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3D Claying: 3D Printing and Recycling Clay

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Abstract: Clay is of great interest as a 3D printing material thanks to its ease of use, recyclability and reusability. This paper analyses the technical aspects of the whole printing process. The behaviour of 3D printing clay is studied with respect to the environment and its specific application as a temporary or definitive formwork system for cement parts. The study addresses the performance of clay and the loss of its properties and characteristics according to the type of protection, whether it is in direct contact with air or cement, or protected with plastics, metal sheets, or combinations of both. A 3D printing system with various printers and 3D models has been considered, observing a direct relationship between the prototype shape, extrusion process and resulting material. The most important variables in 3D printing have been considered: layer height, line thickness, base definition, total model height, overhang angles, overlap between layers, etc. The main technical aspects have been analysed such as raw material properties, kneading, process control, post-treatments and material hardening. As a natural material, clay can be reused indefinitely under certain conditions to be part of a circular economy with low energy consumption and minimal resources. It is concluded that the option of using ceramics in 3D printing for very diverse uses in the architecture, engineering & construction (AEC) sector is very promising due to their ease of implementation, recycling capability and suitability to different environments.

Keywords: 3D claying; 3D printing; additive manufacturing; clay; recycle; carbon print

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1. Introduction

Ceramics have been used in construction and decoration by mankind since the Mesolithic period (between 15,000 and 10,000 B.C.). Their applications, constantly changing in a myriad of different manifestations, have been part of our evolution for thousands of years. There are different theories about the etymology of the word ceramics, although the most widespread is that it comes from the Greek word "keramos" (κέρᾰμος) [1].

Most current research is focused on the 3D printing of concrete [2–4], studying its properties when both fresh and hardened [5], looking at how to optimize it [6,7], how to reduce waste and how to make it more environmentally friendly [8]. Work is being conducted on the life cycle adapted to 3D printing in concrete [9], while materials such as clay are undervalued.

The other element of our research topic, additive manufacturing techniques, also known as 3D printing, have been gaining a greater presence in many areas of industry in recent years. This has come about thanks to the major advantages they present, such as the optimization of material consumption, no waste generation and very complex ad hoc designs, which could not be possible in milling or casting processes. At the same time, 3D printing has disadvantages such as the need, in some cases, for support structures [10] and to improve print quality both mechanically and aesthetically [11].

However, 3D printing is a promising and affordable manufacturing process with the capacity for innovation and real applications in any industrial sector. It has been introduced into the AEC sector in many ways, such as with 3D printing in UHPC resistant concrete [12].

At present, almost all the techniques used in the additive manufacturing of elements with ceramic materials are familiar 3D printing techniques [13,14] adapted to the specific requirements of ceramics. Certain elements, such as the extruder or the pumping system, are adapted to the new material. However, an ad hoc system has not been developed for this material. That is why research has continued with ceramic clay to address its integration into traditional construction processes, a means of promoting low technology and traditional construction materials, without foregoing adaptive designs of great geometric complexity and different use cases. Clay is of interest as a 3D printing material thanks to its ease of use, recyclability and reusability. This paper describes the processes of analysing clay slurries for use in an extrusion 3D printing system similar to fused deposition modeling (FDM), known as liquid deposition modeling (LDM). The main technical aspects such as raw material properties, kneading, process control, post-treatments and material hardening are also analyzed.

This study analyses the use of 3D printing for construction using clay, a material with interesting environmental advantages: high adaptability to different climates, a low carbon footprint, high resource availability and renewability.

3D Printing with Clay

Clay is a completely natural material with a long history in the world of construction. It has been used for aesthetic purposes, for the building of roofing and enclosures, and for waterproofing and finishing walls and other structures [15].

As a raw material extracted directly from the natural environment that requires no further treatment, its inclusion in the context of environmentally conscious construction with low emissions and high material and process efficiency is greatly favoured.

One of the main objectives of this study is, as mentioned above, to guarantee the use of clay in construction processes through possible solutions that would contribute to reductions in energy consumption and waste.

Our definition of "3Dclaying" is being able "to use and reuse clay indefinitely in the context of 3D printers". As such, it can be clearly distinguished from traditional 3D printing. Plastics and other similar non-natural materials are replaced by clay, with its special characteristic of being a 100% natural product and 100% reusable. There is no need for either pre- or post-processing or the use of additives (except water), and its durability in natural environments is very high.

Our review focuses on the comparison of other research in this field, as well as contextualizing these sources in relation to 3D printing for construction and ceramic building materials.

This brief state-of-the-art will present the latest developments in additive manufacturing using ceramic materials.

The first studies into ceramic 3D printing were published in the 1990s by Marcus et al. [16] and Sachs et al. [17]. Since then, advances in materials technology, and 3D printing techniques in particular, have led to the emergence of numerous 3D printing projects [18].

As can be seen in the review by Wolf et al. [19], many of these projects have been design-oriented, taking advantage of the freedom offered by 3D printing [20]. Some were performed using classic bricks [21]. Figure 1 presents a simplified overview of different aspects of additive manufacturing with a special focus on clay.

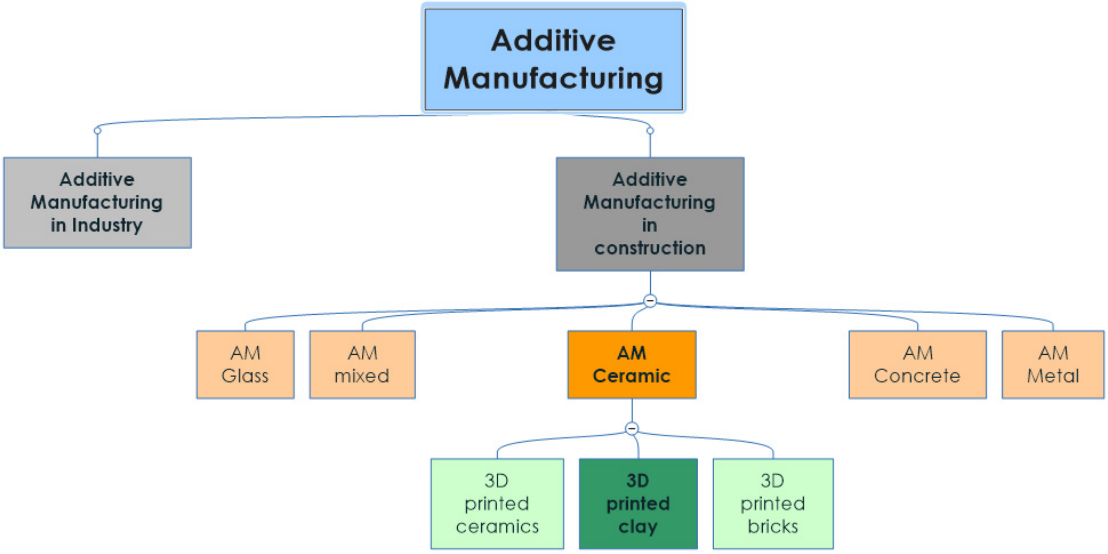


Figure 1. Overview of different aspects of additive manufacturing. Based on Wolf et al. [19] (2022).

Projects involving new formats for aesthetic and/or design value show the impressive capabilities of 3D printing [22]. Other projects have sought to make load-bearing walls [23], taking advantage of the geometric capabilities of additive manufacturing [24,25]. One of the most important features of these projects is that almost all of the solutions are designed to support only their own weight.

The long-term goal of the present research into 3D printing with clay is to provide viable solutions based on assays for ecologically sustainable activities that produce minimal waste and pollution from their origin to their final place of use.

The first part of this research was presented at the X International Congress on Ceramics and Architecture at the School of Architecture of Madrid (ETSAM) of Universidad Politécnica de Madrid (March 2022) and was mostly related to 3D printing processes with commercially-available, general-purpose clay without any type of post-processing work after its deposition.

The test, definitions and conclusions reported in the present document are the second part, based on previous works, with the application of more types of ceramic materials, various printers and 3D models, as well as varied application methods for formwork and molds with different types of protection and final finishes.

The final objective of this study is to transfer all the knowledge gained and the workflow defined to interdisciplinary research and their application in projects in the AEC sector. This particular paper aims to investigate the continued use and reuse of common clay in simple 3D printing machines to develop upscaled alternatives of the models and processes presented that could be used in traditional or industrialized construction.

2. Method and Workflow

Conclusions were drawn from the test planning and the outcomes of the intermediate tests to optimize future results.

All the tests were performed by trained technical staff. Figure 2 illustrates the workflow of the tests.

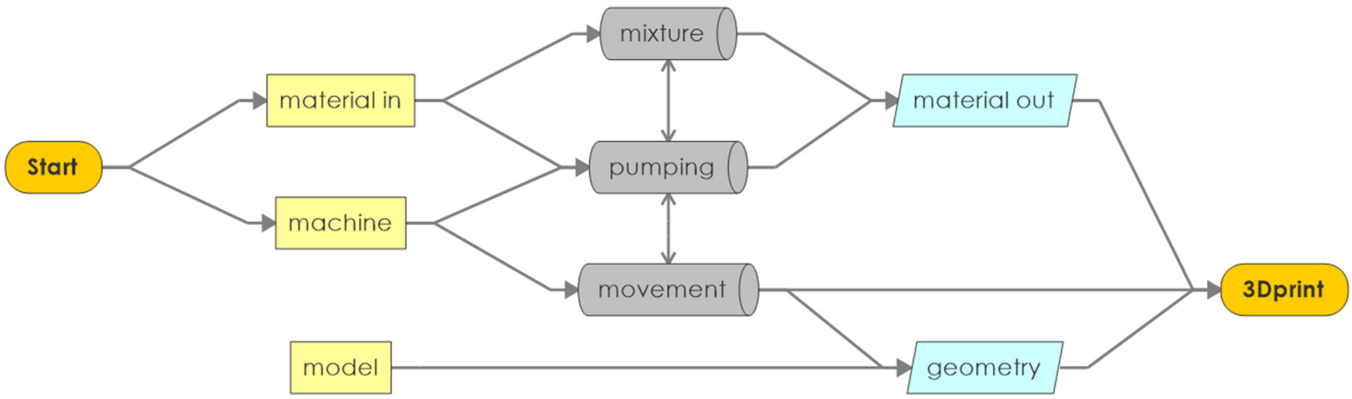


Figure 2. Study workflow including intermediate steps.

The material was subjected to a variety of manipulations of a circular nature, none of which modified the state of the material irreversibly (vitrification, firing, etc.). This facilitated its almost unlimited use in consecutive processes. As explained in Figure 3, three test rounds were conducted, the second round including several iterations.

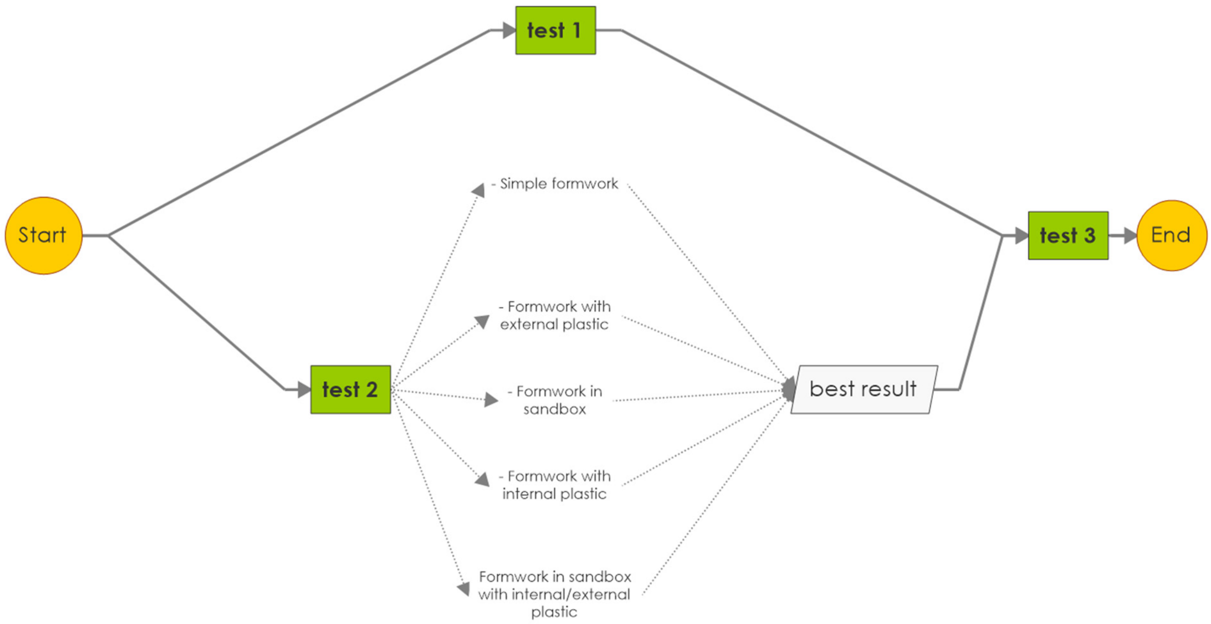


Figure 3. Test types and processes with three main tests and iterations in test 2.

2.1. Conditions, Machines and Software

The tests were conducted in summer in Madrid, under the following environmental conditions:

Temperature: 29.1 to 35.8 °C

Humidity: 22 to 28%

Pressure: 920 to 980 mbar

See Annex for more detailed information.

The tests in this study were performed using commercial clay with two different 3D printers that extrude material from a piston-enabled reservoir.

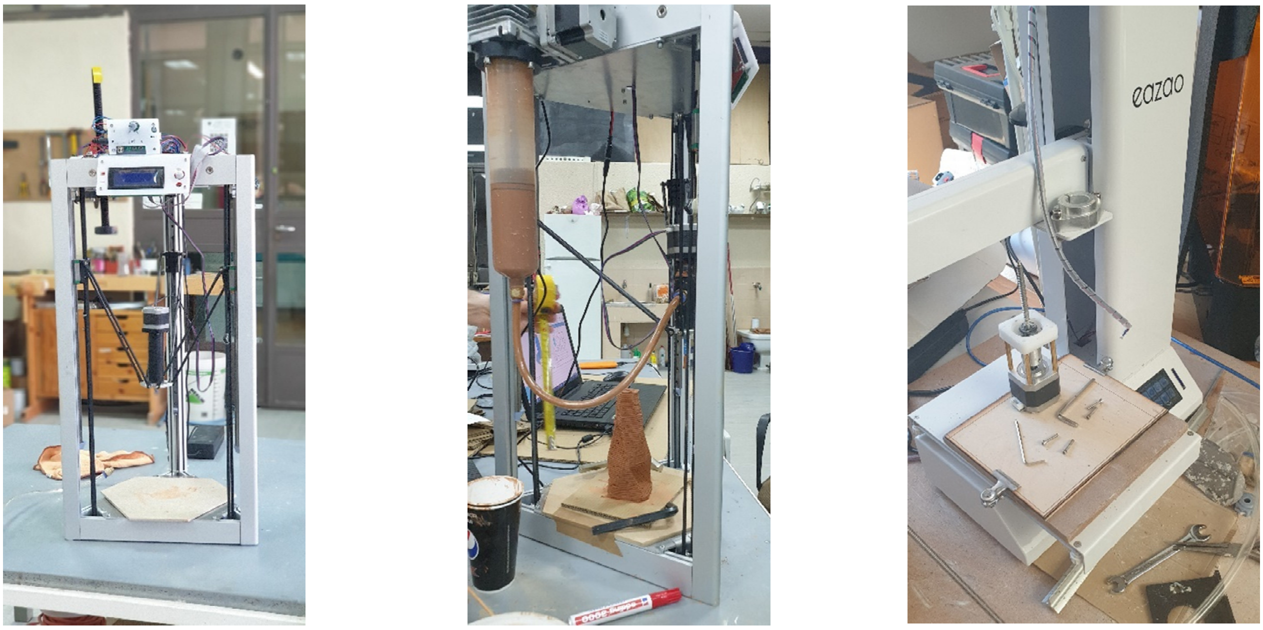
Models used in tests (see Figure 4):

Eazao Cerambot: 3 axes oriented in a delta configuration. Printing Volume: diameter 170 mm × height 285 mm. Layer resolution: 0.4 to 1.0 mm. Nozzle diameter: 0.8 to 1.5 mm. XY accuracy (at centre): 0.1 mm. Maximum print speed: 50 mm/s.

Eazao Cerambot Zero: cartesian configuration with X, Y and Z axis. Printing Volume: 150 × 150 × 240 mm^3. Layer resolution: 0.4 to 1.0 mm. Nozzle diameter: 0.6 to 3.0 mm. XY accuracy: 0.1 mm. Maximum print speed: 40 mm/s.

The extrusion system of both machines is similar, based on a Nema 27 stepper motor pushing a piston against the clay in the reservoir. The deposit capacity is 500 mL, which corresponds to approximately 800 g of clay. No compressed-air extruder system was used in any of these tests.

The main software used to control the 3D printers was CURA 4.12.0 version (November 2021). The source code used to send information to the 3D printer is included as plain text in Appendix A.



(**a**) (**b**) (**c**)

Figure 4. Clay 3D printers (EAZAO models): (**a**) Eazao (**b**) Eazao (**c**) Eazao Zero.

2.2. Material

The material used in all the tests was a traditional red and white earthenware body clay by "Ceramica Collet" (Sio-2 PF*E) with a low content of fine grog. However, with a humidity content of 22% in its packaged form, it is much too thick to be used directly for our 3D printing applications.

Thus, an initial batch was made by adding 500 mL of water to the store-bought clay, mixing thoroughly and storing it in a sealed container. This amount of added water was insufficient, however, as the thick clay was prone to causing pressure buildups in the general pump feed chamber.

Two more smaller batches were tested, the first consisting of 500 g of that initial mixture and 25 mL of water, and the second increasing the quantity of initial clay to 750 g plus the added 25 mL of water. The first proved to be too liquid and runny for the successful building of layers, while the second test batch appeared to be ideal in terms of liquid content.

Details on the humidity and ratios of these mixtures are displayed in Table 1 below.

The table shows the theoretical water contents and the final mixtures used, with the water-to-clay ratio and water and dry clay contents for all uses.

Table 1. Clay mixtures humidity ratios with original information and three adjustments.

	Store-Bought Clay	Original Mixture	Too Fluid Mixture	Final Mixture
Additional Water	0 mL	+500 mL	+25 mL	+25 mL
Base batch weight		12.5 kg	500 g	750 g
Total weight	12.5 kg	13 kg	525 g	775 g
Percentage	100%			
Dry clay weight	9.75 kg	9.75 kg	375 g	562.5 g
Dry clay %	78%	75%	71.43%	72.58%
Water weight	2.75 kg	3.25 kg	150 g	212.5 g
Water %	22%	25%	28.57%	27.42%
Water-to-clay ratio	0.2821	0.3334	0.4	0.3778
Water content				
(per 1 kg)	220 g	250 g	285.71 g	274.19 g
(per 750 g)	165 g	187.5 g	214.29 g	205.65 g
(per 500 g)	110 g	125 g	142.86 g	137.10 g
Dry clay content				
(per 1 kg)	780 g	750 g	714.29 g	725.81 g
(per 750 g)	585 g	562.5 g	535.71 g	544.35 g
(per 500 g)	390 g	375 g	357.14 g	362.90 g

The information provided by the clay supplier is its common name "PF 970/1055 °C", which makes clear reference to its recommended firing temperatures, and also its definition as "Traditional red earthenware body" in reference to its color and origin.

Clay reference data used in tests has reference "PF*E" and is described as "Traditional red earthenware body for throwing and modelling" with extrusion consistency (softness) of 20 mm base for 4.0 to 5.5 kg with approximately 22% water content supplied in 12.5 kg wrapped units.

The following Table 2 lists the chemical elements in the clay, as well as their behaviour against external actions:

Table 2. Technical data with chemical elements of the clay.

Chemical Analysis %										**Plasticity (Atterberg)**		**$CaCO_3$%**
SiO_2	**Al_2O_3**	**Fe_2O_3**	**TiO_2**	**CaO**	**MgO**	**Na_2O**	**K_2O**	**MnO**	**L.O.I**	**L.L.**	**I.P.**	
53.90	17.60	6.33	0.86	5.41	2.67	0.30	3.63	0.11	8.90	41	18	10

Green and drying data			Firing data					Coefficient of thermal expansion $\times 10^{-7}$ °C^{-1}			
Water content %	Drying shrinkage %	Dry strength N/mm^2	Temperature °C	Loss on ignition %	Water absorption %	Firing shrinkage %	Fired strength N/mm^2	25–300	300–500	500–650	25–650
17	2.8		900	8.8	15.9	0.1	26.5				
19	3.3	6.6	1000	8.9	15.7	0.6	27.9	69.7	84.5	112.7	84.8
22	5.5		1100	8.9	12.9	1.5	29.4				

White clay with very similar mechanical characteristics, Table 3, was used for the final tests.

Table 3. White Clay used for final tests (technical sheet).

Technical Sheet	
PA 1050/1080 °C Water content 20% Firing shrinkage at 1050 °C −0.4%	White earthenware body Drying shrinkage 6.8% Water absorption at 1050 °C 12.3%

This special white paste is suitable for high-quality modelling. It is a very versatile paste and is appreciated for its finesse, plasticity and regularity. It has a compensated proportion of calcium carbonate that gives it greater stability compared to traditional faience pastes, while also presenting suitable expansion coefficients for standard pottery enamels, both in single and double firing. It is available as an extruded plastic paste with different humidity levels, Table 4, for application in different forming processes.

Table 4. Behaviour and technical characteristics of the clay used (technical sheet).

Firing temperature (cake)	1050–1080 °C (not used in our work)
Humidity (lathe)	20%
Plasticity (IP Atterberg)	16
Calcimetry ($CaCO_3$)	17%
Drying contraction	6.8%
Firing contraction (1050 °C)	−0.4%
Porosity (water absorption 1050 °C)	12.3%
Dry mechanical strength	5.1 N/mm^2
Fired mechanical strength (1050 °C)	27.8 N/mm^2
Coefficient expansion (25–500 °C)	79.1×10^{-7} °C^{-1}

3. Results and Test Details

Three test rounds were carried out, following the procedures explained in Figure 3. The test is described in the following points of this chapter.

3.1. Test 1: Reusability of Clay

The setup of test 1 is described in Table 5. The same clay was used in five printing cycles. Six samples of clay were tested, each with a slightly different original weight.

Table 5. Test 1 set up.

Definition:	Analyse the capacity of clay to be reused after the 3D printing process
Description:	3D printing a simple geometry, natural 24 h drying process, remixing clay (adding water or not) and repeat process.
Iterations:	5 times (1/day)
Duration:	5 days
Measurements	Geometry variations after 24 h Water lost in 24 h Others to be defined

The table below details the time spent on each part of the tests, Table 6, so all the results were comparable.

Table 6. Steps in each cycle of test 1.

Steps	Description	Duration	Items	Comments
1	3D printing with clay	5 min	3D printer	
2	Clay drying	24 h		Protected space
3	Take measures	5 min	Measure gauges	Environment: Temperature Humidity Figure Height Width on: base mid top Height Layer Width layer
4	Clay remix	15 min	water	Adding water (measure)
5	Repeat 1 to 4	4 days		Step 4 only 3 times

All the weight measurements, Figure 5; were taken with the same scales, subtracting the weight of the wooden bases to compare only the weights of the clay.

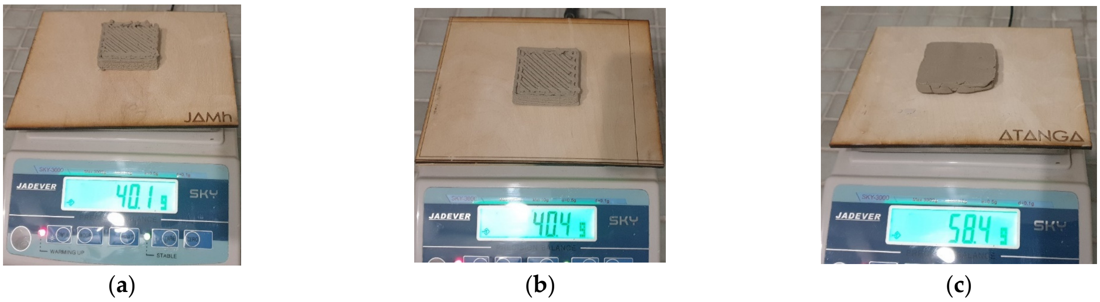
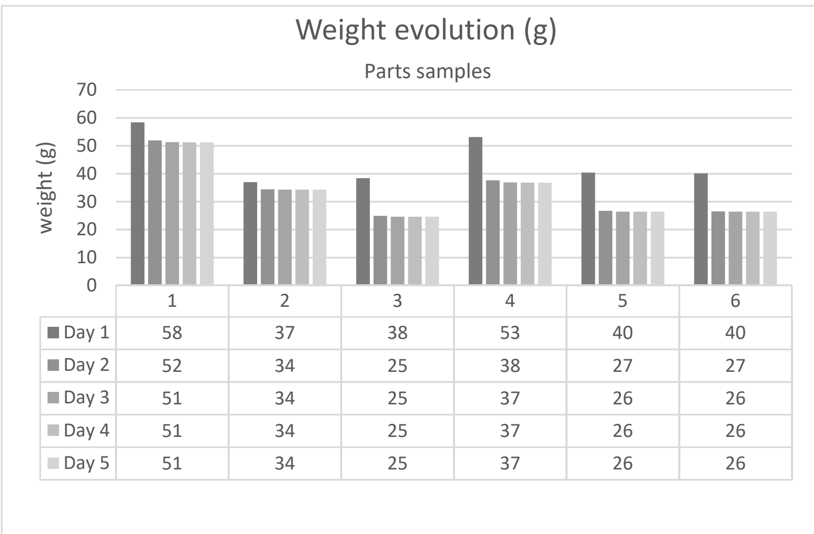


Figure 5. Test 1. Illustration of the original weight of samples: (**a**) part 1 (**b**) part 5 (**c**) part 6.

After the 3D printing, measurement and control tests were carried out for 5 days in exact 24 h periods to analyse the loss of moisture by evaporation, Scheme 1.



Scheme 1. Weight for the six samples through five cycles of 3D printing.

Non-fired clay can be reused indefinitely with controlled contact with other wet materials and/or if filtered/decanted after being sullied. The addition of clean water is always required. In our tests, alcohol was not used, but its use is very common in clay 3D printing because its rapid evaporation allows the part to dry quickly.

3.2. Test 2: Clay Formwork

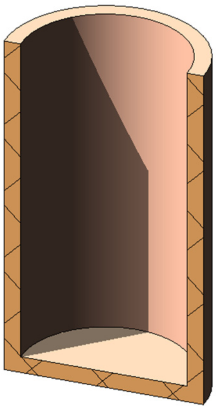
Test 2, Table 7, focused on using clay for different types of formworks.

Table 7. Test 2 set-up and description.

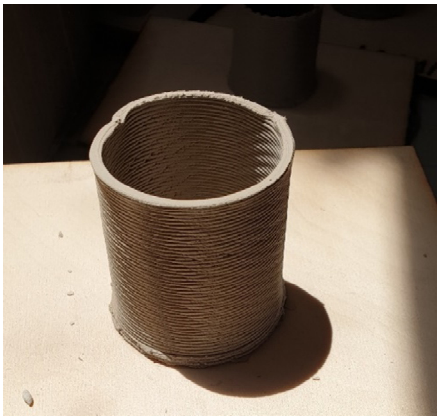
Concept	Value
Definition	Analyse the capacity of clay to be used as formwork for concrete structures
Description	Simple formwork Formwork with external membrane (plastic or aluminum paper) Formwork in sandbox Formwork with internal membrane (plastic or aluminum paper) Formwork in sandbox with internal/external membrane
Iterations	1 each test
Duration	5 days
Measurements	Geometry variations after 24 h Resistance to concrete/cement pouring Others to be defined

3.2.1. Iteration 1 of Test 2

First, one iteration was done with simple formworks of the type presented in Figures 6–8, and as described in Table 8 workflow.



(**a**)



(**b**)

(**c**)

Figure 6. 3D-printed simple formworks: (**a**) 3D model (**b**) 3D-printed clay cylinder (**c**) 3D-printed clay cylinder and L shape.

(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 7. 3D-printed cylinder formworks filled with cement: (**a**) 3D model (**b**) 3D-printed part filled (**c**) Weight measurement (**d**) Visual test (**e**) Final stripping.

(**a**) (**b**) (**c**) (**d**)

Figure 8. 3D-printed formworks filled with cement: (**a**) Turning hexagon extrusion filled with cement. (**b**) Stripping (**c**) Stripping (**d**) L shape part filled with cement.

Table 8. Steps in test 2 for simple formworks.

Steps	Description	Duration	Items	Comments
1	3D printing with clay	5 min	3D printer	
2	Clay drying	24 h		Protected space
3	Fill with concrete	5 min	Concrete	High-speed concrete
4	Concrete curing	24 h		
5	Take measurements	5 min	Measure gauges	Length and weight

In iteration 1, the water stays inside the cement poured and the result is correct; only the upper area (in contact with air) must be controlled (adding water or surface protection). The external surface of the cement has a very similar geometry to the clay formwork, the result being a good shape. The final external texture is soft and non-porous because of the contact with plastic. Thus a complicated formwork has been realised without the addition of formwork products.

3.2.2. Iteration 2 of Test 2

The next iteration in test 2 was with formwork with an external membrane, as displayed in Figure 9 and Table 9.

(**a**) (**b**) (**c**) (**d**)

Figure 9. Formwork with external membrane (plastic): (**a**) 3D model (**b**) Filled clay part with protection (**c**) Stripping (**d**) Final cement part.

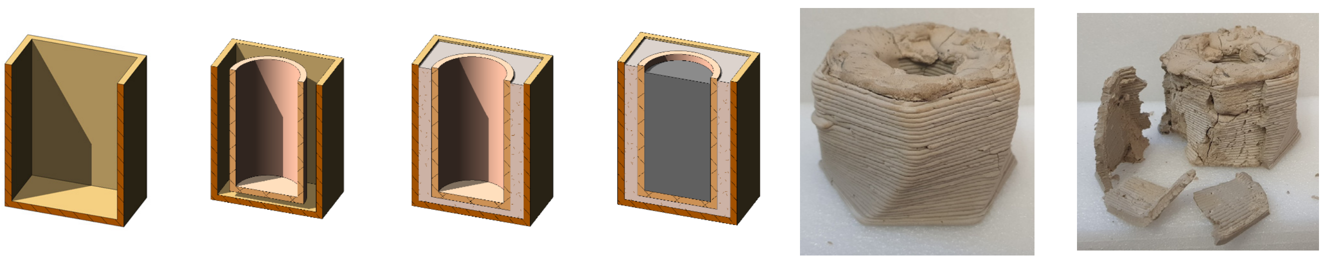
Table 9. Steps in test 2 for formworks with external membrane.

Steps	Description	Duration	Items	Comments
1	3D printing with clay	5 min	3D printer	
2	Clay drying	24 h		Protected space
3	Cover external surface with plastic	5 min	Plastic	Duct tape or aluminum foil
4	Fill with concrete	5 min	Concrete	High-speed concrete
5	Concrete curing	24 h		
6	Take measurements	5 min	Measure gauges	Length and weight

In iteration 2, for formworks with an external membrane, the water stays inside the whole of the envelope and the poured cement, moving from concrete to clay. The final external surface of cement parts is very dry, with too much retraction, resulting in a bad shape.

3.2.3. Iteration 3 of Test 2

A third iteration was done with formwork in a sandbox, as shown in Figure 10 and Table 10.



(**a**) (**b**) (**c**) (**d**) (**e**) (**f**)

Figure 10. Double Formwork: (**a**) 3D model outer layer (**b**) 3D model inner and outer layers (**c**) 3D model with sand between layers (**d**) 3D model with clay inside (**e**) 3D-printed clay cylinder filled with cement (**f**) Stripping.

Table 10. Steps in test 2 for formworks in sandbox.

Steps	Description	Duration	Items	Comments
1	3D printing with clay	5 min	3D printer	
2	Clay drying	24 h		Protected space
3	Fill wood box with sand	5 min	Sand	Sand under clay cylinder
4	Fill with concrete	5 min	Concrete	High-speed concrete
5	Concrete curing	24 h		
6	Take measurements	5 min	Measure gauges	Length and weight

In iteration 3, with formwork in a sandbox, the water stays inside the whole of the envelope and the poured cement, moving from concrete to clay on both sides (internal and external formworks). The final external surface of the cement is very dry, with too much retraction, resulting in a bad shape.

3.2.4. Iteration 4 of Test 2

A fourth iteration was done with formwork with an internal plastic or aluminum foil membrane, as shown in Figure 11 and Table 11.

(a) (b) (c) (d) (e) (f)

Figure 11. 3D-printed formworks with an internal membrane (plastic and aluminum): (**a**) 3D model with internal protection (**b**) 3D model filled with cement (**c**) 3D-printed clay cylinder filled with cement with plastic protection (**d**) 3D-printed clay cylinder filled with cement with aluminum (**e**) Stripping (**f**) Final result.

Table 11. Steps in test 2 for formworks with internal membrane.

Steps	Description	Duration	Items	Comments
1	3D printing with clay	5 min	3D printer	
2	Clay drying	24 h		Protected space
3	Cover inside face with plastic	5 min	Plastic	Plastic wrap or aluminum foil
4	Fill with concrete	5 min	Concrete	High-speed concrete
5	Concrete curing	24 h		
6	Take measurements	5 min	Measure gauges	Length and weight

In iteration 4, the water stays inside the poured cement, not moving from concrete to clay. The final external surface of the cement is perfect, with no retraction and good shape.

3.2.5. Iteration 5 of Test 2

Finally, the last iterations in this test used formwork in a sandbox with internal/external plastic.

For this test, Figure 12 and Table 12 the best results were found using plastic between the clay and cement as the aluminum paper was difficult to fit onto the envelope.

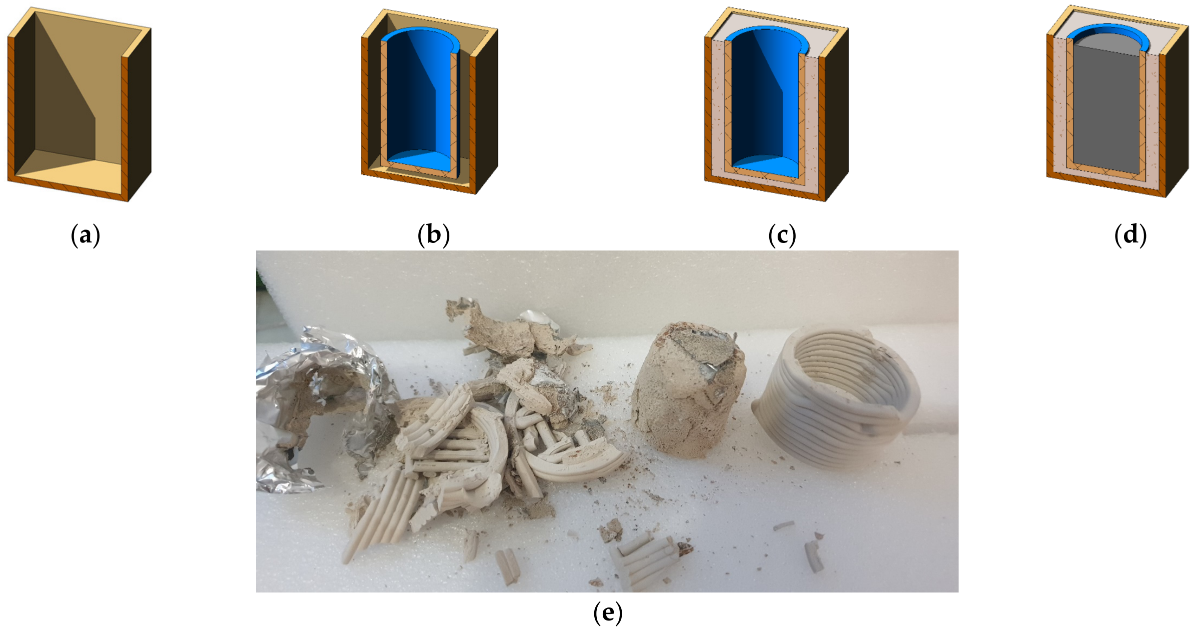


Figure 12. Formwork in sandbox with internal/external plastic: (**a**) 3D model outer layer (**b**) 3D model outer and inner layers with protection (**c**) 3D model with sand between outer and inner layers (**d**) 3D model filled with cement (**e**) Stripping.

Table 12. Steps in test 2 for formworks with internal/external plastic.

Steps	Description	Duration	Items	Comments
1	3D printing with clay	5 min	3D printer	
2	Clay drying	24 h		Protected space
3	Cover inside face with plastic	5 min	Plastic	Alternative: Aluminum foil
4	Cover external face with plastic	5 min	Plastic	Alternative: Aluminum foil
5	Fill wood box with sand	5 min	Sand	Sand under clay cylinder
6	Fill with concrete	5 min	Concrete	High-speed concrete
7	Concrete curing	24 h		
8	Take measurements	5 min	Measure gauges	Length and weight

3.3. Test 3. Clay Formwork Reuse

A third test round was carried out using the set-up from test 3, Table 13, that performed best.

Table 13. Test 3 set-up and description.

Definition:	Analyse the capacity of clay to be reused after 3D printing formwork for concrete structures process
Description:	Simple formwork Formwork with external plastic Formwork in sandbox Formwork with internal plastic Formwork in sandbox with internal/external plastic Note: select only 1 after the results from test 2 (see optional)
Iterations:	5 times (1/day)
Duration:	5 days
Measurements	Geometry variations after 24 h Resistance to concrete/cement pouring Others to be defined

Table 14 indicates the time spent on each of the test steps:

Table 14. Steps in test 3 with all process definitions and timings.

Steps	Description	Duration	Items	Comments
1	3D printing with clay	5 min	3D printer	
2	Clay drying	24 h		Protected space
3	Cover inside face with plastic	5 min	Plastic	Plastic film or similar (optional)
4	Cover external face with plastic	5 min	Plastic	Duct tape or similar (optional)
5	Fill wood box with sand	5 min	Sand	Sand under clay cylinder (optional)
6	Fill with concrete	5 min	Concrete	High-speed concrete
7	Concrete curing	24 h		
8	Take measurements	5 min	Measure gauges	To be defined by CSIC

Clay can be reused repeatedly with controlled contact with other wet materials and/or if filtered after being sullied. A plastic film or aluminum foil surface membrane is needed for good results, ensuring that the whole inside and outside are watertight. The addition of clean water will always be necessary.

4. Discussion

This research builds on previous research into ceramic 3D printing from the 1990s and onwards. There have been major advances in 3D printing techniques in recent years and several design-oriented research projects have been conducted using the freedom in design and production allowed by 3D printing. This study contributes to this body of work with an analysis of the sustainability and reuse of clays as a construction material.

In general, the tests indicate that clay can be reused indefinitely under these conditions:

- No direct contact with other wet materials (concrete, cement, etc.)
- No firing/vitrification

This means that if the surface of 3D-printed clay is protected to prevent it from acquiring sullied water from another material it is in contact with, it can be reused simply by adding water to bring it back from a plastic state to an elastic state. Thorough mixing is recommended as the 3D printing process and surface drying introduces small air bubbles into the clay.

4.1. Challenges

After concluding the small-scale tests (up to 25 cm maximum dimension), it would be of interest to develop them on a larger scale (up to 2.5 m maximum dimension) for greater transferability of the process to the real-life conditions of a construction site. Consideration should also be given to how best to incorporate the operation of these relatively low-tech 3D printers with the local construction personnel at the site. It is also necessary to carry out a detailed study of full-scale extrusion nozzles to build on previous work [26] that has analysed whether the use of square or circular nozzles conditions the compression resistance or the surface quality.

The 3D models can be adapted, if necessary, to real environments (via 3D scanning/photogrammetry) to take full advantage of customized design. Furthermore, this customization and monitoring can be done remotely at technical offices, consequently saving the need for technical workers on site, not to mention high-level computer equipment and other highly-qualified personnel.

In the case of highly complex forms or sites without a 3D printer, objects printed in clay can easily be transported and completely recycled with ease.

4.2. Opportunities

The possibilities of complex building systems, decorative pieces, temporary supports, or simply racks to support other elements are endless.

These include:

- Walls/facades, main rails.
- Interior decoration: wall, ceiling, floor, corners, door frames, etc.
- Formwork for columns, stairs, pipe/duct junctions, foundations, etc.
- Installations: pipes, ducts, cable protection, connection parts, etc.

The greatest opportunities for application are not highly technological since the use and handling of the material is very simple and does not require machinery or high-level technical training. Thus, its application is possible and most recommended in sites with a low technological level and access to unskilled labor, such as non-urban environments, emergencies after natural disasters, countries in situations of poverty, or any environments where the distance or difficulty of access to traditional methods of manufacturing construction elements is complex or impossible.

In a world increasingly concerned with sustainability, where the transfer of raw materials from their origin to the final destination is an exceedingly important factor to consider, the possibilities that clay offers are very relevant given its widespread availability anywhere on the planet, which is why it is part of most of humanity's historically pertinent constructions. With the options that additive manufacturing processes bring to the table, these possible applications are increased.

In addition, reusing a material after its first application should be a trend in the construction sector, which is a great generator of waste globally. In this way, the recycling of auxiliary media in this environment occurs in the same place where they are generated, with the subsequent energy savings in the transport of new materials and waste. The reuse of support materials in 3D printing has been evaluated by different authors [27] for other sectors, but not for construction.

The use of 3D printing technology for the manufacture of concrete formwork has been evaluated by numerous authors [24,28,29]. This work highlights the value of 3D printing with clay because of its reusability. Similar work has been done by other authors with compacted sands as a support structure [30]. Other authors propose to integrate clay 3D printing as the primary formwork and concrete pouring in such a way that the clay formwork acquires structure from the concrete as it cures. As the clay loses moisture, the formwork begins to shrink, crack, and reveal the concrete below. This self-demolding process produces easily removable formwork that can then be recycled by adding water to rehydrate the clay creating nearly zero-waste formwork [31].

Recently, attention has been drawn to clay as potential formwork for concrete. Jipa and Dillenburger [24] report 3D-printed clay formworks for concrete objects with a height of up to 2.5 m. They also mention that clay has the option of being recycled, even though the recycling is not elaborated upon. The lack of water resistance of clay is also mentioned. Furthermore, they found that clay performed very well from a sustainability point of view compared to other 3D-printed formworks due to its minimal specific embodied energy.

The study presented here provides additional information about the recycling properties of 3D-printed clay, which previously seem to have been assumed, but not documented in detail. The presented study also shows that the lack of water resistance of clay formwork can be addressed using additional readily available materials.

Leschok and Dillenburger [28] discuss clay in relation to sustainable 3D-printed formwork systems, highlighting some disadvantages of clay as formwork. According to these authors, clay requires special equipment such as a custom printing setup, the container for the clay to be printed has a limited capacity, and, finally, printed clay tends to be brittle and heavy. They also highlight an advantage of clay compared to many other dissolvable 3D-printed formworks for concrete, namely that clay can be removed without a high risk of damaging the surface of the cast concrete.

This study shows that clay can be printed as formwork with commercially available 3D printers, and it may not require a specialized setup. The brittleness of clay may be a disadvantage, but this can also be an advantage in the sense that the formwork is easy to remove.

4.3. Usability

Perhaps one of the most important issues related to clay stems from its positive and negative relationship with water, and the clay used in this study is basically always mud and not subjected to firing or any other subsequent treatment. Untreated 3D-printed clay can be reused repeatedly as already demonstrated, and this also allows it to be used as a formwork or temporary mold for pieces of other materials such as cement or concrete that can easily be removed with pressurized water.

For this reason, the following types of direct uses in the construction sector can be determined:

- Temporary products
- Permanent products
- Post-processed products

The key, in this case, is whether the final clay product will be in contact with wet areas or materials (in this case it will always be temporary) or is immersed in other pieces or areas without contact with the outside or water, in which case its use may be permanent. It is also possible to have permanent products that are post-processed after 3D printing by means of firing, glazing, etc.

Temporary uses are the most innovative contribution of this material, due to its ease of reuse, recyclability and minimum carbon footprint. Table 15 presents the wide variety of possible direct applications of this digital manufacturing methodology through the use of clay and its recycling:

Table 15. Possible uses of 3D-printed clay with examples.

Type	Denomination	Temporary	Permanent	Post Produced	Examples
Architectural	Interior	X	X	X	Interior design
	Exterior	X	X	X	Historic building reproduction
Structural	Column	X			Mold
	Stair	X			Supports
	Ceiling	X	X	X	Duct support. Saloon deco.
	Roof		X	X	Complex union frame.
	Floor	X	X	X	Installation cell. Deco floor draw.
	Foundation	X			Superior mold for saving material
MEP	Pipe			X	Complex connection part.
	Duct			X	Complex connection part.
	Yard	X	X	X	Internal Installations Yard

MEP = Mechanical, electrical and public health elements.

5. Conclusions

This paper aimed to investigate the use and reuse of common clay in simple 3D printing machines. This is important in the construction sector because it can contribute to the requirements and needs of a circular economy with low energy consumption and minimal resources. Clay is especially interesting as a natural material thanks to its great capacity to adapt to different climates and intensive use without losing its main qualities, namely malleability, extrudability and rigidity to drying.

Three rounds of tests were conducted, the second including several iterations. The tests were performed using commercial clay with two different 3D printers that extrude material from a piston-enabled reservoir. The tests indicate that clay can be reused indefinitely under certain conditions. Regarding the shape and dimensions of the parts or pieces that can be produced with this methodology, what stands out is mainly what in terms of 3D printing is called "vase mode", that is, shapes that can be generated with a single line per layer and in constant ascent, that is, in a vertical extrusion spiral in the form of a spring where the contact surface between successive layers is very high (greater than 75%), with a simple base (1 layer) or several layers and without a top lid, to be able to pour the cement or equivalent material inside.

The main technical aspects such as raw material properties, kneading, process control, post-treatments and material hardening have been analyzed. Combined with different technologies, it is possible to produce a temporary item (formwork, support, etc.) or a permanent object (duct, pipe, internal support, thermal/acoustic insulation) with or without post-processing. The application of firing or vitrification processes is possible and recommended in the case of pieces for permanent use and those exposed to the natural environment (rain, wind, ambient humidity, erosion, etc.).

One limitation of the study relates to the dimensions, as this is a small-scale test with dimensions up to 25 cm. Future studies are recommended on a larger scale, such as up to 2.5 m maximum dimension for greater transferability of the process to the real-life conditions of a building site. Future studies are also recommended into the practical experiences of using 3D printers on construction sites and the need for training the staff involved. However, the opportunities to use clay in a similar way similar to that described here are vast because it is a simple material to use and handle and does not require machinery or high-level technical training.

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Appendix A

SOURCE CODE: Cura Config Text

(NOTE: Save this into a TXT file)

```
eazao_zero_eazao_zero_vase #4[general]
version = 4
name = EAZAO_Zero_vase_4mm VASE
definition = fdmprinter

[metadata]
type = quality_changes
quality_type = normal
setting_version = 19
intent_category = default

[values]
layer_height = 1
layer_height_0 = 0.75
magic_spiralize = True
```

```
prime_tower_size = 3.872983346207417

(eazao_zero_extruder_0_eazao_zero_vase #4[general]
version = 4
name = EAZAO_Zero_vase_4mm VASE
definition = fdmprinter

[metadata]
setting_version = 19
type = quality_changes
quality_type = normal
position = 0

[values]
bottom_layers = 2
bottom_thickness = 0
cool_fan_enabled = False
fill_outline_gaps = True
infill_before_walls = False
infill_sparse_density = 0
line_width = 1.5
machine_nozzle_size = 1.5
material_diameter = 2.25
material_final_print_temperature = 0
material_initial_print_temperature = 0
material_print_temperature = 0
meshfix_extensive_stitching = True
meshfix_union_all_remove_holes = True
retraction_enable = False
retraction_speed = 20
speed_infill = 20
speed_layer_0 = 20
speed_print = 20
speed_topbottom = 20
speed_travel = 20
speed_wall = 20
speed_wall_0 = 20
speed_wall_x = 20
top_thickness = 0
travel_compensate_overlapping_walls_enabled = True
wall_thickness = 1.5
```

References

1. Oldfather, W.A. A Note on the Etymology of the Word "Ceramic". *J. Am. Ceram. Soc.* **1920**, *3*, 537–542. [CrossRef]
2. Khan, M.S.; Sanchez, F.; Zhou, H. 3-D printing of concrete: Beyond horizons. *Cem. Concr. Res.* **2020**, *133*, 106070. [CrossRef]
3. Zhang, J.; Wang, J.; Dong, S.; Yu, X.; Han, B. A review of the current progress and application of 3D printed concrete. *Compos. Part A Appl. Sci. Manuf.* **2019**, *125*, 105533. [CrossRef]
4. Robayo-Salazar, R.; Mejía de Gutiérrez, R.; Villaquirán-Caicedo, M.A.; Delvasto Arjona, S. 3D printing with cementitious materials: Challenges and opportunities for the construction sector. *Autom. Constr.* **2023**, *146*, 104693. [CrossRef]
5. Paul, S.C.; Tay, Y.W.D.; Panda, B.; Tan, M.J. Fresh and hardened properties of 3D printable cementitious materials for building and construction. *Arch. Civ. Mech. Eng.* **2018**, *18*, 311–319. [CrossRef]
6. Hou, S.; Duan, Z.; Xiao, J.; Ye, J. A review of 3D printed concrete: Performance requirements, testing measurements and mix design. *Constr. Build. Mater.* **2021**, *273*, 121745. [CrossRef]
7. Chen, Y.; He, S.; Gan, Y.; Çopuroğlu, O.; Veer, F.; Schlangen, E. A review of printing strategies, sustainable cementitious materials and characterization methods in the context of extrusion-based 3D concrete printing. *J. Build. Eng.* **2022**, *45*, 103599. [CrossRef]

8. Bai, G.; Wang, L.; Ma, G.; Sanjayan, J.; Bai, M. 3D printing eco-friendly concrete containing under-utilised and waste solids as aggregates. *Cem. Concr. Compos.* **2021**, *120*, 104037. [CrossRef]
9. Tinoco, M.P.; de Mendonça, É.M.; Fernandez, L.I.C.; Caldas, L.R.; Reales, O.A.M.; Toledo Filho, R.D. Life cycle assessment (LCA) and environmental sustainability of cementitious materials for 3D concrete printing: A systematic literature review. *J. Build. Eng.* **2022**, *52*, 104456. [CrossRef]
10. Jiang, J.; Xu, X.; Stringer, J. Support Structures for Additive Manufacturing: A Review. *J. Manuf. Mater. Process.* **2018**, *2*, 64. [CrossRef]
11. Jiang, J.; Newman, S.T.; Zhong, R.Y. A review of multiple degrees of freedom for additive manufacturing machines. *Int. J. Comput. Integr. Manuf.* **2021**, *34*, 195–211. [CrossRef]
12. Sotorrío Ortega, G.; Alonso Madrid, J.; Olsson, N.O.E.; Tenorio Ríos, J.A. The Application of 3D-Printing Techniques in the Manufacturing of Cement-Based Construction Products and Experiences Based on the Assessment of Such Products. *Buildings* **2020**, *10*, 144. [CrossRef]
13. Pessoa, S.; Guimarães, A.S.; Lucas, S.S.; Simões, N. 3D printing in the construction industry—A systematic review of the thermal performance in buildings. *Renew. Sustain. Energy Rev.* **2021**, *141*, 110794. [CrossRef]
14. Delgado Camacho, D.; Clayton, P.; O'Brien, W.J.; Seepersad, C.; Juenger, M.; Ferron, R.; Salamone, S. Applications of additive manufacturing in the construction industry—A forward-looking review. *Autom. Constr.* **2018**, *89*, 110–119. [CrossRef]
15. Shibing, D.; Hongsong, L. Conservation and maintenance of the rammed earth of the Historic City Wall of Pingyao, China. *Loggia Arquit. Restaur.* **2019**, *32*, 46–59. [CrossRef]
16. Marcus, H.L.; Beaman, J.J.; Barlow, J.W.; Bourell, D.L. Solid freeform fabrication-powder processing. *Am. Ceram. Soc. Bull.* **1990**, *69*, 1030–1031.
17. Sachs, E.; Cima, M.; Cornie, J. Three-dimensional printing: Rapid tooling and prototypes directly from a CAD model. *CIRP Ann. Manuf. Technol.* **1990**, *39*, 201–204. [CrossRef]
18. Zocca, A.; Colombo, P.; Gomes, C.M.; Günster, J. Additive Manufacturing of Ceramics: Issues, Potentialities, and Opportunities. *J. Am. Ceram. Soc.* **2015**, *98*, 1983–2001. [CrossRef]
19. Wolf, A.; Rosendahl, P.L.; Knaack, U. Additive manufacturing of clay and ceramic building components. *Autom. Constr.* **2022**, *133*, 103956. [CrossRef]
20. Chen, Z.; Li, Z.; Li, J.; Liu, C.; Lao, C.; Fu, Y.; Liu, C.; Li, Y.; Wang, P.; He, Y. 3D printing of ceramics: A review. *J. Eur. Ceram. Soc.* **2019**, *39*, 661–687. [CrossRef]
21. Cruz, P.J.S.; Knaack, U.; Figueiredo, B.; Witte, D.D. Ceramic 3D printing—The future of brick architecture. *Proc. IASS Annu. Symp.* **2017**, *2017*, 1–10.
22. Chen, Y.; Romero Rodriguez, C.; Li, Z.; Chen, B.; Çopuroğlu, O.; Schlangen, E. Effect of different grade levels of calcined clays on fresh and hardened properties of ternary-blended cementitious materials for 3D printing. *Cem. Concr. Compos.* **2020**, *114*, 103708. [CrossRef]
23. Sangiorgio, V.; Parisi, F.; Fieni, F.; Parisi, N. The New Boundaries of 3D-Printed Clay Bricks Design: Printability of Complex Internal Geometries. *Sustainability* **2022**, *14*, 598. [CrossRef]
24. Jipa, A.; Dillenburger, B. 3D Printed Formwork for Concrete: State-of-the-Art, Opportunities, Challenges, and Applications. *3D Print. Addit. Manuf.* **2022**, *9*, 84–107. [CrossRef]
25. Chan, S.S.L.; Pennings, R.M.; Edwards, L.; Franks, G.V. 3D printing of clay for decorative architectural applications: Effect of solids volume fraction on rheology and printability. *Addit. Manuf.* **2020**, *35*, 101335. [CrossRef]
26. Manikandan, K.; Jiang, X.; Singh, A.A.; Li, B.; Qin, H. Effects of Nozzle Geometries on 3D Printing of Clay Constructs: Quantifying Contour Deviation and Mechanical Properties. *Procedia Manuf.* **2020**, *48*, 678–683. [CrossRef]
27. Xu, Y.; Wang, Z.; Gong, S.; Chen, Y. Reusable support for additive manufacturing. *Addit. Manuf.* **2021**, *39*, 101840. [CrossRef]
28. Leschok, M.; Dillenburger, B. Sustainable Thin-Shell 3D Printed Formwork for Concrete. In *Impact: Design with All Senses*; Gengnagel, C., Baverel, O., Burry, J., Ramsgaard Thomsen, M., Weinzierl, S., Eds.; Springer International Publishing: Berlin/Heidelberg, Germany, 2019; pp. 487–501. [CrossRef]
29. Wen, O.X. Feasibility Studies of Printable Singapore Marine Clay-Limestone Composites in Cost Effective Form-Work for Casting Reinforced Concrete Structures. Bachelor's Dissertation, National University of Singapore, Singapore, April 2021. Available online: https://scholarbank.nus.edu.sg/handle/10635/221955 (accessed on 14 December 2022).

30. Battaglia, C.A.; Miller, M.F.; Verian, K.P. Print-Cast Concrete: Additive Manufacturing for 3D Printing Mortar in Robotically Fabricated Green Sand Molds. In *Second RILEM International Conference on Concrete and Digital Fabrication*; Bos, F.P., Lucas, S.S., Wolfs, R.J.M., Salet, T.A.M., Eds.; Springer International Publishing: Berlin/Heidelberg, Germany, 2020; pp. 757–767. [CrossRef]
31. Bruce, M.; Clune, G.; Xie, R.; Mozaffari, S.; Adel, A. Cocoon: 3D printed clay formwork for concrete casting. In *ACADIA 2021: Realignments: Toward Critical Computation, Proceedings of the 41st Annual Conference of the Association for Computer Aided Design in Architecture, Online 3–6 November 2021*; Association for Computer Aided Design in Architecture: Fargo, ND, USA, 2021; pp. 400–409. Available online: https://www.research-collection.ethz.ch/handle/20.500.11850/511290 (accessed on 14 December 2022).

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