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Evaluation of Biocomposite for Implementation as Prosthetic Socket

An Undergraduate Honors College Thesis

in the

Department of Biological Engineering
College of Engineering
University of Arkansas
Fayetteville, AR

by

Chelsea Long

March 8, 2012

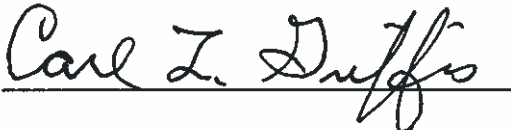
Honors Thesis Title: Evaluation of Biocomposite for Implementation as Prosthetic Socket

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Abstract

According to the World Health Organization, 0.5% of the population in developing countries is in need of prostheses or orthoses. For this population, obtaining a prosthetic is made difficult due to medical and transportation costs as well as a general lack of area resources. One possible solution to these problems would be to design a prosthetic socket from an inexpensive biodegradable material that could be produced in developing countries. One such material has been developed by Ecovative Design, LLC. Ecovative's technology grows mycelium, mushroom roots, throughout a plant fiber matrix. Ecovative products are completely biodegradable and made naturally from local agricultural byproducts allowing it to be produced anywhere in the world. The objective of this project is to test material properties of Ecovative flat stock samples to analyze the material's applicability as a prosthetic socket for developing countries. Properties evaluated include specific gravity, water absorption, coefficient of linear thermal expansion (CLTE), and hardness. The average specific gravity of the samples ranged from 0.1036 to 0.1440; the average water absorption ranged from 298.70 to 350.48%; the average CLTE ranged from -17.42 to $-2.99 \times 10^{-5}/^{\circ}\text{C}$; the top hardness ranged from 30.47 to 37.63 N; the bottom hardness ranged from 17.49 to 38.70 N. From this data, it was determined that the Ecovative samples tested have potential to be used in prosthetic sockets if it can be redesigned to lower the water absorption. A hydrophilic coating would be one of the recommendations to decrease the water absorption. Future research should include further evaluation of a hydrophobic coating for the Ecovative materials, complete characterization of the material as well as implementation within floatation devices, safety mats, and arch support shoe inserts.

Introduction

According to the World Health Organization, 0.5% of the population in developing countries is in need of prostheses or orthoses (WHO, 2011). For this population, obtaining a prosthetic is made difficult due to medical and transportation costs as well as a general lack of area resources. Although prosthetic manufacture is a well-established trade, many countries do not have the materials or the equipment to produce devices similar to those in developed countries (WHO, 2011). As a result, the disabled either handcraft a support device or go without, limiting their quality of life. Even those who are able to obtain a prosthesis are still faced with difficulties as a prosthetic must be replaced many times throughout a lifetime. According to certified prosthetist Scott Sabolich most manufactured prosthetic sockets will need to be replaced after two to four years. (Sabolich, 2006) This results in additional costs for the patient as well as a large quantity of discarded prosthetic devices. In addition, most prosthetic devices are produced by use of nonrenewable fossil fuels in an inefficient and environmentally damaging process.

One possible solution to these problems would be to design a prosthetic socket from an inexpensive biodegradable material that could be produced in developing countries. One such material has been developed by Ecovative Design, LLC. Ecovative's technology grows mycelium throughout a plant fiber matrix. Mycelium is the undifferentiated, highly branched body of a fungus (Mycelium, 2012). In the formation of this material, the mycelium partially digests the byproducts creating a naturally strong bond, gluing the mass together (Ecovative, 2011). This product can be formed at room temperature without any input of petroleum products (Nearing, 2008). Ecovative products are completely biodegradable and made naturally from local agricultural byproducts allowing it to be produced anywhere in the world (Bayer, 2010). It is the

goal of Ecovative Design to replace plastics in all industries with their biodegradable mycelium alternatives (Ecovative Design, 2011).

The objective of this project is to test material properties of Ecovative flat stock samples to analyze the material's applicability as a prosthetic socket for developing countries. Properties evaluated include specific gravity, water absorption, coefficient of linear thermal expansion (CLTE), and hardness. Three types of samples (table 1) were manufactured by Ecovative Design LLC using proprietary manufacturing technology. A total of ten samples were tested.

Table 1. Received samples' manufacturer and laboratory labels

Manufacturer Label	# Samples Received	Laboratory Label
3.3 UArk Ffom FB Prosthetics	4	P1-P4
5.26 preflip woven, H ₂ O ₂ , Cook 5.11.11 hemp, fom 001 pv 10 AC	3	W1-W3
5.26 preflip mat, H ₂ O ₂ , Cook 5.11.11 hemp fom 001 pv 10 AC	3	K1-K3

Materials and Methods

Specific Gravity

The specific gravity of the Ecovative samples was determined according to ASTM D 6111. Testing was conducted at the Biological and Agricultural Engineering Lab, University of Arkansas. Each sample was carefully cut with a razorblade to a length of 15.2 cm with the thickness and width of the sample unaltered. The samples were conditioned at laboratory atmosphere for 48 hours prior to testing. Each sample was weighed in air and this value was recorded as a . The immersion cage and suspending wire (figure 1) were immersed in water and

attached to the balance. This weight of the cage, wire, and sinker was recorded as w . The sample was then placed within the cage and completely immersed in the water with no part of the cage, sinker, or sample contacting the bucket. The balance was allowed to stabilize as air bubbles were removed from the sample surface and the weight was recorded just prior to the observed increase resulting from water absorption. The weight of the immersed sample, wire, cage, and sinker was recorded as b . This process was repeated for each sample being tested and the bulk specific gravity of each sample was calculated by dividing the weight of the sample in air by the weight of the sample in water.

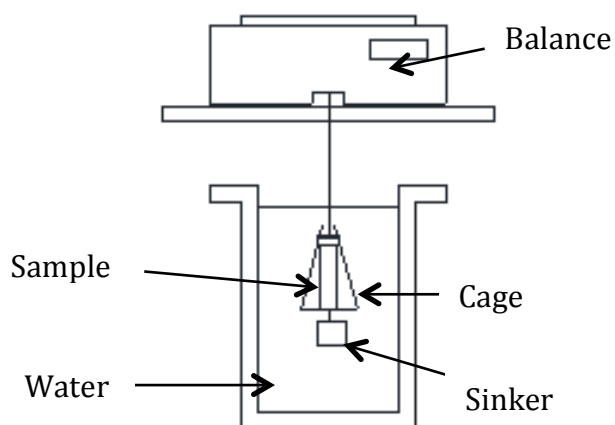


Figure 1. Specific gravity test apparatus

The specific gravity of each sample was calculated as follows:

$$Sp\ gr_{23}^{23\text{ }^{\circ}\text{C}} = \frac{a}{(a+w-b)} \quad (1)$$

where:

a = overall weight of sample in air

b = overall weight of immersed specimen, cage, and sinker with partially immersed wire

w = overall weight of immersed wire, cage, and sinker with partially immersed wire

Water Absorption

The water absorption of the Ecovative samples was determined using section 23 of ASTM D 1037. Testing was conducted at the Biological and Agricultural Engineering Lab, University of Arkansas. The samples being tested were carefully cut with a razorblade to 15.2 cm in length with the thickness and width unaltered. The samples were conditioned in laboratory atmosphere for 48 hours and then each sample's weight was measured and recorded. The samples were placed in an oven at 103°C and the weight of each was measured over five days to determine the bone dry mass of each sample. The samples were then reconditioned until each had reached its initial weight. The weight, width, length, and thickness of each piece was measured. Four thickness measurements were made at different locations on each sample and the average thickness was calculated. The cut surface of each sample was then sealed with adhesive tape and the sample was reweighed to determine the weight of the added tape. The samples were submerged horizontally in 20°C water with a plastic cover plate on top. Due to the low specific gravity of the samples, a five gallon bucket was placed on top of this cover plate and water was added to the bucket until the samples were able to float while completely submerged in water. For the first hour, each sample was weighed every five minutes and replaced in the water. The

samples were then weighed every hour for two hours followed by measurements at least once per day. Testing continued until the percent change of every sample was less than 1%.

Coefficient of Linear Thermal Expansion

The coefficient of linear thermal expansion (CLTE) was determined according to ASTM D 6341. Testing was conducted at the Biological and Agricultural Engineering Lab, University of Arkansas. The samples being tested were carefully cut with a razorblade to 15.2 cm in length with the thickness and width unaltered. The cut samples were conditioned at 23°C for 48 hours. The length of each sample was measured at three points and the average of these lengths was determined as L_2 . The same samples were then conditioned at -19°C for 48 hours and then similarly measured with the average length L_1 . Those samples were then conditioned at 60°C for 48 hours and measured with an average length L_3 .

Hardness

The hardness of the samples was determined by use of the modified Janka-ball test as specified in ASTM D1037 (ASTM, 2006) with an Instron electromechanical material testing machine model 4206. Testing was conducted at the Biological and Agricultural Engineering Lab, University of Arkansas. Each sample was cut with a razorblade to 15.2 cm in length with the thickness and width unaltered. Samples were conditioned in laboratory atmosphere for 48 hours prior to testing. The thickness of each sample was measured at four different locations and the average of those values was determined. Each sample was tested twice on top and twice on the bottom with each penetration at a different location on the surface of the sample. For the purpose of this test, the top of the sample was the side with exposed fungus while the bottom was the side

with exposed fibrous covering. The Instron was fitted with an 11.3 mm diameter ball for hardness testing. The crosshead speed was set to 6 mm/min with continuous load application. Load application continued until half the diameter of the ball penetrated the sample. This recorded load was the hardness of the sample.

Results and Discussion

Specific Gravity

The specific gravity of the samples was quite low (table 2) which corresponds to a light weight material. It is desirable for a prosthetic socket to be produced with a material of low specific gravity as this reduces the weight of the prosthetic device giving the user greater ease of mobility.

Table 2. Results of specific gravity test by sample type

Laboratory Label	Manufacturer Label	Average sp gr 23/23° C	Standard Deviation
P	3.3 UArk Ffom FB Prosthetics	0.1440 ^a	0.0148
W	5.26 preflip woven, H ₂ O ₂ , Cook; 5.11.11 hemp, fom 001 pv 10 AC	0.1036 ^b	0.0050
K	5.26 preflip mat, H ₂ O ₂ , Cook; 5.11.11 hemp fom 001 pv 10 AC	0.1128 ^b	0.0108

* Different letters indicate a significant difference at $\alpha = 0.05$

The determined specific gravity of the Ecovative material was much less than that of wood and plastic materials often used for a prosthetic socket in developing countries (table 3). As a result, the Ecovative samples have the advantage of providing a lighter weight prosthetic socket than the currently used materials presented in Table 3.

Table 3. Specific gravity of woods and plastics

Material	Specific Gravity
Pine	0.37 [*]
Cedar	0.32 [*]
Polypropylene	0.9 ^{**}
Glass Fiber Reinforced Plastics	1.6 ^{**}

* (Shmulsky, 2011)

** (Rosato, 2001)

It was, however, observed that the material properties of the samples may be compromised by contact with water. Upon submersion in water, the pigments from within the fibers were released into the surrounding fungus and water. Both the fungus and water were turned from white to yellow in color. Also, the samples became noticeably softer to touch and more susceptible to bending.

Water Absorption

For a device that will be in contact with the human body as well as factors such as humidity and rain, a relatively low water absorption is necessary. It is, however, desirable for a

prosthetic socket to wick away small amounts of water to ensure the comfort of the user as wicking away of sweat is considered much more comfortable than trapping it in the space between residual limb and socket. The temporal trend in water absorption of the samples is shown in Figure 2. The water absorption over square root of time is not a typical linear curve as is the case for most composites. The large size of the samples, and distinctly different layers (mycelium outer layer and plant fiber with mycelium at the inner layer) may have contributed to this non-linear trend. The 3.3 UArk Ffom FB Prosthetics samples seem to have a slightly lower water absorption compared to the other two samples.

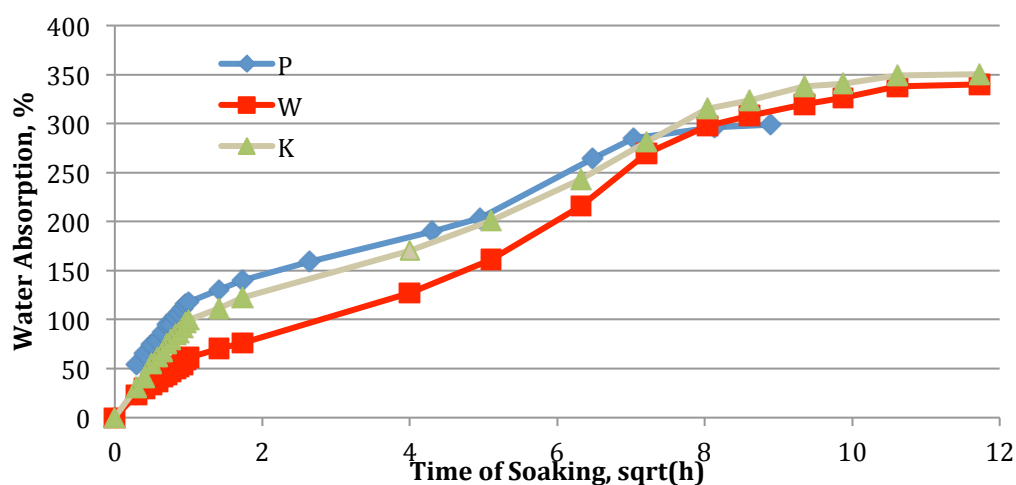


Figure 2. Water absorption results over time

The average long-term (6-day) water absorption for each sample type was determined from the measured water absorption for each sample and is shown in Table 4. The long-term water absorption of the Ecovative samples is extremely high for use as a prosthetic socket without modification. Throughout this testing the material continually lost rigidity and surface firmness as it absorbed more and more water. Also, some debris separated from the material

within the water. The higher water absorption poses a significant concern for use of this material as it must be protected from any amount of exposure to water. There is potential for the samples to be coated with a hydrophobic material on the outer exposed surface to prevent it from contact with water and enabling the samples to be used as a prosthetic socket. The inside surface can be partially coated or left as is to ensure it maintains some desired degree of water absorption.

Table 4. Average water absorption of Ecovative samples

Laboratory Label	Manufacturer Label	Average Water Absorption (%)
P	3.3 UArk Ffom FB Prosthetics	298.70 ^a
W	5.26 preflip woven, H ₂ O ₂ , Cook; 5.11.11 hemp, fom 001 pv 10 AC	340.25 ^{ab}
K	5.26 preflip mat, H ₂ O ₂ , Cook; 5.11.11 hemp fom 001 pv 10 AC	350.48 ^b

* Different letters indicate a significant difference at $\alpha = 0.05$

Coefficient of Linear Thermal Expansion

The average CLTE value for each sample type is summarized in Table 5. The negative values indicate that the material shrank as it was exposed to higher temperatures. This is a common behavior for wood, plant fibers, and other organic materials. However, most of the polymers such as polypropylene used for prosthetic sockets tend to have high positive values for CLTE, indicating expansion under elevated temperatures.

Table 5. Average coefficient of linear thermal expansion (CLTE)

Laboratory Label	Manufacturer Label	CLTE ($10^{-5}/^{\circ}\text{C}$)
P	3.3 UArk Ffom FB Prosthetics	-17.42 ^a
W	5.26 preflip woven, H ₂ O ₂ , Cook; 5.11.11 hemp, fom 001 pv 10 AC	-2.99 ^b
K	5.26 preflip mat, H ₂ O ₂ , Cook; 5.11.11 hemp fom 001 pv 10 AC	-5.93 ^b

* Different letters indicate a significant difference at $\alpha = 0.05$

The coefficient of linear thermal expansion of the Ecovative materials is similar in quantity to that of other materials commonly used in prosthetic sockets (Table 6). However, the Ecovative samples have a negative CLTE which is consistent with other biological materials. Due to the resemblance of these results with other common materials, the Ecovative materials could potentially be used as a prosthetic socket.

Table 6. CLTE of other prosthetic socket materials (Ashby, 1999)

Material	CLTE ($10^{-5}/^{\circ}\text{C}$)
Polymer	3-35
Polyester	4.5-8
Epoxy	6-10
Wood	-1.2-2.8

Hardness

The surface coating by mycelium provided a satiny and soft surface to the material that could potentially provide a comfortable interface to human skin. Also, the surface exhibited

some elastic property. After the Janka ball was pressed into the surface, the surface regained its original shape once the ball was removed. This again indicates a positive attribute for use as a prosthetic socket. The Janka ball hardness of the Ecovative samples were extremely low, verifying the fact that the material has a soft surface. There was much variation in the hardness of the three different Ecovative materials. The average and standard deviation of the hardness of each sample type was calculated as shown in Table 7. The large variability in the surface hardness of the materials (as indicated by large standard deviations) was caused by the nonuniformity of the Ecovative samples evaluated. The surface of many samples had a wavy appearance which was probably caused by non-uniform clustering of mycelium. More research has to be conducted to generate a smoother surface with more even distribution of mycelium and surface hardness.

Table 7. Janka Ball hardness of Ecovative composite samples.

Laboratory Label	Manufacturer Label	Average Hardness (N)	Standard Deviation
P top	3.3 UArk Ffom FB Prosthetics	30.53 ^a	19.82
W top	5.26 preflip woven, H ₂ O ₂ , Cook; 5.11.11 hemp, fom 001 pv 10 AC	37.63 ^a	7.42
K top	5.26 preflip mat, H ₂ O ₂ , Cook; 5.11.11 hemp fom 001 pv 10 AC	30.47 ^a	15.15
P bottom	3.3 UArk Ffom FB Prosthetics	17.49 ^{a*}	12.47
W bottom	5.26 preflip woven, H ₂ O ₂ , Cook; 5.11.11 hemp, fom 001 pv 10 AC	38.70 ^{ab*}	13.02

K bottom	5.26 preflip mat, H ₂ O ₂ , Cook; 5.11.11 hemp fom 001 pv 10 AC	27.45 ^{b*}	12.27
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* Different letters indicate a significant difference at $\alpha = 0.05$

Conclusion

Three different sets of Ecovative composite samples were measured and analyzed to evaluate their suitability for application as prosthetic sockets. The material tested exhibited highly favorable properties such as low specific gravity, low surface hardness and acceptable CLTE. However, the extremely high water absorption was a major concern. To permit the use of these materials in prosthetic sockets, a hydrophilic coating would be necessary. A material such as a plastic could be used for this application but would detract from the biodegradability of the samples. Also, this addition could make it more difficult to produce the prosthetic sockets in developing countries. Additional research is also needed to produce the material with a more uniform surface distribution of mycelium to ensure uniform surface hardness. Further material strength testing is currently being conducted as part of a Masters research project within the Department of Biological and Agricultural Engineering. Tests being conducted include bending, tension, and compression to ensure complete characterization of the material strength. This material has potential to be used in other applications such as floatation devices, arch support in shoe inserts, and safety mats, to name a few.

Future Research

While the Ecovative composite samples are not perfect as manufactured for implementation as a prosthetic socket, further testing should be completed into their potential

use. The application of a hydrophobic material to the external surfaces of the samples would prevent water absorption and could serve to counteract the nonuniformity by more evenly distributing loads.

Due to the low specific gravity of the Ecovative composites, these materials have a high applicability for internal components of flotation devices. Possibilities include buoys and boat insulation. Further testing would be necessary to determine the thermal properties of the composite for implementation as insulation within a boat.

There is also potential for this material to be used for safety applications. The low hardness of the Ecovative composites could be beneficial to applications such as athletics floor mats and wall pads. Based on the low hardness, another application of consideration is shoe insert arch supports.

Since development of the mycelium composites tested in this project, Ecovative Design has continued to adjust the composition of their materials to determine other potential uses. Currently, Ecovative has developed composites for use in packaging, insulation, building products, automotive and consumer products. Each of these composites was designed with specific criteria for usage and therefore each has different material properties. (Ecovative, 2011) With the new development of structural mycelium products, it is probable that Ecovative has designed more uniform composite materials which could be more appropriate candidates for implementation as a prosthetic socket. This possibility should be further investigated by conducting material properties tests on different newly developed Ecovative stock samples. Also, Ecovative is in the process of developing a production method for developing nations which would assist the objective of designing a biocomposite prosthetic socket for use in developing countries.

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