Using Coconut Fiber and Shell as Functional Fillers in Polyolefin to Enhance Properties and Reduce Costs

Walter L. Bradley, Ph.D., P.E. & Steven W. Bradley, Ph.D.
Distinguished Professor Emeritus, Mechanical Engineering & Professor of Entrepreneurship
Baylor University
315 Summit Street, Georgetown, TX 78633, 254-230-5225

Abstract

The goal of this research is to utilize the abundant agricultural waste from the 50 billion coconuts harvested each year as functional filler in polyolefin to enhance their mechanical properties, reduce their costs and create more environmentally friendly products.

Introduction

Coconuts are an abundant renewable resource. Coconut trees that bear fruit (coconuts) are found on land that is within 20 degrees of the equator. Fifty billion coconuts are harvested globally each year. Most of the coconuts are cash crops for 11 million poor coconut farmers who each own several acres of land from which they harvest about 5000 coconuts per year that sell for ten cents each. The farmer opens the coconut husks to reach the coconut, which is a large nut (seed). The mature coconut's constituent parts illustrated in Figure 1 are: the fibrous husk on the outside, the hard coconut shell inside the husk, and a nutrient rich soft solid inside the shell called copra.

The farmer opens the coconuts to remove the white paste called copra, which is a mixture of coconut milk and coconut meal (fine particles that are carbohydrates and protein). The coconut milk is an amalgam of coconut oil and water. Currently, the highest value-added production from coconuts is primarily in the separation of coconut oil from the coconut milk. Alternatively, the coconut shell and husk have found limited commercial value and are, for the most part, considered a difficult-to-dispose-of waste product (Figure 2). The limited use of coconut shells from the 50 billion coconuts harvested each year is as a material for activated carbon filters or charcoal. Likewise, there is a limited market for coir (fibers) from the coconut husks in mattresses or seat cushions.

The goal of this research is to (1) create polymeric composite materials that utilize coir fiber from coconut husks and (2) use fine powders made from coconut shells as functional filler in polyolefin. In doing so, we can enhance current materials' mechanical properties, reduce costs, and produce consumer goods that are more environmentally friendly such as decking, fencing, automobile parts and building materials.

Physical and Mechanical Properties of Fibers (Coir) from Coconut Husks

The coconut husk's (see Figure 6) primary function in nature is to protect the coconut at the end of its 20m-25m fall from the coconut tree. A summary of the other functions in nature and properties of the coconut husk fiber (coir) that enable these functions are summarized in Figure 3. The husk is comprised of two constituents; namely, fibers (called "coir") that gives structural strength and 'pith' particles that act as a binder to hold the fibers together. Coir fibers are comprised of cellulose, hemi-cellulose, and lignin, all three constituents being common in woody materials. Coconut fibers have four relatively unique and very useful properties for end products.

Coconut fibers (and coconut shells as well) have a very high lignin content of ~40%. Most woody materials have a lignin content of 5-20%. The high lignin content of coir 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 safety for such applications as mattress filler or siding for houses. Second, lignin is resistant to microbial attack because the microbes cannot digest lignin. This is important in many applications because microbial attacks reduce durability and create disgusting odor (i.e., think composting of typical organic waste material from your yard, which is low in lignin and therefore susceptible to microbial attack).

A third critical property of the coir fiber in the husk is its low density and high ductility (~20-25%), allowing it to protect coconuts from fracturing on impact after their descent of 20-25m from their high "nests" 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 inside the husk from breaking.. 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 husk fiber is its microstructure, as seen in a scanning electron microscope (SEM) in Figure 4. The coconut fiber (coir) has an irregular honeycomb-like structure that gives the fibers a very high specific stiffness (E/ρ) in bending.

Pathways 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, flexible fabric composite felt. The coir fiber/PP mixture and resulting fabric is seen in Figure 5 along with fabric produced with the common PET/PE blend for comparison. Figure 6 shows coir and PP fibers before being mixed and after being air laid and needle punched in the SEM photo. The larger diameter fibers are the coir fibers while the smaller diameter fibers are the polypropylene fibers (PP), which 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. The production output from carding and needle punching is a flexible felt roll measuring 2 meters wide and 40 meters long as seen in Figure 7. The felt roll is a stage in the whole process which consists of: extracting coir (fibers) from coconut husks, bailing and shipping them, blending the coir fiber with polypropylene fibers to make a flexible piece of felt, die cutting pieces from the felt roll, and finally compression molding the die cut felt pieces into an interior panel part. An example of a compression molded trunk lid "trim" piece for an automobile is shown in Figure 7.

An advantage of the coir fiber/PP blend fabric, trade-named COIRFORM, is that the coir fibers are much stiffer in bending than PET fibers. Tthe flexural modulus of COIRFORM increases with the increasing fraction of coir fiber used in the COIRFORM. The density can also be varied 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 and/or increasing pressing temperature. Because the coir fibers are both stiffer in bending and have a lower density (see Figure 4) than the PET fibers, the COIRFORM will be much stiffer in bending (Figure 8a) at a comparable density.

The dramatic difference in flexural rigidity between a non-woven with PET and a non-woven with coir is due to the much larger diameter and "ragged" honeycomb structure. This difference can also be shown by comparing rigidity versus density for PET/PP non-woven fabric composite to the COIRFORM non-woven fabric composite in Figure 8b. 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.

Products and parts can be formed from COIRFORM using thermoforming as well as compression molding. A small part that was made by thermoforming COIRFORM is seen in Figure 9. The interior panel for a truck cab in Figure 10 demonstrates the excellent formability that COIRFORM has in compression molding.

Successful Partnerships and Supply Challenges

We 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. Working in partnership with Ford Motor Corporation, we demonstrated that specific 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" of a very light but very stiff load floor panel in their electric car with a Materials Innovation award in 2012

The results of these collaborative development projects created some excellent opportunities that we were unable to actualize because we could not find suppliers capable of providing larger orders (i.e., 15,000 lbs.) with the same quality of cleanliness for husk fibers that we had received in small samples of 50-100 lbs that had been hand cleaned. For example, a 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 specification for this part. Unfortunately, this opportunity was missed because of the lack of an adequate supply chain for clean coir fibers at the time. Today, Dignity can provide a large supply of clean coir fiber as a byproduct to their coconut oil business.

We were invited to do a joint research project with one of the largest manufacturers of patio-furniture. They wanted to use natural fibers to make their cushions for their patio chairs. They did a whole battery of tests with sample cushions made with coir fiber filler. The testing included burn tests and resistance to microbial attack with repeated moisture exposure. The manufacturer also ran compression fatigue tests of the cushions filled with coir fiber to see if there was any compacting of the cushions (permanent deformation) at 100,000 cycles. Coir fiber easily passed all the required tests. The furniture manufacturer had successful production runs to create cushions filled with coir fiber at two of their six plants spread around the United States. Unfortunately, the four older plants had air laid equipment that was unable to process coir fiber successfully due to the greater fiber stiffness than the fibers that they had been using. The company decided not to move forward as the upgrade of equipment at the four plants would have been cost-prohibitive and they did not want to have two different cushions for sale.

To summarize for coir fiber, the material has demonstrated valuable properties for finished products, but supply of the quality and quantity needed. We now have our own fully functional production facilities for coir fiber and coconut shell powder in the Philippines. We now turn to look at the exciting opportunities that coconut shell powder provides to enhance the mechanical properties of polypropylene and polyethylene in the next section.

Pathways to Finished Parts Made With Coconut Shell Powder as Functional Filler in PE or PP

What are the unique physical and mechanical properties of the coconut shell (Figure 11) that provide interesting opportunities for its use as functional filler in polymers?

- High lignin content that makes it burn resistant and pest (and odor) resistance;
- High density (1.2-1.3 g/cc) compared to 0.6 g/cc for hardwoods that are native (to the U.S.);
- High hardness that is the consequence of high density and possibly high lignin content.

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

Filler size. Could coconut shell with its excellent physical properties be produced in small enough diameters to meet common polymer filler standards? Yes, very fine coconut shell powder (20-200 microns diameter) can now be produced using a proprietary process that has already been successfully developed!

Coating and bonding. We needed to identify and create a chemical coating for coconut shell powder. The requirements were ease of application that bonds well with the coconut shell powder and with polyethylene, polypropylene and other engineering plastics to allow the hardness, stiffness and strength of the coconut shell powder particles to be effectively transmitted to the plastic matrix. Such a proprietary interfacial bonding agent has already been developed!

Processing. We developed processing parameters for a uniform mixture of coconut shell powder particles in pellets of PE and PP. Now, incorporating coconut shell powder into polyethylene, polypropylene, or other engineering plastic is easily accomplished with a twin-screw extruder.

Environmental exposure. We have examined the resistance to environmental factors such as UV radiation and moisture. A major toy manufacturer and potential partner determined for us that coconut shell powder acts as an UV inhibitor (as well as a mechanical property enhancer) reducing or eliminating the need for additional UV inhibitors depending on the projected life-time exposure.

Microbes and odor. The resistance to microbial attack and associated odor issues is established by the high lignin content organic material and the coconut shell powder has been confirmed for the use of in PE or PP.

Product applications. There are a wide range of products (see Figure 12) that can be made by using PP or PE with 20-40 wt% coconut shell powder incorporated into the pellets prior to injection molding or extruding to consolidated PP or PE pellets with coconut shell powder. Some products such as children's toys 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 PP or PE pellets that will subsequently be 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 13. Clearly, various colored dyes can be incorporated in PE or PP pellets with coconut shell powder to give a wide range of color in the product.

Mechanical properties. Testing in our laboratory has established that there is high retention of ductility and Izod impact toughness in PE and PP with stiffness enhanced by the incorporation of coconut shell powder into engineering plastics.

Perhaps, 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. Our experiments compared (1) neat high density polyethylene to (2) high density polyethylene with 20 wt% cedar "wood flour to (3) high density polypropylene with 20 wt% coconut shell powder added. The results are presented in Figure 14. 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%.

Summary

Coirform non-woven fabric composites made with coir fiber and a polymeric binder fiber (i.e., PE or PP) offer: (1) substantial improvements in stiffness; (2) lower costs; and (3) reduced environmental impact. Coconut shell powder is functional filler that can: (1) significantly improve the modulus of elasticity of PE, PP and other engineering plastics; (2) reduce the cost of using pure PE or PP; and (3) reduce environmental impact.

Acknowledgement

The following students each made significant contributions to the results presented in this paper: Elisa Teipel, Stanton Greer, Sean Conroy, Matt Kirby, David Fait, Ben Peterson, David Hagen, and Ryan Vano.

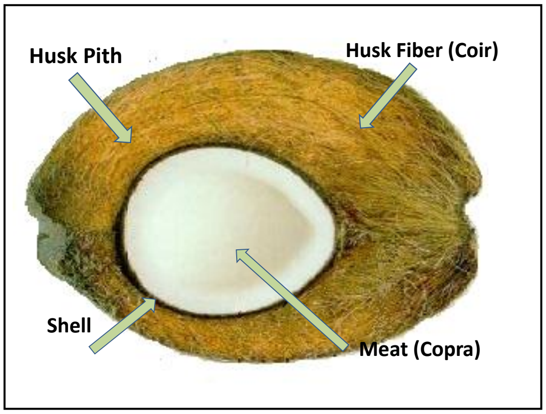

Figure 1: Constituent parts of coconut

Figure 2. Pile of discarded coconut husk as waste

Husk's function in nature

- Help nut survive impact after 60-80 ft drop
- Help nut avoid microbial attack
- Help nut survive forest fires
- High lignin (~40%) content is key

Physical Properties of Coir Fiber

- Naturally burn resistance (high lignin)
- Excellent ductility (~25%) and formability
- Density ~ very low density (shell-high)
- Large diameter fibers (150-250 um)
- Excellent bending stiffness (EI)
- Durable in wet environments
  - Resistance to mold and microbial attack
- No problems with odor
- Moderate tensile strength and stiffness

Figure 3. Coconut husk's properties and function in nature

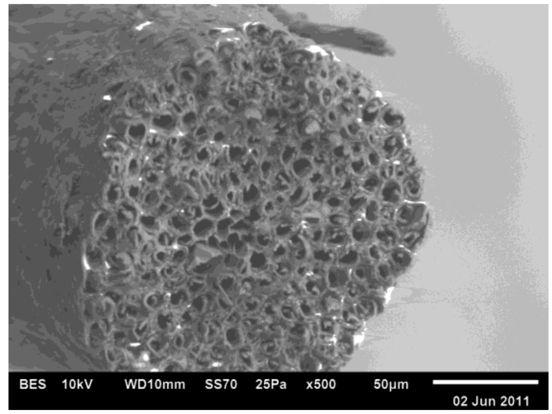

Figure 4. Scanning electron micrograph of cross-section of coconut husk fiber

Figure 5. Comparison of tufts of coir (fiber) and propylene fiber (top) and tufts of PET and PE binder fiber (bottom). These are carded and needle punched for felt used to compression mold into trim parts.

Figure 6 Inside of coconut husk, tuffs of coir fiber from husk and PP binder fiber, seen in scanning electron microscope (SEM) after being carded and needle punched.

Figure 7. (top) Tuffs of coir fiber and PP made into a felt 2-meter wide by 30 meters long. (bottom) PP+PET felted and compression molded into a trunk lid cover.

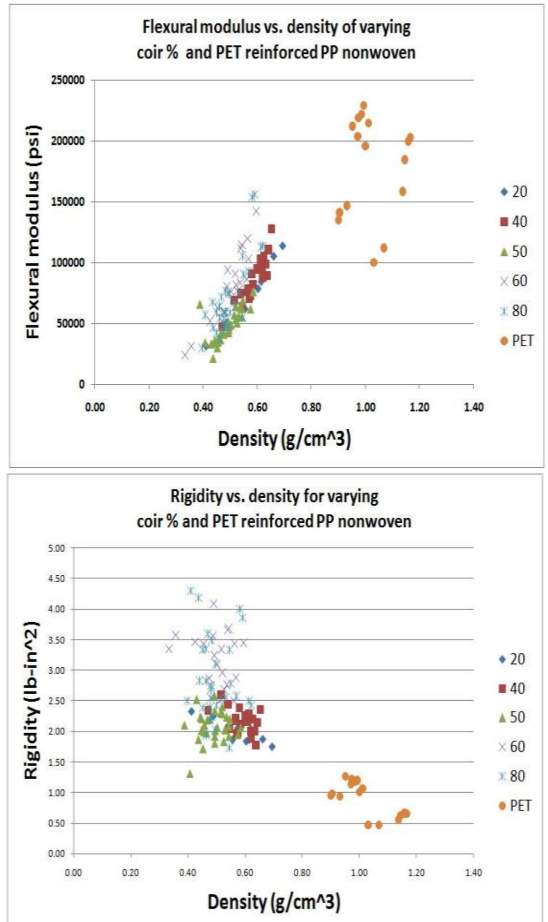

Figure 8. Flexure modulus (a) and rigidity (b) as a function of density for coir/PP vs. PET/PP

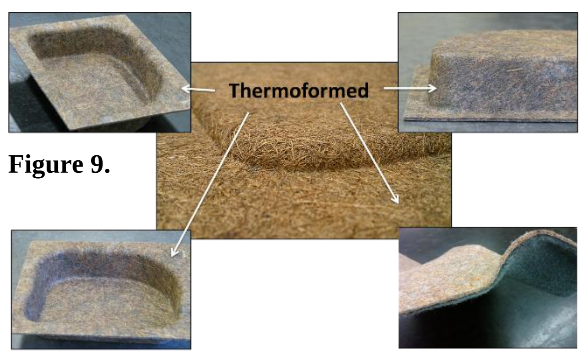

Figure 9.

Thermoformed part from felt with coir fiber and polypropylene.

Figure 10. Truck cabin part for 18-wheeler using compression molding felt of coir fiber and polypropylene.

Figure 11. What is unique about the mechanical properties of coconut shell powder (CSP)?

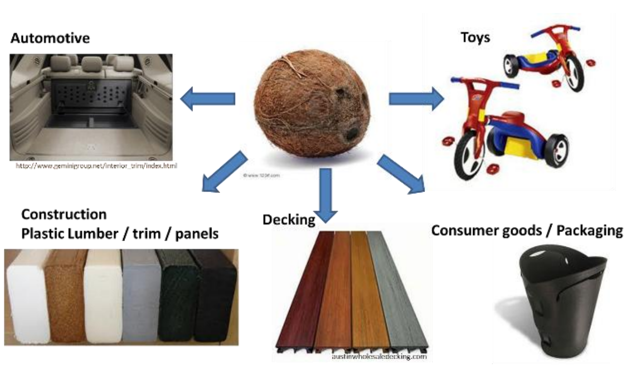

Figure 12. All the products seen in the figure have been made with polyethylene with 20wt% CSP.

Figure 13. Coconut shell powder can easily be dyed to give more pleasing colors than the natural brown.

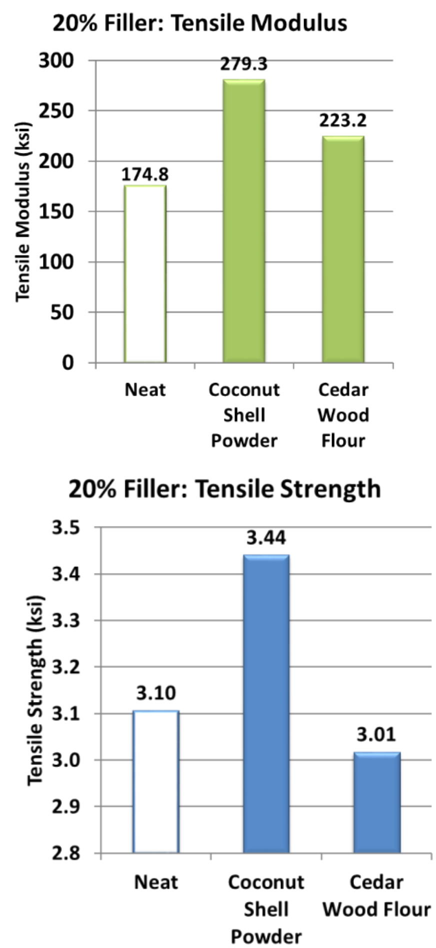

Figure 14. The addition of 20wt% coconut shell powder gives a 56% increase in modulus and 10% increase in tensile strength of polyethylene and, much better than cedar wood flour.