Bacterial Cellulose: Material Science Driven Architectural Innovation

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ABSTRACT

Geometric-driven form generation was the product of the institutionalised division between form, structure, and material that was firmly ingrained in modernist design theory and paralleled by a systematic segmentation between modelling, analysis, and manufacture. This preference for form above substance was included into the creation and design logic of CAD. As a result of current pressures and an increasing understanding of the shortcomings and environmental risks of this strategy, modern design culture is transitioning to a more material-aware mind-set.

Inspired by natural processes, where form development is dependent on local variations in the material properties to maximise performance while using the fewest resources possible. This approach assumes that material comes first and that shape results from the organisation of material qualities in relation to structural and environmental performance. Products that are not based on fuel have outstanding mechanical and biodegradability properties, particularly bio-polymers. Bacterial cellulose has proven to be an extraordinarily versatile bio-polymer, drawing interest in a wide range of practical scientific applications including electronics, biomedical devices, and tissue-engineering. Development of bio-fabrication methods connected to material-informed computational modelling and material science is required by the introduction of bacterial cellulose as a building material. The paper reviews, suggests and demonstrates approaches for a material-based strategy in exploiting the enormous potential of Bacterial Celulose-based bio-materials and their potential to have a profound impact on the ideas of architectural innovation and sustainability for a better future.

Key Words: **Sustainable material, Building Construction, Bacterial Cellulose, Bio- Materials, Architectural Innovation**

I. INTRODUCTION

Modern design theories and architectural techniques have indeed created a distinction between the interpretation of form, structure and material and ultimately the way the three are executed in terms of analysis, modelling and fabrication. The result of this process has led to the common practice of form being given precedence over other aspects of the design process, for instance- the choice of material and fabrication techniques and the final process of assembly. This notion has long 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).**

Understanding how natural systems function, where structure and function, material and form, assembly and growth seamlessly combine and evolve over time, adapting to, and diversifying according to the prevalent ambient condition, can help one address the growing concern over the environmental crisis and adopt sustainability as the primary force guiding the current architectural processes. The concept of using living cells that produce matter as the central component of the design process can fundamentally alter how design and form-making are currently defined on both a theoretical and practical level. The issues surrounding the maker's agency of form and making are addressed from a novel angle while keeping material science at the core of the discussion.

Cellulose, one of these bio-polymers, is one of the most abundant biodegradable materials in nature, and has been the topic of wide investigations in macromolecular chemistry (Mohite et al. 2014). Bio-synthetic cellulose has a high water content (99%), and combined with its mechanical qualities, it may be made in a wide range of sizes and shapes. The high purity, high water retention, hydrophilic nature, tensile strength, thermal stability, and biodegradability of bacterial cellulose are only a few of its many distinctive qualities.

A. WHAT IS MICROBIAL CELLULOSE?

The form, structure, and purpose of structures were prioritised over the materials throughout centuries in architecture. Building materials used in architecture continue to be rigidly traditional despite advancements in building technologies and construction techniques (Konarzewska 2017).

Despite the pressing demand for alternatives to fuel-based goods, self-assembling manufacturing for natural polymers is still in its infancy. The mechanical and biodegradability of non-fuel based goods, in particular bio-polymers, is excellent. Bacterial cellulose has proven to be an incredibly adaptable bio-polymer, garnering interest in a wide range of practical scientific applications including electronics, biomedical devices, and tissue-engineering. The introduction of bacterial cellulose as a construction material necessitates the development of bio-fabrication techniques related to material-informed computational modelling and material science.

The primary component of plant cell walls and vegetable fibres, cellulose is an insoluble material that is also used to make paper. A type of cellulose produced by bacteria, microbial cellulose exhibits excellent levels of purity, strength, moldability, and improved water absorption. The cellulose can be produced from a range of organic raw materials and colours, and once dried, it transforms into a material that can be precisely shaped. Additionally, to further strengthen it, the cellulose is grown atop a mesh made of natural fibres like jute. Bacterial cellulose, also known as microbial cellulose, is a type of cellulose made by bacteria. The cellulose has a high water absorption capacity and good mechanical strength. When dried, cellulose has a tendency to contract.

Fig. 1 : Synthesized cellulose (Source : Growth Based Fabrication Techniques for Bacterial Cellulose, Derme T.(2019)

B. PHYSICAL PROPERTIES OF BACTERIAL CELLULOSE

Bacterial cellulose has a variety of unusual characteristics, such as high mechanical strength, high crystallinity, and an ultra-fine, very pure nano fibril network structure with stability in the presence of chemicals and high temperatures. Bacterial cellulose is more hydrated in its natural condition and can hold more than 100 times its own weight in water (Rani, et al., 2011).

While the high mechanical strength is a result of the inter-fibril hydrogen bonds, which provide the structure stability, the wide gap between the individual fibres, which creates a huge surface area, is responsible for the excellent liquid absorption ability (Scionti, 2010). The nanofibers align parallel to one another and create stacked sheets when the bacterial cellulose dries. These increase the stability and strength of the dried cellulose sheets by forming additional hydrogen bonds between them.

Unique Properties of Microbial Cellulose

Among the most important properties of microbial cellulose which make this material unique are:

- biodegradability
- high mechanical and tensile strength
- hygroscopy
- material versatility
- self-healing ability
- tendency to grow on natural fibers
- plasticity
- brittleness
- different levels of translucency
- layers
- bubbles: spaces in between layers
- variety of patterns | dots, veins, wrinkles

The various distinctive qualities of cellulose nanoparticles make them suitable for a wide range of applications. The key characteristics of cellulose nanoparticles are their resilience, rheological characteristics, reactivity, and propensity to form films. Additionally, they are made from sustainable natural resources and, to the best of our knowledge, are both safe to create and use (Design Driven Value Chains in the World of Cellulose, 2014). Its exceptional mechanical capabilities are the result of a highly intricate, three-dimensional nanostructure. Bacterial Cellulose exhibits remarkable mechanical stability when wet, equivalent to steel, which is particularly noteworthy.

C. MERITS OF USING BACTERIAL CELLULOSE AS A BULK ARCHITECTURAL MATERIAL

Acetobacter xylinum is a cellulose-producing bacterium that, under the appropriate circumstances, can self-organise into bacterial cellulose, a nano-structured, textile-like substance. Cellulose has the potential to be a super material of the future due to its mix of sustainability, biodegradability, recyclability, and novel end-use possibilities. The product's usability, aesthetics, and ethics are all impacted by the usage of ethical biomaterials. Due to the material's capacity to withstand high temperatures, it is safe to use in lights and even in close proximity to light sources, however because of the material's lengthy development phase, it has limited economic viability. Cellulose is a substance that occurs in nature in large quantities and is primarily created by plants, but it is also feasible to grow it at home via a fermentation process using the bacteria Acetobacter. It is a part of the plant's structural system.

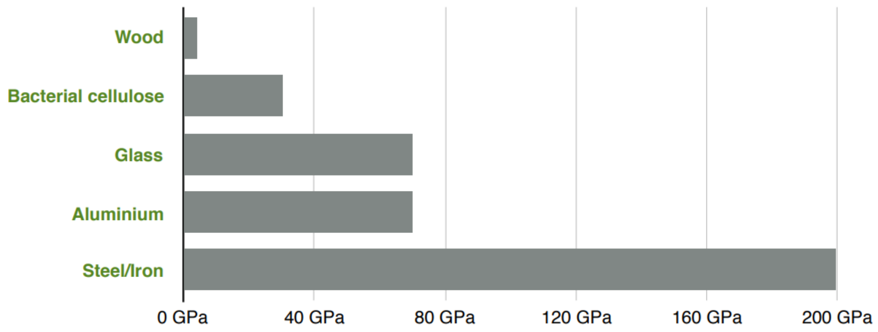


Fig. 2 : Elasticity of cellulose in comparison to other conventional building materials(Source: IAAC Blog - Bio-Fabric | Microbial Cellulose

D. DEMERITS AND LIMITATIONS

Due to the lack of appropriate fabrication techniques and digital design tools, cellulose is still not taken into consideration as a building material despite its attractiveness for a variety of applications, including those in architecture and engineering (such as water-retaining structures, architectural components, etc.). It is still not possible to produce bacterial cellulose on an industrial scale and control the three-dimensional (3D) results using standard manufacturing and digital techniques, despite recent advancements in biochemistry and microelectronic engineering that have improved knowledge of biological materials (Fernandez et al. 2013). The capacity to model and produce with constantly changing material properties is another limitation of current techniques to virtual and physical prototyping with non-fuel-based materials (Oxman 2011).

E. POTENTIAL APPLICATIONS OF BACTERIAL CELLULOSE

A material with specified ranges and gradient conditions, such as hydrophobic or hydrophilic capacity, graded mechanical properties over time, material responsiveness, and biodegradability, can be achieved through potential applications ranging from small architectural components to large structures. Numerous uses and customised products utilising cellulose are possible. The produced cellulose is moldable and can be shaped to exact geometrical shapes. We created an example of how cellulose could be utilised in a public plaza for events; it offers cover and shade, is transient, and can decompose after use. In the process, a structure having growth-induced material qualities is described as responding to outside stimuli to produce hierarchically structured forms (Soldevila 2015). Production of bacterial cellulose is highly dependent on a number of variables, including.

Fig. 3 : Application of cellulose based material to create temporary deployable structure
(source : Feasability Of Bacterial Cellulose In Furniture Design, bachelor;s thesis, Monika Faidi 2011

II. SYNTHESIS AND FABRICATION PROCESS OF BACTERIAL CELLULOSE

A. FACTORS AFFECTING THE GROWTH

Bacteria, ambient conditions, nutrients, and growth media are some of the elements influencing the bio-synthetic pathway of bacterial cellulose. These parameters change the mechanical characteristics, tensile strength, and thickness of bacterial cellulose. New materials with additional functionality and qualities are produced as a result of the bio-synthesis of bacterial cellulose into BC-based bio-composite.

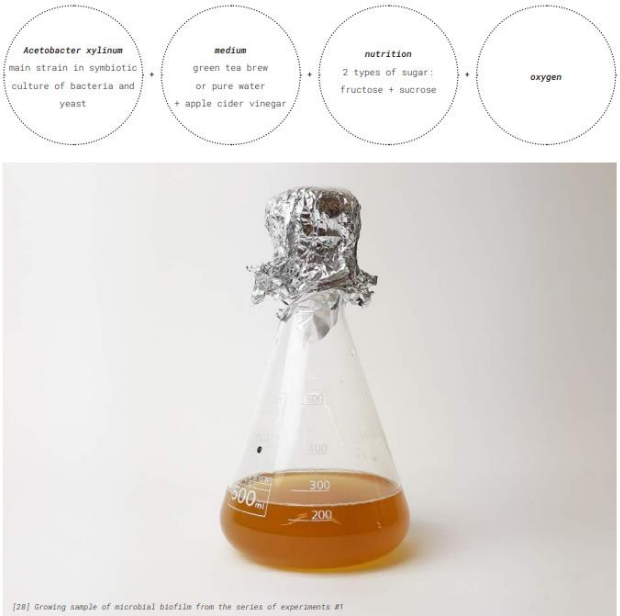


Fig. 4 : Growth medium for the synthesis of bacterial cellulose (source : Feasability Of Bacterial Cellulose In Furniture Design, bachelor;s thesis, Monika Faidi 2017)

Cellulose may be customised and used for a variety of things. The produced cellulose is moldable and can be shaped to exact geometrical shapes. We created an example of how cellulose could be utilised in a public plaza for events; it offers cover and shade, is transient, and can decompose after use.

B. GROWTH OF BACTERIAL CELLULOSE

A polymer called cellulose is present in the cell walls of eukaryotic plants, algae, and fungi. Cellulose is also a substantial component of the cell walls of bacteria. However, some bacteria are also capable of secreting cellulose. Acetobacter xylinum, which is well-known for secreting cellulose as part of its metabolism of glucose and other carbohydrates, is a famous example. The symbiotic colony of bacteria and yeast (SCOBY) that develops on the drink's surfice is made of bacterial cellulose, which when dried has the consistency of leather. A gel-like textile surface up to 400 mm thick is produced during the bio-based production process by using bacteria like Acetobacter to digest glucose into cellulose. (Peters,2014)

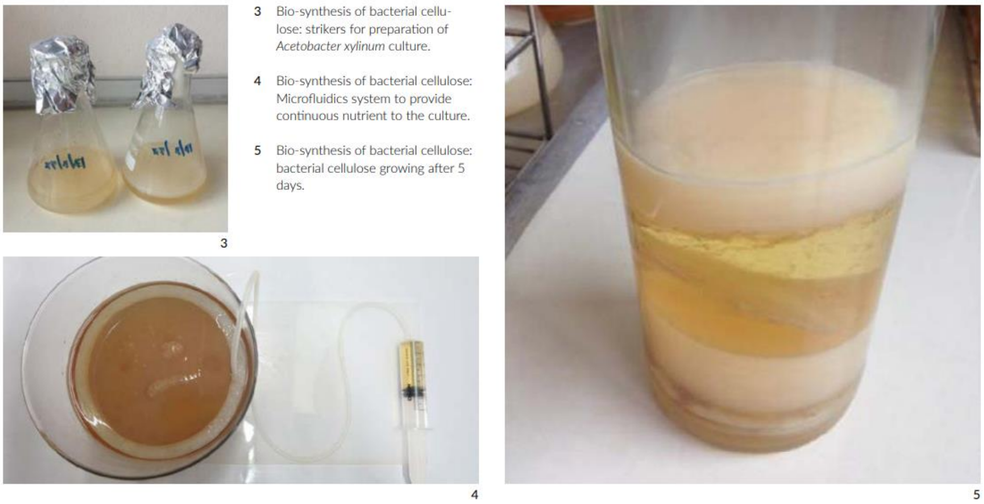


Fig. 5 : Bio-synthesis of bacterial cellulose ; strikers for preparation of Acetobacter Xylinum culture

Fig. 6 : Bio-synthesis of bacterial cellulose ; Microfluidics system to provide continuous nutrient to the culture

Fig. 7 : Bio-synthesis of bacterial cellulose growing after 5 days (source : Feasability Of Bacterial Cellulose In Furniture Design, bachelor;s thesis, Monika Faidi 2017)

Production of bacterial cellulose is greatly influenced by a number of variables, including the culture medium and ambient circumstances. A carbon source, a nitrogen source, as well as other elements necessary for the bacteria to thrive are present in the culture medium (Figure 3). At the surface of the culture media, the bacteria will form a pellicle (flake) under typical static and aerobic condition (Figure 5) The amount of oxygen and nutrients available to the bacteria will limit how much this pellicle may thicken. Recent studies have shown that continuous systems of nutrient sub-ministration can improve the thickness and strength of BC (Figure 4). Due to this, there is a chance that the natural polymer could develop into a structure of any thickness and shape (Gateholm et al. 2012).

Fig.8 : Drying process of cellulose (Source: IAAC Blog - Bio-Fabric | Microbial Cellulose

C. FABRICATION PROCESS OF BACTERIAL CELLULOSE BASED POLYMERS

Designers have begun to get involved in the biofabrication processes due to their creative approach to novel forms of expression and unique material possibilities. Additionally, due to the limits of bio-fabrication, such as the unpredictable nature of it, new elements of design practise may emerge (Camere and Karana, 2018).

A brand-new technology for controlling the three-dimensional forms and material behaviour of BC, as well as in-situ self-assembly fabrication and scaffolding procedures. By modifying the mechanical characteristics, tensile strength, and thickness of bacterial cellulose, it also makes clear the elements influencing the bio-synthetic pathway of bacterial cellulose, such as bacteria, ambient conditions, nutrients, and growth medium.

Bacterial cellulose biosynthesis is transformed into a BC-based bio-composite, which results in the development of novel materials with improved functionality and characteristics. A material with specified ranges and gradient conditions, such as hydrophobic or hydrophilic capacity, graded mechanical properties over time, material responsiveness, and biodegradability, can be achieved through potential applications ranging from small architectural components to large structures.

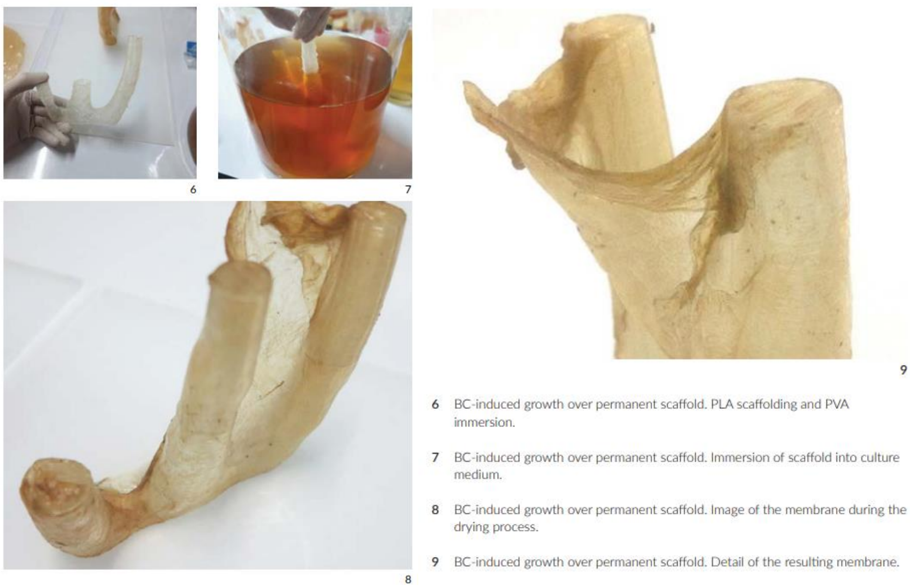


Fig. 9 : BC-induced growth over permanent scaffold and PVA immersion

Fig. 10 : BC-induced growth over permanent scaffold- immersion of scaffold into culture medium

Fig. 11 : BC-induced growth over permanent scaffold. Image of the membrane during the drying process

Fig. 12 : BC-induced growth over permanent scaffold. Detail of the resulting membrane (source : Feasability Of Bacterial Cellulose In Furniture Design, bachelor;s thesis, Monika Faidi 2017)

D. ADDITIVE MANUFACTURING

Some recent advancements in direct digital manufacturing, such water-based fabrication methods, allow a shift towards a material-centric design process (Oxman 2011). Rapid prototyping techniques using additive manufacturing (AM) use computer-aided virtual models that are translated into thin horizontal consecutive cross-sections to define three-dimensional physical items (Sachs et al. 1993).

AM technologies have emerged as an effective and widespread method for producing geometrically accurate functioning prototypes in a short amount of time (Oxman 2012). Bio-fabrication techniques in a water medium aim to provide dynamic feedback or reciprocity within a given setting, in contrast to AM technologies, which pertain to a specific controlled output. In that a substance is formed by interaction with a living organism, this technique avoids the drawbacks of bio-mimicry.

E. SELF ASSEMBLY AND FABRICATION TECHNIQUES

It has been discovered that, as opposed to growing freely in the media, the bacteria strains of A. Xylinum preferentially grow on the surface of natural fibres (Figures 17 and 18) or specific polymer molecules. Thus, starch, soy resin, or polyvinyl alcohol (Figures 6 and 7) provide the bacteria with the proper substrates for growth, which can result in the development of BC-based hybrids or bio-composites.

In every situation, procedures for drying, sintering, or solidification are typically used to produce consolidation. Particularly BC has the ability to become calcified (Figure 10). Tissue solidification using this technique is currently used in medicinal applications

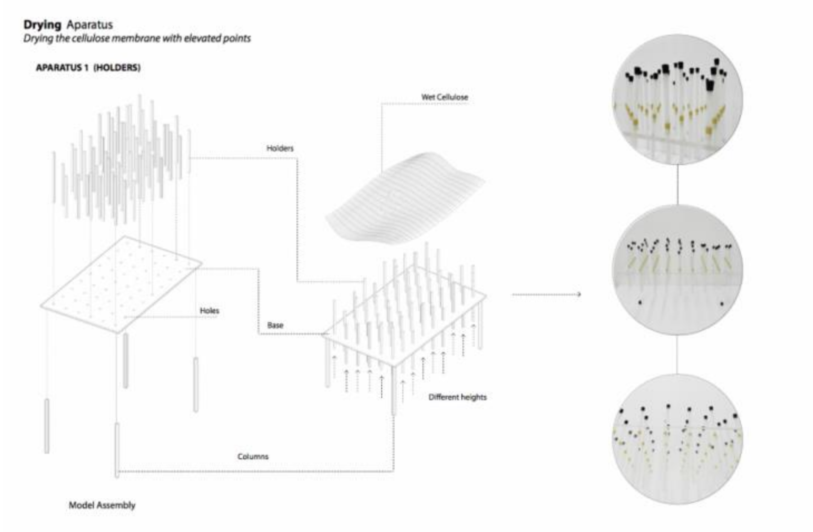


Fig. 13: Drying Apparatus (Source: IAAC Blog - Bio-Fabric | Microbial Cellulose

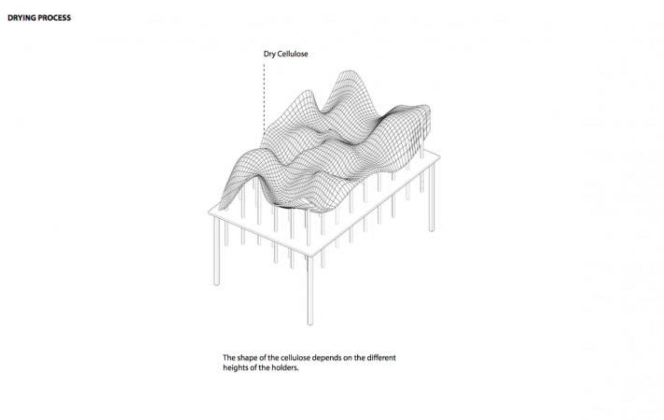


Fig. 14: Drying process – the shape of the cellulose depends on the different heights of the holders (Source: IAAC Blog - Bio-Fabric | Microbial Cellulose

It was discovered that adding fibres at the conclusion of the growth phase will strengthen the material after drying merely the thin layer of cellulose. A strengthened organic fabric was the end result.

Fig. 15: Fibre Reinforcement **(Source: IAAC Blog - Bio-Fabric | Microbial Cellulose)**

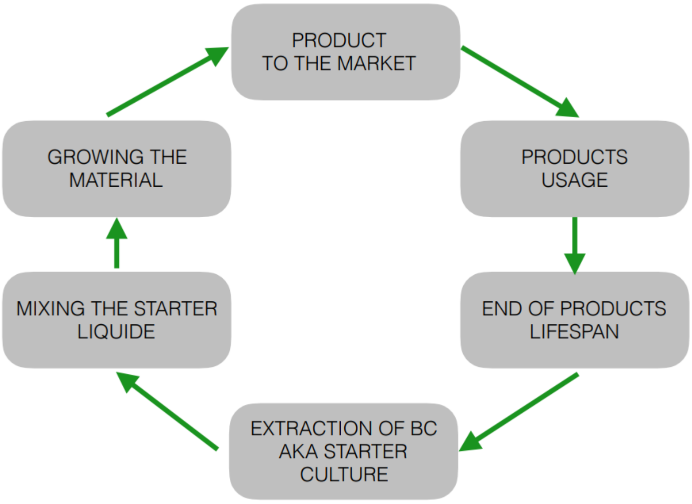


Fig. 16 : Life cycle of Bacterial cellulose as an architectural material(Source: IAAC Blog - Bio-Fabric | Microbial Cellulose

F. METHODS OF FERMENTATION AND SCAFFOLDING

1. In Situ Self-Assembling (Figures 6–9, 11, 12)

Utilizing various scaffolding techniques, BC development can be induced across a specified form. Permanent and bio-degradable scaffolding techniques were introduced. The development of membranes and shells utilising BC as a binding agent is depicted in Figures 6–9 and 12. The scaffold is still a part of the building. Figure 11 illustrates a scaffold's bio-degradability (dissolving following the biosynthesis process) using a sodium-alginate scaffold.

10% of the AXy culture was added to the culture medium after it had been prepared in a glass beaker (2 litres). For seven days, the flask was kept at 25 C without being touched. During the photosynthetic phase, oxygen was provided to guide the growth on the scaffolding.

2. Adhesion Growing (Figures 13 and 14)

This research demonstrated the possibility to develop a target geometry-based three-dimensional morphology. The inversion of the bacteria's metabolism under static and anaerobic conditions led to a growth that was no longer superficial but rather clung to the morphology of the contained element. 10% of the AXy culture was put to the culture media that had been prepared in a 1.5 litre rubber flask. The flask was left at 25 C° for 10 days without disturbance.

3. Bacterial Cellulose with Differential Growing Patterns (Figures 1, 15, 16)

A hypothetical funicular model made of particle springs and BC membranes with various developing patterns and thicknesses is used to simulate the behaviour of the membrane (Figure 16). 10% of the AXy culture was put to the culture media that had been prepared in a glass beaker (2 litres). Without shaking, the flask was kept at 25 C for 4 days while nutrients were continually introduced. After then, the flask was kept at 25 C for five days. Drying procedure: four days at 10 C. followed by four hours of freezing.

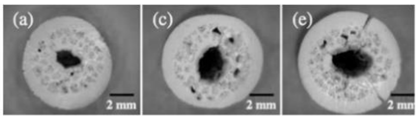
4. Scaffolding Technique Using Sisal Fiber (Figures 17, 18)

A scaffolding method employing sisal fibres that are 60 cm long that have been sterilised and treated with BC (made in an incubation shaker). These were sterilised before being introduced to the culture medium. After 3 days of culture, BC-modified sisal fibres were removed after AXy was injected into the culture fluid. Initial research was conducted by modelling the behaviour of the material in accordance with the pattern of fibre deposition.

III. BACTERIAL CELLULOSE BASED BIO-COMPOSITES

A. BIO-COMPOSITES

Bio-composites are composite materials with natural plant fibres or specific polymers added for reinforcement (Qiu and Netravali, 2014). Architecture, engineering, and product design could all benefit from biosynthesizing the original BC into BC-based composites. This could lead to a significant shift in how structures and products are found, built, and constructed (Oxman 2011). Better mechanical and thermal properties, or extra functionalities, can be obtained by engineering the biosynthesis of bacterial cellulose (BC) into BC-based nanocomposites. They could be classified as high-strength materials, plant-mimicking materials, electrically conductive materials, catalytic materials, antibacterial materials, thermos responsive materials, and a variety of other categories.



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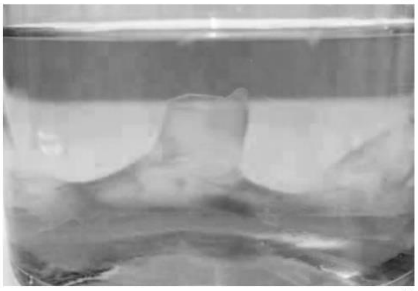

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In the presence of natural fibres or other polymers, the construction of 3D structures and membranes through self-assembly can be compared to a multi-step fermentation process. Additionally, this may result in the creation of nanocomposites or hybrids based on BC (Qiu and Netravali 2014).

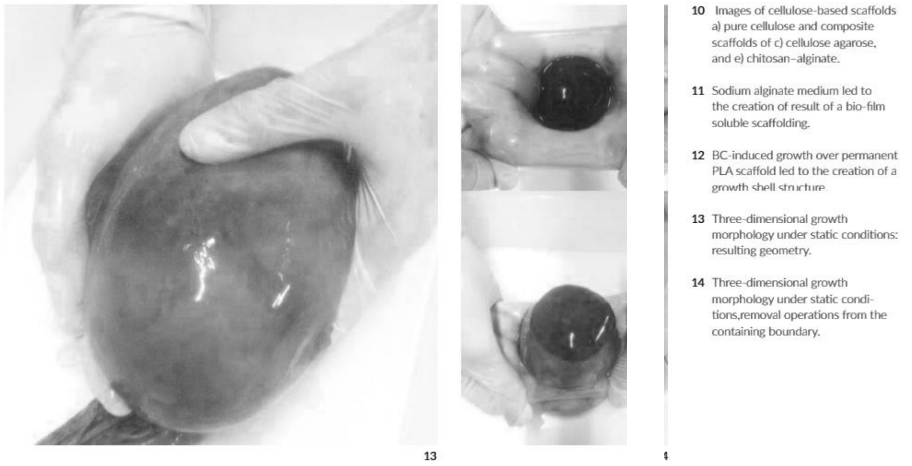

Fig. 17 : Pure cellulose and composite scaffolds of cellulose a ose and chitosan- alginate
Fig. 18 : Sodium alginate medium led to the creation of result c bio-film soluble scaffolding
Fig. 19 : BC-induced growth over permanent PLA scaffold led to the creation of a growth shell structure
Fig. 20 : Three-dimensional growth morphology under static conditions, removal operations from the containing boundary

B. INVESTIGATORY PROTOTYPING TO TEST STRENGTH OF THE COMPOSITE

The feasibility of microbial cellulose growth on natural fibres and scaffolds was assessed and tested during the procedure using series of prototypes #1 and #2. Prototype #3 was one of many that looked into the possibility of biofilm forming three-dimensional elements. Additionally, the fourth set of prototypes explored the translucency of microbial cellulose, a crucial biofilm characteristic that was selected throughout the experimental phase as the one deserving of future investigation. In series #5, natural liquid latex was used instead of microbial cellulose to increase the degree of prototyping freedom and abilities, especially when considering time, which is a critical factor in the creation of any material grown using living organisms.

1. Prototype 1 : BACTERIAL CELLULOSE ON FIBRES

A thin microbial cellulose film has developed on the surface of natural fibres added to a growing medium after the fermentation process took place for 14 days.

A prototype demonstrates the possibility for completely biodegradable biocomposites made of microbial cellulose and other natural fibres. Therefore, microbial cellulose has a significant advantage over composites made of non-biodegradable materials, such as carbon fibre composites that cannot be disassembled once they have been joined.

Fig. 21 : Top view of microbial cellulose growing on the surface of fibres located in the cultivation medium
Fig. 22 : Front view of microbial cellulose growing on the surface of fibres
Fig. 23 : Top view of microbial cellulose grown on the surface of fibres
Fig. 24 : Sample of microbial cellulose grown on surface of fibres
Fig. 25 : Dried sample of microbial cellulose grown on the surface of fibres (source : Design Potential of Microbial Cellulose in Growing Architecture, Maters' thesis, Karolina Bloch 2019)

2. PROTOTYPE 2 : 3D WOVEN FIBRES

No discernible growth of microbial cellulose was seen after 14 days of continuous application of cultured media containing the symbiotic culture of bacteria and yeast on the 3D weaved fibres. However, the use of a cultivation medium improved the stiffness of the fibres.

Prototype #1.2 demonstrates that the fibres must be added to the cultivation medium with a symbiotic culture of bacteria and yeast in order to achieve the growth of microbial cellulose. Furthermore, simply applying the medium to the fibres and allowing them to dry is insufficient. Additional tests examining the spacing between the fibres must be carried out to investigate the potential of microbial cellulose development on natural fibres.

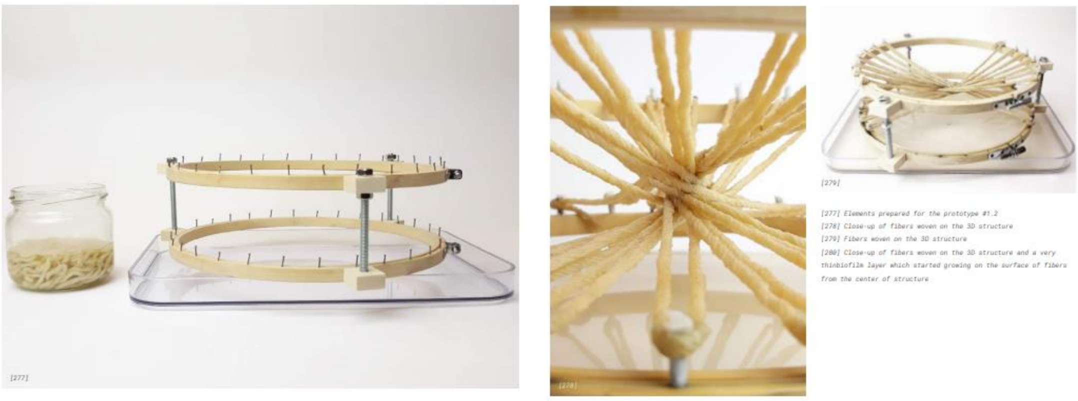

Fig. 26 : Elements prepared for the prototype #1
Fig. 27 : Close-up of fibres woven on the 3D structure
Fig. 28 : Close-up of fibres the 3D structure and a very thin bio-film (source : Design Potential of Microbial Cellulose in Growing Architecture, Maters' thesis, Karolina Bloch 2019)

3. PROTOTYPE 3 – BACTERIAL CELLULOSE WITH VARIOUS FIBRES

A thin microbial cellulose film was developed on the surface of several natural fibres added to a growing medium after the fermentation process took place for 14 days.

The possibility for creating biocomposites made of microbial cellulose and other natural fibres that are 100% biodegradable is demonstrated by prototypes #1.1 and #1.3, respectively. Therefore, microbial cellulose has a significant advantage over composites made of non-biodegradable materials, such as carbon fibre composites that cannot be disassembled once they have been joined.

Fig. 29 : Bacterial cellulose with various fibres

4. PROTOTYPE 4 – COTTON GAUZE

A thin microbial cellulose film has developed on the surface of cotton gauze that was added to a growing medium after the process of fermentation lasted for 14 days. Prototype #1.4, like the earlier models in Series #1, demonstrates the possibility for creating biocomposites made of microbial cellulose and other natural fibres that are completely biodegradable. Therefore, microbial cellulose has a significant advantage over composites made of non-biodegradable materials, such as carbon fibre composites that cannot be disassembled once they have been joined

Fig. 30 : Bacterial cellulose on cotton gauze (source : Design Potential of Microbial Cellulose in Growing Architecture, Maters' thesis, Karolina Bloch 2019)

5. PROTOTYPE 4 – GROWTH ON WOODEN SCAFFOLDING

As a result of the medium being soaked in the wood, a thin biofilm has grown on the surface of the wooden cube above as well as where the wooden cube was in contact with the media. The potential of employing wooden scaffoldings as moulds to directly biofabricate 3D parts in the mold's shape is demonstrated via a prototype.

Fig. 31 : Bacterial cellulose on wooden piece

6. PROTOTYPE 5 – BIOFILMS + WOODEN MOLDS

The application of wet microbial cellulose to the wooden moulds produced 3D elements. Following that, all of the components were dried in an oven at a temperature of 70°C. The employment of microbial cellulose in the synthesis of elements led to the fabrication of stiff and thick components. The prototype demonstrates the possibilities of 3D formations that might be put together to construct larger structures

7. PROTOTYPE 6 | BIOFILM + WOODEN MOLDS + COTTON GAUZE

In contrast to prototype #3, 3D pieces were created by applying wet microbial cellulose first to cotton gauze and then to wooden moulds. Following that, all of the components were dried in an oven at a temperature of 70°C. The employment of microbial cellulose in the synthesis of elements led to the fabrication of stiff and thick components. The usage of cotton gauze led to the construction of more rigid parts as compared to prototype #3. The prototype demonstrates how different natural fibres can be used to create three-dimensional parts that can be combined to make larger structures.

Fig. 32 : Bacterial cellulose on wooden piece and cotton fabric (source : Design Potential of Microbial Cellulose in Growing Architecture, Maters' thesis, Karolina Bloch 2019)

8. PROTOTYPE 7 | LATEX: MATERIAL SUBSTITUTE LATEX + PLASTIC | ELEMENTS: CELLS

Liquid latex was selected as an appropriate material because, after drying, its materiality resembles the dry biofilm that was the subject of the study. The development of the prototype had an impact on the design of the system, which changed from a flat surface intended to be covered with microbial cellulose to a three-dimensional skin made of the system's tiniest components, the cells.

9. PROTOTYPE 8| LATEX: MATERIAL SUBSTITUTE LATEX + PLASTIC | SYSTEM OF CELLS

The use of prototype # 5 directly inspired experiment number three, which investigated the effects of altering the physical condition of the cultivation medium from liquid to solid on the development of microbial cellulose. Additionally, it had a big impact on how a tube system was created.

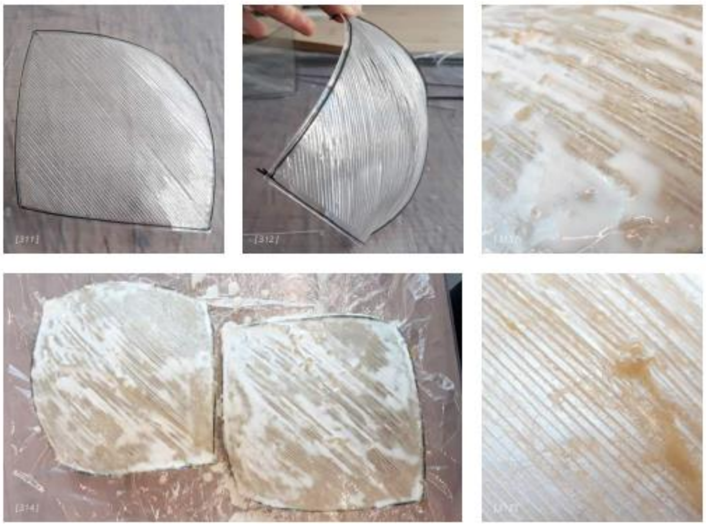

Fig. 33 : Latex: Material Substitute (source : Design Potential of Microbial Cellulose in Growing Architecture, Maters' thesis, Karolina Bloch 2019)

IV. CASE STUDIES

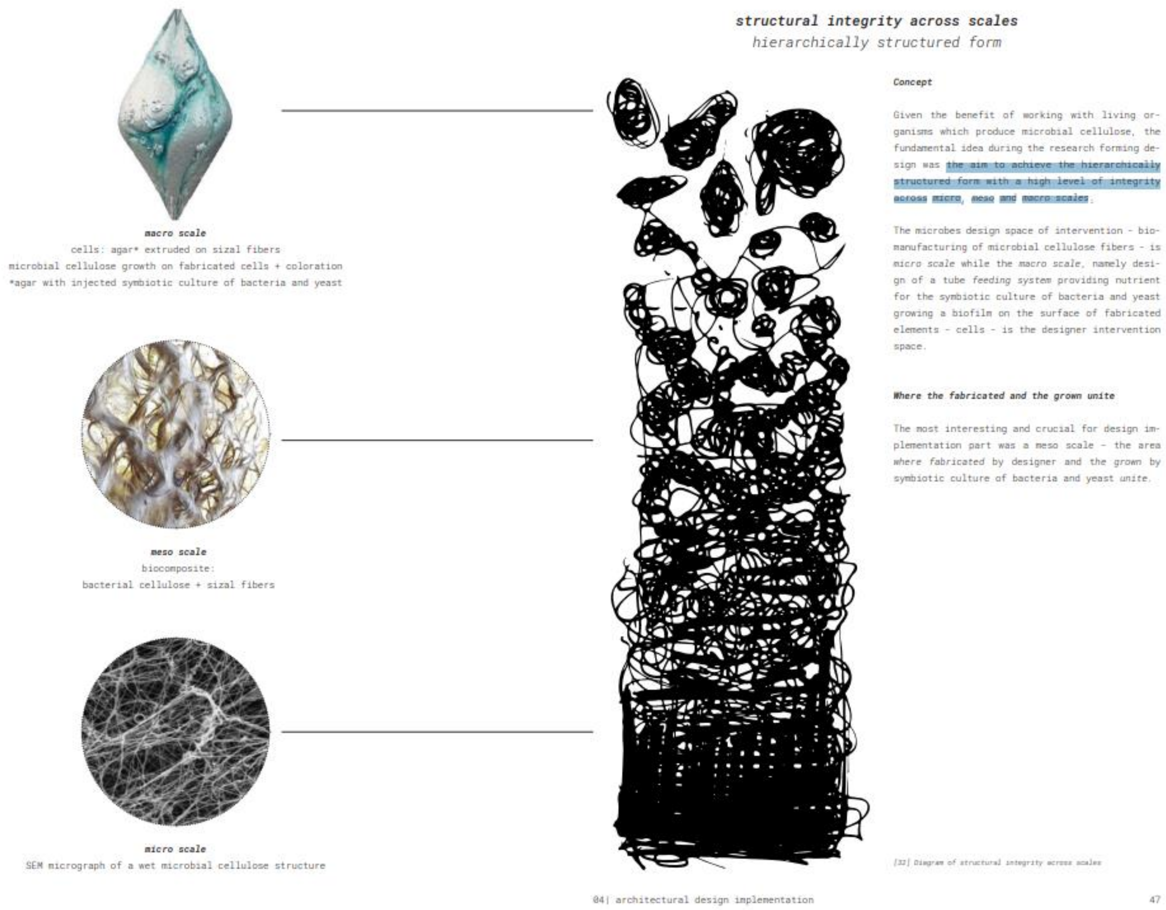

Fig. 34 – hierarchically structured form (source : Design Potential of Microbial Cellulose in Growing Architecture, Maters' thesis, Karolina Bloch 2019)

A. CONCEPT - Structural Integrity across Scales Hierarchically Structured Form

In order to generate a hierarchically structured form with a high level of integrity across micro, meso, and macro scales during the research forming design, it was advantageous to collaborate with living organisms that manufacture microbial cellulose. The macro scale, or design of a tube feeding system providing nutrients for the symbiotic culture of bacteria and yeast growing a biofilm on the surface of fabricated elements - cells - is the designer intervention space. The micro scale, or microbes' design space of intervention, is bio-manufacturing of microbial cellulose fibres.

To investigate and clarify the role that microbial cellulose can play in creating ecologically friendly structures that integrate structure, shape, and material at the micro, meso, and macro dimensions. The symbiotic culture of bacteria and yeast, medium, source of sugar, and oxygen were the most crucial growth variables in all of the conducted studies, and their composition is analogous to that of the fiber-based "feeding" system meant to facilitate the growth of microbial cellulose.

Fig. 35 : Flamingo observation tower (source : Design Potential of Microbial Cellulose in Growing Architecture, Maters' thesis, Karolina Bloch 2019)

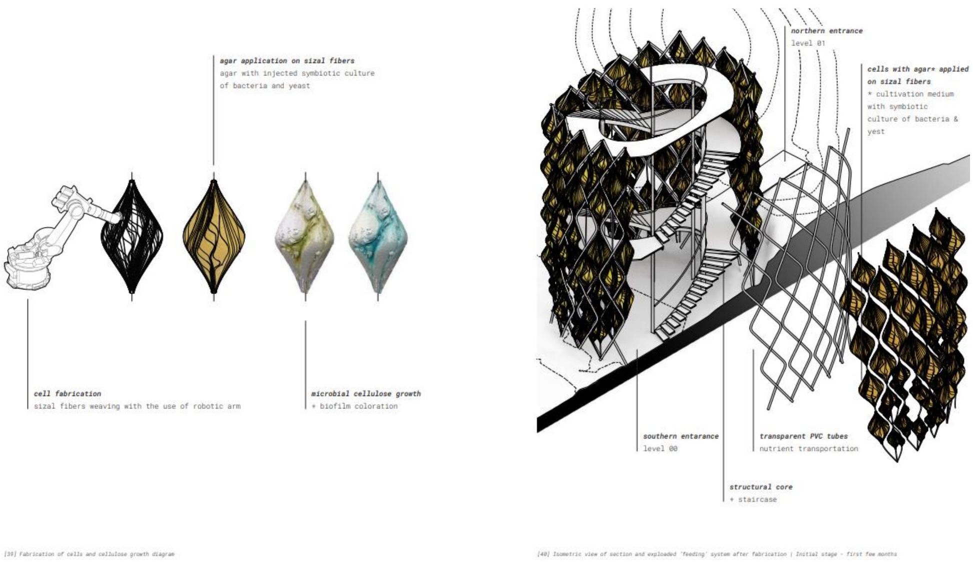

Fig. 36: Flamingo observation tower - structure

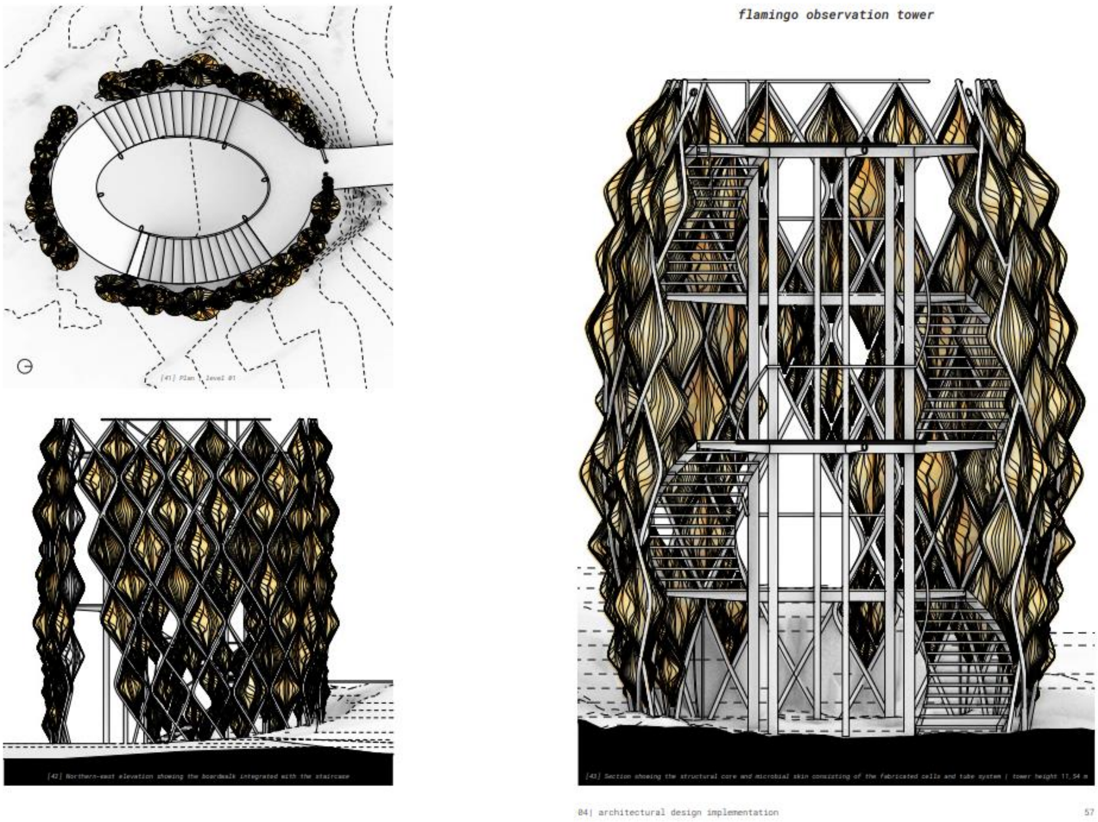

Fig. 37: Flaming Observation Tower a) plan b) elevation c)section (source : Design Potential of Microbial Cellulose in Growing Architecture, Maters' thesis, Karolina Bloch 2019)

B. Hydrogen-Bonding-Aided Fabrication of Wood Derived Cellulose Scaffold/Aramid Nanofiber into High-Performance Bulk Material

Aramid nanofiber (ANF) and cellulose scaffold into a high-performance bulk substance. The increased physical and mechanical capabilities of the hybrid material were mostly attributed to the densification of cellulose microfibers containing ANF and hydrogen bonding between cellulose microfibers and ANF. The produced material displayed exceptional toughness (4.4 MJ/m3 vs. 0.4 MJ/m3 for natural wood), tensile strength (341.7 MPa vs. 57.0 MPa for natural wood), and Young's modulus (24.7 GPa vs. 7.2 GPa for natural wood). In addition, this material's low density gave it a superior specific strength of 285 MPa cm3 g 1, which is noticeably higher than other alloys used in some conventional building materials like concrete.mANFs were also included into the cellulose scaffold, which increased the hybrid material's thermal stability.

The simple and top-down method is efficient and scalable, and it also enables the full use of cellulose scaffolds for the fabrication of various high-tech bio-based materials. By adding a chemical that may increase the hydrogen bonding between cellulose microfibers under compression at a specific moisture content, the wood-derived cellulose scaffold that retains its intrinsic hierarchical structure can be treated into a superior mechanically advanced material. Base materials: Aramid nanofiber (ANF) is typically produced using a "top-down" technique from commercial poly(p-phenylene terephthalamide) (PPTA) threads [28,29]. Like other nanofibers, ANF demonstrates anisotropic properties, nanoscale morphologies, a high specific surface area, and a large aspect ratio. In addition to having great mechanical performance, ANF also has excellent water resistance and thermal stability [30–33].

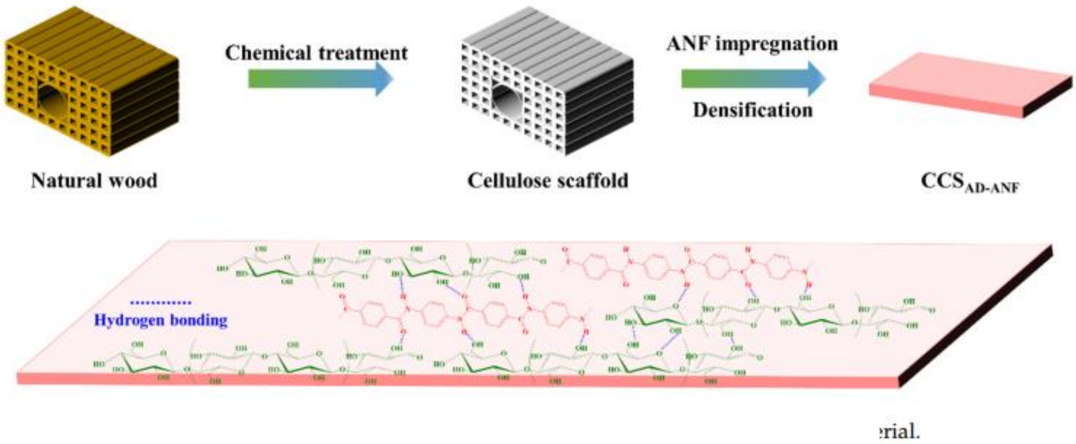

Fig. 38 : The preparation process of a high-performance cellulosic bulk material (**source :** Fundamentals of cellulose lightweight materials: bio-based assemblies with tailored properties, Ferreira E. 2021)

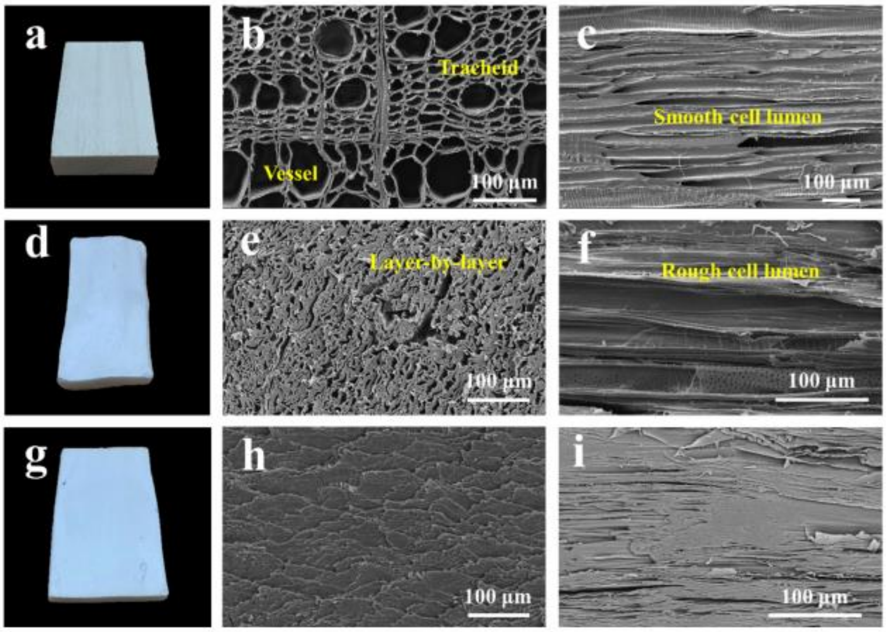

Fig. 39 : Composition of the material at microscopic level (**source :** Fundamentals of cellulose lightweight materials: bio-based assemblies with tailored properties, Ferreira E. 2021)

C. PRODUCTION PROCESS

- **Base materials and chemicals :**

In this experiment, basswood with the dimensions 50 30 10 mm3 (longitudinal, tangential, and radial) was used. DuPont's Kevlar 29 yarn was provided by Changzhou Hualike New Materials Co., Ltd. (Jiangsu, China) Fisher Scientific supplied the following chemicals: sodium chlorite (NaClO2, 80%), sulfuric acid (H2SO4, 72%), acetic acid (HAc, 99.7%), sodium hydroxide (NaOH, 97%), dimethyl sulfoxide (DMSO), potassium hydroxide (KOH), acetone (99.8%), and hexane (99.8%). (Waltham, MA, USA). Without additional purification, all substances were utilised exactly as they were given. DI water, or deionized water, was utilised throughout the entire experiment.

- **Preparation of Aramid Nanofiber (ANF) Suspension**

Using earlier reports [38,39], a 2 mg/mL ANF suspension was made. To create a dark crimson, viscous suspension of ANF, 500 mL of DMSO was combined with 1 g of bulk Kevlar 29 and 0.5 g of KOH. This mixture was then magnetically agitated for 1 week at room temperature.

- **Fabrication of Aligned Cellulose Microfiber/ANF Hybrid Material**

Aligned Cellulose Microfiber/ANF Hybrid Material Fabrication According to our prior research, the natural basswood (NW) sample was chemically processed to remove lignin and hemicellulose in order to produce aligned cellulose scaffold (CS)) [25,40]. ANF suspension diluted to 0.5 mg/mL was infused into the acquired CS. After removing the DMSO using the solvent-exchange technique, the impregnated CS was air dried (CSAD) to 18% MC. In order to create aligned cellulose microfiber/ANF hybrid material, the aforesaid sample was finally densified along radial direction using a hot press (ZG-50TSD, Dongguan Zhenggong Electromechanical Equipment Technology Co., Ltd., Dongguan, China) under 35 MPa pressure for 10 min (CCSAD-ANF). The densified sample was dried at 80 °C for 24 hours after densification, and it was then cooled to room temperature for additional characterization.

V. RESULTS

Three steps were taken to create the material: (1) delignification to remove the majority of lignin and some hemicelluloses, which can explore more cellulose microfibers and increase hydrogen bonding sites; (2) CS was impregnated using ANF, which will participate in subsequent hydrogen bonding assembly of high-performance cellulosic materials; and (3) mechanical compression of infiltrated cellulosic materials with 18% moisture content to induce more hydrogen bonding sites. The specific tensile strength of concrete, stainless steel (304, SS), aluminium alloy (6061-T6, AA), magnesium alloy (MA), bio-based laminate (BBL) , ultrastrong and tough material (UTM) and high-strength composite (HSC) was compared with conventional construction materials and lignocellulosic structural materials. Figure 4d shows this comparison.

The specific strength of CCSAD-ANF is comparable to high-performance timber structural composites and much higher than that of conventional building materials. Additionally, the particular strength is a crucial advantage for applications in fields like new energy vehicles and spacecraft, which need for lightweight, high-strength materials. Delignification, ANF impregnation, and densification techniques were used to successfully manufacture a cellulose scaffold/ANF hybrid bulk composite with exceptional mechanical performance and thermal stability. In comparison to natural wood, the delignified wood produced by the air drying method has mechanical qualities that are 2.5 times stronger, 2.5 times tougher, and 2.3 times more elastic. The cellulose scaffold/ANF hybrid bulk composite gained a more dense structure thanks to the densification of the cellulose scaffold impregnated with ANF.

In comparison to natural wood, the 341.7 MPa tensile strength, 4.4 MJ/m3 toughness, and 24.7 GPa Young's modulus of the cellulose microfibers/ANF hybrid bulk material are, respectively, 5, 10, and 2.4 times greater. The aforementioned findings showed that ANF, through creating hydrogen bonds with cellulose microfibers during compression, was crucial in aiding the assembly of cellulose scaffold into an excellent thermal stability and superior mechanical material. The item may be utilised to create high-performance bio-based hybrid materials for usage in wooden structures, automobiles, and spaceships.

VI. DISCUSSION

This strategy showed the initial stages of creating a complementary technology that could increase the potential of bio-synthesis prototyping procedures. Experiments specifically demonstrated that BC is moldable during cultivation. By carefully controlling the input of fermentation media with the aid of a microfluidic device, BC can expand to a thickness and form that is theoretically limitless. Furthermore, additional research supported the idea that BC prefers natural fibres like sisal to grow on. It has been highlighted that the development of BC-based bio-composites improves the bio-mechanical polymer's characteristics, opening the door to the construction of structural and graded features. The ability to develop BC around a predetermined form has finally been successfully demonstrated; throughout the fermentation process, the oxygen addition forced the cellulose to adhere to particular surface conditions. Despite the findings, all of the studies are still a long way from being applied in a large-scale real world, and further research is needed to determine how accurately material-driven computing approaches compare to prototypes that have grown.

VII. SCOPE FOR FUTURE

Therefore, it's crucial to create bio-fabrication approaches connected to computational modelling with a materially informed perspective in order to introduce cellulose as a building material. The improvement of the polymer's mechanical properties, such as its strength and stiffness, is a crucial area for potential future growth. a variety of structural BC bio-composites can be created by calcifying 3D membranes with hydroxyapatite, chitosan, or lining. Engineering, building, and architecture have traditionally been research hotspots for lightweight structural materials with high mechanical performance. deployable lightweight structures

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ABBREVIATIONS

1. BC – Bacterial Cellulose
2. Et. Al. - And Others
3. ANF – Aranid Nanofibre
4. CS – Cellulose Scaffold
5. BBL – Bio-based Laminate
6. HSC – High Strength Composite

UNITS

1. mg/dL - milligrams (mg) per decilitre (dL).
2. GPa - Gigapascal
3. MJ/m3 - Megajoule per cubic Meter
4. MPa - Megapascal