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BIO-FORMWORK

Large Scale 3D Deposition of Thermoplastic Starch in Architecture

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Abstract. The following research synthesizes biopolymers with digital fabrication tools, such as robotic 3D printing, to complement existing research on reducing the amount of concrete used in buildings. It investigates bio-based and biodegradable polymers for concrete formworks. The climate crisis challenges architects and designers to explore alternative opportunities for sustainable fabrication processes. Biopolymers have emerged as a potential material to replace petroleum-based plastics used in the built environment. This research aims to rethink the materials used in the construction of buildings and suggests introducing bio-based and biodegradable materials in architecture.

1. Introduction

The building and construction sector is with 19% the second-largest consumer of plastics [cf. 1: 1]. Buildings today are composed of conventional material systems, each with different requirements. Non-renewable resources and fossil fuels provide the basis for almost all materials used. Because petroleum-based polymers are cheap to produce and accomplish outstanding properties such as high strength and lightweight, they are implemented in building applications. Plastic elements that can be found in architecture are, for instance, insulations, window frames, piping systems, packaging, and formworks [cf. 2: 5].

One application in the architecture and building industry of petrochemical plastics as an engineering material is concrete formworks. To reduce the amount of material used for traditional formworks and significantly reduce the amount of concrete used, one-of-a-kind molds can be fabricated with digital tools, such as subtractive milling [cf. 3: 427] and additively printing formworks [cf. 4; 5; 6]. These processes benefit the reduction of concrete, but still, petroleum-based plastics are being manufactured.

Although complex single-use formworks decrease the material used for concrete components, the printed plastic formwork increases the element's carbon footprint. Consequently, the aim is to use a bio-based and biodegradable material instead to overcome the issues of disposing of valuable resources.

2. Biopolymers

Unlike petroleum-based plastics, a biopolymer consists of polymers originating from biological matter, e.g., sugar cane, starch, or cellulose from trees, straw, and cotton. Biomaterials can be engineered to achieve properties between biodegradable and compostable and robust and durable. Biopolymers can replace conventional plastics due to their identical chemical structure [cf. 7: 2–6].

2.1 Polylactic Acid (PLA)

A prominent example of bio-polyesters is Polylactic Acid (PLA). Through biotechnology, lactic acid is transformed into a thermoplastic polyester.

Typical applications for PLA are (food) packaging, especially for fresh products such as vegetables and fruits, with almost 70% [cf. 8]. Other typical applications are 3D printing filaments. They find extensive implementation in printing due to PLA's low melting temperature [cf. 9].

The universal assumption is that PLA is highly sustainable due to its biodegradable nature. However, PLA only decomposes well under industrial conditions that are relatively unreachable in our natural environment: stable and warm temperature (55°C), moisture-rich environments [cf. 10: 260], and for a period of approximately 2 to 3 months [cf. 11: 27; 12: 8498].

2.2 Thermoplastic Starch (TPS)

The limitations of the biodegradability of PLA describe the choice to investigate polysaccharides, specifically thermoplastic starch (TPS). The universal use of this material is (food) packaging [cf. 13: 6] and biomedical applications, such as excipients, tablets, and capsules in the pharmaceutical sector [cf. 14: 5]. TPS originates from biomass, such as starch from maize, potatoes, and wheat [cf. 13: 4]. These biopolymers have the advantage of being able to be easily composted. The biodegradation of starch-based polymers is assumed to mitigate the issues deriving from petroleum-based polymers [cf. 15: 75].

3. Research Focus

This research focuses on single-use plastics, which describe the most considerable impact on environmental harm due to their cost-(also energy)-benefit ratio. Short-life plastic elements such as individual plastic formworks for concrete should be replaced with sustainable materials.

The latest 3D printed formwork structures research reveals a highly sophisticated and advanced state that significantly cuts concrete costs, energy use, and related labor [5].

However, disposable plastic formwork is used and demonstrates the following research gaps:

1. The material itself is a petroleum-based plastic.
2. The removal of the formwork requires extensive mechanical labor and energy (fig. 1).
3. More material is needed to avoid hydrostatic pressure.

The hypothesis is to replace conventional plastic formworks with actual bio-based and biodegradable polymers. The choice of material is thermoplastic starch because of the following reasons and assumptions:

1. The material is sustainable and compostable.
2. TPS can be designed with different material characteristics, such as flexible and rigid. In addition, solvable material properties can be introduced. This could be an advantage in solving the removal issues of conventional 3D plastic formworks.
3. To react to the emerging hydrostatic pressure, the low costs and low carbon emissions, and the biodegradability of TPS allow for using more material without severe consequences. Besides that, various bio-additives such as hemp fibers can be incorporated into the system to achieve higher reinforcement properties.

Figure 1: 3D printed plastic formwork (FutureTree, 2017-2019, Gramazio Kohler Research, ETH Zürich).

4. Methodology

4.1 Material Research

The material research examines the material and the goal to achieve properties meeting the demands for 3D printing and formworks. Factors for evaluation are properties such as strength, shrinkage, durability, curing time, additive energy sources (heat), viscosity, stickiness, workability, processability, and material costs. The goal is to incrementally and iteratively analyze formulations and their ratios for plausible three-dimensional deposition and formwork performances.

Figure 2: LDM TPS same size prints with hemp fibers; from left to right: control group 0.00%, 0.79%, and 3.10% fibers (Benjamin Kemper, 2021).

Promising results were already achieved by implementing hemp fibers in the mixture before the glass transition. During the setting stage, TPS tends to shrink due to water loss. The incorporated hemp fibers reduce the shrinkage while drying and improve the tensile strength of the material (fig. 2).

At the laboratory scale, several experiments were conducted to change the material characteristics of the material. Because of its simple production process, extending the material palette with natural additives is possible. Before reaching the glass transition of the starch, bio-additives are added to the formulation. Results prove (a) the receptiveness of the bio-additives and (b) the evident change of material properties. Biowaste such as coffee grounds can help improve water repellency and function as a filler material (similar to concrete fillers).

4.2 Fabrication Research

The fabrication research focuses on extrusion systems for 3D printing TPS. Initially, a liquid deposition modeling (LDM) approach was conducted. Therefore, a Delta Wasp 60100 printer with an attached clay extrusion system was converted to deliver liquid TPS to the printing head. The goal was to explore the possibilities of TPS in combination with several additives (such as hemp seeds, fibers, shives, various wood types, eggshells, coffee grounds, and other bio-wastes) to test the printability of the different TPS formulations. The series of experiments clarify factors for LDM printing and additives for TPS. However, this method is not appropriate because of forceful dynamics in the setting process (fig. 3).

Figure 3: left: LDM TPS print process, right: cured and cracked TPS print (Benjamin Kemper, 2020).

Initial results with TPS pellet extrusion avoid these limitations and provide a suitable fabrication strategy for printing (fig. 4). Because of the thermal stability of TPS, it can be extruded multiple times, as long as it does not exceed 280°C [cf. 15: 64]. The material's melting point in the conducted experiment lay approximately between 200°C and 230°C. The test setup (German RepRap 3D printer with a modified Mahor XYZ small-scale pellet extruder) proves the hypothesis of 3D printing TPS (fig. 5).

All experiments were conducted on a small scale; further steps are scaling up and working with the related tasks. Questions to answer are the maximum nozzle size, the feed and flow rate, heating temperature and zones, and the layer adhesion.

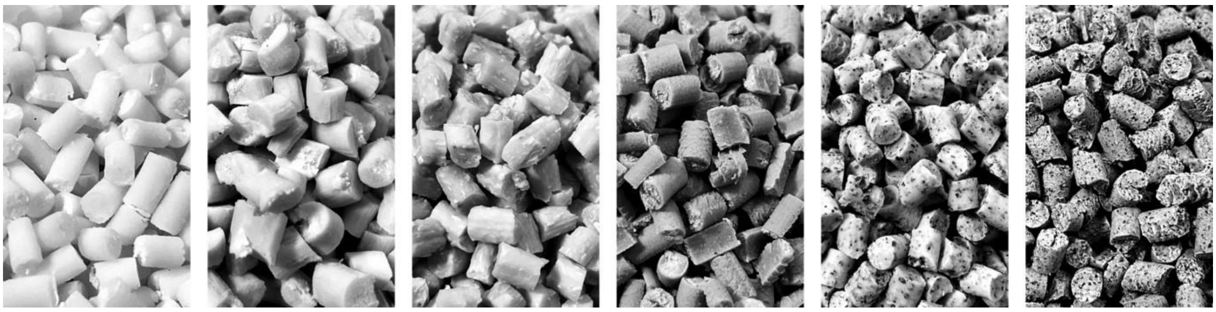

Figure 4: TPS pellets (3-5mm) with additives, from left to right: starch, hemp fibers, hemp shives, bamboo, hemp seeds, coffee grounds (Benjamin Kemper, 2022).

Figure 5: TPS pellet prints (70x100mm), rigid and flexible (Benjamin Kemper, 2021).

4.3 Application and Design Research

The application and design research deals with specific constraints the material system needs to answer for a bio 3D formwork for architectural concrete elements. The benefits and expectations of the TPS formwork approach will be integrated into the latest research and built on top of that, attempting to solve the research gaps mentioned above. This research will include the following topics:

Simple tests were already conducted to examine the casting properties of a 3D printed TPS formwork. The following steps are the scaling up the prototypes to explore TPS printed objects for concrete. For all experiments, a standard mixture of concrete will be used. Further, initial tests will only be performed with pellets of a base TPS formulation and used on simple geometric forms (cylinder).

5. Contribution/Result/Discussion

The research of BIO-FORMWORK will contribute to the scientific field of architecture, aiming for a sustainable future. It focuses on innovation to actively cull processes and materials primarily responsible for carbon emissions and replace them with the help of digital technologies. It searches for a bio-based and biodegradable material system for 3D formworks to create large-scale elements. As a side product, it could also provide an ecological solution for architectural applications and be used as potential interior structures with a short life cycle.

The analysis of bio-based and biodegradable polymers for 3D formworks in architecture describes only a micro aspect of the macro scope (construction material in architecture). The application of TPS on 3D formworks might show how a paradigm shift in the choice of material for architecture could occur. Computation and digital fabrication techniques and the ease of fabricating ephemeral materials and products allow for new speculations about ecologic and economic components in architecture. These products and their inherent complexity in material properties and fabrication process can be understood not as a problem but as an opportunity.

Data availability statement

All data used is either based on personal research or noted in the appendix.

Competing interests

The author declares that there are no competing interests.

List of Figures

1. Figure 1: Burger, Joris. "1f207c53a7aa6ba69475289f1af8fc87_200602_239_Eggshell_Formwork_ removal3_Joris_Burger_PR.Jpg." DFab, 2020, dfab.ch/assets/uploads/img/news/_1200x630_ crop_center-center_none/1f207c53a7aa6ba69475289f1af8fc87_200602_239_Eggshell_Formwork_ removal3_Joris_Burger_PR.jpg.
2. Figure 2-5: Personal photograph by author. 2020-22.

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