A Conservative Approach to Low-cost Housing Through the Use of Expanded Polystyrene

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***Abstract*—This publication analyses how an EPS dome house constructed using unmodified EPS can be re-engineered in order to ensure that the costs of construction are kept low. In the absence of intricate moulding equipment; the purpose of this research is to investigate how unmodified EPS can be moulded into a dome-shape that will conform in magnitude to the minimum values of inhabitancy as specified by various legislative bodies. A hot-wire tool was used to carve multiple sets of dome pieces. In order to appraise the viability of such a model, the EPS pieces were assembled and left exposed to the elements since the main method of analysis was through exposure. Analysis of the stability of the live model was studied in conjunction with the compression, flexural and thermal qualities of EPS under laboratory conditions. Wind speeds of thirty-nine km/hr and rainfall of twenty-eight mm did not alter the state of composure of the model even after three months of placement. Observation of the model revealed that it is possible to successfully re-create an EPS dome house without complex moulding equipment. However, a compressive strength test on EPS revealed that the compressive qualities of EPS are significantly lower than that of conventional materials such as clay bricks. This can also be attributed to the void structure of EPS, since EPS is a polymer. A thermo-gravimetric analyses of three different densities (fifteen kg/m3, twenty kg/m3 and thirty kg/m3) of EPS revealed that contrary to what may be expected, the maximum degradation value decreases as the density of EPS increases.**

***Index Terms*—expanded polystyrene, compression, dome-house, polymers, TGA, flexural tests**

I. Introduction

In a world where natural disasters are on an increase, the rate of climate change along with its effects are becoming a large beacon of thought in the type of materials that residential dwellings ought to be built from. This also puts into question which type of housing posture is more suitable in surviving any occurring natural disaster between conventional box shaped houses and dome shaped houses. These concerns have led to the inclusion of materials such as EPS in the arena of civil engineering and the built environment.

Without EPS, the world as we know it would be strikingly different. This is because it's found in numerous industries and corners of daily life. EPS belongs to the family of polymers [1]. A polymer by definition is a chemical that is made of many repeating units [1]. To make the continuous chain, many links are chemically hooked or polymerized together [2]. Polymers by their nature are very light in weight but harbour significant degrees of strength. EPS is produced in a process that involves the use of pentane. Pentane causes resin to foam during moulding. The process may be run in one of two ways, either as a single step or a two-step process [3].

The one step process employs direct thermal extrusion of the material after blowing and is mostly used for sheet and film manufacture. "The two-step process passes the blowing agent through the polystyrene beads during, or after, polymerisation. The resultant beads are then subjected to steam heating to above their glass transition temperature resulting in the beads expanding (by 40 to 80 times) and produce the cellular form" [3]. The resulting product is then moulded.

Density is a measure of mass per volume. Density implies that the many repeating units begin to be packed closer and closer together as the numerical value of density increases. The EPS beads are demonstrated in Fig. 1. The input and output process of forming EPS is demonstrated in Fig. 2. Polymerization is the process of forming EPS, and styrene as well as Pentane are the two major components that are required.

Figure 1. Polystyrene beads [4]

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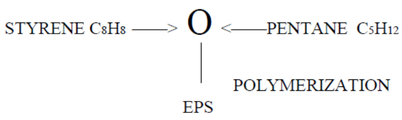

Figure 2. Input and output of forming EPS

A. Box Shaped Structures vs Dome Shaped Structures

A dome shaped structure is more stable than a box shaped structure [5]. Some benefits that dome shaped houses would have over conventional box shaped houses are that they would be gale resistant and earthquake resistant. Dome housing is not new in infrastructure, however, dome houses that are made of EPS are significantly new. Dome structures were constructed as early as the 1300s [6]. The construction of a dome house constructed with conventional material such as masonry takes significantly more time than it would if EPS were used. This is due to the ease with which EPS can be moulded as compared to that of masonry.

B. Industry Leader

Japan Dome House Co. Ltd has developed intricate moulding equipment, capable of moulding large EPS pieces to efficiently form dome houses [7]. Japan Dome House Co. uses proprietary technology to reduce the oxygen absorption potential of EPS [7]. It does this by expanding EPS by 20% instead of the usual 50 to 60%. The result is a highly dense and rigid product that can stand on its own with no further reinforcement [8]. The biggest limitation of the EPS dome houses constructed by Japan Dome House Co. Ltd is that of cost. The total cost of a basic 40m^2 unit costs approximately R1,126,416.13 [8].

II. The Construction of EPS Dome Houses Using Unmodified EPS

In order to achieve the same benefits as those achieved by dome houses that are constructed using modified EPS, it is necessary that the overall construction methodology of assembly remain the same. The biggest variation is that instead of modifying the EPS in order to allow it to stand on its own, steel tubes would be inserted to follow the shape of the dome on the inside in order to increase the rigidity of the structure. This concept is illustrated in Fig. 3.

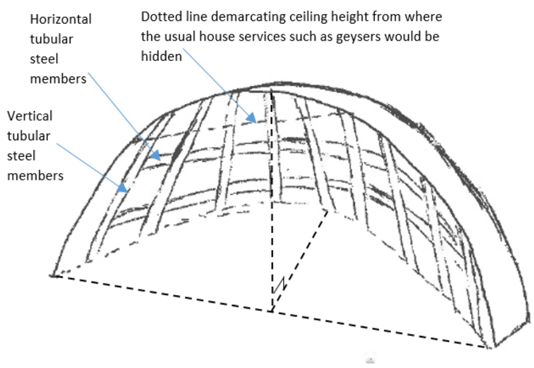

Figure 3. Concept of how tubular steel components would secure the dome structure

The ease with which EPS pieces can be moulded was put to the test by moulding life-size EPS components using a Tolini Hot-Wire machine (Fig. 4). Due to the manual nature of the moulding process, it was observed that efficiency levels are compromised since moulding all 8 pieces required for a complete house, took a period of five days. A live model was constructed and is shown in Fig. 5.

Figure 4. Tolino/Risi 3013 Hot-wire machine [9]

Figure 5. Side-view of live model

A live-model was placed exposed to the elements for a period of three-months. During the three-month observation, the highest temperature was 36 degrees on the 2nd of February 2018. The day with the highest rainfall was the 16th of March 2018 at 28mm. The highest wind speeds were experienced on the 2nd of February 2018 at 39km/hr. Observations made on the model on the 3rd of February 2018 indicate that the high temperature from the previous day did not alter the structural composure of the model in any way. Observations made on the 17th of March 2018 also indicate that no noticeable water penetration could be noted.

A comparison of costs was done by detailing all items that would be required in the construction of an EPS unit for inhabitancy using unmodified EPS. The cost that is required to construct a 40m^2 house using unmodified EPS is R209, 098.00. This was then compared to the costs of construction for a house constructed from modified EPS. The results are shown in Fig. 6:

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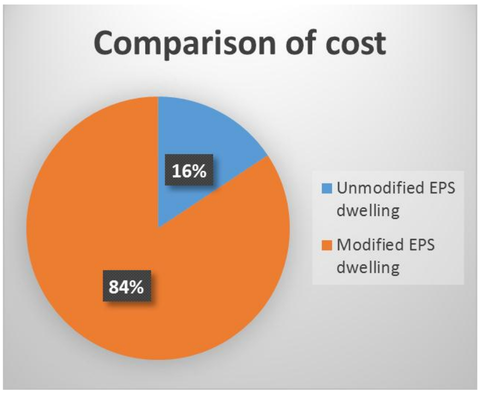

Figure 6. Pie-chart of the comparison of costs between using modified EPS versus unmodified EPS

It is evident from Fig. 6 that the price of one EPS dwelling built using modified EPS is equivalent to 5 unmodified EPS dwellings. It is for this reason that unmodified EPS dwellings are more affordable than EPS dwellings that are built using modified EPS.

Over and above the financial viability of any material, lies the environmental considerations which must be made before it can be said to be holistically viable. The main concern with using cement and concrete for infrastructure development is the energy that it consumes and the subsequent environmental impact that it makes. Cement production is one of the most energy intensive industrial manufacturing processes in the world [10]. Cement and concrete production generate considerable air-pollutant emissions [11]. Emissions include: sulphur dioxide (SO_2) and nitrous oxides (NO_x). SO_2 emissions (and to a lesser extent SO_3, sulphuric acid, and hydrogen sulphide) result from sulphur content of both the raw materials and the fuel [12]. In addition to air-pollution, another environmental impact of cement and concrete production is water pollution. Reference [13] states that on a global scale “they (the cement industry) account for one-sixth of the world’s freshwater withdrawals.” There are also health concerns related to handling and working with concrete and cement. Wet concrete requires that the skin be protected from the high alkalinity of concrete [13].

Masonry is often not perceived as an environmental threat and is usually a large part of “green building” strategies [14]. However, mortar mixing and stone cutting can generate airborne particulate waste such as silica dust [15]. According to the Department of Labour [16], silica can be associated with fibrosis of the lungs (i.e. silicosis). It is therefore critical to take these concerns into account in the use of masonry.

EPS has a negligible impact on the environment in comparison to other pollutants [17]. For example, the energy source for the manufacture of EPS is steam [18]. The steam is produced in boilers through natural gas as fuel. Reference [19] affirms that the amount of “water consumption used in the manufacture of EPS is very low as the water is reused continuously in the manufacturing process”.

According to [20], “The European Manufacturers of Expanded Polystyrene (EUMEPS), estimates that for every litre of oil used to produce EPS insulation, 150 litres of oil is saved in heating costs over the lifetime of any constructed building.”

III. Laboratory Tests

Laboratory tests were undertaken in order to measure the compressive strength, water absorption and thermal resistance of EPS. Findings emanating from these tests were used to determine whether EPS has the ability to protect inhabitants against extreme weather conditions as well as from physical harm.

A. *Compressive Strength Test*

Lateral and vertical impact is always a concern for any structure. Lateral and vertical impact can be as a result of any air-borne object, either self-propelled or assisted, impacting the structure. In order to test whether EPS has sufficient compressive strength, a laboratory test using 50X50mm specimens (Fig. 7) was conducted in terms of the American Society for Testing and Materials (ASTM) D 1621-00 standard.

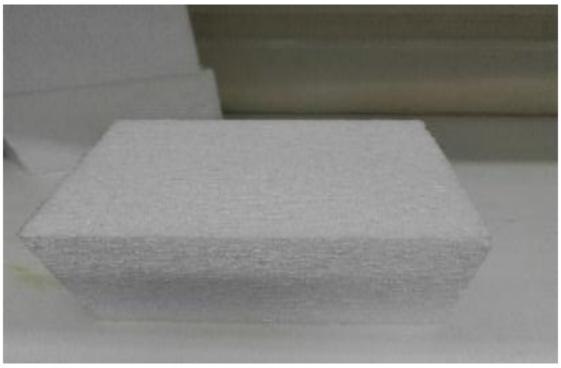

Figure 7. EPS specimen prepared for compression test

The mean modulus of unmodified EPS was found to be 12.56 MPa whereas the mean modulus for conventional materials such as clay bricks is 578 MPa (Fig. 8). Although the recommended thickness for the construction of EPS dome houses using modified EPS is 17.5 cm [7], but from the compressive strength test it is evident that the thickness of EPS dome houses using unmodified EPS would need to be extended to at least 25 cm in order to increase the compressive strength of the dwelling.

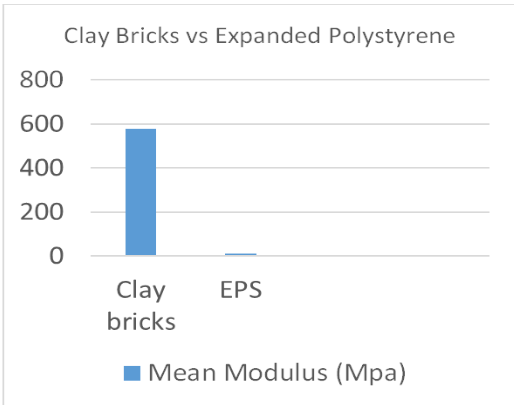

Figure 8. Clay brick versus expanded polystyrene bar graph

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B. Thermal Stability

Reference [21] suggests that clay bricks can resist deformation for a total time of 240 minutes at maximum temperatures of between 1000 ℃ and 1200 ℃. These are remarkable feats in the building industry as the figures demonstrate resilience and reliability.

The Thermal Stability test for EPS was conducted in line with ASTM E 2550-07. The equipment used for the thermogravimetric analysis was the TGA Q500 (Fig. 9 and 10).

Figure 9. TGA Q500

Figure 10. Samples being loaded into heat furnace

The below thermogravimetric graph (Fig. 11) was generated using the TGA Q500.

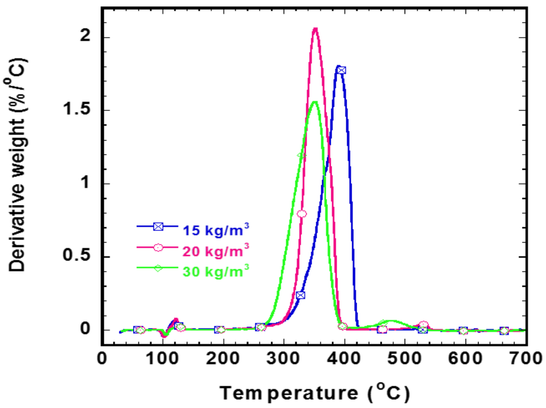

Figure 11. Thermogravimetric graph showing the derivative weight vs the temperature

It is evident from the linear trend of each density in Fig. 11 that as the density increases, the maximum degradation decreases. This is contrary to what would naturally be expected. A natural assumption would be that the higher the density, the lower the susceptibility to being consumed by fire. Fires range up to values in excess of 1000 ℃ [22].

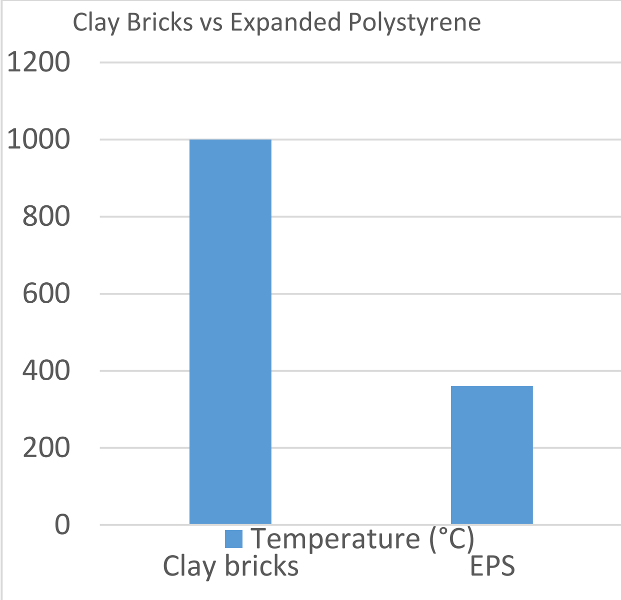

Figure 12. Clay brick vs Expanded Polystyrene temperature bar graph

The degradation value of EPS is 360,08 ℃ whereas that of conventional materials such as clay bricks is 1000 ℃ (Fig. 12). This suggests that the natural face of unmodified EPS would need to be reinforced with a clad layer on the outside surface in order to increase its resistance to heat, and also to off-set its degradation value to a greater value. Data from the thermogravimetric analysis shows that if EPS is exposed to temperatures in excess of 300 ℃ it begins to soften and melt.

C. Flexural Strength

Flexural strength is also frequently referred to as the modulus of rupture. Flexure reveals the stress in a material before it yields during a flexural test. During the flexural test, a rectangular cross section is placed as a simple beam under centre loading in order to determine its breaking load and therefore it’s flexural strength.

During the laboratory investigation, it was found that the differences in the modulus of rupture from a higher density of unmodified EPS to a lower density was significantly large. The difference from the lowest modulus of 30 kg/m3 to the lowest modulus of 20 kg/m3 was 15.81683 Mpa. The differences between the lowest modulus of 20 kg/m3 to 15 kg/m3 was 2.95991 Mpa. The average value of the modulus of rupture for clay bricks was calculated by Shodhganga [23] to be 1.185 MPa. The average value of the modulus of rupture for the lowest density of EPS (15kg/m3) was found to be 1.74659 MPa. This demonstrates that the modulus of rupture of EPS is comparable to that of conventional materials such as clay bricks as shown in Fig. 13.

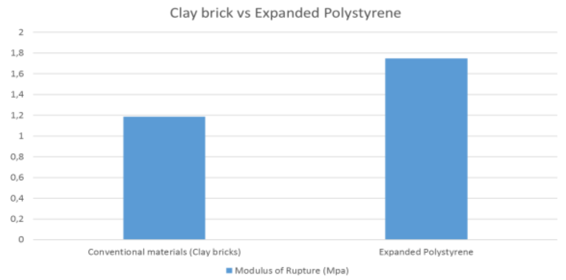

Figure 13. Modulus of rupture bar graph of Clay brick vs Expanded Polystyrene

IV. Conclusion

From the observation of the live model it can be seen that the individual manufacture of similar EPS dome houses as those constructed by commercial suppliers is possible through a hot-wire method. However, from laboratory test results of unmodified EPS, particularly that of thermal stability, it is strongly recommended that EPS always be protected by a facing material, or by complete encapsulation. The data from the Thermogravimetric analysis shows that if EPS is exposed to temperatures in excess of 300 ℃, it begins to soften, to contract and finally to melt. The flexural yield point of EPS bears close resemblance to some aspects of clay bricks. The construction of a live-model as well as the laboratory tests have shown that although improvement is required in terms of efficiency in moulding the EPS components; but the model is viable based on the ease of construction as well as the cost.

V. Recommendations for Further Study

The structure of unmodified EPS was studied under a microscope as shown in Fig. 14 and 15. For the shortcomings identified in unmodified EPS from the laboratory tests such as compressive strength and thermal stability; the void structure of EPS presents some opportunities of further research. Further research may be done in order to strengthen the compressive and thermal qualities of unmodified EPS through the insertion of inexpensive materials such as Bamboo.

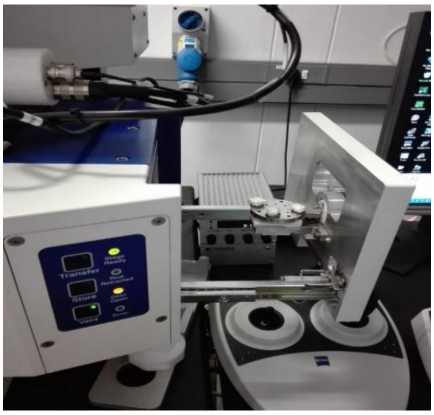

Figure 14. Carl Zeiss Agugiga Cobra fib-fesem control station sample feed

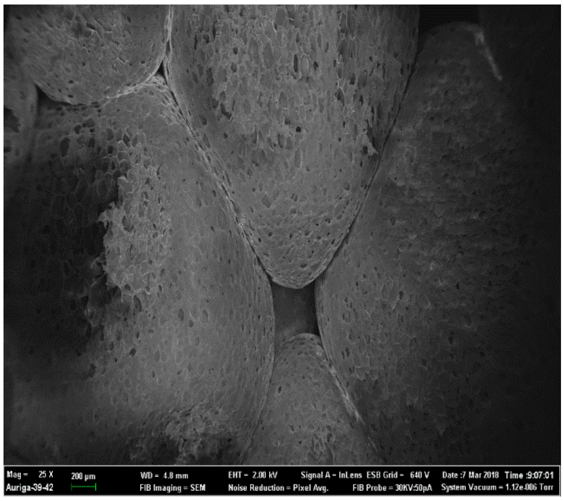

Figure 15. Extent of voids identified in a 30 kg/m3 sample

Bamboo is regarded as a renewable resource that has many economic and environmental benefits. Private companies and governments have begun to promote its commercialisation across Africa because of its potential contribution to sustainable development [24].

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Mr Bonke Mncwango conducted the research. Prof. Allopi assisted with the analysis of the data. Mr Bonke Mncwango wrote the paper and Prof. Allopi assisted with the editing of the written paper. All authors approved the final version.

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