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First Impressions on 3D Printing with Earth-Based Mortar at FEUP

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Abstract: 3D printing with earth-based mortar is still under development and faces challenges. Optimizing the mortar mixture, improving structural strength, determining the relationship between printing speed and the amount of extruded material, and ensuring long-term durability are areas that are still 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 the 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 is 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: 3D printing; earth-based mortar; earth architecture; smooth and textured finishes

1. Introduction

3D printing can potentially be a sustainable alternative with up to 49% less environmental footprint and 78% greater cost-effectiveness compared to conventional construction techniques [1].

3D printing with natural soil is a 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 [2]. While digital construction with earth-based mortar is still in its early development compared to 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 [3].

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 stabilizers. This approach can significantly reduce the carbon footprint of constructions, as earth-based mortar is a material with lower embodied energy compared to 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 customized projects.

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

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Overall, 3D printing with earth-based mortar has the potential to revolutionize 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 increased adoption and a wider array of applications of this technology in the civil construction field.

2. 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, 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 meters in length by 3.0 meters in width by 3.0 meters 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, the 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 20mm to 60mm, making them suitable for extruding various materials, including cementitious mortars and earth-based mortars.

(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. Source: Authors.

3. Potentially suitable soil for 3d printing

As in any of the many techniques used in earthen architecture, the selection of soil potentially suitable 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's 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. This includes the sandy soils of the Aveiro region; the clayey soils near the Pateira de Fermentelos; the banks of the Lis River running through Leiria; the rural areas of Martingança; the Tomar region along 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 100km south of Lisbon, about 6km from Melides Beach, and around 150km 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, with approximately 29% clay content, very close to the traditionally recommended 30% by many authors and builders. About 1m3 of this soil, dry and sieved (4.76mm mesh), was made available for the initial studies and work.

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

The results of the soil characterization from Melides are as follows: grain size analysis (29.0% clay, 29% silt, 39% sand, 3% fine gravel); specific weight (26.6 kN/m^3); liquid limit - LL (34%); plastic limit - LP (18%); plasticity index (16%); expansiveness (14.7%).

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

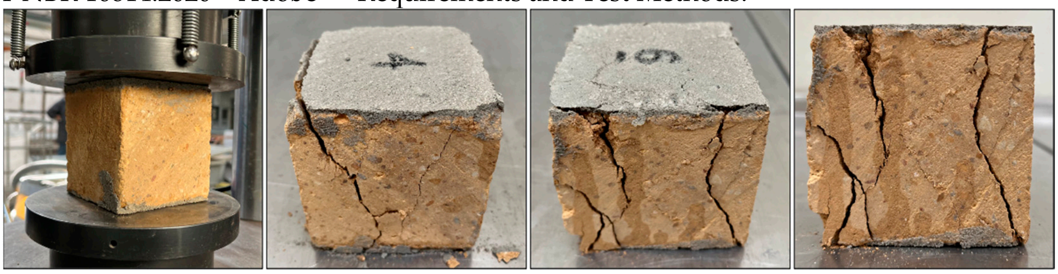

Figure 3. Specimens subjected to simple compression strength tests. Source: Authors.

Adobe bricks produced with only soil and water achieved an average of approximately 3.20 MPa of simple compression strength. The highest-performing specimen reached 3.88 MPa, while the lowest reached 2.57 MPa. The aforementioned standard stipulates that adobe bricks should have individual strength equal to or greater than 1.5 MPa (Table 1). 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 1. Simple compression strength tests of adobe bricks. Source: Authors.

	a1	**a2**	**b1**	**b2**	A_{rup}	**Rupture Strength** f_{rup} **(N)**	**Compressive Strength** f_{ca} **(MPa)**
1	80,75	80,91	86,66	85,05	6.939,66	23150,72492	3,336002929
2	79,50	80,69	80,36	82,62	6.526,94	22016,71377	3,373205291
3	80,70	81,00	79,54	79,02	6.409,79	20881,62079	3,257770895
4	80,63	82,57	79,84	80,96	6.560,64	17701,45521	2,69812933
5	81,00	81,93	79,90	81,41	6.570,56	25544,00414	3,887645161
6	78,33	80,92	80,27	77,80	6.293,16	19612,26091	3,116439923
7	80,88	82,09	82,65	84,70	6.818,26	25558,06339	3,748474425
8	82,98	81,87	80,74	83,18	6.755,55	21021,12696	3,111681155
9	85,61	83,96	81,97	82,10	6.955,34	20319,9707	2,921493137

10	84,02	82,97	83,55	81,25	6.879,99	17683,08654	2,57022055
11	83,03	82,78	80,29	82,65	6.754,27	23366,11748	3,459458427
12	81,54	81,20	82,04	80,37	6.607,65	19621,30442	2,969482629
13	81,89	80,17	82,06	79,90	6.561,81	21218,99575	3,233711078
14	82,12	83,60	83,05	81,77	6.828,49	21169,64534	3,100193056
Medium Compressive Strength (MPa)						f_{cam}	3,1988506
Sample Standard Deviation (MPa)						S_d	0,3613964
Compressive Characteristic Strength (MPa)						f_{caK}	2,6043535

4. 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 meters to match the characteristics and dimensions of FEUP's printer. Mortar was deposited into the funnel using plastic buckets (Figure 4a); 2) To initiate any print, a preparation of at least 25 kg 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 4b); 4) The mortar inserted into the funnel opening often accumulated on the less inclined sides, necessitating some procedure 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. Since this opposite side was difficult to access (Figure 4c), the deposited mortar frequently dried and hardened, resulting in waste and making the cleanup process challenging after printing.

(a) (b) (c)

Figure 4. (a) Material insertion into the funnel using buckets; (b) Limited opening for material insertion; (c) Less accessible opposite side of the funnel. Source: Authors.

Given the above and to optimize and avoid wasting the available soil sample in the study and 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 20mm to 60mm. The option was to use a mortar grouting gun (Figure 5), commercially available in construction supply stores. This device resembles a syringe with a cylindrical body with a 60mm 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 35mm, the same as one of the extrusion nozzles on FEUP's printer.

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

Figure 5. Grout gun used in consistency studies. Source: Authors (b,c), manufacturer's website (a,d).

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

To minimize or even avoid these situations, a manual 3D printer was designed and developed (Figure 6) capable of controlling the relationship between printing speed and the amount of extruded material and ensuring that prints occurred in a straight line. This manual printer was produced using a 2500x1250x15mm plywood sheet, which was cut using a CNC router. It features a system with side fins that allows printing ten overlapping layers of up to 30cm in length and 15mm in thickness, corresponding to the thickness of the plywood. A thickness of 15mm was chosen to achieve a ratio close to 2:1 between the width and thickness of the printed cord, as the extrusion nozzle to be used had a 35mm diameter opening. It also includes a system with a bicycle ratchet that allows for varying the amount of material to be extruded for the same 30cm path.

Figure 6. 3D Electronic model and manual 3D printer. Source: Authors.

As adobes were chosen as the reference material, and we initiated consistency studies using a soil and water mixture that closely resembled what we typically use in adobe production. The soil was sun-dried and then stored in big 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-liter tub, with a ratio of 1kg of soil to 250ml of water, resulting in a mixture with an average moisture content (w) of 24.5%. We produced some adobes with dimensions of 20x20x10cm (Figure 7ac), and the mixture proved to be suitable and very similar to what we typically use in adobe production. The adobes produced did not exhibit cracks and resulted in products with excellent visual appearance and good dimensional regularity (Figure 7b).

(a) (b) (c)

Figure 7. (a) Adobe production; (b) Adobes stored at FEUP to dry and gain strength; (c) Double formwork for producing 20x20x10cm adobes. Source: Authors.

For comparative consistency analyses, we varied the amount of water per kilogram of soil by 50ml, 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 in 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 to the base sample.

We proceeded to produce test specimens with the overlap of ten layers of extruded cords, each with a thickness of 1.5cm. The specimens with the base sample suffered minimal settling or crushing in the layers, resulting in a total height of 14.975cm at the end of printing (Figure 8a). On the other hand, the specimens with 100ml more water per kilogram of soil in the mixture showed a settlement of approximately 0.3cm (Figure 8b).

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

Figure 8. (a) settling measurement with the base sample; (b) settling measurement with a higher amount of water in the mixture. Source: Authors.

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

5. Workability with the base mixture

We initiated the 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 didn't allow the material to be poured out through the small lower opening of the mixer. Practically all 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 a lot of physical exertion to remove all the material from the various corners on the mixer blades (Figure 9a).

We opted for the use of other devices, a manual electric mixer and a 42-liter plastic bucket (Figure 9b). This time, the production on a larger scale of the soil mixture with the consistency of the base sample was easily accomplished. We used a single-shaft manual electric mixer, RUBIMIX model 9N, with a multi-material type shaft with an M14 thread, used for mixing high-density and low-flow materials (Figure 9c). In the end, the cleaning process was very quick and didn't require physical exertion. With medium-pressure water jets, almost all the material could be removed.

(a) (b) (c)

Figure 9. (a) settling measurement with the base sample; (b) settling measurement with a higher amount of water in the mixture. Source: Authors.

The base mixture, the same one used for adobe production, adapted very well to the extrusion process of the large-scale 3D printer. The earth mortar was extruded without difficulty through the extruder nozzle, 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 10).

(a) (b) (c)

Figure 10. (a) Extrusion of earth mortar with the base mixture; (b) Printing of a first layer; (c) Printed curved layers. Source: Authors.

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 since the printing volumes were always very small.

Compared to printing with cement mortars, the final cleaning process after earth mortar printing is much faster and easier. Only medium-pressure water jets are needed to remove almost all the material adhered to the funnel surfaces, the auger, and the extruder nozzle. What isn't removed with the water jet comes off easily with a fine sponge. Cleaning after cement mortar printing requires more physical effort, more time, and the use of brushes, sponges, and water jets, especially for cleaning the auger, which has many corners where cement mortars accumulate and harden. Removing cement mortar from certain parts of the funnel, especially the part opposite the insertion opening where material accumulates, is much more challenging than with earth mortar.

6. Performance of earth mortar in 3d printing

The prints with earth mortar produced construction elements that followed the dimensions and geometry of their electronic models correctly. They were stable, without sagging or layer crushing. However, the first models printed with the base mixture, soil and water, ended up showing several vertical cracks due to shrinkage in various regions on the first day after printing. In the subsequent days, these cracks increased and even separated some parts of the prototypes (Figure 11). This situation was expected, although the adobes produced with the same mortar, the same water content, and the same consistency did not show cracks. The walls of these first test samples, with a thickness of about 3.5cm, were much thinner than the dimensions of the adobes, with the smallest dimension being 10.0cm, which caused faster drying and higher shrinkage.

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

Figure 11. (a) Wall printed with the base sample just after printing; (b) One day after printing; (c) Two days after printing; (d) Three days after printing. Source: Authors.

The effects of shrinkage are also 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) [4]. In earth architecture, the use of natural fibres is common for stabilization and combating shrinkage.

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The use of natural fibres to stabilize 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 with soil and fibres from cement bag packaging was called, was presented in 2009, with the ideal proportion of fibres in the mixture being 6% by mass [5].

To disperse the fibres from the kraft paper from 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 12a-bc), and a Bosch AXT Rapid 2000 garden shredder (Figure 12d). The entire procedure for fibre dispersion followed the recommendations found in Buson's doctoral thesis [5].

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

Figure 12. (a) Manual electric mixer with adapted shaft; (b-c) Detail of stainless-steel shaft for fibre dispersion; (d) Garden shredder; (e) Dispersed fibres from recycling cement bag packaging. Source: Authors.

The Kraftterra mixture, suitable for adobe production due to the addition of dispersed fibres, needs slightly more water than the mixture with soil alone. For every 1kg of soil, 60g of fibres and 333ml of water are required (Figure 13). The moisture content of the Kraftterra mixture with these proportions was 36.87%. The 6% by mass volume of fibres is approximately half the volume of soil to be added to the Kraftterra mixture.

Figure 13. Proportions of soil, dispersed fibres, and water in Kraftterra. Source: Authors.

7. Performance of Kraftterra mortar in 3d printing

Prints with Kraftterra mortar produced construction elements that adhered correctly 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 entirely. The dimensions at the end of printing remained virtually unchanged after drying and gaining strength.

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

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

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However, to verify the performance and workability of Kraftterra with the mortar pump, we printed an "L"-shaped wall measuring 60.0cm on the longer side, 40.0cm on the shorter side, and 20.0cm on the sides, with a height of 30.0cm, consisting of 20 layers, each with a thickness of 15mm. Kraftterra adapted very well to the mortar pump. The injection process went smoothly without any difficulty 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 a bit more material to the reservoir, Kraftterra resumed being injected and fed into the printer's funnel.

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 detaches more easily from the surfaces of the funnel, extrusion nozzle, and screw. Using medium-pressure water jets, it's possible to remove almost all 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.

8. 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 Factor (RPSEF) 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 or not, as the extrusion force will be directly proportional to the increase in the strand width beyond the extrusion nozzle's exit diameter.

When earth mortar is extruded with RPSEF 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 [6-9].

The use of superplasticizers in earth mortar can minimize or even eliminate the occurrence of finishes with less smooth textures or material discontinuity [10].

With different types of printers and mobile extrusion nozzles, it is possible to achieve a very smooth finish when printing earth mortars. For example, [11] 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, providing minimal vertical forces, practically only its own weight. The material was not extruded in all directions but only in the direction of the strand to be printed.

With fixed vertical extrusion nozzles, when RPSEF produces 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 (Figure 10b and Figure 14).

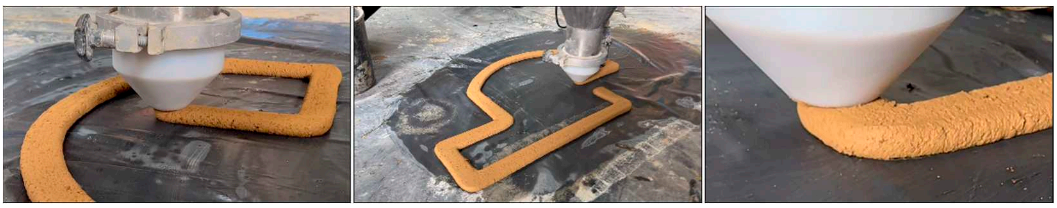

Figure 14. Smooth Finish Printing. An RPSEF was used that produced extrusion strands with the same width as the extrusion nozzle's exit diameter. Source: Authors.

Several RPSEF were tested, always with a 35mm diameter extrusion nozzle, both with earth mortars and Kraftterra mortars. With both types of mortar, RPSEF produced similar finishes. The smoothest finish was achieved with earth mortar when using an RPSEF that produced a print strand

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width equal to the extrusion nozzle's exit width and with a very reduced printing speed (see Figure 14).

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

9. Types of finishes for Kraftterra printed walls

Two L-shaped walls were produced using Kraftterra. Similar dimensions were used in the extrusion axis: 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.

The first wall retained its printed texture, while the second received a smooth finish produced with a simple trowel. This finishing was done without the addition of any material and was performed one day after printing. The use of steel trowels could produce an even smoother and more uniform finish (Figure 15).

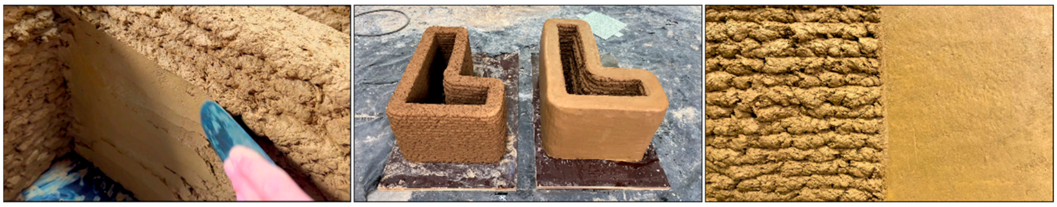

Figure 15. Types of finishes, printed texture, and smooth. Source: Authors.

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 only with 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 can be considered as a plaster to be smoothed later. In this way, when the choice is for walls with a smooth finish, one can eliminate a construction step, namely, 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 16).

Figure 16. Surface smoothing process for Kraftterra wall after three days of printing. Source: Authors.

10. Comparison between the performance of adobe prisms and printed ones

In accordance with NBR 16814:2020 Adobe — Requirements and Test Methods [12], six earth adobe prisms or small walls (Figure 17a) with dimensions of 19.0 cm x 19.0 cm x 48.0 cm were produced, along with three printed prisms or small walls (Figure 17bc) using earth mortar.

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The dimensions of the small walls resulted in slender elements that underwent lateral deformations during the printing process. The walls did not maintain good vertical alignment due to the movement of the extrusion nozzle when traveling from the endpoint of one layer to the starting point of the subsequent layer, as well as due to a slight overlap of material in the same layer while following the spiral path that produced the solid element without voids. The extrusion nozzle ended up pushing the wall laterally as it moved in a spiral and diagonally at the end of the layer, causing small lateral deformations layer by layer. These small movements also led to some sagging in the lower layers, resulting in slightly larger external dimensions than those of the upper parts (Figure 17c).

(a) (b) (c)

Figure 17. (a) Adobe prisms; (b) Printed prisms; (c) Printed prisms with lateral deformations caused by the printing process. Source: Authors.

Given the deformations and sagging that occurred with the printed prisms, the dimensions at the midpoint of their heights, as well as the total height, were recorded for the single compression resistance tests of these printed prisms.

The prisms produced with adobes achieved an average single compression resistance of 2.33 MPa. The adobe prism with the highest performance reached 2.59 MPa, while the lowest performing one reached 2.18 MPa. On the other hand, the printed prisms achieved an average single compression resistance of 1.37 MPa. The printed prism with the highest performance reached 1.56 MPa, while the lowest performing one reached 1.04 MPa (Table 2). It should be noted that printed prism P7 had the greatest vertical misalignment.

Table 2. Single compression resistance tests of adobe (A) and printed prisms (P). Source: Authors.

	a1	a2	b1	b2	A_{rup}	Rupture Strength f_{rup} (N)	Compressive Strength f_{ca} (MPa)
A1	190,00	190,00	190,00	190,00	36.100,00	78707,9	2,180274238
A2	190,00	190,00	190,00	190,00	36.100,00	93774,54	2,597632687
A3	190,00	190,00	190,00	190,00	36.100,00	86950,61	2,408604155
A4	190,00	190,00	190,00	190,00	36.100,00	80813,26	2,23859446
A5	190,00	190,00	190,00	190,00	36.100,00	83069,98	2,301107479
A6	190,00	190,00	190,00	190,00	36.100,00	81853,43	2,267408033
P7	161,00	158,00	180,00	175,00	28.311,25	29598,64	1,045472736
P8	161,00	157,00	178,00	176,00	28.143,00	44120,77	1,567735138
P9	173,00	170,00	170,00	166,00	28.812,00	43265,02	1,501631959
						ADOBE PRISMS	PRINTED PRISMS
Medium Compressive Strength (MPa) f_{cam}						2,332270	1,371613
Sample Standard Deviation (MPa) S_d						0,150532	0,284373
Compressive Characteristic Strength (MPa) f_{caK}						2,084644	0,903819

11. Conclusions

Following the soil characterization analyses, the production of adobes and prisms, the single compression resistance tests of adobes and prisms, and the 3D printing with Melides soil mortar extrusion, it can be 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

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production. This held true for mixtures containing only natural soil as well as mixtures with the incorporation of 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 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 to other techniques.

The comparison between adobe and printed prisms regarding single compression resistance was compromised due to deformations and vertical misalignments occurring with the printed test specimens. Nevertheless, it can be concluded from this activity that very slender printed elements are prone to potential vertical misalignments caused by the printing process if the printing lines of the same layer overlap, even slightly. Therefore, for very slender elements, it is suggested that the printing lines do not touch laterally within the same layer and that, at no point, should the printing path pass over printed lines from the same layer to avoid dragging or lateral displacement.

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 for achieving good workability in 3D printing with earth mortar.

12. Final remarks and future work

As emphasized earlier, these were the 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 printing speed and 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 stabilizers 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 the relationship with other building systems occurs in printed constructions.

Studies and analyses to characterize the physical-mechanical properties should be conducted, aiming not only at defining the performance of construction elements but also at standardizing procedures.

The production of prototypes and post-occupancy analyses are essential to understand the behaviour and performance of buildings during their post-construction periods, especially in the early years of use and maintenance. They also serve to characterize and qualify energy efficiency during use and compare it with simulations used in the design phase.

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