample 2. From sample 2 compared to sample 3, it was discovered that the mass of crumbs used has a significant effect on the product, as there is reduction in crumbs during the production of sample 3 without reduction in the height of compression and chemicals which lowers the density of the product. Therefore, there are reasons to believe that the volume, mass of crumbs input and mass of chemical all have their various effect on the product.

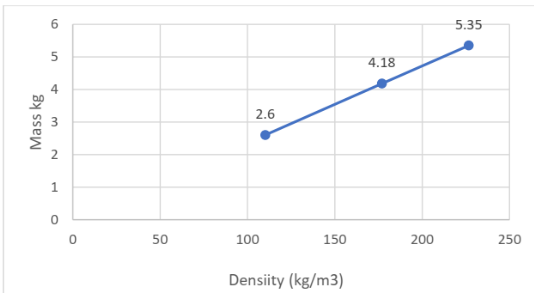


Fig. 10: Graph of mass against density of products without steam.

Fig. 11 illustrates the effect of steam on the instant density of the product. The steam increases the density of the product which means it bring about better compaction, binding and bonding. The steam enhanced the compaction of the

3.3. Laboratory test results

After performance evaluation of the machine, two of the samples produced were taken to the Laboratory for tests in order to ascertain their

Tab. 1: The materials loaded into the machine the recycle machine.

Samples	Crumbs (kg)	Chemicals (kg)	Total materials input (kg)	Steam input (kg)
Sample 1	3.0	2.4	5.4	2.5
Sample 2	3.0	1.2	4.2	2.5
Sample 3	1.5	1.2	2.7	2.5

Tab. 2: The materials loaded into the machine the recycle machine.

Samples Volume (m3)	Mass of product (with steam) (kg)	Mass of product without steam (kg)	Mass of steam retained (kg)	Density of product with steam (kg/m3)	Density of product without steam (kg/m3)	Steam input (kg)
Sample 1	0.0236	6.17	5.35	0.82	261.40	226.70
Sample 2	0.0236	4.80	4.18	0.62	203.40	177.00
Sample 3	0.0236	3.00	2.60	0.40	127.00	110.20

Tab. 3: The materials loaded into the machine the recycle machine.

Samples	Total materials input (kg)	Mass of product without steam also known as recovery (kg)	Materials Loss (kg)	Percentage recovery
Sample 1	5.40	5.35	0.05	99.07%
Sample 2	4.20	4.18	0.02	99.52%
Sample 3	2.70	2.60	0.10	96.30%

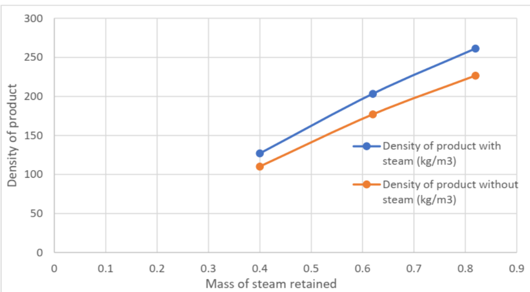


Fig. 11: Graph of mass of water retained against density with and without steam.

mechanical properties. The results obtained were compared with a reference sample that was tested along with the main samples. The tests carried out were the hardness, compression, resilience and tensile. Also, the percentage elongation and peak force were recorded from the machine after necking and breaking had occurred during the tensile test. The test results are given in Table 4.

Sample 1 density is due to compacting with steam curing while Sample 2 density is due to increase in chemical usage. Tests were carried out on three samples. The results of the samples are shown in Table 4. Samples 1 and 2 were produced with the recycling machines developed by the authors of this article. The reference sample R is produced with an industrial recycling machine from the industry. The results of Samples 1 and 2 were compared with the reference sample R. The densities of Sample 1 and Sample R are the same but the density of Sample 2 is almost twice of the other two. The indentation force deflection (IFD) measures the hardness (resistance to depression) of the foam. The higher the IFD the stronger the foam and the better the foam will withstand compressive force (weight). The resilience is the measure of the foam's restoration ability after the withdrawal of the load (IFD). The higher the percentage of resilience the better. Sample 1's resilience is about 2% lower than that of the reference sample, this means they are almost the same in resilience. Both will be restored back to their original dimensional shapes at almost the same rate and time while Sample 2 will take twice the same time to gain back its dimensional integrity after removing the load (IFD) if at all. The peak force is the force that is required to break up the bonds of the foam. The more foam crumbs constituents in the foam sample, the lower the peak force. The peak force of Reference Sample is about half (53%) of Sample 1. Also, the tensile stress of sample 1 is higher than that of the reference sample likewise the percentage of elongation is higher.

Tab. 4: Results of tests carried out on samples [14].

Sample Number	**Density** (kg/m3)	**I.F.D** (N)	**Resilience** (%)	**Force @** peak (N)	**Tensile** stress (MPa)	**Elongation** %	Area (mm2)	Gauge length (mm)
1	110.0	994.33	47.42	13.68	1.708	28.062	78.54	100
2	211.7	994.33	19.35	4.66	0.581	8.445	78.54	100
Ref	110.0	988.75	48.39	7.38	0.921	16.665	78.54	100

Consequently, Sample 1 is better than the reference sample and would therefore perform better. One of the many factors that could be responsible for this is the curing process during production. The density measures the quantities of matter in a particular volume, therefore, if the foam crumbs were properly cured, compressed properly and allowed to cool inside the mold, the cavity and pores will be less and the foam would perform better. These results actually satisfy the condition needed for the sample products produced to be used in orthopedic and as cushion in upholstery, which is a clear indication that the machine fabricated has achieved what the industrial machine can do since the mechanical properties of the products produced from machine compares well with the one produced with the industrial machine.

4. Conclusion

In this paper, a laboratory scale steam boiler was designed and developed for small scale polyurethane recycling machine. This is to reduce waste and financial loss that will be incurred when using the industrial recycling machine for chemical test. The boiler is used to generate high temperature steam for curing and better bonding of the shredded foams. The heating chamber of the machine consists of the steam boiler, pressure hose to enable passage of steam from the steam boiler into the molding box. The total volume of the boiler is 2.5 litres. The outlet steam temperature is 135 ^{0}C and 25 psi pressure. The heat rate is 1.52 kJ/s. This material and space reduction ratio achieved by the fabricated laboratory machine was compared to the industrial size. Series of tests were carried out on the samples produced by the fabricated machine using steam for curing and without using steam, and comparing the test results with that of a reference sample produced from the industrial machine. The percentage difference in I.F.D, Resilience, Tensile Stress and % elongation are +0.56, -2.00, +85.45, and +68.39 respectively. The sample results with steam curing stands out compared with reference results. It is therefore concluded that the objective of this project has been achieved especially when the product was found to be comparable to the product from the industrial recycling machine. It can also be concluded that foam recycling can be done on a low scale, even at the court yards with this machine thereby generating wealth and employments by converting waste to wealth.

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