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Article

First Impressions on Three-Dimensional Printing with Earth-Based Mortar at the Faculty of Engineering of the University of Porto

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Abstract: Three-dimensional (3D) printing with earth-based mortar is still under development and faces challenges. Optimising the mortar mixture, improving structural strength, determining the relationship between the printing speed and the amount of extruded material, and ensuring long-term durability are areas that are being refined. Additionally, regulatory and certification issues must also be considered to ensure the safety and compliance of 3D printed structures. This paper presents for discussion the records, analyses, studies, and considerations regarding initial initiatives involving 3D printing with the extrusion of earth-based mortar developed at the Faculty of Engineering of the University of Porto (FEUP). Through this work, it was possible to strengthen and reaffirm that 3D printing with earth-based mortar has significant potential in the construction industry and that the incorporation of dispersed kraft paper fibres from the recycling of cement bags is an excellent resource to achieve good constructability in 3D printing with earth-based mortar.

Keywords: three-dimensional (3D) printing; earth-based mortar; earth architecture; smooth and textured finishes

Citation: Buson, M.; Varum, H.; Rezende, M.A. First Impressions on Three-Dimensional Printing with Earth-Based Mortar at the Faculty of Engineering of the University of Porto. *Buildings* **2024**, *14*, 312. https://doi.org/10.3390/buildings14020312

Academic Editors: Yanping Zhu and Jingjie Wei

Received: 8 December 2023
Revised: 4 January 2024
Accepted: 6 January 2024
Published: 23 January 2024

1. Introduction

Three-dimensional (3D) printing with natural soil is an original and relevant topic, as well as promising technology that combines traditional construction with additive manufacturing advancements. This approach employs a mixture of earth-based mortar, with or without additives, to create complex structures layer by layer through an automated process.

There is a wide variety of cement mortar mixtures for 3D printing, and this quantity expands each year [1]. Although digital construction with earth-based mortar is still in its early development compared with cement mortar, some scientific studies have demonstrated its potential and showcased its technical concept, and some industrial initiatives have exhibited its applicability as a promising construction method [2].

One of the primary advantages of 3D printing with earth-based mortar is the use of a sustainable and readily available construction material. Earth-based mortar is a blend of earth, water, and other ingredients, such as fibres or stabilisers. This approach can significantly reduce the carbon footprint of constructions, as earth-based mortar is a material with lower embodied energy compared with other construction materials like concrete or cement mortar.

Furthermore, 3D printing with earth-based mortar offers greater design freedom and flexibility in building construction. As the technology is based on successive layers, it is possible to create intricate architectural shapes that would be challenging to achieve with traditional construction methods. This opens possibilities for innovative and customised projects.

As mentioned above, it is important to acknowledge that 3D printing with earth-based mortar is still in development and faces challenges. Optimising the mortar mixture (i.e., its constructability or the load-bearing capacity of the newly formed layer), improving structural strength, the relationship between the printing speed and the amount of extruded material (extrusion rate), and long-term durability are areas being refined. Additionally, regulatory and certification issues must also be considered to ensure the safety and compliance of 3D printed structures.

The process of construction 3D printing by extrusion cannot be described by a linear function because the speed of rotation of the screw is not the only parameter that determines the yield of the mixture by weight per unit of time. Additional operating parameters, with a constant and favourable mixture rheology, are the layer height and the linear movement of the nozzle [3].

Overall, 3D printing with earth-based mortar has the potential to revolutionise the construction industry, offering a more sustainable and efficient approach to building construction. As the technology advances and challenges are overcome, it is likely that we will witness an increased adoption and a wider array of applications of this technology in the civil construction field.

This paper presents for discussion the records, analyses, studies, and considerations regarding initial initiatives involving 3D printing with the extrusion of earth-based mortar developed at the Faculty of Engineering of the University of Porto (FEUP).

2. Materials and Methods

The process began with the research and selection of potentially suitable soils for earth construction in Portugal, followed by the subsequent collection and characterisation of two soil samples. To identify the soil with the best performance, adobes were manufactured, and simple compression strength tests were conducted in accordance with ABNT NBR 16814:2020. Subsequently, studies were carried out to define the ideal consistency for 3D printing, the workability of the mixture, and the optimal relationship between the print speed and extrusion rate. Additional analyses were conducted involving 3D printing with earth mortars incorporating dispersed kraft paper fibres from cement bag packaging, known as Kraftterra, as well as types of finishing techniques. More detailed descriptions of the materials and methods are presented throughout the article.

3. Large-Scale 3D Printer at FEUP

In 2022, a large-scale 3D printer was installed at the Laboratory of Structures at the Faculty of Engineering of University of Porto (FEUP). The model, a SMART 2500, was manufactured by the Spanish company BE MORE 3D (Figure 1a). It features a gantry structure with an effective printing area measuring 4.5 m in length by 3.0 m in width by 3.0 m in height. The system employs an open material feed approach through a large stainless-steel funnel where materials are deposited. These materials are delivered to the funnel through a 2.5 cm inner diameter Rondo BD 570psi hose (Figure 1b) connected to an injector pump, a PFT Swing L (Figure 1c). A continuous screw system is used for material extrusion (Figure 1d), and it employs a vertical extrusion system with a fixed nozzle (Figure 1e). The extrusion nozzles can vary in diameter from 20 mm to 60 mm, making them suitable for extruding various materials, including cementitious mortars and earth-based mortars. The printer allows for movement speed adjustments ranging from 20 mm/s to 150 mm/s and ensures 1 mm precision in the position of the extruder nozzle.

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

Figure 1. (**a**) BE MORE 3D's Smart 2500 printer; (**b**) open material insertion system; (**c**) injector pump; (**d**) continuous screw; (**e**) extrusion nozzles.

4. Potentially Suitable Soil for 3D Printing

As in any of the many techniques used in earthen architecture, the selection of potentially suitable soil for 3D printing is of utmost importance. Adobe, typically produced through mortar compaction, served as a reference. Portugal has several sites where soils traditionally used in adobe production can be found.

In northern Portugal, it is challenging to find more suitable soils. Some examples can be found in the Bragança region and the Angueira region. However, in the central and southern regions, suitable soils are more common. These include the sandy soils of the Aveiro region; the clayey soils near Pateira de Fermentelos; the banks of the Lis River running through Leiria; the rural areas of Martingança; the Tomar region along the watercourses and in the interior; the banks of the Nabão River or Carvalhos de Figueiredo (more clayey); the Sorraia River banks in the Ribatejo region; the Coruche area; the southern banks of the Tejo River in the Moita and Pinhal Novo municipalities; the Rosário region; Sarilhos Grandes Sarilhos Pequenos, and Pinhal Novo; the northern banks of the Tejo River in Manique; Vila Franca de Xira; and the southern regions, including the Algarve and nearby areas.

The chosen soil was from the Melides region (38°11′27.499″ N 8°40′33.701″ W), approximately 100 km south of Lisbon, about 6km from Melides Beach, and around 150 km from Lagos in the Algarve. The soil was obtained from an earthmoving operation at a construction site (Figure 2). It has a yellowish hue, characteristic of the Algarve region, and a clay content of approximately 29%, which is very close to the traditionally recommended 30% by many authors and builders. About 1m3 of this soil, dry and sieved (using a 4.76 mm mesh), was made available for the initial studies and work.

Figure 2. Location where soil samples were obtained. Source: Google Maps.

The results of the soil characterisation from Melides are as follows (Table 1).

Table 1. The results of the soil characterisation from Melides.

Grain size analysis	Clay	29%
	Silt	29%
	Sand	39%
	Fine gravel	3%
Liquid limit (LL)		34%
Plastic limit (PL)		18%
Plasticity index		16%
Expansiveness		14.7%
Specific weight		26.6 kN/m^3

Adobe bricks were produced using the natural soil without any corrections, and simple compression tests were conducted on 14 test specimens (TS) made from adobe bricks (Figure 3), following the recommendations of ABNT NBR 16814:2020—Adobe—Requirements and Test Methods [4].

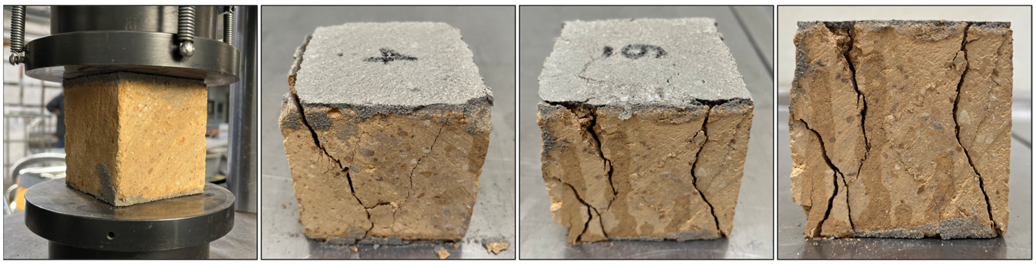

Figure 3. Specimens subjected to simple compression strength tests.

According to the reference standard, the test specimens for the adobe compression strength test were prepared as described below: (a) From each adobe in the sample, we cut a cubic test specimen with sides equal to the smallest dimension of the adobe (Figure 4); (b) to level the working faces of the test specimens (capping), a cement paste or mortar (cement and fine sand at a 1:2 mass ratio) with a strength higher than that of the adobes was used; (c) the surface where capping was performed could not deviate from the plane by more than 0.08 mm for every 400 mm; (d) the capping had to be flat and uniform at the time of the test and patches were not allowed; (e) the maximum thickness of the capping could not exceed 3 mm.

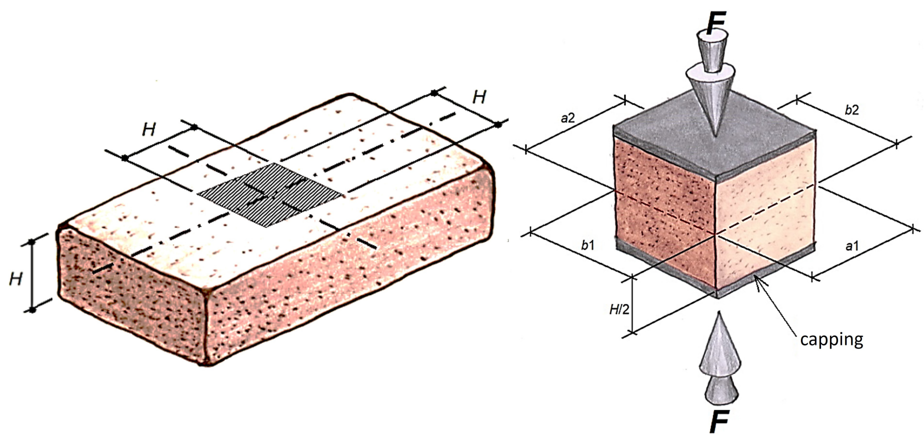

Figure 4. Sectioning and measurement of the dimensions of the fracture section of the test specimen. Source: adapted from ABNT NBR 16814:2020.

Adobe bricks produced with only soil and water that were manually compacted to a moisture content of 24.5%, and dried in a closed environment at room temperature achieved an average of approximately 3.2 MPa of simple compression strength. The highest-performing specimen reached 3.9 MPa, while the lowest reached 2.6 MPa. The aforementioned standard stipulates that adobe bricks should have an individual strength equal to or greater than 1.5 MPa (Table 2). With these results, the use of the Melides soil sample was validated to assess its potential for use in 3D printing with mortar extrusion.

Table 2. Simple compression strength tests of specimens (TS) made from adobe bricks.

TS	**a1 (mm)**	**a2 (mm)**	**b1 (mm)**	**b2 (mm)**	**A_{rup} (mm^2)**	**Rupture Strength f_{rup} (N)**	**Compressive Strength f_{ca} (MPa)**
1	80.8	80.9	86.7	85.1	6939.7	23,150.7	3.3
2	79.5	80.7	80.4	82.6	6526.9	22,016.7	3.4
3	80.7	81.0	79.5	79.0	6409.8	20,881.6	3.3
4	80.6	82.6	79.8	81.0	6560.6	17,701.5	2.7
5	81.0	81.9	79.9	81.4	6570.6	25,544.0	3.9
6	78.3	80.9	80.3	77.8	6293.2	19,612.3	3.1
7	80.9	82.1	82.7	84.7	6818.3	25,558.1	3.7
8	83.0	81.9	80.7	83.2	6755.6	21,021.1	3.1
9	85.6	84.0	82.0	82.1	6955.3	20,320.0	2.9
10	84.0	83.0	83.6	81.3	6880.0	17,683.1	2.6
11	83.0	82.8	80.3	82.7	6754.3	23,366.1	3.5
12	81.5	81.2	82.0	80.4	6607.7	19,621.3	3.0
13	81.9	80.2	82.1	79.9	6561.8	21,219.0	3.2
14	82.1	83.6	83.1	81.8	6828.5	21,169.6	3.1
Medium Compressive Strength (MPa)						f_{cam}	3.2
Sample Standard Deviation (MPa)						S_d	0.4
Compressive Characteristic Strength (MPa)						f_{caK}	2.6

5. Analysis and Determination of the Suitable Mix Consistency

While observing several 3D prints at FEUP using cementitious mortars, the following facts were observed: (1) for small printing volumes, the injection pump was not used because it required a minimum of 30 litres of material to reach the pump's minimum container level (25 litres) and to fill its hose (5 litres), which had an external diameter of 3.5 cm, an internal diameter of 2.5 cm, and a minimum length of 10.0 m to match the characteristics and dimensions of FEUP's printer. Mortar was deposited into the funnel using plastic buckets (Figure 5a), (2) to initiate any print, a preparation of at least 25 litres of mortar was required to fill the funnel and extrusion nozzle, (3) inserting material into the funnel without using the injection pump hose was hindered because the funnel's access had only a small free opening (Figure 5b), (4) the mortar inserted into the funnel opening often accumulated on the less inclined sides, necessitating some procedures to move it to the area of the funnel where the continuous screw was located, (5) the mortar that shifted to the less inclined sides of the funnel, on the opposite side of the entrance often also accumulated there. As this opposite side was difficult to access (Figure 5c), the deposited mortar frequently dried and hardened, resulting in waste and making the cleanup process after printing challenging.

Given the above, and to optimise and avoid wasting the available soil sample in the study as well as the determination of a suitable consistency, a device was sought that required a small quantity of material for extrusions and had extrusion nozzles with the same dimensions as those used in FEUP's printer, ranging from 20 mm to 60 mm. The option was to use a mortar grouting gun (Figure 6), commercially available in construction supply stores. This device resembles a syringe, with a cylindrical body with a 60 mm diameter, an effective capacity for 0.8 litres of mortar, and different extrusion nozzles. One of the extrusion nozzles had part of its tip cut so that its effective opening was 35 mm, the same as one of the extrusion nozzles on FEUP's printer.

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

Figure 5. (**a**) Material insertion into the funnel using buckets; (**b**) limited opening for material insertion; (**c**) less accessible opposite side of the funnel.

Figure 6. Grout gun used in consistency studies.

The procedure to fill the gun with mortar was simple, quick, and prevented air from entering the cylindrical body. The gun was vertically positioned above the grouped mixture, without the nozzle and with the plunger fully inserted into the cylindrical body; the handle was kept still with one hand and force was only applied to the cylindrical body with the other hand to allow the mixture to enter the gun. The procedure was repeated until it was filled. The entire procedure was carried out in one attempt; this was very quick if the mixture was grouped with a thickness greater than or equal to the length of the cylindrical body.

The grout gun proved to be a highly efficient device to simulate the extrusion that occurred with the large-scale printer. However, some difficulties were encountered in its use regarding stabilising the nozzle when producing extrusions. Using only hands, it was not easy to produce cords with a consistent thickness, constant printing speeds, or in a straight line.

To minimise or even avoid these situations, a manual 3D printer was designed and developed (Figure 7) capable of controlling the relationship between the printing speed and the amount of extruded material and ensuring that prints occurred in a straight line. This manual printer was produced using a 2500 × 1250 × 15 mm plywood sheet, which was cut using a CNC router. It featured a system with side fins that allowed the printing of ten overlapping layers of up to 30 cm in length and 15 mm in thickness, corresponding with the thickness of the plywood. A thickness of 15 mm was chosen to achieve a ratio close to 2:1 between the width and thickness of the printed cord, as the extrusion nozzle used had a 35 mm diameter opening. It also included a system with a bicycle ratchet that allowed for a variance of the amount of material to be extruded for the same 30 cm path.

Figure 7. Three-dimensional electronic model and manual 3D printer.

As adobes were chosen as the reference material, we initiated consistency studies using a soil and water mixture that closely resembled that typically used in adobe production. The soil was sun-dried and then stored in large bags on the lower floor of the FEUP Structures Laboratory in a weather-protected location. The base mixture was prepared by hand on a small scale in a 35-L tub with a ratio of 1kg soil to 250 mL water, resulting in a mixture with an average moisture content (w) of 24.5%. We produced some adobes with dimensions of 20 × 20 × 10 cm (Figure 8a,c) and the mixture proved to be suitable and very similar to that typically used in adobe production. The adobes produced did not exhibit cracks and resulted in products with an excellent visual appearance and good dimensional regularity (Figure 8b).

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

Figure 8. (**a**) Adobe production; (**b**) adobes stored at FEUP to dry and gain strength; (**c**) double formwork for producing 20 × 20 × 10 cm adobes.

For comparative consistency analyses, we varied the amount of water per kilogram of soil by 50 mL, both less and more. With less water, the extrusion process was hindered, requiring much more force with the mortar grouting gun to extrude the earth mortar. It was also possible to observe the emergence of voids in the extruded cords. This led us to discard the use of a smaller amount of water in the mixture than the base mixture proportion.

With the addition of more water, the mixture became more fluid, and the mixing process was faster and easier. The mortar cords had a good appearance, and extrusion required less force compared with the base sample.

We proceeded to produce test specimens with an overlap of ten layers of extruded cords, each with a thickness of 1.5 cm. The specimens using the base sample suffered minimal settling or crushing in the layers, resulting in a total height of 14.975 cm at the end of printing (Figure 9a). On the other hand, the specimens with 100 mL more water per kilogram of soil in the mixture showed a settlement of approximately 0.3 cm (Figure 9b).

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

Figure 9. (**a**) Settling measurement with the base sample; (**b**) side view of samples; (**c**) front view of samples; (**d**) settling measurement with a higher amount of water in the mixture.

Based on the above, we decided to use the consistency of the base sample, the same one used in the adobe production, to print with the large-scale printer.

6. Workability with the Base Mixture

We initiated production on a larger scale of the soil mixture with the consistency of the base sample using the same mixer that we used for cement mortar mixtures. The mixing process itself was quite efficient and fast. However, the consistency of the base mixture did not allow the material to be poured out through the small lower opening of the mixer. Most of the material had to be manually removed from the mixer, resulting in a loss of time and excessive physical effort. The final cleaning process was also time-consuming and required significant physical exertion to remove all the material from the various corners of the mixer blades (Figure 10a).

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

Figure 10. (**a**) Mixer of cement mortar with the earth-based mixture; (**b**) Rubimix model 9N and bucket; (**c**) manual electric mixer at work.

We opted to use other devices; these were a manual electric mixer and a 42-L plastic bucket (Figure 10b). Thus, the production of a soil mixture with the consistency of the base sample on a large scale was easily accomplished. We used a single-shaft manual electric mixer, a RUBIMIX model 9N, with a multi-material-type shaft and an M14 thread, as used to mix high-density and low-flow materials (Figure 10c). The cleaning process was very quick and did not require physical exertion. With medium-pressure water jets, almost all the material could be removed.

The base mixture, the same as used for the adobe production, adapted very well to the extrusion process of the large-scale 3D printer. The earth mortar was extruded through the extruder nozzle without difficulty, forming continuous cords without the formation of bubbles or voids. The consistency of the base sample performed excellently in producing continuous and consistently dimensioned printed cords (Figure 11).

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

Figure 11. (**a**) Extrusion of earth mortar with the base mixture; (**b**) printing of a first layer; (**c**) printed curved layers.

The 3D printing took place inside the FEUP Structures Laboratory in a covered and weather-protected area. During the printing period, the average temperature was around 24 °C and the humidity was approximately 75%.

The injection pump was not used in the earth mortar printing processes. The use of buckets was the chosen option because the printing volumes were always very small.

Compared with printing with cement mortars, the final cleaning process after earth mortar printing was much faster and easier. Only medium-pressure water jets were needed to remove almost all the material that was adhered to the funnel surfaces, the auger, and the extruder nozzle. What was not removed with the water jet was easily removed using a fine sponge. Cleaning after cement mortar printing requires greater physical effort, more time, and the use of brushes, sponges, and water jets, especially when cleaning the auger, which has many corners where cement mortar accumulates and hardens. Removing cement mortar from certain parts of the funnel, especially the part opposite the insertion opening where material accumulated, was much more challenging than with earth mortar.

7. Performance of Earth Mortar in 3D Printing

The prints with earth mortar produced construction elements that correctly followed the dimensions and geometry of their electronic models. They were stable, without sagging or layer crushing. However, the first models printed with the base mixture, soil and water, displayed several vertical cracks in various regions due to shrinkage on the first day after printing. In the subsequent days, these cracks increased and even separated some parts of the prototypes (Figure 12). This situation was expected, although the adobes produced with the same mortar, same water content, and same consistency did not show cracks. The walls of these first test samples, with a thickness of about 3.5 cm, were much thinner than the dimensions of the adobes; the smallest dimension was 10.0 cm, which caused faster drying and higher shrinkage.

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

Figure 12. (**a**) Wall printed using the base sample just after printing; (**b**) one day after printing; (**c**) two days after printing; (**d**) three days after printing.

The effects of shrinkage have also been considered in 3D printing with cement mortar. The fibres that can be used as reinforcements in 3D printing with cement mortar include steel, carbon, glass, polyvinyl alcohol (PVA), polyethylene (PE), and polypropylene (PP) [5]. In earth architecture, the use of natural fibres is common for stabilisation and to combat shrinkage.

The use of natural fibres to stabilise the material for printing and combat shrinkage was planned in the ongoing research methodology. Therefore, we started using soil with the incorporation of dispersed fibres from multi-folded kraft paper from cement-bag packaging. The good performance of Kraftterra, as the composite produced from soil and fibres from cement bag packaging is called, was identified in 2009, with the ideal proportion of fibres in the mixture being 6% by mass [6].

To disperse the fibres from the kraft paper of cement-bag packaging, we used a Rubimix 9N manual electric mixer with a shaft adapted with toothed stainless steel plates produced in the FEUP Structures Laboratory (Figure 13a–c), and a Bosch AXT Rapid 2000 garden shredder (Figure 13d). The entire procedure for fibre dispersion followed the recommendations found in Buson's doctoral thesis [6].

The Kraftterra mixture, suitable for adobe production due to the addition of dispersed fibres, required slightly more water than the mixture with soil alone. For every 1 kg of soil, 60 g of fibres and 333 mL of water were required (Figure 14). The moisture content of the Kraftterra mixture with these proportions was 36.87%. The 6% by mass volume of fibres was approximately half the volume of soil added to the Kraftterra mixture.

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

Figure 13. (**a**) Manual electric mixer with adapted shaft; (**b**,**c**) detail of stainless-steel shaft for fibre dispersion; (**d**) carden shredder; (**e**) dispersed fibres from recycling cement-bag packaging.

Figure 14. Proportions of soil, dispersed fibres, and water in Kraftterra.

8. Performance of Kraftterra Mortar in 3D Printing

Prints with Kraftterra mortar produced construction elements that correctly adhered to the dimensions and geometry of their electronic models. They remained stable without any sagging or layer crushing. They did not show any cracks or other pathologies during the curing and drying period.

Shrinkage was significantly reduced, if not-eliminated. The dimensions at the end of printing remained virtually unchanged after drying and strength was gained.

Working with Kraftterra mortar was somewhat easier than with earth mortar. The higher water content in the mixture combined with the presence of fibres produced a cohesive mortar with a good consistency, slightly more paste-like than the mortar produced with soil alone. The dispersed fibres from the kraft paper recycled from cement bags, which had an average length of 12 mm, incorporated very well into the soil and did not hinder the printing process.

A mortar pump was not used in most of the Kraftterra printing processes. The use of buckets was the chosen option because the print volumes were always very small.

However, to verify the performance and workability of Kraftterra with a mortar pump, we printed an L-shaped wall (Figure 15) measuring 60.0 cm on the longer side, 40.0 cm on the shorter side, and 20.0 cm on the sides. It had a height of 30.0 cm and consisted of 20 layers, each with a thickness of 15 mm. Kraftterra adapted very well to the mortar pump. The injection process was smooth without any difficulties and without the formation of bubbles or voids. When the amount of mixture in the pump's reservoir began to fall below the minimum required, we noticed air entering the hose, and the material stopped being injected. However, by adding more material to the reservoir, Kraftterra resumed being injected and fed into the printer's funnel.

Figure 15. A printed L-shaped wall.

The final cleaning phase after printing with Kraftterra proved to be even easier and faster than with earth mortar. Probably due to the presence of fibres incorporated into the soil, Kraftterra detached more easily from the surfaces of the funnel, extrusion nozzle, and screw. Using medium-pressure water jets, it was possible to remove almost all of the remaining material from the surfaces of the funnel, extrusion nozzle, and screw.

The entire cleaning process of the mortar pump after using Kraftterra (reservoir, screw, injection nozzle, and hose) was very quick and straightforward.

9. Relationship between Printing Speed and Extrusion Factor (RPSEF)

The FEUP 3D printer has a vertical extrusion system and a fixed extrusion nozzle, causing extruded materials to tend to be ejected in all directions upon contact with support surfaces. This occurs even when the strand widths are equal to the extrusion nozzle's diameter.

Various relationships between printing speed and extrusion factors (RPSEFs) can control the final widths of the print strands and walls as well as the vertical forces applied during layer overlap in the extrusion process. This can lead to sagging as the extrusion force is directly proportional to the increase in the strand width beyond the extrusion nozzle's exit diameter.

When earth mortar is extruded with RPSEFs that produces wider strands than the extrusion nozzle's exit diameter, it often results in finishes with less smooth textures and some material discontinuity. Such behaviour can be found in various 3D printing studies with earth mortars [7–10].

The use of superplasticisers in earth mortar can minimise or even eliminate the occurrence of finishes with less smooth textures or material discontinuity [11].

With different types of printers and mobile extrusion nozzles, it is possible to achieve a very smooth finish when printing earth mortars. For example, [12] used a robotic arm and an inclined extrusion nozzle. The extrusion nozzle moved forward and followed the axis of the print strand, causing the printed mortar to settle into the support layers. This provided minimal vertical forces, practically only its own weight. The material was not extruded in all directions, only in the direction of the strand to be printed.

With fixed vertical extrusion nozzles, when RPSEFs produce extrusion strands with the same width as the extrusion nozzle's exit diameter, there is a tendency for the print strands to have a smooth finish without material discontinuity, as was the case with the previously mentioned earth mortar test piece that later developed shrinkage cracks (Figures 10b and 16).

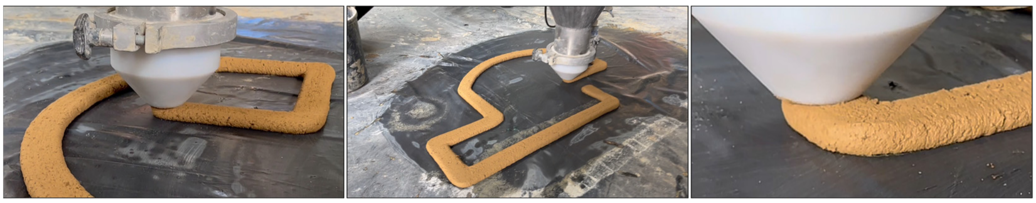

Figure 16. Smooth Finish Printing. An RPSEF was used that produced extrusion strands with the same width as the extrusion nozzle's exit diameter.

Several RPSEFs were tested, always using a 35 mm diameter extrusion nozzle, both for earth mortars and Kraftterra mortars. With both types of mortar, the RPSEFs produced similar finishes. The smoothest finish was achieved with earth mortar when using an RPSEF that produced a print strand width equal to the extrusion nozzle's exit width and with a very reduced printing speed (see Figure 14).

RPSEFs must be defined for each type of mortar and consistency. Final products can vary with changes in temperature and relative humidity. All prints in this study were produced in the summer, with temperatures ranging from 23 °C to 26 °C and relative humidity consistently near 70%.

10. Types of Finishes for Kraftterra-Printed Walls

Two L-shaped walls were produced using Kraftterra. Similar dimensions were used in the extrusion axis of 60.0 cm in length on the longer side, 40.0 cm on the shorter side, and 20.0 cm on the sides. The height was 30.0 cm with 20 layers, each 15 mm thick.

Both walls used an extrusion nozzle with a 35 mm exit diameter. The first wall was printed with a Printing Speed (PS) of 22 mm/s and an Extrusion Factor (EF) of 30, resulting in extrusion strands that were 5.5 cm wide. The second wall was printed with a PS of 40 mm/s and an EF of 40, resulting in a width of 7.5 cm. Neither wall exhibited any cracks during the drying and strength gain period.

Despite 3D printing allowing all operations to produce an object to be performed by a robotic device, the possibility of manual finishing was also explored solely to investigate its applicability. Surface smoothing procedures were carried out one and three days after the walls were printed. No deformations were detected in the walls resulting from the pressure of the smoothing tool.

The first wall retained its printed texture, while the second received a smooth finish produced with a simple trowel. This finishing was conducted without the addition of any material and was performed one day after printing. The use of steel trowels produced an even smoother and more uniform finish (Figure 17).

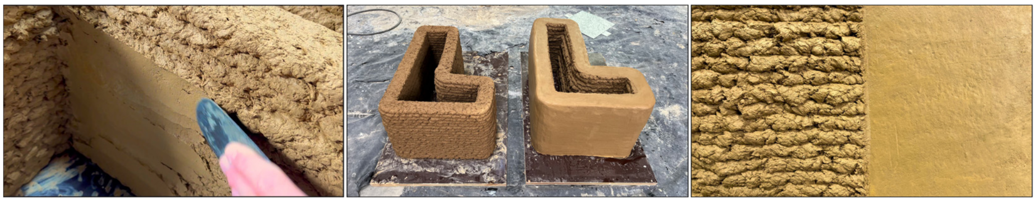

Figure 17. Types of finishes, printed texture, and smoothing.

The wall-smoothing process was easy and quick. One day after printing, the wall had already dried somewhat and exhibited good stability and strength-gain. However, its surfaces were still malleable and workable. The yellowish colour of the wall was enhanced and the finish produced using only a damp trowel not only provided good smoothing but also imparted a pleasant sheen to the surfaces.

Apparently, the material extruded to the sides during printing could be considered to be a plaster that could be smoothed later. When the choice is for walls with a smooth finish, one could eliminate a construction step, the application of plaster.

After printing another L-shaped wall with Kraftterra, we waited for three days to carry out the surface-smoothing process, also using a trowel. Three days after printing, the bulging surfaces of the print layers were still malleable, and the smoothing process continued to be quick and easy (Figure 18).

Figure 18. Surface-smoothing process for Kraftterra wall three days after printing.

11. Conclusions

Following the soil characterisation analyses, the production of adobes and prisms, the single compression resistance tests of adobes and prisms, and 3D printing using Melides soil mortar extrusion, it was affirmed that it is highly suitable to produce construction elements using both adobe techniques and 3D printing with mortar extrusion.

Furthermore, it can be stated that the Melides soil demonstrated excellent workability in 3D printing with the same consistency and the same percentage of water used in the mixtures for adobe production. This held true for mixtures containing only natural soil as well as mixtures incorporating dispersed fibres from the recycling of kraft paper packaging from cement bags, known as Kraftterra.

During the 3D printing process, cracks were observed during the drying and strength-gain period in some of the construction elements produced using only natural soil, especially when the layer widths were narrower (around 3.5 cm). With wider widths, the occurrence of cracks was reduced in terms of both the number and dimensions.

The incorporation of dispersed fibres from cement bags enhanced the use of earth mortar throughout the 3D printing process with mortar extrusion. Kraftterra exhibited good workability and excellent buildability, both with the injection pump and the large-scale 3D printer.

The FEUP printer has a fixed vertical extrusion nozzle, resulting in the production of construction elements with curved external surfaces in each layer. It was observed that the curved material remained malleable, at least for the first three days under the previously mentioned climatic conditions, making it possible to easily and quickly smooth the external surfaces and produce smooth and uniform finishes without the addition of new material. This finding allows for the elimination of some finishing steps for enclosure construction elements, such as roughcasting, plastering, and rendering, as well as material savings in comparison with other techniques.

This work reinforces and reaffirms that 3D printing with earth mortar has great potential for use in the construction industry. Furthermore, the incorporation of dispersed kraft paper fibres from cement bag recycling is an excellent resource to achieve good workability in 3D printing with earth mortar.

12. Final Remarks and Future Work

As emphasised earlier, these were initial studies and work conducted at FEUP on 3D printing with earth mortar. There is much to study and analyse to achieve the appropriate, correct, and safe use of earth in 3D printing processes.

For future work, we suggest conducting studies and analyses to better understand the relationship between the printing speed and the extrusion factor when using earth mortar in 3D printing, as this relationship directly affects the production and printing time of a construction, as well as the homogeneity of the construction elements.

The use of stabilisers such as cement, lime, and fibres should be part of future studies and analyses to ensure the production of quality, energy-efficient, safe, and durable buildings.

In this initial work, walls up to 30 cm in height were printed. Therefore, future research should focus on studying and analysing the entire production process of enclosure elements with heights commonly used in buildings. Studies and analyses are also needed to define how a relationship with other building systems occurs in printed constructions.

Author Contributions: Conceptualization, M.B., H.V. and M.A.R.; methodology, M.B., H.V. and M.A.R.; validation, M.B., H.V. and M.A.R.; formal analysis, M.B.; investigation, M.B.; resources, M.B.; data curation, M.B.; writing—original draft preparation, M.B., H.V. and M.A.R.; writing—review and editing, M.B.; supervision, H.V. and M.A.R.; project administration, M.A.R.; funding acquisition, M.B., H.V. and M.A.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by CONSELHO NACIONAL DE DESENVOLVIMENTO CIENTÍFICO E TECNOLÓGICO (CNPq), grant number PDE 201091/2022-4. This work was financially supported by: Base Funding—UIDB/04708/2020 and Programmatic Funding—UIDP/04708/2020 of the CONSTRUCT—Instituto de I&D em Estruturas e Construções—funded by national funds through the FCT/MCTES (PIDDAC). The research "EDIQUALI_3D PRINTING—Construction process with printed earth mortar" received support from the University of Brasília through Edital DPI—UnB N° 04/2019.

Data Availability Statement: Data are contained within the article. No new data were created or analysed in this study. Data sharing is not applicable to this article.

Acknowledgments: We would like to thank the support provided by the company OLIVEIRAS S.A. in the collection, transport, and provision of soil samples. We would like to thank the support provided by INSTITUTO DA CONSTRUÇÃO—IC in the purchasing and donation of some materials necessary to carry out the laboratory tests. We are also grateful for the support provided by VELURB—RENT A BIKE in donating some of the parts necessary to produce the manual 3D printer. We would like to express our gratitude for the assistance provided by the Centro da Terra Association, especially to the member and architect Maria Fernandes, for providing information on locations in Portugal for soil sampling. The authors would like to acknowledge the excellent work of the technicians from the Structural Laboratory of FEUP—namely, Paula Silva, Guilherme Nogueira, Cláudio Ferraz, and Nuno Pinto. We would also like to thank the support provided by FEUP postgraduate students—namely, Sofia Pessoa, Manuel Jesus, João Teixeira, Tassia Latorraca, Donatella Mazzola, and Stelladriana Volpe.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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