3D PRINTING WITH NATURAL MATERIALS IN CIVIL CONSTRUCTION: APPLICATIONS FOR THE THERMAL PERFORMANCE OF BUILDINGS

IMPRESSÃO 3D COM MATERIAIS NATURAIS NA CONSTRUÇÃO CIVIL: APLICAÇÕESVOLTADAS AO DESEMPENHO TÉRMICO DE EDIFICAÇÕES

IMPRESIÓN 3D CON MATERIALES NATURALES EN LA CONSTRUCCIÓN CIVIL: APLICACIONES ENFOCADAS EN EL RENDIMIENTO TÉRMICO DE LAS EDIFICACIONES

LUANA TORALLES CARBONARI, Dra. | UEL – Universidade Estadual de Londrina, Brasil
BERENICE MARTINS TORALLES, Dra. | UEL – Universidade Estadual de Londrina, Brasil
LISIANE ILHA LIBRELOTTO, Dra. | UFSC– Universidade Federal de Santa Catarina, Brasil
MONIQUE DE BRITO FILGUEIRAS, Msc. | UEL – Universidade Estadual de Londrina, Brasil
THALITA GORBAN FERREIRA GIGLIO, Dra. | UEL – Universidade Estadual de Londrina, Brasil

ABSTRACT
The construction industry has experienced a number of transformations due to the use of digitalization and automation. Additive manufacturing, also known as 3D printing, is a current example. The purpose of this paper is to analyze the use of natural materials based on soil applied to 3D printing technology, with a focus on the thermal performance of buildings. A exploratory literature review was used to identify applied research that has explored these materials. The data obtained was systematized in a comparative table to identify the main strategies used. The analysis of applied research indicates that construction using 3D printing with materials based on soil is promising, taking advantage of the soil's natural thermal insulation properties and being able to incorporate parametric design and digital fabrication strategies to create complex, customized solutions for different contexts.

KEYWORDS
Civil Construction; Additive Manufacturing; Soil; Earth construction; Thermal Performance.

RESUMO
A construção civil tem passado por diversas transformações devido ao emprego da digitalização e automação. Um exemplo atual é a manufatura aditiva, também chamada de impressão 3D. Este artigo visa analisar o uso de materiais naturais a base de solo e argila aplicados à tecnologia de impressão 3D com foco no desempenho térmico das edificações. Utilizou-se de revisão bibliográfica exploratória para identificar pesquisas aplicadas que têm explorado esses materiais. Os dados obtidos foram sistematizados em um quadro comparativo para identificar as principais estratégias utilizadas. A análise das pesquisas aplicadas indica que a construção com o uso da impressão 3D com materiais a base de solo e argila é promissora, aproveitando as propriedades naturais do solo de isolamento térmico, podendo incorporar estratégias de design paramétrico e fabricação digital para criar soluções complexas e personalizadas para os diferentes contextos.

PALAVRAS-CHAVE
Construção Civil; Manufatura Aditiva; Solo; Construção com Terra; Desempenho Térmico.

http://dx.doi.org/10.29183/2447-3073.MIX2024.v10.n4.17-29
ISSN: 2447-0899 (IMPRESSA) | 2447-3073 (ONLINE)

RESUMEN

La construcción civil ha experimentado diversas transformaciones debido al empleo de la digitalización y la automatización. Un ejemplo actual es la manufactura aditiva, también conocida como impresión 3D. Este artículo tiene como objetivo analizar el uso de materiales naturales a base de suelo y arcilla aplicados a la tecnología de impresión 3D con un enfoque en el rendimiento térmico de las edificaciones. Se utilizó una revisión bibliográfica exploratoria para identificar investigaciones aplicadas que han explorado estos materiales. Los datos obtenidos fueron sistematizados en un cuadro comparativo para identificar las principales estrategias utilizadas. El análisis de las investigaciones aplicadas indica que la construcción con el uso de la impresión 3D con materiales a base de suelo y arcilla es prometedora, aprovechando las propiedades naturales del suelo para el aislamiento térmico, pudiendo incorporar estrategias de diseño paramétrico y fabricación digital para crear soluciones complejas y personalizadas para diferentes contextos.

PALABRAS CLAVE

Construcción Civil; Manufactura Aditiva; Suelo; Construcción con Tierra; Desempeño Térmico.

1. INTRODUCTION

According to the International Energy Agency (IEA), the building sector is responsible for 36% of global final energy consumption and 39% of total direct and indirect CO2 emissions (INTERNATIONAL ENERGY AGENCY, 2018). In addition, cooling systems represent 60% of total energy in buildings worldwide, as thermal comfort is one of the main priorities, especially in hot climates (AL-OBAIDI *et al*., 2017). Due to this, various studies have sought alternatives for more optimized construction, with less environmental impact and better thermal performance, as well as greater savings in time, materials and costs, seeking to promote energy conservation and reduce carbon emissions (ALHUMAYANI *et al*., 2020; WENG *et al*., 2020). In this sense, one technology that has been increasingly explored is additive manufacturing, which combines manufacturing with digital fabrication, also known as 3D printing (COSTA; RIBEIRO, 2020; PESSOA *et al*., 2021).

The use of additive manufacturing in construction meets current issues such as Smart Cities, Sustainable Development and Digital Transformation, incorporating the concepts of digitization, automation and connectivity of Industry 4.0. 3D printing could make construction more efficient and provide sustainable growth, stimulating the principles of circularity, with the use of recycled and environmentally friendly materials (PESSOA *et al*., 2021). Cement-based materials have proven to be suitable for 3D printing, but they are one of the biggest contributors to the environmental footprint of construction, due to their high energy consumption and CO2 emissions during clinker production (COSTA; RIBEIRO, 2020).

Because of this, applied research has been carried out using alternative materials in order to reduce the environmental impact of buildings (AKMAN; SADHU, 2024; FIGLIOLA; BATTISTI, 2021). The materials that have been most studied and which have properties similar to those of concrete are: Portland cement-based materials with mineral additions; geopolymeric materials; gypsum-based materials; and soil-based materials (TEIXEIRA *et al*., 2023).

Environmental and sustainability concerns are central to discussions about the future of construction, and soil-based building materials are among the most eco-friendly options available. Earth is a widely available resource, and structures made from local soils can be found in nearly every part of the globe. Over the past twenty years, numerous building codes, guidelines, and standards for earthen construction have been developed worldwide. These are based on extensive research and field observations on the seismic, thermal, and moisture durability of earthen buildings, paving the way for a burgeoning revival in earth-based construction (FRATELLO; RAEL, 2020).

Therefore, the aim of this study is to analyze the use of natural materials based on soil applied to 3D printing technology with a focus on the thermal performance of buildings, in order to identify the main design and construction strategies that have been used.

In 2015, the UN established the "2030 Agenda for Sustainable Development", with the definition of 17 Sustainable Development Goals, to be implemented worldwide over the next 15 years. Among the goals of this agenda, this research adheres to those numbered 9 "Industry, innovation and infrastructure", 11 "Sustainable cities and communities", 12 "Responsible consumption and production", 13 "Action against global climate change" and 15 "Life on land" (NAÇÕES UNIDAS, 2024). Thus, this study addresses current problems affecting social well-being around the world, especially considering the major impact of the construction sector on the environment and the thermal performance of buildings.

2. METHODOLOGICAL PROCEDURES

The methodology applied is based on an exploratory literature review to identify applied research using 3D printing technology with natural materials based on soil. The following categories of analysis were evaluated in each case: a) general characteristics; b) composition of the printing material; and c) aspects related to thermal performance.

The selection of more than one case allowed for a comparative analysis, highlighting aspects of convergence and divergence between them. The qualitative analysis of the data was carried out through the process of analysis-reflection-synthesis (PATRICIO-KARNOPP, 2004), using the content analysis technique (BARDIN, 1991) to evaluate the information.

3. RESULTS AND DISCUSSIONS

Although the use of 3D printing technology is still relatively new in large-scale construction, with some limitations, it promotes the reuse of traditional materials. This could revitalize the use of natural materials in order to replace energy- and carbon-intensive industrial materials (EL-MAHDY; GABR; ABDELMOHSEN, 2021). Natural materials based on soil are increasingly being used in 3D printing construction as they are recyclable, low-cost and have a low environmental impact (ALHUMAYANI *et al*.,

2020; KONTOVOURKIS; TRYFONOS, 2020; LIBRELOTTO *et al*., 2023; PERROT; RANGEARD; COURTEILLE, 2018). Their application is similar to cement-based digital construction technology (GOMAA *et al*., 2019).

The main properties of these materials highlighted in the literature are (ALHUMAYANI *et al*., 2020; KONTOVOURKIS; TRYFONOS, 2020; PERROT; RANGEARD; COURTEILLE, 2018; TEIXEIRA *et al*., 2023):

- Fresh state properties: biopolymers such as alginate can be used to improve shape retention;
- Mechanical performance and durability: the material achieves mechanical performance similar to conventional earth construction;
- Texture: they are smoother when printed with a circular nozzle; and
- Color possibilities: shades of brown and yellow.

In order to evaluate aspects related to thermal performance, which is another important property of soil-based materials applied to 3D printing technology, the results of some applied research were analyzed and will be described below.

3.1 WASP 3D printing technology

a) General characteristics:

The Italian company WASP (World's Advanced Saving Project) has a humanitarian character and environmental principles of ecology and sustainability. Its aim is to develop ecologically sustainable buildings and structures, using natural materials such as soil and agricultural waste, and to build houses in poor, densely populated areas or those devastated by natural disasters, with low costs, energy consumption and environmental pollution (WASP, 2024).

One of the technologies developed by the company is the WASP Crane system, which is a collaborative modular manufacturing system consisting of a main printer unit that can be assembled in various configurations, depending on the printing area and the size of the architectural object to be built. The single module has a diameter of 6.60 m and a height of 3 m and can be extended by adding crossbars and printer arms. This construction strategy implies a potentially infinite print area, as the individual modules can be reconfigured and advanced with a generative attitude (WASP, 2024).

One of the main projects developed by WASP is the "Gaia" houses (Figure 1a and 1b), printed in 2018 in Italy. The walls of the houses were printed layer by layer using the WASP Crane system. The houses have an area of 30 m^2 and it took 10 days to build the external walls, which are 40 cm thick. The roof of the houses was made of wood and the foundations were printed in concrete. Door and window frames were installed during the construction process, as well as the electrical and plumbing systems. The total cost of the materials used in the wall construction was 900 euros (VALENTE; SIBAI; SAMBUCCI, 2019).

b) Printing material:

Material composed of a mixture of 25% local soil (mixture of sand, soil and silt), 40% chopped rice straw, 10% rice husk and 10% hydraulic lime. Muller (SOOD, 2018) was used to make the mixture homogeneous and workable.

c) Aspects related to thermal performance:

In the process of printing the walls, internal vertical cavities were created and filled with waste from rice production (Figure 2a), such as chopped rice husks and straws, filling the voids for thermal insulation. In addition, the walls were designed with the aim of integrating natural ventilation systems and thermoacoustic insulation systems (VALENTE; SIBAI; SAMBUCCI, 2019).

According to the WASP company, this method of insulation keeps the internal temperature of the house comfortable, avoiding the need for heating or cooling. Rice husks have also been used to create a cladding for the inside of walls and as an insulation layer on the top of the roof (Figure 2b) (JORDAHN, 2019).

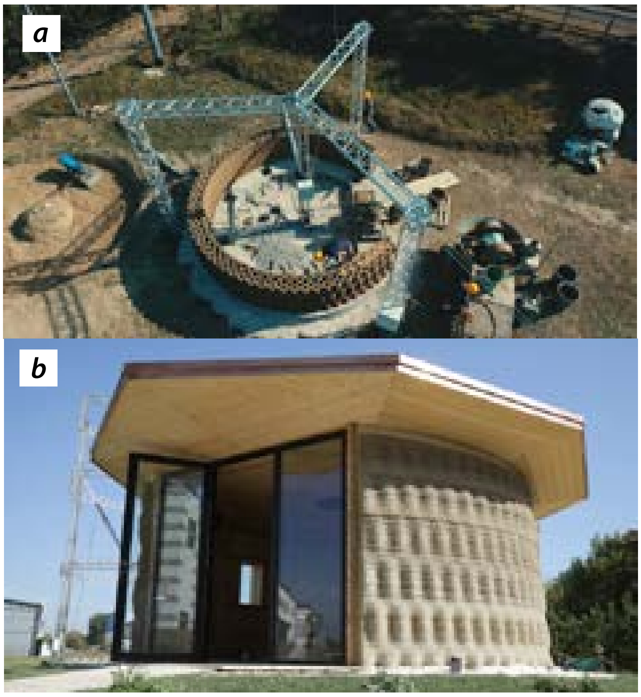

Figure 1: (a) Gaia House being built; (b) Gaia House finished.
Source: (JORDAHN, 2019).

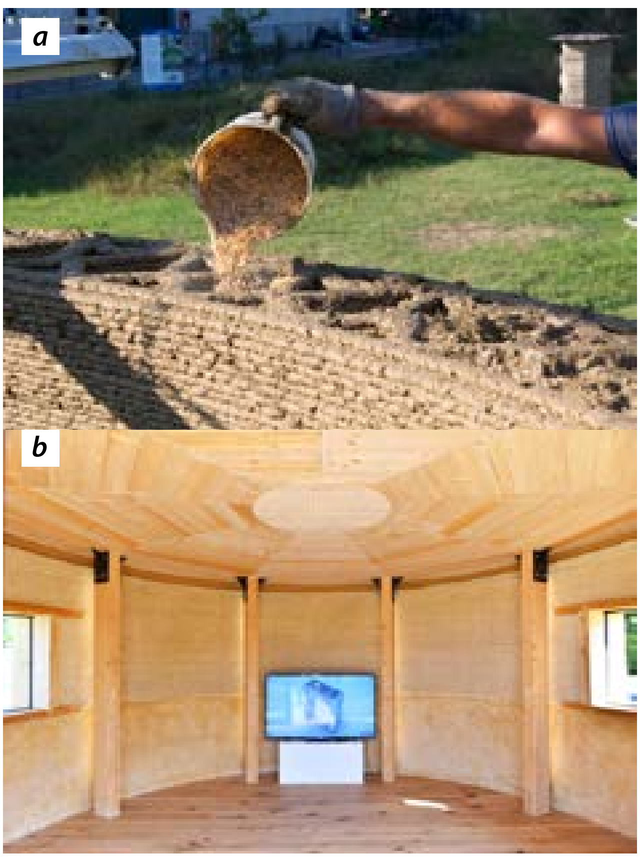

Figure 2: a) Filling the walls with waste; b) Internal cladding.
Source: (JORDAHN, 2019).

3.2 TECLA - 3D Printed House

a) General characteristics:

The TECLA (Technology and Clay) House is the result of a collaboratige research made by the SOS (School of Sustainability), the Mario Cucinella Architects and the 3D printing technology of WASP. The house is located in Massa Lombarda, Ravenna-Italy, and it aims to responds to the increasingly climate emergency, to the need for sustainable homes at Km0 and to the great global issue of the housing emergency, particularly in the context of urgent crises generated by large migrations or natural disasters (PINTOS, 2021).

For the building WASP's 3D printing technology Crane WASP was used. The 3D printer is modular and multilevel. It consists of a stationary fixture with two synchronized printer arms that can simultaneously print an area of 50 m^3 each (Figura 3b). The TECLA house brings together research on vernacular construction practices, the study of bioclimatic principles and the use of natural materials. It is a nearly zero-emission project that uses entirely local material, combining the matter and spirit of timeless ancient homes with the world of 21st-century technological production (PINTOS, 2021; WASP, 2019).

The TECLA House project is the result of a composition of two continuous elements that through a sinuous and uninterrupted sine curve culminate in two circular skylights (Figura 3a e b) (PINTOS, 2021).

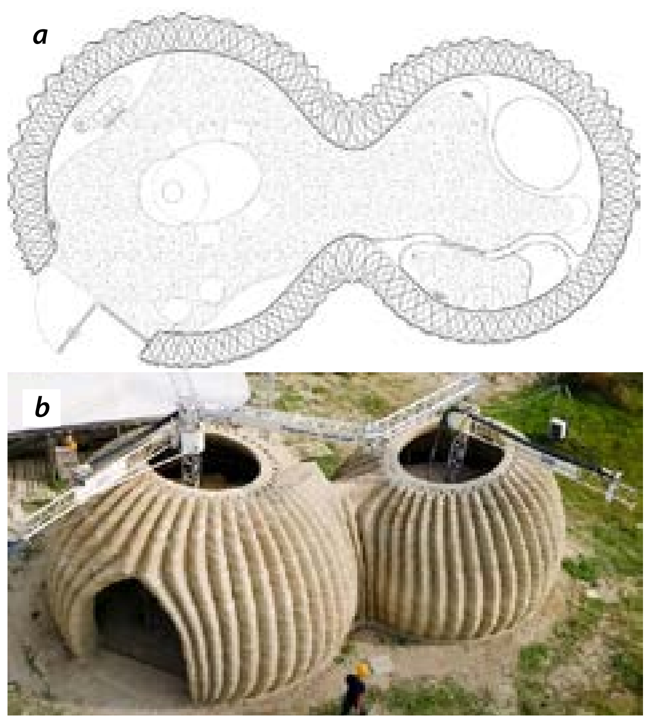

Figure 3: (a) TECLA House floor plan; and (b) House printing
Source: (PINTOS, 2021)

The shape designed enabled the structural balance of the construction, both during the 3D printing phase of the envelope and once the covering is completed (Figura 4a) (PINTOS, 2021).

With an area of about 60 m^2, it comprises a living zone with a kitchen and a night zone which includes services. The furnishings were partly printed in local soil and integrated into the raw-earth structure, and partly designed to be recycled or reused (Figura 4b). The house can be delivered with 200 hours of printing, 350 12 mm layers, 150 km of extrusion, 60 cubic meters of natural materials for an average consumption of less than 6 kW (PINTOS, 2021).

Figure 4: (a) TECLA house finished externally; (b) internally
Source: (PINTOS, 2021)

b) Printing material:

Mapei (2019) developed a specific mix-design with locally sourced soil in order to obtain a mix with rheological properties suitable for the printing phase and with mechanical properties suitable for the type of use. The mix is composed by a powdered stabilising agent used to consolidate soil (MAPESOIL, 100), a super-plasticising admixture (DYNAMON SR4), a synthetic latex rubber (PLANICRETE), and a ready-mixed water-repellent (PLANISEAL WR 100) applied with a spray bottle on dry facing walls, highly effective in waterproofing structures after just 12 hours.

c) Aspects related to thermal performance:

The composition of the earth mixture and the building's shape were designed to respond to local climatic conditions. The geometry of the envelope is parametrically optimised to balance thermal mass, insulation and ventilation according to the local climate needs (Figure 5a e b). The infilling material for thermal insulation consists of rice husk and rice straw from rice cultivation waste (PINTOS, 2021; WASP, 2019).

Figure 5: (a) and (b) Wall section geometry
Source: (WASP, 2019)

3.3 IAAC's Pylos, Digital adobe and TerraPerforma projects

a) General characteristics:

The Institute of Advanced Architecture of Catalonia (IAAC) has developed a series of applied research projects related to the digitization of soil-based materials produced using 3D printing. The Pylos project was the first to be developed by the IAAC, aimed at large-scale construction based on the use of biodegradable and recyclable soil, seeking to optimize the mix by using locally available natural materials. The research aimed to build printed soil columns to explore the potential for customizing the shape according to performance criteria and the technical advantages of the robotic production procedure (FIGLIOLA; BATTISTI, 2021; IAAC, 2024c). In addition, the project's main objective is to develop solutions for housing construction in developing countries, or in densely urbanized areas in developed countries. Due to the associated low cost, it should provide easier and cheaper access to housing for the neediest people. The estimated price is 0.5 euros per kilogram .

The project focuses on the natural properties of soil, whose main advantages are thermal insulation, fire protection, air circulation, low initial cost, recyclable structures, structural rigidity, low CO2 emissions and climate control. The importance of the chosen material (soil) for this additive manufacturing research is not only related to the unlimited quantity available, but also to the decrease in the emerging degree of energy incorporated into the manufacturing process, transportation risks, independent production of electricity and the availability of fuel (IAAC, 2024c; VALENCIA, 2015).

Based on the results of the Pylos project, the IAAC continues to examine the correlation between performance-based morphologies and robotic additive manufacturing through the Open Thesis Fabrication (OTF) research program. The Digital Adobe and TerraPerforma projects use the same material and method as Pylos, but with a focus on full-scale printing of unconventional shapes, such as modular curved walls, with self-shading properties and climate-appropriate performance design (IAAC, 2024a, 2024b; KONTOVOURKIS; TRYFONOS, 2020).

During OTF 2016/2017, TerraPerforma built a 1:1 scale experimental prototype (Figure 6a and b) to study optimized geometric patterns for thermal and structural performance, as well as analyzing a module to enable an easy and quick assembly process, directly on site. The modular approach was considered best due to the difficulties of taking a robot outdoors and facing adverse weather conditions. The modules are designed parametrically to perform optimally depending on solar radiation, wind behavior and the structural reasoning of 3D printing, both on their own and as a complete project (FIGLIOLA; BATTISTI, 2021).

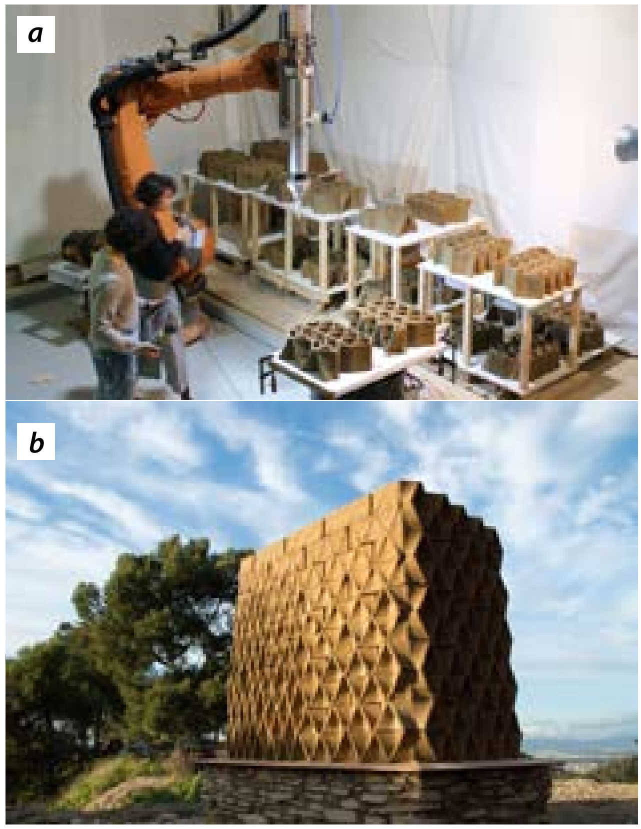

Figure 6: a) and b) Modules and 1:1 scale prototype of the TerraPerforma project.
Source: (IAAC, 2024a)

b) Printing material:

The material created by the IAAC is made up of 96% soil, plus additives to improve its characteristics.

c.1) Aspects related to the thermal performance of the TerraPerforma project:

The complex morphology of the external surface of the prototype developed by TerraPerforma was defined considering the angle of incidence of direct solar radiation and natural ventilation. The aim was to reduce the temperature of the external surface through self-shading in order to minimize radiation from the east and west directions, thereby reducing the thermal load required to provide cooling for a building (FIGLIOLA; BATTISTI, 2021). This way, during winter the conductivity of the facade is maximized as there is maximum penetration, also, in comparison to a straight wall, there is a 436% rise in total radiation (GIRAUD, 2017).

The interior infill is divided into two zones. One zone is primarily optimized for structural performance with some thermal optimization, featuring small closed cavities that act as insulation. The other zone is optimized solely for thermal performance, containing large cavities of stagnant air. These large cavities, combined with the branched infill, significantly increase the thermal lag of the wall (GIRAUD, 2017).

In addition, the modules were designed to incorporate various types of openings in order to maximize the potential of natural light (the openings are strategically positioned and range from micro-openings to complete openings between the elements). The same panels were also designed to aid wind behavior through convection properties, as well as the placement of the micro-perforation that would direct the airflow. To this end, simulations and physical tests were carried out on prototype walls (Figure 7a and b), testing solar radiation, daylight, thermal conductivity, convection, thermal mass and structural behavior (DUBOR; CABAY; CHRONIS, 2018).

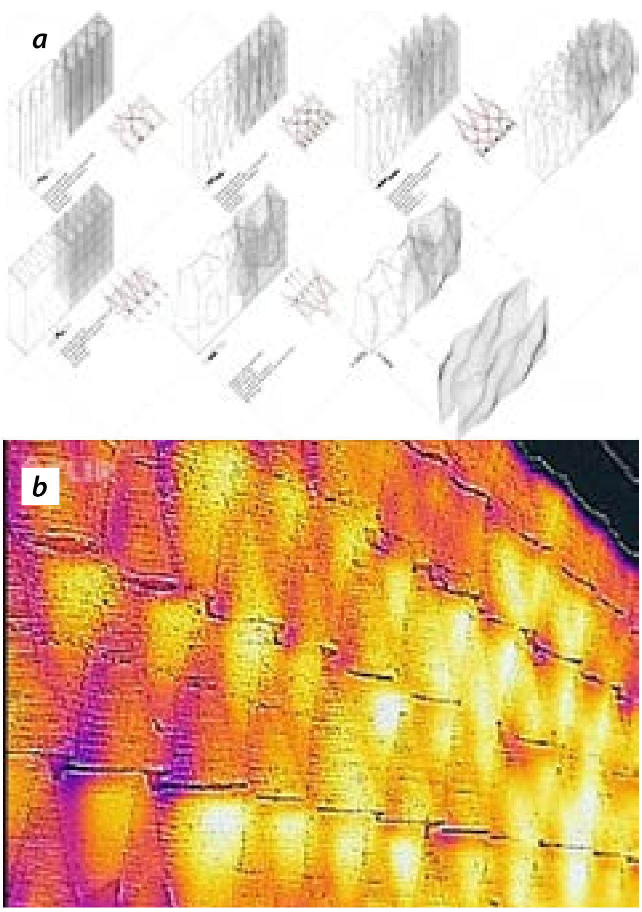

Figure 7: a) Graph of conceptual geometries for controlling conductivity by design; b) thermographic analysis.
Source: (IAAC, 2024a)

In general, the research conducted by TerraPerforma investigates how thermal properties can be integrated into wall sections through the intelligent design of infill. Specifically, it examines the potential for controlling thermal lag by managing conductance. This goal can be achieved by exploring the relationship between various infill patterns and the air-filled hollow cavities within the wall (GIRAUD, 2017).

Digital Adobe:

Digital Adobe is a research project on 3D printing for Performative Habitat, which was developed in the OTF 2017-18 program. The research concluded with the construction of a 1:1 prototype (Figure 8a and b) of a wall that adapts its morphology to local structural and climatic needs (IAAC, 2024a).

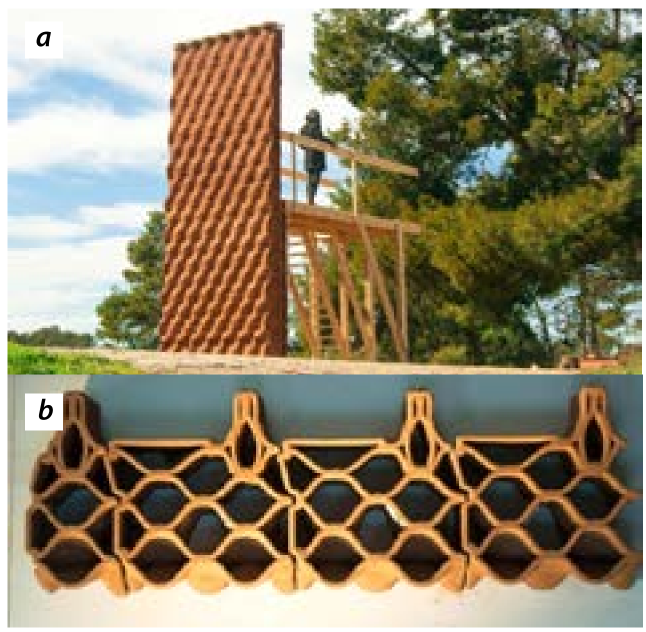

Figure 8: a) Wall built by the Digital adobe; b) wall modules.
Source: (IAAC, 2024a)

c.2) Aspects related to the thermal performance of the Digital Adobe project:

In this study, a ventilated wall design was developed, with operable openings at the top and bottom, to reduce heat gain in summer through convection between the openings and to retain heat in winter when the openings are closed. The external geometry consists of a surface of protrusions for self-shading, optimizing cooling in summer and the absorption of solar radiation in winter, taking into account the solar incidence angles of the site (Barcelona), so that the west direction has greater heat gain, while the east direction has less heat gain depending on the solar incidence throughout the day. Thus, there is more thermal mass and less ventilation on the west wall, and less thermal mass and more ventilation on the east wall. The internal wall cavities are filled with earth to act as thermal mass and with air for insulation. The final project resulted in 99 individual elements, assembled in 5 days on the campus of the IAAC Laboratory in 2018 (IAAC, 2024a).

3.4 3D printed Cob

a) General characteristics:

3D printed Cob is an applied research that explores a construction technique based on robotically extruded subsoil and local organic fibers. This technique is an attempt to examine the transition from vernacular construction to a digitally enabled process. In a study carried out by researchers (GOMAA *et al*., 2019), the thermal conductivity of four 3D-printed samples is evaluated and the result is then compared with seven samples that were built using manual techniques. The printed samples have dimensions of 300×300×90 mm and the manually constructed samples have 300×300×70 mm. The samples were printed at Cardiff University, UK, using a Kuka KR60HA robot and a customized material extrusion system.

Each sample took around two hours to produce and was designed to represent a different thermal wall insulation solution. The first was designed as a solid wall; the second as a double-layer wall with a single continuous air space; the third as a triple-layer wall with air pockets; and the fourth was designed as a double-layer wall with straw-filled pockets (Figure 9) (GOMAA *et al*., 2019).

b) Printing material:

Mixture of subsoil (72-73 %), fiber (2 %) and water (25-26 %). The subsoil used is composed of clay (21.5 %) and aggregate/sand (79.5 %) (GOMAA *et al*., 2019).

c) Aspects related to thermal performance:

To assess the thermal performance of the material, thermal conductivity tests were carried out with a heat flow meter. The results show that the four samples have approximate thermal conductivity (0.32, 0.37, 0.40, 0.48 W/mk), with a 10% difference between them. However, it can be seen that the cavities in the three samples affect their performance and provide relatively better conductivity in relation to their density manufacturing (GOMAA et al., 2019).

In addition, the results indicate that the combination of air cavities with the addition of straw significantly improves conductivity in relation to its density. Specifically, the straw-filled airlock sample showed a 15.0% improvement in conductivity (0.32 W/mk) and an 8.0% increase in density compared to the airlock sample without straw. In terms of absolute conductivity, this sample showed the best result among the printed samples due to its lower conductivity, regardless of density. Although the 3D printed samples did not significantly outperform the handmade samples, the research results suggest that 3D printing can be used without compromising construction performance, revealing further research opportunities by exploring the additional benefits of robotic manufacturing (GOMAA et al., 2019).

Figure 8: Solid prototype, single slit prototype with straw filling and double slit prototype.
Source: (GOMAA et al., 2019)

25

3.5 Analytical overview

Based on the 5 cases analyzed in this research, an analytical synthesis was made in Table 1 with the main strategies used to improve the thermal performance of the buildings.

Case	Printing material	Strategies
3D WASP	Soil (25%), rice straw (40%), rice husk (10%), hydraulic lime (10%) and muller	- Internal cavities filled with rice waste for thermal insulation. - Rice husks used for internal lining and as an insulation layer on the top of the roof. - Roof with eaves to protect from direct solar radiation.
Terra Perfor-ma	Soil (96%) and additives (4%)	- Complex morphology of the external surface designed for self-shading. - Modules designed to incorporate various types of openings: micro-openings and windows. - Micro-perforations that direct air flow
Digital Adobe		- Ventilated wall with operable openings. - External geometry with protrusions for self-shading. - Internal wall cavities filled with earth for thermal mass and air for thermal insulation.
TECLA House	Soil, powdered stabilising agent, super-plasticising admixture, synthetic latex rubber, ready-mixed water-repellent	- Composition of the earth mixture. - Building shape. - Wall section geometry. - Infilling material: rice husk and rice straw.
3D Printed Cob	Subsoil (72-73 %), fiber (2 %) and water (25-26 %)	- Walls with air cavities and added straw showed the best conductivity in relation to density.

Table 1: Synthesis of the main strategies for improving the thermal performance of applied research
Source: Authors

4. FINAL CONSIDERATIONS

The analysis of the applied research carried out in this study indicates that additive manufacturing with soil-based materials has the potential to reintroduce traditional materials into contemporary design, and can meet current demands for sustainability, energy efficiency and cost in construction, with greater precision and surface quality, which is often not possible with traditional techniques.

The printing materials used in the research analyzed vary in terms of composition and percentage of additives and additions, demonstrating a wide range of possibilities. It also uses local resources in the composition of the mixture, which indicates the possibility of adapting soil-based 3D printing to the local context.

With regard to thermal performance, it was observed that, in general, the applied research that was analyzed in this study takes advantage of the natural properties of the soil, which has thermal insulation as one of its main advantages. However, they use different design and construction strategies to improve the thermal performance of fences using 3D printing technology, such as: filling internal cavities with materials such as rice waste, earth or straw (3D WASP, TETRA house, Digital Adobe and 3D Printed Cob); using parametric design and digital fabrication to create complex self-shading morphologies (TETRA house, TerraPerforma and Digital

Adobe); ventilated wall systems with operable openings (Digital Adobe), among other strategies.

It is observed that the complex geometries and the ability to control matter on a large scale can only be achieved thanks to the precision of 3D printing technology, giving the necessary liberty to integrate the design parameters into the final design and construction.

Finally, this study highlights the potential solutions that can be explored with Additive Manufacturing to improve the thermal performance of 3D-printed buildings using soil-based materials, adapting building elements in a personalized and optimized way to local needs.

REFERENCES

AKMAN, A.; SADHU, A. Recent Development of 3D-Printing Technology in Construction Engineering. **Practice Periodical on Structural Design and Construction**, v. 29, n. 1, 2024.

ALHUMAYANI, H. et al. Environmental assessment of large-scale 3D printing in construction: A comparative study between cob and concrete. **Journal of Cleaner Production**, v. 270, p. 122463, 2020.

AL-OBAIDI, K. M. et al. Biomimetic building skins: An adaptive approach. **Renewable and Sustainable Energy Reviews**, v. 79, p. 1472–1491, 2017.

BARDIN, L. **Análise de conteúdo**. Rio de Janeiro: Edições 70, 1991.

COSTA, F. N.; RIBEIRO, D. V. Reduction in CO2 emissions during production of cement, with partial replacement of traditional raw materials by civil construction waste (CCW). **Journal of Cleaner Production**, v. 276, p. 123302, 2020.

DUBOR, A.; CABAY, E.; CHRONIS, A. Energy Efficient Design for 3D Printed Earth Architecture. In: HUMANIZING DIGITAL REALITY. Singapore: Springer Singapore, 2018. p. 383–393.

EL-MAHDY, D.; GABR, H. S.; ABDELMOHSEN, S. SaltBlock as a 3D printed sustainable construction material in hot arid climates. **Journal of Building Engineering**, v. 43, 2021.

FIGLIOLA, A.; BATTISTI, A. **Post-industrial Robotics**. Singapore: Springer Singapore, 2021.

FRATELLO, V. S.; RAEL, R. Innovating materials for large scale additive manufacturing: Salt, soil, cement and chardonnay. **Cement and Concrete Research**, v. 134, p. 106097, 2020.

GIRAUD, I. **Incorporating thermal performance in clay 3D printing**. 2017. Disponível em: https://www.iaacblog.com/programs/incorporating-thermal-performance-clay-3d-printing/. Acesso em: 14 jul. 2024.

GOMAA, M. et al. Thermal performance exploration of 3D printed cob. **Architectural Science Review**, v. 62, n. 3, p. 230–237, 2019.

IAAC. **Digital Adobe.** 2024. Disponível em: https://iaac.net/project/digital-adobe/. Acesso em: 20 fev. 2024a.

IAAC. **PYLOS.** 2024. Disponível em: https://iaac.net/project/Pylos/. Acesso em: 20 fev. 2024b.

IAAC. T**erraPerforma – OTF 2016/2017.** 2024. Disponível em: https://iaac.net/project/terraperforma/. Acesso em: 20 fev. 2024c.

INTERNATIONAL ENERGY AGENCY. **Global energy & CO2 status report**. 2018. Disponível em: https://www.iea.org/reports/global-energy-co2-status-report-2019. Acesso em: 20 fev. 2024.

JORDAHN, S. **3D-printed Gaia house is made from biodegradable materials**. 2019. Disponível em: https://www.dezeen.com/2019/02/27/gaia-wasp-3d-printed-house-biodegradable-video/. Acesso em: 20 fev. 2024.

KONTOVOURKIS, O.; TRYFONOS, G. Robotic 3D clay printing of prefabricated non-conventional wall components based on a parametric-integrated design. **Automation in Construction**, v. 110, p. 103005, 2020.

LIBRELOTTO, L. I.; et a. O Design, Os Materiais Naturais E As Bolhas: Alternativas Mais Sustentáveis Para A Construção. **Plural Design**, v. 6, p. 5-17, 2023

LOPES, G. T. F. **Exploração das possibilidades da impressão 3D na construção**. 2016. Mestrado em Engenharia Civil - Faculdade de Engenharia da Universidade do Porto, 2016. Disponível em: https://core.ac.uk/download/pdf/143393036.pdf. Acesso em: 20 fev. 2024.

MAPEI. **Mapei research and technology for TECLA**. 2019. Disponível em: https://www.mapei.com/it/en/news/event-detail/2019/11/04/mapei-research-and--technology-for-tecla. Acesso em: 14 jul. 2024.

NAÇÕES UNIDAS. **Os Objetivos de Desenvolvimento Sustentável no Brasil**. 2024. Disponível em: https://brasil.un.org/pt-br/sdgs. Acesso em: 20 fev. 2024.

PATRICIO-KARNOPP, Z. M. **O processo ético e estético de pesquisar: um movimento qualitativo transformando conhecimentos e a qualidade da vida individual-coletiva**. Florianópolis: Núcleo de Estudos das Águas/UFSC/CNPq, 2004.

PERROT, A.; RANGEARD, D.; COURTEILLE, E. 3D printing of earth-based materials: Processing aspects. **Construction and Building Materials**, v. 172, p. 670–676, 2018.

PESSOA, S. et al. 3D printing in the construction industry - A systematic review of the thermal performance in buildings. **Renewable and Sustainable Energy Reviews**, v. 141, p. 110794, 2021.

PINTOS, P. **TECLA Technology and Clay 3D Printed House / Mario Cucinella Architects**. 2021. Disponível em: https://www.archdaily.com/960714/tecla-technology-and-clay-3d-printed-house-mario-cucinella-architects. Acesso em: 14 jul. 2024.

SOOD, G. **Gaia is the World's First 3D Printed Mud House**. 2018. Disponível em: https://www.homecrux.com/gaia-is-the-worlds-first-3d-printed-mud-house/110107/#google_vignette. Acesso em: 20 fev. 2024.

TEIXEIRA, J. et al. A road map to find in 3D printing a new design plasticity for construction – The state of art. **Frontiers of Architectural Research**, v. 12, n. 2, p. 337–360, 2023.

VALENCIA, N. https://www.archdaily.com.br/br/776401/pylos-a-impressora-3d-que-imprime-com--terra. 2015. Disponível em: https://www.archdaily.com.br/br/776401/pylos-a-impressora-3d-que-imprime-com-terra. Acesso em: 20 fev. 2024.

VALENTE, M.; SIBAI, A.; SAMBUCCI, M. Extrusion-Based Additive Manufacturing of Concrete Products: Revolutionizing and Remodeling the Construction Industry. J**ournal of Composites Science**, v. 3, n. 3, p. 88, 2019.

WASP. **DeltaWASP Crane**. 2024. Disponível em: https://deltawasp.com.au/shop/deltawasp-crane/. Acesso em: 20 fev. 2024.

WASP. **TECLA**. 2019. Disponível em: https://www.3dwasp.com/en/3d-printed-house-tecla/. Acesso em: 14 jul. 2024.

WENG, Y. *et al*. Comparative economic, environmental and productivity assessment of a concrete bathroom unit fabricated through 3D printing and a precast approach. **Journal of Cleaner Production**, v. 261, p. 121245, 2020.

ACKNOWLEDGEMENTS

We would like to thank the post-doctoral scholarship granted by the National Council for Scientific and Technological Development (CNPq) (168166/2022-4) in partnership with the Araucária Foundation to one of the authors of this research.

AUTHORS

ORCID: 0000-0003-2132-3389
LUANA TORALLES CARBONARI, DRA. | Universidade Estadual de Londrina - UEL | Curso de Arquitetura e Urbanismo | Londrina, PR - Brasil | Correspondência para: CTU – Centro de Tecnologia e Urbanismo Rodovia Celso Garcia Cid | PR 445 Km 380 | Campus Universitário | Cx. Postal 10.011 | CEP 86.057-970 | Londrina – PR |
e-mail: luanatcarbonari@gmail.com

ORCID: 0000-0001-8828-7250
BERENICE MARTINS TORALLES, DRA. | Universidade Estadual de Londrina - UEL | Curso de Engenharia Civil | Londrina, PR - Brasil | Correspondência para: CTU – Centro de Tecnologia e Urbanismo Rodovia Celso Garcia Cid | PR 445 Km 380 | Campus Universitário | Cx. Postal 10.011 | CEP 86.057-970 | Londrina – PR | e-mail: toralles@uel.br

ORCID: 0000-0002-3250-7813
LISIANE ILHA LIBRELOTTO, DRA. | Universidade Federal de Santa Catarina - UFSC | Curso de Arquitetura e Urbanismo | Florianópolis, SC - Brasil | Correspondência para: CTC-UFSC / Campus Trindade CP 470 - CEP 88040-970 - Florianópolis - Santa Catarina - Brasil |
e-mail: lisiane.librelotto@gmail.com

ORCID: 0000-0003-0842-7829
MONIQUE DE BRITO FILGUEIRAS, ME. | Universidade Estadual de Londrina - UEL | Curso de Engenharia Civil | Londrina, PR - Brasil | Correspondência para: CTU – Centro de Tecnologia e Urbanismo Rodovia Celso Garcia Cid | PR 445 Km 380 | Campus Universitário | Cx. Postal 10.011 | CEP 86.057-970 | Londrina – PR | e-mail: monique.filgueiras@uel.br

ORCID: 0000-0002-4609-0705
THALITA GORBAN FERREIRA GIGLIO, DRA | Universidade Estadual de Londrina - UEL | Curso de Engenharia Civil | Londrina, PR - Brasil | Correspondência para: CTU – Centro de Tecnologia e Urbanismo Rodovia Celso Garcia Cid | PR 445 Km 380 | Campus Universitário | Cx. Postal 10.011 | CEP 86.057-970 | Londrina – PR | e-mail: thalita@uel.br

HOW TO CITE THIS ARTICLE:

CARBONARI, L. T; TORALLES, B. M; LIBRELOTTO, L. I; FILGUEIRAS, M. B; GIGLIO, T. G. F. 3D Printing with natural materials in civil construction: Applications for the thermal performance of buildings. **MIX Sustentável**, v. 10, n. 4, p. 17-29, 2024. ISSN 2447-3073. Disponível em: <http://www.nexos.ufsc.br/index.php/mixsustentavel>. Acesso em: _/_/_.doi: <https://doi.org/10.29183/2447-3073.MIX2024.v10.n4.17-29>.

SUBMITTED ON: 19/07/2024
ACCEPTED ON: 01/08/2024
PUBLISHED ON:
RESPONSIBLE EDITORS: Lisiane Ilha Librelotto e Paulo Cesar Machado Ferroli

Record of authorship contribution:
CRediT Taxonomy (http://credit.niso.org/)

LTC: conceptualization, data curation, formal analysis, funding acquisition, investigation, methodology, project administration, supervision, visualization, writing - original draft, writing - review & editing.

BMT: conceptualization, funding acquisition, methodology, project administration, supervision, visualization, writing - review & editing;

LIL: conceptualization, methodology, visualization, writing - review & editing;

MBF: conceptualization, methodology, visualization, writing - review & editing;

TGFG: conceptualization, funding acquisition, methodology, project administration, supervision, visualization, writing - review & editing.

Conflict declaration: nothing has been declared.