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Effects of Wood Particle Sizes on Bonding and Mechanical Strength of Wood Plastic Composites

Muthoni N. Mwanzia*, Waweru Mugo, Timonah N. Soitah

Department of Physics, Jomo Kenyatta University of Agriculture and Technology, Juja, Kenya
*Corresponding author: muthonimwanzia@gmail.com

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Abstract Due to an increasing amount of household plastic waste, sustainable plastics waste management systems have become increasingly important. We report on the feasibility of using recycled polypropylene (PP) from the commonly used plastics to process composite panels for different applications. The plastics were obtained from polymer with Resin Identification Code (RIC) 5, for the PP. The samples were melted and then moulded using an injection molding machine. Other samples were mixed with different wood flour sizes and an investigation carried on the strength of wood-plastic composites (WPCs). The wood flour particle size of 0.268 µm and 1.23 µm were compounded with the plastic at a ratio of 1: 9. Fourier Transform Infra-Red (FTIR) spectra analysis, indicated a decline in the absorption peak of the spectrum for the smallest wood flour particles after the alkali treatment as compared to large particles. The wood flour of particle size of 0.268 µm had the highest ultimate tensile strength values of 15.36 MPa, while wood flour of particle cross-section size of 1.23 µm had the lower ultimate tensile strength values of 10.71 MPa. Analysis showed that as the cross-section size of the wood flour particles within the WPCs decreased, there was a concurrent increase in the ultimate tensile strength of the material. The investigation presents empirical evidence establishing a direct positive relationship between the strength characteristics of wood-plastic composite and the particle dimensions of the constituent wood particles. This has been shown to be due to interfacial bonding and effectiveness of load transfer within the composite material.

Keywords: *tensile strength, wood flour particle sizes, household plastics, wood flour, wood-plastic composite, polypropylene*

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1. Introduction

In the literature, wood-plastic composites (WPCs) have been presented as potential substitute materials for traditional polymer composites [1]. However, the polymers to be utilized, should possess a melting temperature lower than the thermal decomposition point of wood in order to prevent the wood fibers from degrading during the manufacturing process [2]. Numerous technological methods have been introduced in literature for creating single polymer composites using diverse thermoplastic polymers, including polyethylene [3], polypropylene [4], polyethylene terephthalate [5], polyethylene naphthalate [6], polyamide [7], polymethyl methacrylate [8] and liquid crystal polymers [9]. These studies have shown that these polymers have been used as a matrix and a reinforcement material that enhanced eco-efficiency of WPCs products, with reasonable mechanical and physical properties and at low cost.

The fundamental requirement for creating a high-quality single-polymer composite with strong mechanical characteristics incorporates the use of a high mechanical performance polymer fiber or tape, which serve as the reinforcing component in the composite material. Therefore, optimizing the mechanical properties of the precursor fiber is important for successful application of such a composite [10]. Cellulosic materials are increasingly been utilized as reinforcements in thermoplastic matrix composites [11]. Wood flour (WF), when used as cellulosic reinforcements, offers favorable mechanical properties, a lower density, diminished health risks. In addition, it offers several benefits, including enhanced biodegradability of the end products and the accessibility of renewable natural resources [12]. The alkali solution concentration used for treating the fibers varies in a range of 0.5% up to 28%, but the majority of researchers used alkali solutions below 10%. It helps prevent excess degradation to the wood fibers, while still allowing effective surface modification for better bonding between wood and plastic components in the composite materials [13]. The treatment of the natural fiber in the solution involves temperature and soaking durations ranging from 20°C to 180°C and 15 minutes to 48 hours. The required temperature to dry a natural fiber must be lower than 80°C for 24 hours to 48 hours period of time, to ensure that fiber undergo modification without excessive degradation. [14].

Studies on the flexural properties of WPC with different wood modification reported that an increase in NaOH concentration from 5% to 17% resulted in 12% higher flexural strength as compared to the unmodified WF composites, which was attributed to the fact that the interfacial adhesion between the WF and PP was increased, improving the bonding [13].

This paper reports on the surface to volume interaction on wood flour particle size in PP and their impact on the mechanical properties in WPCs.

2. Materials and Methods

2.1. Recyclable Plastic

Recyclable plastic waste was sorted into different categories using curbside collection. The plastics were then cleaned using detergent and water to remove dirt, oil, and labels. The plastics were reduced using a shredder to smaller particles. A 10 g sample was be transferred into a metallic container within an oven and the melting point determined. The heat was increased at an interval of 10°C until all plastic had completely melted. The molten plastic was transferred to a metallic plate then allowed to cool at room temperature.

The 10 g of the sample was inserted into an injection machine, then placed on an electric hot plate. It was set to rotate continuously at a rotation speed of 0.5 Hz ensuring even heating of the blend for 20 minutes.

2.2. Preparation of Processed Stem

The wood flour was processed from 1.5 Kg of the *Melia Volkensii* (Chinese Parasol) tree pieces, that had been dried for 3 months to reduce the moisture content. The wood flour was processed by different sandpapers; P40 (grain size 425-500µm), and P80 (grain size 180-220µm), to produce the finer wood components. The wood flour was then dried in an oven at 60°C for 24 hours to reduce moisture. The WF sanded using grit size P80 was code named P1, while with P40 was code named P2. LX 400 0ptical microscope images were obtained and image J software was used to analyze the WF particle cross-section size.

Later, the WF samples were soaked separately, in the solution of 5 % NaOH for 2 hours to remove the impurities, lignin and hemicellulose. They were later rinsed with clean water to remove any traces of NaOH. Dilute acetic acid was used to reach a neutral pH of 7. Samples were dried in an oven at 60°C for 24 hours reduce moisture. The samples were weighed and stored in a moisture free container.

Shimadzu FTIR spectrophotometer (FTS—8000, Japan) was used to identify the chemical bonds and functional groups of the sample. To obtain the FTIR spectra, 2 mg of the sample and 200 mg of KBr was grounded into fine particle size, then placed into the FTIR cell for determination of element content. The FTIR transmission spectra were obtained by setting the spectral resolution at 4 cm^{-1} and the scanning range from 400 to 4000 cm^{-1}.

2.3. Synthesis of Wood Plastic Composites

Blending of WF and recyclable plastic sample of the PP was performed with aid of a magnetic stirrer at room temperature at 60 rpm for 10 minutes for different mixtures according to WF particle sizes. The blend was transferred to an injection machine, which was placed on an electric hot plate, set for the melting point of the plastic. It was set to rotate continuously at a rotation speed of 0.5 Hz ensuring even heating of the blend for 20 minutes.

Subsequently, the mold was cooled at room temperature over a duration of 10 minutes, and the procedure repeated for blends with different wood particle size.

During this sample preparation procedure, the piston, screw and melting chamber were thoroughly cleaned after every sample preparation using acetone. The mold was extracted tensile strength analysis done, using SM 1002 top bench tensile testing machine.

2.4. Mechanical Strength Measurement of WPCs

The mechanical properties were conducted using the SM 1002 top bench tensile testing machine (TTM). A mechanical analysis was performed to assess the mechanical characteristics of the recycled polymer samples reinforced with WF in order to investigate the disparities in their strength. The test specimens were moulded into dumb-bell shape with a uniform thickness. It had a total length (L) of 35mm, width (W) of 5mm, a thickness of 2mm. The force and the elongation of the sample were recorded at every instant until the fracture point of the samples.

The stress-strain curve was calculated from the results obtained from the TTM for force applied and elongation on the samples using Equation 1 and 2, for stress σ and Strain ε respectively.

$$\sigma = \frac{F}{A} \tag{1}$$

$$\varepsilon = \frac{\Delta l}{l} \tag{2}$$

The ability of the WPCs fabricated to resist deformation, or the ability to which they are expected to deform elastically when subjected to a particular load was investigated as the Modulus of Elasticity (M.O.E) as in equation 3.

$$M.O.E = \frac{FLO}{A\left(L_n - L_o\right)} = \frac{\Delta\sigma}{\Delta\varepsilon} \tag{3}$$

3. Results and Discussion

3.1. Wood Particle Characterization

Figure 1 displays the optical images of the wood flour particles under LX 400 optical microscope with a magnification of X10. In Figure 1 a) the particles are noted to be densely packed, thicker from contrast and smaller in size as compared to Figure 1 b).

Using the image J software, analysis was made on particle cross-section size. The field number (F.N) was used to calculate the field of view (F.O.V) by use of equation 4.

$$F.O.V = \frac{F.N}{Magnification} \tag{4}$$

This was used to analyze the size of the wood particles. The wood particle cross-section sizes were analysed and represented in the histogram distribution.

From the graph in Figure 2(a), the average wood flour size for particles (P1) was indicated as 0.268 µm, which had the smallest dimension, and its standard deviation was 0.1396. The distribution curve was skewed to the right indicating that most of the particles were less than 0.268 µm, while less particles had a length above the average size. These wood flour particles being smaller, means that many were packed within smaller cross-sectional area. Their particle density was calculated to be 3.682 x 10^{10} particles/m^2.

In Figure 2 b) the average wood flour cross-section size (P2) was indicated as 1.23 µm, with a standard deviation of 0.2102. The distribution curve was skewed to the right indicating that most of the particles were less than 1.23 µm. These wood flour particles being relatively larger than wood flour particles (P1), meant that less particles were packed within the same cross-sectional area as compared to P1 particles. The wood flour particle density was calculated to be 2.591x 10^9 particles/m^2, which was lower than that of P1. This reveals that as the grit value increases, a reduction in size of the resulting wood particle was realized.

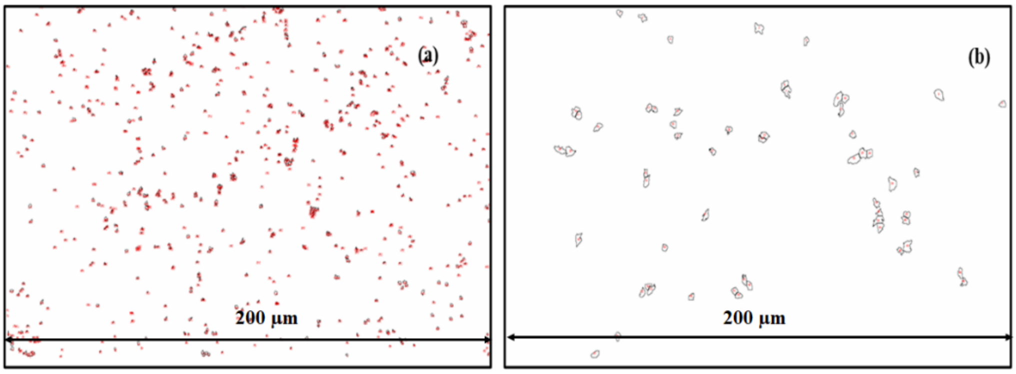

Figure 1. Optical microscope images; a) showing particle P1 b) showing particle P2

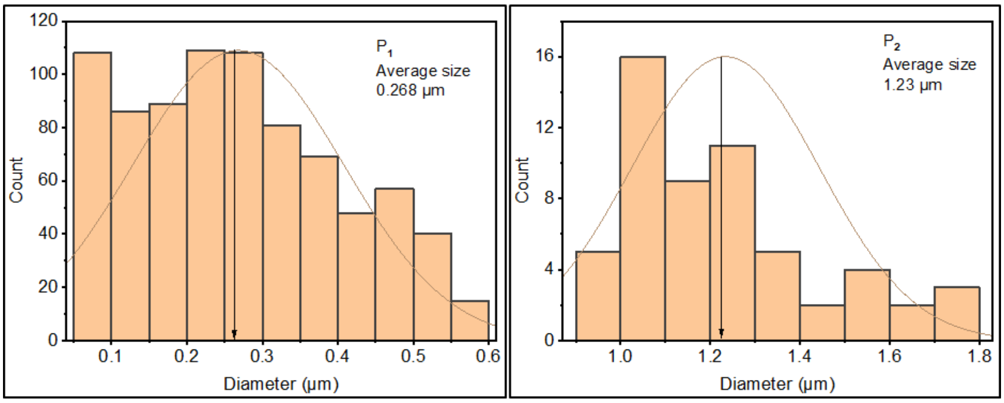

Figure 2. Histogram distribution of particle count with wood particle diameter: a) for particle P1 b) for particle P2

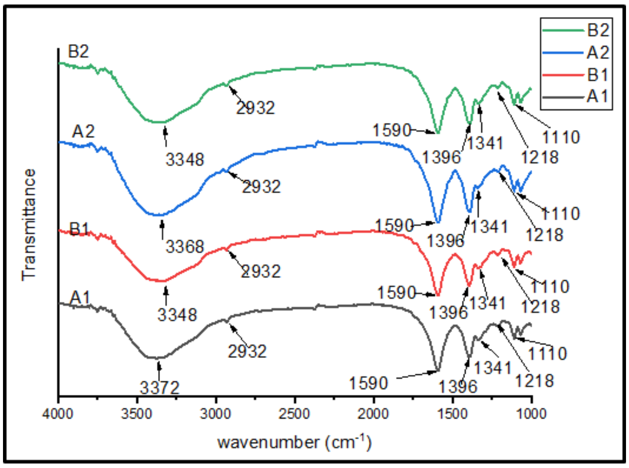

Figure 3. Elemental composition analysis on mercerization of WF

3.2. Elemental Composition Analysis on Mercerization of WF

FTIR transmittance spectra for changes regarding untreated wood flour particles P1 and P2 (A1 and A2) and treated wood flour particles P1 and P2 (B1 and B2) analysis were illustrated in Figure 3, which displays shift in peak positions and indicates changes in intensities at different wavenumbers, due to different bond vibration as a result of molecular interaction, for spectra B1 and B2 as compared to A1 and A2 after mercerization was done.

The wide absorption band detected at 3372 cm^{-1} for A1, 3348 cm^{-1} for B1, 3368 cm^{-1} for A2, and 3348 cm^{-1} for B2, was associated with the stretching vibration of hydrogen bonding (OH) [15]. After 5% NaOH treatment, a noticeable decrease in the intensity was observed in the spectrum. Specifically, the vibration peak at 2932 cm^{-1} which corresponding to the stretching of the C–H aliphatic group, exhibited a reduction following the removal of hemicelluloses. Additionally, a decline was observed in the band around 1590 cm^{-1} correlating to the carbonyl peak C=C, within the treated wood flour. The shift in the peak at 1396 cm^{-1} was caused by deformation in the alkene groups resulting from cellulose. Additionally, the reduction in the peak at 1341 cm^{-1}, representing the C=H vibration of alcoholic group (cellulose) was noticeable. Moreover, the peak at 1218 cm^{-1}, denoting the C=O stretch of acetyl group of lignin, displayed a decrease in intensity. This is attributed to the partial removal of lignin from the fiber surface [16]. The peak at 1110 cm^{-1}, which is C=H vibration of alcoholic groups (cellulose) was reduced. The intensity of the FTIR spectra for smaller particles, B1, was much reduced compared to larger particles, B2, after the alkali treatment. The anticipated outcome of the alkali treatment was a decrease in the hydrogen bonding within cellulose hydroxyl groups due to the removal of the carboxyl group. As per the results, the alkaline treatment induced alterations in the chemical surface, attributes of the natural fiber by selectively eliminating hemicellulose, while maintaining the presence of both lignin and cellulose components [17]. Alkaline conditions induced the de-esterification of carboxylic groups within xylan polymers, resulting in the release of the hemicellulose into the solution by formation of acetic acids [18].

3.3. Mechanical Strength Analysis of WPCs

Figure 4 displays stress-strain curve of the sample with R, R/P1/WF and R/P2/WF for the sample moulded from the plastic sample only (no wood fillers added), the sample moulded from the mixture of recycled plastic and P1 WF particles, and sample moulded from the mixture of recycled plastic and P2 WF particle respectively.

From the graph it can be seen that at lower strain value the materials have a lower stress value. Both stress and strain increase non-uniformly, describing a thermoplastic behavior. The region below yield point obeying the Hooke's law, while beyond the yield point, they undergo a plastic deformation.

The graph was used to analyze the yield point, ultimate tensile strength and tensile modulus for the sample fabricated from the plastic with no WF, with WF of smallest particles cross-section area (P1), and with WF of largest particles (P2).

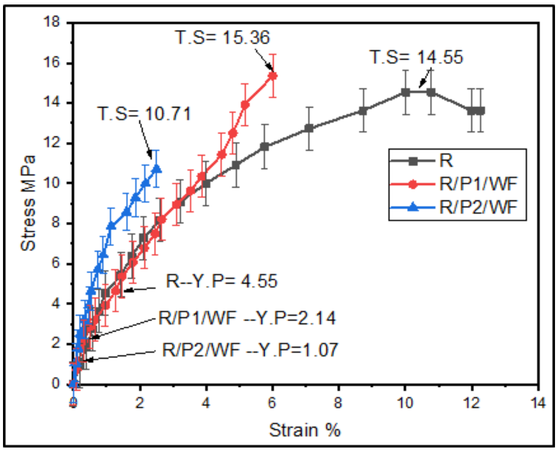

Figure 4. Stress – Strain curve for the recycled polymer and their WPCs

The M.O.E values for wood plastic composites produced from the recycled plastics; with no wood fillers, with WF of particle size (P1) and with WF of particle sizes (P2), was 4.74×10^2 MPa, 7.13×10^2 MPa, and 1.528×10^3 MPa respectively, as in Figure 5 (a). The ultimate tensile strength obtained for the WPC from the recycled plastics; with no wood fillers, with WF of particle size (P1) and with WF of particle sizes (P2), was 14.55 MPa, 15.36 MPa and 10.71 MPa respectively as in Figure 5 (b).

The ultimate tensile strength for the WPC produced by using (P1) had the highest value of 15.36 MPa. While the lowest ultimate tensile strength was recorded in the WPC produced by using the relatively larger particles (P2) of 10.71 MPa. The highest MOE values for the recycled sample were recorded for the WPC synthesized with the largest particles P2. The ultimate tensile strength for the sample was noted to increase with the decrease in the wood flour particle cross-section size [19]. An increase in the wood flour particle cross-section size, lead to an increase in the tensile modulus. The larger the wood flour particle cross-section sizes, the larger the stress concentrations along the naturally weak interface of the hydrophilic wood flour and hydrophobic polypropylene. This phenomenon could be attributed to the interaction between the hydrophilic nature of wood flour and the hydrophobic characteristics of the polypropylene matrix [20]. Moreover, the insufficient interface between the hydrophilic wood flour and the hydrophobic polypropylene contributed to the observed outcome [21].

From the physics of material, when the particles become smaller, their surface area relative to their volume increases [22]. The enhanced surface-to-volume ratio leads to stronger interaction with the material surrounding them, such as increased chemical reactivity and greater adhesion forces. This is because a larger portion of the particles atoms or molecules is exposed to the surrounding environment, allowing for more interaction to occur. For the bigger wood flour particles, they were seen to be sparingly apart, hence having a lower particles density, meaning that their surface interface was less than that of the smaller wood flour particles. Therefore, this resulted to less bonding between the wood flour particles and the plastic matrix.

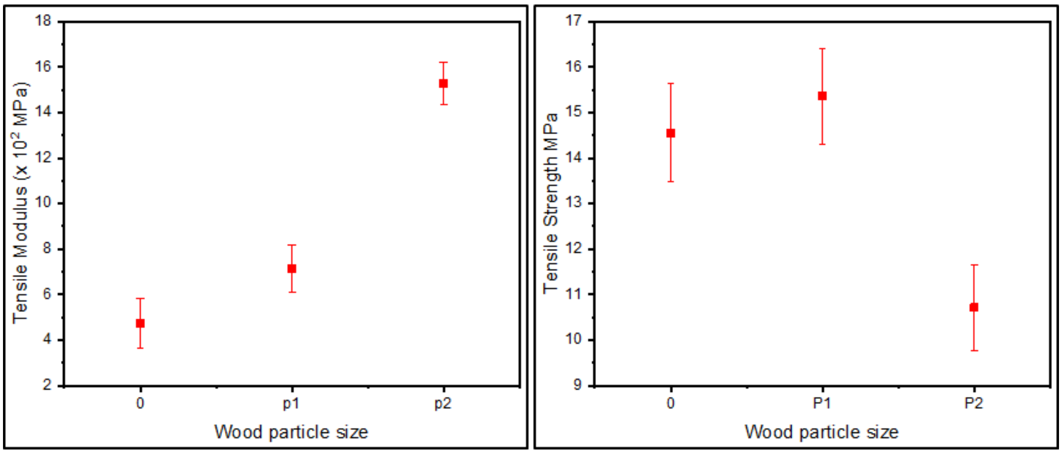

Figure 5. Mechanical strength with wood particle size: a) The Tensile Modulus b) The Tensile Strength

Complementary test from FTIR indicated change in the intensity in the spectra at different wavenumber. It was noted that the intensity of the peak of B1 spectrum were weaker than those of the B2 spectrum. This was attributed to the fact that since

particle P1 were relatively smaller than P2, they had a higher surface area to volume ratio, hence they absorbed a higher amount of alkaline treatment as compared to the relatively larger particles, P2.

Additionally, the WPCs produced by using the smaller particles, P1, had a higher ultimate tensile strength as compared to those of P2, which could be attributed to the fact that their chemical surface properties were much altered by the alkali treatment in comparison to those of P2 [23].

4. Conclusion

The elemental composition analysis showed a significant reduction in intensity observed among particle size of 0.268 µm, following alkali treatment of 5% of NaOH in comparison to particle size of 1.23 µm. This variation in intensity alteration highlighted a more pronounced effect on the smaller particles as a consequence of the alkali treatment. The application of Alkali treatment resulted in a noticeable reduction in the hydrogen bonding present within the cellulose hydroxyl groups, achieved by removal of carboxyl group. This treatment corresponds to a discernible decrease in the quantity of hydroxyl groups (OH) within the structure. Furthermore, an observable portion of the lignin was removed from the wood flour as a consequence of this process.

As the wood flour particle size decreased, a notable decrease was observed in tensile modulus, while an increase in WF particle sizes within WPCs resulted in a corresponding reduction in the tensile strength of WPCs. Remarkably, the smallest wood particle size demonstrated an elevated ultimate tensile strength of 5.57 %, attributed to a greater surface area facilitating enhanced interaction and superior adherence, which promoted stronger bonding. This effect also contributed to the reduction of internal stresses within the composite material.

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