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Abstract

Wood plastic composite (WPC) specimens were fabricated in shapes relevant to flute (musical instrument) production using African blackwood powder and phenolic resin in a hot compression molding setup. The roles of composition and processing parameters on the mechanical properties (flexural strength, elastic modulus, and impact failure energy) were systematically investigated. Cracks were observed in composites with more than 70% wood particles due to the formation of gas in the system during manufacturing, and lack of fluidity in the system to flush out entrapped air and the produced gases. Based on these results, the optimum temperature, pressure, and wood volume fraction for manufacturing WPC in the form of a flute is developed. A further series of experimental procedures were performed to improve the mechanical properties of WPC samples by studying the addition of short glass fibers to the molding compound prior to hot pressing. The results showed that the addition of short fiber did not improve the strength of WPC but rather reduced its strength compared to unreinforced composite. This was attributed to lack of bonding between the short fibers and composite matrix.

Keywords

wood plastic composites, E-glass fibers, mechanical properties

Introduction

The erosion of forest resources caused by the rising usage of wood and by global warming encourages the exploitation of wood product waste, which can be converted into wood plastic composites (WPCs) suitable for innovative applications.[1–3] WPCs are made of ground-up wood particles (wood flour), a polymer thermoset or thermoplastic matrix, and potentially additional reinforcing fibers. The demand for WPCs has rapidly grown in recent years, due to their moisture resistance, low maintenance costs, durability, and ability to make use of normally discarded wood scraps.[4–9] WPCs are now considered even for manufacturing musical instruments due to cost savings and durability. On the other hand, the mechanical properties of WPCs are generally much lower than those of natural wood. This is mainly due to the low interfacial adhesion between the wood particles and the polymer matrix, and the small aspect ratio (length/diameter) of wood powder.[7] With recent advances in materials processing, attempts have been made to improve the wood powder dispersion, compatibility, and bonding with the matrix binder by the inclusion of coupling agents to the matrix.[10–13] WPCs with large particles have superior mechanical properties compared with fine wood powder.[14–17] However, for using WPCs in manufacturing musical instruments – one of the motivations for this study – a finer wood particle is esthetically more desirable.

In order to compensate for the small wood-powder aspect ratio, short glass fibers with a higher aspect ratio are often added to the mixture.[1,5,8,11] But this causes

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problems such as low adhesion between fiber glass and matrix, extra process complexity, and the need to orient fibers in the load-bearing direction. A few attempts have been made to incorporate long glass fibers to increase the mechanical properties of WPCs.[7,11,18,19] Deng and Tang[7] inserted sisal and glass fiber fabrics to the wood–high density polyethylene composites. The fabricated sandwich structure had mechanical performance comparable to solid wood. However, the use of two processes increased the cost and production time.

The purpose of this research is to develop a methodology to produce flute-shaped WPC specimens. It would be desirable to manufacture WPC flutes from African blackwood (Mpingo is an African black wood, which is used in expensive flutes) powder, with a goal of maintaining the esthetics and appearance, while lowering the cost and perhaps improving the moisture resistance of the flute. The tensile and impact properties of African blackwood powder/phenolic composites were optimized by varying the molding temperature and pressure, wood/phenolic weight fraction, and wood powder size. Finally, the effect on mechanical properties of adding short and long glass fibers (without compromising the natural wood-like appearance of the final product) is evaluated.

Materials and methods

African blackwood sawdust with an average particle size of 30 μm was supplied by the Burkart-Phelan Corporation (flute manufacturer in Shirley, MA). In the laboratory, the sawdust was dried at 130°C for 30 min. Phenolic resin product 14695 intended for bonding wood powder was provided by PLENCO (resin manufacturer in Sheboygan, WI). Two custom-made molds were manufactured from tool steel. The first mold was a $38.1 \times 190\,mm^2$ cylinder with a central square hole with cross-section $16 \times 16\,mm^2$. The plunger had a cross-section of $15 \times 15\,mm^2$. The second mold was manufactured from a cylinder with a 43.17 mm outer diameter, 24.7 mm inner diameter, and 200 mm length. In order to produce hollow specimens, a solid rod of 12.5 mm was supported along the axis of the bore. The plunger for manufacturing this composite was a hollow cylinder with an outer radius of 24.5 mm and an inner radius of 12.95 mm. Mold release (Xtend 19SAM, AXEL) was applied to the steel mold surfaces prior to specimen's production.

A schematic diagram of the WPC production setup is shown in Figure 1(a). The wood powder and phenolic were mixed and poured into the mold. The assembly was heated to 196°C using OMEGA (Stamford, CT) band heaters and temperature controller while being compressed in an Instron 5582 machine under 35 MPa (5 ksi) pressure. In '*Effect of mold temperature and pressure on flexural properties of WPC*' section, we systematically studied the role of mold temperature and pressure on the mechanical properties of WPCs. The composite/mold was held under constant temperature and pressure for 30 min and then cooled to room temperature under the same pressure. Figure 1(b) shows the finished WPC specimens, which have an appearance quite close to solid African blackwood. For mechanical testing, the square samples were sliced in half lengthwise with an electric saw, and then milled to 7 mm thickness.

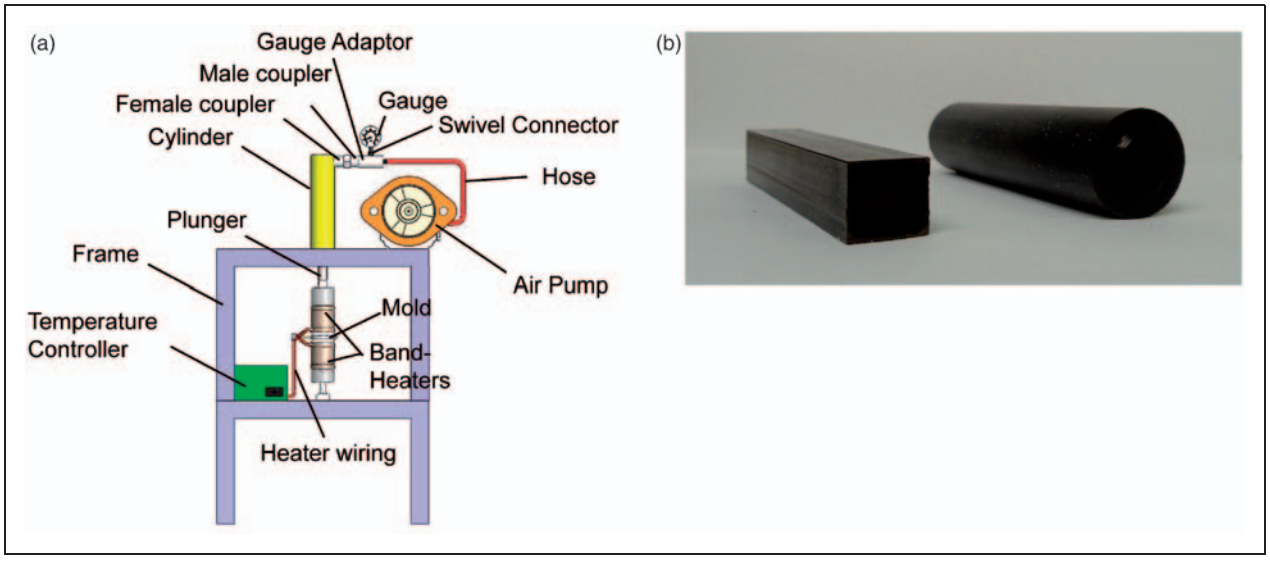

Figure 1. (a) Schematic diagram for the production of WPC test specimens. (b) Typical WPC samples, produced from two different molds.

Fiber reinforcement

Cut-up E-glass fibers FGI 1334, provided by Fiber Glass Industries Inc. (Amsterdam, NY), were used to reinforce some WPC samples. According to the manufacturer, fiber tensile strength is $\sigma_{fu} = 2.25$ GPa, and radius $r = 17.5\,\mu$m. Prior to the addition of glass fibers, the critical pull-out length was evaluated based on $l_c = \sigma_{fu}.r/\tau_{fu}$, where τ_{fu} is the interfacial shear strength between the fibers and WPC matrix.[20] It was assumed that $\tau_{fu} = 8.3$ MPa[21] gives $l_c = 4.74$ mm. The fibers were cut into 5 and 10 mm lengths, and mixed in various weight fractions with wood powder and phenolic. The phenolic weight was kept at 40% for this series of experiments, and the glass fiber percentage was adjusted in conjunction with the wood content for every experiment. The same molding and curing procedure was followed.

Mechanical property measurement

An Instron model 5582 universal tester was used to obtain the force–displacement response of the fabricated specimens with different wood/phenolic ratios in three-point bending. All experiments were performed under considerably small strain rate. At least four samples for each composite were tested to obtain the flexural strength and modulus of elasticity. Euler–Bernoulli beam theory[22] was used to calculate the flexural strength σ and modulus of elasticity E of the WPC. These are presented as $\sigma = 3PL/2bd^2$ and $E = L^3m/4bd^3$, where P is the failure load, and L, b, and d the support span, width, and thickness of the WPC sample, and m the specimen stiffness (i.e. the slope of the load deflection curve). Impact properties of WPC samples were measured at room temperature in accordance with ASTM D4495. Test samples were cut and polished to 25.4 mm length, 16 mm width, and 7 mm thickness. The impact failure energy was calculated from the drop height of a 25.4 mm diameter 0.225 kg steel ball which causes complete specimen separation. The drop height was systematically varied by 2 cm until total failure was observed. Virgin specimens were used in each impact test.

The same tests were repeated to obtain the mechanical properties of solid African blackwood specimens. The ultimate strength, elastic modulus, failure load, and impact failure energy of the African blackwood are denoted by $\bar{\sigma}$, $\bar{E}$, $\bar{P}$, and $\bar{U}$, and used as benchmarks to normalize the mechanical properties of WPCs.

Results and discussions

Effect of mold temperature and pressure on flexural properties of WPC

A set of experiments for WPCs containing 60% wood powder and 40% phenolic without fiber reinforcement were carried out to identify the relationship between the

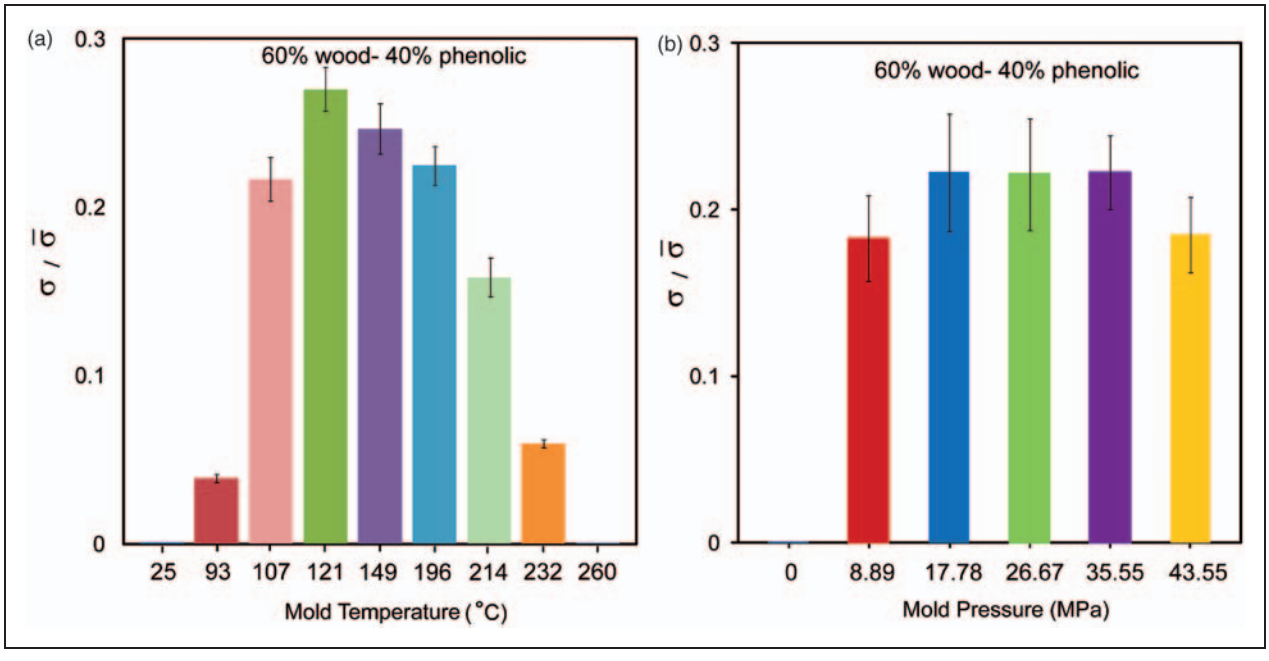

Figure 2. The effect of processing temperature (a) and pressure (b) on the tensile strength of WPC. Four specimens were tested for each processing condition. The error bars show the standard deviation from the average value.

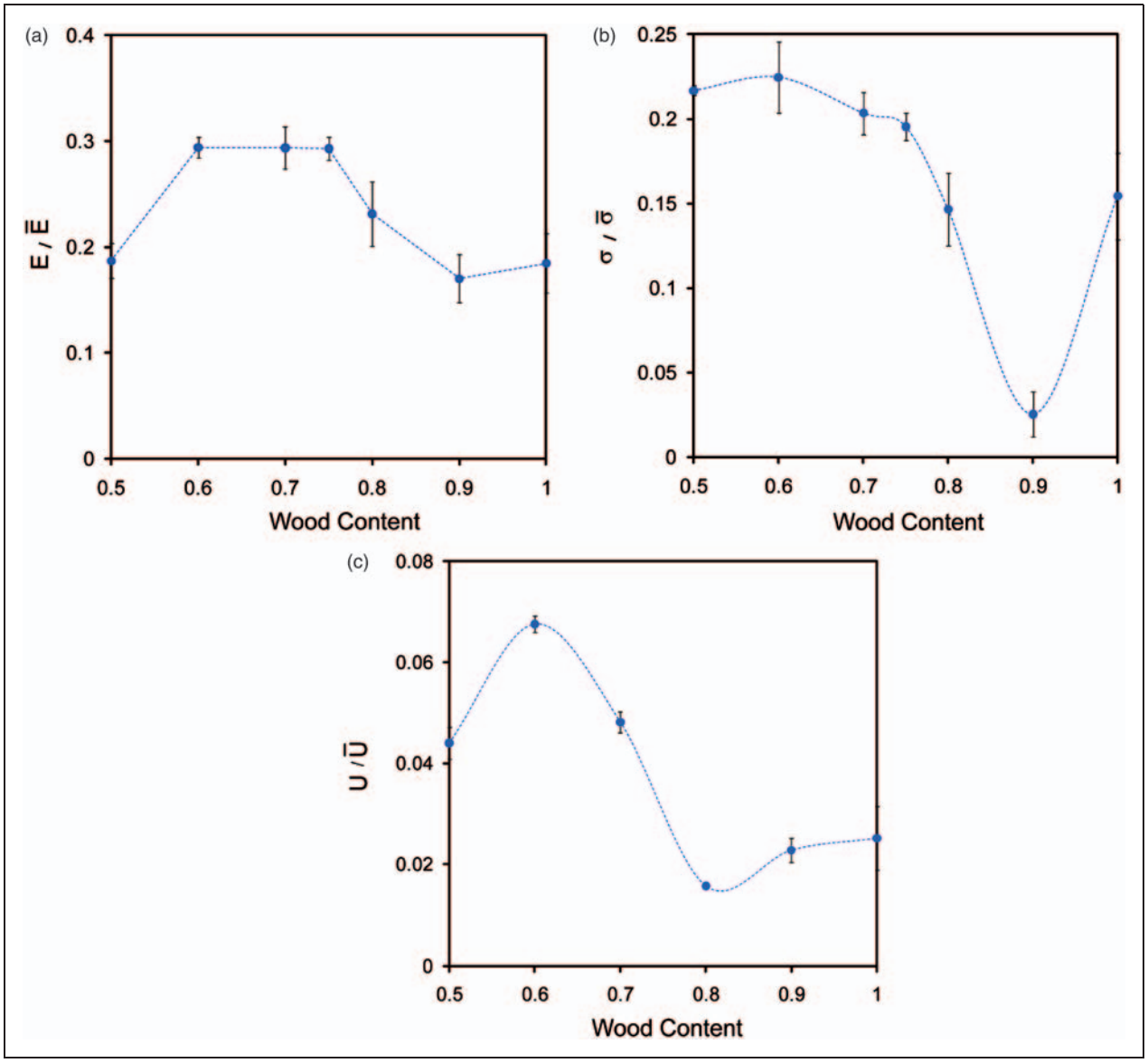

Figure 3. Effect of particle wood weight fraction on: (a) elastic modulus, (b) flexural strength, and (c) impact failure energy of WPC. Four specimens were tested for each processing condition. The error bars show the standard deviation from the average value.

processing temperature and flexural strength of WPC samples. Finite element analysis using the commercial finite element package ABAQUS (SIMULIA, Providence, RI) was used to obtain the temperature distribution in the specimen during the manufacturing. The results showed that after 30 min of mold-surface heating from an initial cold state, the temperature in the specimen is relatively uniform, and the difference between mold and the core composite temperatures is minimal (The core has a temperature that is ~90–97% of the mold surface temperature.) Thus, the results are presented in terms of mold temperature. Figure 2(a) shows the normalized flexural strength of WPC samples, $\sigma/\bar{\sigma}$, manufactured at different mold temperatures ranging from 93°C to 260°C. The results show that samples manufactured at the mold temperatures of range 121–196°C have higher values of tensile strength, with the samples manufactured at 121°C being the strongest. This range of temperature is apparently sufficient to melt the phenolic resin, so that it can flow in the matrix. Mold temperatures lower than 121°C did not result in complete melting of the phenolic component, resulting in a weak bond between the wood and phenolic matrix. Mold temperatures exceeding 196°C cause the wood content to burn, which results in various crack formations within the sample's cross-section. Specimens cured at 232°C showed some structural integrity and had flexural strength 8% of solid

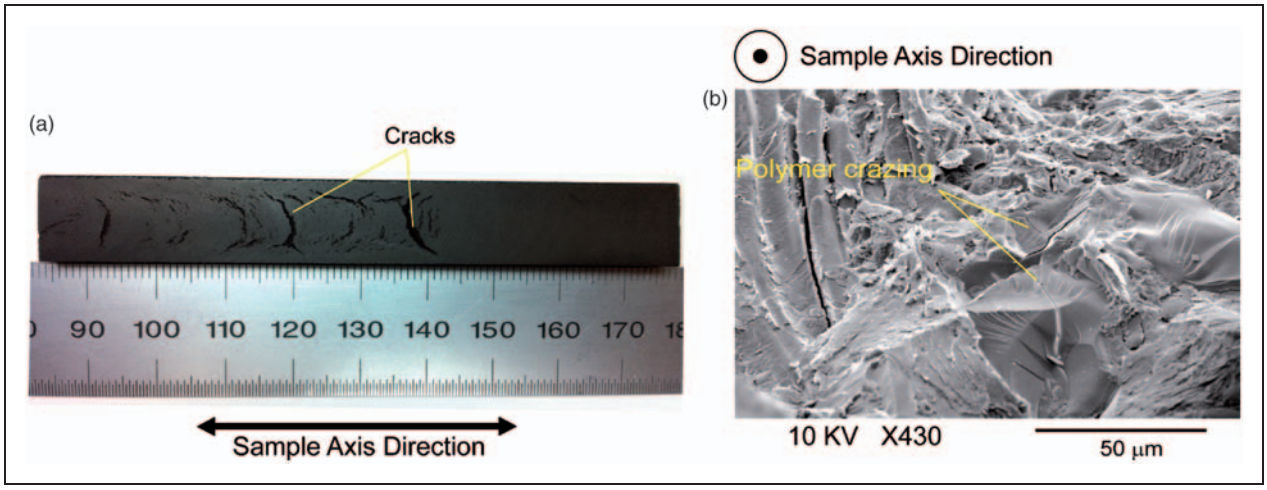

Figure 4. (a) Image of 80/20 wood/phenolic ratio WPC specimen, showing crack formation during production. (b) SEM result for 60/40 wood/phenolic WPC showing possible crazing in the resin-rich section of WPC.

Table 1. Normalized failure flexural strength and elastic modulus for WPC with 40% phenolic resin reinforced at 10% short E-glass fiber content with different fiber lengths normalized to the pull-out length, $l_c = 4.74$ mm

	No fiber reinforcement	$l/l_c = 1.05$	$l/l_c = 2.11$
$\sigma/\bar{\sigma}$	0.225	0.107	0.114
$E/\bar{E}$	0.294	0.268	0.321

African blackwood. Specimens manufactured at the mold temperature 260°C resulted in total wood burning and char formation, with no apparent strength. There was no exhaustive attempt to characterize any chemical reaction between phenolic resin and wood powders. However, since the processing temperature was below the char formation temperature (260°C), there was little reaction between phenolic and cellulose materials. The bond between phenolic resin and wood powder is believed to be a Van der Waals one.

Figure 2(b) shows the effect of mold pressure on the flexural strength of WPC. In general, increasing mold pressure reduces voids and porosity, and enhances the mechanical bonding of wood particles and phenolic. This leads to better mechanical properties of WPC.[23] However, in our experiments, the flexural strength of WPCs produced with 43.55 MPa (6 ksi) mold pressure is lower than those of specimens manufactured at lower mold pressure. The exact reason for this observation is not yet clear: one hypothesis is that considerably high mold pressure may cause significant bonding between particles, resulting in the entrapment of high pressure gases evolved in molding, with the potential to cause damage when the confining pressure is removed.

Effect of wood content and particle size on flexural and impact properties of WPC

We next studied the effect of the wood/phenolic mass ratio on the mechanical properties of WPCs, by systematically varying it. The normalized ultimate flexural stress, elastic modulus, and impact failure energy values for various wood/phenolic ratios show that a 60/40 wood/phenolic ratio provides the best mechanical properties, Figure 3. Samples with more than 70% wood content had lower mechanical properties and impact resistance. A detailed analysis of the microstructure of these composites revealed numerous cracks formed during molding, Figure 4(a). Chemical reactions between the wood and phenolic resin result in gas formation which could be entrapped in the composite.[24] For composites with more than 70% wood particle, there is not enough liquid resin to flow and push the gas out of the system (bleeding). This could be the reason for numerous cracks in WPCs with more than 70% wood. The lower mechanical properties of WPCs produced in comparison with the normal African wood could be due to low adhesion properties, intrinsic wood fiber size, and craze formation in polymer-rich areas of the WPCs as in Figure 4(b). Among the fabricated specimens, composites with 90% wood particle have inferior mechanical properties, as quantified in Figure 3. Wood-like specimens can be made from pure wood particle (i.e. 100% wood particle), as also studied in detail in the work of Imanishi et al.[2]

Effect of short E-glass fiber inclusion on flexural properties of WPC

In order to improve the mechanical properties of WPCs, the effect of short fiber addition to the wood

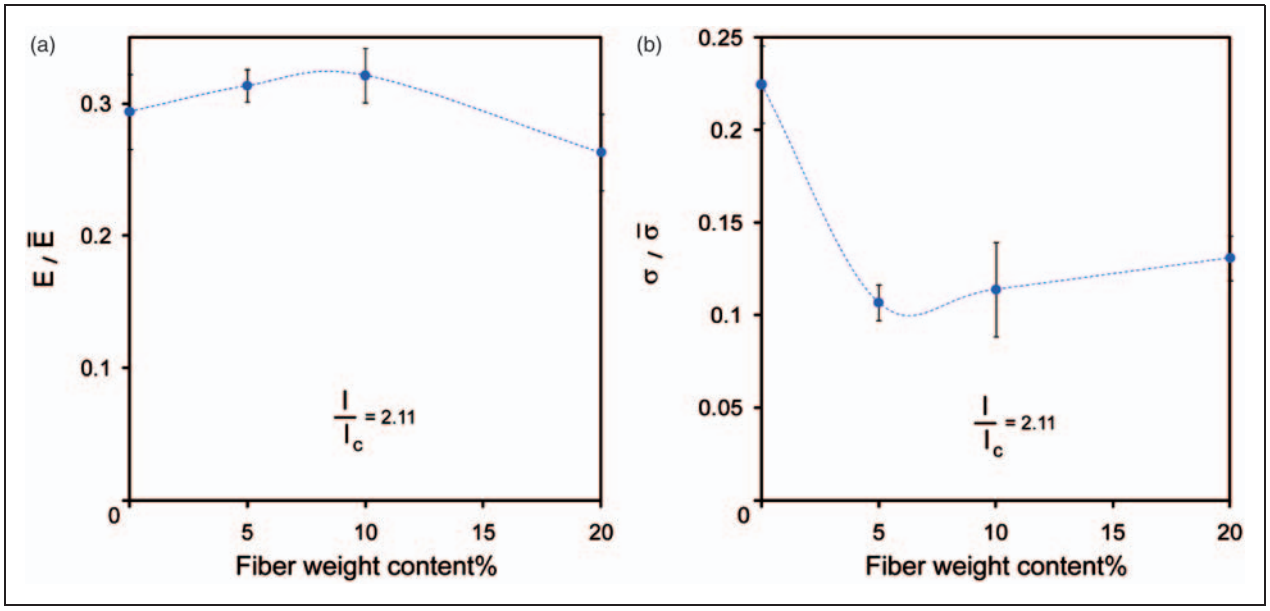

Figure 5. Effect of short E-glass fiber addition on: (a) elastic modulus and (b) flexural strength of WPC reinforced by 10 mm E-glass fibers. Four specimens were tested for each processing condition. The error bars show the standard deviation from the average value.

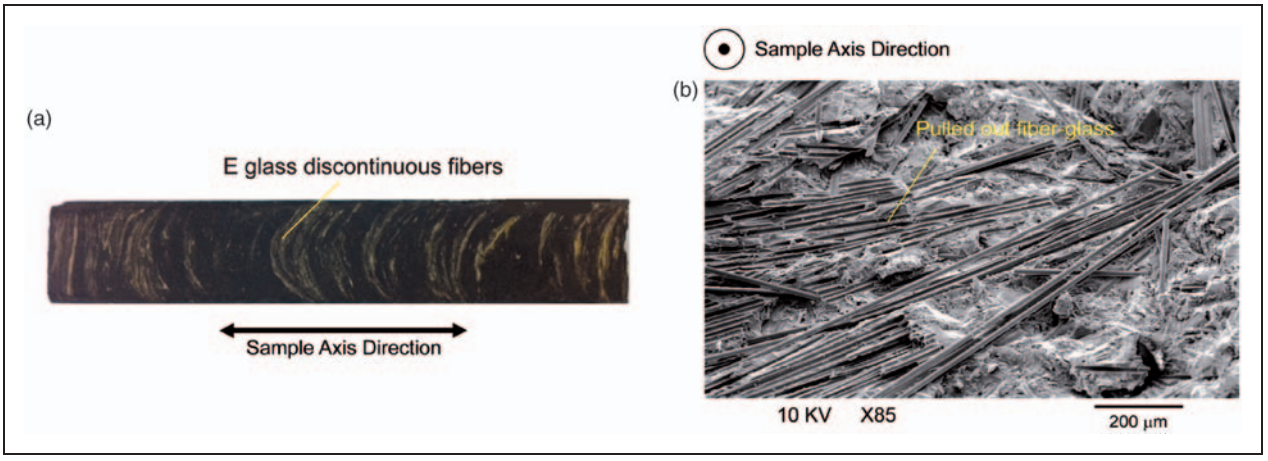

Figure 6. (a) Cross-sectional of WPC containing short E-glass fiber showing E-glass fibers are aligned transverse to the hot press molding direction. (b) SEM photograph of the fracture surface indicating low adhesion between fibers and WPC.

matrix was studied while maintaining 40% phenolic resin. Table 1 gives the ultimate flexural stress and elastic modulus values for WPC containing 10% (weight %) of E-glass fiber for two different fiber lengths ($l = 5$ and 10 mm). Fiber reinforcement does not have a significant effect on the elastic modulus of WPC. However, the flexural strength of WPC reinforced with fibers is considerably lower than the unreinforced one. In Figure 5, we extended these results for WPCs reinforced with 10 mm E-glass fiber, by varying the fiber weight content between 0% (no fiber reinforcement) and 20%. Again, the presence of fibers does not have significant effect on the elastic modulus, while even 5% addition of fibers results in significant reduction in the flexural strength of WPCs. Orientation of the fibers in the direction of the load is critical for enhancing the mechanical properties of composites.[7] As shown in Figure 6(a), E-glass fibers tend to orient normal to the plunger motion, reducing the flexural strength of the WPC. SEM results for the E-glass fiber-reinforced samples indicate that some E-glass fibers were pulled out of the WPC matrix in the sample's fracture surface. This is due to their low adhesion properties, Figure 6(b).

Conclusions

We studied the effect of different parameters such as wood content, mold temperature, mold pressure, wood particle size, and inclusion of discontinuous E-glass fiber on the mechanical properties of WPC made of African blackwood and phenolic. WPC specimens containing 60% wood have the optimum mechanical and impact properties. The use of discontinuous E-glass fibers with different lengths and contents reduced the flexural strength of WPC. This was due to formation of E-glass fibers in the transverse direction and poor adhesion between the incorporated fiber and WPC matrix.

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