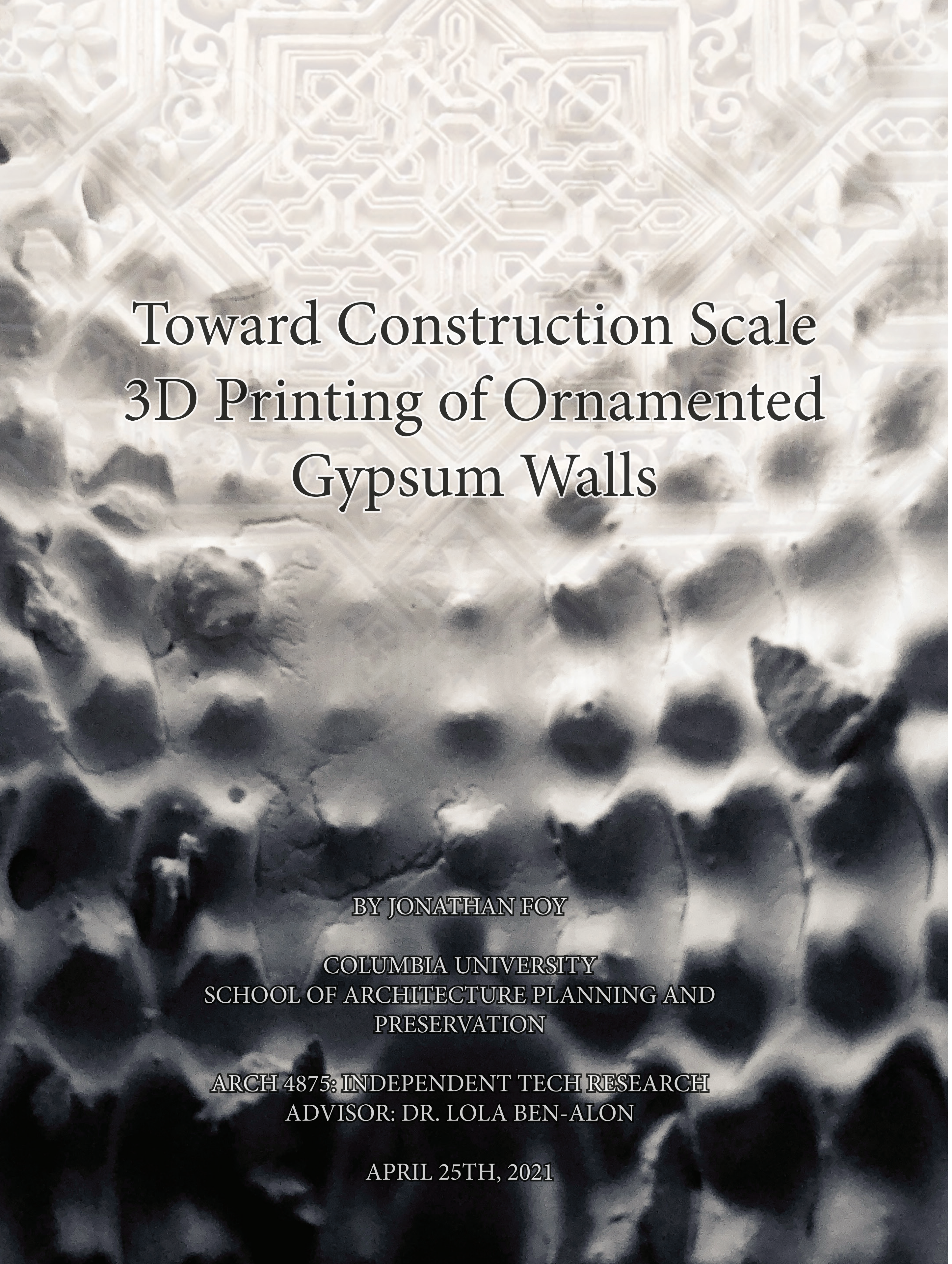

Toward Construction Scale 3D Printing of Ornamented Gypsum Walls

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Abstract

Verifying the printability of gypsum plaster composites via 3D robocasting is at the center of this investigation. A-hemihydrate gypsum, calcium carbonate, crystalline silica, polycarboxylate, hydroxypropyl methyl cellulose, and starch ether in parallel with varying proportions of kaolinite and plaster retarder composed the ingredients of the gypsum plaster composites used in this study. Rheological properties were measured. Curing times were observed in open air as well as sealed conditions where certain mixtures were extrudable in excess of 72 hours. The final printed mixture which included a small amount of kaolinite and excluded plaster retardant showed quality in adherence to shape and adequate setting time. However, unlike the best performing experimental mixtures, this sample cured shortly after completion of the print. Gypsum plaster composites have demonstrated potential for use in 3D robocasting. Moreover, these mixtures broaden the application of gypsum plaster printing in architecture and construction toward durable ornamented forms and large-scale manufacturing.

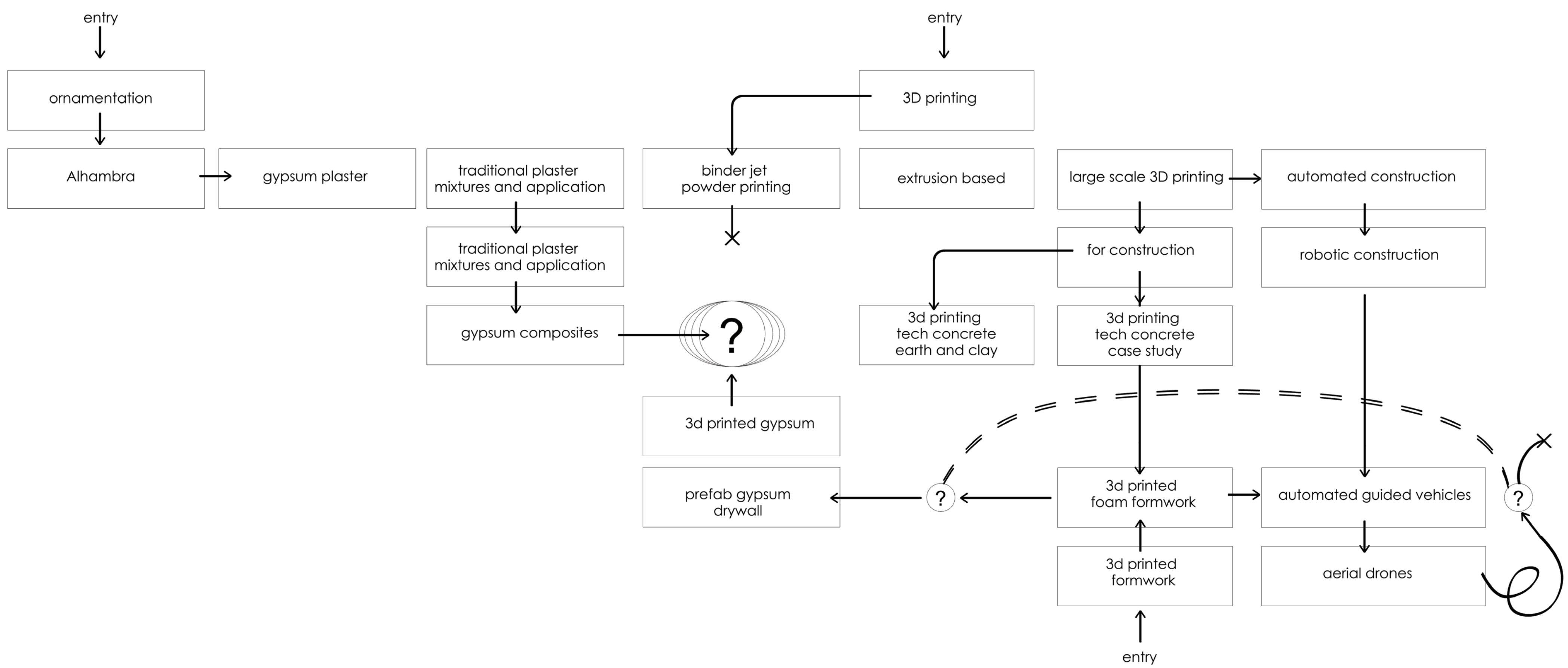
SAMPLE OF SOLUTION 01: BASED ON LIU ET AL. STUDY

1. Introduction

Gypsum plaster powder: calcium sulphate hemihydrate, know as bassanite and plaster of Paris is rarely printed by way of 3D robocasting due to its material behavior and curing process(Liu et al., 2018). The success of these experiments not only opens a way toward administering this material in construction-scale 3D printing, but also presents a possible alternative for creating intricately crafted plaster motifs through an additive manufacturing processes for application in design and architecture.

In terms of construction-scale 3D printing, concrete has been the most thoroughly researched material. It is extruded at scale by way of contour crafting (Lublasser et al., 2018), a cousin of 3D robocasting. Clay and soil composites are also very frequent in the literature. Another method gaining momentum is the on site printing of habitable buildings by automated guided vehicles using polymer-foam molds supporting freshly poured concrete (Lublasser et al., 2018; Subrin et al., 2018).

With regard to the 3D printing of ornamented plaster motifs, plaster of Paris, which transforms into gypsum when hydrated, is most often printed using binder jet technology (Yuvaraj et al., 2021). This method, while being very accurate and detailed, is inefficient, the green strength of the finished plaster is significantly weaker than the traditionally molded alternative; and it is not feasible for construction scale. The binder jet method of printing is most often utilized in medicine, bone grafting, and dentistry; it is also used in art and other creative fields(Lowmunkong et al., 2009).



In the past three years there has been research out of Southeast University in China 3D robocasting gypsum-based materials (Liu et al., 2018); The extent the material has been studied compared to concrete and clay is negligible. Moreover, the focus of these studies has been material durability and the quality of crystallization, not ornamentation and craft. This presents an opening for further examination of this method using commercially available materials and equipment.

The tools Liu et al. employed in their research were relatively duplicable using a 3D potterbot. Although this machinery is designed for 3D printing clay, altering the mechanical properties of a calcium sulphate hemihydrate-based solution as Liu et al. had done in their study, might improve mechanical suitability. Moreover, since a 3D Potterbot was the chosen machinery, experimenting with clay additives was considered for improving the compatibility of the plaster with the equipment.

2. Literature Review

One of the catalysts of this examination was an interest in how components of a 3D printed building made from gypsum plaster are prefabricated rather than printed on site. Manual means of assembling walls with prefabricated components are preferred (Furet et al., 2019). This presents an underutilization not only of automated technology, but also the freedom of form and material intricacy that additive manufacturing, in concept, should allow (Zou et al., 2020). Concrete and

S.01: Original Solution Based on Liu et al. study	WT% (by mass of gypsum)	Weight (g)	alt.
DAP Composite	100 wt%	100	0
Polycarboxylate (PC)	0.20 wt%	0.2	0
Hydroxypropyl Methyl Cellulose (HPMC)	0.40 wt%	0.4	0
Starch Ether (SE)	0.20 wt%	0.2	0
Kaolinite	0 wt%	0	0
USG Retarder	0 wt%	0	0
Water	22 wt%	22	0
Total		122.8	-
Result: Not Printable			

S.02	WT% (by mass of gypsum)	Weight (g)	alt.
DAP Composite	100 wt%	100	0
Polycarboxylate (PC)	0.2 wt%	0.2	0
Hydroxypropyl Methyl Cellulose (HPMC)	0.40 wt%	0.4	0
Starch Ether (SE)	0.20 wt%	0.2	0
Kaolinite	0	0	0
Retarder	0	0	0
Water	50 wt%	50	+28g
Total		150.8	-
Result: Not Printable			

earth materials dominate the literature of construction-scale 3D printing (CS3DP). There is little available information on gypsum. Thus the potential for applying methods used in concrete and soil for forming and scaling up gypsum plaster is an avenue of discussion.

Prefabricated components are considered only in the context of on-site robotic assembly methods; that is to say, alternative automated additive processes in construction will not be discounted. An overview of the prevalent and progressive methods of 3D printing gypsum plaster is a subject of focus. The historical and contemporary application of gypsum plaster on walls and the potential for mechanization of these processes is also explored.

CS3DP is a widely discussed method of construction that generally centers on two material groups; earthen materials like soil composites and clay on one side, concrete on the other (Melenbrink et al., 2020). Additive manufacturing by way of contour crafting (Lublasser et al., 2018) is the predominant method of scaling these materials, though it is not the only one attempted. Furet et al., 2019 has built a structure using polyurethane foam as both a formwork to cast a concrete pour, and a permanent insulation. However Furet et al., 2019 manually installed the gypsum wall partitions in their construction to comply with regulations regarding fire resistance. This is an example of where researchers may be further challenged to innovate automated processes for applying gypsum plaster to wall surfaces as Forsberg et al., 1995 successfully achieved using a spray plastering technique. More

S.03	WT% (by mass of gypsum)	Weight (g)	alt.
DAP Composite	100 wt%	100	0
Polycarboxylate (PC)	0.20 wt%	0.2	0
Hydroxypropyl Methyl Cellulose (HPMC)	1.0 wt%	1	+0.6g
Starch Ether (SE)	0.20 wt%	0.2	0
Kaolinite	0	0	0
Retarder	0	0	0
Water	50 wt%	50	+28g
Total		151.4	-
Result: Not Printable			

S.04	WT% (by mass of gypsum)	Weight (g)	alt.
DAP Composite	100 wt%	100	0
Polycarboxylate (PC)	2.0 wt%	2	+1.8g
Hydroxypropyl Methyl Cellulose (HPMC)	3.0 wt%	3	+0.6g
Starch Ether (SE)	2.0 wt%	2	+1.8g
Kaolinite	0	0	0
Retarder	0	0	0
Water	40wt%	40	+18g
Total		147	-
Result: Not Printable			

contemporary literature concerning gypsum plaster is limited. However similar research by (Lublasser et al., 2018) explored the robotic application of foam concrete insulation to bare walls in addition to proposing appropriate end effectors.

As an alternative to contour crafting, other methods that stretch the boundaries of what may be considered 3D printing may also be applied to gypsum plaster. Goessens et al., 2018 researched the use of unmanned aerial vehicles UAV in assembling droxels (Goessens et al., 2018) in structurally sound patterns. This progress is an intriguing trajectory of research. Though when implemented on the unitized nature of gypsum wallboard the issue of added value to already efficient methods of construction is of significant concern (Melenbrink et al., 2020). Mobile robots using safety laser scanners and a direct geometrical model have created the superstructure to a serviceable building (Subrin et al., 2018). Similar functionality and technology of autonomous grounded robots have been applied to UAV in construction (Solly et al., n.d.). Documentation of UAV utilized in contour crafting however is scarce if nonexistent. A study inspired by Forsberg et al., 1995 implementing UAV in the application of gypsum plaster onto finished wall surfaces may be a worthwhile study to consider.

Gypsum plaster printed through additive manufacturing has applications in medical science and design (Liu et al., 2018). Binder jet, also known as ink jet printing is the most widely used method. Producing localized reactions with binder agents on a bed of powder, layer by layer it creates complex structures and rapid prototypes

S.05	WT% (by mass of gypsum)	Weight (g)	alt.
DAP Composite	100 wt%	100	
Polycarboxylate (PC)	0.20 wt%	0.2	0
Hydroxypropyl Methyl Cellulose (HPMC)	0.40 wt%	0.4	0
Starch Ether (SE)	0.20 wt%	0.2	0
Kaolinite	50 wt%	50	+50g
USG Retarder	0	0	0
Water	75 wt%	75	0
Total		225.8	-
Result: Low Potential			

SAMPLE OF SOLUTION 05

(Christ et al., 2015). In the case or gypsum, water is the binder that reacts with the powder without any need for extra liquid solutions (Shakor et al., 2020). Printing delay, build orientation, print head resolution, post treatment procedures, binder–powder interaction, particle size, and layer thickness, are some of the determining factors in resolution and accuracy of 3D printed prototypes (Farzadi et al., 2015). Practical drawbacks include a relatively low initial green sample strength, which may lead to the collapse of large structures during removal from the powder bed and post processing(Christ et al., 2015). Speed is also affected since each thinly built layer requires powder leveling, rolling, printing, removing, as well as post-processing (Liu et al., 2018). This as well as other factors greatly limit the viability of binder jet printing at construction scale. Nevertheless, Christ et al., 2015 found fiber reinforced 3D printed gypsum had a 180% bending strength increase and a work of fracture value up to 10 times higher compared to non-reinforced powder printed samples. Moreover, in a break from binder jet powder methods, Liu et al., 2018 printed specimens using gypsum-based material adapted to 3D robocasting. The results were samples with a mechanical strength comparable to molded gypsum plaster(Liu et al., 2018).

Ease of installation and affordability make gypsum board a preferred component for interior wall assemblies (Abden et al., 2020). Gypsum plaster has fire retardant properties and is a material that has been used in building and construction since ancient times (Jia et al., 2021). The advent of machine production in modern

SAMPLE OF SOLUTION 06

S.06	WT% (by mass of gypsum)	Weight (g)	alt.
DAP Composite	100 wt%	100	0
Polycarboxylate (PC)	0.20 wt%	0.2	0
Hydroxypropyl Methyl Cellulose (HPMC)	0.40 wt%	0.4	0
Starch Ether (SE)	0.20 wt%	0.2	0
Kaolinite	50 wt%	50	+50g
Retarder	1.5 wt%	1.5	+1.5g
Water	75 wt%	75	+28g
Total		226.6	0
Result: Potential			

construction and Post-War building made plasterboard one of the most readily used panelized materials for interior walls. Efficiency replaced intricacy and craftsmanship in the gypsum plaster component of modern wall assemblies. The aesthetic complexity in gypsum can be reintroduced through digital modeling and automated through 3D printing. Prefabricated panelization of ornamented 3Dprinted gypsum wallboard is commonplace(Zuo et al., 2019). However an on-site printed version is not yet widely utilized.

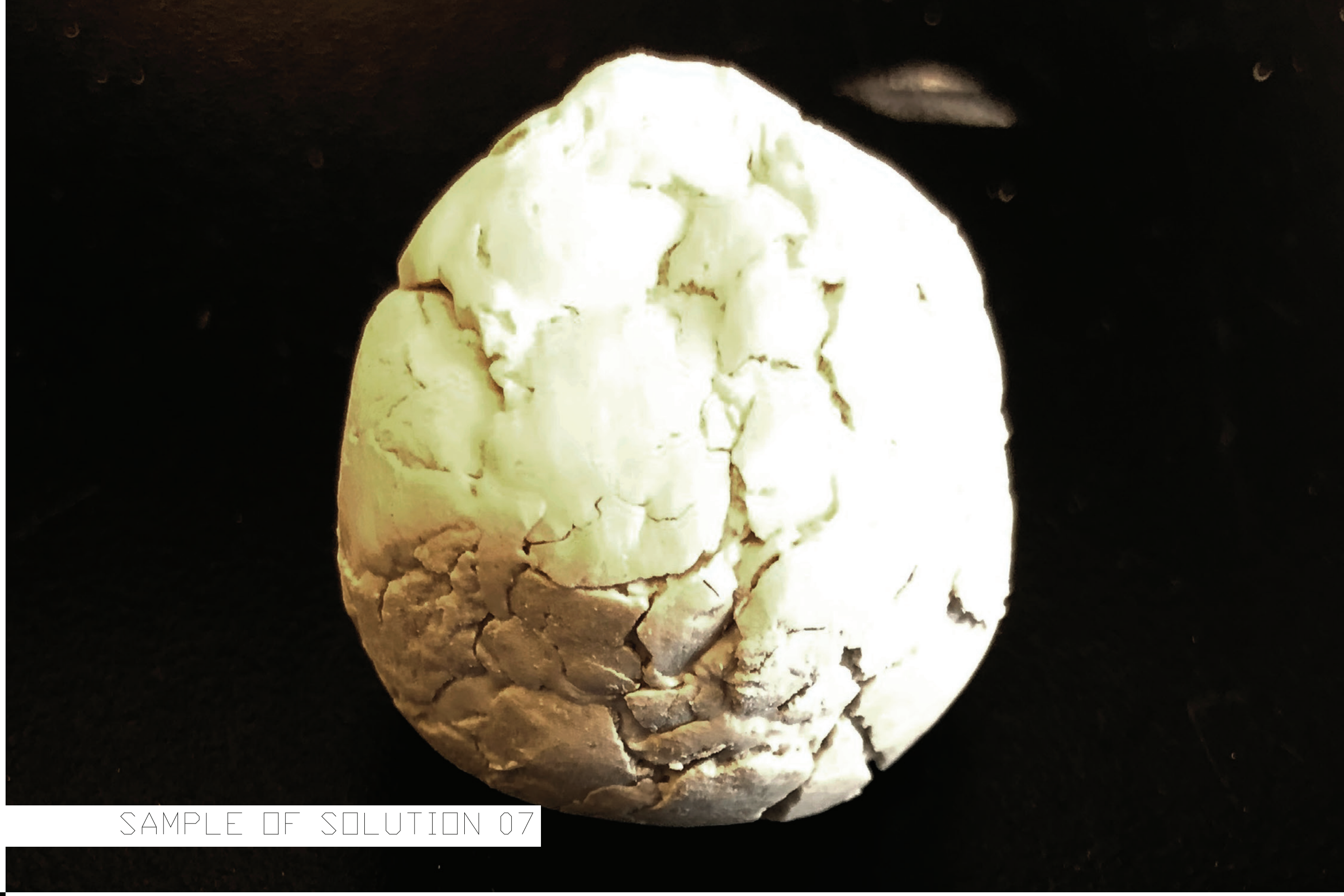
From the available literature CS3DP applied to gypsum plaster in situ as a wall material is not widely discussed. The efficiency and low cost of current methods of installation may limit the impetus of exploring this particular field.

3. Materials and Methods

3.1. Research Aim

The objective was to verify the potential of robocasting gypsum plaster composites on a consumer product; investigate the boundaries of its application to design, architecture, and construction; present an alternative to current standards of 3D printing gypsum plaster. The intended method was to create different plaster mixtures; assess their printability; and print the best performing composites on the 3D potterbot.

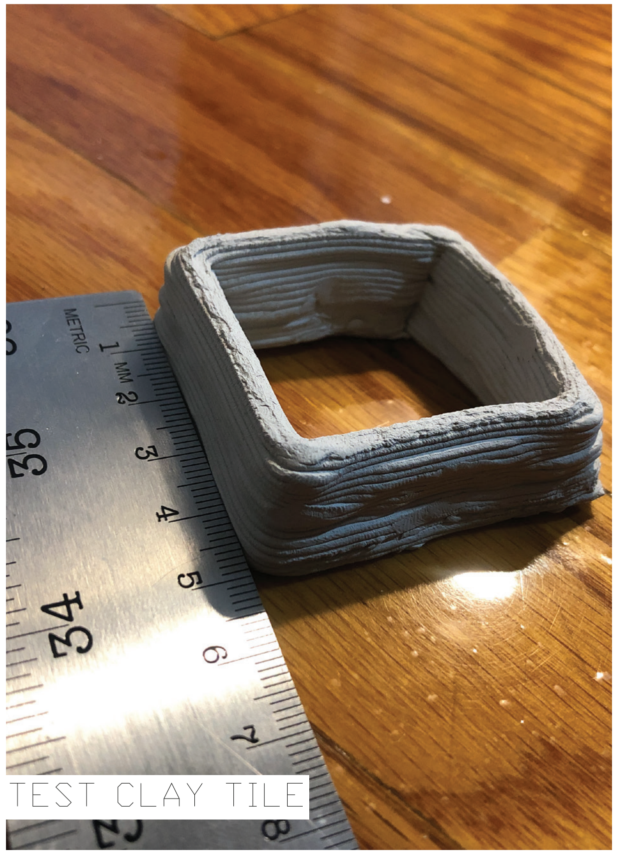
S.07	WT% (by mass of gypsum)	Weight (g)	alt.
DAP Composite	100 wt%	100	0
Polycarboxylate (PC)	2 wt%	2	+1.8g
Hydroxypropyl Methyl Cellulose (HPMC)	3 wt%	3	+0.6g
Starch Ether (SE)	2 wt%	2	+1.8g
Kaolinite	0	0	0
Retarder	0	0	0
Water	30	30	+8g
Total		137	0
Result: Low Potential			

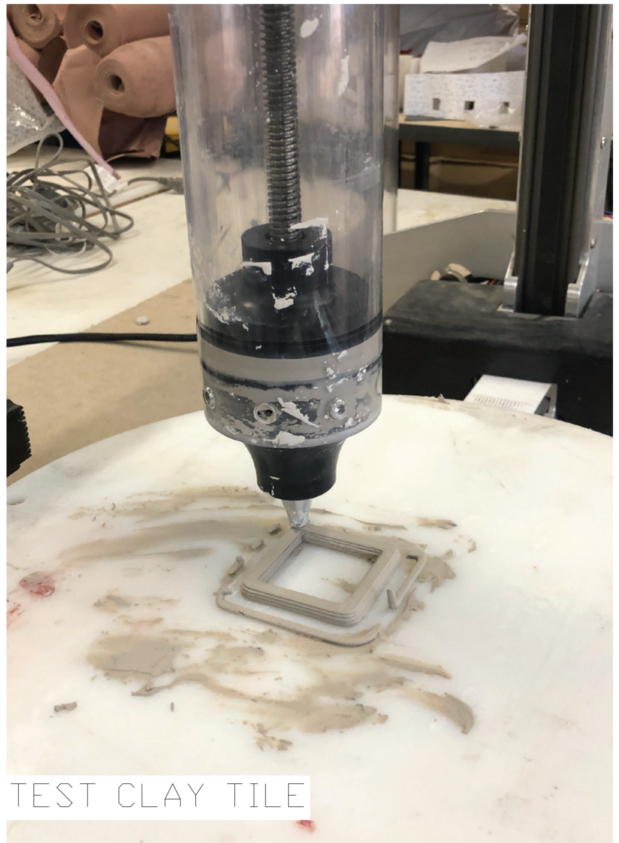


3.2. Research Methodology

The procedure included mixing various portion of the aforementioned chemicals with plaster of Paris; measuring the curing times and rheology of the composites; assessing compatibility and printability with a 3D Potter by testing the layer adhesion and shape adherence of the various mixtures; injecting the final slurry into the 3D potter culminating in the extrusion of a printed result.

Rather than being pure, the plaster of Paris used in this study was a blend of hemihydrate gypsum with calcium carbonate, and crystalline silica. Aside from the plaster of Paris, polycarboxylate (PC), starch ether (SE) and hydroxypropyl methyl cellulose (HPMC) was added to the mixture. Polycarboxylate is used as a



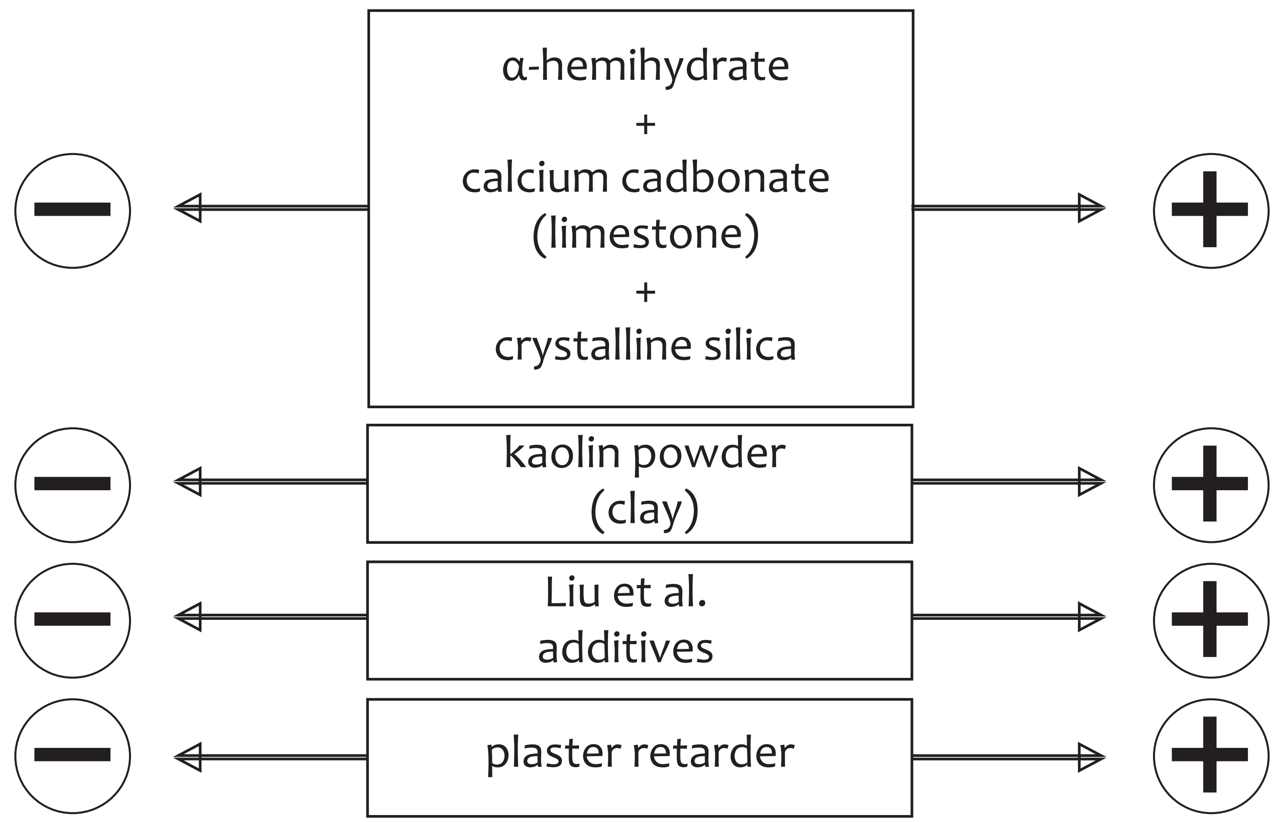


superplasticizer: it not only reduces the amount of water required for cementitious materials to cure, but also extends the curing time. Starch ether also changes the consistency of the mixture. Hydroxypropyl methyl cellulose when mixed with water creates a semisolid gelatin and therefore when added to a plaster slurry, increases its viscosity.

Unlike the Southeast University study, kaolin clay in its dry powdered form is included in some of the mixtures. To extend the curing time of the plaster mixture even further, gypsum plaster retarder was also incorporated in one of the mixtures.

3.2.1. Equipment Test

The 3D potterbot was initially tested with the native clay intended for the



S.01 Time	Substance Quality	Extrusion	Number of Layers
@ 10 min	solid, dry, powdery	no	0

S.02 Time	Substance Quality	Extrusion	Number of Layers
@ 10 min	liquid	yes	0
@ 30 min	paste	yes	0
@ 60 min	paste	yes	0
@ 90 min	paste	yes	0
@ 120 min	dry paste	no	0

S.03 Time	Substance Quality	Extrusion	Number of Layers
@ 10 min	liquid	yes	0
@ 30 min	liquid	yes	0
@ 60 min	cream	yes	0
@ 90 min	cream	yes	0
@ 120 min	cream	yes	0

S.04 Time	Substance Quality	Extrusion	Number of Layers
@ 10 min	adherent liquid	yes	4
@ 30 min	adherent cream	yes	-
@ 60 min	adherent cream	yes	-
@ 90 min	adherent cream	yes	-
@ 120 min	cream	yes	-
@ 2 days	solid	yes	

machinery. The machine was made to produce two tiles. One tile shaped as a 5cm x 5cm x 1.5cm square ring was used as a base comparison for the manual material experiments that followed. Another tile borrowing from the plaster ornamentation of Alhambra, Granada, Spain was attempted in order to scope the limitations of the printer. The printer default settings did not permit the articulation of the tile details. Printing times, drying times, and the tactile consistency of the clay were accounted for before moving on with the manual experiments.

3.2.2. Material Sources

The different slurries were prepared using a commercially bought plaster of Paris blend of α-hemi-hydrate gypsum, calcium carbonate, and crystalline silica (DAP Products Inc, USA), PC (United Mineral and Chemical Corp., USA), HPMC (H3785-25G MilliporeSigma, USA), SE (Bob's Red Mill Natural Foods, USA), kaolin clay powder(Clear Lee, USA), gypsum plaster retarder(USG Corporation, USA), and tap water(City of New York, USA). The 3d printer used was the 3d Potterbot Micro 10 located in The Maker Space, Columbia University, USA.

3.2.3. Material Behaviors

The curing time, viscosity, and layer cohesiveness was the next concern. A range of seven plaster composite mixtures were produced. One mixture was based directly on the Southeast University study. Two out of the seven mixtures included

S.05 Time	Substance Quality	Extrusion	Number of Layers
@ 10 min	cream	yes	9
@ 30 min	cream	yes	-
@ 60 min	solid	yes	-

S.06 Time	Substance Quality	Extrusion	Number of Layers
@ 10 min	cream	yes	11
@ 30 min	cream	yes	-
@ 60 min	cream	yes	-
@ 90 min	cream	yes	-
@ 120 min	cream	yes	-
@ 150 min	cream	yes	-
@ 2 days	Solid	yes	-

S.07 Time	Substance Quality	Extrusion	Number of Layers
@ 10 min	taffy	yes	2
@ 30 min	taffy	yes	-
@ 60 min	taffy	yes	-
@ 90 min	taffy	yes	-
@ 120 min	taffy	yes	-
@ 150 min	taffy	yes	-
@ 2 days	Solid	yes	-

Kaolin clay. One mixture included plaster retarder.

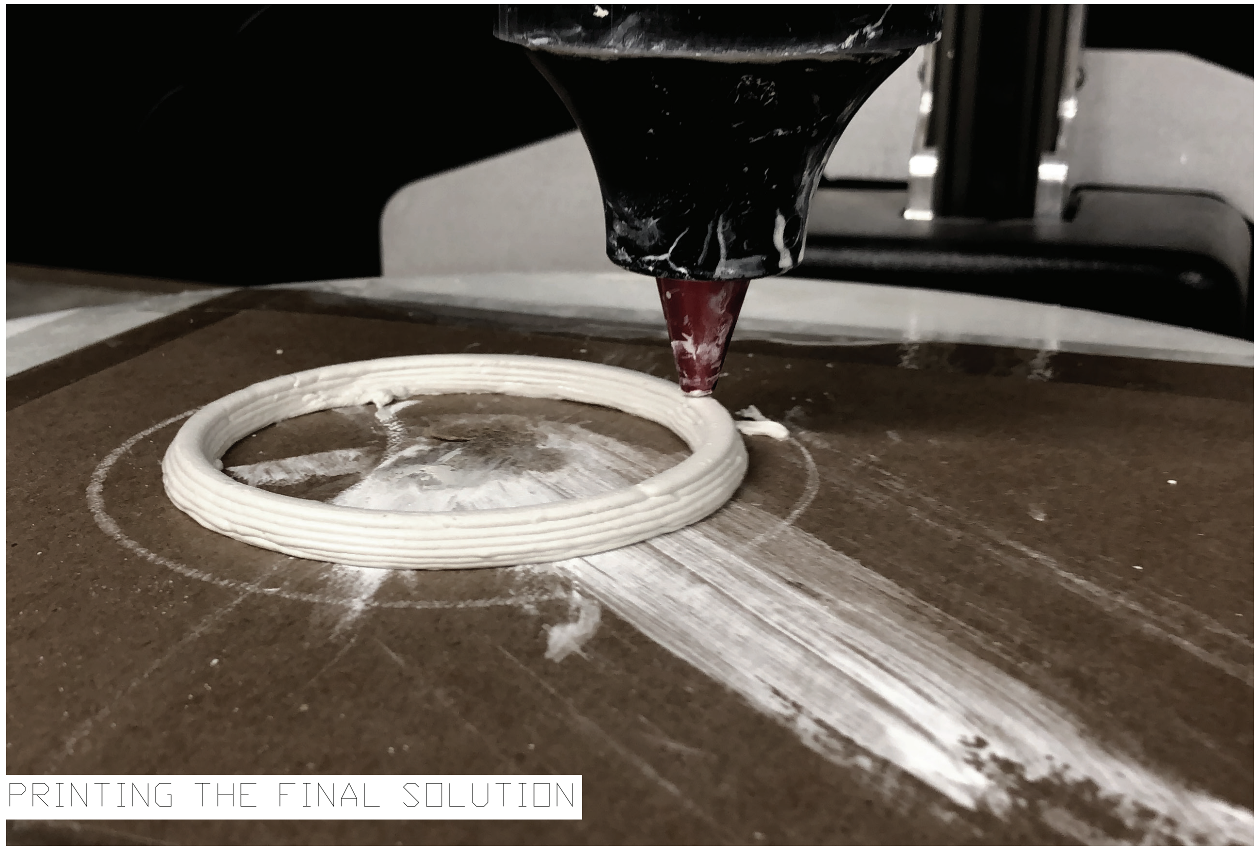
All the proportions of each dry mixture were recorded by weight and added to water. The moment water was added to a dry mixture, a timer was initiated; the slurry was poured into a Petri dish, at specific time intervals the gypsum material composite would be punctured to observe whether it had hardened. If the material hardened before two hours, it would be disqualified as incompatible for printing.

To Measure the viscosity and rheology, again, the moment water was added to a dry mixture, a timer was initiated. The slurry was fed into a syringe; at specific time intervals pressure would be applied while observing if the contents of the syringe would eject. The length of time every mixture remained workable would be documented. If at too early a time interval the material was excessively difficult to extrude, the mixture would be disqualified.

To Measure layer adhesion, a timer was initiated the moment a dry mixture made contact with water. The material was manually extruded from a syringe in the shape of the roughly 17 layer test tile from the initial equipment test. If the material reached a moderate number of layers without collapsing it would be considered for use in the 3Dpotter. Materials with a higher concentration of gypsum were prioritized since they related more to the research intensions.

4. Results

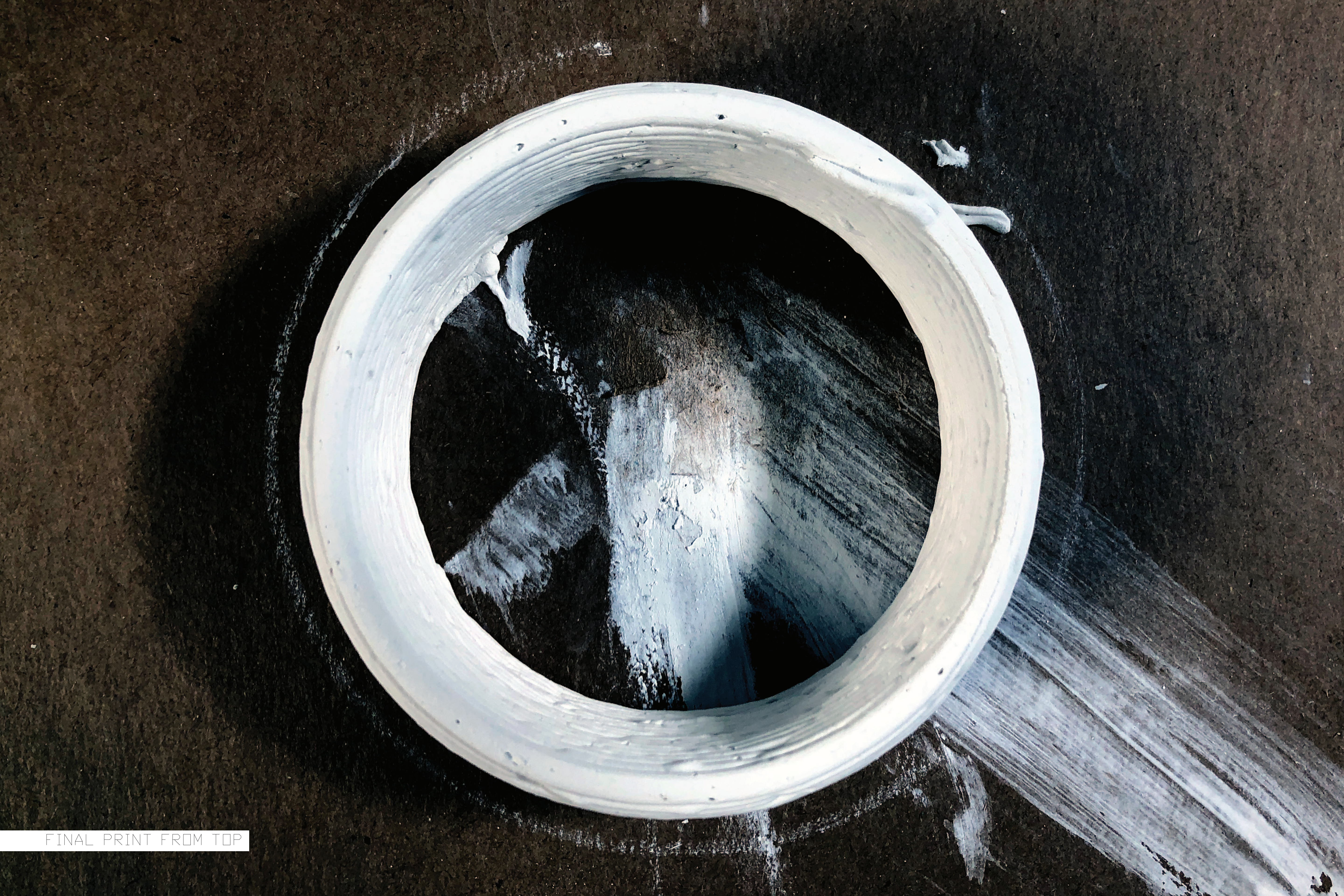
A suitable material mixture was inserted into the 3D potterbot and printed



using the gcode of a default test cylinder provided in the machine software. The behavior of the material was observed during the printing process until completion. There was full layer adhesion and no visible distortion of the finished form. The slurry maintained a manageable viscosity and flow rate through the completion of the print. Soon after the print was finished, the solution cured and was no longer able to be extruded by the machine.

Conclusion

The final mixture was haphazard and loosely based on solution 07 (S.07). The intended difference was to use a bit more water. Unlike S.07, about a table spoon of kaolin clay was added to a 16oz portion of plaster of Paris to thicken the mixture; though such a small amount had no visible affect. Comparing the data of both S.05 and S.06, USG retarder has a substantial effect on mixtures with kaolinite additives. In parallel S.02 and S.07 which both excluded kaolinite show how the higher proportion of PC, HPMC, and SE additives similarly slow down the curing process in a concealed and unconcealed solution. Adding kaolinite to a mixture similar to S.07 however seems to have upset this trend. This is exemplified by the printed mixture prematurely solidifying within the printer. More research should be done to verify the effects of kaolin clay on the gypsum plaster curing process. There is ample room to improve upon these mixtures, making them more fitting for 3d robocasting and the eventual production of larger and more complex objects.



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