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# Carbon negative textiles issued from marine materials

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Carbon negative textiles issued from marine materials

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## Abstract

Marine materials are a potential new raw source for the production of organic and vegan leather and cushioning materials. Being a carbon sink, seaweed and marine plants like seagrass and seaweed farming activity could have a crucial role in the current environmental crisis for the absorption of carbon dioxide in the atmosphere. Products extracted from brown and red seaweed can be used for the production of a variety of material categories.

This study takes into account the potential of seaweed exploring through an experimental approach different paths for the development of new materials for the textile industry and compliant to the IKEA 2030 agenda. These new materials will be developed from an initial exploration of the known material sources (seaweed, seagrass and by-products, including alginate, fibers). The study will cover the first steps of material development, exploration and ideation through an experimental approach aimed to uncover the potentials of seaweed as future resources for textile production.

## Introduction

### Background

The study is a collaboration between IKEA of Sweden and Lund School of Industrial Design that belongs to the given macro topic of “Disruptive Textiles”. For this research, the scope has been framed within the topic of material development associated with marine materials. The scope of the project has been agreed between the two parties and would start with an initial study of the chemistry of seaweed, going through hands-on exploration of seaweed by-products and further development of the most successful results.

IKEA is a leading company in the textile industry and during recent years the range has seen different directions concerning the type of fibers and textiles that can be created from renewable resources. Four main projects stand out for their contemplation of natural fibers and renewable materials from wood wool to rice straws (from Fig. 1 to Fig.4).



Fig.1 Wood wool, Piotr Jakubiak



Fig.2 Hao Nguyen Van, nipa palm fibers



Fig.3 Implementing bamboo fibers  
Anna Granath and Emma Olbers



Fig.4 FÖRÄNDRING, rice straw collection  
Akanksha Deo Sharma & Iina Vuorivirta

Additionally, according to the latest Sustainability report (Fig.5) the major portion of the carbon footprint of the company is given by the raw materials considered for the range, from the extraction to the processing (45%). We can then support the conclusion that, according to the directions of the materials used in the product range and the data from the sustainability report, IKEA would benefit from the integration of more renewable sources able to offset the carbon footprint of its material portfolio.

Among the renewable sources that can be considered, seaweed and marine flowering plants (seagrass) represent the only options able to accomplish the task for the following reasons: seaweeds and seagrasses are considered carbon sink, they grow at a fast rate (for instance, kelp tends to grow on average 60 cm/day) and contain major components usable for material development, from cellulose (fibers) to polymers (alginate, agar-agar, carrageenan).



Fig.5 Extract from the latest IKEA's Sustainability report

## Carbon sink and blue carbon

Blue carbon is the carbon extracted from the atmosphere by the ocean and the actions of marine organisms and ecosystems, like kelp forests. These absorbing ecosystems are considered carbon sinks: they absorb and retain the carbon until the end of their cycle of life. The carbon is, in fact, released once the organism dies and decomposes, unless the organism sinks to the bottom of the ocean and gets buried within the ocean floor. As Fig.6 shows, this doesn't often occur naturally. In order to promote the retention of carbon within the organism, the life cycle of seaweed needs to be surveyed and controlled, like it already happens with farming initiatives that take over the issue by farming species of seaweed for food production, packaging, cosmetics and polymers like Kelp Blue, Sea6 Energy, Cascadia Seaweed and more.

According to the most recent findings, these cultivations are able to absorb about 1500 tonnes CO<sub>2</sub>/km<sup>2</sup>/year, which equates to the annual CO<sub>2</sub> emissions of about 300 Chinese citizens (Lym Yong W. T., Yee Thien V., Rennielyn R., Rodrigues F. K., 2022), showing a promising result for carbon offsetting. Although, as the Greenhouse Gas institute states, there aren't rules, institutions or regulations able to account for blue carbon. Hence, we don't dispose of the essential tools to correctly measure the blue carbon and its offsetting power.

Taking into account the numerous research and data about blue carbon available, this study is finalized to



demonstrate the value of seaweed as raw material for the production of innovative materials for the textile industry and raise awareness about the potential of seaweed farming for the development of these materials, while offering the company a competitive advantage for what concerns the topic and promoting the sustainable living of the 2030 agenda.

Taking charge of material development within the field of industrial design has two main purposes: curate the CMF (Color, Material, Finishing) of the material while applying design thinking for the production process. The end result, gathering knowledge of design and chemistry, aims to find a balance between form and function, cost-consciousness and quality.

Background research about the topic gathered and existing results considered initially the first patent deposited in the late XIX century for the extraction of sub-products derived from seaweed. In fact, seaweeds contain polysaccharides useful for the creation of polymer and fibers: brown algae contains alginate and red algae contains agar-agar and carrageenan. The patent deposited in Stanford regarded the extraction of sodium alginate which is gonna be the one sub-product considered for the development of seaweed material. Sodium alginate is in fact extracted from an alkali (containing sodium carbonate) hot bath where seaweed is immersed: the result is a gelatinous mixture mostly made of sodium alginate. Sodium alginate can form fibers when mixed with a metallic salt (containing metallic cations), going from calcium to zinc. When sodium alginate comes in contact with the salt the cations bind with the alginate rearranging themselves forming a long chain of polymer. The waste products from this process are fibers and sodium chloride (table salt).



Fig. 6 Shore with a variety of seaweed, from rockweed to seagrass

On the basis of this previous research, the development started with considerations regarding the potential of alginate as main biopolymer for the development of textiles.

For this study, mostly sodium alginate will be used and considered for the development of the materials for the following reasons:

- Sodium alginate is extracted from brown algae, like kelp, which constitute the major carbon absorbing species on the planet;
- Sodium alginate can be worked with a cold process;
- Sodium alginate is a natural flame retardant.

## Methodology

The study will be led according to an experimental approach that consists in an initial exploration of the possibilities that the seaweed offers and the continuation of the most promising result.

The method is structured according to the exploration of three different material families: plastic, foams/cushioning, and non-woven. The collaboration with IKEA hasn't set any limitations or constraints regarding this exploration (materials, processes, methodology) except for the use of certain chemicals that aren't allowed in the materials used in the range.

The study then proceeded from the initial background research to the hands-on part where each experiment was independently led by the author of this paper and each result was presented and discussed with the company, assessing risk/benefits, possibilities and approaches to move forward.

Fig. 7 shows an overview of the first iterations that included experiments regarding extractions of the sodium alginate from brown algae, application for agar-agar and fibers.



Fig.7 Samples of bio plastic, bio foam and "sea wool"

## Seaweed plastic for 3D printing filament

The first experiment involved the extraction of sodium alginate with an alkali bath (as presented by the patent exposed in the background research) that resulted in a mixture containing sodium alginate mixed with fibers as filler. The mixture got molded into a silicon mold and dried for 15 days at room temperature. The result was a rock hard material with an unpleasant odor and color. It results to be impossible to work with since it would flake and, as alginate behaves like a thermoset, it wouldn't melt.

## Bio foam

For the development of the first iterations of the foams, agar agar has been used as the main polymer in order to assess its potential and benefits over alginate. The agar-agar has been dissolved in boiling water and then mixed with a plant-based plasticizer (glycerol) to preserve flexibility. Glycerol is, in fact, a water-soluble plasticizer containing two fatty acid chains and a phosphate head. The two chains are hydrophobic while the phosphate head is hydrophilic. Then, when mixed with agar-agar the water contained in the solution evaporates leaving the glycerol molecule. The hydrophilic part attracts water from the surrounding humid air, maintaining the material relatively flexible.

The solution of agar and plasticizer is then mixed with a foaming agent whose surfactant creates bubbles, introducing air in the material.

Since agar does not set immediately, part of the air escapes from the mixture. The foams takes 10 days to dry completely, recording a consistent retraction of about 50%.

The problem with agar agar (and the reason why the study won't continue using it) is related to the physical properties of this polysaccharide: it softens with heat modifying and rearranging its structure with temperature above 40°C. Hence, due to the low melting point, it seems difficult to consider agar-agar as an efficient polymer.

## Sea wool

For the non-woven, seagrass has been chosen as being part of the category of marine material as being one of the species more commonly found on the Scandinavian coasts (Fig. 8) together with brown algae. Seagrass is, with kelp, the second most important carbon sink on the planet: its presence in the marine ecosystem concur with 10% of the carbon totally absorbed by the ocean.

Seagrass is a flowering plant growing in shallow water. This organism is mostly made of cellulose and historically used for insulation. Most of the species of seagrass employed for the creation of textiles and furniture are harvested in south-east Asia, mostly in Vietnam. These plantations are family-run and its fibers are normally employed for the production of containers and decorations.

As for the wood wool cushioning developed by IKEA, these fibers can be employed for cushioning solutions contributing to local businesses in Vietnam and striving for social impact.

The first iteration shows the organization of the dried fibers in a mold and bond with a water-based binder. Although, the result wasn't nearly acceptable due to the dryness of the material. Also, the European seagrass used for these experiments are considered an endangered species in Europe, so the raw material can only be gathered dead from the shore, limiting the availability and quality of local Scandinavian resources.





Fig.8 Species of seaweed found on scandinavian coasts

## Alginate film

Within the category of plastic, sodium alginate has been used for the creation of a plastic film soft to the touch, relatively strong to tear and fully transparent. For this experiment, a combination of alginate, calcium lactate and glycerol has been used in order to get a thin film of 0.2 mm (as previous patents describe this “curing” phenomenon) . Calcium lactate is here the curing agent for the sodium alginate, offering calcium cations for the formation of the polymer. The choice of calcium as the main ion is explained by the large availability on the market and low price compared to, for instance, zinc and magnesium, both costing more than twice as much. The formula has been inspired by an open source one available through a FabLab that creates alginate film (Fig.9).

The open source (available for the audience online) formula has been modified in order to obtain a very flexible film, hence the quantity of the plasticizer has been elevated to 5% of the overall formula. According to the proposed process, the alginate gel is formed with water and plasticizer, then the mixture is poured on a fabric support and left for more than a week in a dryer to obtain the end film. This process cannot eventually be supported by this study since the huge quantity of energy coming from the drying process would have an impact on the carbon emissions of the development.



Fig.9 First experiment for plastic film

After the first round of experiments, it follows different iterations per category. These iterations will be presented and the material that will continue to be developed will be chosen according to the relationship between positive and negative features.

## Plastics

Firstly, there comes the plastics (Fig. 10). Due to the poor result of the first experiment for seaweed plastic, the study considered another approach: using seaweed fibers as filler material. The fibers have been then washed several times to eliminate any residues and salt, dried in a dehydrator for 48 hours and mixed with molten PLA and pigment.

Due to the scarce contribution given to the material and the complexity of the process, due to the melting of the plastic in an inappropriate environment, the study decided to present the results without any further continuation. Overall, the outcomes gave a PLA composite similar to wood plastic, material already implemented in the IKEA range, for example, in the ODGER chair. The main problem is now related to the smell, color and finish of the samples: all of them are unpleasant and would require firstly actions related to the processing of the fibers in order to solve at least issued related to the smell and the presence of residue salt that could interfere with the quality and longevity of the material.

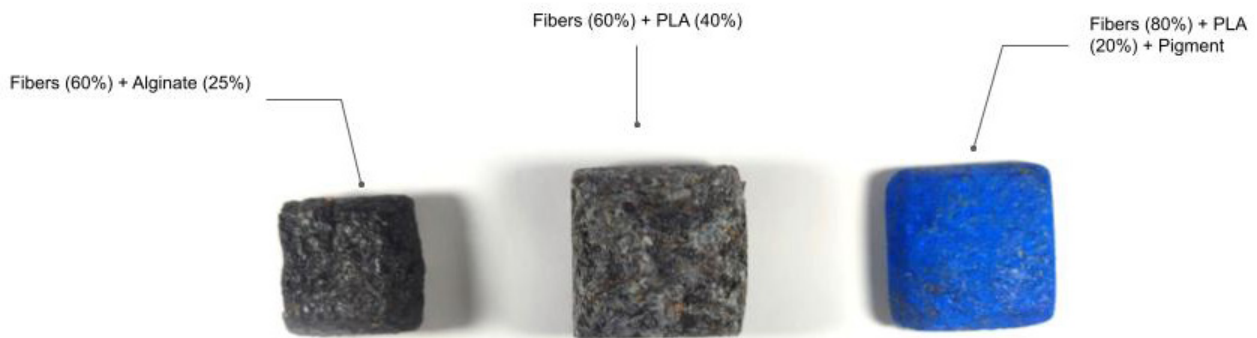


Fig.10 Plastic samples

## Foams

The most intriguing results have been given by the iterations on the foams. In Fig.11, there is a comparison between the first iteration (dried) and the second and third iterations implementing alginate as the main polymer. The first iteration is in fact consistently smaller and the oxidation of the agar gives it a brownish hue, meaning that the material needs a preservative in order to maintain its color (white) given by the emulsification of the agar with the plasticizer.

For the iterations with the agar the process needed a different approach that was consistent in the dosage of calcium lactate. It appears in fact that the concentration of calcium lactate in the formula influences the consistency of the material. In the middle a concentration of 10% of water solution with the calcium salt gave a consistency similar to PU foam, instead on the right the consistency is closer to PS: the concentration of the salt has been doubled.

Both samples required a long drying time in the dehydrator, that varied with the thickness of the layer: for the sample in the middle (about 2mm) the drying time was about 48 hours at 120°C; for the sample on the right (about 7mm) the drying time was about more than 72 hours at 120°C.

We can remark an overall yellow hue to the alginate samples, common for organic-based material.

The retraction was still consistent (50%-60%) but the color remain the same even after an observation time lasted three months: this is due to the use of this salt that acts like a preservative while curing the mixture of alginate, plasticizer and foaming agent.

The results were overall satisfying. The main problem with the first agar iterations were due to the density as well as the long drying time: the sample results in fact heavier than a sample of PU foam of the same size. This is due to the loss of air during the drying time as well as the ineffectiveness of the foaming agent. For the two iterations made with the alginate, the drying time is the main issue: since it takes more than three days to dry completely such a small sample, a layer of several centimeters of Sea Foam wouldn't be able to dry in a reasonable amount of time, giving concerns about implementation and scalability.

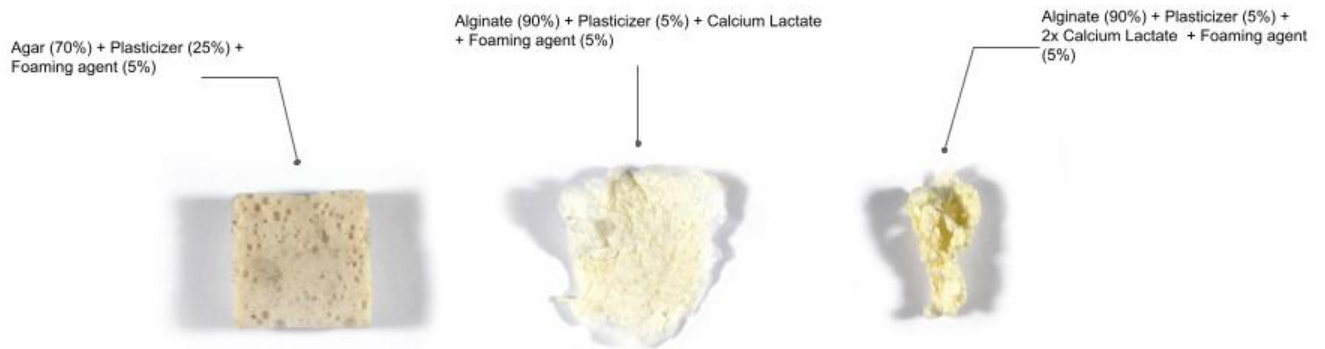


Fig.11 Foam samples

## Sea wool

After observing the first iterations made with European seagrass gathered on the shore (the initial choice was to use Vietnamese seagrass but due to the schedule and availability the European variety, gathered dead on the shore, has been chosen as a replacement), the material needed flexibility and moisture retention. For this reason the fibers of seagrass have been submerged in a solution of plasticizer (90%) and water for 48 hours and then dried for 7 days at room temperature. Once the fibers were dried, they were mixed with water based glue for textiles and compressed in a mold. The result was a composite, flexible enough to bend without cracking. The main issues with this material were the overall treatment of the fibers, presence of salt residue and debris, smell, color. This variety of seagrass grows underwater (the asian varieties only have the roots submerged), and this presents a problem for the overall cleaning and preparation of the fibers that could result, later, in relevant damages to machinery. For its similarity with wood wool, the material has been presented as having potential but for the sake of this study its development has been stopped for the advantage of materials with less issues. (Fig. 12)

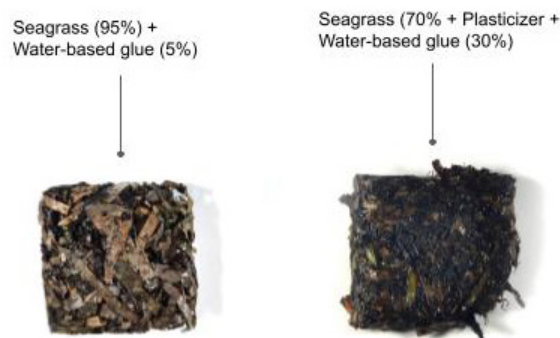


Fig.12 Sea wool samples

## Sea leather

The exploration with alginate for the production of plastic film was the initial ground for the development of seaweed-based textiles. While using a known formula available in open-source, the material has been developed considering the features of textile, in this case leather. Specifically, the formula has been modified to the need of the research since leather and plastic film have different features and are set in different environments with different constraints. Furthermore, the process has considered the integration of drying methods uncommon for the textiles production.

In Fig. 13 the first iteration with alginate and calcium cations shows the potential to develop a thin sheet of material with pattern imprinted on the surface. In fact, the first iteration has been dried on a fabric and it got the imprint of the fabric. It resulted in a transparent film, similar to plastic for the finish and touch, strong in one direction of the pattern but weaker in the other



Fig.13 Relevance of pattern on thin film of alginate

Although, the main problem with this material was due to the long drying time. In order to palliate, the method considers the only process able to transform a liquid in a solid without any energy, but instead with the property of a material with absorption properties: slip casting in ceramic. In this process (Fig 14 and Fig.15) the liquid ceramic called slip is poured in a plaster mold. The mold absorbs the humidity from the slip leaving a moist yet firm shape whose wall thickness depends on the time the slip rests in the mold.

Following these directions, an iteration has been led with the introduction of a plaster slab to observe how long the side facing the slab would dry compared to the side not facing the slab.





Fig.14 and 15 Slip casting

In Fig.16, the result gave the intuition a game-changing relevance. In fact, the side facing the slab dried quicker, the plaster drained the water from the mixture of alginate, plasticizer and salt creating a cured layer of 2 mm in 3 hours at room temperature. After three hours the face of the sample facing up was still liquid at room temperature and it indeed needed to be either dried in a dehydrator or on the plaster slab.

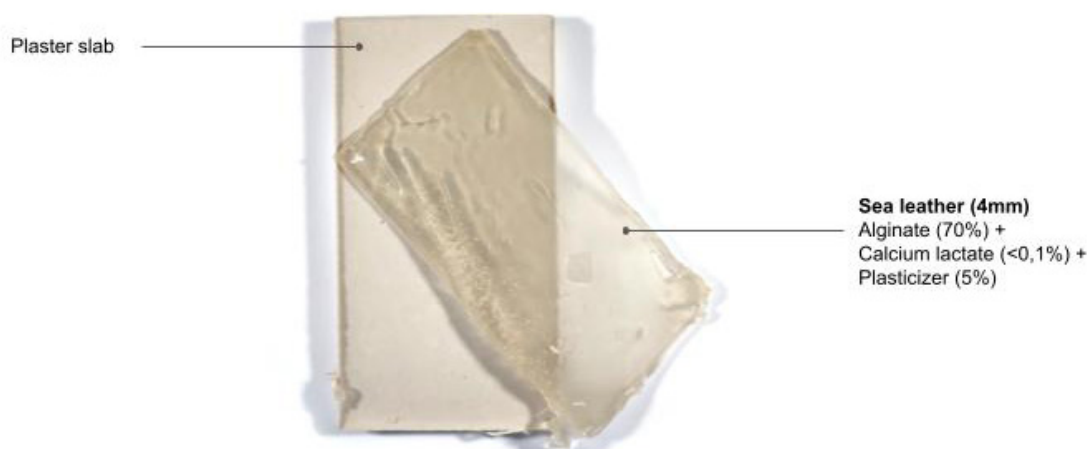


Fig. 16 A sample of about 7mm in thickness drying on a plaster slap

After this iteration, it was clear the plaster molds were the right way to go to cope with the long drying time of the first iteration. This also offered potential to create patterns and grains on the plaster and to see how the material would be influenced by them.

The sea leather has been then chosen as the material continuing the development and further research has been done to assess originality and uniqueness of the process and formula.

The most relevant research led to an experimental project implementing agar-agar based formulas with silicone molds. The creator, Anna Watkin started these iterations in 2020 with an open source formula found online. The creator doesn't reveal the content of the formula but standing from the pictures of her process and the material named "powder seaweed", it can't be anything else than agar-agar. In fact, in order to make what she calls "seaweed jelly" she needs to melt the powder in a pan. Both agar agar and carrageenan melts with heat, alginate doesn't get influenced by heat at all. Then the mixture is poured in silicone molds. (Fig. 17 and Fig 18)



Fig 17 and 18 Show the only footage available about the process



Fig 19 and 20 Result of the process and deployment

Despite what appears to be a successful development of a seaweed-based leather, there aren't any tangible proofs of the properties of the material. Considering that the material is for sure made of agar agar or carrageenan we can observe why these two polymers aren't the right choice for the development of materials.

Both agar agar and carrageenan behave like thermoplastic: their structure is in fact rearranged for temperature above 40°C and this is already a problem concerning performance related to the environment. About toxicity, according to several studies led on carrageenan, this polysaccharide is highly toxic for the digestive tract (carcinogenic) meaning that it poses a significant risk for ingestion hazard. Assuming that the creator is using agar agar and according to the previous experiment led by this research on agar agar-based foam, agar poses a several number of problem that can limit the deployment, going from deformation due to the humidity and temperature of the environment, to discoloration, preservation, retraction, energy consumption.

The analysis of the main competitor offers the opportunity to solve the problem related to Anna Watkins material with an approach considering alginate for the formula and plaster for the mold. In order to get to a scalable "sea leather", multiple iterations have been led considering the design of the mold and the composition of the formula. All the iterations will be presented chronologically and studied one by one.

## #1 Intuition of plaster as absorbing material

The very first iteration presented above shows that using plaster is the right way forward, although it was clear that a two-part mold was necessary in order to dry effectively both sides of the sea leather layer. For the formula, calcium lactate has been replaced with calcium chloride as it contains more calcium and also being less expensive than calcium lactate. Due to the bigger quantity of ions, the formula needed adjustment regarding his curing agent.

## #2 Double plaster slab

The second iteration in Fig.21 shows the result with a double slab used both for drying and compressing. One of the samples also features the integration in the formula of powder pigment at high coverage. The choice of powder pigment over liquid dye is reasoned according to the versatility of powder versions of pigmentation: powder pigments can be dosed to create either translucent, transparent and opaque effects, instead liquid dye, despite the fact they can add water or solvent to the formula denaturing the composition or making it wetter, are mostly diluted and don't offer the same effects.

The use of the plaster mold not only speeds up the drying process but it also prevents excessive retraction and warping. The result of these iterations is in fact a flat yet thick sheet of alginate film.

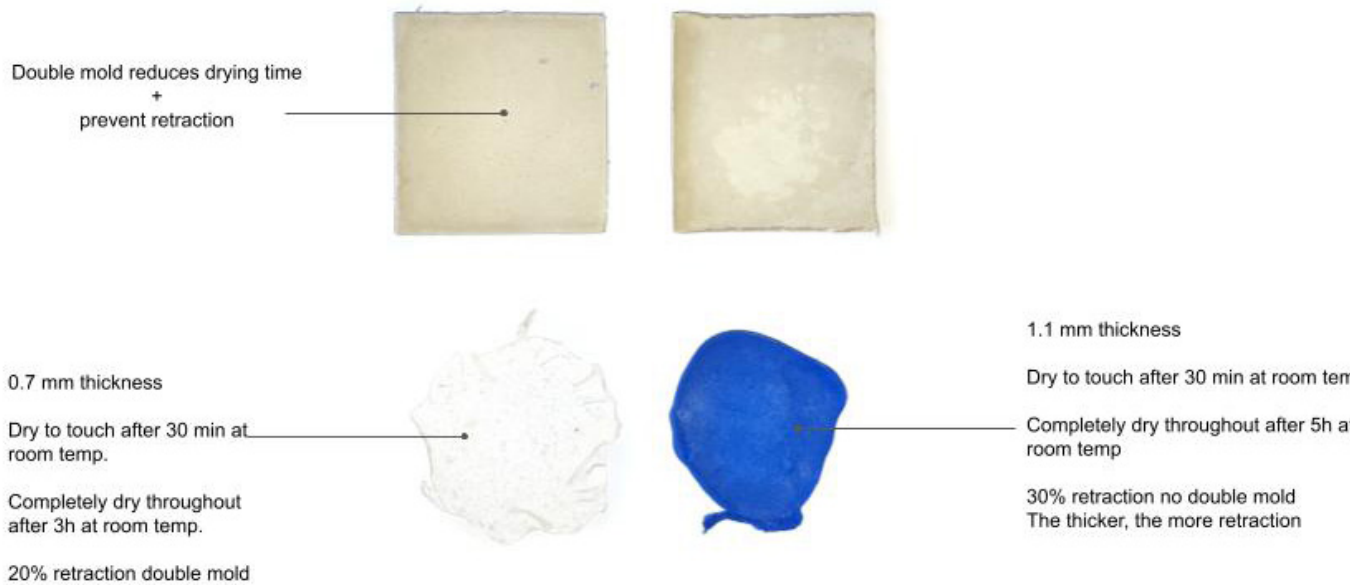


Fig. 21

### #3 Complex molds (Fig. 21)

The next phase was to elaborate the molds in order to understand if it was possible to create a pattern on the alginate film. The iteration on the left (Fig. 22) shows a double mold with a core and a cavity created with a wavy pattern. Pigments have been used to observe behaviors of the alginate to different colors. Overall the pigment does not influence the nature of the alginate, although excessive quantities of pigment for thin layers might dry it and make it crack.

The molds have been realized with 3D printed molds with the desired pattern.

After completely drying for 10 hours the alginate has been laying at room temperature and observing the denaturation of the shape. After 5 days at room temperature, the inconsistency in the thickness of the film due to the complexity of the pattern made the alginate leather warp and deform. This means that it might be difficult to control the finish of the material when it comes to complex shapes.

Then, the study proceeds by keeping the finish smooth to the touch and testing the CMF limits.



Fig. 22 Iterations with complex molds and grains.

#### #4 CMF experiments (Fig. 23)

From the top left, alginate film with integration of 3d printed structure to limit retractions, gradient effect, dye effect and opaque.

The integration of 3D-printed structure is explained by the necessity of controlling the retraction of the film. Despite the intuition, the film warped anyway and in some areas it also broke escaping from the constraint of the structure.

The gradient experiment (Fig.24) was aimed to test the versatility of the mixture with different concentration of pigment.

The yellow sample has been realized without any particular finish or effect. The color has been chosen to replicate the one of animal leather and the concentration of the pigment has been adjusted to be opaque.

In order to move forward with the formula and craft the correct one without any major problem, a test has been conducted specifically to assess the need for a supplementary component for the formula or steps in the process.



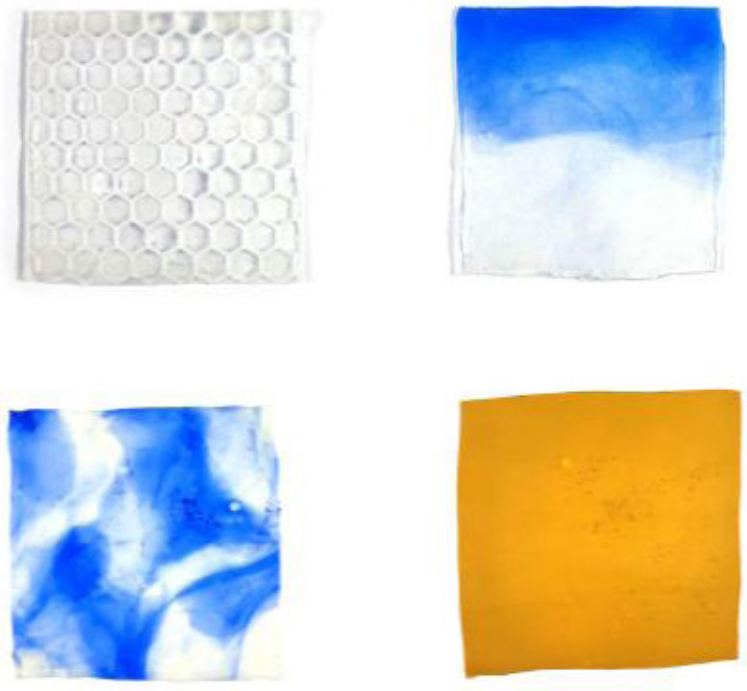


Fig. 23 CMF experiments

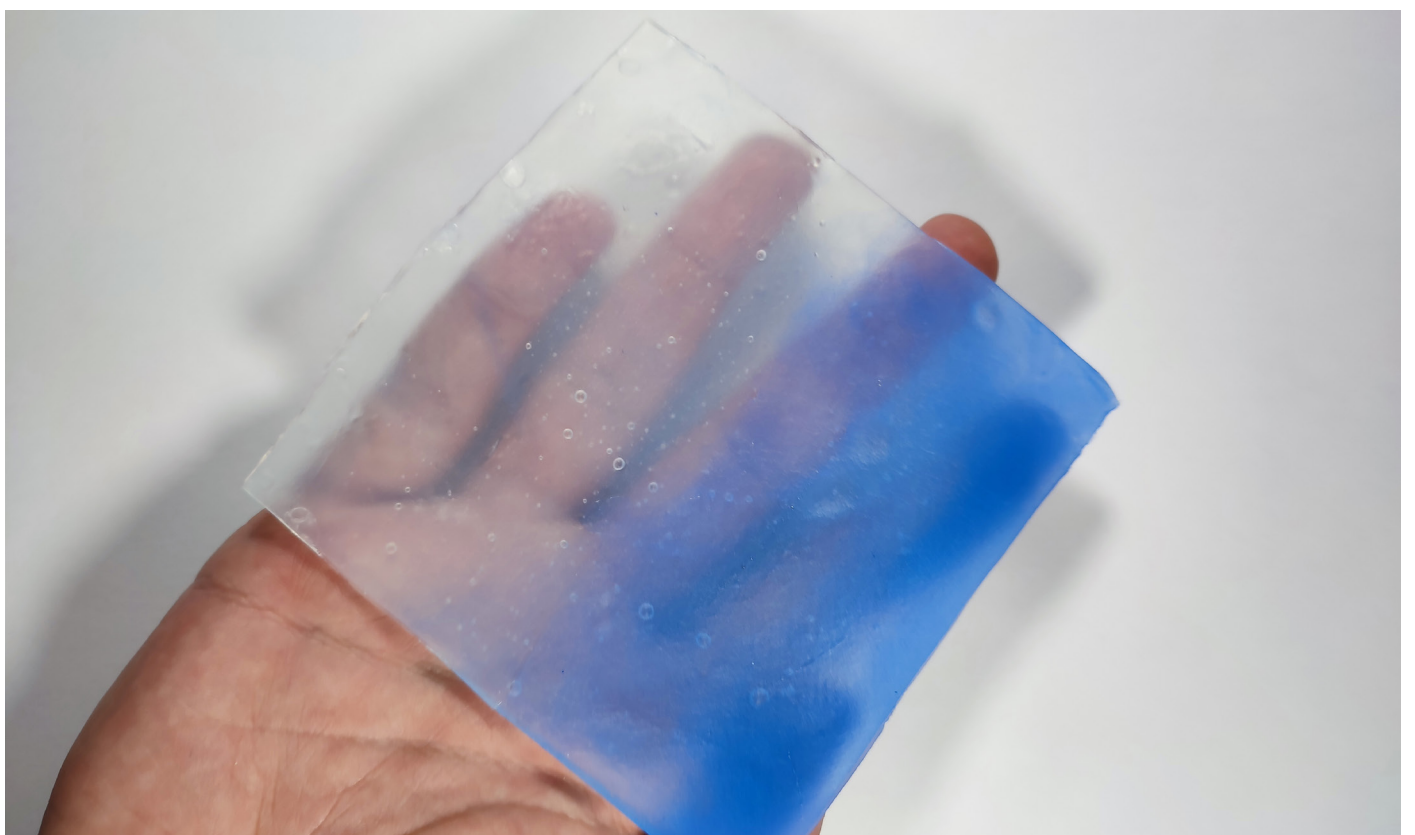


Fig. 24 Gradient effect

## 5# Flammability

In order to assess the safety of the alginate film, the flammability test has been conducted on a sample of 0.9 mm. The sample has been exposed to the flame (from a lighter) for two minutes; the samples didn't ignite but it charred instead proving the alginate has flame resistance properties. The fact the formula only contains natural and non-flammable components helped the positive outcome of the test.

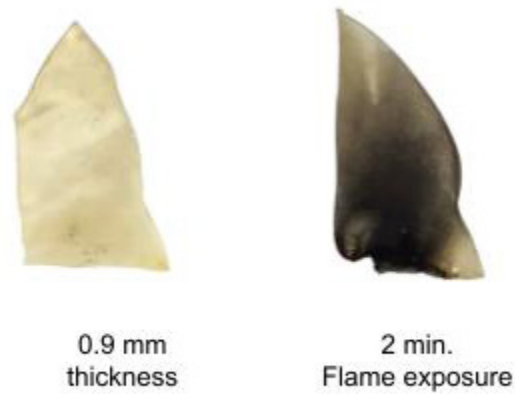


Fig. 24 Flammability test : before and after

## 6# Bubbles

During the formation of the hydrogel mixture comprising sodium alginate, water and plasticizer, the formation of bubbles is inevitable. This poses a problem for the strength and appearance of the material (Fig. 25).

The bubbles in fact alter the texture of the alginate film creating pockets of air.

In the absence of a vacuum chamber, the hydrogel needs to sit for at least 24 hours: all the bubbles come to the surface and the alginate particles have the time to absorb the liquid part. The result is a smooth and denser hydrogel. The increase in density is due to the evaporation of part of the liquid part.



Fig. 25

## 7# “Differential growth” effect

Some samples show an effect known as differential growth. This effect is common in plants whose cells grow at different rates. Specifically for the leather, this phenomenon is produced anytime the sample measures less than 1 mm in thickness: this might be due to the different rates of humidity throughout the surface of the alginate film. This phenomenon is absent when the material reach thickness around 1.2mm-1.5mm

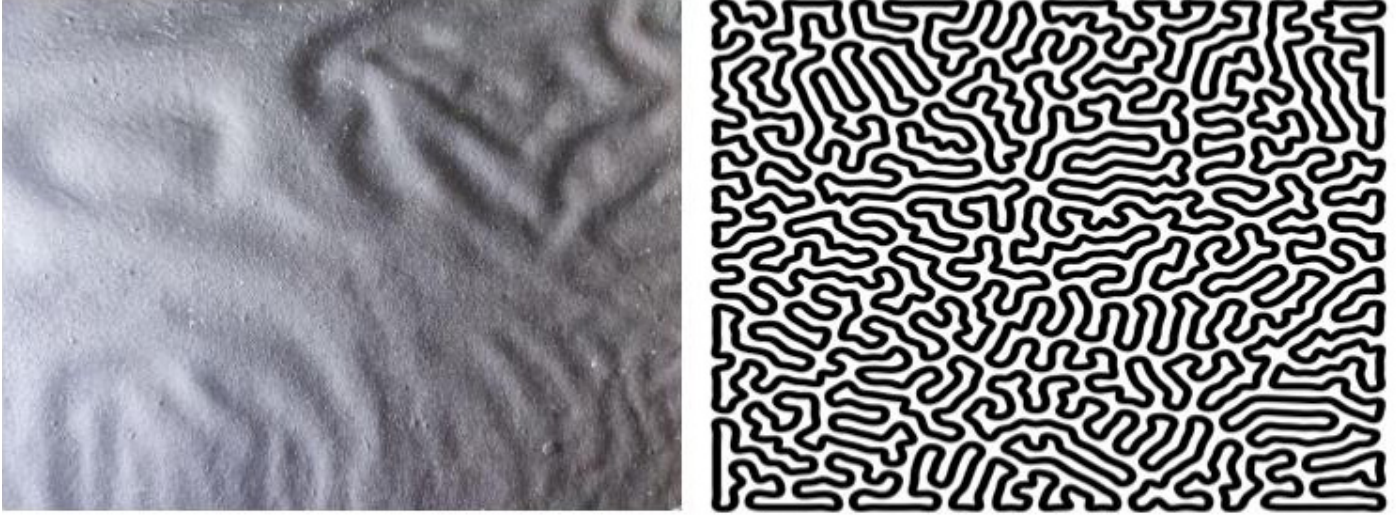


Fig. 26

## 8# Test on concentration of curing agent (calcium chloride)

Several tests have been led to ace the right quantity of calcium chloride. When the concentration of calcium chloride reaches 40% of the formula the outer layer does, in fact, dry quicker but it also loses all the humidity afterwards, making it crack. When the concentration is less than 5% like most open source formulas suggest, the alginate doesn't cure properly.

A test conducted to understand the effect of the curing agent on the alginate revealed interesting features of this material.

When the film of alginate is submerged in a solution of curing agent (20% and water), due to the capillarity, the curing agent passes throughout the thickness of the film making it cure faster. Although, since calcium alginate doesn't seem chemically compatible with itself, the curing agent cures a layer at the time creating a laminated material similar in consistency to rubber.

Instead, considering a process involving the nebulization of the hydrogel with a solution of calcium chloride and water that creates a protective patina to the exterior making the alginate film water resistant and antimicrobial, avoiding problems related to decomposition.

## 9# From alginate film to “Sea leather”

For the final iterations, the formula containing 9 parts of water and 1 part of sodium alginate and plasticizer (87%) are shaped with a leather-like finish.

Firstly a mold for the plaster mold is made. This pre-mold is built mostly with cardboard and faux leather. Then the plaster is poured and left to dry completely.

Once it is dry, the hydrogel containing pigments is poured into the cavity of the mold having the leather pattern and compressed with the core on top. Both parts of the mold have been nebulized with the calcium chloride solution preliminarily. The leather is demolded after 5 hours (Fig. 27 and Fig.28) In order to avoid warping it is suggested to leave the leather inside the mold for at least 24 hours. Powder pigments have been chosen over liquid dyes and gel dyes for their high coverage capability. In fact, liquid dyes mostly offer transparent and translucent results. Powder pigments offer the possibility to adjust the opacity of the end result with a relatively small quantity of powder.

The result is a leather-like material (Fig. 29) that looks like leather. The smell is subtle and mostly depends on the quality of the pigment. The orange pigment smells stronger than the white and the black one, but the hydrogel itself doesn't emanate any odor.

The sample is then left to dry under a weight which reduce the thickness of the sea leather and the height of the pattern



Fig. 27 and 28 Process of molding and demolding





Fig. 29

## Final CMF and directions for the deployment

Due to the novelty of the raw source for the development of the leather, the strategy for the final samples will follow the MAYA principle.

The MAYA (Most Advanced Yet Acceptable) principle applied by R. Loewy in the XX century states that products need a balance between innovation and familiarity in order to be successful.

In this study, the novelty of the material needs to be mitigated with patterns already common to the users. For this reason, the CMF of the final samples will take into account the colors and finishes of real animal leather.

The CMF board in Fig.30 expresses some directions for colors and deployment.

The colors considered belong to the palette of colors normally associated with animal leather: black, white, beige. Deep forest green has been added to recall the commonly associated green of seaweed.

The material is overall versatile for what concerns the CMF, previously the study has shown how it is possible to reach different effects, from gradients to opaque.

For the deployment, due to the issue of warping, it is suggested to consider the material in the form of flat sheets that can be wrapped, framed or sewn like fabric.

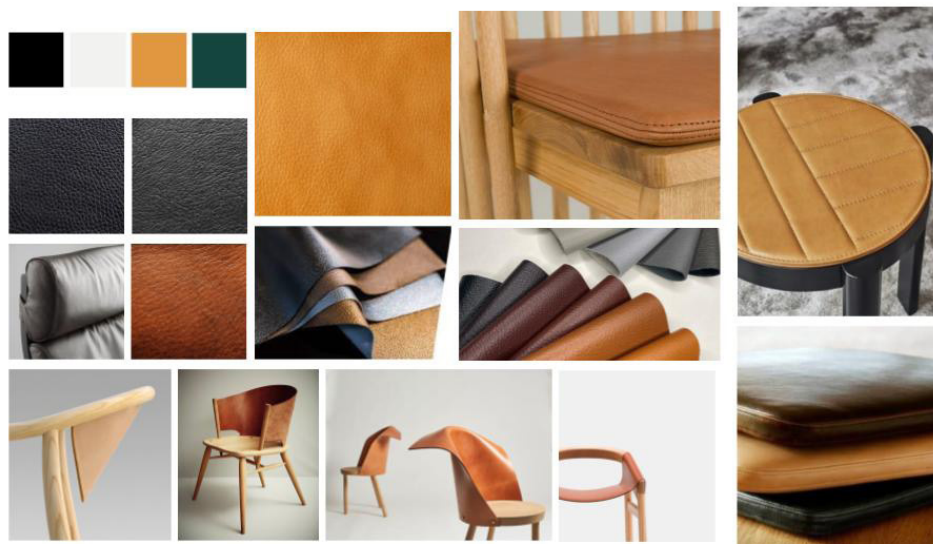


Fig. 30 CMF directions



## Discussion of the results

The final samples show that sodium alginate can be considered as an alternative material for textile development. It is considerably better than alternative polysaccharides, like agar agar and carrageenan for the creation of leather resistant to water and flame.

Sodium alginate-based hydrogel is versatile when it comes to CMF decisions, in fact all pigments used for the development do not show any side effects during and after the drying. The grain is subtle yet it doesn't worsen the warping of the sheet during drying and it also confers more strength to the leather.

The end material is overall flexible enough to be folded at 90° without breaking. The final formula has an improved tensile strength: the material can be stretched without any breakage, it mostly yields. We can state that the main contribution of this study for the development of textiles from marine materials are the following:

- The open-source formula has been adapted and improved for the production of textiles (leather);
- The main intervention regards mainly the process that brings from the gel to the end material. The involvement of a process common to ceramics (slip casting and plaster molds) for textile production was fundamental to avoid energy-consuming alternatives for drying the gel.
- The study opened the path for further development of agar-agar-based foams for cushioning and alginate-based packaging and use of seagrass as alternative material for cushioning wool ("sea wool")

From the point of view of a company striving for democratic design, the material can be assessed at this stage only according to three of the five democratic design principles: low cost, form and sustainability. In fact, the end result looks and feels like a leather-like material thanks to the choice of the colors and the grain of the mold. From a cost point of view, it has been estimated that, in order to produce one square meter of material there will be needed between 500-700 SEK. From the sustainability point of view, we could estimate that a square meter of sea leather would need about 804L to be produced, from the harvesting to end result.

This quantity is considerably low compared to the water footprint of cow leather, estimated to be around 20.862 L/m<sup>2</sup>, as seaweed does not need fresh water to grow. Carbon emission-wise, we know that cow leather produces 110 KG/m<sup>2</sup> of carbon dioxide. As we can't estimate the accurate amount of Co<sub>2</sub> emitted and absorbed by sea leather, the study won't proceed with any speculation.

To end, the material shows good potential to be scaled up, although it must be considered that, at the current state, the size of the sheet of sea leather is limited to the size of the mold (30x30cm), which is not adapted to continuous production.



Fig. 31





Fig. 32 Full palette



Fig. 33 Close-up of the grain

## Limitations

Limitations of this study are related to the harvesting and farming of the seaweed. In fact, despite the fact that the study has given an overview of the environmental benefits of seaweed farming, we are not taking into account the by-catch involved nor the process that brings to the refined sodium alginate used for the production of the samples as well as the energy involved for the extraction of sodium alginate from the raw materials.

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