Shape-Changing Clay-Dough: Taking a Material-Oriented Approach to 3D Printing Ceramic Forms

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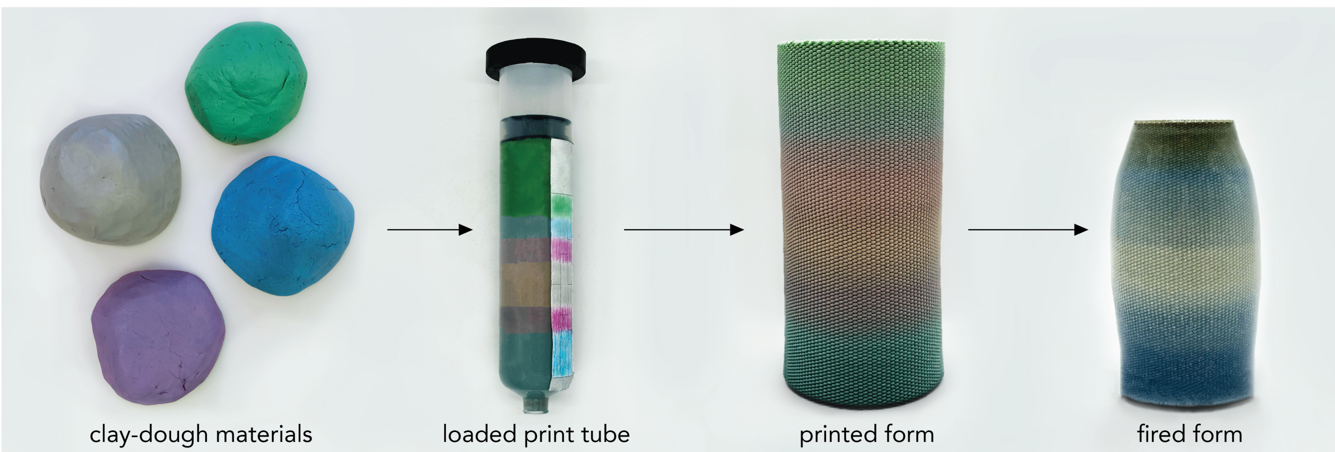

Figure 1: We developed a collection of clay-dough materials that shrink at different rates. Depending on how we load a print tube with materials, we can control the form a 3D printed cylinder takes when the materials shrink during the firing process.

ABSTRACT

This paper presents *clay-dough*, a 3D printable ceramic material that is made from a mixture of stoneware clay and a biomaterial dough. While all clays shrink when they are fired at high temperatures, clay-dough enables more dramatic shrinkage due to the dough burning away. We developed three clay-dough recipes made from different ratios of clay-to-dough and characterized the properties of each recipe; ultimately correlating shrinkage, density, strength, and porosity to the amount of dough in the recipe. We then leveraged clay-dough's shrinkage in our *material-oriented approach* to create ceramic forms, where form is dictated by the pattern we load the clay-dough materials in for 3D printing. To exemplify this approach, we built a design space around basic cylindrical forms that change shape during the firing process into more complex forms and explored a range of non-cylindrical applications. Lastly, we reflect on the limitations and opportunities for clay-dough and material-centered research.

CCS CONCEPTS

• **Human-centered computing → Interaction design**.

KEYWORDS

Shape-Changing Interfaces, Clay 3D Printing, 4D Printing, Digital Fabrication, Ceramics, Biomaterials, Material-Driven Design

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1 INTRODUCTION

Clay is a material that naturally shrinks, with each type of clay shrinking at different rates and amounts as they dry and are fired in a kiln [85]. The majority of clay's shrinkage occurs as the clay loses water and undergoes chemical changes in the firing process, transforming into ceramic [19]. Shrinkage is often thought of as a material property that must be understood and accommodated, however, shrinkage is not necessarily controlled or leveraged in the design of new ceramic forms. With this in mind, we explore how designers can *control the shrinkage of clay* and use its *shrinkage as a method for creating ceramic forms* through the adoption of a new material—clay-dough.

Clay-dough is a mixture of white stoneware clay and a corn-flour-based dough. In comparison to other clays, clay-dough's shrinkage is significantly more dramatic when it is dried and fired. When fired in a kiln at high temperatures, the corn-flour-based dough within the clay-dough mixture burns away, resulting in the left-over clay shrinking significantly more than it would have normally. The drastic shrinkage caused by the inclusion of dough inspired us to develop a collection of clay-dough recipes, each with a different ratio of clay-to-dough. Through testing, we correlated *the amount of dough to the amount of shrinkage*, where the shrinkage increased linearly with the amount of dough. With further testing (of density, strength, and porosity) we built a deep understanding of clay-dough's material properties, which informed our approach for controlling and tuning the shrinkage of our resulting ceramics. In this approach, we position clay-dough's controllable shrinkage as a mode of *shape-change*, where we can combine different clay-dough materials that each shrink in different amounts to develop forms.

Form refers to the three-dimensional shape and structure of an object. In ceramics, the form of a clay artifact can be achieved through many techniques such as hand building (i.e., sculpting clay), wheel throwing (i.e., sculpting clay on a spinning wheel), or slip casting (i.e., pouring liquid clay into a mold) [3]. 3D printing is another newer technique to achieve clay forms that are typically designed in computer-aided design (CAD) software; this technique is gaining interest as an area of research within Human-Computer Interaction (HCI) [17, 33, 90, 119]. In our case, we create clay forms via *shape-changing clay-dough*, where *the form is driven by the material itself as opposed to distinct actions made by a human or a machine*.

Our *material-oriented approach* to creating ceramic forms involves 3D printing a basic cylinder that changes shape into a different form once it is fired, as demonstrated in Figure 1. This process begins with sketching out a form that we translate into a material loading pattern using our deep understanding of clay-dough's properties and a custom guide that we adhere to the print tube of our extruder. We then load the clay-dough materials required for the pattern and 3D print a cylinder. We specifically use 3D printing as our primary mode of physical fabrication because of its linear deposition, which seamlessly transitions from one material to the next. 3D printing also ensures that we always have the same starting form, thus highlighting how the clay-dough materials control the final form the cylinder takes when it is fired. This approach uses shape-change as a novel mode of material-oriented design and fabrication that employs 3D printing, but does not require the use of CAD or CAM softwares. We employ pre-made 3D printer files (.gcode files) to keep the workflow material-focused and entirely in the physical realm.

Employing this material-oriented approach, we built out a design space of possible ceramic forms, some of which are shown in Figure 2. In this design space, we 3D printed the same exact cylinder, while only changing the way that the clay-dough materials are loaded into the print tube. We specifically demonstrate forms created through different loading patterns, starting with simple divided patterns (e.g., halves, thirds, quarters), then more complex patterns, and lastly, randomized patterns. By organizing our design space in this way, we showcase a wide variety of ceramic forms that can be achieved with simple .gcode through clay-dough's shape-change. Inspired by this exploration, we generate a broader set of applications that not only exhibit the potential of clay-dough as a compelling, interactive material for tangible interfaces, but also for shrinkage as a mode of shape-change.

Figure 2: Forms created through our material-oriented approach with clay-dough that started as identical 3D printed cylinders and then shrunk into differently shaped vessels when fired.

With the recent interest in shape-changing interfaces [84] and morphing materials [80] in HCI, we present two entwined contributions—a controllable, shape-changing ceramic material called *clay-dough* and a *material-oriented approach* for creating ceramic forms that are determined by clay-dough's shape-changing behavior. To this end, we use the following pages to unfold these contributions by:

- characterizing a series of clay-dough recipes and their material properties.
- introducing a material-oriented approach for creating ceramic forms through clay-dough's shape-change.
- exploring a generative design space of ceramic forms using our material-oriented approach.
- demonstrating applications and identifying future research directions for clay-dough.
- reflecting on potential users, research limitations, modes of unmaking, and maker-material agencies.

2 RELATED WORK

2.1 Clay 3D Printing and Ceramics

This work primarily focuses on developing ceramic forms through a 3D printed material—*clay-dough*—that changes shape over time with heat. We draw upon the growing pool of works in HCI and ceramic art that utilize clay 3D printing [25]. Notable research in this area includes: using 3D printed clay to tangibilize data such as sounds and vibrations in the form of ceramic objects [32, 33, 90], extruding metal clays to print solid bronze objects [21], building software to generate tool paths for 3D printing non-cylindrical ceramic forms [17], assembling a Python library for g-code generation for clay 3D printing based on Turtle geometry [22], creating slicer software to successfully print clay forms with large overhangs [45], printing deep learning generated models [52], and restoring ceramic objects through 3D printing [119]. Clay 3D printing has also been used in architecture to build large-scale structures [4, 82] and material science to design specialized ceramic components [58]. Within the art space, 3D printing has been employed to support creative ceramic practices. While there are numerous artists that have engaged with 3D printing clay, a few notable practitioners include Piotr Wásinowski [113], Jolie Ngo [74], Bryan Czibesz [31], Unfold Studios [107], and Slip Rabbit Studios [93]. This natural combination of creative practice and digital fabrication with clay, also highlights the broader rise in collaborations between artists and HCI researchers with the advent of experimental art residences [34]; which is reflected in several recently published works that showcase the outcomes of collaborations between HCI researchers and ceramic artists [17, 45, 90, 118].

Beyond clay 3D printing, we also recognize other ceramics research in HCI which has focused on developing hybrid fabrication methods for sculpting clay [36, 87], software for slab-form pottery [54], glazing techniques [38, 70, 100, 118], and critical insights into humans-technology relationships via ceramic objects [110, 111]. One of the most applicable related works is from Arredondo et al. who developed grooved, 2D ceramic slabs that morph into 3D structures [2]. Their work only focused on the shape-change of purely ceramic materials (e.g., porcelain and stoneware clays) and how shrinkage can be leveraged to go from 2D to 3D. In contrast, we use a mixture of stoneware clay and a biomaterial dough (i.e., *clay-dough*) to intensify the shape-changing mechanics, and we employ a method in which we print an initial 3D form that morphs into a different 3D form, thus taking a 4D printing approach to shape-changing ceramics.

2.2 Biomaterials

We achieve dramatic shape-change by combining clay, which shrinks slightly when fired, with a biomaterial dough that precipitates further shrinkage. This dough recipe speaks to a larger trend in HCI that is focused on developing biomaterials (materials that are biologically based and biodegradable [14]) for creating sustainable artifacts; popular biomaterials including mycelium [48, 50, 106, 114], microbial cellulose [12, 73, 78], bio- plastics and foams [11, 61, 62, 96], and clay-like biomaterials [13, 37]. In the space of 3D printing, there have been several clay/paste-like biomaterials made from mycelium [46], wood fibres [63], eggshells [76], olive pomace [6], mussel shells [91], spirulina algae [44], coffee grounds [86], and flour-based doughs [67, 69, 108, 116]. In this work, we use corn-based dough we use is based on a recipe from Buechley and Ta [23], which was developed specifically for 3D printing purposes. However, we do not use the dough as a sustainable biomaterial like in [23], rather we use the dough to arrive at a shape-changing ceramic material.

2.3 Shape-Changing Materials

In the past decade, there has been a push to develop interactive materials in response to Ishii’s call for "Tangible Bits and Radical Atoms" [56], which emphasized the need for responsive, transformable, smart materials in developing tangible user interfaces. As opposed to shape-changing interfaces that utilize motors to digitally control shape-change [42, 72, 95], shape-changing materials (also known as morphing materials) rely on external stimuli to trigger the material to change shape. Shape-changing materials themselves are naturally dynamic, making them suitable for ubiquitous, tangible interfaces [28]. Correspondingly, there has been a steadily growing library of shape-changing materials in HCI [80, 84], to which we contribute clay-dough.

While some shape-changing materials rely on stimuli such as humidity [117], light [53], water [57, 98], or pH [105], some of the most common shape-changing materials transform via *heat* such as shape memory alloy (SMA) and thermoplastics. SMA has been used to create shape-changing wearable knit structures [60], paper crafts [81], and architectural curtains [27]. Meanwhile, thermoplastics like PLA and TPU, which are lower-cost than SMA and can be easily 3D printed, have been used to create self-folding forms [1], deforming fabrics [94], paper actuators [112], shrinking circuits [66], and the popular craft toy, "Shrinky Dinks" [47].

Clay-dough similarly changes shape via heat, which evaporates all the moisture within the material and causes a chemical transformation where the clay transforms into ceramic. The shape-change of different clay bodies due to shrinkage during drying and firing has been thoroughly studied by soil scientists [16, 29] and ceramic artists [30, 85]. Material scientists have furthermore studied the shrinkage properties of clay bodies mixed with materials such as cement [41], natural fibers [83], thermoplastic fibers [97], and even stainless steel [58]. Shape-changing ceramics in HCI have been previously explored in the context of morphing 2D ceramic slabs into 3D structures [2]. In this work, we specifically leverage clay-dough’s shape-changing affordances to introduce a new, *material-oriented approach* for designing and fabricating ceramic forms that contrast traditional methods of dictating ceramic forms such as sculpting, molding, or CAD and 3D printing.

2.4 Material-Centered Design

Material-centered design approaches place the inherent properties and affordances of materials at the heart of the design process, recognizing the pivotal role of *materiality* in shaping design outcomes [51, 88, 104, 115]. Karana et al. notably introduced *material-driven design* as a method in which the designer gains a deep *material understanding* via technical and experiential characterization, to develop a *materials experience vision*, which drives the development of a new product/application that is best suited to the material [59].

Researchers have further explored ways of gaining material understanding through approaches such as hands-on *material tinkering* [77] and designing *material experiences* [49, 79] to complement traditional technical and engineering approaches of material characterization (e.g., testing material properties such as strength and density). These material-driven approaches to design can help in the identification of material affordances, which generate potential applications [9].

Bringing focus to the material in design has also been highlighted by posthumanist scholars such as Barad [7], Ingold [55], Bennett [15] and Wakkary [109], who position materials as *agents* in the design process. In this framing, human designers must *decenter* [43, 75] themselves to work with the nonhuman material through *correspondence* [55]. This concept of corresponding with a material in a non-hierarchical manner has been specifically discussed in the context of clay by Devendorf and Ryokai in their development of hybrid craft fabrication methods to support the act of sculpting clay with digital tools [36], Rosner et al. in their reflections on the tension between hand-building versus 3D printing clay for data visualization [90], and Bell et al. in their use of hands-on fabrication techniques for working with the inconsistencies of an agentic compost-based clay [13].

In this work, we take a multidisciplinary approach to material-driven design that is aimed at gaining a deep understanding of clay-dough's properties, behaviors, and affordances using both technical characterization techniques from ceramics and materials engineering, as well as our felt material experiences (see Section 3). Based on this gained understanding, we developed a *material-oriented approach* for creating ceramic forms that highlight clay-dough as an active agent in the design process that ultimately drives the form through its shape-change (see Section 4). We then use our knowledge of the material and our material-oriented approach to designing and fabricating forms as our foundation for a more open exploration of clay-dough forms (see Section 5) and applications (see Section 6). Ultimately, by focusing firstly on gaining a material understanding of clay-dough and then by developing a material-oriented approach for creating forms with clay-dough, our overarching methodology for this research project was material-driven and generative, as opposed to application-driven and solutionist.

3 CLAY-DOUGH DEVELOPMENT AND CHARACTERIZATION

All clay shrinks when dried and fired; fired porcelain shrinks 14-15%, fired stoneware shrinks 11-13%, and fired earthenware shrinks 5-8% [85]. Prior research has shown that biomaterial doughs shrink more during drying than most clays shrink during firing; a corn-flour-based dough shrinks 17-19% when it dries (it cannot be fired because it burns away) [23]. In this work, we specifically explore the shrinkage of a stoneware clay called WH8 [26] mixed with a biomaterial dough inspired by other dough recipes used for 3D printing [65, 67, 69, 108, 116], Buechley and Ta's corn-flour-based "play-dough" [23] being the most influential recipe. While Buechley and Ta introduced a mixture of play-dough and clay (25% stoneware clay, 75% play-dough) in this past work, the clay was used purely as a stabilizing agent for the development of a compostable and recyclable biomaterial for 3D printing. The purpose of this past work was focused on *non-fired* sustainable biomaterials (i.e., materials that never became ceramics). In contrast, we extend beyond this framing, by focusing on *fired ceramic* materials, that were developed for their shape-changing properties rather than their sustainability.

We initially arrived at clay-dough through an experiment of combining the 3D printable biomaterial dough with clay in an effort to increase the strength and stability of the biomaterial as prescribed by Buechley and Ta [23]. Inspired by the fact that other clay-biomaterial mixtures like paper clay [99] are fired, we, in turn, decided to fire our experimental clay-biomaterial mixture in the kiln. However, when we fired this clay-biomaterial mixture, we observed interesting shrinkage behavior as demonstrated by the bowls in Figure 3, which were printed identically, but shrunk differently once fired. From this experiment, we noticed that the shrinkage of the clay-biomaterial mixture was significantly more dramatic than regular clay and that the shrinkage seemed to increase as a function of the amount of biomaterial within the mixture. This motivated a series of more carefully calculated recipes and material characterization tests.

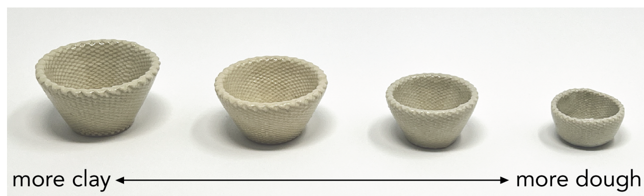

Figure 3: Initial clay-biomaterial experiments that began as identically printed bowls, but shrunk once fired into different sizes based on the amount of biomaterial dough within the mixture.

3.1 Developing Clay-Dough Recipes

In an effort to leverage and control clay-dough's unique behavior (i.e., dramatic shrinkage), we developed three recipes, measured by weight: *(1) 25% clay and 75% dough, (2) 50% clay and 50% dough, and (3) 75% clay and 25% dough.* To make our three recipes we began by preparing the WH8 stoneware clay [26], which we mixed in a kitchen mixer with water to an indention hardness between 0.5 and 0.6 kg/cm^2, following a hardness testing method outlined in [23]. Once the clay was ready, we mixed the dough, which consisted of 150g corn flour, 50g wheat flour, 30g vegetable oil, and 150g vinegar (ingredients shown in Figure 4). We then added water until the dough reached an indention hardness between 0.5 and 0.6 kg/cm^2. We then combined the clay with the dough at our ratios of interest, adding food coloring to aid in tracking/identifying the materials and water to achieve a final indention hardness between 0.5 and 0.6 kg/cm^2, which we found to be a suitable hardness for 3D printing on our specific 3D printer. We present each clay-dough recipe, as well as the pure WH8 stoneware clay to benchmark against in Figure 5. We do not include any experimentation or characterization of the pure biomaterial dough because the dough burns away completely in the firing process.

Figure 4: Ingredients used to make clay-dough from left to right: corn flour, WH8 stoneware clay, vegetable oil, vinegar, wheat flour, food dye, and (not pictured) water.

3.2 3D Printing Clay-Dough

To test each clay-dough recipe, we 3D-printed cylinders with no bottoms using an Eazao Zero printer [40], which is commonly used for small-scale clay 3D printing. We had to find a balance between tuning the indention hardness of our recipes in Section 3.1 and tuning the printing parameters of the Eazao to successfully print the recipes. We arrived at our print settings (as well as indentation hardness for our recipes) through informal material tinkering and experience prototyping approaches [20, 49, 77, 89]. We also note that many of our printer settings were tuned for one printer. As each 3D printer is slightly different (e.g., some motors are more powerful, some printers have a sharper auger), we expect some of our settings to slightly vary on each printer.

For testing clay-dough recipes, we wrote a .gcode file to generate small cylinders, which are 30 mm tall with a diameter of 30 mm and a wall thickness of 1 mm. We used a 1.5 mm inner diameter nozzle at an extrusion rate of 1.2 mm of filament extruded per mm traveled, and a layer height of 1.0 mm. We used the same .gcode file and printer settings across all recipes to ensure that differences cataloged between each recipe could be confidently attributed to the behaviors and properties of the material itself. The more complex forms shown in Figures 1 and 2 were generated with a different cylindrical .gcode file which we provide the specifications of in Section 5.

3.3 Drying and Firing Clay-Dough

Once printed, all our small clay-dough cylinders went through a drying stage, followed by a two-step firing stage, which is the most common process followed in ceramics practices [30, 85]. We first dried all our clay-dough cylinders in a dehydrator set at 110°F (43°C) for 8 hours, to reach a "bone dry" state. It is important to dry clay before it is fired to reduce the chance of cracking.

Once dry, we fired the clay-dough cylinders first at a low temperature (bisque firing) and then at a higher temperature (glaze firing). We refer to temperatures by their *cone* value, which is used in ceramics to refer to kiln firing temperatures ranging from cone 022 (~1087°F or ~586°C) to cone 14 (~2523°F or ~1384°C) [30]. For our test cylinders, we first fired our clay-dough to cone 04 (1945°F or 1063°C), this firing stage typically takes 12 hours. At this bisque firing stage, the dough within the mixture burns away, while the clay within the mixture loses all of its water (through evaporation) and chemically transitions from *clay to ceramic.* Bisque firing is typically done to achieve a stronger and less porous material that is easier to glaze. Glazing is optional at this stage; we note samples that have been glazed.

Lastly, we fired our clay-dough to cone 6 (2232°F or 1222°C), this firing stage took approximately 8 hours. During this second glaze firing stage, the ceramic becomes more vitrified, meaning the ceramic becomes more like glass, gaining a crystalline structure that makes the material significantly stronger and non-porous [19]. We chose these cone values for firing clay-dough based on traditional mid-range clay firing values that are suitable for our WH8 stoneware clay [26]. In Figure 5, we showcase the 3D printed cylinders and shrinkage behavior of each clay-dough recipe at each stage of its life: wet, dry, bisque-fired to cone 04, and glaze-fired to cone 6. The color from the food dye disappears during firing, when the dough burns away.

3.4 Characterizing Clay-Dough's Properties

To gain insight into the shape-changing mechanics of the clay-dough and how clay-dough's other material properties vary between recipes and throughout the drying and firing process, we tested shrinkage, density, compressive strength, and porosity. We chose these four properties to test as they are often used in describing and benchmarking different clay materials in ceramic arts, materials science, and mechanical engineering [24, 25, 85]. These material properties (especially shrinkage) also hold valuable information for potential users regarding how to design artifacts made from clay-dough.

3.4.1 Shrinkage. We first conducted tests to understand the shrinkage behavior of each clay-dough recipe throughout the drying and firing process. For this test, we printed a set of five small cylinders (dimensions described in Section 3.2) made from each recipe. We then measured the height of the cylinders immediately after printing, drying, bisque firing to cone 04, and firing to cone 6. We then calculated percent shrinkage at each stage using Equation 1:

$$\text{shrinkage (\%)} = \left| \frac{\text{initial height} - \text{height after stage}}{\text{initial height}} \right| * 100 \quad (1)$$

Figure 5 (and Table 1 in Appendix A), shows the average % shrinkage of the five cylinders made from each clay-dough recipe at each stage. This test reveals that the 100% clay shrinks the least amount throughout every stage, resulting in a *14.61%* cumulative shrinkage once it is fired to cone 6; meanwhile, the 25% clay experiences the most shrinkage of the recipes, with a *41.33%* cumulative shrinkage once it is fired to cone 6.

3.4.2 Density. We also measured the mass and volume of the cylinders to calculate the average density of five samples after each round of drying and firing using Equation 2:

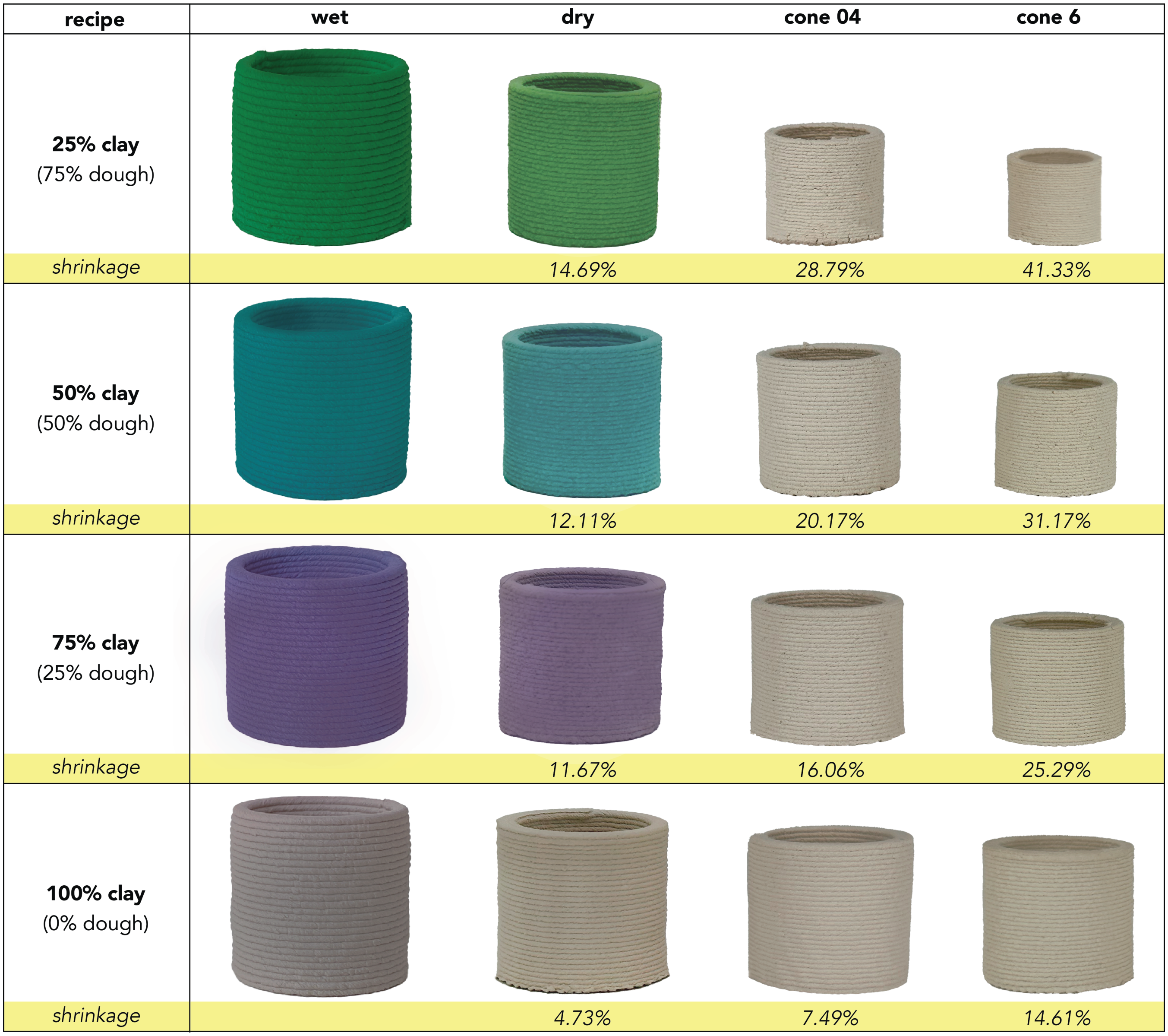

Figure 5: 3D printed cylinders of each clay-dough recipe shown at each stage in the drying and firing process. Each cylinder shown is associated with a percentage value that refers to the average amount that the cylinder has shrunken since it was printed (i.e., average cumulative shrinkage) (N=5).

$$\text{density} = \frac{\text{mass (g)}}{\text{volume (cm}^3\text{)}} \tag{2}$$

As shown in Figure 6 (and in Table 2 in Appendix A), we found that the 100% clay was the most dense, with each clay-dough recipe getting less dense as the amount of dough in the recipe increased. Moreover, we found that every material got less dense as it was dried and bisque-fired to cone 04; all the materials then got denser when fired to cone 6, indicating that the ceramic material became fully vitrified. It is worth noting that while the 100% clay and 75% clay recipes were densest after firing to cone 6, the 50% clay and 25% clay materials were densest before firing. This is due to the dough component of the material burned away. Though dramatic shrinking occurs in these materials, significant voids still remain. Glazing the materials with Shaner Clear [10] before glaze-firing to cone 6 also increased the density because the cylinders absorbed glaze. The density of the 25% clay recipe increased the most. We believe this is because the material was able to absorb a large amount of glaze due to its extreme porosity.

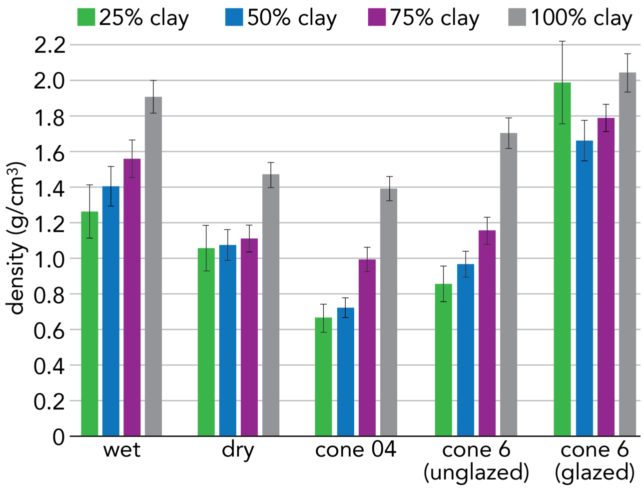

Figure 6: Average density in g/cm^3 (N=5).

3.4.3 Compressive Strength. We then ran uniaxial compressive strength tests based on the standard, ASTM C773 [5], for compressive strength testing of whiteware materials (e.g., clay, silica, and feldspar). We slightly modified the test sample shape dictated by the standard, instead of going with the standard solid cylinder, we tested hollow cylinders like those shown in Figure 5. Like the other tests, we tested five samples of each clay-dough recipe at each stage of the drying and firing process. For compression testing, we placed a cylinder sample in a universal testing machine set up with a 50-kilonewton force load cell, which compressed the sample at a rate of 10 mm/min. The machine compressed each sample for 120 seconds during which failure (i.e., cracking) occurred. We recorded the maximum force applied to each sample, which we then used in Equation 3 to calculate maximum compressive strength:

$$\text{strength (MPa)} = \frac{\text{maximum force (N)}}{\text{cross-sectional area (mm}^2\text{)}} \tag{3}$$

In Figure 7 (and Table 3 in Appendix A), we present the average compressive strength in MPa for five samples of each material. The results show that the strength of the dried clay-dough recipes (i.e., 25%, 50%, and 75% clay) are initially stronger than 100% clay. We note that this aligns with traditional ceramics practices that combine clay with organic materials such as paper to give the clay more strength during the drying process [30]. We see that the clay significantly increases in strength when bisque-fired to cone 04 and then fired to cone 6. Meanwhile, the clay-dough materials get weaker when fired to cone 04, but then stronger when fired to cone 6, which aligns with the results of our density tests. We also see that among the clay-dough materials, the 25% clay is consistently the weakest, while the 75% clay is the strongest across all stages in the process. When we glaze the materials between the two firing stages, we see a different pattern. While the glaze increased the strength of all the materials, the glaze only slightly increased the strength of the 100%, while it vastly strengthened the 25% clay, which became stronger than the glazed 50% clay. Again, we saw this pattern echoed in our density test.

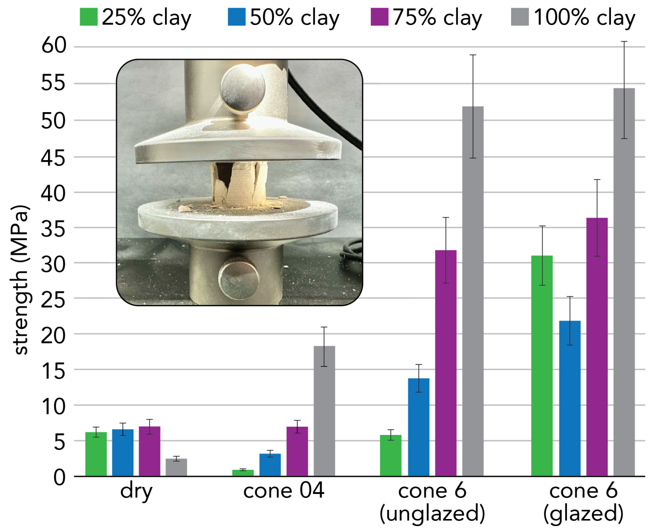

Figure 7: Compression testing setup and average compressive strength in MPa (N=5).

3.4.4 Porosity. For our final test, we measured the porosity of each recipe to gain insight into how much liquid they absorb as a fully matured/vitrified ceramic when fired to cone 6. Following a standard porosity testing procedure used in ceramics [85], we prepared five sample slabs (5 by 140 by 25 mm^3) of each clay-dough recipe. All the test slabs were dried, bisque-fired to cone 04, and then fired cone 6. We weighed each slab, then vigorously boiled them for five hours, after which we removed the slabs and weighed each one again. We calculated the average percent porosity using Equation 4:

$$\text{porosity (\%)} = \left| \frac{\text{initial slab mass} - \text{boiled slab mass}}{\text{initial slab mass}} \right| * 100 \tag{4}$$

As shown in Figure 8 (and Table 4 in Appendix A), porosity significantly increased with the amount of dough, with 100% clay having an absorbency of ~2.5%, while the 50% clay recipe had an absorbency of ~48%. We experienced difficulty creating a 25% clay slab; the material shrank so dramatically, that the slab began to

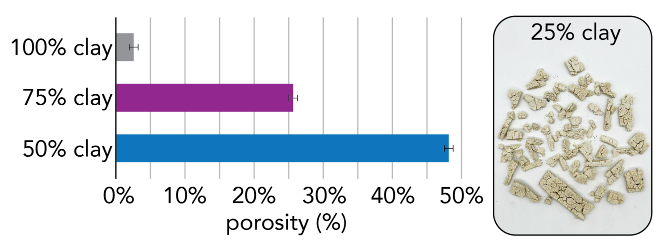

Figure 8: Average porosity of clay-dough recipes all fired to cone 6 (N=5). Porosity of the 25% clay recipe could not be determined because the slabs all cracked apart during testing.

exhibit cracks during firing. We were unable to obtain accurate porosity readings for this material due to the slabs completely breaking apart during the porosity testing. Figure 8 right shows the cracked pieces after boiling.

Our porosity results showcase an interesting property of clay-dough. Clay-dough samples are porous even when fully vitrified. In clay, porosity typically is correlated with vitrification [85]. The porous nature of the clay-dough materials also highlights the necessity for glazing our final forms—glaze reduces the water absorbency, thus improving the everyday usability of ceramic artifacts.

4 OUR MATERIAL-ORIENTED APPROACH

In this work, we take a *material-oriented approach* to creating ceramic forms with shape-changing clay-dough. To design a form, we begin by utilizing a *custom sketching and mapping guide* that takes inspiration from shrink rulers used to gauge how much the clay will shrink by ceramic artists [101], which can be found in Appendix B. In this approach, we 3D print the same starting cylinder (same .gcode) for all of our forms. We specifically chose a *cylinder* as our base form because it is an *easy form to 3D print* and it is a *key form used in traditional ceramics practices.* By 3D printing the same starting form every time, we also showcase how *clay-dough* and its unique affordances as a shape-changing material drive the creation of form rather than sculpting form by hand or 3D printing a form designed in CAD software. Our *material-oriented* approach to clay 3D printing is in contrast to typical CAD and CAM workflows associated with 3D printing that rely on the designer being fluent in a variety of software programs. In this alternative approach, *designers work entirely in the physical world*, designing forms for digital fabrication through sketching, hand-loading, and embodied material knowing.

We summarize our entire workflow for the material-oriented design and fabrication of clay-dough forms in Figure 9: (1) sketching and mapping a form to a pattern, (2) transferring the pattern onto a print tube, (3) preparing the materials, (4) loading the print tube, (5) 3D printing a cylinder, (6) drying, (7) bisque firing to cone 1, (8) glazing, and (9) glaze-firing to cone 6.

(1) *Sketching and mapping a form to a pattern.* We first envision a final form that is generally based on the form of a cylinder (i.e., our starting form). We follow our custom guide to draw a side profile of our envisioned form on the left "SKETCH" side. The guide provides lines that indicate what the radii of the final cylindrical form will be depending on each clay dough recipe's shrinkage. Based on the guide and our knowledge of clay-dough's material properties, we translate our sketch to each recipe—wider parts of the form are mapped to recipes with more clay, while narrower parts of the form are mapped to recipes with more dough. We then use the right "PRINT" side of the guide to arrive at out our final loading pattern.

(2) *Transferring the pattern onto a print tube.* Once the "PRINT" side of the guide is colored in with the mapped recipes, we cut it out and paste it onto the print tube attached to our extruder. The guide includes a ruler next to the design to help the designer know how much of each material is needed.

(3) *Preparing the materials.* Once our design is set up on our tube, we prepare the required clay-dough materials following the recipes in Section 3.1. We also added Amaco Velvet Underglaze [18] to color each clay-dough recipe, so that the green, blue, and purple colors show up in our final forms after they are fired. For each clay dough recipe, the amount of underglaze we incorporated correlated to the amount of clay incorporated; the amount of underglaze was 10% the mass of the clay (e.g., if we added 300 g of clay, we added 30 g of underglaze). Lastly, we made sure that each recipe reached a final indentation hardness of 0.5-0.6 kg/cm^2 to ensure a successful print.

(4) *Loading the print tube.* We then load the print tube with our desired clay-dough materials by following the marks on our customized guide, pressing the materials down with a stamper to align with the designated pattern, and removing air bubbles.

(5) *3D printing a cylinder.* Once the tube is loaded with our given design and attached to the printer, we 3D print a cylinder with 90 mm diameter, 200 mm height, and 4.5 mm wall thickness. This cylinder has a woven-like surface texture as each layer of the print consists of an oscillating path. This path structure enables us to print a larger and stronger form. We use the same printer parameters (e.g., printer speed) described in Section 3.2. However, we had to adjust our extrusion rate to 1 mm of filament extruded per mm traveled and our layer height to 0.5 mm to accommodate the larger-sized cylinders.

(6) *Drying.* We dry our printed clay-dough cylinders in a dehydrator set to 110°F (43°C) for 8 hours. We use a dehydrator to ensure uniform drying from all sides, which we observed helps prevent cracking. At this point, the cylinder begins to shrink due to water evaporation.

(7) *Bisque firing to cone 1.* Based on our tests from Section 3, we found that bisque firing to cone 04 led to very delicate ceramics that were hard to glaze without breaking. Accordingly, we increased the temperature of our bisque fire to cone 1 (1945°F or 1063 °C) for easier glazing. At this point, the biomaterial dough has burned away within the cylinders, leaving behind the clay which has undergone its initial chemical transformation into ceramic.

(8) *Glazing.* We then glaze all our final forms with Shaner Clear glaze [10]. This glaze goes on opaque, but turns completely clear when fired. It does not impact the color of the final forms, however, it slightly alters the surface texture, making the ceramics feel smoother and more glass-like. It also gives the typically matte ceramics a shiny finish.

(9) *Glaze Firing to cone 6.* Lastly, we glaze fire our clay-dough forms to cone 6 (2232°F). Once fired, the form has fully vitrified, meaning that it has shrunk as much as it can and has reached its final maturity from a chemical perspective. At this point, the final form is reached (reflecting the initial sketch) and the ceramic artifact is ready for use.

Figure 9: Material-oriented approach for creating ceramic forms via shape-changing clay-dough. (1) We sketch out our envisioned final form and map it to a material loading pattern using our custom guide, (2) which we transfer onto a print tube. (3) We then prepare the necessary materials and (4) load them into the tube following our guide. (5) Next, we 3D print our basic cylinder and (6) let it dry. (7) Once dry, we bisque fire the cylinder, then (8) dip it in a clear glaze, and (9) lastly glaze fire it to cone 6, where it reaches its final form and is ready for use.

5 DESIGN SPACE

Following our material-oriented approach, we present a design space of forms that emerged from the same 3D-printed cylinder. We leverage the precision and reproducibility that 3D printing affords for our initial cylindrical forms to highlight that the final forms are directly driven by clay-dough’s shape-change as opposed to direct actions taken by the machine or human maker. We organize our design space via the complexity of the print loading patterns, which were dictated by our custom guide.

5.1 Simple Loading Patterns

Our first set of exploratory forms were directly inspired by the basic divisions we provide on our custom guide that break up our print into halves, thirds, and quarters. The forms in Figure 10 demonstrate how we can develop a wide array of results through simple loading patterns. We note that we do not test every possible variation of material loading pattern, instead providing a few forms for each division as a generative starting point for other designers to take inspiration from.

5.1.1 Halves. When dividing our print in halves, we were limited to only loading two materials resulting in forms that were either small on the bottom and large at the top (10a and 10b) or large at the bottom and small at the top (10c). Through some experimentation, this simple print pattern taught us that we cannot print 25% clay directly next to 100% clay because the drastic shrinkage of the 25% recipes causes a crack or fold to propagate at the transition between the two materials. These forms also brought attention to how clay-dough not only shrinks in radius, but also shrinks in height—10a and 10b are the same in their overall shape, but are vastly different in height. 10a is composed of 25% clay on the bottom and a 50% clay on the top, resulting in drastic shrinkage in radius and height, while 10b is composed of a 50% clay on the bottom and a 100% clay mixture on the top, resulting in a considerably larger form. Note that the top half of 10a is the same size as the bottom half of 10b and the top half of 10c.

5.1.2 Thirds. For thirds, we experimented with implementing three materials. With a third material, we could successfully transition from 100% clay to 25% clay by adding 50% clay between the two materials as seen in 10d. We also experimented with only two materials in 10e, which shows 25% clay sandwiched in between the 50% clay. From 10e, we gained insight into how the loading order of the materials impacts the form. As demonstrated, the printer creates a steady ombre when transitioning from a denser material (50% clay) to a less dense material (25% clay), leading to a subtle change in form. However, when transitioning from a less dense material (25% clay) to a denser material (50% clay), the change is very quick, leading to a more dramatic change in form.

5.1.3 Quarters. By diving our print into quarters we had the ability to print forms that utilize all four materials, leading to more complex forms such as the oscillating profile curves of 10f. Quarter divisions

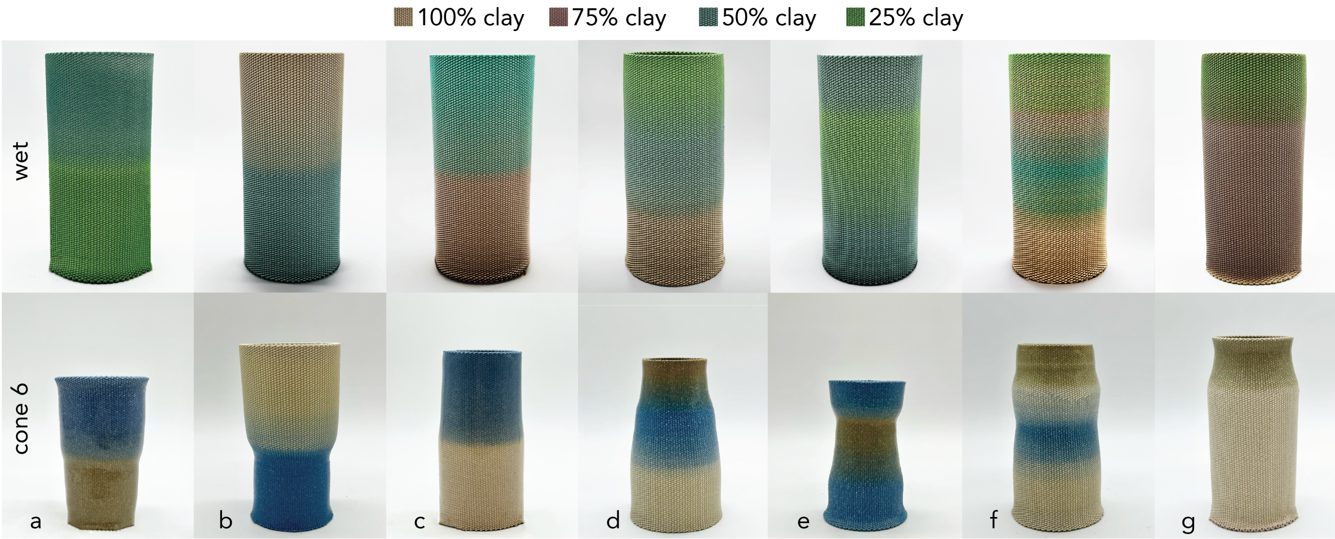

Figure 10: Forms created by printing the cylinder in halves, thirds, and quarters. (a) 25% clay on bottom - 50% clay on top. (b) 50% clay on bottom - 100% clay on top. (c) 75% clay on bottom - 50% clay on top. (d) 100% clay on bottom - 50% clay in middle - 25% clay on top. (e) 50% clay on bottom - 25% clay in middle - 50% clay on top. (f) 100% clay on bottom - 50% clay on bottom middle - 75% clay on top middle - 25% clay on top. (f) 75% clay on bottom three quarters - 25% clay on top quarter. Note: all images are all to scale.

also lead to a significantly wider variety of loading patterns that can be potentially printed. In 10g we demonstrate another simpler form with the bottom three quarters consisting of 75% clay and the top quarter consisting of 25% clay; this form was interesting because we found that if we printed it in the opposite direction with the 25% clay on the bottom quarter, failure would occur due to the 25% clay not being able to hold the weight of denser materials.

5.2 Complex Loading Patterns

We then experimented with more complex patterns that did not adhere directly to the divisions displayed on our custom guide. Instead, we focused on translating more complex sketches into a loading pattern that accurately prints the envisioned form, as shown in Figure 11. When sketching and translating these forms into load patterns, we had to consider the constraint of not being able to put 25% clay next to 100% clay. Accordingly, to create dramatic ins and outs like 11b, we used a small amount of 50% clay or 75% clay to make the transition more manageable.

5.3 Randomized Loading Patterns

Our final exploration utilized leftover waste materials from all of our other prints to create random forms in Figure 12. We filled our print tube with unused materials that got mixed with each other. We then loaded these mixed materials into the tube in a random way, without sketching and translating an envisioned form. Unlike the previous forms, which had distinct divisions of the materials stacked horizontally on top of each other, our randomized materials were mixed together in often unknown ways, often resulting in materials being stacked vertically next to each other in the tube. This vertical loading of materials meant that new recipes were created in real-time in our printer, with unknown quantities of each material mixing together as they went through our extruder, resulting in new ratios of clay-to-dough. These prints were incredibly fun to watch as they printed because the pattern of materials revealed was unexpected. The resulting forms fully demonstrate the *agency of the clay-dough as the active driver of ceramic form.*

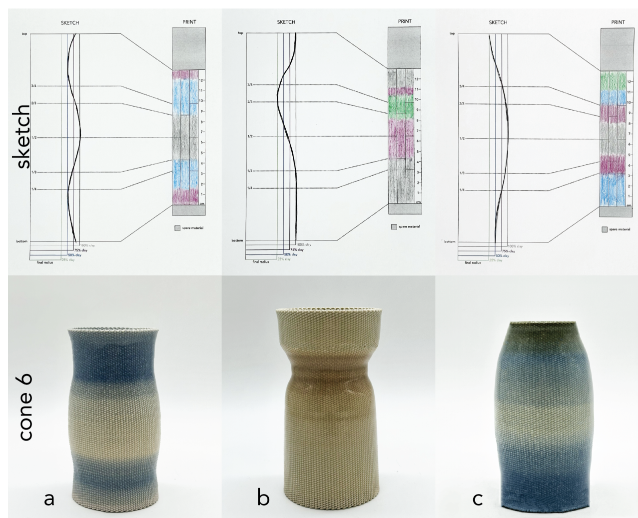

Figure 11: Forms derived from more complex sketches and loading patterns: (a) form made with 75% clay, 50% clay, and 100% clay, (b) form made from 100% clay, 75% clay, and 25% clay, and (c) form made with 50% clay, 75% clay, 100% clay, and 25% clay.

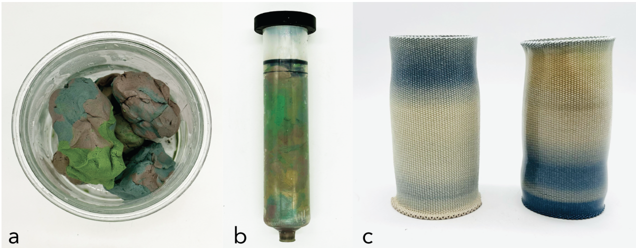

Figure 12: (a) We collected leftover clay-dough material from other prints that got mixed together. (b) We loaded up print tubes randomly with these scrap materials. (c) The final forms produced were unpredictable and surprising, as they were not actively designed like our other forms.

6 APPLICATIONS

We specifically chose to design and demonstrate our material-centered approach through cylinders in Sections 4 and 5, because of the simplicity of their form and their ability to print, which highlights how we can arrive at complex, 3D printed forms solely through clay-dough's shape change rather than modeling software. Stemming from these explorations, we arrived at the following application directions that extend past cylindrical forms to illustrate other ways shape-changing clay-dough can be implemented by HCI practitioners in the future.

6.1 Transforming 2D Prints into 3D Forms

Drawing inspiration from the simplicity of the cylinders and their ability to highlight the dramatic shrinkage of clay-dough, we generated .gcode for a simple square plate with the intention of designing a form that could transform from 2D to 3D. This concept took inspiration from past work that explored shape-changing slabs that folded into 3D forms by layering different types of clay such as stoneware, earthenware, and porcelain [2]. The resulting artifact in Figure 13 stays as a flat plate when printed entirely from clay, however, when printed with clay-dough, the plate slowly curls into a bowl-like form. To create this application, we loaded our print tube with 100% clay (printed on the bottom of the plate), followed by a small amount of 75% clay (printed in the middle), and 50% clay (printed on the top of the plate). This intentional process of purposely loading materials in an intended pattern followed our material-oriented approach. Once printed and dried, the 50% clay began to shrink, thus pulling the corners of the plate upward and into itself, which dramatically changed the overall form. Through this application, we highlight a direction for future work where the intentional utilization of clay-dough can dramatically transform simple 2D printed structures into complex 3D artifacts.

6.2 Deforming More Complex Artifacts

We then explored the impact of clay-dough on more complex designed forms. In Figure 14 we showcase: a wide *bowl*—chosen for its use as another common form in ceramics, the *Stanford Bunny*—chosen for its complex geometries and use as a test model in computer graphics [103], and a *teapot*—chosen for its use as a test model in computer graphics and as an artifact that has historically been

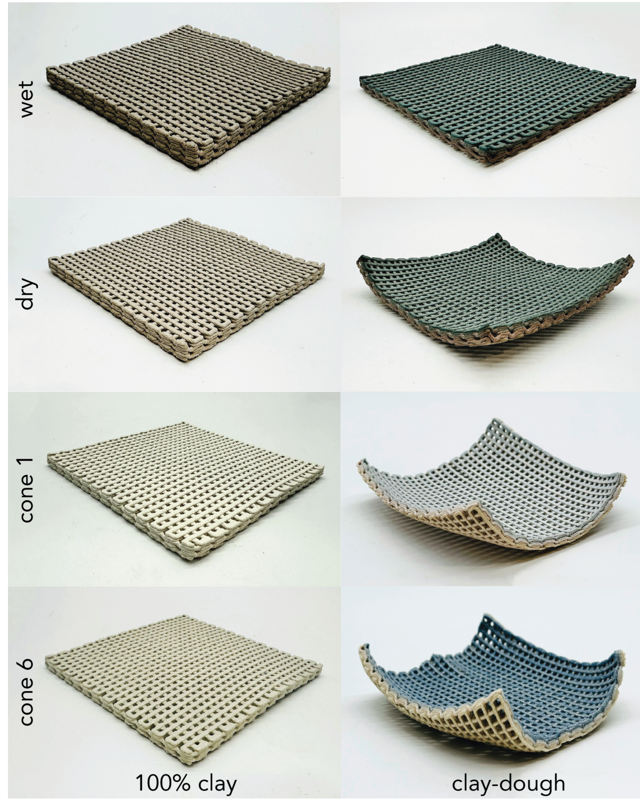

Figure 13: A plate that changes shape into a bowl due to clay-dough's shrinkage.

used to display the craftsmanship of the ceramicist [17, 82]. All three artifacts were designed without a specific loading pattern or final form in mind. Subsequently, materials were loaded in relatively random amounts and patterns, with only a general sense of how much material in total would be required for the print (including material for printed supports removed after printing). For comparison purposes, we printed each artifact in 100% clay, and then printed another version in a random pattern of clay-dough. As seen in 14a, several variations of the bowl were printed, resulting in forms that are both taller and flatter than the designed form (i.e., the form printed in 100% clay). Meanwhile, the clay-dough bunny in 14b cracked along its backside due to the density of the head (printed in 100% and 75% clay) compressing the legs printed in 50% clay. The teapot in 14c was mostly printed from 50% clay and 25% clay resulting in a significantly smaller form that emphasized the belly of the pot and the narrowness of the top where the lid sits, which shrunk so much that the lid was not able to securely fit on top. The resulting ceramics present uniquely deformed versions of the original artifact that reflect the agency of both the human maker who designed the CAD model and the clay-dough material that controlled the final physical form through shrinkage.

In the future, we imagine designing corresponding sketching and mapping guides for some of these more complex, non-cylindrical forms to assist in conceptualizing and printing with clay-dough's shrinkage in mind. However, we note that these physical guides become exponentially more difficult to design accurately as the complexity of the printed form increases. Accordingly, we also see a future direction focusing on the development of software within Grasshopper and Rhino to model the final form an artifact takes after being dried and fired based on the clay-dough materials used in the print.

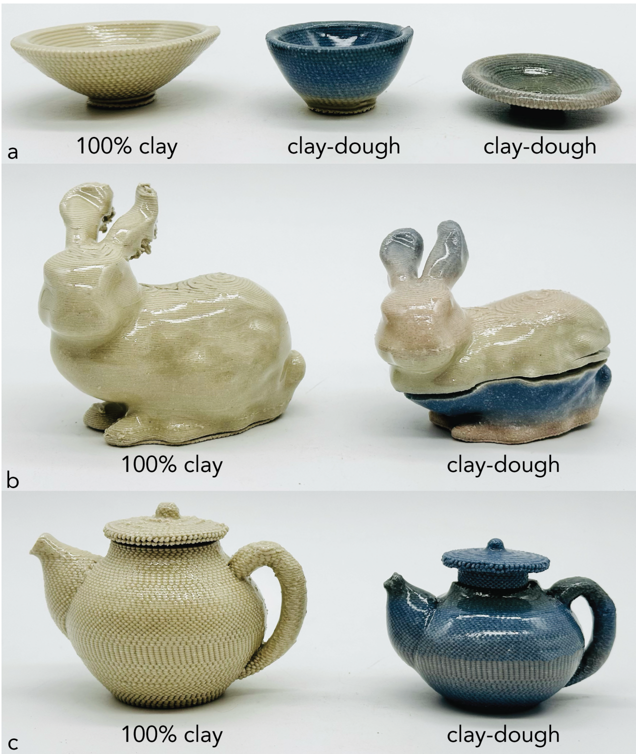

Figure 14: (a) Bowl, (b) Standford Bunny, and (c) Teapot forms printed in 100% clay and printed in a random pattern of clay-dough.

6.3 Using Clay-Dough Recipes Separately

Lastly, we see each clay-dough recipe being used on its own rather than in combination with other recipes to create compelling applications. For instance, we could create objects that nest perfectly together by printing the same form with each clay-dough material separately, such as our initial test bowls (Figure 3) shown nested together in Figure 15. The uniform shrinkage allows the bowls to appear almost identical while being at different scales.

Utilizing the 25% clay recipe on its own also provides a range of potential applications. When compared to un-fired 100% clay, the un-fired 25% clay recipe is significantly stronger and less dense, which could be beneficial for printing forms with dramatic overhangs. We saw this when printing the Standford Bunny in Figure 14b, where the ears drooped slightly more when printing with 100% clay than with the clay-dough materials. However, more testing is required to validate this application space. The high shrinkage rate of the 25% clay recipe could also be leveraged to make ceramic "Shrinky Dinks" [47]. For this case, we envision printing artifacts that would be impossible to print at their intended small scale on a large scale and then shrink them down to the desired size.

Figure 15: Initial test bowls nested together.

7 DISCUSSION

7.1 Potential Users

We envision clay-dough in parallel with our material-oriented approach benefiting several different user communities. First, we see this benefiting students, artists, designers, and HCI practitioners who do not have fluency in CAD or CAM softwares, but are interested in engaging with 3D printing. Our material-oriented approach keeps the design process entirely in the *physical realm*, which provides a more familiar and less intimidating design workflow; especially for ceramic artists who already have a deep understanding of ceramic materials, as well as kids who have minimal (if any) experience with digital technologies, but might be familiar with a craft materials such as play-dough. Accordingly, we believe this approach inhabits an important conceptual space in digital fabrication research and the broader HCI community as *a making process that employs digital fabrication but does not require computer-based design*. Workflows that remain in physical space—enabling people to continue to work with their hands, uninterrupted by computer-based tasks—have a lower barrier of entry and other distinct benefits that may inspire different groups of people (people who would not typically engage in 3D printing) to adopt and experiment with digital fabrication.

On top of acting as a potentially profound means of entry to digital fabrication for several user communities, we find that our material-oriented approach still holds use for HCI practitioners who have experience with CAD and CAM softwares and 3D printing. Most of the authors on this paper have extensive experience with digital fabrication, yet found that the material-oriented approach inspired new physical forms and ways of thinking about fabrication as exemplified by the applications in Section 6 that utilized more complex CAD designs. Most importantly it brought all authors closer to the materials and sensitized us to the importance of materiality and material agency in digital fabrication, which we find is often overlooked. As such, we see our approach challenging digital fabrication experts to shift perspectives in their design workflows by *engaging with materials in a more intimate, mindful, and generative way.*

7.2 Design Considerations and Limitations

As we explored the potential ceramic forms we could create through clay-dough's shape-change, we discovered several limitations that we had to consider in our design process. Most notably, we found that we could not print the 25% clay next to the 100% clay because the shrinkage of the 25% clay is so dramatic that it caused the form to crack or fold at the material transition point (Figure 16, left and middle). The dramatic shrinkage of the 25% also made it incredibly delicate to work with as it would occasionally crack when fired, especially during bisque-firing. We also found that printing a small quantity of the 25% clay that shrinks significantly at the bottom of a print and then printing denser materials that do not shrink as much (like the 75% clay or 100% clay) on the top would often lead to structural collapse (Figure 16, right). In fact, the height and weight of the wet printed cylinders caused most of the cylinders to compress and slightly flare out at the base in order to stay standing. We note that the flared bases of the cylinders only got more pronounced throughout the drying and firing process as the material at the base had to fight against the friction of whatever surface it was placed on (e.g., a shelf in the kiln), thus slowing down shrinkage and sometimes introducing small cracks.

Figure 16: Left: a form that cracked when transitioning directly from 100% clay on the bottom to 25% clay on the top. Middle: a form that folded on top of itself when transitioning from 25% clay to 100% clay on the top. Right: a form that collapsed onto its side due to the 25% clay being on the bottom and trying to hold up denser materials. Note: these were some of our initial tests that were based on shorter cylinders.

Another challenge we faced was with the Amaco underglazes [18] that we added to our clay-dough materials for the final forms. While the blue underglaze led to a vibrant blue ceramic after firing, the green underglaze led to a muddy olive color that looks almost brown. Meanwhile, the purple underglaze was barely perceptible, being a slightly warmer cream color in comparison to the white/tan 100% clay that did not have any underglaze. In the future, we plan to do further testing to ensure underglaze colors are of similar intensity in the final fired pieces.

We also struggled to achieve high material resolution in terms of transitioning from one material to the next in our prints. This is not necessarily a limitation of the material but a limitation of our clay 3D printer. Our printer has an auger mechanism that mixes the material to push it out of the extrusion head. This means that the transition from one material to another occurs as an ombre over the course of many print layers. Resolution is further exacerbated by how little material is used for each layer, which makes it incredibly difficult to load a print tube precisely enough to print a new material on each layer. This limitation also impacts the size of forms that we can print to successfully exhibit shape-change. The forms we print should ideally require a significant amount of material within the print tube so that multiple materials can show up in the print, thus leading to shape-change.

7.3 Unmaking through Shrinkage

Through the unintentional cracking of many of our forms (often due to the significant shrinkage of the 25% clay recipe), we became more sensitized to the chemical processes the clay-dough goes through when it dries and is fired. When we fire clay-dough, all the dough (i.e., the corn-flour-based biomaterial) gets completely burned away, which leaves more room between each molecule in the atomic structure of the material mixture. By burning away the organic molecules of the dough into gasses, the clay molecules left behind must move closer together to reorder themselves into stable crystalline structures causing visible shrinkage [19]. We can view this process of firing (and thus shrinking) clay-dough as a form of *unmaking*, in which we quite literally unmake the molecules of the biomaterial dough to remake the molecular lattice structure of the remaining ceramic material.

Song and Paulos introduce the term "*SHRINK*" as an unmaking operation that defines a decrease in size and volume [92]. Through our extensive experiences with clay-dough's shrinkage, we extend the design vocabulary for unmaking presented in [92] by proposing four new terms that more precisely describe the distinct operations of deformation and destruction caused by shrinkage:

- *SQUEEZE* — to shrink or bend inward from exterior surfaces
- *SCALE* — to shrink or expand uniformly in overall volume
- *FOLD* — to bend over onto itself without cracking or splitting
- *COLLAPSE* — to fall over without cracking or breaking apart

Squeeze is best demonstrated by the vessels in Figures 10e and 11b that have a distinct bottleneck, where the vessel dramatically shrinks inward before flaring out again, providing a distinct form. *Scale* is most distinctly demonstrated through the nested bowls in Figure 15 where the forms are uniformly shrunken down by using each clay-dough material separately. *Fold* and *collapse* were inspired by the failed clay-dough tests in Figure 16, where dramatic shrinkage led to structural failures that were distinct from "cracking", "splitting", or "sagging" [92]. We envision celebrating and leveraging these operations of unmaking caused by clay-dough's shrinkage in the future to create Auto-Destructive Art [68] or destructive artifacts that purposefully fold, squeeze, or collapse into new ceramic forms. In appreciating these aesthetics of destruction, we position clay-dough amongst the longstanding tradition of *wabi-sabi* in ceramics [102], in which imperfections are honored for revealing the "voice" of the material and our lived experiences with the artifact.

On a more conceptual level, we can think of shrinkage (and more broadly shape-change) as *unmaking* [64, 71], where the original form of a material is *un*made and then *re*made into a new form. As the material evolves through different forms (and often functions that accompany the form), we see the material taking on different "lives" across timescales as showcased by the plate that transforms into a bowl in Figure 13. We speculate on a scenario in which the artifact could be used at each stage in its drying and firing process—using the artifact as a plate once dry, as a shallow dish once fired to cone 1, and as a bowl once fired to cone 6. As all of our ceramic forms took on multiple "lives" through each stage of the drying and firing process, we learned to embrace the *transience* [102] and *ephemerality* [39] of the forms, thus finding the beauty in the temporal experiences and interactions with the artifact before it transitioned into a new stage in its life. We find that the temporal nature of unmaking and remaking a material's form applies to all shape-changing interfaces. By more broadly positioning *shape-change as a mode of unmaking*, we speak to a fundamental shift in design values that could strengthen the link between novel material development and more intentional making/using practices.

7.4 Navigating Control and Agency

In this work, we highlight clay-dough as an agent in the creation of ceramic artifacts by developing a material-oriented workflow. In traditional ceramic practices, the human maker controls the form of the ceramic, most often controlling clay through physical actions/touch. In this instance, the maker and material are engaged in conversation, where the form of the material responds to the maker's movements and the maker adjusts their movements according to the material's form; the final form reflects both the agency of the maker and material [13, 36, 55]. When 3D printing clay, the form of the clay artifact is designed by the human maker in CAD or CAM software, however, the machine physically controls the material rather than the human hand. In this instance, the maker is in conversation with both machine and material [35], having to adjust printing parameters such as extrusion speed to adjust for material inconsistencies and changes in pressure within the machine or even having to act as a physical support for the material [17] to arrive at the envisioned final form.

In this work, we attempt to reorganize the roles maker, machine, and material play in controlling the final form of a 3D printed ceramic artifact. We do so by embracing clay-dough as the primary agent engaged in the physical action of forming (rather than the maker or machine). As such, clay-dough itself destabilizes the typical relations between maker-machine-material in the 3D printing process. While we as the makers learn to anticipate (and design with) the physical actions clay-dough exhibits when it changes its shape, clay-dough will ultimately form in its own way, resulting in unexpected geometries (like the vessel sloping unevenly in Figure 9) and failures (like in Figure 16). Clay-dough's agency also manifests in the test cylinders in Section 3.4, where there are notable error values in average shrinkage, density, and strength, potentially caused by differences in the material itself, how the material printed (e.g., the pressure within the printer impacting material extrusion rates), and how the material responded to each step in the drying and firing process. We further embrace the *performative nature* [8] of clay-dough's unexpected shape-change through our randomized prints in Figures 12 and 14, which emphasize clay-dough as an active designer of the final ceramic form.

Clay-dough's material agency in controlling form is also what enables us as human makers to avoid using any modeling or slicing software. We let go of digital control and opt for a less precise, but more intimate by-hand method that relies on our *embodied understanding* of the material and its shape-changing mechanics. Because we devoted extra time to gaining a deep understanding of clay-dough properties and affordances, our material-oriented design approach, exploratory design space, and applications unfolded in a very natural way that was clearly informed by the clay-dough. As such, we found that clay-dough was our main guide in the overarching design process; which reminds us of the growing trend in HCI that is focused not only on material-driven design [9, 59], but the broader importance of material experiences [49, 79] and materiality [80, 88, 104] in designing interactive, tangible artifacts.

With this being said, we still recognize that our goal as human designers is often to create artifacts that fit our pre-determined vision, and thus we still exert a level of control over both machine and material in the making process. However, by *designing-with* [109] the clay-dough's physical actions at the forefront of the process, rather than designing to strictly control the clay-dough's form, we make steps towards reorganizing structures of control and diminishing existing hierarchies that exist between makers, machines, and materials.

8 CONCLUSION

In this paper, we introduce *clay-dough*, a new 3D-printable, shape-changing ceramic material that extends the growing library of interactive, morphing materials in HCI. We offer a material-centered exploration of clay-dough, that began with an in-depth characterization of clay-dough's shrinkage, density, strength, and porosity. Based on these tests, we developed a material-oriented design approach and workflow for creating clay-dough artifacts that change form based on shrinkage. This fed into a design space of forms based on cylinders that leverage clay-dough's unique material properties and shape-changing mechanics that further inspired a collection of other applications. Through this work, we learned to celebrate shrinkage as a modality of shape-change and clay-dough as an interactive design material.

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A MATERIAL CHARACTERIZATION

We provide data tables 1-4 supplement Figures 5-8.

Material	Dry	Cone 04	Cone 6 (Unglazed)
25% Clay	14.69 ± 0.26	28.79 ± 0.28	41.33 ± 0.48
50% Clay	12.11 ± 0.21	20.17 ± 0.57	31.17 ± 0.30
75% Clay	11.67 ± 0.69	16.06 ± 0.78	25.29 ± 0.33
100% Clay	4.73 ± 0.17	7.49 ± 0.21	14.61 ± 0.15

Table 1: Cumulative Shrinkage in % Height Lost (N=5).

Material	Wet	Dry	Cone 04	Cone 6 (Unglazed)	Cone 6 (Glazed)
25% Clay	1.27 ± 0.06	1.06 ± 0.05	0.67 ± 0.03	0.86 ± 0.04	2.01 ± 0.10
50% Clay	1.40 ± 0.11	1.08 ± 0.09	0.72 ± 0.06	0.97 ± 0.08	1.66 ± 0.13
75% Clay	1.56 ± 0.11	1.11 ± 0.08	0.99 ± 0.07	1.16 ± 0.08	1.75 ± 0.12
100% Clay	1.91 ± 0.10	1.47 ± 0.07	1.39 ± 0.07	1.71 ± 0.09	2.05 ± 0.10

Table 2: Density in g/cm^3 (N=5).

Material	Dry	Cone 04	Cone 6 (Unglazed)	Cone 6 (Glazed)
25% Clay	6.06 ± 0.55	0.80 ± 0.10	5.91 ± 0.63	31.03 ± 2.96
50% Clay	6.59 ± 1.05	3.04 ± 0.33	13.84 ± 2.22	21.78 ± 3.64
75% Clay	6.97 ± 1.13	6.93 ± 0.85	31.57 ± 5.28	36.15 ± 4.68
100% Clay	2.62 ± 0.41	18.35 ± 2.89	51.53 ± 6.22	54.40 ± 7.04

Table 3: Maximum Compressive Strength in MPa (N=5).

Material	Cone 6 (Unglazed)
25% Clay	cracked into pieces
50% Clay	48.26 ± 0.49
75% Clay	25.35 ± 0.60
100% Clay	2.49 ± 0.64

Table 4: Porosity in % Weight Gained (N=5).

B CUSTOM GUIDE

We provide a blank version of our custom setting and mapping guide in Figure 17. This is the guide used in Sections 4 and 5.

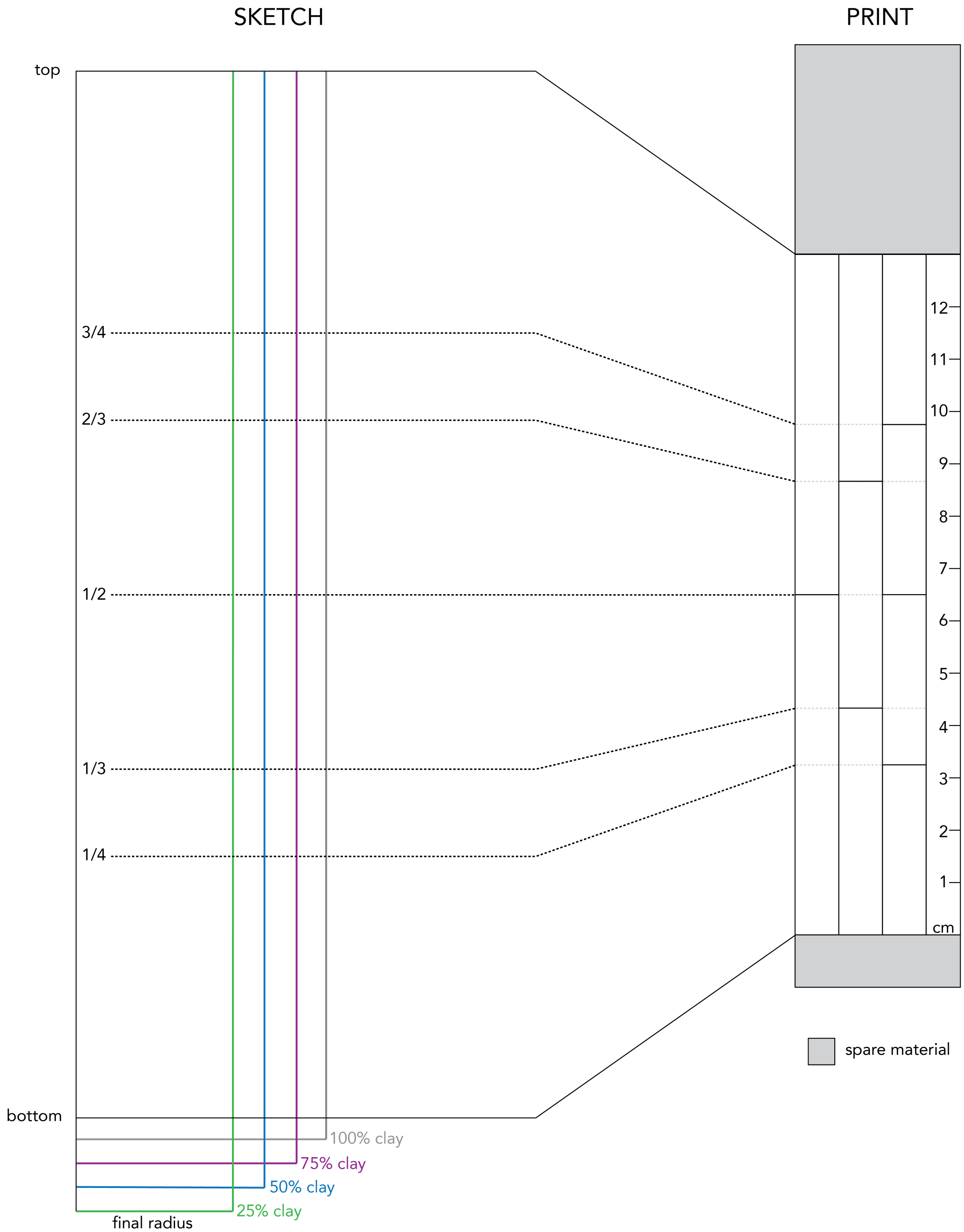

Figure 17: Custom guide for sketching cylindrical ceramic forms and mapping the envisioned shrinakge and deformation to a material loading pattern.