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Comparative Evaluation of Mechanical Properties, Scanning Electron Microscopy (SEM) Analysis, and Water Holding Capacity of Recycled and Virgin High-Density Polyethylene (HDPE) Plastics: A Study on the Morphological and Physical Characteristics of Thermoplastic Materials

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Abstract

Municipal solid waste management when poorly done serves as a breeding ground for pathogens which cause loss of arable land and diseases directly or indirectly. In a bid to combat the geometrical increase in waste conditioned by the subsequent increase in human population, recycling has become a solution. One major throwback to recycling is the belief that due to the thermal decomposition of plastic, the recycled product would have different properties from that of the original plastic product hence rendering its suitability for use in production invalid. This research evaluated the recycling process of High Density Polyethylene (HDPE) plastic and carried out mechanical property characterization tests which included tensile test, hardness test and impact test on the recycled HDPE product. 200g of HDPE plastic was used as specimen melted in a furnace and poured into a wooden mold to cool. The cooled material was subjected to tensile, impact and hardness tests. The test exposed that the Rockwell Hardness Number (RHN) for the examined HDPE material was given as 50.0mm. The tensile test was evaluated to be 25.60MPa. The sample had an impact test value of 284J/m^2. It was also determined that the sample had a yield strength of 21.412MPa. The mechanical properties of hardness number, tensile strength, impact strength and yield stress of an original un-recycled HDPE plastic material are given respectively as (60.0-70.0mm), (21.4–30.3)MPa, (158–505 J/m2) and (17.9–31.0)MPa respectively. The water absorption test revealed that the % absorption from the virgin and recycled HDPE plastics were 0.015% and 0.027% respectively. The high value of the recycled HDPE owing to the presence of additives and impurities. Comparison of these properties between un-recycled (virgin) and recycled HDPE plastic show that the values gotten are within the acceptable range and hence, recycled HDPE plastic is very suitable for use in production as its mechanical characteristics are similar to that of un-recycled HDPE plastic.

Keywords: Municipal solid waste, Recycling, High density polyethylene plastic, Tensile test, Impact strength, Rockwell hardness number.

1 | Introduction

Municipal solid waste is unwanted material generated in residential areas. The quantity of such material has increased geometrically over the last few years due to the spiralling increment of population sizes and

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urbanisation [1]. These "urbanised waste" constitute to the propagation of disease vectors and environmental decadence. This is because more and more arable land has been converted to dump sites. So doing, we are forgoing land that would have been used for agricultural or residential purposes to be used as dump sites [2]. There are various types of municipal solid waste. They include: food waste, tin cans, paper, plastics and bottles. Regardless of the nature of recycled waste, they still constitute hazard. Recent trend has seen the recycling of these MSW. Recycling aids in reducing pollution and enhances a healthier environment [3].

Polymers, or also known as plastics, are a major class of materials and possess a very wide range of mechanical, physical, chemical, and optical properties. Unlike metals, polymers generally are characterized by a lower density, strength, elastic modulus, thermal and electrical conductivity, and cost [4]. Also, by a higher strength-to- weight ratio, higher resistance to corrosion, higher thermal expansion, wider choice of colours and transparencies; and by a greater ease of manufacture into complex shapes [5]. Hence, plastics are been used mostly in agriculture, appliances, clothing, construction and numerous other fields which required their existence.

The most common polymer that has been used for industrial and commercial products nowadays is High Density Polyethylene (HDPE) [6]. HDPE is one of basic types under Polyethylene (PE) polymer. It is a thermoplastic polymer; meaning that it can be melted to a liquid and remoulded it to a solid state. It is tough, relatively inexpensive and has excellent process ability. It is used in numerous applications ranging from plastic grocery bags to heavy duty plastics containers. Moreover, HDPE also it has widely been used in construction industry for producing pipes and as insulator in electrical appliances [7]. The use of HDPE plastics has increased greatly during the last decade due to the advantages mentioned above, both in areas of applications and in actual quantities employed. However, improper and uncontrolled plastics production and consumption causes wastes, which eventually causes loss to certain companies and also lead to pollution to environment [8]. In addition, because HDPE plastics are composed of organic compounds, their main disadvantage is that their decay process takes a very long time [9].

1.1 | Statement of the Research Problem

The high rate of destruction of plastic waste is very alarming. In 2015 alone, it is estimated that a total of 80% of plastic wastes were destroyed while only 20% were recycled. The destroyed plastic waste constituted pollution to the atmosphere and took space that would have been used for agricultural purposes [10]. Hence it can be seen that the 80% of plastic waste destroyed constituted a loss as they could have been recycled and sold there by increasing revenue generation and reducing unemployment. To this end it can be categorically stated that plastic recycling is a gold mine which should be tapped.

Paramount in the recycling process of plastic is to ensure that the resulting material has mechanical properties which can compete favourably with other counterpart materials in the construction industry [11]. To this end, this research aims at determining the mechanical properties of recycled HDPE plastics with the aim of carrying our performance assessment on the recycles.

1.2 | Objectives of the Study

The main objective of this research is to study HDPE plastic recycles with the aim of evaluating the products by determining their mechanical, morphological as well as water retention properties.

The specific objectives include to:

I. Recycle locally sourced HDPE plastic.

II. Determine the hardness number, impact stress value and tensile stress value of the recycled HDPE plastic.

III. Investigate the surface morphology of the recycled and virgin HDPE plastic.

IV. Investigate the water retention capacity of the recycled and virgin HDPE plastic.

V. Determine the suitability for use of recycled HDPE plastic in production.

VI. Compare the mechanical properties, morphological and water retention properties of recycled HDPE plastic determined with that of virgin HDPE plastic.

2 | Methodology

In this project, there are seven major stages that have been involved. They were:

I. Mould design.

II. Recycled material preparation.

III. Material melting process.

IV. Material mixing.

V. Compression moulding process.

VI. Sample testing process.

VII. Data analysis.

The flow of process for this project is illustrated in a methodology flow chart (see *Fig. 1*). Flowchart is a visual representation of the sequence of the project. The flowchart shown will give the whole picture of this project from the initial step until the final step.

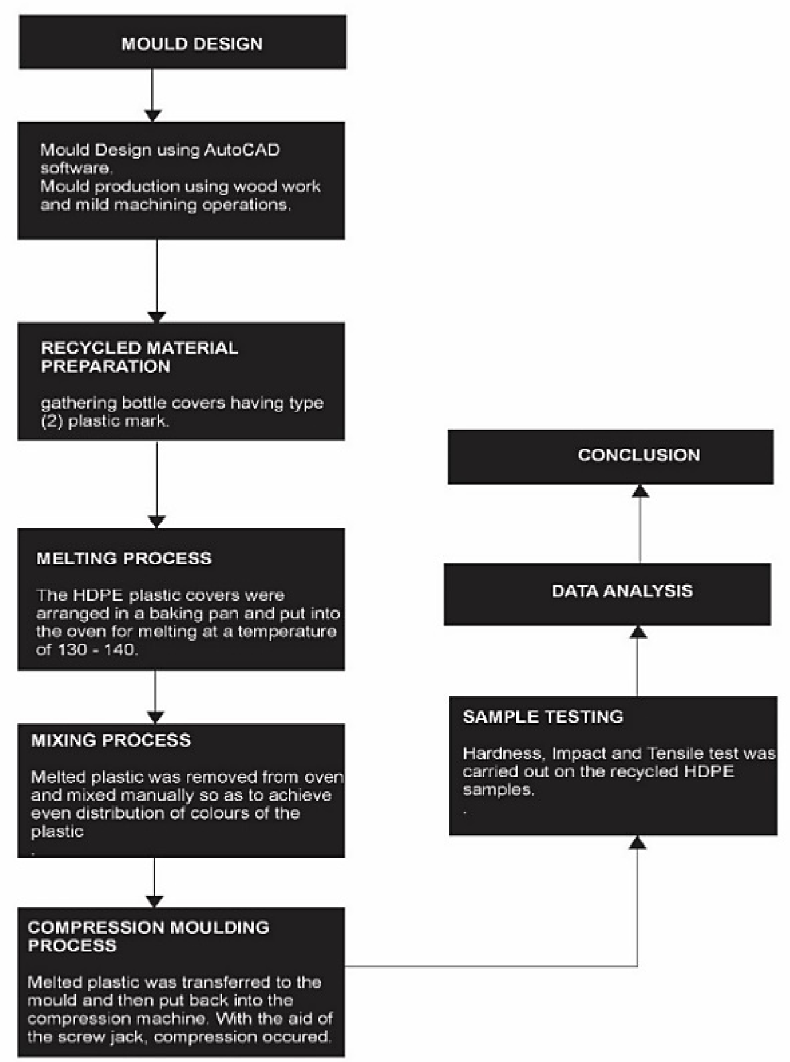

Fig. 1. Flowchart that illustrate on experimental methodology.

2.1 | Mould Design

The mould was first designed in 2D and 3D drawing by using AutoCAD software. After confirming the design and the dimensions, the mould then was machined through woodwork machining operations, such as roughing, drilling and other operations needed. Next, the assembled wooden mould will be put in the compression moulding machine that will be compressed later with the aid of a screw jack in order to obtain recycled material. The mould was designed in such a manner as to aid in accomplishing the scope of the research. The mould was made of wood. Its function is to ensure that the melted plastic occupies a specific shape. Below is a picture of such mould in *Figs. 2-4*.

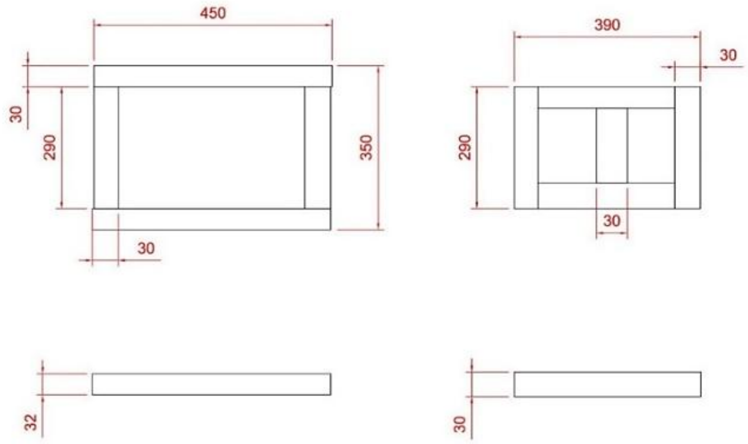

Fig. 2. Schematic of mould in (mm).

Fig. 3. 3D render of plastic mould.

Fig. 4. Real constructed plastic mould.

2.2 | Recycled Material Preparation

Raw material (pure HDPE)

The material selected for this project was HDPE. HDPE material was gotten from the gathering and accumulation of waste bottle covers having the type 2 plastic mark. These are shown in *Fig. 5*.

Fig. 5. Type 2 HDPE plastic.

Recycled HDPE materials were obtained from the melting of HDPE plastic covers in an oven inside the compression moulding machine to get a semi molten plastic material form. After that, the recycled materials of HDPE were transferred to the mould and manually put back into the machine where it was lifted up to the top by rotating the handle of the screw jack. Hence, the material in the mould was compressed. This involves all processes from start to finish in the conversion from used plastic to a proper recycled product. These processes include the below listed:

I. Sorting/selection.

II. Preliminary material preparation.

III. Classification.

High quality HDPE plastic was obtained and the selection criteria was based on the cleanliness of the specimen. This criteria was chosen so as to reduce the amount of impurity introduced into the melting process which would result in the increment of the melting point of the entire system. In *Fig. 6* is a picture of the sample specimen selected for the recycling process.

Fig. 6. Plastic samples selected for recycling.

This material was gotten after a rigorous process of sorting.

2.2.1 | Material processing

This process involved the recycling process. Here, the plastic samples were divided into different stages discussed below. These being:

I. Weighing used (waste) plastic specimens.

II. Preparing sample for melting.

III. Melting specimen.

IV. Compression moulding of the specimen.

2.2.2 | Weighing plastic specimens

In this stage, the sample waste plastic material was carefully selected and weighed. The total weight used per melting process was 10.64 kg.

Calculation to know mass of plastic to be used,

Mass of plastic = Volume x Density.

Where:

Length = 39cm.

Width = 29cm.

Height = 10cm.

Density of HDPE = 0.941 g/cm3.

Mass = 39 x 29 x 10 x 0.941.

Mass = 10642.71g / 10.64kg.

The weight is important as a sample with excess weight would produce a melt too much for the capacity of the mould and hence constitute a loss. This loss is what the entire project seeks to eliminate hence the sample weight. *Fig. 7* shows the sample on a weighing equipment.

Fig. 7. Weighing of waste plastic specimen.

2.2.4 | Preparing sample for melting

In this stage, the sample was prepared for melting. The sorted out HDPE plastic covers were arranged and placed in a baking pan. An aluminium foil was first laid on the pan, the purpose of this is to prevent sticking of the melted plastic material to the baking pan. A silicone lubricant spray was also used to achieve that purpose. *Fig. 8* shows the aluminium foil used prior to melting.

Fig. 8. Aluminium foil used prior to melting.

2.3 | Melting Process

In this stage, the entire specimen in the pan was placed in the oven inside the compression moulding machine and the heat temperature increased gradually with time. The oven is operated by a 220 voltage circuit which is regulated with a PID controller. A type K thermocouple is attached and the PID controller displays the temperature inside oven and temperature set limit, the oven can heat up plastics and melt at a range of 170 – 220c but it was observed that the specimen melts within the range of 130c-140c. *Fig. 9* shows the compression moulding machine used for the melting process.

Fig. 9. Compression moulding machine.

2.4 | Mixing Process

This process involved removing the molten material from the mould and mixing to achieve even coloration and fusion of the melted material. This was done with the use of a wooden stick.

2.5 | Compression Moulding Process

After melting, the hot semi molten plastic was transferred into the mould and lifted up to the top of the machine with the aid of a screw jack after which it was left to solidify. After solidification, the solid recycled material took the shape of the wooden mould and it was machined using a lathe machine to produce finished products such as tiles. The resulting moulded recycled material is shown below in *Figs. 10.a* and *10.b*.

a.

b.

Fig. 10. Recycled plastic materials.

2.6 | Recycled Material Testing

The recycled material will be tested in three conditions being:

I. Tension.

II. Hardness.

III. Impact.

These tests will assist in revealing the mechanical properties of recycled HDPE plastic. The properties observed will be placed side by side with properties of substances like wood and metal to see its suitability when applied in real life manufacturing scenarios.

2.7 | Data Analysis

Evaluation was done on the cooled recycled material to determine its mechanical properties.

3 | Discussion of Data and Results

3.1 | Preparation for Tests

Here, the specimen was cut to shapes to make easy the experimentation process. *Fig. 11* shows the shapes to which the specimen was cut to.

Fig. 11. Prepared plastic recycle for testing.

3.2 | Rockwell Hardness Test

The aim of this test was to determine the Rockwell Hardness Number (RHN) of the given Specimen using "Rockwell Hardness tester". *Fig. 12* shows the test equipment.

Apparatus

I. Rockwell hardness testing machine.

II. Diamond cone indenter, ball indenter.

III. Specimens.

Fig. 12. Rockwell hardness tester.

The samples used for this test are shown in *Fig. 13* and the test set up shown in *Fig. 14*.

Fig. 13. Samples used for hardness test.

Fig. 14. Specimen readied for Rockwell hardness test.

3.2.1 | Procedure used for hardness test

I. Make the specimen clean by removing dust, dirt and grease.

II. Place the specimen securely on the anvil and ensure the load lever is in position a.

III. Note the diameter of the ball and elevate the specimen so that it comes into contact with the indenter and ensure the deflecting meter on the small scale doesn't exceed the red point.

IV. Put specimen under a preliminary load by selecting 60N on the load selector.

V. Move the load lever from position a to position b and wait for at least 15 seconds as the load gradually and automatically applied

VI. Watch the pointer until it comes to rest and read the 'b' hardness scale.

VII. Remove the specimen from the support table and locate the indentation so made.

VIII. View the indentation through microscope and measure the diameter,'d' through the attached micrometre.

IX. Repeat the entire operation three times and record your observations.

3.2.2 | Precaution

I. The specimen should be cleaned properly.

II. Readings must be taken carefully and correctly.

3.2.3 | Result and discussion

For comprehensive data presentation, data was displayed in *Tables 1* and *2*.

Table 1. Test introduction table.

Type of Specimen	Type of Indenter	Scale	Total Load (KgF)
HPVN plastic	Ball (1/8 inches = 3.175mm)	A	60

Table 2. Rockwell testing table.

S/N	Specimen	Type of Indenter	RHN			Average RHN
1	HPVN plastic	Ball	88.5	58.5	80	50
2	HPVN plastic	Ball	70	40	80	50
3	HPVN plastic	Ball	78.8	48.8	80	50

The RHN was discovered to be 50.00mm in average.

3.3 | Impact Test

An impact test usually used to evaluate the brittleness of a material under high strain rates [12]. While tensile stress is normally performed at low strain rate, which can be define that the specimen is very slowly elongated. On the other hand, impact test is subjected material to a sudden, intense blow, in which the strain rate extremely rapid, hence the material may behave in a much more brittle manner than is observed in tensile stress. Whereas, energy required to break the samples per original cross section area is impact strength. The test equipment is shown in *Fig. 15*.

3.3.1 | Component and equipment

I. Pendulum impact tester (Charpy) *Fig. 15*.

II. Vernier caliper *Fig. 16*.

Fig. 15. Charpy impact tester.

Fig. 16. Vernier caliper.

3.3.2 | Procedure used for impact test

I. Ensure all safety guards are in place and the path for swing of pendulum is clear.

II. Label each specimen using punch and hammer.

III. Move the pendulum up to its locked position and ensure that it is locked.

IV. Place the specimen in impact testing device valve in such a way that the notch faces the hammer and is half inside and half above the top surface of the vice.

V. Review safety considerations and release the pendulum using the release mechanism.

VI. Record the read out from the scale.

VII. Pull the handle brake for the pendulum to its locked position.

3.3.3 | Result and discussion

For comprehensive data presentation, data was displayed in *Table 3*, *Fig. 17* shows how these values where gotten and *Fig. 18* shows the graphical representation of the data acquired.

Table 3. Test introduction table.

S/N	Samples	Initial Impact Value, I_1 (J/m)
1	HPDE recycled plastic (A)	286
2	HPDE recycled plastic (B)	282
3	HPDE recycled plastic (C)	284
	Average impact value (J)	284

Fig. 17. Impact test readings.

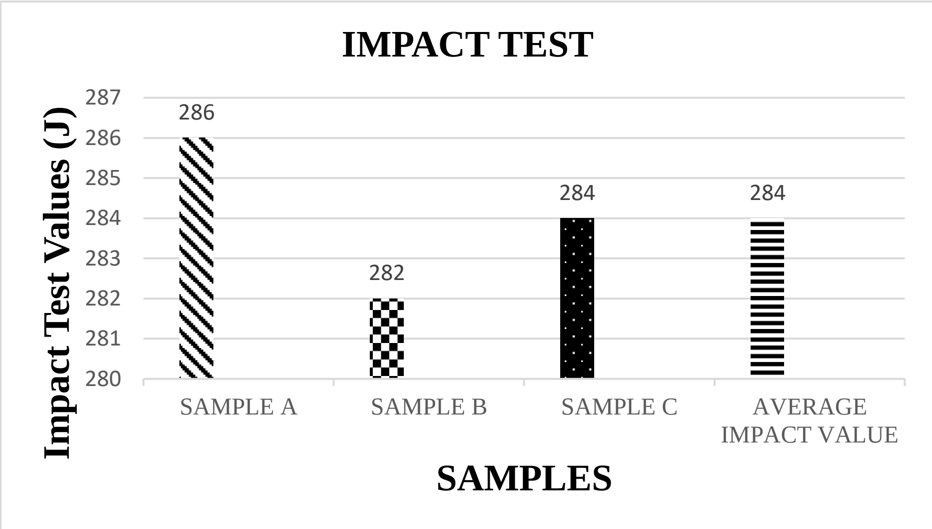

Fig. 18. Impact test chart.

3.3.4 | Discussion on impact test

The impact test readings exposed that the sample of HDPE recycled plastic has an average value of 284 J. The first sample gave an impact value of 286J, the second 282J and the third 284J.

3.4 | Tensile Test

The strength of materials can be determined using a tensile test, in which a tensile load (force) is applied to a specimen of the material and its extension is measured with respectto this load, i.e. Tensile test is used to measure the force required to break a specimen and the extent to which the specimen stretches or elongates to that breaking point [13].

Applying this test, the stressstrain diagram is produced, and we can investigate the tensile behavior of the m aterial and its properties from this diagram.

3.4.1 | Component and equipment

I. Tensile testing machine (*Fig. 19*).

Fig. 19. Tensile testing machine.

3.4.2 | Procedure used for tensile test

I. Measure the original length of the specimen which is the length of the gauge section marked on the specimen with a punch or the total length of the specimen.

II. Insert the specimen into the grips of the test machine.

III. Present the load and the displacement on the digital indicator to zero.

IV. Begin the load application by pressing unload (blue) button on the tensile machine and record load versus elongation data.

V. Continue test until fracture occurs.

VI. By joining the two broken halves of the specimen together, measure the final length.

3.4.3 | Result and discussion

For comprehensive data presentation, data was displayed in *Tables 4* and *5*.

Table 4. Test material property table.

Material	Thickness (mm)	Width (mm)	Gauge Length
HDPE	3.06	6.12	25

Table 5. Tensile property determination table.

Material	Load (KN)	I_O	I_F	E	A_O (10^{-3})	A_F(10^{-3})	Stress = (Load/Area) (MPa)	Strain = (Extension/Original Length) (MPa)
HDPE	9.68	25	29	4	3.69	4.2	2.63×10^6	2.63×10^{-1}

Where, I_O is original length.3.

I_F is final length.

E is elastic limit.

A_O is original area.

A_F is final area.

3.4.4 | Stress strain diagrams

The stress strain diagram for each specimen was drawn by the automatic recording system of the tester and you can see them in the next pages. This is shown in *Table 6*.

Table 6. Stress strain representation.

Material	Tensile Strength (MPa)	Yield Stress YP (MPa)
HDPE recycled plastic	25.6061	21.4127

3.4.5 | Discussion on tensile test

After the tensile test experiment it was discovered that the material had the following properties shown in summary style in the table below. This is shown in *Table 7* and *Fig. 20* shows the Stress/Strain chart for HDPE recycled plastic.

Table 7. Tensile test results.

S/N	Tensile Property	Value
1	Stress	2.63×10^{6}
2	Strain	2.63×10^{-1}
3	Tensile strength	25.6061
4	Yield strength	21.4127

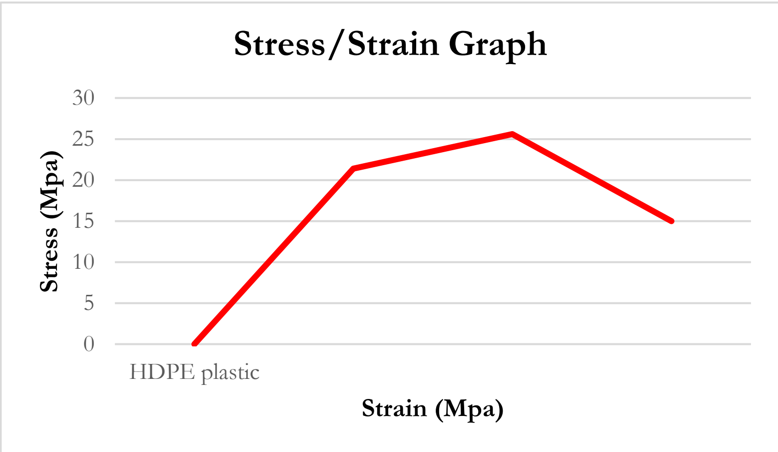

Fig. 20. Stress/strain chart for HDPE recycled plastic.

4 | Discussion on Mechanical Properties

The research investigated the mechanical properties of HDPE recycled plastics to determine its suitability in usage for production.

These tests were carried out on the recycled specimens. The tests were:

I. Rockwell hardness test.

II. Impact test.

III. Tensile test.

The Rockwell hardness test revealed that the average RHN was given as 50.0mm, the average Impact test value was put at 284J and the tensile test exposed the tensile strength to be 25.606 MPa and the specimens yield strength to be 21.412 MPa.

With these values, it can be asserted that composite material like HDPE can be considered as alternative material for use in some areas such as production and manufacturing in automotive interior panels, automobile roof covers, and rear storage shelf amongst others.

It is strongly believed that HDPE plastics are substantial replacements for certain wood used in production. This is because they shear almost the same tensile strengths [14].

Apart from the reactions to extreme heat and temperature changes. This research has exposed that due to slightly same and in some instances higher tensile strength, HDPE plastics are good replacement for certain woods used in production. Below is the tensile strength of some wood in comparison with the researched tensile strength of HDPE plastics. This is shown in *Table 8*.

Table 8. Materials and tensile strength.

S/N	Material	Tensile Strength (MPa) Used in Production
1	HDPE recycled plastic	25.606
2	Australian buloke wood	34.887
3	Schinopsis balansae / quebracho colorado / red quebracho wood	31.50
4	Snakewood / letterhout / piratinera guinensis wood	26.20
5	Brazilian olivewood	25.51
6	Lapacho wood	25.09
7	Cumaru / "brazilian teak" sometimes: "brazilian chestnut," "tiete chestnut,", "south american chestnut," "southern chestnut" wood	24.40
8	Ebony wood	22.20
9	Blood wood	19.994

With this, it is evident that HDPE plastics have considerable similar tensile strength with some woods used for production and manufacture hence it is suitable for use and this further goes to expose that recycled HDPE plastics are suitable and economically viable for manufacturing purposes [15].

The chart in *Fig. 21* shows the display of tensile strength of HDPE plastics in comparison with other wood sources.

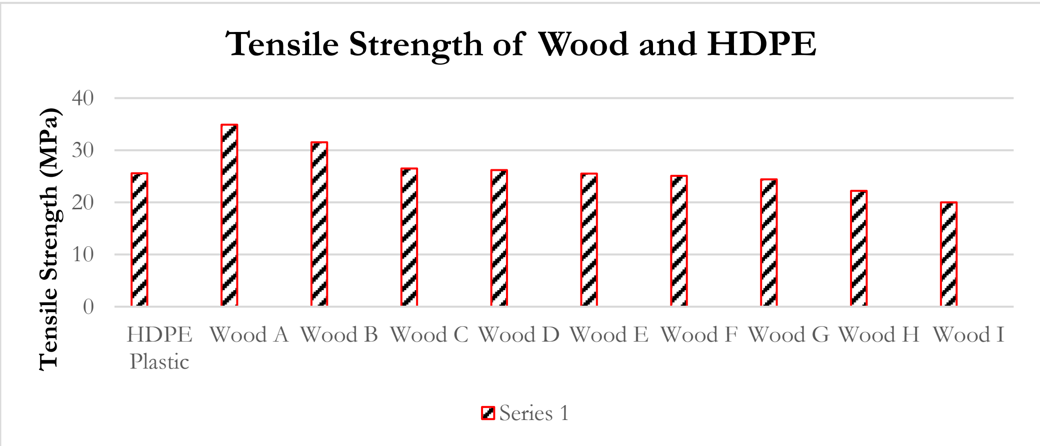

Fig. 21. Tensile strength of HDPE in comparison with wood sources.

5 | Comparrisson of Scanning Electron Micrograph Analysis for Recycled and Virgin Hdpe Plastic

5.1 | Scanning Electron Micrograph Analysis Comparison

A Scanning Electron Micrograph (SEM) comparison of recycled HDP plastic and virgin HDPE plastic reveals several distinct differences in their surface morphology and properties [16]. The SEM analysis provides valuable insights into the effects of recycling on the physical structure and integrity of the plastic materials [17].

Virgin HDPE plastic, also known as virgin HDPE, exhibits a smooth, glossy surface with minimal surface defects (*Fig. 22*). The surface is characterized by a uniform texture, indicating a well-ordered molecular structure. The SEM image shows a high level of crystallinity, with a compact and dense arrangement of polymer chains [18]. This is due to the controlled manufacturing process, which involves extrusion and molding under precise conditions. The resulting material has a high degree of purity, minimal impurities, and a consistent chemical composition.

Fig. 22. SEM image for virgin HDPE plastic.

In contrast, recycled HDPE plastic shows a rougher, more porous surface with increased surface defects (*Fig. 23*). The SEM image reveals a higher level of surface roughness, indicating a more disordered molecular structure. The presence of micro-particles, pits, and cracks is evident, suggesting that the recycling process has introduced impurities and defects into the material [19]. These defects can arise from various sources during the recycling process, such as contamination from other plastics, metals, or chemicals. Additionally, the repeated melting and re-molding cycles can lead to molecular degradation, causing the polymer chains to become shorter and more disordered.

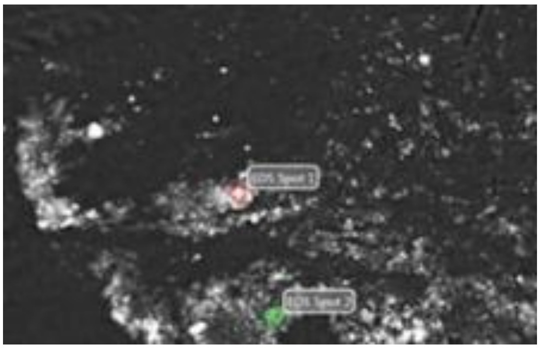

Fig. 23. SEM image for recycled HDPE plastic.

Recycled plastics often contain additives such as fillers, pigments, and antioxidants to improve their mechanical properties and aesthetics [20]. These additives can be seen in the SEM image as small particles or agglomerates scattered throughout the surface (*Fig. 23*). In contrast, virgin HDPE typically does not contain these additives.

The surface roughness and porosity of recycled HDPE can have significant implications for its performance and durability [21]. The increased surface area and defects can provide more sites for chemical reactions to occur, making the material more prone to degradation over time. This can lead to reduced mechanical properties, such as strength and flexibility, as well as increased susceptibility to chemical attacks. In contrast, virgin HDPE maintains its integrity and mechanical properties due to its smoother surface and well-ordered molecular structure [22].

5.2 | Water Absorption Capacity Comparison

The water absorption test was conducted in concordance with the following steps in concordance with ASTM D570 which is the standard for carrying out water absorption tests.

I. Preparing samples by cutting into desired shape, drying and weighing.

II. Submersing weighed sample in water at room temperature for a duration of 24 hours

III. Removal of sample from water, surface drying and weighing after submersion.

IV. Calculation for water absorption using the formula:

$$\text{Water Absorption Capacity} = \frac{\text{Wet Weight} - \text{Initial dry weight}}{\text{Initial dry weight}} \text{X } 100.$$

From the result, the recycled HDPE specimens absorbed more water compared to virgin HDPE specimens. This could be due to the microstructure of the recycled HDPE, which has more voids and pores that result in water filling the gaps more effectively [20]. Both specimens seem to absorb water, but the percentages of the absorption are very small, 0.015% and 0.27% for recycled HDPE and virgin HDPE respectively after 24 hrs of testing. The water absorption test results are shown *Fig. 24* the higher value for recycled HDPE plastic is due to the presence of impurities and additives [20].

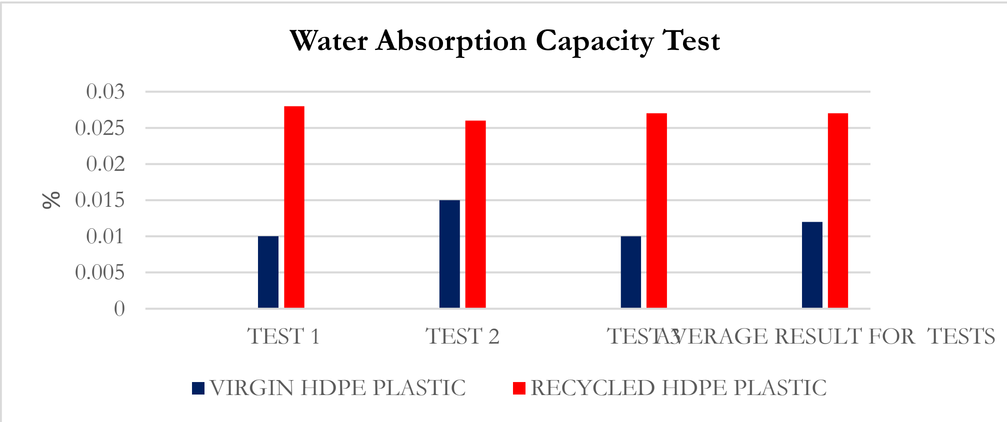

Fig. 24. Water absorption test results.

Both water absorption values are low in comparison to polymers and this is why HDPE is often used in water-related applications like pipes and containers.

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