Using Agricultural Waste to Create More Environmentally Friendly and Affordable Products and Help Poor Coconut Farmers

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Abstract. Each year, 64 000 000 000 coconuts are harvested around the world. The coconut water, coconut milk and/are coconut oil are produced from the coconut, leaving behind the coconut shells and the coconut husks, which are not well utilized. Exciting new ways to utilized coconut shell powder as function filler in engineering plastic such as polypropylene or polyethylene and to utilize coir fiber from the husk with polypropylene in non-woven fabric composites. These application demonstrate that the resulting environmental friendly composite materials have enhanced mechanical properties at a reduced cost.

Keywords: Coconut shell filler, coir non-woven, polypropylene composites,

1 Introduction

Coconuts are an abundant renewable resource [1]. Coconut trees that bear fruit (coconuts) are found on land that is within 20° of the equator. Globally, 64 000 000 000 coconuts are harvested each year; 15 000 000 000 of these harvested in Indonesia [2]. Most of the coconuts are cash crops for 11 000 000 poor coconut farmers who own several acres of land from which they harvest about 5 000 coconuts per year. The coconuts husks are opened to release the coconut, which is a large seed. The coconuts are subsequently opened, allowing the farmer to "harvest" copra and "coconut water". Harvesting the coconuts when they are "immature" and green provides primarily nutrient rich "coconut water" that is very tasty and nutritious. As the coconut matures, the inside of the coconut is gradually transformed into a fibrous husk and a hard shell (see Figure 1) that is lined on the inside with a nutrient rich, soft solid called "copra", with the residual coconut water remaining in the center of the coconut becoming somewhat bitter.

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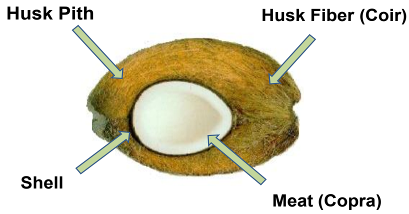


Fig. 1. Constituent parts of coconut.

The husk protects the "coconut" from fracturing on impact at the end of its 60 ft to 80 ft (18.288 m to 24.384 m) fall from the coconut palm tree. The coconut inside of the husk has both seeds and nutrients to jump start a new coconut tree. The copra is an amalgam of ~50 % coconut oil and ~50 % water, the amalgam being called coconut milk. Coconut milk can be processed to remove the water from the amalgam (plain water, not to be confused with nutrient rich coconut water found in a young, green coconut), leaving behind coconut oil. The constituent parts of the coconut are seen in Figure 1 for an opened coconut. Figure 2 gives the market value of each of the constituent parts. Currently the primary value of the coconut is found in either coconut water that is present in an immature coconut or in the coconut copra (sometimes called coconut meat) that replaces most of the coconut water coconut as the coconut matures. It is clear from Figure 2 that the coconut fiber in the coconut husk (usually called coir) and the coconut shell have little if any commercial value.

Value of Constituent Part of Coconut

- Coconut water ~USD 8.00 kg^{-1}
- Coconut meat
  - Coconut oil ~USD 30.00 kg^{-1}
  - Coconut milk ~USD 3.00 kg^{-1}
- Coconut shell ~USD 0.25 kg^{-1} burned as a fuel
- Coconut pith ~USD 0.25 kg^{-1} from husk for gardening
- Coconut fiber ~USD 0.25 kg^{-1} from husk for mattresses

Fig. 2. Value of constituent parts of coconut.

Fig. 3. Indonesian coconut farmer and family and coconuts.

Fig. 4. Coconut tree in kenya.

An Indonesian coconut farmer and his children are seen in Figure 3 and one of the 50 coconut trees that he owns is seen in Figure 4. The copra (white meat) that he extracts from the 5 000 coconuts yr^{-1} that he harvests brings him a total income of ~USD 500 (U.S.), or about USD 0.10 per coconut, which is hardly sufficient to support his family. Subsequently the buyer separates the coconut milk (coconut-oil-water amalgam) to produce coconut oil. Finally, the water is removed from the coconut milk to produce pure coconut oil. Depending on how the water is removed, the coconut oil produced will sell for between USD 5.00 L^{-1} and USD 30 L^{-1}. Figure 3 also shows a typical pile of coconut husks that have been discarded by the farmer who has opened the coconut husks to remove the nuts, which they subsequently open to reach the copra, with the husks considered trash/waste. The opening of the coconuts and the removal of the copra (white meat) create a second waste stream of coconut shell for which there is also limited commercial demand. The goal of this research (which is on-going) is to create value-added opportunities that utilize coconut shell powder and coconut husk fibers (coir) to make polymeric composite materials that can be competitive in high volume industries like automotive parts or building construction materials.

1.1 Physical and mechanical properties of fibers from coconut husks (coir)

The coconut husk's singular function in nature is to protect the coconut [3]. The husk is comprised of two constituents; namely, fibers (coir) which give structural strength and pith particles which act as a binder to hold the fibers together [4]. A piece of coconut husk viewed from the inside of the husk is seen in Figure 5 along with summaries of its functions in nature and the properties of coconut husk fiber (coir) that enable these functions.

Coir fibers are comprised of cellulose, hemi-cellulose, and lignin, all three constituents being common in woody materials [5]. What is relatively unique to coconut fibers (and to coconut shells as well) is it's very high lignin content of ~46 % [6, 7]. Most woody materials would have a lignin content of 5 % to 20 %. This high lignin content provides two benefits to the fiber (and therefore the husk). First, lignin is much more difficult to burn than cellulose or hemi-cellulose, making it more likely that a coconut can survive forest fires. This property of coconut husk fibers is also essential for such applications as mattress filler in China. Second, lignin is resistant to microbial attack because the microbes cannot digest lignin [8, 9]. This is important in many applications because microbial attacks create disgusting odor (i.e., think composting of typical waste organic material from your yard which is relatively low in lignin and very susceptible to microbial attack). For car parts, building materials, children's toys, and other applications, microbial attack reduces durability and creates odor problems. The high lignin content facilitates the function of the husk in protecting the coconut.

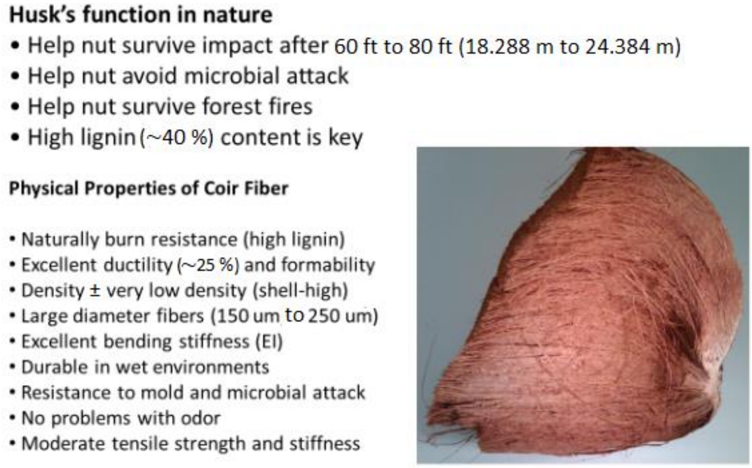


Fig. 5. Coconut husk's properties and function in nature.

A third critical property of the coconut fiber in the husk is its low density (1.1 g cm^{-3}) and high ductility (15 % to 40 %), [10, 11] allowing it to protect coconuts from fracturing on impact after their descent of 60 ft to 80 ft (18.288 m to 24.384 m) (from their high "nest" in the coconut tree. This excellent ductility gives the coconut husk the capacity to absorb a large amount of energy on impact, protecting the coconut from breaking on impact. It also means that composite materials that use coir fiber will have good formability as well as good impact strength.

A fourth unique property of the coconut fiber is its microstructure, as seen in a scanning electron microscope (SEM) Figure 6. [12]. The coconut fiber (coir) has an irregular honeycomb- like- structure, giving the fibers a very high specific stiffness (E/ρ) in bending.

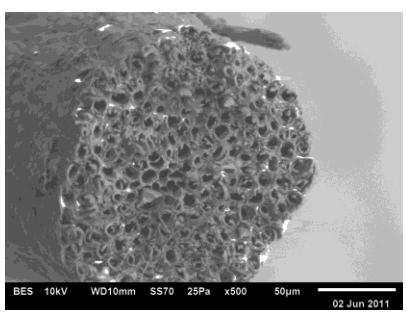


Fig. 6. SEM results on coconut fiber.

2 Research Methodology

2.1 Pathway from husks to finished parts made with coir fiber

Coir fibers from coconuts are blended with polypropylene fibers using a process called "air-laid carding and needle punching" to produce a non-woven fabric composite (flexible) felt, as seen in Figure 7, where the coir and fiber are seen before being mixed and after being air laid and needle punched to produce a flexible felt that is 2 m wide and 50 m long (in the shape of a roll). A scanning electron microscope picture of a piece of the non-woven fabric composite is seen in Figure 8. The larger diameter fibers are the coir fibers while the much finer fibers are the polypropylene (PP) fibers, which will subsequently melt and flow during compression molding at an elevated temperature and subsequently cooled to give a rigid part that has the shape of the mold. Figure 9 is an example of a compression molded trunk lid "trim" piece for an automobile. The whole process of extracting coir (fibers) from coconut husks and bailed, the blending of the coir fiber with polypropylene to make a flexible piece of felt, and the compression molding of the felt into an interior panel for a truck cabin.

Fig. 7. Polypropylene and coir fibers as non-woven fabric.

Fig. 8. SEM results for non woven fabric composite felt.

Fig. 9. Trunk lid made using non-woven fabric composite felt

A comparison of the flexural modulus of compression molded non-woven fabric composites of coir and polypropylene (PE) to those of polyethylene terephthalate (PET) and polyethylene (PE) is seen in Figure 12. The trade name for non-woven fabric composites of coir and polypropylene is COIRFORM, which will be used here after in this paper. Products and parts can be formed using thermoforming as well as compression molding. Figure 11 is a small part that has been made by thermoforming COIRFORM, demonstrating the excellent formability that COIRFORM has.

The flexural modulus of COIRFORM increases with the increasing fraction of coir fiber used in the COIRFORM because the coir fiber is much stiffer (2.6 GPa) [13] than the polypropylene binder (1325 MPa) [14]. The density can also vary by varying the pressure applied in the compression molding process since the free space in any non-woven fabric composite decreases with increasing processing pressure. Because the coir fibers are both stiffer in bending and have a lower density (see Figure 6) than the PET fibers, the

COIRFORM will be much stiffer in bending (Figure 12(a)). This is more clearly seen in Figure 12(b) which compares the rigidity versus density for PET/PE non-woven fabric composite to the COIRFORM non-woven fabric composite. The coir fibers significantly outperform the PET fibers in non-woven fabric composites, even at significantly lower densities. It is also worth noting that the coir fibers are much less expensive per pound than PET or other synthetic fibers and are obviously more environmentally friendly.

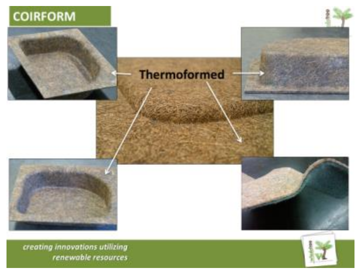
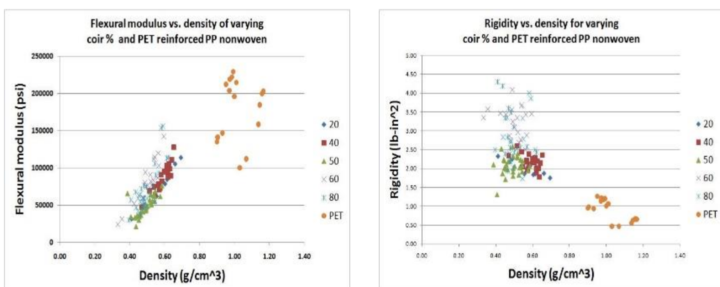


Fig. 11. Thermoformed part from felt with coir fiber and polypropylene.



(a) (b)

Fig. 12. Mechanical properties of Coir:PP and comparison to PET:PP which is wide used today [12].

Coir fiber can also be used as filler for chair cushions or mattresses. In fact, coir fiber is already widely in use in China as filler for mattresses. Collaborative work has been done with a major producer of seat cushions for patio furniture.. Alternative fiber possibilities do not have the mechanical properties that coir fibers have, especially resilience for more than a million cycles of fatigue without “pan caking” and without odor problems due to microbial attack.

2.2 Pathway from coconut shells to finished parts made with coconut shell powder as a functional filler in Polyethylene (PE), Polypropylene (PP), etc.

What are the unique physical and mechanical properties of the coconut shell that provide interesting opportunities for its use as functional filler in polymers (Figure 13)?

i. High lignin content that make it burn resistant and pest (and odor) resistance;
ii. High density (1.2 g mL^{-1} to 1.3 g mL^{-1}) compared to 0.6 g mL^{-1} hardwoods that are native (to U.S.);
iii. High hardness that is the consequence of high density and possibly high lignin content.

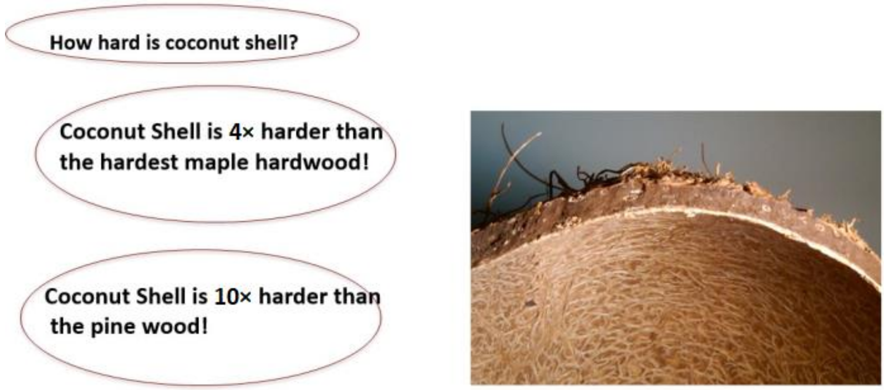


Fig. 13. What are the unique mechanical properties of coconut shell powder (CSP).

Fig. 14. CSP can easily be dyed to give more pleasing colors

The challenges that must be overcome in utilizing the outstanding properties of coconut shell powder as functional filler in PE and PP are listed below along with the current status in resolving each challenge.

i. How to create very fine (20 μ to 200 μ diameter) coconut shell powder from coconut shells? A proprietary process has been developed to make very fine coconut shell powder.
ii. Create a chemical coating that can be easily applied to the coconut shell powder that also bonds well with polyethylene, polypropylene and other engineering plastics to allow the hardness, stiffness and strength of the coconut shell powder particles to be efficiently transmitted to the plastic matrix. A proprietary interfacial bonding agent has been developed.
iii. Develop processing parameters to make a uniform mixture of coconut shell powder particles in pellets of PE and PP. Mixing the coconut shell powder into pellets for PE or PP is readily done on a twin screw with proper parameter settings determined.
iv. Determine resistance to environmental factors such as UV radiation and moisture. A major toy manufacturer has determined for us that the coconut shell powder actually acts as an UV inhibitor which can reduce and sometimes eliminate the need for additional UV inhibitors to be added, depending on the projected life-time exposure.
v. Determine resistance to microbial attack and the odor that it brings. The resistance to microbial attack for high lignin content organic material has already been established and has been confirmed for the use of coconut shell powder as functional filler in PE or PP.
vi. Testing in our laboratory has established that there is good retention of ductility and Izod impact toughness in PE and PP that has been made stiffer by the incorporation of coconut shell powder into these engineering plastic.
vii. Some products need to have bright colors rather than the natural brown color that results when PP or PE have 20 wt% coconut shell powder incorporated in the PP or PE pellets that will subsequently injection molded or extruded. A company that makes

toys paid to have various colored dyes incorporated into the pellets along with the coconut shell powder. These pellets were subsequently used for injection molding of pill cases of various colors, as seen in Figure 14. Clearly, various colored dyes can be incorporated in PE or PP pellets with coconut shell powder.

3 Results and discussion

The most interesting result of our experimental work has been to demonstrate the effectiveness of utilizing coconut shell powder as functional filler in PE and PP to increase the tensile strength and the tensile modulus. This experiments compared neat high density polyethylene to high density polyethylene with 20 wt% cedar “wood flour” and to high density polyethylene with 20 wt% coconut shell powder added. The results are presented in Figure 15. The coconut shell powder increased the tensile modulus by 56 % while the cedar “wood flour” increased the modulus by 32 %. It is possible to add up to 40 wt% coconut shell powder to nearly double the tensile modulus in high density polyethylene. The tensile strength is also enhanced by the addition of 20 wt% coconut shell powder to high density polyethylene, but the increase in tensile strength is only 10 % and the incorporation of cedar “wood flour” actually reduced the tensile strength by 3 %.

There are a wide range of products (see Figure 16) that can be made by using PP or PE with 20 wt% to 40 wt% coconut shell powder incorporated into the pellets prior to injection molding or extruding the consolidated PP or PE pellets with coconut shell powder.

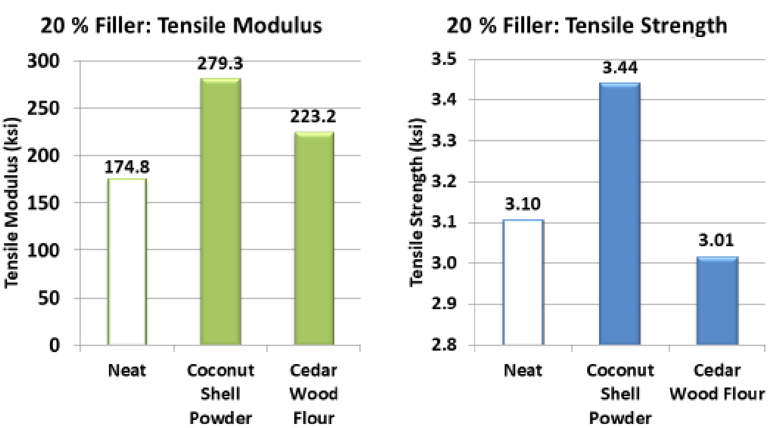


Fig. 15. The addition of 20 wt% coconut shell powder on tensile modulus (left) and tensile strength(right).

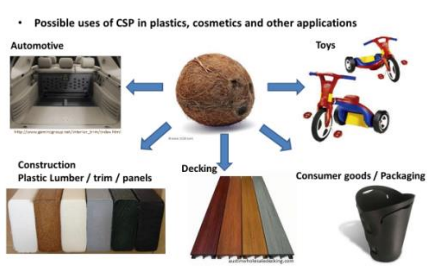


Fig. 16. All the products seen in the figure have been made with polyethylene with 20 wt% CSP.

3.1. Partnering with various companies

The authors have greatly benefited from working with several major companies who were interested in using coir fiber or coconut shell powder in the production of parts for their products. The results of these collaborative development projects created some excellent opportunities because they could provide larger orders (i.e., 15 000 lbs/6803.9 kg.) with the same cleanliness husk as fibers and coconut shells . It took more than two years to develop private production facilities for coir fiber and coconut shell powder in the Philippines.

With a toy company, we learned that pellets could be made with any color. They also determined that the PP or PE with shell powder made could be used to make toys, and these toys were very resistant to ultraviolet radiation induced degradation. Insufficient production of clean coir fibers compromised this opportunity.

With Ford Motors, the author demonstrated that some car parts could indeed be made using a non-woven fabric composite comprised of coir fiber and polypropylene. The Society of Plastics Engineering recognized this "invention" with an innovation award. Another major automotive company was able to make some trial door panels using coir fiber and polypropylene. The panels passed all of their tests and were their first choice for materials. Unfortunately, this opportunity was missed again because of the lack of sufficient supply of clean coir fibers.

One of the largest manufacturer of patio furniture want to do joint research project because. They wanted to make their cushions for their chairs with natural fibers. They did a whole battery of tests with sample cushions made with coir fiber filler. The testing included burn tests, resistance to microbial attack with repeated moisture exposure. They also ran compression fatigue tests of the cushion filled with coir fiber to see if there was any compacting of the cushions (permanent deformation) to 1 000 000 cycles. Coir fiber passed all of the required tests with flying colors. They made very successful production runs to create cushions filled with coir fiber at two of their six plants spread around the United States. Unfortunately, the other four older plants had equipment that was unable to process coir fiber successfully due to the greater fiber stiffness than the fibers they had been using, so they decided not to move forward as the cost to upgrade the equipment at the four plants would have been prohibitive.

4 Conclusion

Coirform non-woven fabric composites made with coir fiber and a polymeric binder fiber (i.e., PE) offer substantial improvements in performance at a lower cost as well as being more environmentally friendly. Coconut shell powder is functional filler that can significantly improve the modulus of elasticity of PE, PP and other engineering plastics and reduce the cost of pure PE and PP as well as providing a material with a reduced environmental impact.

Acknowledgments

The authors are grateful for assisted updating references by Jonathan Herlianto Wibowo.

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