Programming Material Intelligence Using Food Waste Deposition to Trigger Automatic Three-Dimensional Formation Response in Bioplastics

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Bioplastics are by their very nature parametric materials, programmable through the selection of constituent components and the ratios in which they appear, and as such present significant potential as architectural building materials for reasons beyond sustainability and biodegradability. This paper presents a system through which rigid three-dimensional doubly curved hyperbolic paraboloid shapes are automatically formed from two-dimensional sheet casts by harnessing the inherent flexibility and expressiveness of bioplastics. The system uses a gelatin-based bioplastic supplemented with granular organic matter from food waste in conjunction with a split-frame casting system that enables the self-formation of three-dimensional geometries by directing the force of the bioplastic's uniform contraction as it dries. By adjusting the food waste added to the bioplastic, its properties can be tuned according to formal and performative needs; here, dehydrated granulated orange peel and dehydrated spent espresso-ground coffee are used both to impart their inherent characteristics and also to influence the degree of curvature of the resulting bioplastic surfaces. Multi-material casts incorporating both orange peel bioplastic and coffee grounds bioplastic are shown to exert a greater influence over the degree of curvature than either bioplastic alone, and skeletonized panels are shown to exhibit the same behavior as their solid counterparts. Potential developments of the technology so as to gain greater control of the curvature performance, particularly in the direction of computer-controlled additive manufacturing, are considered, as is the potential of application in architectural scale.

Keywords: Bioplastics, Composites, Fabrication, Materials
INTRODUCTION
While contemporary plastic manufacturing is readily available and relatively cheap, it does not attend to environmental issues. With the growing global demand for energy, chemicals and materials, bioplastics offer several advantages including sustainable production and consumption, using renewable raw materials to meet global targets. Food waste contributes to excess consumption of freshwater and fossil fuels which, along with methane and carbon dioxide emissions from decomposing food, impacts global climate change. With the goal of a sustainable bioplastic, this paper explores a programmable food waste composite, thereby using waste relative to local production. The fabrication methods used include embedding self-assembly properties within the material program to create semi-autonomous plastic panels as a result of dehydration. Such panels can be used in various scales from product design to large scale, temporary, local ephemeral architectural applications. This study focuses on the exploration of the programming of material intelligence via digital and physical simulations, using food waste deposition to trigger a self-assembly response in bioplastic.

Previous work on biodegradable plastics has been researching different mixes for enhancing mechanical properties (Kretzer, et al. 2013) but as well as variation of mechanical properties in anisotropic surfaces based on multi-material deposition. The current research additionally focuses on self-assembly processes based on the material properties of the new composite.

METHOD
Exploration of the potential of bioplastic as a computationally designable and digitally fabricable material was conducted along two distinct but interrelated axes: investigation of the components comprising the bioplastic and their proportions - the recipe - was performed concurrently with the design of processes and equipment for fabrication using the material. A recipe and a process which, when applied together, form a system with a unique performance and the potential for application in the fabrication of low-cost, large-scale complex geometric architectural surfaces.

This system enables the automatic formation of a rigid bioplastic three-dimensional hyperbolic paraboloid from a two-dimensional sheet cast. Materially, the system combines a gelatin-based bioplastic with granular organic matter from food waste, which confers specific characteristics depending on the type used. This material is cast into a flat frame laser-cut from medium-density fiberboard, which is split at two points to enable the bioplastic’s self-formation into a three-dimensional doubly curved panel.

Experimentation was performed with the aims of achieving control over the degree of deformation of the material and, in parallel, empirically quantifying this action in relation to its informing variables in order to develop a parametric model and simulation with which to investigate formal possibilities and potential architectural applications.

Base Bioplastic Composition
Extensive testing of bioplastic recipes was performed, with particular attention paid to interactions with potential food waste particles and fabricability through a variety of methods including two-dimensional casting, three-dimensional casting and syringe extrusion, all at a variety of scales. (Figures 1 & 2). As the tests of both material and technique iteratively converged on the system described above, the following base bioplastic recipe - adapted from Materiability (Rodriguez 2012) with the addition of vinegar - was found to offer the most synergistic pre-casting, post-casting and post-curing properties among those tested:

- 20 parts (by mass) water
- 4 parts dry gelatin powder
- 1 part glycerin
- 1 part vinegar
Figure 1
Material Recipes

[1] corn starch
[2] gelatine
[3] corn starch + silicone
[4] gelatine + silicone
[5] gelatine + cornstarch + silicone

Figure 2
3D Printing Recipes

[1] corn starch
[2] gelatine
[3] corn starch + silicone
[4] gelatine + silicone
[5] gelatine + cornstarch + silicone

Figure 3
Orange Peel Deformation

TRANSFORMATION [OP]

[parameter] none
original / 0 / 5 / 10 / 20%

[parameter] frame split
 curing time 48hrs
original / 0 / 5 / 10 / 20%

[parameter] splits
 curing time 24hrs
original / 0 / 5 / 10 / 20%

[parameter] heat 1min
 applied at 100mm
original / 0 / 5 / 10 / 20%

[parameter] water
 soaking for 9hrs
original / 0 / 5 / 10 / 20%
To prepare the bioplastic, these ingredients are added to a pot in the order listed and heated on a hot plate while being stirred continuously until the gelatin becomes amorphous (between 40 and 60 ºC).

The process of deriving this recipe emphasized the parametric nature of plastics: each constituent played an observable role in the outcome of the material. For this recipe, gelatin and glycerin form the basis of the plastic, lending among other qualities transparency and cohesion respectively, while vinegar rigidifies the cured result. Previous iterations using ingredients such as corn starch and silicone in large proportions were also revealing of plastics’ ability to take on their components’ characteristics, though their effects were not always desirable. For example, starch-based recipes remained glutinous despite weeks of curing time and attracted populations of Drosophila, while recipes containing silicone were not evenly miscible and readily became moldy. Overall, the gelatin-based bioplastic conferred the best mix of characteristics among the recipes tested, and was chosen for its stability, transparency, post-curing rigidity, and compatibility with the split-frame fabrication system.

**Addition of Granular Organic Matter from Food Waste**

The addition of organic particles to the bioplastic was initially investigated as an avenue by which to augment its characteristics through incorporating those of other materials. Granulated orange peel, for instance, was trialed as a means to integrate the structural properties of cellulose - namely strength (Genet, et al. 2005), rigidity (Bayer, et al. 1998) and bulk - through the use of an abundant and largely unused food waste. Simultaneously, spent espresso-ground coffee was tested with the aim of enhancing the water resistance of the bioplastic via unextracted flavor compounds, which are hydrophobic (Wouda 1981).

Tests of bioplastic samples impregnated with granulated orange peel and spent coffee grounds - hereinafter referred to as orange peel bioplastic and coffee grounds bioplastic respectively, for brevity - were performed in parallel on samples containing increasing amounts of dehydrated food waste (five, 10 and 20 percent by mass), alongside a control containing no food waste. Each test was performed on a sample created by casting into a 100 mm square, 3 mm deep MDF mold.

Among the tests performed, two in particular revealed generalizable results. Subjecting the samples to one minute of heating from a 600 ºC heat gun from a distance of 100 mm exhibited deformation inversely proportional to orange peel content and casting in a diagonally split frame exhibited deformation proportional to food waste content upon drying, for both orange peel bioplastic and coffee grounds bioplastic - though the latter showed more acute deformation. (Figures 3 & 4)

In this way, the added granular organic matter from food waste became a major parameter in its own right, with both the type of waste used and the amount used influencing the characteristics of the bioplastic.

Additional testing revealed structural potentials in the orange peel bioplastic. Three equilateral triangular sheets with a side length of 150 mm, cast at 5 mm thick and containing food waste particles, were suspended from their vertices and allowed to dry into catenary arches - as in Gaudi’s technique (Huerta 2006) - and inverted. Load was incrementally applied using weights, with the arch containing 30 percent orange peel successfully bearing 18.45 kg without collapsing, and rebounding to its original shape within 24 hours (Figure 5).

**Split Frame Design and Automatic Formation**

The automatic formation of a doubly curved panel in this system is a result of the bioplastic and the frame in which it is cast working in concert. As the bioplastic dries, the egress of water through evaporation causes the material to contract. Left unconstrained, this contraction occurs anisotropically and to a degree proportional to the bioplastic’s food waste content (Figure 6). However, if the bioplastic is cast into a frame
Figure 4  
Coffee Ground Deformation

TRANSFORMATION [CP]

[parameter] none  
original / 0 / 5 / 10 / 20%

[parameter] frame split  
curing time 48hrs  
original / 0 / 5 / 10 / 20%

[parameter] splits  
curing time 24hrs  
original / 0 / 5 / 10 / 20%

[parameter] heat 1min  
applied at 100mm  
original / 0 / 5 / 10 / 20%

[parameter] water  
soaking for 9hrs  
original / 0 / 5 / 10 / 20%

Figure 5  
Strength Test
such that its edge conditions are regulated, then it is possible to passively exert control over the result of the contraction.

By casting the bioplastic into split frames laser-cut from medium-density fiberboard, an axis of freedom which dominates the bioplastic’s natural anisotropy can be established. This effect is a function of both the frame’s material and its geometry. Because the bioplastic adheres to the porous fiberboard, its edge condition is regulated where it contacts the frame, thereby constraining the material’s contractive tendency. Any points of weakness in the frame therefore become outlets for the force of contraction - thus, by splitting the frame at two points, an axis of freedom is inscribed between them, around which the material is free to bend as it contracts (Figure 7).

Experimentation has revealed a number of points to consider pertaining to this technique. Firstly, the bioplastic should be cast upon a minimally porous surface for ease of release. Testing has shown that a cast bioplastic surface, once sufficiently solidified as to be non-liquid - typically after one hour of drying - can be peeled from the casting surface and hung up vertically to cure with minimal effect from gravity on the geometry of the result. Secondly, the curvature of the edges of the panel is influenced by the rigidity of the frame; for a given panel size and to a limit, a frame cut from thicker fiberboard yields straighter edges.

**Investigating the Nature of Contraction**

With a technique enabling the formation of three-dimensional hyperbolic paraboloid surfaces from two-dimensional panel casts established, experimentation was performed to explore methods by which the degree of bending might be controlled.

Early split frame tests indicated that, for a given proportion of food waste matter, panels cast from coffee grounds bioplastic contracted more than those cast from orange peel bioplastic. To investigate whether the materials’ different contraction rates could be leveraged to influence the curvature of a panel, contrasting multi-material casts were made: one featuring a strip of coffee grounds bioplastic running from one corner split to the other with orange peel bioplastic comprising the rest; and another with the same materials in the opposite orientation. The results of the test were dramatic: at a 100 mm square panel size, the coffee grounds panel with the orange peel strip contracted to roughly a 100 degree angle when viewed from the side, while the opposite panel contracted to only approximately 30 degrees. This contrast is considerably more marked than that between mono-material panels, indicating that the two bioplastics can be used in conjunction to either amplify or temper the automatic formation effect (Figure 8). Tests with larger scale panels revealed the potential of the multimaterial in prescribing geometric formations to the panel (Figure 9).

In addition, tests were performed to assess the geometry of the contraction itself, with a view to parameterizing the deformation. In the next series, the grid was skeletonized - that is, a mold was created so that the bioplastic was cast only on the grid lines, at a width of 7.5 mm, with the cells of the grid left empty - to observe whether the introduction of void space affects the pattern of contraction. Both series of tests showed that both bioplastics contract uniformly on a per-material basis, with neither the edges nor the center of the panels contracting materially faster or more than the other.
Figure 7
Split Frame Assembly

Figure 8
Multimaterial Contraction Rate Comparison
FURTHER WORK AND CONCLUSION
The research performed to this point establishes a system to produce a material performance - the automatic formation of a rigid three-dimensional doubly curved bioplastic panel from a two-dimensional sheet cast - with a number of possibilities for further development. Having shown that a skeletonized panel exhibits the same contraction and automatic formation behavior as a solid panel, there exists significant potential for the employment of additive manufacturing techniques in the fabrication of lightweight, geometrically tuned panels. Printing the bioplastic rather than casting it would allow for precise control of the geometry, particularly if informed by a parametric model negotiating the transition from two dimensions to three. In particular, computer-controlled fabrication using a six-axis robot in concert with an air pressure extruder would potentially enable the fabrication of large-scale self-forming panels for architectural applications.

However, the biological nature of bioplastic must not be forgotten. Organic matter decays as it biodegrades, presenting the challenge of designing materials that are strong and durable enough to be architecturally valuable, but not so robust so that they remain in the environment after they are no longer needed. Indeed, the ephemeral nature of biological materiality proposes an ephemeral architecture, subject to change over time under the processes of metabolism and decay. In this sense, a construction material made from food waste has a role to play in urban strategy by diverting waste products away from landfills and into value-added goods.

In digital materiality, there is an intrinsic link between technology, material science and organic form (Gramazio and Kohler 2008). Digitally fabricated self-forming panels bioplastic derived from food waste present the potential for design and industry alike to engineer functionally graded materials at low cost using abundant and largely untapped material resources. This research demonstrates the potential presented by food waste as a future sustainable building material.

REFERENCES