ARTICLE IN PRESS

Computer-Aided Design ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Computer-Aided Design

journal homepage: www.elsevier.com/locate/cad

Material driven design for a chocolate pavilion

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HIGHLIGHTS

- Determination of structural properties of compound chocolate.
- Physical exploration of material appropriate structural systems for chocolate.
- Parametrically integrated design-to-construction process for free-form chocolate shell structures.
- Integration of material specific structural, manufacturing, and construction constraints into the design process.

ARTICLE INFO

Keywords:
Form finding
Optimization
Chocolate
Parametric structural design

ABSTRACT

This paper presents a study of chocolate's structurally unusual material properties and a parametric design-to-construction approach for an architectural chocolate pavilion. Chocolate's rheological properties suggested exploration of four structural typologies: a pneumatic form, an inverted branching form, a saddle form, and an inverted hanging cloth form. Material tests revealed a compressive strength/weight ratio 24 times smaller than standard concrete. To use unreinforced chocolate, this restriction dictated a form with minimal bending: an inverted hanging shell with voids. An integrated form-finding, void-optimization and mold layout process was employed to minimize self-weight. Pre-casting planar pieces allowed for best control of material quality but added further design constraints. Prototypes demonstrated how the parametric workflow allows design exploration driven by adjustable material constraints, further integrating design and construction into an interdependent process.

1. Introduction

Given the challenge to explore chocolate's structural capabilities, the design of architectural shell structures made from compound chocolate is investigated. When first introduced to the idea of using chocolate as a building material, one might jump to the imagery of Charlie and the Chocolate Factory. Just like the appeal of Willy Wonka's factory lies in the technological complexity of his extraordinary uses for chocolate, the challenge of this project is to utilize novel design practices to create a structural system that allows chocolate to be seen from a new perspective as an experimental building material. Chocolate is often used for artistic purposes, but using chocolate as a structural material and not just as a sculptural medium poses significant challenges. Its relative structural weakness and unique rheological properties require a system of design specifically tailored to the material itself. To achieve this, a parametric design process is used for the design and construction of a force-modeled long span structure from this unorthodox building material.

In this paper, we describe the development of the design process for chocolate shells. Since chocolate has not been analyzed as a structural material before, Section 2 describes the determination of the chocolate formula best suited for this purpose and what engineering properties can be expected from it. Section 2 also includes the process of physical experimentation with chocolate. These experiments explore the possible formal expressions that relate to the physical processes of pouring, dipping and coating and their physical form finding potential for chocolate. The parametric design-to-construction workflow that enables integrated form-finding, structural analysis and optimization, design exploration, and production of manufacturing layouts is presented in Section 3. Section 4 reports on the small-scale mock-up that sheds light on the viability of the digital workflow. Section 5 discusses the design and construction process of the full-scale structure designed for a

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0010-4485/$ – see front matter
http://dx.doi.org/10.1016/j.cad.2013.12.002

café exhibit, and Section 6 concludes with how and why the digital design and construction process must be inseparably connected to the chocolate properties and how this process allows for an exploration of expressive forms by the designer. Overall we present this paper to develop awareness for material specific computational workflows and approaches on how to integrate from finding principles into the steering of structural form.

2. Physical form finding driven by material structural behavior

2.1. Chocolate material properties

The first step in a material driven design process is to understand the material properties that need to be designed for. The word "chocolate" encompasses a wide range of mixtures that contain elements from the cocoa bean. For a product to be legally considered "chocolate" in the United States, it must go through the processes of blending and conching, and contain a minimum amount of cocoa and cocoa butter as its only fat source. This form of chocolate is expensive, melts at temperatures near room temperature, and can become unstable very quickly. For use in structural applications, these properties can all be improved by changing the product's formula to create a "compound chocolate". Many commercially available chocolate products and chocolate-covered baked goods use compound chocolate, not strict "chocolate". The major difference between the two is that the fat used for compound chocolate does not need to be cocoa butter; it can be other types of vegetable fat. This change in ingredients as well as differences in manufacturing means that the material can be melted and cast many times without degradation. Throughout this paper the word "chocolate" is used to refer to the "compound chocolate" used as the primary material in the investigation. Food scientists have intensively studied and optimized chocolate to control properties such as taste, texture, appearance, rheology, production and shelf life [1]. However, no studies have been carried out to identify structural material properties such as strength and elasticity. This effort is quite complex, since the effects of changing the formula or manufacturing procedure on chocolate's structural behavior are unknown.

The first tests compared two formulations of chocolate, whose ingredients are shown in Table 1. Hydrogenated palm kernel fat was chosen because of its high melting point, nearly 43 °C—given the label HMP. The second formula replaced one third of the fat with a lower melting point variant, given the label LMP. To establish the strength and Young's modulus of these two formulas, standard uniaxial compression (see Fig. 1) and tensile split cylinder tests were used. To create the test specimens, the chocolate was melted at 52 °C, cast into standard 3" diameter concrete cylinder molds preheated to the same temperature as the chocolate, and set at 4 °C. HMP was stronger and stiffer than LMP, while also being more consistent in casting and easier to handle. Based on the encouraging results of HMP, four additional formulas were developed. Milk permeate was replaced with Inulin, a type of dietary fiber, and the fat content and particle size were varied. The particle size was controlled by refining the dry ingredients before liquefying the chocolate. The four variants were Low-Fat Refined, Regular-Fat Unrefined, Low-fat Unrefined and Regular-fat Granulated, which used granulated instead of powdered sugar. The variants were designed with the hypothesis that less fat and smaller particles, with greater surface area for cohesion, both make the chocolate stiffer. The same compression and tension tests performed on HMP and LMP were performed on these four variants.

An unintended consequence of lowering the fat content and having larger particle sizes was that the molten chocolate became more viscous and tended to entrap air during the setting process. Furthermore, the material's quick setting time made vibration less effective for removing entrapped air, and this air reduced

Table 1
Ingredients of two compound chocolate formulations.

Formula	Ingredients by (%)				
	Powdered sugar	Cocoa powder	Fat	Milk permeate	Soy lethicin
HMP	57.77	7.97	30.03	3.98	0.40
LMP	57.64	7.95	29.88	3.97	0.41

Table 2
Material properties of compound chosen as building material.

Chocolate formulation	HMP
Density	12.9 kN/m^3
Compressive yield stress	0.6 N/mm^2
Tension rupture stress	1.0 N/mm^2
Young's modulus	47,000 kN/m^2
Creep viscosity	2.66E11 Pa s

Table 3
Comparison of material properties with common engineering materials.

Material	Strength (N/mm^2)	Density (kN/m^3)	Young's modulus (kN/m^2)
Steel	413	76.98	199E6
Concrete	27	23.56	29E6
Chocolate	0.6	12.88	45E3

the strength of the material. The Young's modulus did not vary significantly between the variants. HMP remained the best choice, based on its having highest compressive yield stress (0.6 N/mm^2) and tensile rupture stress (1 N/mm^2) and its ease of manipulation. From an engineering perspective, the compressive and tensile load bearing capacities were within a small enough range for the material to be considered isotropic. Since the material was very close to its melting point at elevated room temperature, we hypothesized that creep would pose a material concern. For this purpose, we performed a three point bending relaxation test, which was used to estimate a material's creep viscosity [2]. The results of these tests revealed that chocolate creeps in a time-logarithmic manner, relatively quickly compared to other materials such as concrete or wood. A simplified creep calculation estimated that the material under modest compression would creep at 0.3% per day. Table 2 summarizes the relevant structural properties of the chosen formulation, HMP. Table 3 compares the properties of this formulation with the more common structural materials steel and concrete. These observations suggest the necessity of form-finding techniques to generate membrane/shell systems that will reduce the material stress and size optimization to bring the self-weight down.

2.2. Physical form finding

In order to find a suitable structural typology for chocolate, physical form finding experiments were employed. These experiments also allowed exploration of the less quantifiable properties that affected the potential designs. Experimentation based on chocolate's rheological properties, such as the viscosity's dependence on temperature, layering based on surface tension, and the visual quality of the surface changed how the material read aesthetically. Four different historic physical form finding techniques that lent themselves to this application were used for the fabrication of small models. These models were analyzed based on structural ability, ease of construction, and aesthetic expression. These small models were structurally valid for a structure on a larger scale because at both scales, the only load was self-weight. Other, possibly asymmetric, loads on a large structure, such as wind and snow, did not need to be considered, as the design would be exhibited in temperature controlled indoor environments.