TWO SUSTAINABLE BUILDING SYSTEMS: THE IMPACT OF SHRINKAGE ON NATURAL MATERIALS IN ADDITIVE MANUFACTURING

Tatiana Campos
Paulo J. S. Cruz
Bruno Figueiredo

The growing demand for sustainable building solutions requires a shift from conventional building materials to biodegradable, recyclable and reusable alternatives. A comparative analysis of two architectural systems was undertaken using natural materials – biodegradable, recyclable and sustainable – such as cellulose, which was combined with other raw materials. This work explores the use of additive manufacturing (AM) technologies – Paste Extrusion Modelling (PEM) – to produce individualized components, using three-dimensional modelling programs such as Rhinoceros and Grasshopper to develop the digital design. It compares a set of mixtures, analyses a range of printing specifications, to evaluate the opportunities as well as potential limitations of AM, as well as those due to drying and, finishing in.

INTRODUCTION

The use of natural, sustainable, and biodegradable materials in architecture is essential for reducing the consumption of inorganic materials and, consequently, minimizing environmental impact, thereby promoting more energy-efficient buildings. According to González & García Navarro (2006) [1], the adoption of materials such as wood, ceramics, cork, and natural fibers not only has a low environmental impact but also significantly contributes to the reduction of CO_2 emissions into the atmosphere. With the increasing demand for sustainable construction solutions, the integration of eco-friendly materials in architecture represents a fundamental strategy for building a more resilient and environmentally re-sponsible future. [2]

The present article aims to develop a comparative study on the analysis of shrinkage architectural components made from natural-origin materials. The comparative study involves the analysis of different architectural systems, designed for distinct purposes and utilizing various material compositions. Kusudama is a self-supporting wall composed of a set of individual hexagonal blocks with distinct internal geometries (Figure 1a). Designed as a proof of concept inspired by traditional origami, often used as decorative elements or in architectural applications, the structure consists of two types of differentiated geometric blocks: triangular negatives and pentagonal positives. [3-6] The combination of these elements generates a wavy pattern with topographical variations, imparting innovative aesthetic and functional properties to the wall. Pulpbaffle is a self-supporting wall composed of a set of individual undulating blocks with acoustic properties (Figure 1b). Developed based on the concept of sound propagation waves, the undulating geometry is generated from a set of variable parameters, which, when manipulated, allow a differentiated response to the environment, adjusting to the absorption or reflection of sound according to the user's needs. [6]

The study includes a comparative analysis of the material mixtures used during the AM process, drying, shrinkage index, and, finally, the finishing of the various blocks.

MATERIAL

Cellulose (Figure 2) is a natural, organic, biodegradable, and recyclable polymer com-posed of glucose chains, serving as the primary structural component of the cell walls of plants, algae, and oomycetes. It is derived from Eucalyptus globulus, ...an important plantation species in subtropical regions, including southern Europe (Spain, Portugal)... [7], selected for its high-quality fibers for paper production, as 50% of its fibers consist of cellulose. It is the most abundant biopolymer in nature and has extensive applications across various sectors, including the paper, textile, pharmaceutical, and construction industries.

The cellulose production process consists of three main stages: (1) the cultivation of Eucalyptus Globulus through forest plantation; (2) the harvesting of the wood, during which the logs undergo rigorous inspection, are debarked and fragmented into particles of controlled dimensions, referred to as chips, shavings, or wood flakes; and (3) the production of cellulose pulp, which involves a cooking process aimed at individualizing the cellulose fibers, facilitating the separation of lignin to obtain raw pulp with a brownish hue. Subsequently, the raw pulp undergoes a bleaching process using a solution of caustic soda and sodium sulphide. [8] All the constituent elements in eucalyptus are utilized, from the leaves to produce essential oils, cellulose for the production of paper and lignin, a macromolecule, for the production of thermal insulation foams. The reuse of all the elements eliminates possible waste.

PRINTING MIXTURES

To produce both prototypes, a mixture made up of a set of materials in different proportions was developed, as shown in Table 1. The preparation of the mixtures results in the combination of 9 to 10% of corn starch (w/v) (VRW, Radnor, PA) with 60 to 64% of water (v/v). To produce the pulpable mixture, in addition to the starch, 3% gelatine and 2% black cork agglomerate are added. After homogenising the materials, heat them with vigorous stirring until a highly viscous hydrogel is formed. After the temperature of the hydrogel has dropped, 25 to 27% micronized cellulose (w/v) is added in small amounts until a completely homogeneous mixture is formed. Each natural material was properly selected with the aim of developing a natural, biodegradable and sustainable mixture capable of being returned to the environment. The use of local materials was also taken into consideration, thus reducing possible environmental impacts associated with transport and production. [3-6]

Table 1: Comparative analysis between the Kusudama and Pulpbaffle mixture.

	Kusudama	Pulpbaffle
Water	64%	60%
Starch	9%	10%
Cellulose	27%	25%
Gelatine	-	3%
Cork	-	2%

The mixtures used in the production of both architectural systems have been analysed and, it can be concluded that the Pulpbaffle mixture was enhanced by incorporating new ingredients and adjusting the proportions of the base components. This modification was necessary to improve the final quality of the produced elements.

PRINTING SPECIFICATIONS

When analysing the various printing parameters to manufacture the prototypes, visible differences were observed, as shown in table 2.

Table 2. Comparative analysis between the Kusudama and Pulpbaffle printing specifications.

	Kusudama	Pulpbaffle
Printing pad	One direction	Two directions
Velocity	20mm/s (100%)	14mm/s (70%)
Air pressure	3bar	4.5bar
Nozzle	3mm	5mm
Internal Structure	Yes	No
Plate	Smooth surface	Perforated surface

The first aspect to consider was the printing path. In the Kusudama blocks, the presence of three distinct surfaces – internal, external, and structural – resulted in multiple

Figure 1: The picture on the left is the Kusudama wall (1a) and on the right is the Pulpbaffle wall (1b).

Figure 2: Micronized cellulose provided by RAIZ – Institute Research of Forest and Paper.

Figure 3: a) Study that determinates the maximum degree of curvature supported by the cellulose. b) Internal walls of the Kusudama Blocks.

Figure 4: Pulpbaffle block after printing.

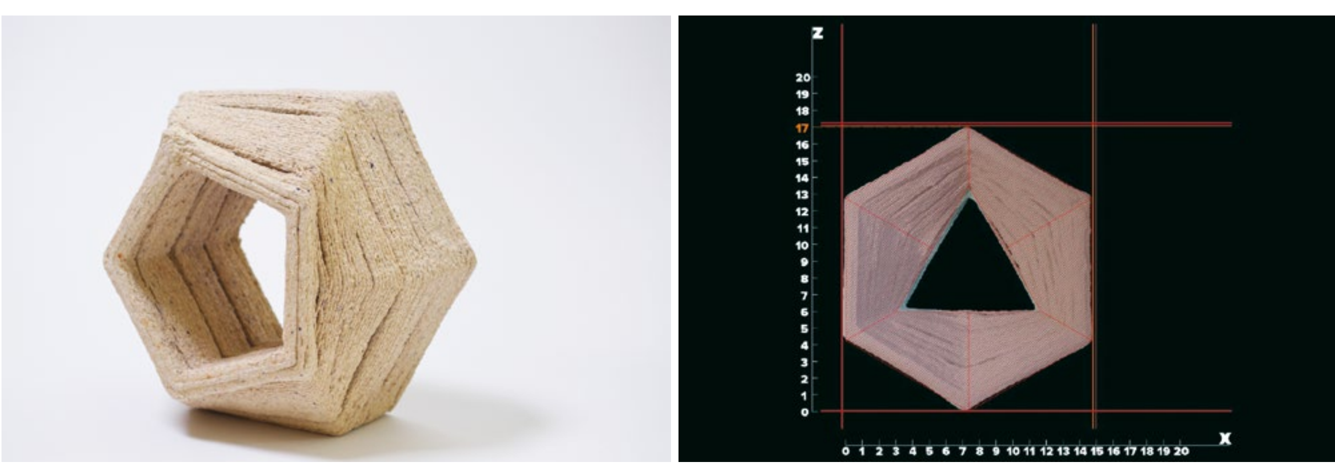

Figure 5: Shrinkage of Kusudama blocks. Delamination between layers due to evaporation of water.

interruptions throughout the layers, leading to material accumulation in the seam regions of the geometries. In contrast, the Pulpbaffle blocks were designed with a continuous geometry, allowing for the inversion of the printing path between layers, thereby enabling the use of two printing directions. Another critical factor was the printing speed. For the Kusudama blocks, a speed of 20 mm/s was selected, whereas for the Pulpbaffle blocks, a reduced speed of 14 mm/s was chosen to enhance the final quality of the piece and minimise wall deformations. Furthermore, due to modifications in the composition of the mixtures, it became necessary to increase the air pressure applied during the extrusion process in the Pulpbaffle blocks, as well as to enlarge the diameter of the extrusion nozzle. Another factor considered was the use of a perforated surface, which facilitated the drying process, promoted uniform material shrinkage, and prevented undesired deformations.

PRINTING LIMITATIONS

Both prototypes under study are modular wall systems; however, the blocks are arranged differently and exhibit distinct geometries. The Kusudama blocks consist of linear geometries, whereas the Pulpbaffle blocks are composed of undulating geometries. When analysing the Kusudama blocks, it was observed that they feature walls with varying inclinations, making it essential to determine the maximum curvature permitted by the material. To address this, a set of conical geometries was developed, varying the curvature of the walls (Figure 3a), leading to the determination that the maximum allowable wall curvature for the Kusudama blocks is 30º.[3] Additionally, a set of internal walls (Figure 3b) was incorporated into the digital model to connect the inner and outer geometries, reducing deformations caused by the drying process and providing structural support for the inclined walls.

Regarding the Pulpbaffle blocks, it was essential to determine the most effective way to prevent potential wall deformations, thereby ensuring better overlap between the different blocks that compose this architectural system (Figure 4). To achieve this, a black cork agglomerate additive was incorporated into the mixture, aiming to reduce layer shrinkage due to water evaporation and enhance the material's acoustic performance. Furthermore, to ensure greater consistency between the digital model and the fabricated model, minimum and maximum dimensions were established for the base and height of the block. The greater the height, the higher the susceptibility to wall deformation due to the material's viscosity and the pressure exerted during the extrusion process.

DRYING

Considering that the construction systems under study were produced using different mixtures and printing parameters, the material's behaviour during the drying process also varies, which indirectly resulted in different shrinkage rates. When analysing the drying process of the Kusudama blocks, delamination between layers and wall deformations were quickly observed. This is attributed to the high-water content in the mixture, the absence of a natural adhesive to effectively bond the layers, and the use of a small extrusion nozzle. As water evaporates during drying, the material contracts; the higher the water content, the greater the shrinkage. As shown in Figure 5, the shrinkage rate of the blocks in height is 10%, whereas at the base, it is only 1%. Although the block retains its base dimensions, it tends to shrink at the top due to the absence of a drying system that could indirectly mitigate the occurrence of potential deformations.

It was quickly concluded that the mixture used for the AM of the Kusudama blocks missing certain essential ingredients. Therefore, for the production of the Pulpbaffle blocks, a refined mixture was formulated, consisting of a liquid component, a binder, a fibrous element, and an aggregate, ensuring superior final quality. Additionally, a drying system was developed, comprising two perforated plates connected by an extendable spring (Figure 6). The block is printed onto one of the bases and left to air-dry for approximately two hours, allowing the gelatine to begin solidifying and bonding the layers together. Once the drying system is assembled, the block is placed inside a drying chamber and rotated multiple times to ensure uniform drying.

After 24 hours, the drying system is disassembled, as the outer surface is already dry, allowing the block to continue drying internally. The complete drying process for a single block takes 36 hours. Analysing the shrinkage data presented in Figure 7, it was observed that the shrinkage rate in height is 19%, whereas at the base, it is 3%.

DISCUSSION

By analyzing the mixture and drying method used for the AM of the different blocks that constitute each construction system, it was concluded that the final quality primarily depends on the ingredients forming the mixture. The higher the water content, the greater the delamination between layers. The introduction of gelatin into the mixture also has a significant impact on the quality of the block, as it helps prevent delamination between layers. However, due to its adhesive properties, it increases the shrinkage rate in the block's height, rising from 10% to 19%. Nevertheless, this adjustment ensures greater stability between the digital model and the fabricated model. [3-6]

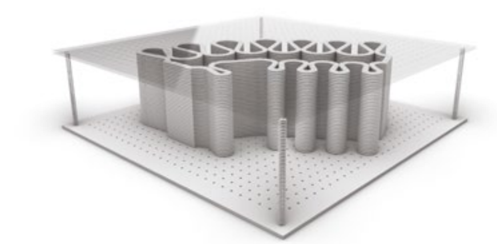

Figure 6: Drying system developed for drying Pulpbaffle blocks.

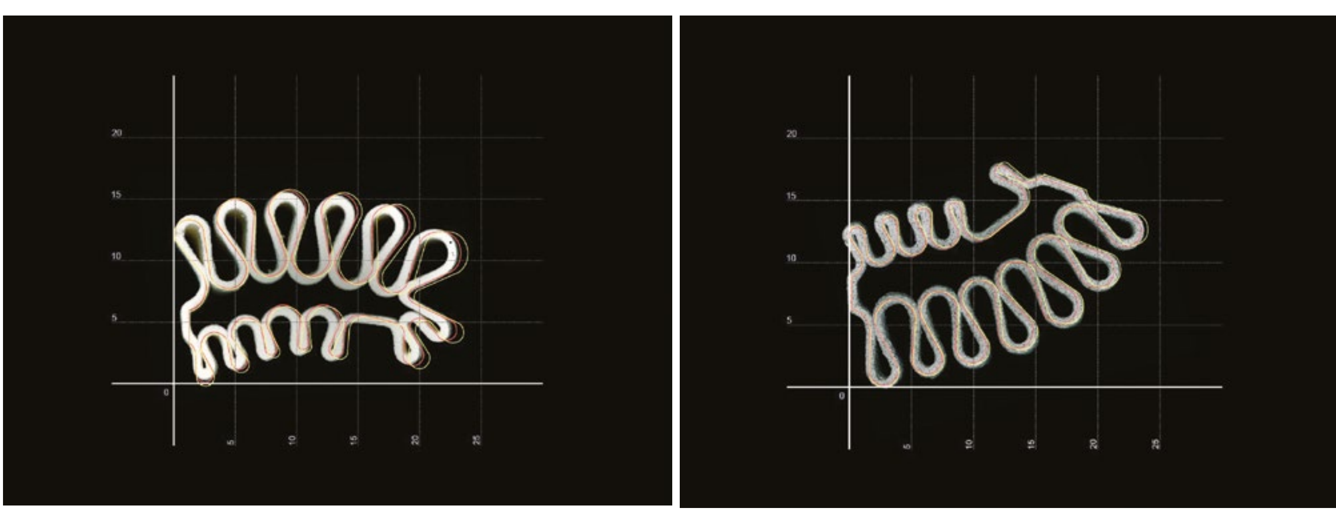

Figure 7: Shrinkage of Pulpbaffle blocks. The figure on the left shows the shrinkage of the block without a drying system and additives. The figure on the right shows the shrinkage of the block with the drying system and cork additive.

Figure 8: Final finishing of one Kusudama and Pulpbaffle block using different additives.

The additives introduced strongly influence the final color obtained. In the Kusudama blocks, it was observed that the mixture without additives produces a white finish, whereas the addition of wood powder results in a brownish tone (Figures 4-5-6-8). In contrast, the Pulpbaffle blocks acquire a greyish hue due to the color of the black cork agglomerate. Regarding the texture of the material after drying, it is determined by the presence of micronized cellulose fibers.

CONCLUSION

Through the analysis of the behavior of the mixtures under study, we concluded:

- The ideal mixture for additive manufacturing (AM) should consist of: 1 liquid material + 1 binding material + 1 fibrous material + 1 aggregate material. The binding material (starch), in conjunction with the liquid material (water), binds the fibrous particles (cellulose). The aggregate material (gelatin), when combined with the others, forms a natural adhesive, preventing the occurrence of delamination between the layers of the different blocks.
- By analyzing both mixtures, it was easy to identify that some of the defects observed in the Kusudama blocks stem from the lack of ingredients in the mixture, as well as the proportion of these ingredients.
- The greatest vulnerability observed when using natural materials lies in the drying phase, where the evaporation of water from the material causes it to shrink.
- Comparing both mixtures, it was observed that, although the height shrinkage of Mixture Kusudama is approximately 10% – less than the 19% observed in Mixture Pulpbaffle – this phenomenon is primarily attributed to delamination between layers. Although the block dimensions closely match the digital design, the wall layers tend to separate. However, delamination does not occur in Mixture Pulpbaffle, as the layers adhere to each other due to the presence of gelatin, resulting in a higher shrinkage rate. The greater the delamination between layers, the lower the shrinkage rate.
- Despite the lower shrinkage rate in Mixture Kusudama – height shrinkage of 10% – compared to Mixture Pulpbaffle – height shrinkage of 19% – greater deformations in the walls were observed, which indirectly difficult the fitting of the different modules. To ensure ease of assembly during the production of the Pulpbaffle blocks, a perforated cage was used – a system consisting of two perforated plates connected by two springs – to prevent potential deformations in the walls during the drying process.

It is essential to promote the use of sustainable, recyclable, and biodegradable materials, as the production and consumption of inorganic and non-renewable materials far exceed actual needs. The construction sector is one of the largest contributors to global pollution, making it imperative to responsibly change this scenario through the adoption of more sustainable practices, with the aim of preserving our planet. The presented case studies are clear examples of potential solutions to be adopted. Furthermore, it is crucial to implement a circular system, in which we choose eco-friendly materials that can be easily returned to the earth, fostering the growth of new species, rather than disposing of them in landfills, such as the use of cellulose and cork – natural materials. As Franklin and Till, 2018 [9] say, in a closed-loop or circular economy – the most desirable model for sustainability – materials that originate from nature are returned to nature. [10]

ACKNOWLEDGEMENTS

This work was financed by the project Lab2PT - Landscapes, Heritage and Territory Laboratory - UIDB/04509/2020 through FCT – Fundação para a Ciência e a Tecnologia and the FCT Doctoral Grant with the reference SFRH/BD/144794/2019. We thank to RAIZ – Institute Research of Forest and Paper, for their support and partnership in this research, namely through the supply of cellulose. We are grateful to the Institute of Design of Guimarães for hosting and supporting the Advanced Ceramics R&D Lab on the use of their facilities and equipment.

REFERENCES

[1] González, M. J. García Navarro, J. 2006. Assessment of the decrease of CO_2 emissions in the construction field through the selection of materials: Practical case study of three houses of low environmental impact. Building and Environment, 41, 902-909.

[2] Kibert, C. J. 2016. Sustainable Construction: Green Building Design and Delivery. John Wiley & Sons.

[3] Campos, T. Cruz, P.J.S. Figueiredo, B. 2019. Exploração da utilização de pasta de papel na fabricação aditiva em arquitetura. Universidade do Minho, Guimarães.

[4] Campos, T. Cruz, P.J.S. Figueiredo, B. 2021. *Exploration of natural materials in additive manufacturing in architecture: use of cellulose-based pulps*. In Hvejsel, M., Cruz, P.J.S. (Eds) Proceedings of the 5TH International Conference on Structures and Architecture, (pp.87-8). Aalborg, Denmark, 6-8 July 2022.

[5] Campos, T. Cruz, P.J.S. Figueiredo, B. 2021. *Experimentation of natural materials: The use of chitin in additive manufacturing.* In Hvejsel, M., Cruz, P.J.S. (Eds) Proceedings of the 5TH International Conference on Structures and Architecture, (pp.87-8). Aalborg, Denmark, 6-8 July 2022.

[6] Campos, T. Cruz, P.J.S. Figueiredo, B. 2024. *Natural Material Innovation in Sustainable Building Systems*. In 1st International Conference on Design and Industry, Braga, Portugal, May 20-22, 2024.

[7] Sisko, M. Pfaffli, I. 1995. Fiber Atlas: Identification of Papermaking Fibers. Springer.

[8] The Navigator Company. (2025). *O processo de fabrico do papel.* https://www.thenavigatorcompany.com/produtos/papel/o-processo-produtivo-do-papel/

[9] Franklin, K. Till, C. 2018. Radical Matter: Rethinking materials for a sustainable future. Thames & Hudson.

[10] Treggiden, K. 2020. *Wasted: When Trash Becomes Treasure.* Brussels: Ludion Publish.