PRODUCTION OF BIO-COMPOSITE POLYMERS WITH RICE AND COFFEE HUSKS AS REINFORCING FILLERS USING A LOW-COST COMPRESSION MOLDING MACHINE

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ABSTRACT

A compression molding machine was developed to produce bio-composite polymers using rice and coffee husks as reinforcing filler (5% weight) with high density polyethylene (95% weight) as the base polymer. Rice and coffee husks are typically disposed by open burning in fields. Their use as reinforcing fillers therefore reduces on the negative impacts of their disposal. The developed compression molding machine was constructed using mainly mild steel and stainless steel. It consisted of heating chamber, mold base, compression shaft and observation window. A temperature controller was incorporated to regulate the temperature in the heating chamber. Elongation, tensile strength and water absorption tests were carried out on the developed bio-composite polymers. Results indicated that inclusion of rice husks (5%) reduced the tensile strength and percentage elongation of the developed bio-composite polymer. Similar results were observed with coffee husk. Highest water absorption rates of 8% were observed for bio-composite polymers developed with Arabica coffee husks.

INTRODUCTION

Polymer production worldwide continues to grow but not that for synthetic fibers (Borghesi et al., 2016). Commodity polymers constitute 80% of the polymer market. Most of them are based on non-renewable petroleum, whose price is unstable, are non-biodegradable and not sustainable (Satyanarayana et al., 2009). Research continues to focus on the need for polymers that have specific characteristics for specific purposes, but at the same time are non-toxic and environmentally friendly (Yang et al., 2007). In order to produce fully renewable and biodegradable composites, both the polymeric matrix and the reinforcement must be derived from renewable resources, normally produced by plants in a period of less than one year (Narayan, 2006).

Various synthetic polymers are being prepared combined with various reinforcing fillers in order to improve the mechanical properties and obtain the characteristics demanded in actual application (Favaro et al., 2010; Pritchard, 1998; Rozman et al., 1998; Satyanarayana et al., 2009; Sharma et al., 2001). Studies are ongoing to find ways of using lignocellulosic fibers in place of synthetic fibers as reinforcing fillers (Angelini et al., 2000; Beg & Pickering, 2008; Bullions et al., 2006; Favaro et al., 2010; Fuad et al., 1994; George et al., 1998; Hardinnawirda & SitiRabiatull, 2012; Josepn et al., 1886; Pothan et al., 1997; Premalal
et al., 2002; Raju et al., 2012; Sgriccia & Hawley, 2007; Sgriccia et al., 2008; Tsou et al., 2014; Tsou et al., 2015; Zhao et al., 2009). These natural fillers are especially being sought because the production of composites using natural substances as reinforcing fillers will reduce and environmental pollution will be minimized (Premalal et al., 2002; Yang et al., 2007). Advantages of lignocellulosic materials include: (1) lightweight; (2) wear reduction of machinery used; (3) low cost; (4) biodegradability; (5) renewability and abundance; (6) low density; (7) non-abrasiveness; (8) recyclability; (9) absence of residues or toxic by-products; and, (10) high specific strength (Bledzki & Gassan, 1999; Campos et al., 2015; Favaro et al., 2010; Gacitua et al., 2005; Garcia et al., 2007; Ismail and Nasir, 2001; Kim et al., 2004; Maya & Sabu, 2008; Mohanty et al., 2000; Mohanty et al., 2002; Oksman & Clemons, 1997; Panthapulakkal et al., 2005; Premalal et al., 2002; Raju et al., 2012; Re et al., 2013; Satyanarayana et al., 2009; Yang et al., 2005).

Two common and readily available agricultural wastes in Uganda are rice husks and coffee husks (GoU, 2007). Expected production trends for rice and coffee production are shown in Figure 1 (MAAIF, 2009; MAAIF & UCDA, 2015). The disposal method of choice for rice and coffee husks is open-burning in fields which have negative environmental consequences (Bevilaqua et al., 2013). The use of rice husks and coffee husks as a raw material for the production of bio-composite polymers can be both an environmentally and economically viable means of tackling this problem. Fiber glass is commonly used in the production of composite polymers and the use of fiber glass contributes to the high costs of production and reduces its biodegradability in the environment. Replacement of fiber glass with lignocellulosic fibers as reinforcing filler will reduce the overall production cost incurred during the manufacture of bio composite polymers (Espindola et al., 2014; Zhao et al., 2009).

Therefore, in this study, bio-composite polymers were produced with rice husks and coffee husks as reinforcing filler using a locally developed compression molding machine. Bio-composite polymers were developed from a combination of high density polyethylene (HDPE) as the base matrix polymer and rice husks, Arabica coffee husks and robusta coffee husks as the lignocellulosic reinforcing filler.

![Figure 1: Projected production trends of rice and coffee in Uganda (MAAIF, 2009; MAAIF & UCDA, 2015)](image-url)
EXPERIMENTAL

1.1 Materials

HDPE (Marlex K606) was used as base polymer. HDPE in the form of homopolymer pellets was supplied by Ultrachemis Uganda Limited. The physical, mechanical and processing properties of the supplied HDPE are shown in Table 1. Rice husks (wita 9) were purchased from Kibimba Uganda Limited, in Bugiri District. The Arabica and Robusta coffee husks were purchased from Ugacoff Limited, in Bweyogerere. The structural morphology of the rice and coffee husks that were used in this study are shown in Figure 3.

Table 1 Physical, mechanical and processing properties of HDPE

| Property                        | Metric       |
|---------------------------------|--------------|
| Physical                        |              |
| Density                         | 0.964 g/cm³  |
| Environmental stress crack resistance | 15 hr         |
| Melt flow                       | 0.65 g/10 min|
| Mechanical                      |              |
| Tensile strength, yield         | 30.0 MPa     |
| Elongation at break             | ≥ 300%       |
| Flexural modulus                | 1.654 GPa    |
| Processing                      |              |
| Processing temperature          | 140 – 170 °C |

Figure 1: Coffee husks (A) and Rice husks (B)

1.2 Compression molding machine

A schematic of the compression molding machine that was used in the production of the bio-composite polymers is shown in Figure 3. It shows the different components of the compression molding machine including the heating chamber from which heating and compression of the bio-composite materials occurs, the support frame and the mold base in which the material is placed for compression. Mild steel with a thermal resistance of $1.333 \times 10^{-5}$ m²K/W was used in the construction of the frame of the compression molding machine. It was purchased from Roofings Limited, Uganda. The temperature controller, thermo-couple and
heating element were purchased from Guarantee Electricals limited, Kampala.

**Figure 3:** Schematic of the compression molding machine

In modeling of the heating systems, the following assumptions were made: (1) temperature of the ambient surroundings is constant; (2) ambient temperature is the reference temperature; and, (3) there is no heat loss to the environment. The elements that were used in the design of the heating system were, temperature controller, thermo-couple, heating coil with a 2700W power rating and a metal blade fan (see Figure 4).

**Figure 4:** Schematic representation of the heating system
From the energy balance equation:

\[
Heat \, in = Heat \, out + Heat \, stored
\]

\[q_i = \frac{\theta_h - \theta_a}{R_{ha}} + C_h \frac{d\theta_h}{dt} \quad \ldots \quad (1)
\]

Where: \(q_i\) – Heat into the chamber; \(C_h\) – Thermal capacitance of the air; \(\theta_h\) – Temperature of the cabin; \(\theta_a\) – Thermal resistance

However, using the stated assumptions, ambient temperature is zero therefore

\[q_i = \frac{\theta_h}{R_{ha}} + C_h \frac{d\theta_h}{dt} \quad \ldots \quad (2)
\]

In order to determine the unknowns, thermal capacitance of the heating cabin is considered and it is given by the equation (3)

\[C_h = V \times \rho \times C_P \quad \ldots \quad (3)
\]

Using the constants of specific heat of air, 1.013KJ/KgK, the density of air, 0815 Kg/m\(^3\) and the volume of the cabin, 0.1275 m\(^3\), the thermal capacitance is then determined. The thermal resistance of the mild steel used in the compression molding machine is calculated from:

\[R_{ha} = \frac{L}{K}
\]

Where; \(L\) is the thickness of the material \(1.2 \times 10^{-5}\), \(K\) is the conductivity of the material and conductivity of mild steel, \(K = 90\, W/mK\)

Using equation (ii), the heat equation of the compression molding machine is

\[q_i = \frac{\theta_h}{R_{ha}} + C_h \frac{d\theta_h}{dt}
\]

\[\int dt \left(\frac{q_i}{R_{ha}} \frac{\theta_h}{c_h} \right) + \int d\theta_h q_i = \frac{\theta_h}{R_{ha}} + C_h \times \frac{\theta_h}{t}
\]

\[q_i = \frac{\theta_h}{1.333 \times 10^{-5}} + 0.1053 \times \frac{\theta_h}{t} \quad \ldots \quad (4)
\]

Equation (4) is the heat equation considered during the design and construction of the compression molding machine.

### 1.3 Bio-composite production

The rice and coffee husks were grinded into flour and sieved using a 1mm mesh in order to maintain a 1mm particle size. The rice and coffee husks were oven dried at a temperature of 110\(^\circ\)C for 4 hours to reduce the moisture content in the flour. HDPE pellets were used to produce bio-composite polymers in ratios of 95% and 100% with the remaining being filler material. Pellets were poured into the mold base of the compression molding machine and a temperature of 170\(^\circ\)C was set on the temperature controller and the polymer was heated for 20 minutes in order to reach its melting temperature (140\(^\circ\)C). The heating rate of the cabin taken at 5 minute intervals is shown in Figure 5.
Dried husks were then added to the molten HDPE and mixed using a fabricated metal mixer and the mold base was raised by cranking the scissor jack. The bio-composite was then compressed at 170°C for 10 minutes. Cooling to room temperature was done through forced convection by the action of a metallic fan. The mixture of reinforcement/resin only becomes a composite material after the last phase of the fabrication, that is, when the matrix is hardened (Gay et al., 2003).

1.4 Physical and mechanical properties

Moisture content of the rice and coffee husks were determined using thermogravimetric analysis (Lubwama & Yiga, 2017). The water absorption properties were obtained through the ASTM D570 procedure. Mass of the samples to be tested was measured prior to starting the test. The conditioned specimens were placed in a container of distilled water maintained at a temperature of about 23 °C and left for 24 hours. After 24 hours, the specimens were removed from the water one at a time, all surface water wiped off with a dry cloth, and weighed to the nearest 0.001 g immediately. The water absorption was obtained as the difference between the weights. Tensile strength measurements were obtained using ASTM D638 procedure. Elongation was determined by measuring the difference in initial and final lengths (Hattotuwa et al., 2002).

RESULTS AND DISCUSSION

The developed compression molding machine is shown in Figure 6. Samples of developed bio-composite polymers are shown in Figure 7. From Figure 7 it can be observed that the distribution of the reinforcing filler material was non-uniform. This was expected because the mixing method used in this study did not enhance mobility of both the molten base polymer and reinforcing filler. Scratches were observed on all of the developed bio-composite samples because the mold plate was not smooth. Scratches also developed when removing the developed bio-composite from the mold plate after cooling.
Figure 6: Developed low cost compression molding machine

Figure 7: Developed bio-composite polymers. A (5% Robusta coffee husks); B (5% Arabica coffee husks); C (5% wita-9 rice husks); and D (100% HDPE)
The results for moisture content and water absorption rate are shown in Figure 8 and Figure 9 respectively. The bio composite polymers produced using 5% Robusta coffee husks as filler material had the highest water absorption percentage. Lignocellulosic fillers have been reported to absorb moisture even when in a plastic medium (Yang et al., 2006). The low water absorption of the pure HDPE sample can be attributed to the hydrophobic nature of the polymer (HDPE). The bio composite polymers formed with 5% wita 9 rice husks had low water absorption due to the hydrophobic nature of the silica contained within the rice husks. When compared with wood-based composites however, the amount of water absorbed is so low and negligible (Yang et al., 2006). Robusta coffee husks had higher moisture content than both rice husks and Arabica coffee husks (see Figure 8).

![Figure 8: Percentage moisture content of the rice and coffee husks](image)

![Figure 9: Water absorption percentage of the bio-composite polymers](image)
The results for elongation at break and tensile strength are shown in Figure 10. Generally, the elongation at break and tensile strengths are lower for all of the developed bio-composite polymers. The least tensile strength of approximately 33 MPa was obtained for bio composite polymers with Robusta husks as reinforcing filler. The lower tensile strength in the developed bio-composite polymers is attributed to the irregularly shaped fibers that decrease the ability of the filler to support stress transferred from the polymer matrix and the poor interfacial bonding between the filler and the matrix polymer (Yang et al., 2006). The least elongation at break was in the composite formed with rice husk filler. The reduction of the elongation at break can be attributed to the induction of brittleness caused by the reinforcing filler as well as creation of voids in the composite that obstruct stress propagation in the bio composites. The low elongation at break for the composite formed with rice husks as reinforcing filler can be attributed to the brittle nature of the silica contained within the rice husks (Hattotuwa et al., 2002).

![Figure 10: Mechanical properties of the developed bio-composite polymer samples](image-url)
CONCLUSION

A compression molding machine was developed to produce bio-composite polymers using rice and coffee husks as reinforcing filler (5% weight) with high density polyethylene (95% weight) as the base polymer. The development of compression molding machine was constructed using mainly mild steel and stainless steel. Highest water absorption rates of 8% were observed for bio-composite polymers developed with Arabica coffee husks. Results indicated that inclusion of rice husks (5%) reduced the tensile strength and percentage elongation of the developed bio-composite polymer. Similar results were observed with coffee husk. Tensile strengths of the bio-composites decreased with inclusion of filler; however the composites retained an acceptable level of strength. When filler material was used, the poor interfacial bonding between the filler and the matrix polymer caused the tensile strength of the bio-composites to reduce. This poor interfacial bonding resulted in an increase in the number of micro voids, causing increased water absorption. The results indicate that the compression molding machine has to be modified in the following ways: (1) Incorporation of a more elaborate mixing stirrer or screw mechanism for mixing; (2) Enhancement of heating in the cabin to ensure that it is uniform; (3) modification of the mold plate to ensure that it is very smooth in order to avoid micro-cracks that become points of crack initiation and propagation.

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