LIVING MATTER:

BIOMATERIALS FOR DESIGN AND ARCHITECTURE

by

Merav Gazit

BArch, Tel-Aviv University, 2010

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ABSTRACT

For over a decade, we have witnessed a new emphasis in digital architecture on modes of production and material-based approaches rather than on form, geometry, and representation alone. As a result, fabrication techniques and material systems generally not accessible to architects can now become an integral part of the design workflow.

In this thesis, I explore the possibility of using bio-materials for design and architecture, placing a special emphasis on bio-materials that *grow* from a few bacteria cells. As a case study, I present the development of a bio-pneumatic cellular envelope that functions—through pneumatic and fluid actuations—as a system for growing, shaping, and enhancing the material properties of 3D bacterial cellulose inflated structures. Bacterial cellulose is produced by bacteria that create membranes of cellulose, layer by layer, in a fashion similar to additive manufacturing. The cellulose can be grown into virtually any given shape in a process that requires almost no waste or energy. The great tensile strength, biodegradability, and renewable nature of bacterial cellulose make it especially suitable as an environmentally-friendly material for design and architecture.

The bio-pneumatic system is computationally controlled, enabling a measured flow of air and liquids in and out of each cell in the system. This facilitates the creation of cellulose-based material with varied properties in each cell. Throughout the entire timeline of material production, the envelope is a tangible architectural object that changes in accordance with production phases: the material transforms from a liquid medium to a hydrogel composite to a pneumatic aerogel. The emphasis is therefore not merely on the final artifact but on the process of making itself.

This research presents the process of making matter as a design process. It stands at the intersection of design, architecture materials science, and biology, and therefore leaps naturally between scales, from nano to macro, and opens up new design possibilities. The ability to shape material behavior at different scales enables a unique construction of material properties and informs processes and outcomes at the architectural level.

A key interest in this thesis is exploring the tension between making and growing by confronting conventional methods of architectural making. Such methods require extensive preliminary planning, detailing, and tolerance handling for a precise assemblage of parts and components, and result in clear and pure aesthetics. Bio-materials and their changing nature, on the other hand, may present irregularity and imprecision, often resulting in "impure" aesthetics, are vulnerable to contamination and decay, yet also display the ability to renew and self-heal.

Thesis Supervisor: Terry Knight, Title: Professor of Design and Computation

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1 INTRODUCTION

This thesis consists of four chapters: chapter 1 grounds and motivates this work and outlines key issues I wish to address. Chapter 2 provides background and review relevant literature and previous work in the fields of bio-materials (Bacterial Cellulose in particular) and bio-materials in design and architecture. Chapter 3 introduces the Bio-Pnuematic Cellular Envelope that was developed as a case study for this thesis, describes its different components, methods and materials in use, and presents research results. Chapter 4 reflects and concludes by summarizing the key points of the thesis and making suggestions for further work.

1.1 RESEARCH INCENTIVES

1.1.1 New Design Domains and Possibilities

For over a decade, we have witnessed a new emphasis in digital architecture on modes of production and material-based approaches. As a result, fabrication techniques and material systems primarily not accessible to architects can now become an integral part of the design workflow.

One of the aims of developing the bio-pneumatic cellular envelope as a case study for this research for this research, was to examine how design processes and outcomes can benefit from exploring new, potential relationships between designers and architects and their tools, methods and materials. The envelope is a sort of installation which functions—through pneumatic and fluid actuations—as a system for growing, shaping, and enhancing the material properties of 3D bacterial cellulose-based inflated structures. In order to craft BC[1]-based membranes with desired properties, processes 'borrowed' from the world of material science and biology, combined with computation and fabrication techniques, were used. These processes began in biology with microbial culture and cellulose growth in different mediums, and included material science methods such as the fabrication of nano-composites and freeze-drying. Computation and fabrication techniques such as monitoring pneumatic and fluid actuations by code, molding and casting, 3D printing, and the development and fabrication of custom electronic circuits were also involved.

The system demonstrates a *process*-based understanding of matter and its creation.

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[1] BC stands for Bacterial Cellulose. From now on in this thesis, I will use this abbreviation

In modernist design theory and processes, we tend to see a fairly clear-cut definition between form, structure and material, followed accordingly by their execution methods of modeling, analysis and fabrication. This view gives rise to a linear process where form tends to be prioritized, while materials and construction or assembly methods become secondary or are incorporated only later in the process (Oxman, 2010). The Western tradition of prioritizing mind over matter, along with the long time governed architectural discourse, developed in the sixteenth century by Leon Battista Alberti, draws a clear distinction between the responsibilities of the architect and those of the builder, separating the mental labor of design from the physical labor involved in materials and construction (Cardoso Llach, 2015).

The introduction of digital tools and associative modeling into design in the last few decades enabled architects and designers to create complex geometries relatively easily. Although allowing great freedom in form generation, these design cultures further increased the gap between form and matter, and between form and its realization and production methods.

By incorporating and integrating matter from early design stages, new design understandings and spaces can emerge, thus decreasing the gap between the designer and her artifact while creating alternative relationships between the designer and his tools and methods.

1.1.2 Growing Matter: Biomaterials Centered Design and Fabrication

"Form came to be seen as imposed by an agent with a particular design in mind, while matter, thus rendered passive and inert, became that which was imposed upon." (Ingold, 2010)

As mentioned in the previous chapter, this thesis aims to demonstrate a material-centered approach towards design, and to display the possibilities this kind of approach suggests in terms of both design processes and outcomes. Working with bacterial cellulose, a biomaterial that grows, allowed me to ask and expose unique aspects in the design process and in the role of the designer within it. Using living cells that create matter as an integral part of the design process can refresh and inform traditional definitions in design and making processes, both on theoretical and practical levels. Questions that deal with topics like designer's agency, form finding and methods of making, become redefined when these new materials are added to the design-making workflow.

In the bio-pneumatic envelope that was developed for this research, one can actually witness how matter *assembles* into form. Two of the most exciting features of BC are that its production mechanism is part of the material itself and has a unique ability to grow into a given shape. That allows the designer to interact

with the creation of matter in an entirely new way. By intervening and adding different substances throughout that natural process, the designer facilitates and 'oversees' the creation of unique shapes and matter with varied properties. The bio-pneumatic envelope demonstrates a system for material programing, where in order to craft BC-based membranes with varied properties and structures, the designer – thorough computational control – regulates, adjusts, and manipulates chemical and physical *in-situ* conditions and performs post-growth processing (Figure 11 and Figure 16).

Another significant aspect of integrating biomaterials into design and architecture is sustainability, especially when looking toward future implementation of such materials in the building industry and in mass production. The process of producing BC has promising environmental aspects and the material itself has unique mechanical properties.[2]

See chapter 2.2 for more background and precedents of using bio-materials in design and architecture.

1.1.2.1   From Biomimicry to Bio-Integration and Bio-Fabrication

It is important to define the difference between bio-inspired and bio-integrated design. Biomimicry is defined as imitating or taking inspiration from nature's forms and processes to solve human problems (Benyus, 1997). Materials chosen for the designed artifact are not necessarily related to the biological source of inspiration. In bio-integrated design, on the other hand, which is the main perspective for this work, biology is not merely a source of inspiration. Living systems are physically integrated into design and take part in material production. Organisms like bacteria, fungi and algae are cultured with various nutrients in various environments, at times being modified using synthetic biology, in order to create biomaterials with different functions and properties. These material systems are usually associated with environmentally aware design, responsible use of resources, and waste.

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[2] See chapter 2.1 for a description of BC properties and production processes, alongside with challenges of shifting production into mass quantities.

Figure 1: bio-inspired vs bio-integrated (a) Woodcut from Cesare Cesarianos's edition of Vitruvius (1521) "Building in the first age of the human world. Many people imitated the shelters built by animals". Source: (Hersey, 1999) (b) Hy-Fi, The Living, 2014. Each brick in the structure consists of farm waste and fungi that is grown to fit a brick-shaped mold. Digital image. http://www.wired.com/wp-content/uploads/2014/06/Copyright_BarkowPhoto_HY-FI_ExteriorFinal.jpg.

1.1.3   Design, Material Science and Biology: The Multidisciplinary Approach

This research presents the process of *making matter* as a design process. It stands at the intersection of design, architecture, material science, and biology, and thus leaps naturally between scales, from nano to macro, opening up new design possibilities. The ability to shape material behavior at different scales enables a unique construction of material properties and informs processes and outcomes at the architectural scale. I believe this kind of design thinking can also inform processes and enrich perspectives in the nano-micro scale of material science and biology research.
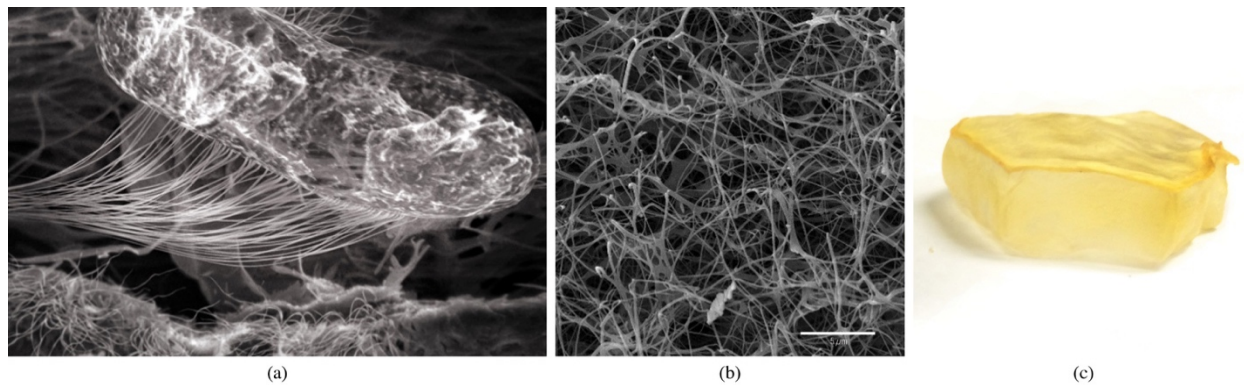

Figure 2: Design with living matter - from nano to macro. (a) Bacteria producing cellulose fibres, Animation by Emilia Forstreuter. Source: http://www.stschwabe.com/work/XylinumCones/images/XylinumCones_Dublin_02.jpg. (b) SEM micrograph of a bacterial cellulose sample showing a 3-D network formed by cellulose fibers. Source: (Fernando G. Torres, Solene Commeaux, & Omar P. Troncoso, 2012). (c) BC building block - Pneumatic membrane structure made of BC, dry state. Image by auther.

The multidisciplinary environment at MIT has greatly contributed to the collaboration between design, science and biology discussed in this thesis. The hands-on work of developing the research prototypes and experiments was made using the facilities of the Ortiz lab for structural biological and biomimetic materials at the Department of Materials Science and Engineering, and the facilities of the Architecture Shops at the School of Architecture and Planning.   Preparation for this research included participation in relevant training for operating tools and facilities in material science labs, learning methods, protocols and techniques for bacterial culture, fabrication of bio-composites and more, and becoming familiar with the relevant scientific literature.

1.1.3.1   A Note on the Non-Empirical Aspects of Design Experiments

This work is a design experiment, made by a designer. Scientific work demands empirical results and

scientific experiments should be held in controlled environments and follow strict protocols so that they may be repeated. Design processes, however, are by nature not as strict, more open-ended, and often do not follow a linear workflow or a specific protocol. Lydia Kallipoliti, an architect, engineer and theorist, describes this nature of design experiments: *"One could argue that design experiments seem "hypothesisless," while the value of contingency—mediated by the interaction of materials and their deployment tactics in varied circumstances—constitutes a key feature of design experimentation."* (Kallipoliti, 2011).

I believe that 'colliding' these two predominantly different worlds of design and science could inform and enhance processes and outcomes on both ends. Design thinking can open science to more critical, speculative and open-ended ways of thinking, leading us, for example, to re-examine such dominant positivistic schemes as "science will save the world." Scientific work and approaches can, of course, greatly enhance and promote design and architectural projects, and can help ground and manifest design thinking.

1.1.4   Thoughts on Growing and Making

Additional interest in this thesis is to explore the tension between making and growing by confronting conventional methods of architectural making. Such methods require extensive preliminary planning, detailing, and tolerance handling for a precise assemblage of parts and components, and result in clear and pure aesthetics. Biomaterials and their changing nature, on the other hand, may present irregularity and imprecision, often resulting in "impure" aesthetics. Yet while they are vulnerable to contamination and decay, they also display the ability to renew and self-heal.

In nature, everything grows in tissues and fibers. Variation in density, composition, and fiber alignment can create different material properties inside a single tissue. In architecture, we work with standardized components that assemble together into a built artifact. Variation can be achieved by using components with different functions and properties.

In the introduction to their book "Making and Growing: Anthropological Studies of Organisms and Artefacts" Tim Ingold and Elizabeth Hallam describe growth as a process of self-making or *autopoiesis*. They state that *"making is to growing as being to becoming"* and wonder whether growing can be thought of as an act of spanning *"the intervals between fixed stages of being."* The maker is then the *"one who stands at the threshold, easing the persons and materials in his or her charge across from one phase of life and growth to the next."* (Hallam & Ingold, 2014).

The act of growing is an act of transformation through time and chemical and physical interactions. Matter *assembles* into form. When working with bio-materials the ability to fully control outcomes and aesthetics is limited. As mentioned, these materials can be exposed to contamination and the resulting aesthetics are not necessarily homogeneous and 'sterile' looking. As a new design approach, I suggest looking at the changing nature of biomaterials as an opportunity to let go of some of our aspirations to achieve full control on our design processes, outcomes and aesthetics, and to open ourselves to alternatives.
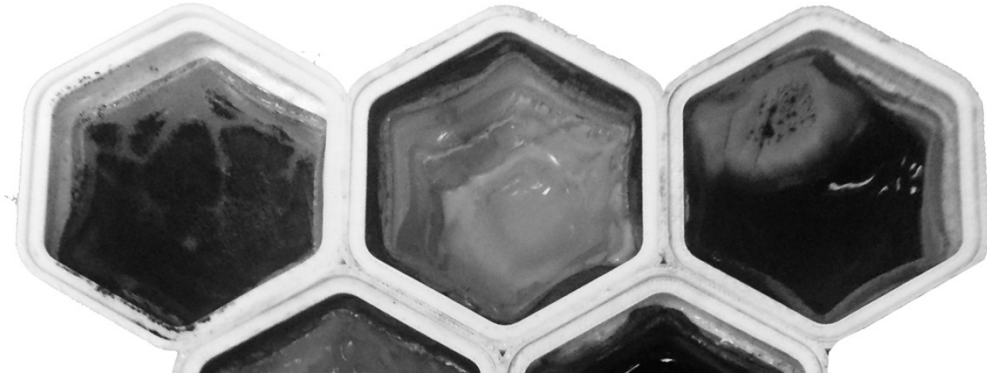

Figure 3: Unexpected visitors - contamination during growth period. Image by author.

2 BACKGROUND

2.1 BACTERIAL CELLULOSE – GROWING MATTER FROM LIVING CELLS

Bacterial cellulose is produced by bacteria that create membranes of cellulose at the growth medium-air interface, layer by layer, in a fashion similar to additive manufacturing. The cellulose can be grown into virtually any given shape in a process that requires almost no waste or energy. The great tensile strength, biodegradability, and renewable nature of bacterial cellulose make it especially suitable as an environmentally-friendly material for design and architecture.

Bacterial cellulose is a highly versatile, natural, macromolecular hydrogel that has been reported to have unique mechanical properties, biocompatibility, and high moldability (Iguchi, Yamanaka, & Budhiono, 2000, Nakayama et al., 2004, Nogi & Yano, 2008, Czaja, Young, Kawecki, & Brown, 2007, Lin et al., 2013), and thus holds great potential for a range of applications, such as textiles (Yamanaka et al., 1989), biomedical applications (e.g. drug delivery, tissue engineering scaffolds) (Svensson et al., 2005, Bäckdahl et al., 2006), and sustainable building components (Long & Rolison, 2007). The intracellular synthetic mechanism of bacterial cellulose has been documented (Brown, 1985, Okuda, 2002). At the end of complex biosynthetic pathway, cellulosic elementary fibrils are released into the growth environment through terminal complexes (TCs) and aggregated into ribbons, while cell subdivision contributes to branching of cellulose fibers. The structure of bacterial cellulose has been studied by standard materials characterization methods and is summarized in Figure 4 (Iguchi, Yamanaka, & Budhiono, 2000, Czaja, Young, Kawecki, & Brown, 2007, Lin et al., 2013 , Johnson & Neogi, 1989). The hydrogel accumulated on the air-medium interface (Figure 4(a)) is comprised of a random assembly of fibrils, <130 nm wide, with bacteria still embedded in it (Figure 4(b)); the fibrils are composed of finer microfibrils, 2-4 nm in diameter (Figure 4(c)). Bacterial cellulose is known to have the supermolecular crystallographic form of "cellulose I", predominantly of Iα type, with molecular orientation parallel to the direction of the length of the fibrils (Yamanaka et al., 1989).
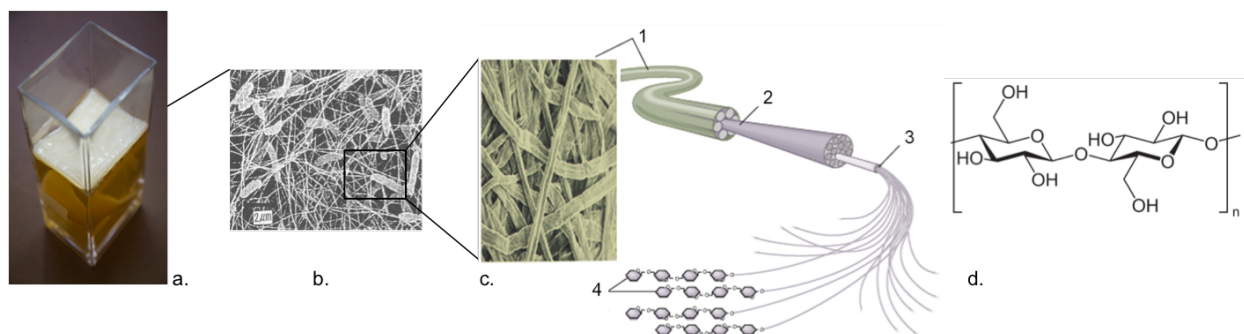
Figure 4: *The hierarchical structure of bacterial cellulose produced by Gram-negative bacteria Gluconacetobacter xylinus. (a) Bacterial cellulose hydrogel (white) is formed on an air-liquid interface. Image by K. Zolotovsky. (b). Scanning electron micrograph of the surface of freeze-dried bacterial cellulose hydrogel (Iguchi, Yamanaka, & Budhiono, 2000). (c) Schematic of the hierarchical structure of cellulose fiber.image source: http://nutrition.jbpub.com/resources/images/images/fiber.gif. (d) chemical composition of bacterial cellulose (Watanabe & Yamanaka, 1995).*

Taking advantage of high moldability of bacterial cellulose, recent studies have proposed that shaping the air-medium interface allows to shape the bacterial cellulose as it grows. Oxygen-permeable substrates were fabricated from PDMS in simple tube shapes to create bacterial cellulose structures with oriented fibers (Yoshino, Asakura, & Toda, 1996, Putra et al., 2008, Putra, Kakugo, Furukawa, Gong, & Osada, 2008, Bodin et al., 2007). New additive manufacturing technologies, such as 3D printing, provide powerful methods to create precisely designed structures for PDMS molds (Singh, 2009, Melchels, Feijen, & Grijpma, 2010). The ability to custom design and fabricate complex three-dimensional structures from bacterial cellulose will allow for unprecedented control over function and performance and open up avenues for new range of larger scale sustainable applications.

As a major component in plants, cellulose is the most abundant biopolymer in nature. It is used excessively for industrial purposes, derived mainly from wood pulp (Klemm, Heublein, Fink, & Bohn, 2005). The environmental damage of the industrial use of plant-derived cellulose is immense. The need for alternative cellulose sources is crucial, and Bacterial Cellulose can be a potentially good candidate for that. Waste from sources rich in glucose can be used as nutrients for the BC growth medium, and the produced cellulose can be biodegraded back to glucose by using *cellulase* enzyme.

Yet, there are a few major setbacks before BC can enter into mass production. The current production process is not efficient and rapid enough, which makes the whole cycle too expensive, and therefore not economically viable for large quantities (Steinbuchel et al., 1998).

Furthermore, bio-materials such as BC often characterized by some amount of inconsistency in their material properties due to environmental conditions and other factors involved in their growth process. It

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may be even more challenging to achieve that consistency when aiming for big mass of production. That aspect may explain the limited use of natural materials in the building industry (Fernandez, 2006).
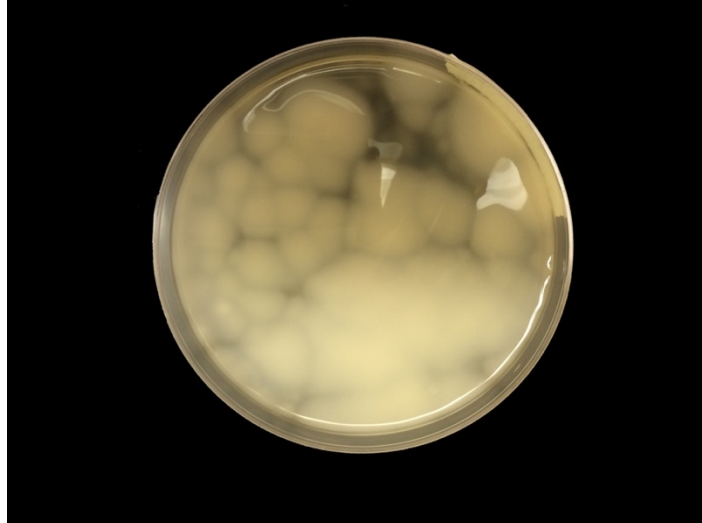

Figure 5: Bacterial Cellulose pellicle, grown in a petri dish. Image by author.

2.2 BIO MATERIALS IN DESIGN AND ARCHITECTURE

With today's increasing awareness of environmental issues and responsible use of materials and waste, it is important to advocate for more extensive use of natural, sustainable materials in the built environment (Fernandez, 2006). If we look, for example, at the environmental damage created by the use of concrete in construction, the need to pursue alternatives is obvious. The cement production industry alone is one of the three primary producers of CO_2 emissions, responsible for 5-10% of total global anthropogenic CO2 emissions (Worrell, Price, Martin, Hendriks, & Meida, 2001). Looking back at the use of natural materials by the building industry (mainly the use of wood), we see that the outcomes were more environmentally harmful than beneficial, characterized by unmonitored exploitation that has led to irreversible damage to ecosystems and desert expansion (Fernandez, 2006).

A key feature of some biomaterials such as Bacterial Cellulose and Mycelium [3] is their ability to *grow* into a given shape. All that is needed in order to produce Bacterial Cellulose are a few bacteria cells and a culture medium. Using biomaterials that *grow*, and incorporating them into the building industry, can be a unique opportunity to use materials with excellent mechanical properties and a truly sustainable production method. The traditional growing process of BC involves almost no waste or energy investment and no carbon emissions. Additionally, in the BC production process, there is hardly any exploitation of *existing* resources since the material is growing "from scratch." Moreover, the culture medium can be provided from local resources or waste.

Bacterial Cellulose is an excellent source of pure cellulose. Cellulose is the most common biopolymer on earth and a main component in wood (over 50%). Using Bacterial Cellulose as an alternative substitute for the depletion of wood in construction has enormous potential (Brown, 1999). One can only imagine the benefits of minimizing the ecological footprint of the wood industry in construction, including the potential to dramatically minimize cycles of shipping and storage.

In comparison to other industries, manufacturing and construction techniques in the building industry have not evolved much in years. The possibility of growing construction materials on site from local, sustainable resources can create a shift in the way we perceive and organize our construction sites, along with our

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[3] Mycelium is the vegetative part of a fungus or fungus-like bacterial colony, consisting of a mass of branching, thread-like fibers ("Mycelium," 2016).

assembly fabrication and pre-fabrication methods.

The following paragraphs present relevant past work and precedents for this research. Some work has been more speculative and experimental, while other work is more directly applicable and industry driven. All the work examines the potential of incorporating bio materials that grow into design and architecture, and was undertaken by designers and architects who integrated biology and material science into their design processes, using them not merely as a source of inspiration.

In BioCouture, fashion designer Suzanne Lee used Bacterial Cellulose in order to grow fabrics and produce clothing, while addressing environmental and ecological issues around design and fashion (Figure 6(a)). BioMASON is a company founded in 2012 by architect Ginger Krieg Dosier. The company creates bricks using bacteria (*Sporosarcina pasteurii*) that have the ability to solidify sand. The production process includes filling a mold with layers of sand and adding a solution made of *Sporosarcina pasteurii*, urea and calcium chloride. A chain of chemical reactions eventually bonds the ingredients together into a brick. Unlike clay brick construction, no burning of fuels is involved. The main challenges for mass production of these bricks includes time of production (5 days as opposed to 2 days for clay bricks) and cost (around 5 times higher than for clay bricks) (Larson, 2010) (Figure 7 (c)). Another project involving the making of bricks out of growing biomaterials is Hy-Fi by The Living, who built a real-scale structure at the court yard of the MoMA PS1. Each brick in the structure consisted of farm waste and fungi that was grown to fit a brick-shaped mold ("Hy-Fi, The Organic Mushroom-Brick Tower Opens At MoMA's PS1 Courtyard," 2014). 'The Future of Plastic' was an exhibition that displayed the research and grown artifacts developed in 'The Growing Lab' by Officina Corpuscoli. The lab uses Mycelium in order to explore new and alternative materials and their possible applications in design. They exhibit ceramic and plastic-like objects produced from Mycelium, in a process they describe as "slow 3D printing." They perceive the fungi as "agents of cohesion and transformation of organic elements, such as fibers and agricultural waste." The produced material and its properties varied according to the growth conditions and added substances. The exhibition aimed to demonstrate a turn from traditional industrial production to what they call 'a novel cultivation model' ("The Future of Plastic," n.d.) (Figure 7 (b)).

Figure 6: *Biocouture, Suzanne Lee, 2010. Digital image. http://www.xsead.cmu.edu/uploads/media/path/365/biocouture_l.jpg.
(b) COSMO, Andres Jaque /Office for Political Innovation, 2015. Digital image.
http://momaps1.org/slideshows/2015_YAP/150620 Cosmo PS1 026_web.jpg.*

Figure 7: *(a) Hy-Fi, The Living, 2014. Digital image. http://www.wired.com/wp-content/uploads/2014/06/Copyright_BarkowPhoto_HY-FI_ExteriorFinal.jpg. (b) The Future of Plastic, Officina Corpuscoli, 2015. Digital image. http://static1.squarespace.com/static/54144f94e4b06505bdae686d/t/555b9d75e4b0eb155ce478f9/1432067468454/?format=750w. (c) BioMASON, Ginger Krieg Dosier, 2012. Digital image. http://static1.squarespace.com/static/54144f94e4b06505bdae686d/t/55645635e4b00576f844a4ba/1432639035311/?format=1000w.*

3 PROTOTYPE: THE BIO-PNUEMATIC CELLULAR ENVELOPE

A Macro-Fluidic Device

(M. Gazit – in collaboration with K. Zolotovsky and Ortiz Lab, Department of Materials Science and Engineering, MIT)

Figure 8: *The system before fluid and pneumatic actuation*

3.1 OVERVIEW

This chapter describes the development, fabrication and outcomes of the Bio-Pneumatic Cellular Envelope. The envelope functions—through pneumatic and fluid actuations—as a system for growing, shaping, and enhancing the material properties of 3D bacterial cellulose-inflated structures.

The bio-pneumatic system is computationally controlled, enabling a measured flow of air and liquids in and out of each cell in the system. This facilitates the creation of cellulose-based material with varied properties in each cell. Variation in material properties is achieved by regulating physicochemical growth conditions and post-growth processing. The system allows the adjustment of medium composition, *in-situ* substance concentration, solvent exchange in order to create bio-composites, and post-growth pneumatic actuation (Figure 16).

Throughout the timeline of material production, the envelope is a tangible architectural object that changes in accordance with production phases: the material transforms from a liquid medium to a hydrogel composite to a pneumatic aerogel (Figure 11). The emphasis is therefore not merely on the final artifact but on the process of making itself.

Living cells can be described as fluid-filled spaces enclosed by thin membranes. Frei Otto, who studied the cell structure while working together with biologists, defined cells as either *pneus* filled with air or *hydros* filled with water (LeCuyer, 2008). Similarly, each cell in the Bio-Pneumatic Envelope acts as a fluid-filled unit, filled either with air or liquid, according to material production phases. Each cell has built-in outlets and inlets for fluids flow.

In order to craft BC-based membranes structures with desired properties, processes 'borrowed' from the world of material science and biology, combined with computation and fabrication techniques, were used. This chapter will describe these processes and techniques in depth – beginning with biological processes such as microbial culture and cellulose growth in different mediums, through material science methods such as the fabrication of nano-composites and freeze-drying. In addition, computation and fabrication techniques such as monitoring pneumatic and fluid actuations by code, molding and casting, 3D printing, and the development and fabrication of custom electronic circuits were also employed.

Despite the very promising aspects of working with BC-based materials for design and architecture projects, there are few critical concerns to address in order to make them applicable. Among these concerns are - the

BC membranes fail to maintain their 3D shape after removing the liquid growth medium, they lose significant thickness when transforming from hydrogel to dry membranes, and tend to be very brittle in their dry state. As part of the Bio-Pneumatic Envelope, I developed a novel workflow in order to overcome the aforementioned difficulties. I designed the workflow to include composing the 3D BC membranes with PVA to achieve greater toughness and increase fracture strain, performing pneumatic actuation in order to maintain desired 3D shape, and freeze drying in order to preserve 3D fiber network and porosity of the material (Figure 30). Chapter 3.3 explains this process and chapter 3.3.3 presents the results of tensile testing made in order to validate the outcomes.
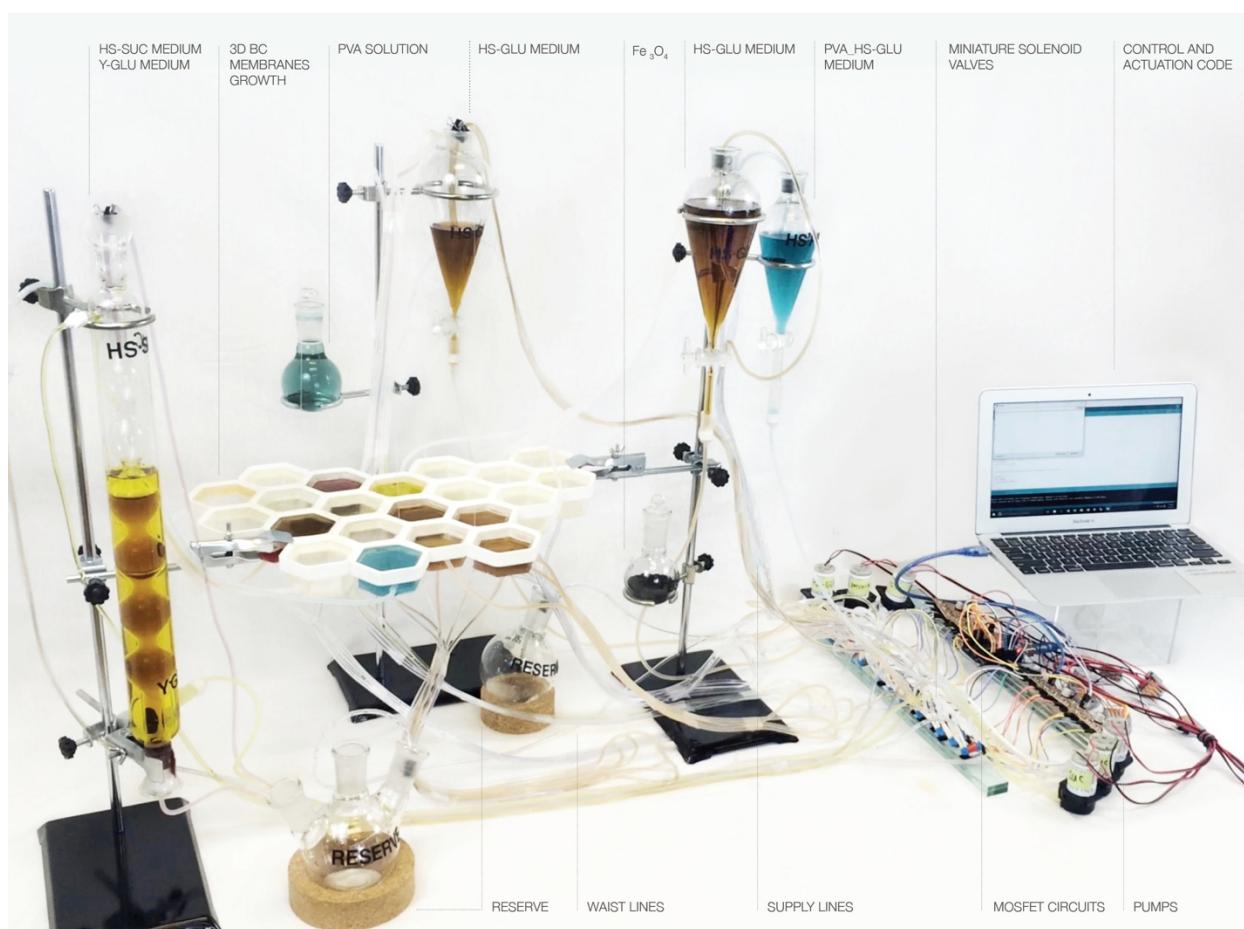

Figure 9: System overview with its different components. The system allows control of physicochemical conditions in each of the growth vessels.
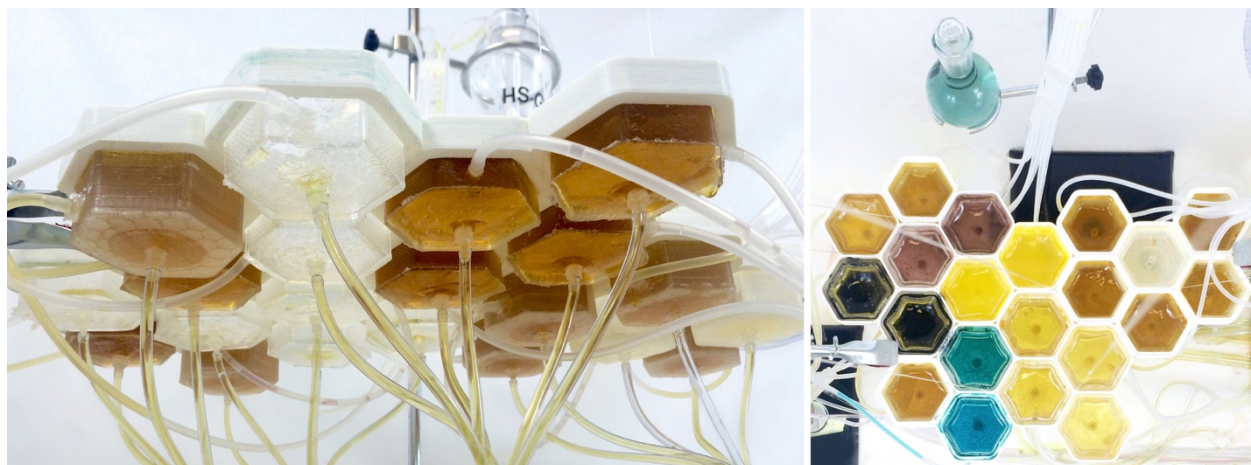
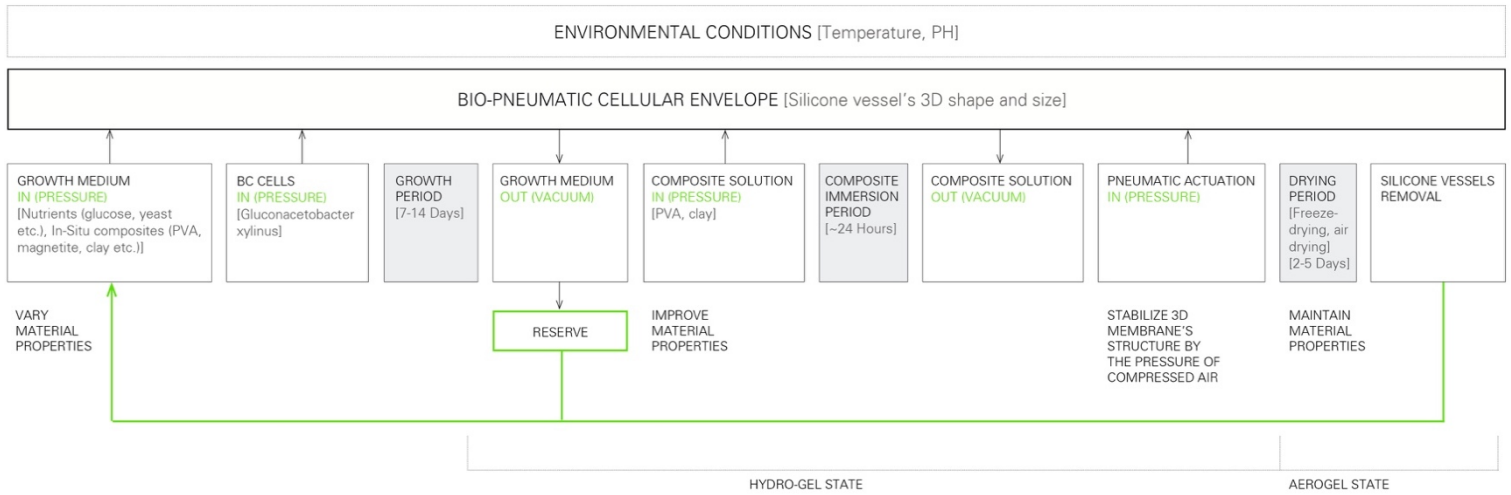*Figure 10: Hexagon growth vessels routed with silicone tubes*

3.1.1 The System

The system consists of 21 hexagon cells, 4 types of growth medium for variation in *in-situ* growth conditions, PVA solution and Fe$_3$O$_4$ powder for post-growth bio-composites[4], reserve containers for renewable waste, 10 miniature solenoid valves, 6 liquid and air pumps, custom made MOSFET circuits, and Arduino microcontroller connected to a laptop in order to actuate, monitor and receive feedback from the system[5] (Figure 9). The entire system is routed by silicone tubes (Figure 10). The hexagon cells can be easily attached and detached to and from the system's frame (Figure 23).

The Macro-Fluidic Device is used in order to investigate a matrix of parameters and their effect on BC structure and properties (Figure 16). Each hexagon cell in the system has an inlet connector through which to insert growth medium, composite solution and air, and an outlet connector to remove liquids into the reserve container. Each pair of cells contains a unique composition of the parameters described in Figure 16, in order to grow BC membranes with varied structure and properties. Figure 13 maps the layout of the cells in the system. Figure 11 schematically illustrates the different phases and actuations in the system through time, and their effect on material properties and material state – from a culture medium with *Gluconacetobacter xylinus* cells to a hydrogel membrane >> a bio-composite hydrogel >> a pneumatic

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[4] See chapter 3.3 for an in-depth description of the bio-composites in the systems.

[5] See chapter 3.2 for an in-depth description of actuation and control in the system, using electronics and code.

hydrogel, and finally to a 3D pneumatic aerogel.

ENVIRONMENTAL CONDITIONS [Temperature, PH]

BIO-PNEUMATIC CELLULAR ENVELOPE [Silicone vessel's 3D shape and size]

| GROWTH MEDIUM IN (PRESSURE) [Nutrients (glucose, yeast etc.), In-Situ composites (PVA, magnetite, clay etc.)] | BC CELLS IN (PRESSURE) [Gluconacetobacter xylinus] | GROWTH PERIOD [7-14 Days] | GROWTH MEDIUM OUT (VACUUM) | COMPOSITE SOLUTION IN (PRESSURE) [PVA, clay] | COMPOSITE IMMERSION PERIOD [~24 Hours] | COMPOSITE SOLUTION OUT (VACUUM) | PNEUMATIC ACTUATION IN (PRESSURE) | DRYING PERIOD [Freeze-drying, air drying] [2-5 Days] | SILICONE VESSELS REMOVAL |

VARY MATERIAL PROPERTIES — RESERVE — IMPROVE MATERIAL PROPERTIES — STABILIZE 3D MEMBRANE'S STRUCTURE BY THE PRESSURE OF COMPRESSED AIR — MAINTAIN MATERIAL PROPERTIES

HYDRO-GEL STATE   AEROGEL STATE

* Square brackets show the variables at each stage. Different variables and different compositions of these variables affect material properties and structure.

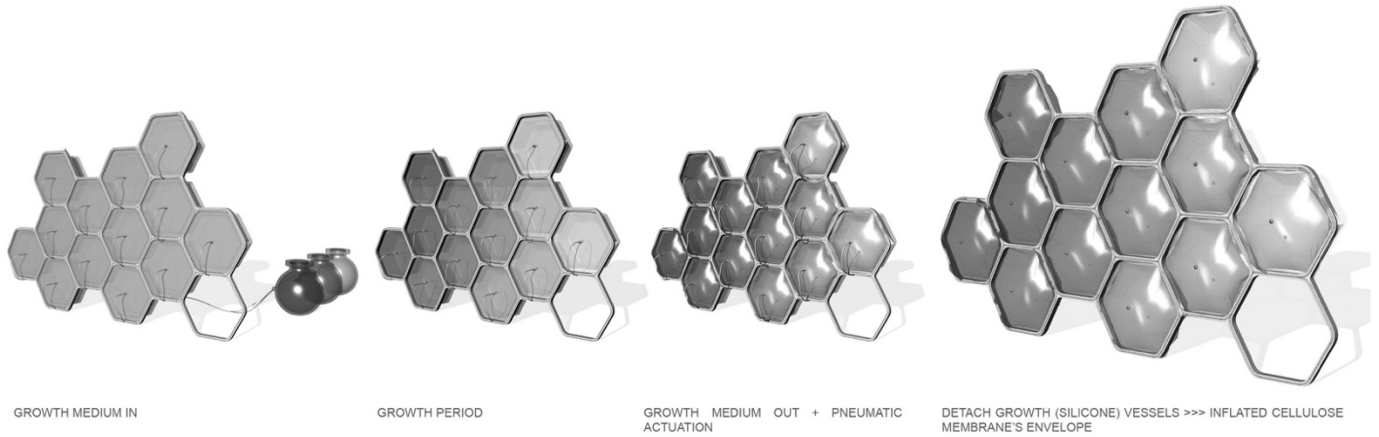*Figure 11: The phases of the Bio-Pneumatic Envelope through time*

GROWTH MEDIUM IN   GROWTH PERIOD   GROWTH MEDIUM OUT + PNEUMATIC ACTUATION   DETACH GROWTH (SILICONE) VESSELS >>> INFLATED CELLULOSE MEMBRANE'S ENVELOPE

Figure 12: Conceptual renderings of the bio-pneumatic envelope during core phases

Cells Diagram

Interval_Control_0*

Control *

Y-GLU Growth Medium

Interval_1 *

Interval_3 *

Y-GLU Growth Medium

HS-SUC Growth Medium

Interval_2 *

BC - Fe₃O₄ Composite *

HS-SUC Growth Medium

Interval_1 *

Interval_3 *

BC - Fe₃O₄ Composite *

BC - 6% PVA Composite *

Interval_2 *

in-situ BC-PVA Composite *

BC - 10% PVA Composite *

Interval_Control_0*

BC - 6% PVA Composite *

in-situ BC-PVA Composite *

BC - 10% PVA Composite *

———— Casted PDMS (Silicone) Vessels
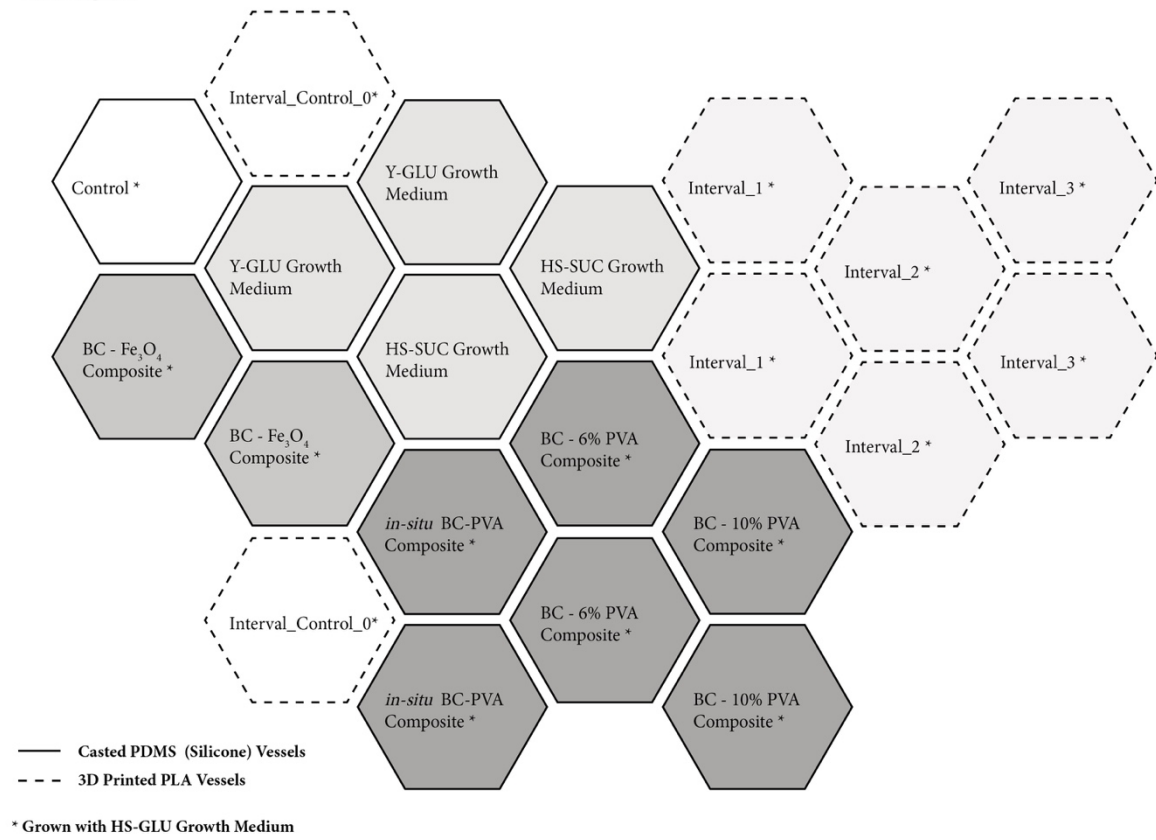- - - - 3D Printed PLA Vessels

* Grown with HS-GLU Growth Medium

Figure 13: Envelope's Cells layout. Each pair of cells comprises a unique composition of parameters in order to grow BC membranes with varied structure and properties.
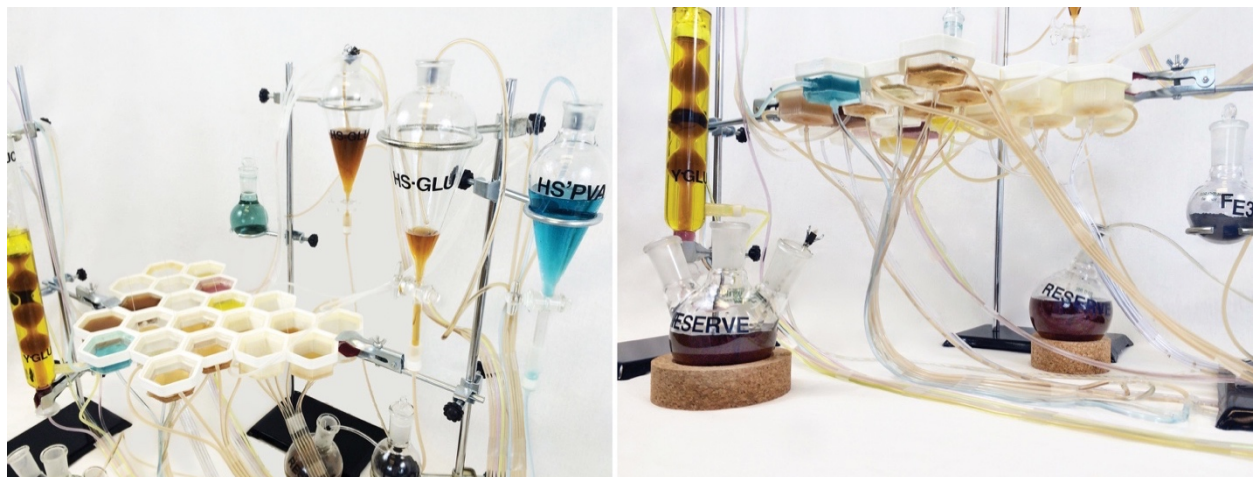

Figure 14: The envelope from above and below

Figure 15: Zoom- in photos of the various growth mediums

BC characterization			Structure				Properties		
Design strategy			composition	density	orientation	crystallinity	mechanical	thermal	acoustic
In-situ chemical conditions	Medium composition								
	In-situ added substances	PVA*					▓		
		Magnetite					▓		
		Clay*							
		Starch							
		Chitosan							
	pH								
In-situ physical conditions	Agitation	speed							
		velocity							
	Flow intervals	oxygen							
		medium					▓		
	Substrate	shape					▓		
		material							
		thickness							
		texture							
	Temperature						▓		
Post-	Composite	PVA					▓		
growth processing	Pneumatic Actuation						▓		
	Drying	Air-drying					▓		
		Freeze-drying					▓		
		Critical point drying							

Figure 16: Matrix of possible design strategies (divide into 3 categories: in-situ chemical and physical conditions and post growth processing) and their effect on BC characterization in terms of structure and properties. Fields marked in gray were tested and evaluated in this research.

3.1.2 Bio-Molds: The "Cells" of the Bio-Pneumatic Envelope

As mentioned, the prototype consists of 21 hexagon growth vessels. 15 of them are made of cast PDMS (silicone), and 6 are made of 3D printed PLA (Figure 13, Figure 18 *(left)*)

Growing BC membranes inside 3D PDMS vessels is a key aspect in the ability to produce 3D cellulose membranes. BC grows only at the interface between medium and *air*. PDMS has a unique property of being liquid-proof and at the same time oxygen-permeable. Therefore, culturing BC cells in 3D PDMS vessels filled with growth medium enables the replication of the shape of the oxygen-medium interface created by the PDMS substrate, hence allowing the ability to *shape* BC as it grows (Figure 17 *(left)*). For this specific prototype, a hexagon shape for the vessels was arbitrarily chosen. BC membranes can grow into *any* desired 3D shape inside PDMS vessels. In contrast, The PLA vessels (or any other material that is not oxygen-permeable, for that matter), enable growth only at the upper surface of the vessel, where the interface between air and medium occurs[6] (Figure 18 *(right)*).

After the growth period, when removing the liquid medium from the PDMS vessel, or when the liquid gradually evaporates naturally, the 3D cellulose membranes fail to maintain their shape (Figure 17 *(middle)*). Pursuing this problem, I discovered that the 3D cellulose membranes grown in the PDMS vessels were *air tight*, and that compressed air pressure could inflate and re-stabilize their shape and structure (Figure 17 *(right)*). This revelation was crucial to my seeing how the shape and structure of the 3D cellulose membranes could be maintained. I therefore designed each hexagon cell with an inlet for liquid and *air* at the side of the cell, and an outlet for liquids at the bottom. The Inlet connector sticks into the vessel so that the BC membrane pocket can grow around it. The connector 'penetrates' the membrane and enables pneumatic actuation from the inside of the cellulose pocket (Figure 19). Figure 21 summarizes the aims and benefits of coupling pneumatic actuation with BC membranes.

The design of the PDMS hexagon molds went through several iterations until the desired outcome was achieved. One of the objectives was to be able to grow the 3D cellulose membranes with *edges*, so that they can stay connected to the system after detaching the PDMS vessels; the surface of the hexagons can

---

[6] The PLA vessels in the system were used in order to examine how exchanging the growth medium at different time intervals during the growth period would affect the properties of the BC membranes. A frequent exchange of medium during growth would have damaged the growth of the delicate 3D cellulose membranes, and therefore we decided to perform the interval experiment in PLA vessels, which only allow the growth of a flat cellulose membrane at the top of the vessel.

then function as an envelope made of BC pneumatic units. See Figure 20 and Figure 23 for conceptual renderings of core phases in envelope timeline. In order to grow an enclosed BC membrane with *edges*, a unique section was designed. See Figure 22 for BC membrane grown with edges. Material growth, shape and thickness can be tuned according to the design of the bio-mold.
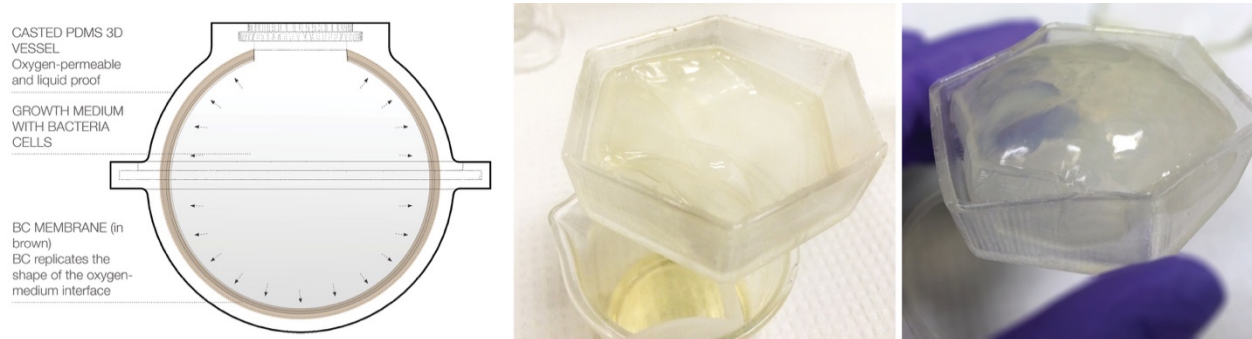

Figure 17: *(left) Growing BC in PDMS molds - BC grows at the oxygen-medium interface, replicating PDMS vessel's shape and texture. (middle) BC membrane grown in PDMS hexagon vessel – the membrane losses its shape after the liquid medium is removed. (right) BC membrane after pneumatic actuation. Compressed air pressure re-stabilizes 3d membrane's shape.*
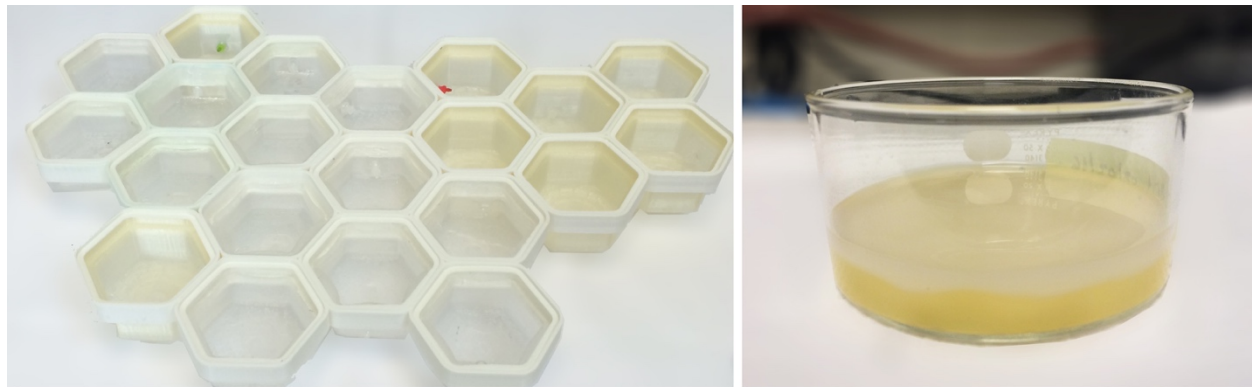

Figure 18: *(left) 21 growth vessels in the system. 15 of them are made of casted PDMS (silicone), and 6 are made of 3D printed PLA. (right) BC grown in a non oxygen-permeable vessel – cellulose membrane grows only at the upper surface of the vessel, where the air-medium interface occurs*
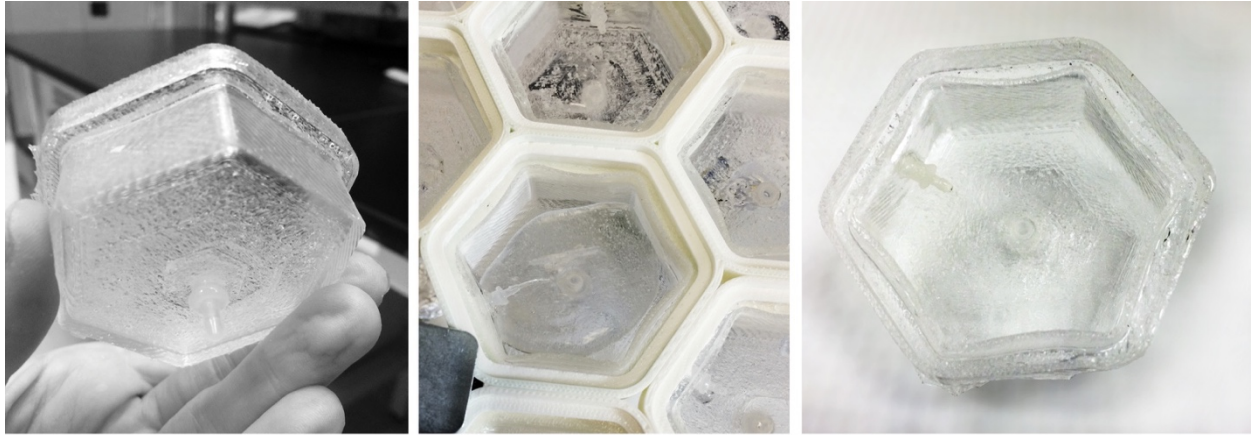
Figure 19: *Cast PDMS hexagon cells. The Inlet connector sticks into the vessel so that the BC membrane pocket can grow around it. The connector 'penetrates' the membrane and enables pneumatic actuation from the inside of the cellulose pocket. The outlet connector is at the bottom of the vessel. The bottom is slightly sloped in order to enable full removal of liquids.*
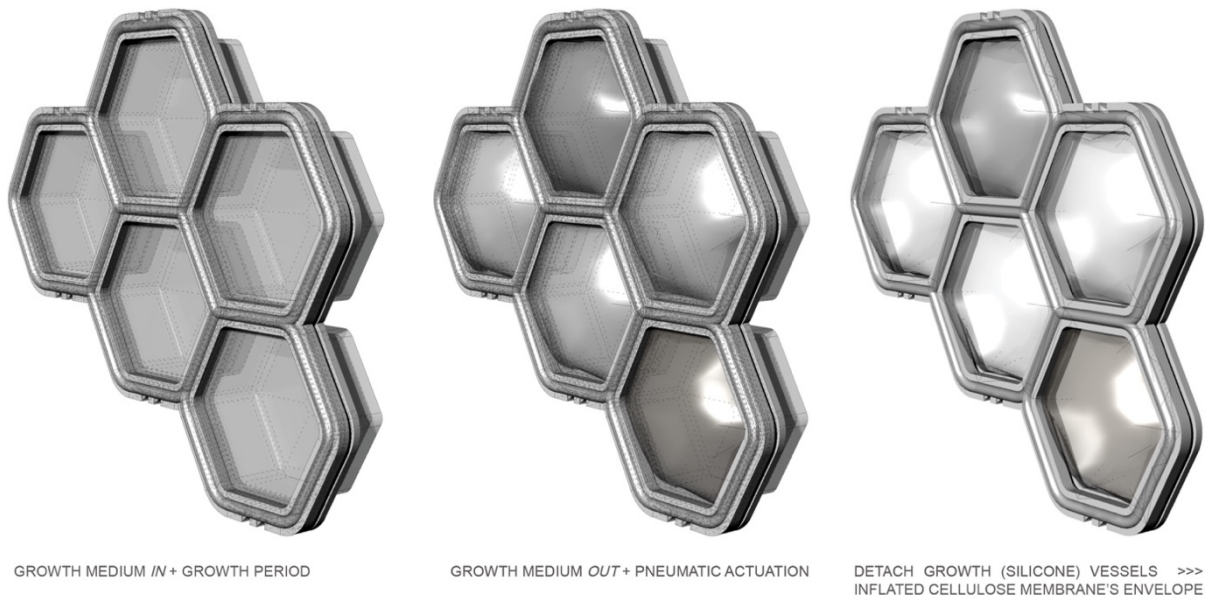

GROWTH MEDIUM *IN* + GROWTH PERIOD

GROWTH MEDIUM *OUT* + PNEUMATIC ACTUATION

DETACH GROWTH (SILICONE) VESSELS >>>
INFLATED CELLULOSE MEMBRANE'S ENVELOPE

Figure 20: *Conceptual renderings of the bio-pneumatic envelope during core phases*

WHY BACTERIAL CELLULOSE + PNEUMATICS?

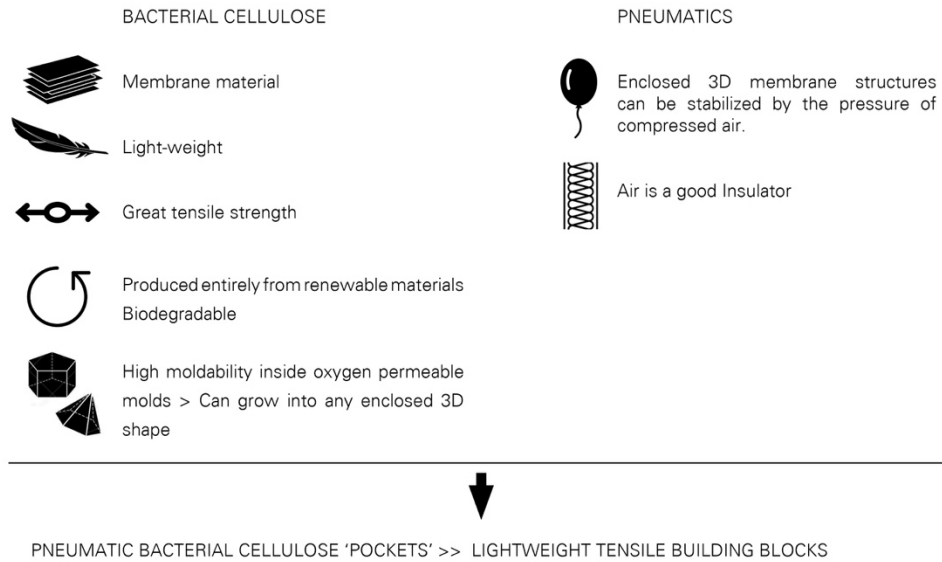BACTERIAL CELLULOSE

Membrane material

Light-weight

Great tensile strength

Produced entirely from renewable materials
Biodegradable

High moldability inside oxygen permeable molds > Can grow into any enclosed 3D shape

PNEUMATICS

Enclosed 3D membrane structures can be stabilized by the pressure of compressed air.

Air is a good Insulator

PNEUMATIC BACTERIAL CELLULOSE 'POCKETS' >> LIGHTWEIGHT TENSILE BUILDING BLOCKS

Figure 21: Summary of the aims and benefits of coupling pneumatic actuation and BC membranes
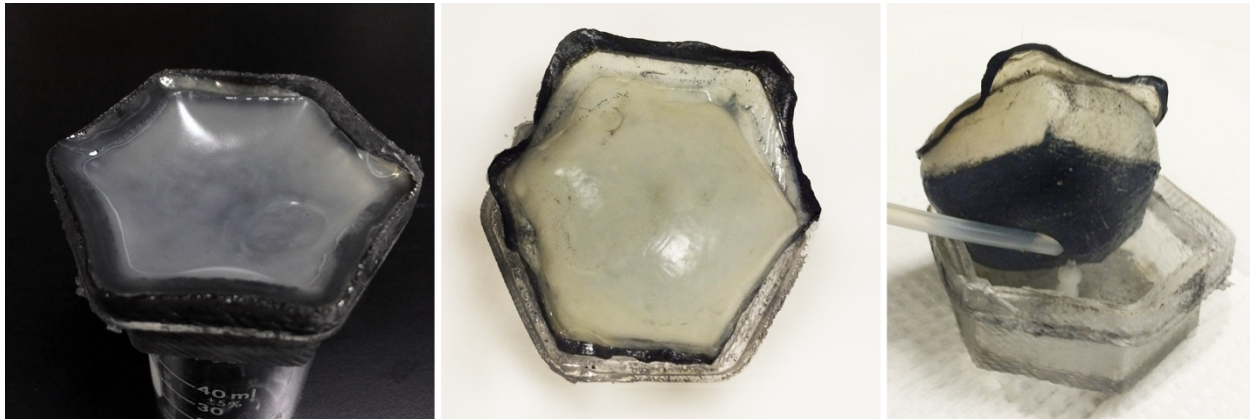

Figure 22: Growing enclosed 3D BC membranes with edges. Material growth, shape and thickness can be tuned according to the design of the bio-mold. (left) during growth period. (middle and right) after pneumatic actuation.
The membranes above are in-situ composites of BC and Magnetite. Due to the unique section of the PDMS vessels, the magnetite particles were added to the growth medium only in desired areas, resulting in enclosed 3D BC membranes with magnetic features at the edges and at the bottom part (those parts can easily be seen in the images due to the magnetite's black pigment).

Figure 23: *Growth vessels can be easily attached and detached to and from the system's frame*
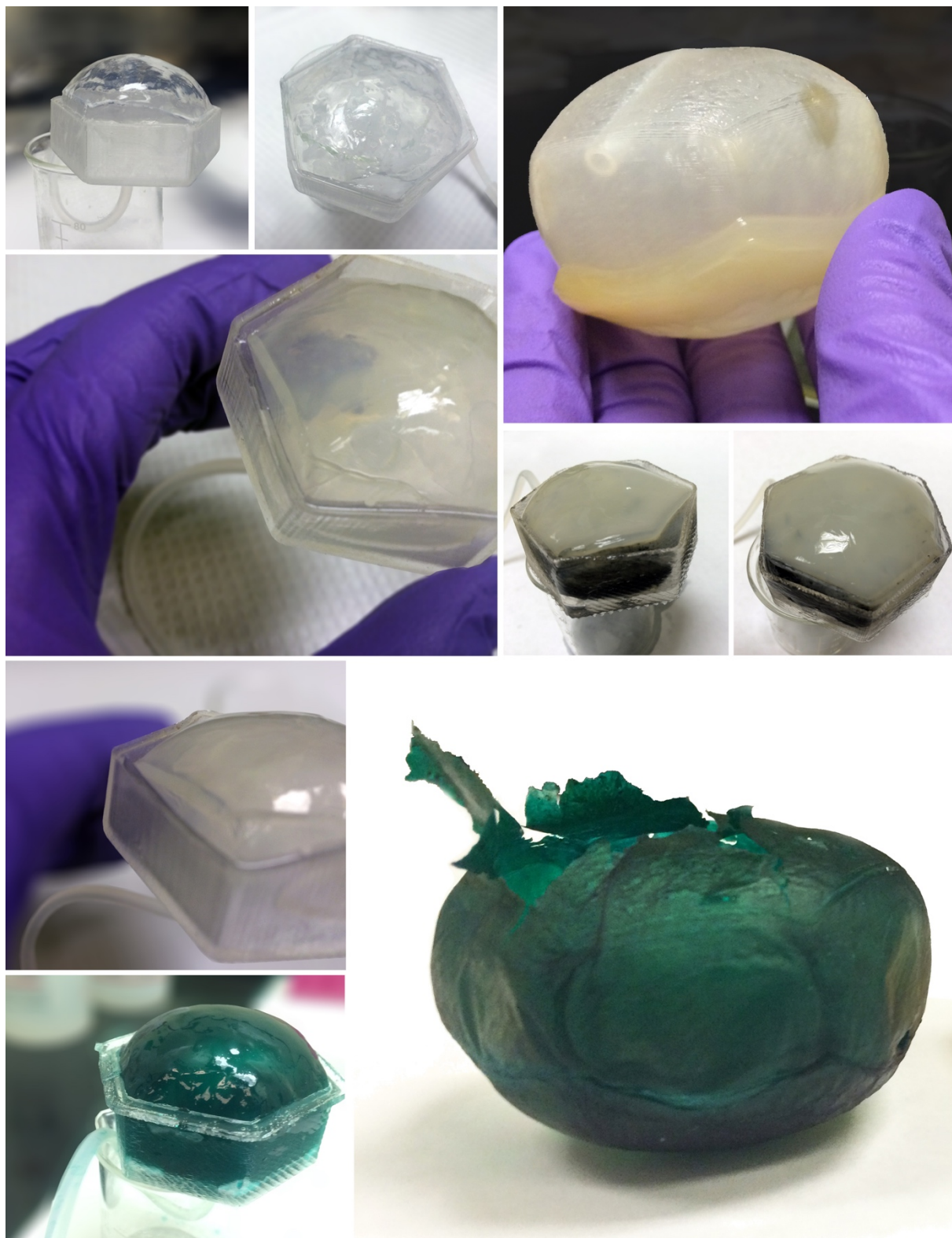
Figure 24: Various samples of inflated 3d cellulose membranes made during system's 'cell' studies

3.2   AIR AND FLUIDS ACTUATION AND CONTROLS

In order to computationally control a measured flow of air and liquids in and out of each cell in the envelope, I designed the following system:

Two miniature solenoid valves (X-Valve by Parker) were connected to each pair of hexagon cells. One solenoid monitored incoming flows and the other monitored waste flows. The solenoids were also connected to pumps which either injected or vacuumed fluids in and out of the cells and the different growth medium and other substances in the system. The solenoids were connected to a MOSFET circuit, which I designed and fabricated. Figure 26 describes the circuit's components. The MOSFET circuits were connected to an Arduino microcontroller, which enabled communication and feedback with the programming environment. A script to actuate and monitor measured flows in different conditions and compositions was written in Arduino IDE. Future work includes incorporating sensors in the system in order to allow better feedback mechanism.
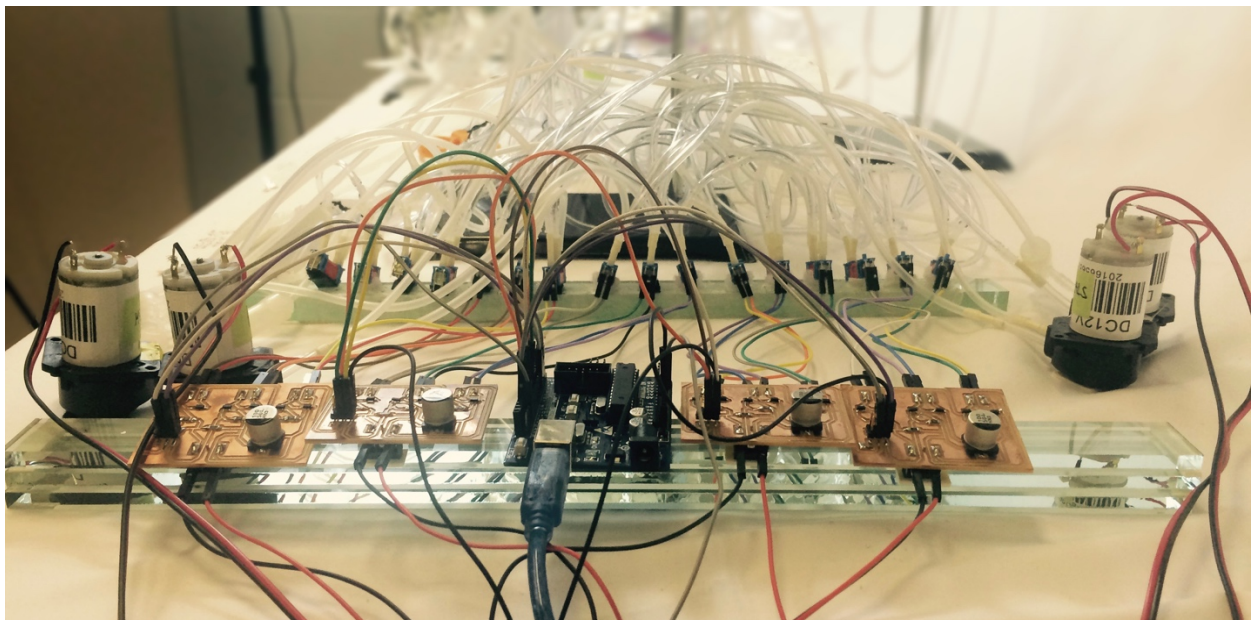

Figure 25: *The electronics control system – solenoids valves, pumps, MOSFET circuits, and microcontroller.*

Socket connectors (at the bottom): fits solenoid valves pins

MOSFET N-channel power transistor: switches digital signal to power level current

Resistor: prevents false positive signals

Six pins header: signal connection to Arduino

Schottky Diode: protects MOSFET when solenoid coil discharges

Capacitor: store energy and smooth voltage
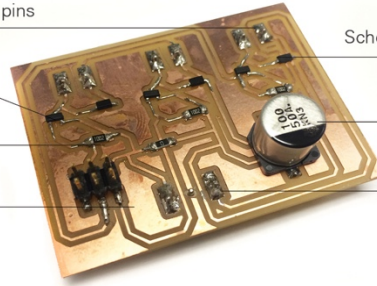
5V power supply connection

Figure 26: *MOSFET circuit's components*


```
bio-pneu_v3 §
}
int grow(int in) {
  //Inject 60ml HS medium into Cell:
  digitalWrite(in, HIGH); //open valve_in
  delay(120000); //wait 120 sec
  digitalWrite(in, LOW); //close valve_in
  // Inject 5ml of pre-cultured G.xylinus into Cell_X??
}

int interval(int in, int out) {
  //Pump 15ml G.xyl+HS medium out of Cell:
  digitalWrite(out, HIGH); //open valve_out
  //Inject 15ml G.xyl+HS medium into Cell:
  digitalWrite(in, HIGH); //open valve_in
  delay(30000); //wait 30 sec
  digitalWrite(out, LOW); //close valve_out
  digitalWrite(in, LOW); //close valve_in
}

int harvest(int out) {
  //Pump 40ml G.xyl+HS medium out of Cell:
  digitalWrite(out, HIGH); //open valve_out
  delay(80000); //wait 60 sec
  digitalWrite(out, LOW); //close valve_out
}

void loop() {

  //==================================== grow all cells

  grow(cell_0_in);
  grow(cell_1_in);
  grow(cell_2_in);
  grow(cell_3_in);

  //==================================== cell_0 (control) 1 interval
  if (time == 691200000) {
    harvest(cell_0_out);
  }

  //==================================== cell_1 (control) 2 intervals
  if (time == 345600000) {
    interval(cell_1_in, cell_1_out);
  }
  if (time == 691200000) {
    harvest(cell_1_out);
  }

  //==================================== cell_2 4 intervals

  if (time == 172800000) {
    interval(cell_2_in, cell_2_out);
  }
  if (time == 345600000) {
    interval(cell_2_in, cell_2_out);
  }
  if (time == 8640000) {
    interval(cell_2_in, cell_2_out);
  }
  if (time == 691200000) {
    harvest(cell_2_out);
  }

  //==================================== cell_3 8 intervals

  if (time == 86400000) {
    interval(cell_3_in, cell_3_out);
  }
  if (time == 172800000) {
    interval(cell_3_in, cell_3_out);
  }
  if (time == 4320000) {
    interval(cell_3_in, cell_3_out);
  }
  if (time == 345600000) {
    interval(cell_3_in, cell_3_out);
  }
  if (time == 7200000) {
    interval(cell_3_in, cell_3_out);
  }
```

Figure 27: *(left) overview look of the system. (right) Snapshot of the actuation script in Arduino IDE.*

3.3 BIO-COMPOSITES

In the past years there has been an ongoing interest in bio-based materials as alternative materials for the production of nanocomposites. Applications include packaging, biomedical products and more. Bacterial cellulose is considered to be an excellent candidate for the fabrication and development of novel nanocomposite materials due to its unique properties, among them high tensile strength, purity and water-holding ability (Figueiredo, Vilela, Neto, Silvestre, & Freire, 2014).

In this chapter I present two types of BC based composites I fabricated. One with Poly(vinyl alcohol) – PVA, and the other with Fe_3O_4 (Magnetite). The aim of experimenting with these materials was to improve and enhance BC properties, so as to make them more compatible with design and architectural projects.

3.3.1 BC-PVA Composite

Dried BC membranes tend to be very brittle, and lose significant thickness when transforming from hydrogel to dry membranes. That can be a major setback when aiming to create BC based materials that are applicable to design and architecture. In order to achieve greater toughness and increase elongation at break, I fabricated a composite between the BC membrane and Poly(vinyl alcohol) – PVA.

Poly(vinyl alcohol) is a water-soluble synthetic homopolymer (Leitão, Silva, Dourado, & Gama, 2013). PVA is used in textiles, as a coating material, and in other applications. PVA fibers also performs as reinforcement in concrete. The combination of PVA and BC has been previously proposed mainly for biomedical applications (Leitão, Silva, Dourado, & Gama, 2013). BC-PVA composites consider to be a good match due to PVA's water solubility, biocompatibility and good mechanical properties (Figueiredo, Vilela, Neto, Silvestre, & Freire, 2014).

The preparation of the BC-PVA composites was made by solvent exchange and produced as follows: BC membranes, grown for 7 days, with thickness of ~3mm were washed from the growth medium with distilled water and purified by immersing in NaOH. The samples were then immersed in PVA solution with concentration of 6% or 10%[7] for 18H in ~35c, followed by 14H in ~90c. The samples were then frozen for 17H in -20c and thawed for 6H in room temp. After thawing, the samples were reheated in ~65c to

---

[7] PVA solution was prepared by mixing PVA and distilled water for 30 min in 80c.

remove access PVA. They were then frozen again at -20c followed by -80c in preparation for freeze-drying. The samples were then freeze-dried for 6 days.

Chapter 3.3.3 presents the outcomes of the BC-PVA composites and the results of tensile testing done in order to evaluate their mechanical properties.

As mentioned, the fabrication of the BC-PVA composites is part of a novel workflow I developed in order to overcome a few critical difficulties when working with BC, with the aim of making it applicable to design and architecture projects. Figure 30 describes that workflow schematically.

Figure 28: *The BC-PVA composite after pneumatic actuation. Hydrogel state.*
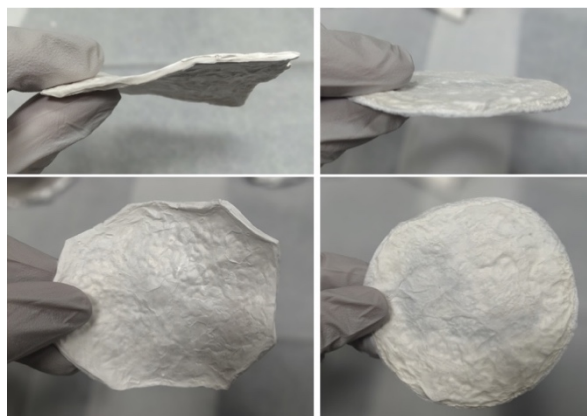

Figure 29: *BC membranes after freeze-drying. (left) BC-PVA 10% composite. (right) Native BC control sample. Significant loss of thickness after freeze drying was measured in the BC native sample.*

GROWING BC MEMBRANES IN AN OXYGEN-PERMEABLE PDMS
VESSEL (WITH ANY DESIRED SHAPE)

FABRICATING NANO-COMPOSITES FROM THE BC MEMBRANES
AND PVA, IN ORDER TO REDUCE BRITTLENESS, ACHIEVE GREATER
TOUGHNESS AND INCREASE FRACTURE STRAIN

PERFORMING PNEUMATIC ACTUATION IN ORDER TO MAINTAIN
DESIRED 3D SHAPE

FREEZE DRYING IN ORDER TO PRESERVE 3D FIBER NETWORK
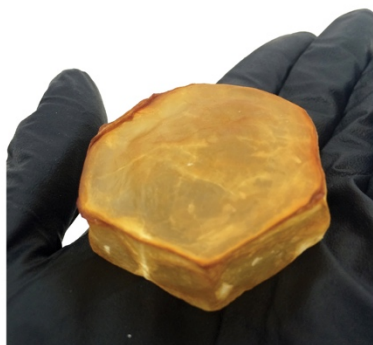AND POROSITY OF THE MATERIAL

Figure 30: *Novel workflow for the production of 3D pneumatic Bacterial Cellulose membranes*

3.3.2 BC - Fe_3O_4 (Magnetite) Composite

Fe3O4 is the formula of the chemical compound iron oxide (also called Magnetite). Magnetite is a ferrimagnetic mineral and It is the most magnetic of all natural minerals on earth. It is drawn to magnets and can become a magnet itself if being magnetized (Wasilewski & Kletetschka, 1999). Composing BC and Magnetite was previously proposed and reported (Zhang et al., 2011). The main objective of fabricating BC-Magnetite composites is the magnetic properties achieved by the addition of the iron oxide nanoparticles (Figueiredo, Vilela, Neto, Silvestre, & Freire, 2014).

For this research I fabricated the BC-Fe_3O_4 composites in order to enhance the cellulose membrane with magnetic features, and in order to explore the possibility of producing *in-situ* composites. BC-Fe_3O_4 composites can have compelling applications in design and architecture due to their flexibility, high tensile strength, their ability to perform as magnetic connectors between different parts and components, and more.

The composite was prepared by adding magnetite particles into the culture medium. During growth, the BC nano-fibril network uses as a matrix for an *in-situ* synthesis of the magnetite particles. Due to the unique section of the PDMS vessels, the magnetite particles were added to the growth medium only in desired areas, resulting in enclosed 3D BC membranes with magnetic features at the edges and at the bottom part (Figure 22, Figure 31, Figure 32).

Compelling future work in that context includes performing tests to evaluate whether the magnetic particles got linked to the bacteria (and not merely to the cellulose nano-fibrils). In that case the location and the orientation of nano-fibrils might be controlled magnetically *in-situ* during growth (Figueiredo, Vilela, Neto, Silvestre, & Freire, 2014).
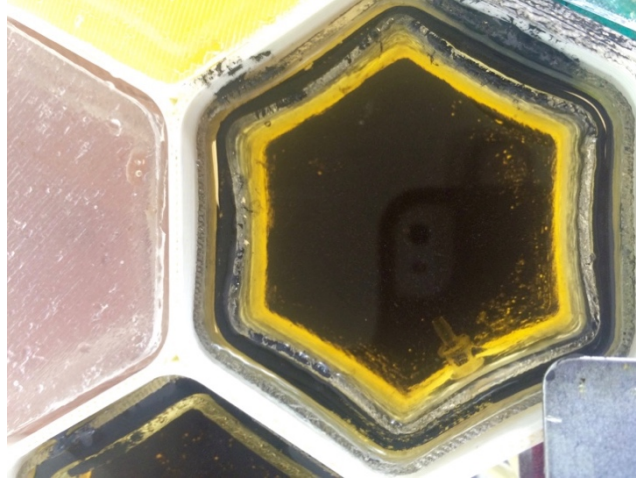
Figure 31: *Fabrication of in-situ BC-Magnetite composites, pre-growth state. Magnetite particles are added to the culture medium in desired areas.*

Figure 32: *(left) Fe_3O_4 (Magnetite) particles. (middle and right) BC-Magnetite composites display magnetic features.*

3.3.3 RESULTS

The following charts and tables presents the results of tensile testing performed on five BC samples that were treated with different post growth processing. The main objective for the tests was to evaluate the effects of composing BC with PVA, in comparison to a native BC sample.

	Sample	# of growth days	Added substances	Washing	Drying
1	BC AD	7	-	NaOH +DI	Air-drying
2	BC FD	7	-	NaOH +DI	Freeze- drying
3	BC AD (no NaOH)	21	-	DI	Air-drying
4	BC-PVA 6% FD	7	PVA 6%	NaOH +DI	Freeze- drying
5	BC-PVA 10% FD	7	PVA 10%	NaOH +DI	Freeze- drying

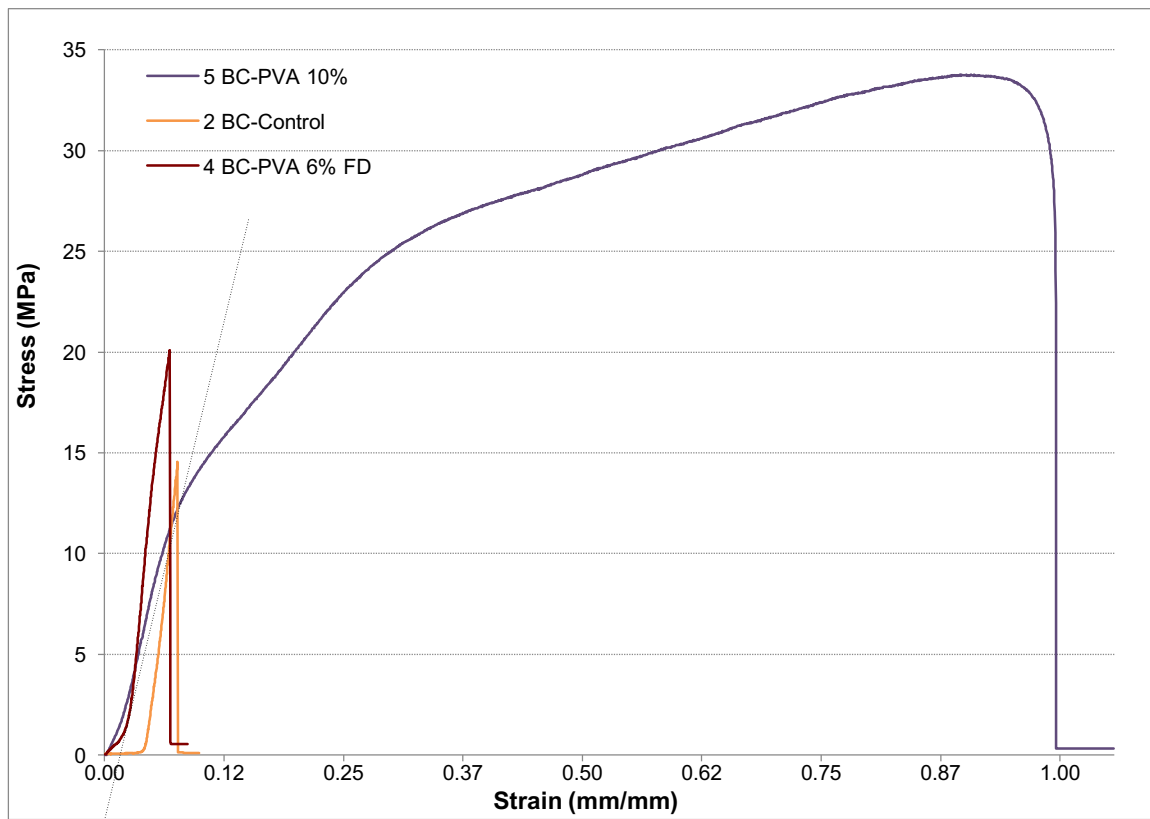**Table 1:** *Samples description*

Figure 33: *Stress-Strain curve for BC-PVA composites*

#	Sample	Elastic modulus (GPa)	Ultimate tensile strength (MPa)	Elongation at break (%)	Toughness (MJ/m^3)	Density (g/cm^3)
1	BC AD	0.55	45	7.9	2	TBC
2	BC FD	0.43	15	7.4	0.2	TBC
3	BC AD (no NaOH)	16.5	227	2.3	1.8	TBC
4	BC-PVA 6% FD	0.46	20	6.7	0.5	TBC
5	BC-PVA 10% FD	0.2	34	99.6	25.8	TBC

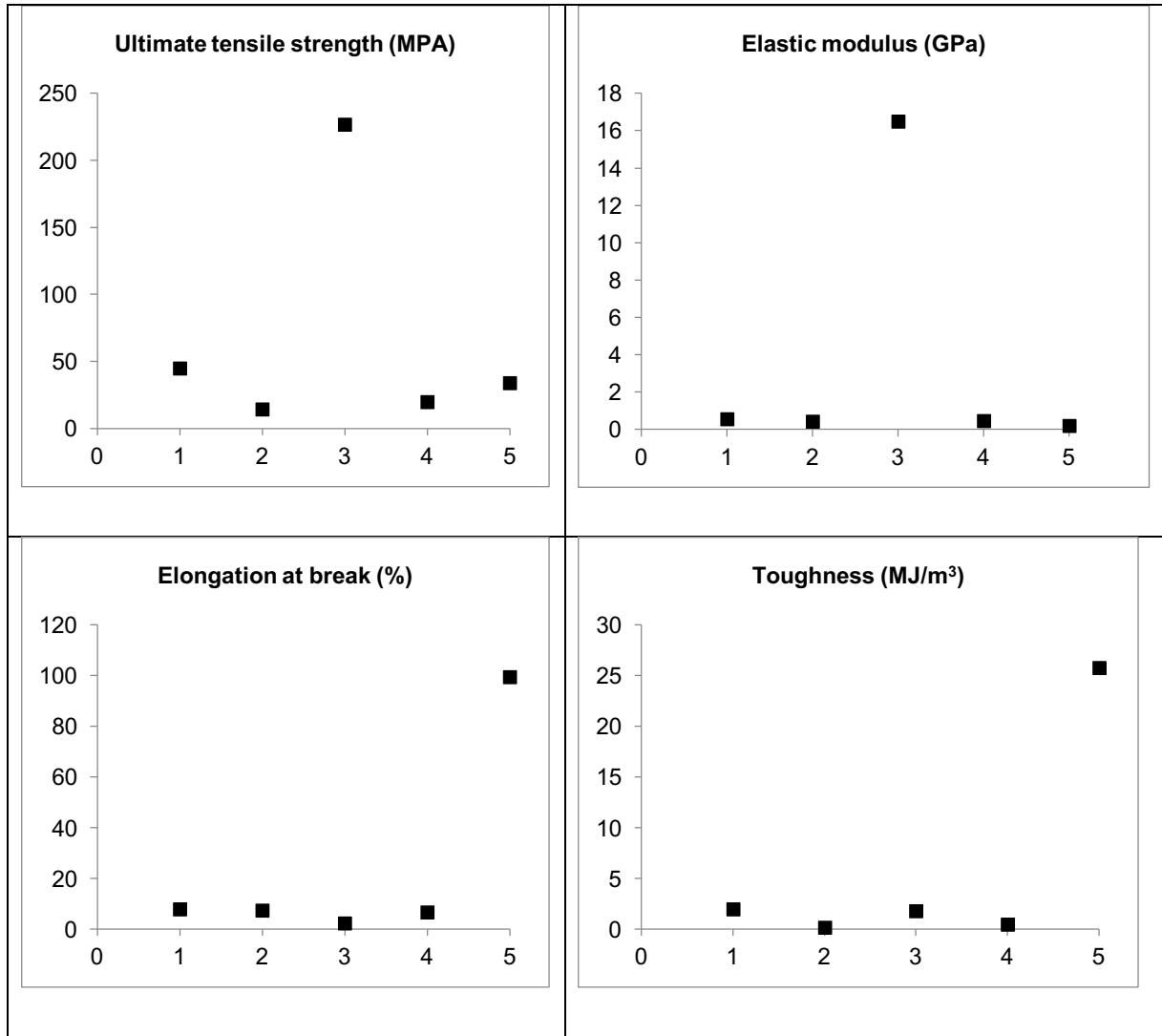*Table 2: Summary of mechanical properties.*

Figure 34: *Plot of mechanical properties from* ***Table 2***.

Discussion:

The control sample of native bacterial cellulose (sample 2 BC-Control) displays behavior of brittle material (Figure 33). After initial horizontal portion that results from wrinkles on the material, the curve shows linear relation between stress applied and the resulting elongation (strain) of the material. This phase is the elastic phase, where the deformation of the material is reversible. If tension was released in this phase, the sample would return to its initial state. For the brittle material such as native cellulose, the failure of the sample occurs in the elastic phase. The failure is sudden and the sample breaks at once (we could hear the crack sound occurring as the sample broke). It breaks very sharply, without plastic deformation, in what is called a brittle failure. Both the native cellulose and the 6% BC-PVA composite exhibit typical behavior of brittle material. The 6% BC-PVA composite was somewhat stronger, withstanding stress up to 20MPa, compared to 15MPa of the control sample (Table 2).

However, the BC-PVA 10% composite demonstrates completely different deformation mechanism. This composite exhibits ductile stress-strain behavior. The initial liner region of elastic deformation (shown in dotted line in Figure 33), is followed by a region of plastic deformation. This plastic deformation shows the ability of the composite to deform under stress without fracture, or failure. Plastic deformation is irreversible, meaning that if the stress is removed, the material won't return to its initial shape. Due to the ability to deform plastically, the BC-PVA 10% composite shows higher strength than native BC --34MPa compared 15MPa of native BC (Table 2). More importantly, the composite shows order of magnitudes higher toughness -- 25.8 MJ/m^3 compared to 0.2 MJ/m^3 (Table 2). This demonstrates the versatility of bacterial cellulose properties and the ability to modify properties of BC by post-growth treatment, in this case PVA 10% solution. As future work, it is possible to regulate BC properties *in-situ*, by adding PVA solution to the medium during growth (Gea, Bilotti, Reynolds, Soykeabkeaw, & Peijs, 2010). We have successfully demonstrated this possibility by growing BC in PVA solution in the Bio-Pneumatic Cellular Envelope (Figure 35).
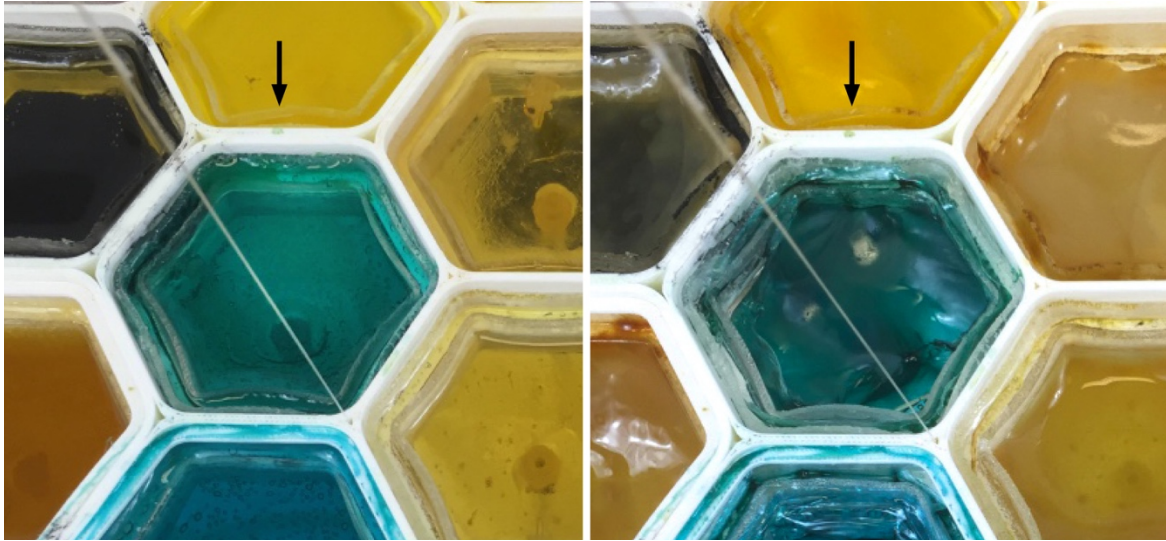
Figure 35: In-situ BC-PVA Composite. 5% PVA solution was mixed with the culture medium prior to growth. (left) Second day of growth. (right) After 10 days of growth.

3.4 METHODS AND MATERIALS

As described in the previous subchapters, in order to fabricate the various components of the Bio-Pneumatic Cellular Envelope processes and techniques from the world of material science and biology, combined with computation and fabrication techniques were used.

The following paragraphs describes the methods and materials that were used for the fabrication of the Bio-Pneumatic Envelope, and that were not mentioned in the previous sub-chapters:

BC Cells: The macroscopic material sample of bacterial cellulose was produced by cultivation of *Gluconacetobacter xylinus* in static culture. The microorganism used was *G. xylinus* (American Type Culture Collection (ATCC) 53582).

Growth Medium: Hestrin-Schramm's medium was used as a culture medium, the constituents were as follows: 2.0% D-glucose, 0.5% yeast extract, 0.5% peptone, 0.51% di-sodium hydrogenphosphate heptahydrate, 0.115% citric acid

Hexagon PDMS growth vessels: In order to enable proper BC growth inside the PDMS vessels, the air-medium interface should be maximized, and therefore the vessels should be as thin as possible – up to 1.5mm thickness. Casting of PDMS into 3D printed molds made of *flexible* filament (NinjaFlex TPU 3D Printing Filament) made the task of de-molding the very thin and delicate vessels possible, and enabled me to fabricate extremely thin vessels with thickness of 1-1.5mm (Figure 36).

Preparation of PDMS mixture for casting: Silpot 184 and Silpot 184 catalyst were purchased from Dow Coning Inc. The elastomer and curing agent were mixed in 10:1 ratio. The mixture was then placed in a vacuum chamber for 10 minutes in order to avoid air bubbles. After de-gassing, the mixture was poured into the 3D printed molds and baked for 20min at 125 0C in an oven until cured.

Tensile Testing: The mechanical properties of the BC membranes were measured using a Zwick mechanical tester (Zwick Z010, Zwick Roelle, Germany). Specimens were laser cut into ASTM-standard "dog bone" geometries and loaded in uniaxial tension at a strain rate of 0.5 mm/min until failure.
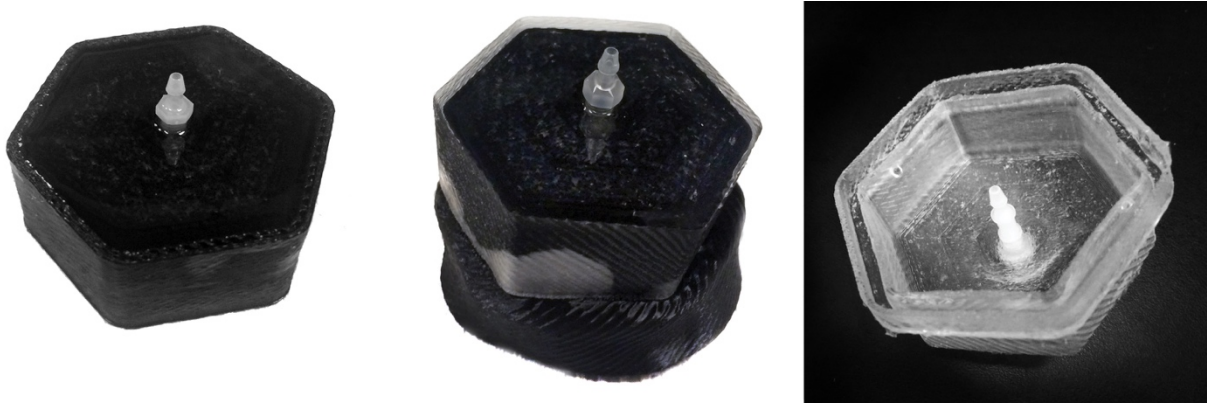
Figure 36: *Casting PDMS into flexible 3d printed molds enbled the fabrication of very thin PDMS vessles with thickness of 1-1.5mm. The thin vessles maximize the air-medium interface and therfore enables and enhence the growth of BC inside the vessles. (left) The liquid PDMS mixture after being poured into the flexible mold. (middle) easy de-molding of the silcone vessel after curing.(right) The thin PDMS vessel after de-molding.*

4 CONCLUSION

Biomaterials that *grow* holds great potential for applications in design and architecture, and can enrich and enhance design processes and outcomes. I believe this thesis provides insights to some of the challenges and questions these fascinating new materials provoke.

I suggest that in order to integrate these novel material systems into design and architecture, a few key aspects will be considered - foremost, integrating matter from preliminary stages of the design process and adopting material based approaches for design, can advocate for a creative, yet responsible use of these materials. Second, multidisciplinary approaches, such as the one presented in this thesis, where design, biology and material science meet (and at times 'collide'), are highly promising. The reciprocal transfer of expertise, knowledge and ways of thinking between the disciplines can be very informative and opens up new possibilities and domains. In a more personal note, my own experience with getting exposed to the world of material science and biology, has proved me the benefits of this sorts of collaborations, both in terms of shifting my perspectives and ways of thinking as a designer and architect, and in terms of the unique design outcomes that were produced.

In order to exploit the full potential of using biomaterial in the design and architecture, and to make these novel materials applicable to design and architectural projects, a few aspects should be addressed in the future, mainly in the fields of mass production and the ability to scale the material products.

Synthetic biology, which is a new, bottom-up engineering discipline, is already a next step of this project, to be developed in the near future. Genetic regulation of native biomaterials, such as bacterial cellulose, holds unexplored potential for design of materials. It has the potential to generate a new class of materials that not only combines unique material properties and shapes, but also can be selectively functionalized for programmable behavior and tailored for applications that require biological sensing and responsiveness, and possibly even capture biological phenomena of self-repair and self-assembly.

4.1 CONTRIBUTIONS

The main contributions of this research are as follows:

- I Designed and Fabricated the Bio-Pneumatic Cellular Envelope that functions as a system for growing, shaping, and enhancing the material properties of 3D bacterial cellulose inflated structures. This system has two main potential benefits – first, the outcomes and variety of bacterial cellulose based materials with different properties that the system 'produced, has a potential for exciting applications in design and architecture. Second, the system itself as a tangible design object that changes thorough time in accordance with material production phases: the material transforms from a liquid medium to a hydrogel composite to a pneumatic aerogel. All these processes are visible and expose the unique ways of producing biomaterials that grow, and biomaterials based composites. The emphasis is therefore not merely on the final artifact but on the process of making itself. The system can therefore be used for alternative purposes such as education.

- Despite the very promising aspects of working with BC-based materials in design and architecture, there are few critical concerns to address in order to make them more applicable to design and architectural projects. In this thesis, I presented a novel workflow for producing robust 3D BC-based inflated structures, which overcomes a few of these concerns. I designed the workflow to include composing the 3D BC membranes with PVA to achieve greater toughness and increase fracture strain, performing pneumatic actuation in order to maintain desired 3D shape, and freeze drying in order to preserve 3D fiber network and porosity of the material. Coupling BC and pneumatics was a crucial step in the development of this workflow. The benefits and aims of this unique match is explained in the thesis.

- I exhibited the benefits and outcomes of a multidisciplinary, material centered design approach, and documented a variety of techniques and methods from the fields of design, biology and material science, that were used in order to realize this research.

- I demonstrated the use of an alternative sustainable material - Bacterial Cellulose, which holds a true potential to be integrated in design and architecture projects. Additionally, I surveyed relevant literature and past work in the field of BC research and applications, and suggested future work.

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