Shape Changing Biofoam

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ABSTRACT
Shape-changing designs and technologies are an emerging topic and allow us to imagine a future where moving materials help us humans or other species. In this paper, the creation of a new Shape Changing Biofoam material is discussed, which uses no petroleum-based or chemical ingredients. Through the Material Driven Design method and material tinkering, a recipe for a biofoam was developed and a bilayered structure was created with other biodegradable ingredients. The material is hygromorphic because of its porous structure. So exposure to water causes the material to move, depending on its shape and the amount of water it is exposed to. The ingredients, making process, and explorations are described and visually supported by the results. And finally, the possible future applications are discussed.

Authors Keywords
Materials Experience, Material Driven Design, Materials, Biofoam material, Shape Change

INTRODUCTION

Shape-changing designs are an emerging phenomenon in the fashion industry and architecture. Biobased materials are getting more popular to apply for this purpose, and also get everyday applications like clothing brands using mycelium-based leather[14]. However, the focus on biodegradable materials is often overlooked. Within this study, the goal was to create a material that does not harm the environment when it is at the end of its life-cycle, but still has the possibility when it is exposed to water. The main ingredients are water, konjac powder and gelatine. With these ingredients, a biofoam material was created which was finally used to create a bilayered structure together with a layer of linen covered in beeswax. This hygromorphic material is easy and cheap to manufacture and proves that making biodegradable materials is not as hard as it seems.

In this paper first, the relevant topic specific research is discussed about biodegradable materials. After this, the application of the Material Driven Design method and the explorations of the possibilities within the field of biodegradable and shape-changing materials is explained. Then a recipe for a Shape Changing Biofoam was visualized, with the ingredients and utensils necessary. Finally, all the tinkering with this recipe was described and the outcome was visually represented with discussions and conclusions of every test. Some possible applications for the material, like a plant shelter was suggested and the limitations of the study like the limited amount of time was further discussed.

Figure 1. The imitation of flower blooming using the shape changing biofoam

RELATED WORKS

The Principle behind Water Absorption

To create a hydro-responsive material, it is important to understand the basic principles of hydrophilicity and other water absorption mechanisms. The characteristic hydrophilic is given to a material when it can attract water on a molecular level and bind it to its surface [3].

In our recipe, konjac and gelatin are both hydrophilic substances[6][13], which means they both have the ability to absorb water. Meanwhile, they are also the common ingredients of bioplastic [10][5]. Therefore, they are included in our recipe for an eco-friendly, hydro-responsive material.

Hydro-responsive materials are also described as 'hygromorphic' materials, which refers to 'objects respond to environmental humidity by changing their shape' in Reyssat and Mahadevan's article[15]. In their article, they studied the mechanism of the shape-changing behavior of pine cones and introduced the biomimetic hygromorphs with bilayers they created by applying the mechanics of flow through a porous medium in one of the layers.

This corresponds to our inspiration from sponges, which also have a pore structure to absorb water. Hygromorphic materials usually feature bilayered structures, where one layer is more responsive to water than the other. This kind of structure can be seen in many other applications like artificial composite actuators[20], biohybrid wearables[18], and materials for responsive architecture[11].

Benchmarking shape changing materials

The material benchmarking reveals the basis ingredient, structure, and applications of other hygromorphic materials. This helps us understand more about the mechanism behind their shape-changing behavior, as well as, have more ideas about the applications of the material. (Table 1.)

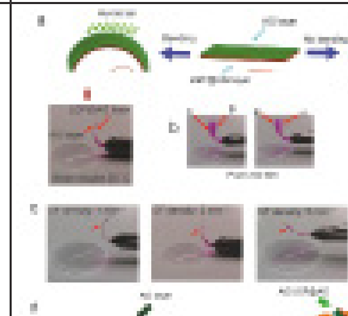
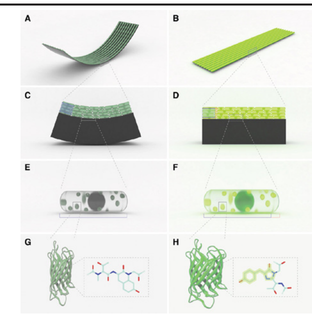
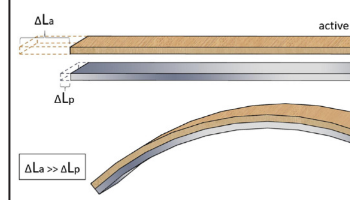
	Biomimetic actuators	Biohybrid wearables	Responsive architecture
Basic ingredient	Cellulose microfibrils: glass fibers (GFs) and agarose (AG)	Biohybrid films (Escherichia coli cells)	Wood veneer
Size	small	medium	large
Structure			
Application	Could be combined with a piezoelectric generator into energy transducers that convert the potential energy of humidity into electricity		

Table 1. Benchmarking of shape changing materials

Biodegradable ingredients

With the vision of sustainability, we consciously selected natural materials that are natural and biodegradable. Both gelatin and konjac are biodegradable ingredients that have been used in other explorations of sustainable design[9][19]. Meanwhile, linen and beeswax can also be seen in some eco-friendly products such as linen bags or beeswax wraps (Figure 2). Linen is one of the most biodegradable fabrics and untreated linen can be decomposed in two months[16]. While combined with beeswax, which is also biodegradable[4], we expected the material can still be decomposed. These eco-friendly ingredients have added a value of sustainability to the novel material we are designing.

Figure 2. Reusable beeswax wraps[1]

METHOD

Introduction to the Material Driven Design (MDD) method

The topic 'Hydro-responsive structures' was proposed to the team by the department of Industrial Design at the Eindhoven University of Technology. The logical equation of 'what' +'how' leads to 'value' can be used to analyze our design situation[8]. The only known is to design a hydro-responsive 'what'. And the 'how' and 'value' were yet to be discovered. As described in Material Driven Design[12], our project is about designing an exploratory material proposal. Our challenge was that foamy bioplastic is a semi-developed material. The knowledge of the material could only be accumulated by referencing other materials and through the hands-on experience of the material (including making and tinkering).

Development of Shape-changing Biofoam

With our previous experience of making a foamy bioplastic[17], we know that pore structure can be observed on it. (See Appendix X) Therefore, we continued to explore ways of creating foam during the making process of bioplastic and preserving the foam until the material was stable.

Create Pore Structure in Bioplastic

Baking soda (NaHCO3) is used in recipes as a chemical leavener. When heated above 80 degrees Celsius, it undergoes a decomposition reaction and produces carbon dioxide. It was used in our first recipe for foamy bioplastic. (See Appendix X) However, the foam dissipated quickly while poured from the pan into the mold, and the solution stratified when it was in the pan. We then moved on to seek other ways to create foam. Eventually, we tried to include a blender in the making process, to physically stir air into the solution. Also, we added Konjac to the recipe to make a thicker solution to avoid the dissipation of foam.

Double Layered Material

It requires two layers to create the structure of shape-changing. In the first iteration, we attached the selected fabrics which are less sensitive to water to the biofoam during the making process before putting them into the dehydrator. The selected fabrics are bee wax, cork, linen, and jute (Figure 3). The material for the second layer must not only respond less to water but also serve as a reinforcing element, while maintaining the flexibility necessary for the entire structure to bend when exposed to water. Thus, we chose linen incorporated with beeswax as the second layer material. Beeswax, serving as both a water-resistant barrier and an adhesive, effectively binds the two layers together. More experiments were conducted and to find the best proportion of konjac and gelatin to create the most ideal material for hygromorphic behavior[7]. (Figure 4)

Figure 3. Four types of fabric to attach to foam, from left to right: wax, cork, linen, jute.

Figure 4. Same size samples of conjac and gelatine, in different proportions.

The Making Process

Five ingredients were used to make the shape changing biofoam, being konjac powder, gelatin, linen, beeswax and water. All the ingredients for the material are easy to get in the store or online and inexpensive in The Netherlands. First we will discuss the ingredients in more detail, after which the recipe is explained.

Figure 5. Exploded view of the material

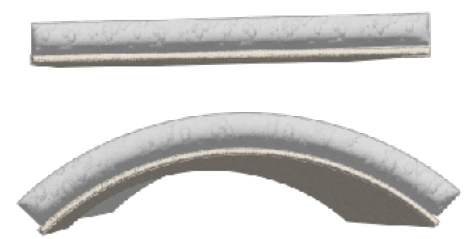
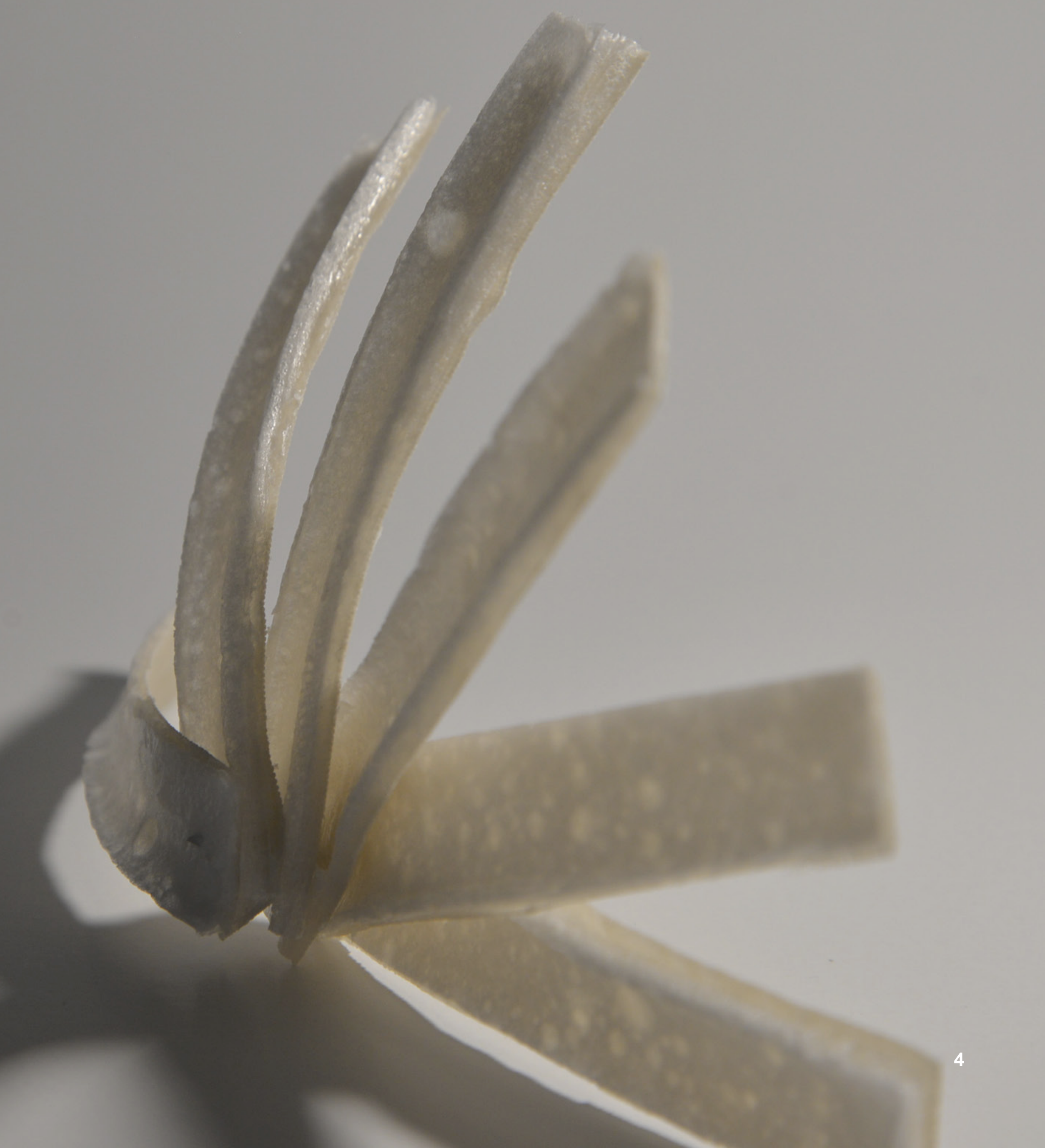


Figure 6. The bilayered structure when bended

Things you need:

- a stove
- a pot
- a spoon
- baking paper
- a blender
- a mold
- tweezers
- a dehydrator



Ingredients for foam layer

Konjac powder, also called glucomannan, is made from the combs of the konjac plant (Amorphophallus konjac). Konjac powder is often used to replace gelatine for a vegan plant-based alternative. Mixed with water it can create a solid bioplastic (figure X). In the process of making this bioplastic, the stirring of the mixture can cause accidental bubbles (figure X). Stirring the mixture strongly, for example with a blender, creates many bubbles. However, when the mixture is left after the blending, most bubbles disappear again.

Function in material: foaming agent

transparant
thin and fragile
flexible
plastic foil like
slightly wrinkly

thicker and hard
uneven structure
uneven thickness

Gelatine is a strong binding agent made from collagen, often retrieved from animal bones and skin. At room temperature, up until 40 degrees gelatine is solid and holds itself together as brittle sheets. On a molecular level gelatine has a honeycomb structure which makes it somewhat flexible, but mostly strong in its solid form combined with another material. For this study the sheets of gelatine were used. In many dishes, gelatine is a binding agent as it can hold other substances together. When warmed it crosslinks proteins, for which it can create a solid material together with other substances. In the shape changing biofoam it functions as a stabilizer; it stabilizes the bubbles which are formed when blending the konjac with water.

Function in material: binding agent

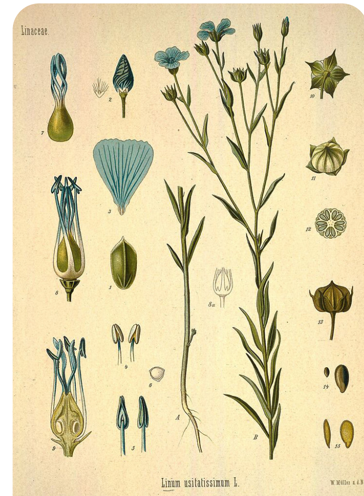
transparant
fragile
inflexible
reflects light

white and solid
thicker and hard
inflexible
uneven structure
uneven thickness

Ingredients for fiber layer

To create the layered structure for the shape-changing material made in this study, a layer of material that is not affected by water in the sense of absorption was needed. After experimenting with several materials and fabrics, it was found that linen had the best attachment and had the biggest bending quality compared to the others.

Function in material: fiber



scientific drawing of flax [2]

fabric stretches slightly in one direction and does not in the other.

To attach the layers to each other it was preferred to also use a natural biobased and biodegradable 'glue'. As beeswax is also water repellent this helps to keep the other layers attached. For the shape changing biofoam a translucent beeswax was chosen, which contains less 'pollution' like pollen and silk when its of lighter color.

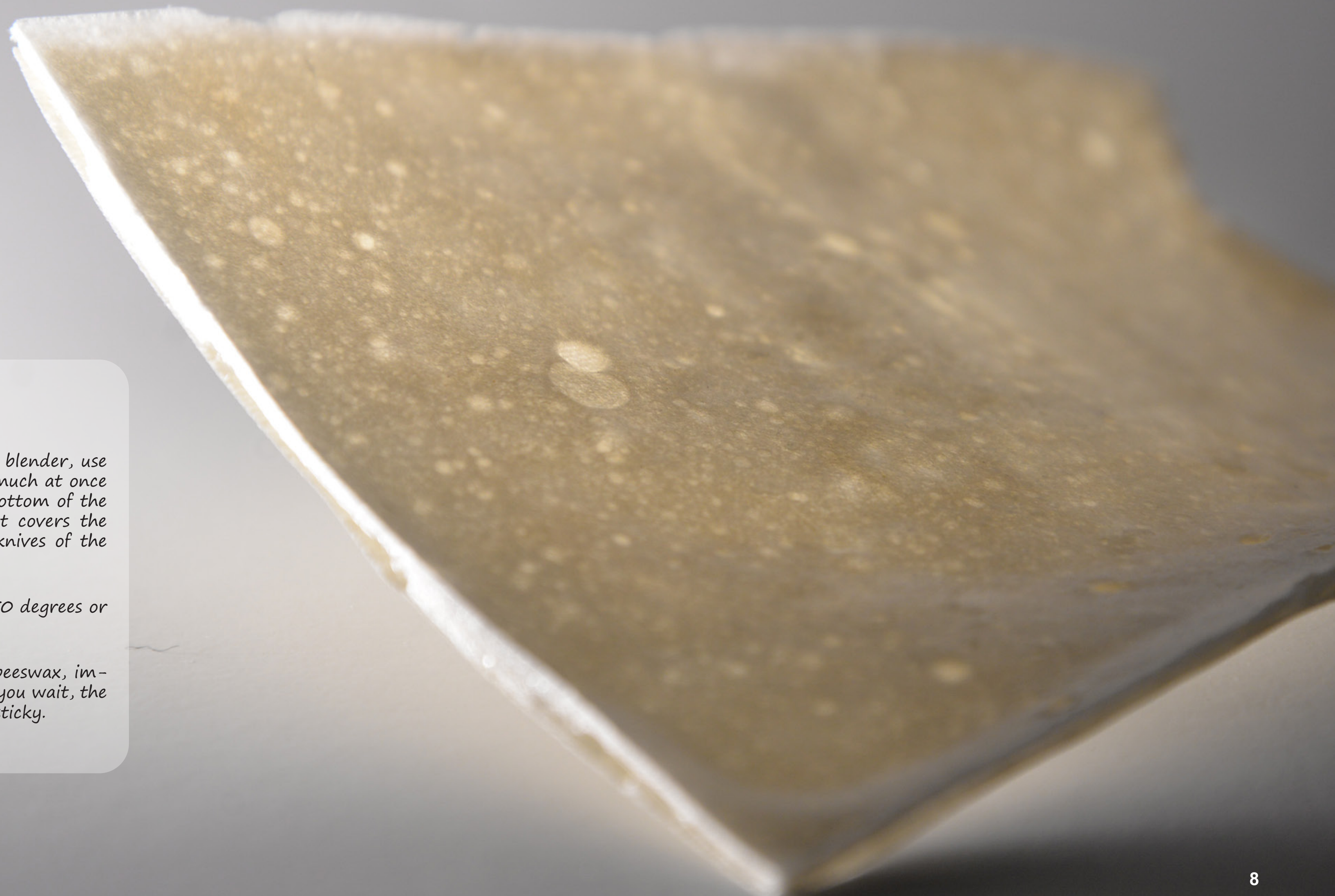
Function in material: glue


melting the beeswax

typical smell
burns easily
slight color change

Recipe

1. Use a **digital scale** to accurately weigh the ingredients. Start with the gelatine. Soak the dry gelatine sheets in water until soft.
2. Pour a small portion (less than half) of the water into **the pot** and heat the water to about 40 degrees Celcius.
3. Put the soaked gelatine into the pot, keep the pot about the same temperature on **the stove**, and stir constantly with **a spoon** until the gelatine is completely melted.
4. Take the pot off the stove and add the remaining water. Allow the gelatine solution to cool to room temperature.
5. While stirring, slowly add the konjac powder into the pot in several batches. Continue stirring until the solution becomes a uniform solution.
6. Pour the konjac gelatine aqueous solution into **the blender** and let it sit for one minute so that the konjac powder can fully absorb the water. Then using the blender on lowest setting, blend the solution for 15 seconds.
7. Pour the solution slowly and evenly into **the mold**.
8. Place the mold in an **air dryer**, set the temperature to 35 degrees Celsius, and dry for at least 24 hours. The konjac gelatin foam material is now ready.
9. Put the beeswax in a **non-stick pot** and melt it to less than 40 degrees Celcius.
10. Cut the linen in the same shape to the shape of your konjac gelatine foam material. Soak it completely in the melted bee wax.
11. **Place** the soaked linen on top of the corresponding shaped konjac gelatin foam material.
12. Press firmly on the entire piece of material to ensure that the gradually cooling wax can bond the two layers of material.



Important Notes:

- When the solution is put in the blender, use small amounts. If you add too much at once the foam will be stuck at the bottom of the blender. Blend an amount that covers the bottom, up to a bit over the knives of the blender.
- Do not heat the beeswax over 50 degrees or it will melt and burn.
- After dipping the linen in the beeswax, immediately take the next step. If you wait, the beeswax cools and is no longer sticky.

Tinkering with the material

Making process test

In the process of exploring the best preparation method of konjac foam, we sought the answer by controlling variables. The variables we have included are: the blender, boiling the konjac-gelatine solution, the order of adding the ingredients in the konjac-gelatine solution. It was found that the function of blender is to introduce a large amount of air into the solution which forms the bubbles for the foam structure of the material.

Through the experimentation, we arrived at following conclusion. Firstly, the function of blender is to introduce a large amount of air into the solution to form bubbles. Secondly, we should maintain the low temperature of the solution when entering the blender, which can prevent the density of bubbles from decreasing due to high temperature rupture.

Additionally, adding gelatin to the solution before adding konjac powder can prevent konjac flour from absorbing too much water and causing the solution to clump. The best preparation method for the final stage is in the previous description of 'recipe'.

Proportion test

To obtain the optimal proportion of the formula, we used the method of controlling variables. Without changing the quantity of other components, we separately changed the proportions of water and gelatin. We found that high proportion of water can cause the solution to be too dilute, resulting in the inability to form many bubbles in the mixer; Low proportion of water can cause the solution to be too viscous and unable to fill the entire mold smoothly. At this point, we have determined that for 3 grams of konjac flour, 100 grams of water has the best ability to shape the sample.

In addition, Gelatin seems to have a function of preventing konjac flour from absorbing water. Without changing the ratio of konjac flour to water, as the quantity of Gelatin in the formula decreases, the solution will eventually become too viscous and even exhibit blocky structures. In subsequent testing, based on the differences in the ability of samples with different formulations (3:4:100 and 3:5:100) to produce deformation when other conditions are consistent, we found that too much gelatin may reduce the water absorption capacity of the finished product samples. Finally, it was confirmed that 3 grams of konjac flour, 4 grams of gelatin, and 100 grams of water are the optimal formulas for the current stage.

Mold

The thickness of the mold should not exceed 3 millimeters. Because after testing molds with different thicknesses, we found that as the thickness of the mold increased, the dried sample remained a thin sheet of material thinner than 3 millimeters, and this sheet always adhered to the top layer of the mold. Therefore, an excessively thick mold would cause the sample to fail to adhere to the mold. Combined with the influence of gravity and air flow during the drying process, the surface of the obtained sample would be uneven.

In addition, the sample attached to the top layer of the mold will hinder the drying of the lower space of the mold, which may lead to water accumulation or residual solution below the sample, resulting in incomplete drying of the lower surface of the sample or a decrease in sample quality.

Figure 7. Konjac foam with different proportion, before (up) and after drying (down).

Technical Characteristics

Structure

We found that the foam (pore structure/bubble) of this material is uneven, the smaller bubble diameter is not 0.2 mm, and the larger bubble diameter is more than 1.2 mm (Figure 8). We also observed the giant cavity on the surface of konjac foam material, whose diameter can exceed 4mm (Figure 9). This may lead to differences in the water absorption capacity of the material in different regions.

We observed the Biofoam after soaking it in water (Figure 10). We refer to the side of the mold that is exposed to air as the front, and the side that is wrapped in the mold as the back. When observing the front of the material, we found that water can easily enter and disperse throughout the material, blurring the edges of the bubbles, indicating that water fills the bubbles.

In addition, from the observation of the back of the material, we found that water is dispersed in a small area and there are large flat images. This may be because during the drying process, the bubbles in the solution move like the top due to buoyancy greater than gravity, resulting in more bubbles at the top of the material. Therefore, the bottom of the material is considered more suitable as the side that fits with the linen.

We observed the Biofoam after two wetting and drying processes under the microscope and found that the bubble/porous structure in the foam was not round and shrunk compared with the original shape (Figure 11). This may be due to repeated water absorption and loss, which may lead to a decrease in the elasticity/expandability of bubbles, and this can also result in a decrease in the water absorption performance of the material after repeated water absorption.

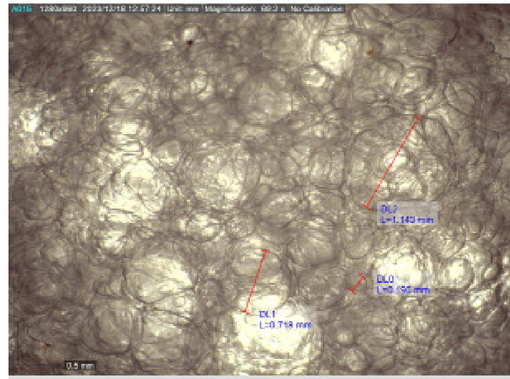


Figure 8. Original Biofoam material

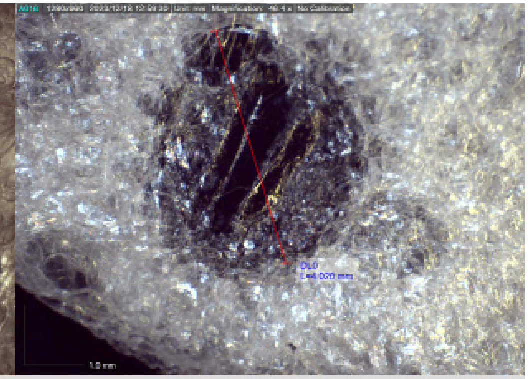


Figure 9. Cavity found in the same piece

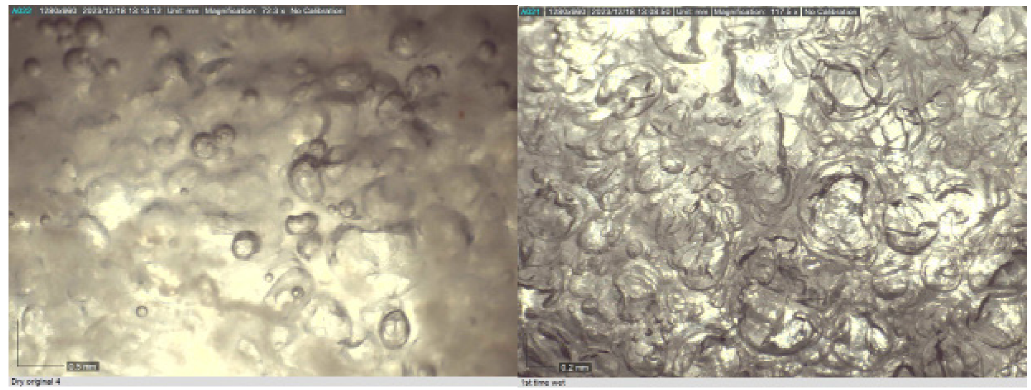


Figure 10. Biofoam material soaked in water, top side (left) and bottom side (right)

Figure 11. Biofoam after two wetting and drying processes

Absorption and evaporation of water
The process of shape changing bio foam water absorption and deformation takes about 10 minutes, but the time required for its drying and recovery process at roomtempereratur is distributed between 0.5-5 hours due to individual sample differences.

One piece with a size of 10 × 550 ×1 (in millimeters) sample weighs 1.9 grams and can absorb 4 grams of water (when completely immersed in water), resulting in a self-weight of 5.9 grams. And recover to a weight of 2 grams after drying.

Through experiments, it was found that the first wetting-drying process may lead to a slight increase in sample quality, but subsequent wetting-drying processes hardly change the quality of the sample. This may because the sample making process is carried out in an air dryer, while subsequent drying is carried out in the air.

Displacement when wet
We measured the deformation data of three samples of the same size after being completely immersed in water. For samples with a length of 55 millimeters, a width of 15 millimeters, and a thickness of 2 millimeters, the height of the central bulge reached 3-4 millimeters after soaking in water. The difference in bulge height is due to individual differences in the sample, and the bulge height is reduced due to the influence of gravity. In subsequent experiments, we found that if the aspect ratio of the sample is cut to about 5.6 (85mm/15mm) and the sample is suspended in the air to counteract the influence of partial gravity, the height of the central bulge of the sample can exceed 20 millimeters.

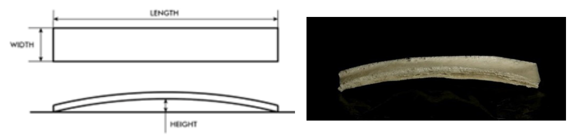


Figure 12. Sample deformation completely immersed in water

Ideal ratio of size
We compared the degree of deformation of samples with different size ratios to seek the ratio with the highest degree of deformation (only for rectangular samples). It was found that if the aspect ratio of the sample is trimmed to about 5.6 (85mm/15mm), the deformation degree of the sample reaches its maximum.

At the same time, it was found that if the aspect ratio further increases, the liner layer may not be able to support the water absorbing konjac layer, resulting in the sample becoming too soft.

Repetition of the exposure to water
At present, the sample can be reused approximately 10-15 times, and some samples can be reused more than 20 times. After more than 15 cycles of the 'wet dry' process, the sample's response to water significantly decreased.

Force
We tested the rigid strength of the final sample when it was dry. We bent the sample from two directions and found that bending the sample along the direction of the konjac layer did not cause fracture and maintained the bent shape, demonstrating good ductility. However, bending the sample along the direction of the linear layer will quickly cause the sample to fracture.

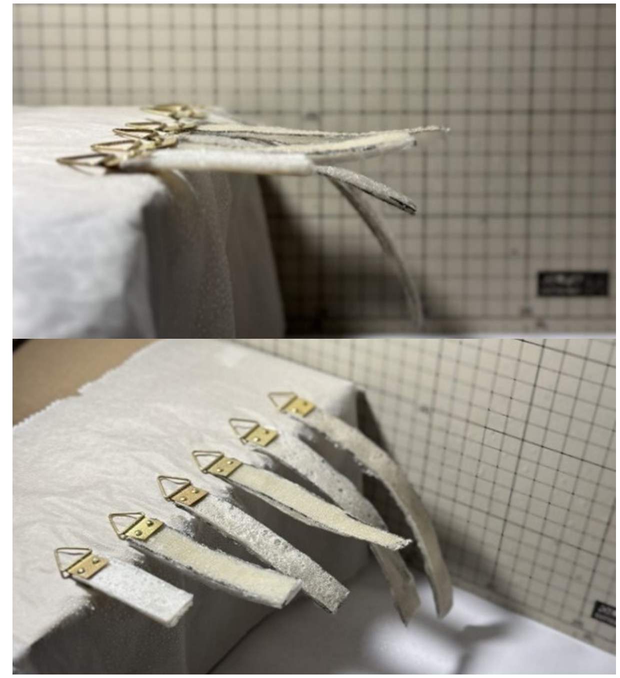


Figure 13. Difference of deformation degree of samples with different lengths after spray wetting

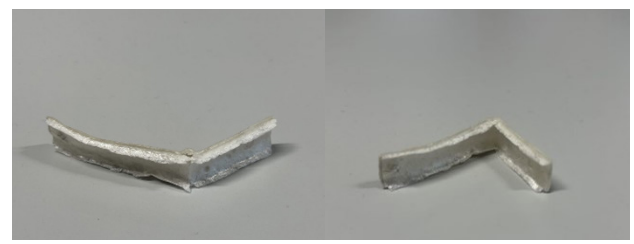


Figure 14. Bend the final material sample in two directions, towards the linen layer (left) and towards the foam layer (right).

Experiential Characteristics

We invited the audience to review the konjac foam material, and they evaluated the material and described their feelings. We collected this feedback and made two word clouds.

Figure 15. Feedback from audience on the biofoam material samples

DESIGN

Our material name is Shape Changing Biofoam. It can absorb water through capillary phenomenon and produce bending deformation when in contact with water. And this deformation process is reversible. When the material is dried in air, it will return to its original form as water is lost.

Nyctinasty of flowers

We associate the blooming and closing of flowers with the deformation ability exhibited by the material in its reaction with water. After spraying mist on the surface of the petals, it takes about 10 minutes for the petals to open, causing them to "bloom".

Figure 16. Immortal flowers made of Biofoam

Application of the material

If the reusable times and material strength of shape changing biofoam can be improved, and more uniform foam can be produced to better control deformation, then this material may be used in the construction field. We have envisioned an application field where this material can be used to build a shell, as shown in the figure, and its roof can be constructed using biofoam. When encountering rainy days, biofoam will bend downwards to form a roof to block the rainwater; When it is sunny, biofoam will lose water and contract upwards, allowing sunlight to shine in.

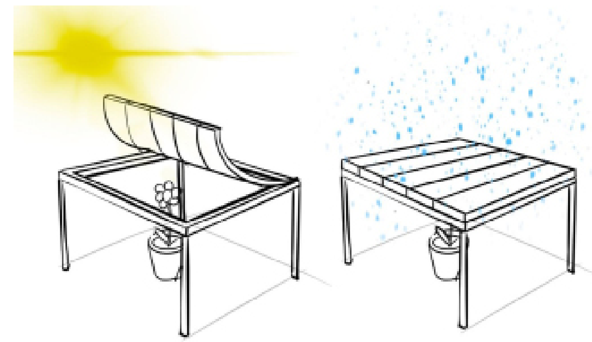


Figure 17. Possible applications: plant shelter

DISCUSSION

Limitations

Since we do not have scientific backgrounds, we encountered some limitations on technical characterizations, for instance the toughness and the accurate swelling ratio of the material. Therefore, this information is not provided in this paper. Additionally, the method to control the swelling and shrinking ratio is not completely discovered yet. It is clear that the ratio of the size can influence the deformation. However, we are still unclear about how to precisely control its behavior.

Future Steps

One of the values of the material is that the ingredients are biodegradable. It requires more experiments to confirm the biodegradability of the combined material since we are not completely sure about whether the making process would change its properties. On the other hand, it is also worth exploring other plant-based ingredients to replace gelatin in the recipe. Other plant-based binding agents such as agar agar or pectin can be explored.

While exploring more possible ingredients, there are also multiple methods to create the pore -

structure more evenly. We believe that the uneven pore structure is a possible reason why the material does not behave constantly.

During the demo day, we received some feedback from the audience, mostly regarding the application of materials. In response to our envisioned 'shelter' application scenario, someone has proposed that a deformation time of 10 minutes is too long, which can cause people attempting to take shelter from the rain to get wet. They believed that using it as a shelter for plants is more reasonable, as it can not only prevent excessive rainfall on rainy days from drowning flowers and plants, but also allow plants to receive sufficient sunlight on sunny days.

In addition, potential applications included in the feedback include jewelry design, making umbrellas, and materials for soft robots.

CONCLUSION

The Shape Changing Biofoam is a hydro-responsive material that is constructed with a bilayered structure. The foamy layer acts as a porous medium with a good ability to absorb water, whereas the other layer is linen combined with beeswax which is less responsive to water. All of the ingredients are biodegradable and, therefore, featured as a sustainable material. We used the Material Driven Design method and focused a lot on tinkering with the material.

A series of experiments with different variables including making process, proportion, and mold. These experiments led us to the most optimal recipe for creating a shape-changing biofoam material. Some more scientific characterizations should still be done, and there are still limitations to controlling the shape-changing ratio.

The future steps will be conducting experiments to prove the biodegradability of the material, exploring plant-based replacements of gelatin, and finding a method to create a more even pore structure. Several imaginations of applications are provided by audiences on demo day, such as shelter for plants, wearable accessories, and soft robotics.

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