Innovative technologies of waste recycling with production of high performance panels

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Abstract

The use of waste materials within the construction industry has been studied in an attempt to reduce the nuisance of waste disposal and recycling these wastes into sustainable engineering products. Sawmill dust bonded with polystyrene waste as the binder are being considered in producing wall panels that would exhibit improved physical and mechanical properties. A measured volume of polystyrene waste binder was mixed with a known quantity of sawmill dust to produce sawmill-dust-polystyrene composite. Test specimens were then produced from the various composites which were used to perform flexural, tensile and water absorption tests. The samples were left to cure in room temperature for 12 days and 28 days. The results obtained showed that the composition of 60% sawdust 40% polystyrene slurry was the optimum composition yielding the highest tensile and flexural strength, with desirable water absorption properties when compared to some of the manufactured wood samples (particle Board and Plywood). It was also noted that the strength of the composite increased with curing time. Therefore the use of Sawmill dust bonded with polystyrene waste adhesive introduces a sustainable approach on reducing pollution caused by sawdust and polystyrene wastes.

Keywords
Sawmill Dust; polystyrene waste; flexural properties; tensile strength; water absorption

1.0 Introduction

Waste management is the collection, transportation, processing, recycling or disposal, and monitoring of waste materials after their service life. Proper waste management is essential to preserve our environment as well as it reduces the harmful effects that waste has on our health. According to Erik *et al* (2013) a general problem regarding recycling is that recycled plastics may contain brominated flame retardants and pigments or stabilisers based on heavy metals (lead, cadmium) additives or blowing agents such as Chlorofluorocarbons (CFC) gases. Expanded Polystyrene (EPS) is a lightweight cellular plastics material consisting of fine spherical shaped particles which are comprised of about 2% solid mass and 98% air. Therefore, EPS has good sound and thermal insulation characteristics as well as impact resistance (Cook, 1983). EPS is a voluminous lightweight material; therefore the disposal of EPS in landfills will require a large of space for only a small mass which has detrimental effects especially in small islands in the Caribbean such as Trinidad and Tobago, where the rate of EPS wastes have annually increased while the price for land remains high for waste disposal.

As early as 1998 researchers such as Noguchi *et al.*, (1998) studied the recycling of polystyrene by shrinking it to $1/20^{th}$ its original size using a natural solvent limonene, However it was found that limonene would not be in a sufficient supply due to its high demand and it is very costly. The construction industry consumes a large amount of raw materials, hence alternative recycled materials and construction techniques can be implemented in an attempt to spawn a sustainable approach (Treloar *et al*, 2003) and (Horvath, 2004). Sustainable approach such as recycling of the solid plastic wastes as well as timber wastes such as sawdust would hence bring fort a reduction in the consumption of energy and pollution whilst maintaining high quality structural characteristics. Sawdust or wood dust is a by-product or waste product of woodworking operations such as sawing, milling, planning, routing, drilling and sanding. According Harkin, (1961) sawdust can be used as fuel, wood-base boards as well as chemical uses.

The possibilities of using cementing materials to create a composite material has been studied by many researchers such as Del Menezzi *et al.* 2007) who investigated the production of a medium density wood cement boards (wood-base board) by using oriented strands and silica fume. According to Sridah and Prompunjai, (2010), polystyrene has van der Waals forces between its polymer chains which may consist of thousands of hydrocarbon atoms, making the attractive force very high, hence polystyrene may tend to contribute flexural properties of the composites developed from them with the increased physical properties due to the polymeric nature of the polystyrene. Other researchers such as Okoroafor *et al.,* (2017) studied the structural characteristics of Sawdust-Sand-Cement Composite. Most of the literature reviewed showed that the Sawdust-Sand-Cement Composite dominated as effective method of disposing polystyrene wastes. Concrete's production, use and disposal cause a significant amount of pollution. However the use of Ordinary Portland Cement (OPC) has number of negative effects in our natural and built environment. The potential for the use of Polystyrene wastes as substitute for OPC to create Saw-Mill-Polystyrene Composite could reduce the environmental impact caused by both OPC and Polystyrene wastes.
In this paper, the combination of the sawmill dust and Polystyrene Waste Adhesive (PWA) is being considered in an attempt to produce wall panels. In which the sawmill dust is being used as the filler material whilst the Polystyrene Waste Adhesive (PWA) is used as the bonding agent. The use of the Sawmill dust and polystyrene waste as a construction material will help in the reduction of the quantity of polystyrene wastes in the environment and would reduce the amount of incineration and disposal therefore resulting in a decrease in pollution. Thus this approach to the development of wall panels using Sawmill dust and Polystyrene Waste Adhesive (PWA) is a good idea, as the materials are readily available and cheap, and the production process requires minimum skill levels. However its structural properties and its suitability for the required use must be evaluated.

The aim of this study was to determine the suitability of Sawmill dust bonded by a Polystyrene Wastes Adhesive (PWA) to be used for a structural application of wall panels in an attempt to reduce pollution and therefore encourage sustainability. Since the composite would be used as a construction material, that of namely wall panels, they would be subjected to tension, flexural and bending challenges when loads are applied to them and since these materials are likely to come into contact with water, therefore tensional, flexural and water absorptivity tests will be determined.

2.0 Literature Review

2.1 Theory on applications of supercritical fluids for the densification and manufacturing of the EPS slurry

According to Goodship and Ogur, (2000) a supercritical fluid (SCF) is a substance (liquid or gas) which is in a state above its critical temperature (Tc) and critical pressure (Pc). As demonstrated further by Goodship and Ogur(2000) , at this critical point, both liquids and gases coexist, exhibiting unique properties that are different from those of either liquids or gases under standard conditions .According to Laitinen, (2000) a SCF gives unusual properties, for example a viscosity like that of a gas, a density like that of a liquid, and a diffusion coefficient that lies between that of gas and liquid. In addition SCF possesses no surface tension hence no capillary forces therefore SCF having gaseous property that could easily penetrate porous and fibrous solids and the liquid property that could dissolve materials into their components hence chemically densifying them. As suggested by Noguchi *et al.,* (1998) as well as US EPA, (2012), chemical densification has recently gained popularity due to reduced waste management cost, energy and other environmental impacts such as pollutions and gaseous emissions. The choice of SCF for densification of wastes involves many factors, such as evaporation rate, solution viscosity, environmental and health hazards, and the effectiveness of a solvent ability to adequately dissolve one material while leaving other materials unaffected. Moroka, (2004) proposed the use of Methyl methacrylate (MMA) solution in dissolution of plastics as method of recycling plastic wastes, however, it was noted that the manufacturing of MMA is based on the reaction of hydrogen cyanide (HCN) and acetone to give acetone cyanohydrin. The cyanohydrin then undergoes acid assisted hydrolysis and esterification with methanol to give MMA. The toxicity caused by HCN compound poses a threat to humans and the environment. Other authors such as Turk and Yuengert (2006) investigated possible methods of controlling the pollution caused by polystyrene wastes using 12 solvents having a similar molecular structure to that of the styrene monomer. They recorded initial and final masses of both the solvent and the EPS. The results regarding percent mass change showed that the EPS absorbed large amounts of solvent over the course of dissolution. Xylene (the quickest), lemon oil, turpentine, and camphor oil completely dissolved all grades of EPS. The exceptions to the above patterns were water (the control, which had no effect on EPS), acetone, and diluted acetone. These authors observed an unexplained discrepancy between the initial and final masses of their solutions, and large bubbles appeared when EPS was in contact with these solvents. However these authors did not identified the gas emitted. García et al (2007) pointed out that the dissolution of polymeric wastes with suitable solvents is one of the cheapest and more efficient processes for polystyrene waste management. The authors investigated the solubility of polystyrene foams in several solvents benzene, toluene, xylene, tetrahydrofuran, chloroform, 1,3-butanediol, 2-butanol, linalool, geraniol, *d*-limonene, *p*-cymene, terpinene, phellandrene, terpineol, menthol, eucalyptol, cinnamaldheyde, nitrobenzene, and *N,N*-dimethylformamide. However, most of these solvents (such as benzene, toluene, xylene, chloroform and tetrahyd rofuran) are carcinogenic. It was also found that a renewable solvent such as the terpenic (limonene and cymene) would have high capacity to dissolve the polystyrene, however, the use of the natural solvent like Limonene is quite effective as it is a renewable solvent. According to (Harvey et al., 2007) Limonene is a clear, colourless liquid hydrocarbon classified as a cyclic monoterpene, and is the major component in oil of citrus fruit peels. According to Renniger and McPhee, (2010) terpenes have niche to serve as advanced biofuel precursors and is being pursued as an alternative biosynthetic diesel in the market Therefore there is concerns of the availability of this natural solvent. Mwasha (2011) investigated ways in which polystyrene waste could be easily disposed and densified in Small Caribbean Island where the land for waste disposal is critical. Mwasha *et al.,* (2013) found that, by using a super critical solvent the polystyrene waste can easily break down into smaller less bulky materials and hence reduce waste management cost, energy and other environment impacts such as pollution. These authors pointed out that the dissolution of polymeric wastes with suitable solvents is one of the cheapest and more efficient processes for polystyrene waste management. Upon conducting the experiment it was observed that 1000 litres of polystyrene pebbles were fully dissolved by 30 litres acetone to produce 15 litres of EPS-Acetone slurry. Thus using this method of waste disposal the volume of polystyrene waste reduced to 98.5%, in which a pliable solid was formed upon the change in viscosity, when the acetone vaporized this slurry turned to solid glue-like mass. This process was used as the basis of developing the Polystyrene Waste Adhesive (PWA). Besides densification, these dissolved and densified wastes could be used to manufacture new materials such as composite boards.

2.2 Manufacturing of the composite boards using wood saw dusts and polymeric slurry

Price, (1972), investigated a method of making a composite board product from scrap materials such as paper, paperboard, plastic and aggregates and compressed them under heat and pressure to form a composite board. This method is quite effective as the fibrous components of the paper is encapsulated with the plastic hence producing a high solvent and wear resistant composite board, which are suitable for applications as floor tiles, wall panels and counter tops. However this method uses heat energy and pressure. The densification of polystyrene was conducted by Noguchi et al., (1998). In their experiment, a natural solvent limonene was used to shrink the polystyrene waste into $1/20^{th}$ of its original size.

Fakhrul et al., (2013) carried out an investigation on the properties of wood sawdust and wheat flour reinforced polypropylene composites. From the research it showed that the wheat flour composites exhibited higher yield strengths, young's modulus and flexural modulus than that of wood sawdust composites. Upon examination of the fractures surfaces it was seen revealed the presence of micro voids as a results of weak filler matrix interfacial adhesion. Therefore it was determined that the addition of wheat flour and Sawdust to the Polypropylene altered its mechanical and physical properties considerably whilst the thermal properties of the both composites were significantly increase. Other researchers such as Okoro, Oladele, and Omotoyinbo, (2015) carried out a research to develop a composite that would have structural applications such as ceilings and partitioning boards. This was done using rattan particulate reinforced paper pulp where the paper pulp was obtained by chopping waste papers into smaller pieces and boiling it, while the rattan canes was beaten, chopped and milled to produce the rattan particulate. Varying masses of the rattan particle and paper pulp was then mixed and bonded using natural rubber. The mixtures were then compacted in a mould and allowed to cure. Flexural and water absorptivity tests were then carried out. The increase in natural rubber decreases the amount of water absorbed by the composites. Following year Oladele and Afolabib, (2016) studied the combination of brown paper pulp with that of natural rubber composites to be used in structural applications. Natural rubber was used as the bonding agent to bind the pulverized brown paper pulp. Various volumes of natural rubber were mixed with fixed amounts of pulverized brown paper pulp that were compacted in a mould and allowed to cure for 27 days. The flexural property tests along with water absorptivity tests was conducted in each sample and the best result of flexural properties was found to be 70 % brown paper pulp 30% natural rubber. Upon addition of rubber below 10% it was deemed to have too little material to aid proper wetting and bonding whilst over 35% was too much and give a higher ductility. The sample with 60-40% emerged as the best composition for water absorption, which also showed that as the natural rubber content increased, the rate of diffusion of water molecule within the pores of the paper-pulp composites decreased significantly. Hence the rubber was effectively used as a binder for brown paper-pulp composite materials and these materials could be blended together to develop strong, cheap and lightweight materials for structural applications. Natural rubber is renewable resource that would need to be in a steady supply and upon disposal would contribute to harmful effects to the environment. Recently Okoroafor et al., (2017) studied the structural characteristics of Sawdust-Sand-Cement Composites which was deemed at addressing the problem of the absence of structural characteristics of Sawdust-sand-cement composites. There nine cubes of size 150mm x 150mm x 150mm, nine (9) cylinders of size 150mm x 300mm and nine (9) beams of size 150mm x 150mm x 600mm were produced from different mix ratios and was tested for compressive strength, split tensile strength and flexural strength respectively. In this literature review, various articles that were done in different aspects of this research, and were examined paying close attention to the factors of which the uses of different material composites and different solvents would contribute to different structural characteristics as well as the integrated developmental focus of sustainability and reducing the quantity of polystyrene and sawdust waste.

3.0 Materials and Equipment

For this research the main materials used were sawdust waste, polystyrene wastes and supercritical fluid (Acetone). The Acetone used in this paper was manufactured by J.T. Baker Soluso RB in USA. Recently as discussed by Mwasha et al (2013), the production of Acetone using abundant supply of cellulose and hemicellulose in Domestic Organic Waste (DOW) in developing world has been introduced by Pieternel at el (2000) and López-Contrera et al (2004). The sawdust was obtained from a wood factory located in Caroni in which the sawdust retained by the #200 sieve was processed as suggested by Verma *et.al*. (2017).

The main equipment used in this study was Tinius Olsen Tensometer, Electronic Balance and oven.

4.0 Sampling

Production of polystyrene slurry was conducted as was suggested by (Mwasha et al, 2013).

4.1 Preparation of samples

The procedure that was carried out in order to obtain the samples for testing was as follows:

1. A known quantity of the polystyrene slurry (using the ratio of 1000 litres of polystyrene beads to 30 litres of acetone giving 15 litres of polystyrene slurry according to Mwasha et al, 2013) was mixed with known quantities of sawmill dust to produce ratios of compositions by trial and error.
2. Upon the trial and error the mixing proportion of sawdust: polystyrene slurry is shown in table 1. At “D” the sample had lowest workability while the sample at “D” had highest consistency

Table 1: The various compositions obtained by the trial and error

Compositions/Samples	A	B	C	D
Sawdust %	60	55	50	45
Polystyrene wastes %	40	45	50	55

3. Each composition was then placed in molds and left to cure in air at room temperature for 12 days.
4. Upon curing the compositions were detached and cut into test specimens.
5. Another test specimen from each composition was left to further cure for an additional 16 days.
6. Property tests of tensile, flexure and water absorption tests were performed at the 12 days for each of the compositions, followed by a 28 day tensile test.
7. The results obtained were then compared to the results obtained from using particle board with for the same property tests of tensile, flexure and water absorption.

Figure 1: The EPS and acetone slurry

Figure 2: The Sawmill dust waste

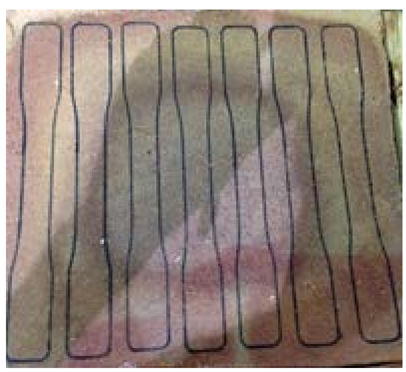

Figure 3: The composite in the mold to be cut out into the test specimen

5.0 Tests

Since the composite would be used as a construction material i.e. wall panels. These panels would be subjected to tensional, flexural and bending challenges when loads are applied to them. Since for the materials purpose, it is likely to come into contact with water as a building material, water absorptivity tests were important, to determine the extent of water absorption.

5.1. Tensile Test

The tensile test was carried out using the Olsen Tensometer in accordance with ASTM D3500

5.2 Flexural Test

The flexural test was also carried out using the Olsen Tensometer according with the ASTM D3043

5.3 Water Absorption Test

The water absorption test was done to determine the extent to which the formed composites can absorb water. For this test the composites were weighed in air using an electronic balance and then immersed in $1000cm^3$ of water. This test was carried out for six hours as every hour the composite was removed cleaned and then weighed again, the water absorption capacity as then determined using the ASTM D 570 in which the following formula 1 was used.

% water absorption = eq. 1

6.0 Results and discussion

6.1 Tensile Test 12 Days

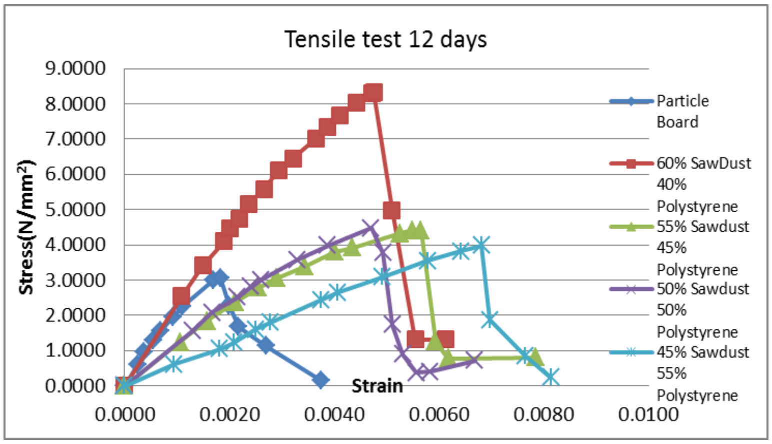

Figure 4: The graph of stress vs strain for the tensile test of 12 days

The compositions underwent various tests, the first of which was that of a 12 day tensile testing. From the results obtained and from in figure 4, it was noted that the 60 % Sawmill dust, 40% Polystyrene waste adhesive comprised of the highest tensile strength of $8.355N/mm^{-2}$, whilst the 45 % Sawmill Dust 55% Polystyrene had the lowest tensile strength of $3,980N/mm^{-2}$ of the four compositions. It was noted that the tensile strength of the composites increased as the amount of sawmill dust increased while the addition of more polystyrene the ductility of the material increased. The 45/55 composition was seen to have the greatest extension before breaking however it required very little stress as compared to that of the 60/40 composition in which a high stress was required to cause deformation and thus leading to failure.

6.2 Tensile Test 28 Days

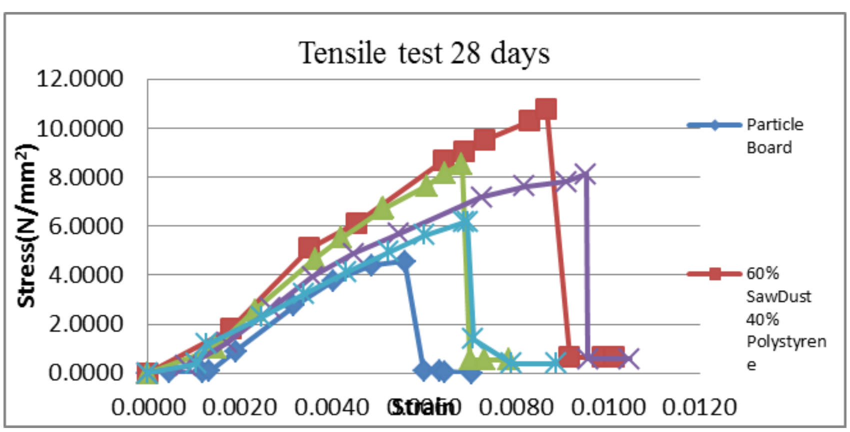

Figure 5: The graph of stress vs strain for the tensile test of 28 days

For 28 day tensile test, the results obtained are shown in Figure 5. It was observed that, the 60/40 composition had the highest tensile stress of 10.735N/mm^{-2} as compared to the 12 day tensile test where a value of 8.355 N/mm^{-2} was obtained. Since all the stresses for the 28 day tensile test increased from those of the 12 day tensile test, it suggested that with increasing curing time the strength of the compositions increased.

6.3 Flexural test 12 days

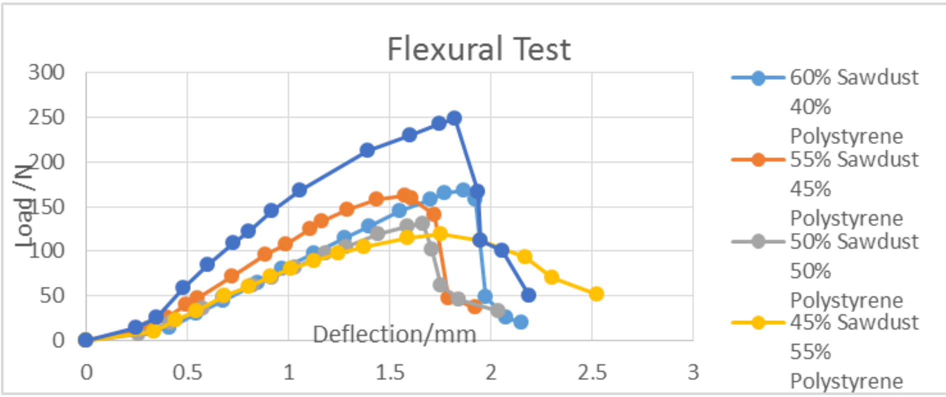

Figure 6: Load/N against Deflection/mm for the Flexural Test 12 days

A 12 day flexural test was also done on the samples, obtaining results of load and deflection as shown in Figure 6. From these results it was seen that the 60/40 composition required the highest load of 168.7N and the highest deflection of 1.869mm, whilst the 45/55 composition required the lowest load of 119.15N with a deflection of 1.751mm. The bending strength at the peak results for the samples were determine, also called the Modulus of rupture in which the 60/40 composition had the highest modulus of rupture 830.13N/m^{-2} whilst the 45/55 composition had the lowest modulus of rupture of 193.85N/m^{-2}. The flexural strength was seen to increase with the increased amount of wood content as expected, in which although plastics have great ductility and bending properties the stresses required to cause the bending is little as compared to that required to bend the timber by product. Wood may tend to bow down due to the stresses but requires a high stress to cause the actual breaking

From the data obtained above the Modulus of Rupture for each composition is shown in figure 7.

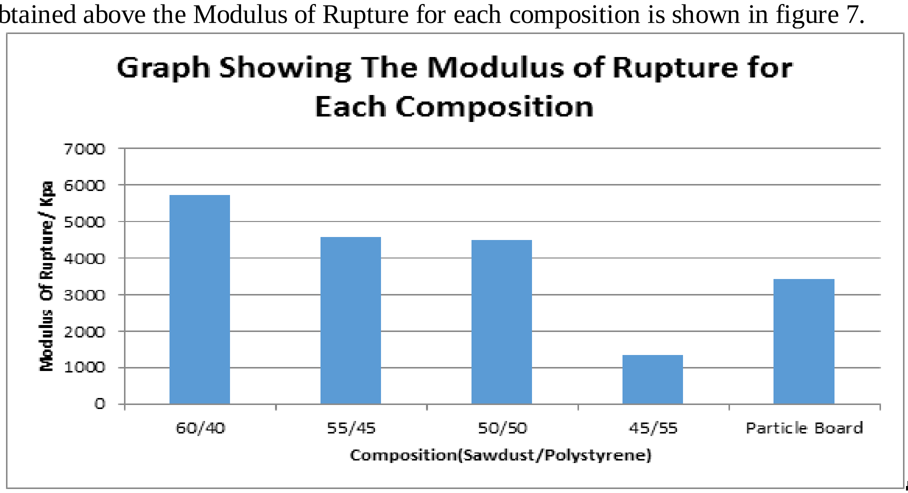

Figure 7: The modulus of rupture of the various compositions

6.4 Water Absorption Test 12 days

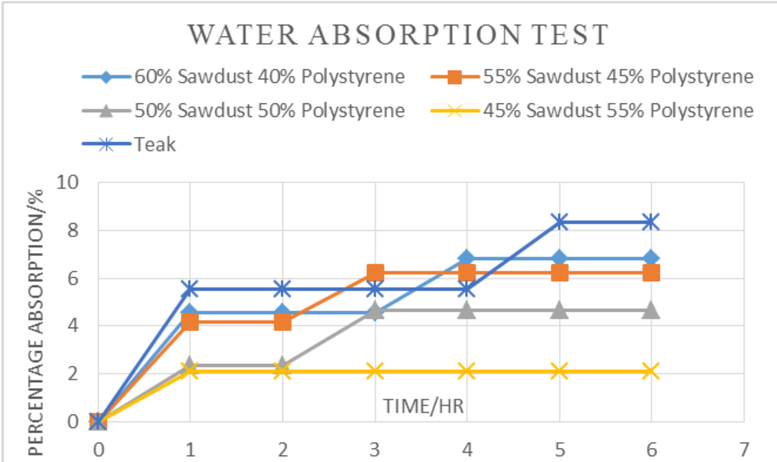

Figure 8: The results obtained for the different compositions as well as teak wood sample from the Water Absorption test

On observing the water absorption of the samples in figure 8, it was found that, on increasing the amount of polystyrene waste, the level of water absorption decreases, while the increased amount of sawmill dust increased the levels of absorption. The results obtained showed that for the 6 hour period the 60/40 composition absorbed 6.82% water as compared to the 45/55 composition 2.08%. The water absorption between the ratios of the sawmill dust and the polystyrene waste can be explained by the differences in water absorption between wood and plastics. The water absorption in the composites therefore is mainly due to the presence of lumens, fine pores and hydrogen bonding sites in the wood and the gaps and flaws at the interfaces. However by the addition of the plastic it reduces the rate of diffusion of water molecules in gaps and pores within the sawmill dust therefore reducing the water absorption. On comparing with natural timber (Teak) it was found that Teak absorbed 20% more water compared with samples with composition 60% sawdust40% Polystyrene wastes. As was expected, the lowest water absorption was recorded for the samples composition 45% sawdust 55% Polystyrene wastes.

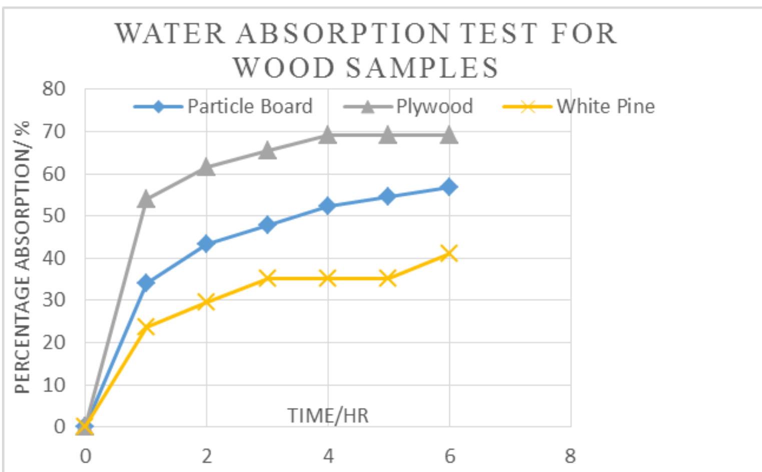

Figure 9: The water absorption test for three wood samples

In order to compare the water absorption of the commonly used manufactured wood, the particle board and plywood were tested for water absorption. As shown in Figure 9 it was found that plywood boards and particle boards absorbed a lot of water 70% and 58% respectfully. It was also observed that natural timber “white pine” absorbed 41%. On comparing with sawdust 60%–polystyrene 40% composite, it was found that plywood absorbed more that

700% and particle board 600%.of the moisture content. On comparing with the soft wood "Pine" it was found that pine wood absorbed 400% more moisture as compared to sawdust 60%–polystyrene 40% composite. Similar results were observed by Rodolfo de Melo et al. (2014) who suggested the highest percentages of water absorption for these plywood and the particleboards can be related to the high content of silica and to the lower content of lignin present. On comparing with saw-mill polystyrene composite which had chemical constituents with hydrophilic materials such as plastics and lignin the water absorption was low.

7.0 Conclusion

This paper was done for the purpose of reducing and recycling Polystyrene and sawdust wastes by combining them to form a composite for the use of a structural application of wall panels. The polystyrene wastes adhesive was combined with the sawdust by trial and error in which four compositions were developed. The developed composites were investigated for its physical and mechanical properties. From the 12 day tensile test the composition of 60% Sawdust 40% Polystyrene yields the highest Tensile strength of 8.355 N/mm^{-2}, whilst the 45 % Sawmill Dust 55% Polystyrene had the lowest tensile strength of 3.980 N/mm^{-2} of the four compositions. The next test done was that of Flexure where the 60/40 composition had the highest modulus of rupture 5723.55 KPa whilst the 45/55 composition had the lowest modulus of rupture of 1336.55KPa. With the water absorption test it was observed that with increasing polystyrene waste content the water absorption decreased.
These findings suggest that the 60 % Sawdust 40% Polystyrene wastes adhesive is the optimum composition and upon comparison with that of a manufactured wood, particle board it came out as being superior. As a result of conducting this research, I propose that the combination of the Sawdust and the polystyrene waste would be able to serve as wall panels more effectively than the manufactured board, reducing and recycling the waste of polystyrene and sawdust as well as the pollution cause by its large quantity in the environment and society.

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ASTM D 570 – 98 Standard Test Method for Water Absorption of Plastics1
ASTM D3043 – Structural Panels in Flexure
ASTM D3500 – Structural Panels in Tension

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