The impact of Digital Manufacturing on Earth Construction: Focus on Adobe Bricks

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Abstract

The field of architecture is currently witnessing a surge in the utilization of digital tools, which are continuously reshaping the dynamics between design and production. The incorporation of digital technologies in earth construction has led to a notable shift in the construction sector, enabling the creation of unconventional architectural forms and pushing the boundaries of traditional design and structural concepts. Adobe, a key focus of this investigation, is frequently employed in this transformative process due to its versatility and potential for innovation. This study delves into the realm of traditional construction practices and examines the influence of digital manufacturing techniques on the sustainability, efficiency, and architectural possibilities within earth construction. Technologies such as 3D printing and robotic fabrication play a crucial role in this exploration, paving the way for new design possibilities and construction methodologies. To underscore the significance of earth construction, this article provides an overview of the environmental advantages associated with this construction method. It delves into the historical context of earth construction while also shedding light on its contemporary applications. Additionally, the article delves into different instances of integrating adobe into digital manufacturing processes. Alongside an experimental case study, its results demonstrated a noteworthy enhancement in compressive strength for specific printed samples, with values that were twice as high as those of the conventional samples.

Keywords: *Adobe bricks, earth architecture, Digital manufacturing and fabrication, 3d printing*

1. Introduction

The global focus on sustainability has brought attention to the pressing need for sustainable practices across various sectors, including environmental and economic concerns. The World Business Council for Sustainable Development (WBCSD) highlights that the building industry accounts for approximately 40% of the world's energy consumption [1]. Consequently, many nations are now prioritizing efforts to reduce the carbon footprint of buildings by exploring alternative sustainable materials that have a lesser impact on the environment. This underscores the urgency of decarbonizing buildings as a critical challenge facing the construction sector today[2].The construction industry plays a significant role in carbon dioxide (CO_2) emissions, with the choice of materials being crucial in energy conservation and emission reduction [3]. Traditional materials like fired and cement bricks are widely used but come with high energy consumption and environmental impact during production and transportation[4]. As a result, there is a growing necessity to enhance the environmental sustainability of modern construction by exploring more eco-friendly building materials.

The necessity to reduce the environmental impact of contemporary construction practices has prompted scholars to explore alternative, more sustainable building materials. This shift has sparked an interest in utilizing earth materials as a substitute for cement-based constructions, which are notorious for their high carbon dioxide emissions, substantial embodied energy, and depletion of natural resources stemming from concrete usage[4]. It has various techniques utilized in encompassing a range of methods. Various techniques are commonly utilized in construction, such as adobe, cob, and blocks or rammed earth, each representing a distinct method of utilizing earth-based materials [5]. These techniques involve different processes, such as molding, stacking, or compacting earth blocks, and often incorporate soil, water, and fibers like straw in varying proportions to create durable structures. They have gained popularity as a sustainable building option due to their thermal properties and cost-effectiveness compared to traditional materials like concrete and masonry[6]. Despite the benefits they offer, the use of earth materials in contemporary construction endeavors has declined because of the perceived advantages of concrete, such as its greater strength, quicker construction schedules, and reduced labor needs [7]. It is argued that various technical, social, economic, and political factors have recently contributed significantly to the decline of traditional urban structures and the distinctive mud architecture of the western desert [8].
On the other side, the term "construction 4.0" has emerged to signify the growing interest in utilizing digital manufacturing, machine learning, and artificial intelligence (AI) technologies within the construction sector [9]. The demand for these technologies has notably increased due to empirical evidence from various studies conducted over the past decade, which have demonstrated the substantial benefits of automating the construction process in terms of productivity, efficiency, and quality, while also allowing for greater design flexibility (Zareiyan and Khoshnevis, 2017). It has become evident that the adoption of modern manufacturing technologies in the construction industry is rapidly expanding, as the number of companies offering advanced manufacturing services is growing worldwide in response to the evolving market demand. Additive manufacturing (AM) methods, particularly 3D printing of building components, have garnered significant attention in both research and practical applications. [10] . Digital manufacturing provides the chance to alter the conceptual design frameworks, enabling the provision of customized and precise solutions in response to end-user demands. The ability to alter conceptual design paradigms through digital manufacturing enables the provision of tailored and spontaneous responses to end-user needs. The historical weakness associated with Earth construction, which has always been a topic of discussion, may now be addressed with the respect it warrants, potentially leading to its redemption.

The primary objective of this study is to conduct a thorough evaluation of the current cutting-edge research on digital manufacturing for earth constructions focusing on Adobe bricks, with the aim of shedding light on the potential benefits and comprehensively understanding the obstacles that impede the widespread implementation of this innovative construction approach. The paper culminates in an in-depth analysis of the documented research findings, accompanied by a detailed discourse and concluding remarks. The findings derived from this research endeavor are anticipated to address the existing knowledge gaps present within the diverse array of research studies, thereby collectively furnishing essential insights for the effective integration of digital methodologies in forthcoming earth construction projects.

2. Traditional Earth Construction

Earth construction has been in existence since the early agricultural societies, a period ranging from 12,000 to 7000 BC. Numerous examples of earth buildings constructed a millennium ago have managed to endure until the 21st century[11]. It also approximately 30% of current buildings worldwide have been built using earth-based materials, showcasing its widespread use across different countries and cultures (Gado et al., 2010). Presently, most of the earth construction can be found in less developed nations. Regrettably, the association of earth construction with low-income status is likely one of the primary reasons why less developed countries tend to imitate the use of unsustainable construction materials prevalent in most developed countries. However, earth construction is not exclusive to less developed nations, as an increasing awareness of the significance of this construction method can now be observed in developed countries.[3]. It is linked to low embodied energy, minimal carbon dioxide emissions, and negligible pollution impacts. This also contributes to indoor air relative humidity, which is beneficial for human health[12]. Consequently, earth construction presents clear competitive advantages in terms of sustainability over traditional construction methods, ensuring a promising future in the years ahead [3].

Earth architecture, a form of vernacular architecture, is characterized by its reliance on local resources, needs, and the skills of the builders. Numerous scholarly investigations have sought to categorize the methods of earth construction, with one such classification based on the CRATerre wheel, as depicted in figure (1), outlining 12 primary earth construction processes, predominantly reliant on manual labor [13]. These processes are further delineated into three main sectors - Completing, solidifying, and building with masonry, as presented in a pie chart by Houben H. and Guillaud H. CRATerre (2006) Handbook of Earthen Construction Éd. Parenthèses [14]. However, the findings of (Hamard et al., 2016) have highlighted the significance of the disparities between wet and dry compaction techniques in shaping the mixtures and forming the structures, as depicted in figure (2).

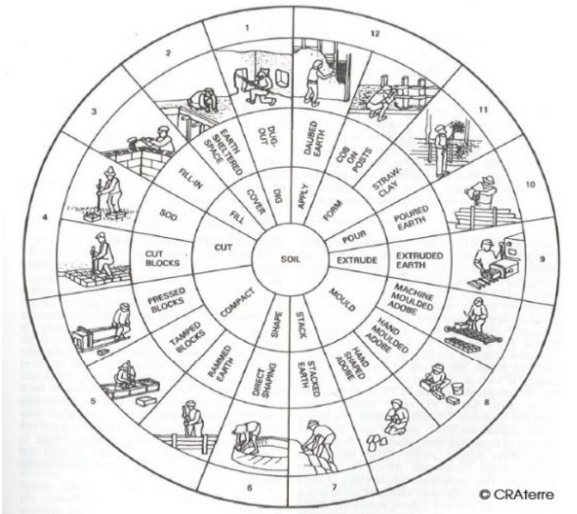

Figure 1. CRATerre wheel on raw earth applications

source: (Houben H, Guillaud H, 2006, Traité de construction en terre, Éditions Parenthèses), [14]

In the wet approach, earth mixes are utilized in a plastic state with a relatively high moisture content. The structure acquires mechanical strength through compaction and solidification during the drying and shrinkage phase, which persists until the optimal moisture content is achieved. This approach includes techniques such as cob, adobe, wattle and daub, and earth plaster, although they are not the sole methods. However, only adobe and cob are capable of bearing loads. Conversely, load-bearing techniques such as rammed earth and compressed earth block are classified under the dry approach [7]. While in dry processes, the earth mixture is placed at the optimal Proctor water content, and mechanical strength is achieved through compaction densification, as seen in Compressed Earth Block and rammed earth construction methods [15].

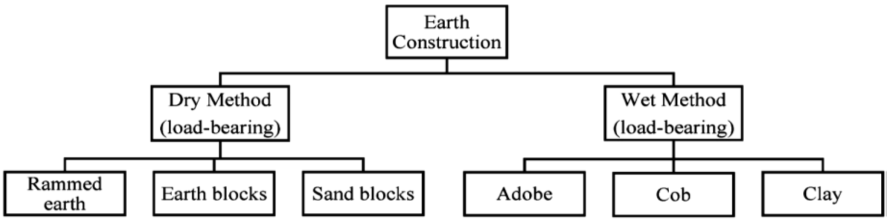

Figure 2. Identification and classification of soil with their size ranges [16]

A common resource, earth or soil is a mixture of solid aggregates, or particles, including sand, gravel, silt, and clay, and sometimes fibers or binders to improve durability and strength. These aggregates differ based on their sizes, as shown in Figure 3. The smallest aggregates, called clays, serve as binders. Salts, water, and other organic minerals are frequently found in soils. The formation of earthen materials, such as walls, involves thoroughly combining soil with the appropriate amount of water, then shaping the resulting mixture. Construction techniques also refer to the process of shaping the wet earth [16].

Figure 3. Suggested classification of earth construction [15], [7]

One of the earliest earthen walls and most common used techniques through history are Adobe bricks [17]. Adobe bricks, also known as green bricks or unbaked bricks, are created through a process that involves manually excavating subsoil clay, mixing it with water, kneading and stirring it to improve the binding between the elements. The resulting mixture is then placed into a wooden form and allowed to dry in the sun as shown in figure 4. The use of adobe bricks in this particular mold configuration has persisted over time without any modifications to its structural design. Various additives are often incorporated to alter the properties of the clay. For instance, straw, is added to enhance the binding forces, decrease shrinkage, and minimize the occurrence of cracks in the bricks [8], A stabilizer, often known as a binder, is typically incorporated into the soil to enhance its compressive strength and resistance to water infiltration. [16].

Adobe Earth construction has demonstrated numerous environmental, social, and economic benefits that are often overshadowed by misconceptions. Despite this, its capacity to offer intricate designs and innovative solutions could seamlessly integrate it into modern architectural practices. As a result, several developed nations have begun reintroducing earth construction into their building landscapes and advocating for its utilization. Nonetheless, skepticism still surrounds the use of earth in contrast to traditional building materials such as concrete and steel, particularly in regions like Egypt[4].

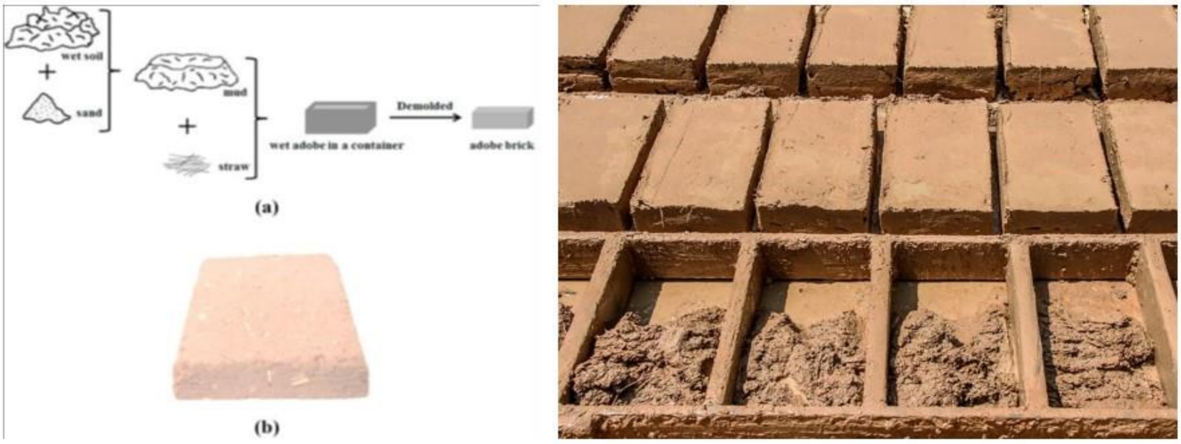

Figure 4. Steps of making traditional adobe bricks

source: left one [29] , *right one https://www.homestratosphere.com/adobe-home/*

2.1. Advantages of Traditional Earth Construction

Constructing with earth offers numerous advantages in different aspects environmental, economic, social, and political that set it apart from alternative building materials such as concrete as represented in figure 6. They are representing in [18] [4]:

1. Effective thermal regulation: The capacity to mitigate and delay fluctuations in temperature and external heat transfer is attributed to the favorable thermal inertia characteristics of the soil and the customary substantial walls found in earthen structures.
2. The enhancement of a comfortable and healthy indoor environment can be achieved by regulating air humidity, ensuring effective noise insulation, and providing fire resistance within the structure.
3. The recyclability of earth as a building material stands out as it is completely recyclable and environmentally friendly, with components of earthen buildings capable of being recycled without generating any waste at the end of their lifespan as shown in figure 5.
4. Earth construction exhibits a low environmental impact in comparison to other building materials, as it possesses low embodied energy during production and transportation processes.
5. The construction process using earth is relatively simple and affordable, as individuals with basic tools can construct a house without the need for specialized labor due to the straightforward nature of most earth construction methods.

Figure 5. Earth Building life cycle

source: [6] from Schroeder (2016)

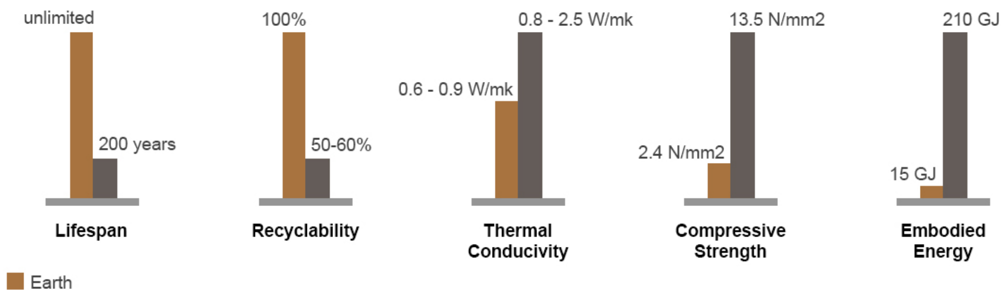

Figure 6. Potentials and challenges of Earth

source: [14] *from Heringer, A., Howe, L. B. & Rauch, M. (2019). Upscaling Earth.*

2.2.Challenges of Traditional Earth Construction

The employment of soil as a building material comes with notable limitations, in addition to the drawbacks linked to utilizing soil for construction, which can be classified into five primary categories: economic, organizational, political, social, and technical obstacles. They are highlighted by [4] [18] (Hafez et al., 2023) (Pacheco-Torgal & Jalali, 2012):

1. The lack of standardization, skilled educated builders, and the absence of regulations or design guidelines in many countries.
2. Structural limitations are represented in low compressive strength of unstabilized earthen materials, particularly in terms of tensile strength, leading to brittle behavior that renders them more vulnerable to seismic activity, thereby restricting construction to low-rise buildings in regions with moderate seismic risks.
3. The reduction in strength caused by drying shrinkage can lead to cracking in materials, impacting the overall integrity of a structure. The selection of a suitable building method should consider the extent to which the soil is prone to shrinkage.
4. When faced with low water resistance, it is common practice to enhance stability by incorporating binders such as lime, cement, or bitumen to mitigate the effects of rain or other forms of precipitation.
5. Earthen constructions typically require more frequent maintenance compared to modern buildings, necessitating regular upkeep to ensure their longevity and structural integrity.
6. While insects are often attracted to earth constructions, the risk can be minimized by reducing the use of straw or other organic materials in the composition of the walls.
7. The absence of diverse soil types and limited access to locally available soils that are appropriate for construction purposes.

Various obstacles hinder the widespread adoption of earth construction in contemporary times, extending beyond the discussed technical limitations of the material. These include social and economic factors such as client perceptions, insufficient awareness, limited education, and lack of experience. Additionally, the high costs associated with machinery, materials, and transportation further impede the utilization of earth construction methods(Hafez et al., 2023). Although there are numerous challenges and limitations associated with this approach, it is imperative to take substantial steps to bolster the construction sector. The advantages of earth construction necessitate its promotion within the building industry, with discussions on modernizing and automating construction techniques through the prefabrication of components and mechanization. Furthermore, businesses and academics have been actively involved in innovating traditional earth construction methods by utilizing less labor-intensive formworks and equipment, as well as integrating digital tools.[19] .

3. Digital Manufacturing in Earth Construction (DMEC)

In the current era, digital manufacturing is recognized as a key tool for enhancing the construction process sustainably within the context of the fourth industrial revolution [20]. Not only businesses and academic institutions, but also professionals in the field of architecture, have shown keen interest in utilizing this technology in the construction sector. Nowadays, 3D printing is considered a versatile technology, with numerous 3D-printed structures being developed worldwide using various materials like clay, concrete, steel, wood, glass, and others [21]. Nevertheless, major cement companies with exclusive 3DCP formulations are leading the current trend of cement-based techniques in the digital construction market. The aim is to combine earth materials with digital manufacturing methods to create a cleaner and more sustainable alternative, potentially challenging or replacing a portion of the market share currently dominated by cement-based products in digital construction [7].

Digital fabrication can be divided into two main categories: 2D and 3D techniques. 2D techniques encompass cutting technologies such as laser and water-jet nozzles, while 3D techniques include additive, subtractive, formative, and assembly methods [7]. Additive manufacturing has gained a lot of traction in the building and architectural industries and resulted in notable developments in large-scale 3D printing technologies for building projects[22]. It exhibits differences in terms of both the materials employed and the technologies utilized [23]. A variety of techniques for additive manufacturing of clay are shown in Figure 7, including binder jetting, extrusion, photopolymerization, sheet lamination, powder fusion, and computer-controlled arrangement. Each technique is distinguished by its unique approach and the specific materials utilized. These materials may come in the form of solid, slurry, or powder, depending on the chosen technique [23].

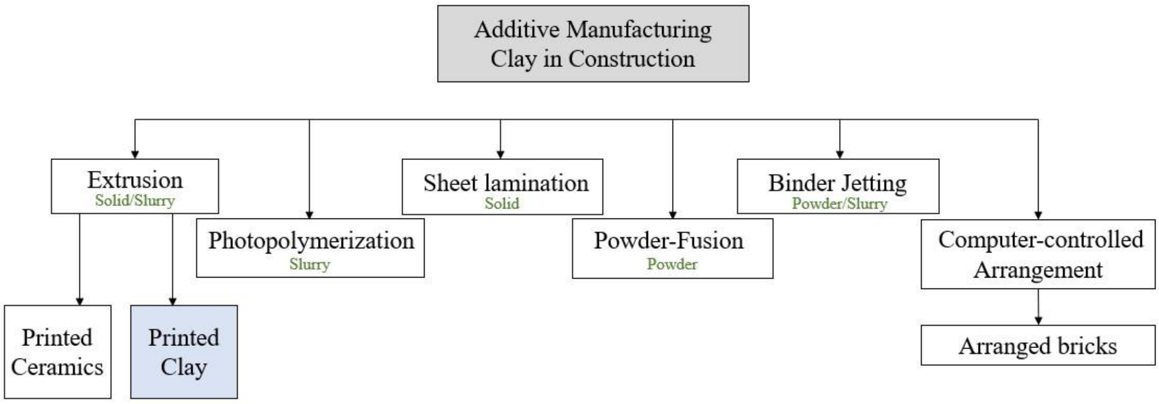

Figure 7. Additive manufacturing techniques for clay

source: by Author from [23]

The most used technique for additive manufacturing clay is extrusion (Fused deposition modeling) which is the fundamental process of earth extrusion (FDM) and is widely utilized with 82% usage comparing to other techniques[7]. It involves the controlled layering of clay by a robot on top of previous layers to create the desired shape of the object. The process is affected by printers' specifications, such as size, production speed, and clay particle size, which is managed by the extruder's diameter or geometry. Additionally, the geometric dimensions (width, depth, and height) of the printed objects are further constrained by subsequent handling and transportation. While this technology offers low acquisition and operating costs, it is often hindered by the issue of achieving a satisfactory surface finish. [24][23]. Adobe and cob are the most commonly used earth construction techniques, both of which involve a combination of earth material and additional fibers. The methods vary from 3D printing smaller brick-like components that are later assembled into buildings, to adobe bricks made with 3d printed molds, to monolithic printing of complete buildings using house-sized 3D printers and locally excavated material or recycled as shown in figure 8. TerraPerforma was unveiled in 2017 by scholars from the Institute of Advanced Architecture of Catalonia (IAAC). It featured a life-size 3D printed clay wall, as depicted in Figure 9. The wall consisted of small modular blocks made of 3D-printed clay, showcasing a modular construction method. Once assembled, the blocks were meticulously designed and fine-tuned parametrically to ensure superior thermal efficiency and structural strength.

Figure8. left: 3d printed adobe brick from Digital Adobe, middle: Terrablocks adobe bricks from 3d printed molds, right: monolithic printed wall of Gaia project by WASP

sources: https://iaac.net/project/digital-adobe/ , https://www.designboom.com/technology/students-mexican-university-terrablocks-parametric-adobes-3d-printed-molds-05-28-2024/ , https://www.3dwasp.com/en/3d-printed-house-gaia/

Figure 9. Manufacturing stages of terraperorma project

source: https://iaac.net/project/terraperforma/

3.1.Advantages and potentials of Digital Manufacturing in Earth Construction

The utilization of digital manufacturing in the construction industry has experienced a surge in popularity over the past two decades, driven by the growing need for more intricate designs, streamlined processes with reduced labor requirements, and expedited construction timelines[25]. This integration of digital fabrication techniques in construction is paving the way for enhanced efficiency, precision, and design flexibility in modern construction practices [23]. Adopting digital manufacturing techniques in modern construction, specifically additive manufacturing (AM) methods, offers three significant sustainability advantages [7]:

1. Improving the efficiency of materials and resources in the production process has led to a significant decrease in material usage by 25-60% and a 30% reduction in production time when compared to conventional manufacturing methods. This enhancement also allows for higher quality output by optimizing printing paths and minimizing unnecessary movements of the printer [26].
2. Prolonging the estimated product lifespan (from a technical perspective) by facilitating repair and refurbishment processes.

3. Improving value chains by enabling simpler, shorter, and more localized production and supply chains, such as supporting single-material options for construction elements with heightened performance requirements such as doorways, thus eliminating the need for (concrete) lintels. [24].

The extent to which these advantages can be realized is largely contingent upon the scale and intricacy of the building project, with traditional construction techniques potentially surpassing digital methods in terms of both cost-effectiveness and environmental impact, especially for smaller and less complex projects. The incorporation of digital manufacturing techniques with natural materials presents a sustainable and more environmentally friendly option, which is anticipated to challenge or replace a portion of the market currently controlled by cement-based products in the digital construction sector. However, there are potentials for digital manufacturing to improve earth construction are represented in [24]:

1. **Erosion behavior:** digital fabrication offers the opportunity to adjust the composition by digitally controlling the deposition of different types and ratios of aggregates. Consequently, erosion characteristics can be altered by incorporating water-resistant aggregates and adding admixtures in a controlled manner, where necessary. When selecting suitable admixtures for earthen materials, it is essential to carefully consider the trade-offs between performance improvements and ecological impacts, in order to safeguard the recyclability of the materials.
2. **Material properties:** The mechanical strength of earthen materials relies on various factors, including the cohesive strength of clay content, moisture content, and dry density. The dry density is heavily influenced by the material composition, hygroscopic properties, and proper densification during the manufacturing process. Achieving consistent material deposition and densification on a construction site is challenging, leading to significant fluctuations in material properties.
3. **Construction tolerances and deviations:** Prefabrication provides a controlled environment for manufacturing and drying, reducing defects caused by shrinkage. It also offers the possibility of subtractive reworking, both during drying and in the fresh state of the materials. As a result, the precision of additive and subtractive digital fabrication methods enables the production of building elements with tighter tolerances, simplifying the planning and execution processes for subsequent trades. By implementing online quality control through 3D scanning, the overall precision can be further improved.
4. **The visual surface quality:** Innovative approaches to digitizing earthen construction involve reducing the size of formwork by utilizing an active, robotically controlled slip form or eliminating the need for formwork altogether.

3.2. Challenges and Limitations of Digital Manufacturing in Earth Construction

The research on automating earth construction has shown significant progress over the last decade demonstrating the potential of earth construction as a modern and sustainable method, offering various benefits to the environment and economy [27]. However, conventional earth construction still lacks some of the workability advantages and structural performance qualities compared to established cement-based methods. There are identified three domains requiring further improvement on DMEC. Recognizing the potential and challenges within each domain is crucial for establishing a strong framework for the future development of DMEC. These domains include:(Gomaa et al., 2022).

1. **Manufacturing technologies:**
   The successful incorporation of earth materials into a digital construction process heavily relies on the technological advancement of digital tools and machines. It is represented in 2 main challenges are:

a. Motion control system: various constraints exist for alternative methods of 3D printing, such as the point-to-point approach. Although not as prominent in 3DP clay, it becomes more apparent in 3DP cob/adobe due to the rheological characteristics of the materials hindering control. This restriction necessitates the use of a continuous printing path line in the planning process, potentially constraining design options and diminishing overall efficiency.
b. Material delivery system: The current manufacturing systems are not yet classified as fully automated. They involve minimal human intervention in the digital construction workspace, with human involvement primarily centered on material mix preparation, material refilling, reloading, and certain assembly tasks. The automation of the material delivery process has the potential to enhance efficiency and save time in the forthcoming period.

2. **Performance aspects:** Building performance analysis offers stakeholders crucial data to enhance the building's efficiency for occupants and the surrounding environment. This includes structural, thermal performance, and the building's life cycle. The studies conducted on these aspects, along with their environmental and economic potentials, are currently only applied to prototypes rather than large-scale projects in order to maximize their value.
3. **Research reliability, validity, and visibility:** Most of the documented research conducted thus far consists of student endeavors, conceptual demonstrations, or prototypes intended for commercial purposes. Additionally, there is a scarcity of information regarding material processing and the practicality of digital systems.

4. Case Studies

The utilization of this technology in extensive projects is presently constrained by the costly nature of the advanced equipment required for printing on an architectural scale. This limitation hinders the widespread adoption of this technology. However, recent studies suggest a bright outlook for this technology in the prefabrication of minor components by deconstructing the mass into pixels and distributing the manufacturing process through 3D printing of clay bricks that conform to standard industrial sizes. Three instances of digital manufactured adobe projects are presented, one being assembled using 3d printed bricks (Digital Adobe), one used traditional pre-casted blocks (TERRABLOCKS), and one erected on location (Casa Covida):

4.1. Digital Adobe IAAC [28] , https://iaac.net/project/digital-adobe/)

Date: March 2018

Location: Barcelona, Spain

Time: Aprox. 10, Days assembly, 5 days/4 persons

Max. height: 5m

Printer configurations: KUKA robotic arm

Mixture composition: water 13%, clay 43%, aggregates 25%, Bio-Based additives 1%

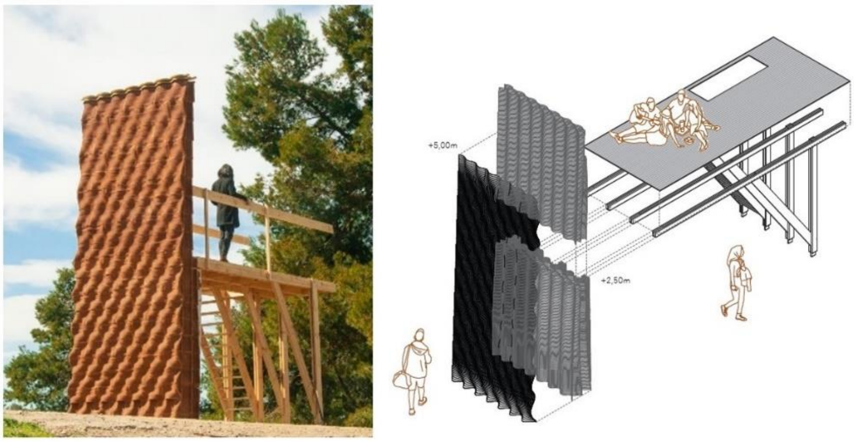

Figure 8. Digital Adobe standing wall

source: https://iaac.net/project/digital-adobe/, [28]

Digital adobe project was a groundbreaking research initiative that was part of the broader Open Thesis Fabrication program focusing on Adobe 3D printing for the performative habitat. The primary objective was to explore architectural solutions using common materials like clay, alongside additive manufacturing techniques. The aim was to facilitate the customization of building forms at different levels, resulting in a final product with exceptional structural integrity and passive climatic performance. The project commenced with the development of small-scale prototypes to analyze and refine the behavior of the final structure. Subsequently, a life-size prototype representing a section of the entire building was created. This prototype featured a self-supported wall 2-meter wide and 5-meter-high clay wall with varying thicknesses, oriented towards the south. The construction relies on sustainable recycled clay material, thereby minimizing the environmental impact of previously printed materials in 2017. The internal infill patterns were developed as the height increased, in order to create a support system for four wooden beams and a wooden platform resembling a typical building's first floor. This platform was connected at a height of 2.6 meters to examine how the load is transferred from the slab to the wall. The final design consisted of 26.254 meters of 3D printing path, which was segmented into 99 individual elements and constructed at IAAC’s Valldaura Self-Sufficient Lab campus in March 2018. The study concluded that longer paths with more bifurcations were more effective in managing conductivity. As a result, walls with broader sections and intricate infill patterns are preferred over simpler, air-filled sections.

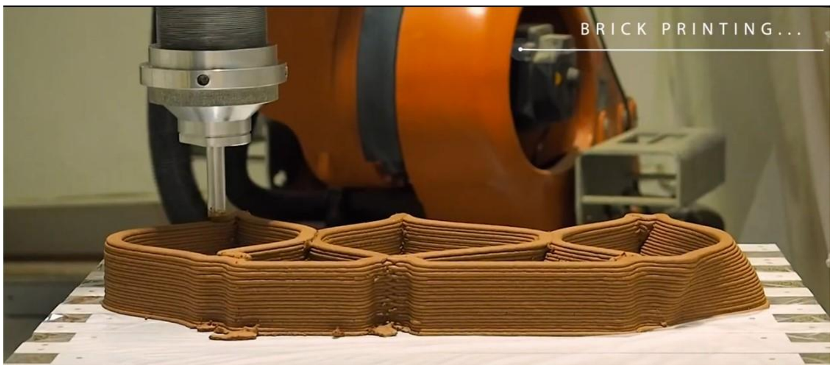

Figure 11. Brick Execution phase

source : https://iaac.net/project/digital-adobe/

4.2. TERRABLOCKS

(https://www.designboom.com/technology/students-mexican-university-terrablocks-parametric-adobes-3d-printed-molds-05-28-2024/)
Date: 2024
Location: Mexico City, Mexico
Time: aprox. 4 weeks
Mixture composition: Water, Soil, Aggregates

Figure 12. The phases of Terrablocks parametric adobe made with 3D printed molds

source: https://www.designboom.com/technology/students-mexican-university-terrablocks-parametric-adobes-3d-printed-molds-05-28-2024/

TERRABLOCKS is a research project in the Digital Fabrication Workshop that involves investigating an innovative approach to producing earthen adobes, departing from conventional methods by utilizing 3D printing PLA to create molds. Subsequently, the negative of the mold is taken using silicon, enabling the preparation of a mixture consisting of raw earth and natural fibers. This process aims to facilitate a circular economic cycle. They are divided in 3 teams: The design group focused on optimizing the 3D printing process by using computational design tools like Rhinoceros and Grasshopper to develop the most efficient geometry with curvatures and slopes. This geometry was based on the replication of nine circles, strategically interspersed to find the optimal curvature formed at the junction of the circumferences, pushing the material to its limits. The second team worked on developing the material, experimenting with five different mixtures to test the potential of the soil with various aggregates and explore its limits by manipulating their weights. In an effort to enhance sustainability, the materials were sourced from a location just 60 kilometers away from the university campus in Mexico City. The fabrication team then explored different mold making strategies to replicate the original geometry and determine the most efficient process for construction and mass production. The process of mixing and pouring the soil into the mold was completed within a day, while the drying process took three days. A total of 20 pieces were produced within four weeks, and the molds had the potential to produce 270 partitions. With reduced time and labor, the total cost of producing 20 parts amounted to only 7.40% of the initial investment.

4.3. Casa Covida

(https://www.rael-sanfratello.com/made/casa-covida,
https://www.archdaily.com/963516/casa-covida-emerging-objects)

Date: 2020
Location: ANTONITO, UNITED STATES
Max. height: 4m
Printer configurations: portable 3-axis SCARA (Selective Compliance Articulated Robot Arm)
Mixture Composition: water, clay, silt, sand, straw

Figure 13. Casa Covida outside and inside the space

source: *https://www.archdaily.com/963516/casa-covida-emerging-objects*

Casa Covida is an innovative example of earth construction created by Emerging Objects. It is a dwelling designed for communal living during the time of covid, serving as a pilot project that combines 3D printing technology with traditional indigenous building materials and techniques, while incorporating both modern and ancient lifestyles. Located in the high alpine desert of Colorado's San Luis Valley, the house uses adobe as its main building material, a blend of sand, silt, clay, water, and straw that is sun-dried and has been traditionally used in the region. The residence consists of three spaces, each intended for two individuals to sleep, bathe, and socialize around a fire and meals, with openings that connect to the sky, horizon, and ground as shown in figure 14. The 3D printing system features a portable 3-axis SCARA (Selective Compliance Articulated Robot Arm) specifically designed for on-site additive manufacturing, capable of constructing structures larger than the printer itself through a continuous flow process. A stator-driven mortar pump delivers adobe material to the nozzle. During the construction of Casa Covida, a 4th axis rail was utilized to provide a stable structure on which the printer could be moved after each printing session, with each session producing layers approximately 400mm in height. The deposited adobe material is left to dry and harden under the sun and wind. The printer, which can be easily transported by two individuals, can be operated by a single person using a cell phone to control the printing process. While mixing and sifting the earth mixture is done manually, a mortar mixer assists in the process. Design files are generated using a sophisticated software application derived from Potterware, ceramic 3D printing software developed by Emerging Objects as a result of architectural ambitions to print with clay.

Figure 14. The entrance and socializing spaces inside

source: *https://www.archdaily.com/963516/casa-covida-emerging-objects*

5. Experimental Case study

In an effort to advance earth construction techniques using additive manufacturing and reduce the gap between theory and practical application, our study involved the design and 3D printing of sixteen earthen blocks utilizing a six-axis robotic arm (ABB IRB 6700-175/3.05) with a 175 kg payload and a maximum reach of 3.05 meters at the AUC robotic arm laboratory. The primary aim of this investigation was to analyze the compressive strength of the printed samples and evaluate the impact of intricate infill shapes on adobe bricks compared to traditional adobe bricks with solid infill. The research framework is based on 4 phases: concept design phase, parametric modeling, printing and validation.

After the printing and drying phase, the samples were categorized into two groups (A and B). The blocks were meticulously designed using Rhinoceros® Grasshopper® software with a parametric design methodology in the design phase, featuring dimensions of 6*6*6 cm for facilitating the tests and incorporating 7 various infill patterns such as patterns from triply periodic minimal surface (TPMS) patterns at two different heights as shown in figure 15. The layer height was adjusted to 3 (equivalent to 20 extrusion layers) and 2.5 mm (equivalent to 24 extrusion layers). A circular nozzle with a 4mm diameter was utilized, printing speed set at 10mm/s, and pressure maintained at 6 bar.

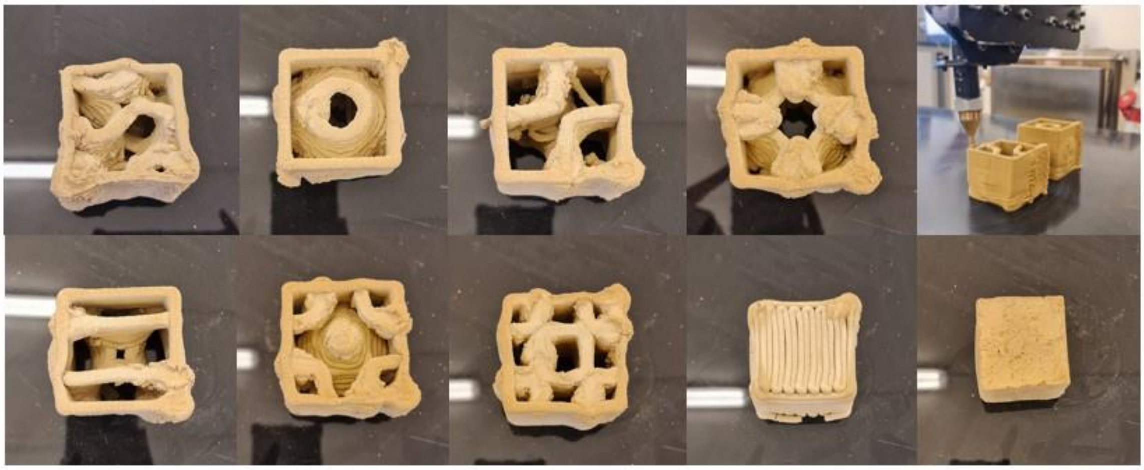

Figure 15. 3d printed samples *Source: by Author*

In comparison to the traditional method, a mold measuring 6*6*6 cm was filled with a similar mixture to create a base sample. The mixture consisted of locally sourced materials including Nile Clay, Silica Sand, binder (lime) in a ratio of 75%, 20%, 5%, and water comprising 34% of the total mixture. This specific recipe was formulated to achieve a balance between fluidity for consistent material flow during printing and solidity to prevent deformation. Subsequently, the printed samples underwent a 14-day air-drying process in the laboratory at an average temperature of 28 degrees Celsius before being prepared for testing using the ASU Material Research Center's universal testing machine as shown in figure 16.

Figure 16. Universal Testing Machine conducting compression tests& failure modes in samples

Source: by Author

The findings from our study reveal that the geometric configuration of the infill within the blocks plays a crucial role in determining their compressive strength, even when the void ratios remain consistent. The tested samples outperformed the average compressive strengths documented for both 3D-printed earthen materials and the conventional samples utilized in this research. This performance not only highlights the potential for material conservation but also indicates a reduction in cross-sectional dimensions. Notably, certain samples demonstrated strength values that were twice as high and comparable to those of the mold sample.

6. Conclusion and Discussion

The primary focus of this study is on earth construction, with an emphasis on its advantages and the factors contributing to its degradation in applications despite its potential. Additionally, the research explores digital fabrication techniques for earthen building construction as a new approach that is still under investigation, along with the potentials they offer. Traditional earth construction has been utilized for many years, and its advantages are evident in its good thermal performance, favorable indoor environment, recyclability, and availability. However, the construction field faces significant challenges in continuing to apply this technique, including issues related to structure performance, the absence of standards, and the high need for maintenance. The emergence of digital fabrication has the potential to add value and transform the traditional potential of earth construction into a new approach, leveraging its advantages while addressing its challenges.

Digital fabrication techniques and technologies are increasingly essential for production processes, and robotic manufacturing has shown promise in expanding design possibilities. A new understanding of construction is rapidly gaining traction, driven by the objective of combining low-cost and sustainable materials with the emerging digital construction sector. This fresh perspective incorporates local knowledge as the foundation for current digital innovations. Over the past decade, the development of digitally produced earthen buildings has successfully unlocked the potential of earthen structures and broadened the scope of digital manufacturing in construction beyond cement-based materials. The collective efforts in this area have laid the groundwork for bringing digital earth engineering closer to an industrial scale and bridging the gap between earth engineering and modern digital practice. It is crucial to highlight the potentials and challenges that hinder progress in this field in order to establish a robust framework for the future development of digital fabrication.

The integration of digital fabrication techniques and technologies into the construction sector has the potential to revolutionize the industry. By leveraging these advancements, it is possible to address the challenges associated with traditional earth construction and unlock new opportunities for sustainable and efficient building practices. The combination of low-cost and sustainable materials with digital innovation has the potential to reshape the construction landscape, offering a pathway towards more environmentally friendly and economically viable building solutions. As such, understanding the potentials and challenges of digital fabrication in the context of earth construction is essential for guiding future research and development efforts in this area. By doing so, it is possible to establish a strong foundation for the continued advancement of digital fabrication in construction and the realization of its full potential.

The benefits of digital fabrication techniques lie in their ability to enhance efficiency, precision, and design flexibility within modern construction practices as illustrated in the experimental case study. These advantages address the limitations of traditional techniques while simultaneously improving upon their strengths. However, challenges persist within this field, including issues related to manufacturing technologies, performance aspects, and a lack of information and studies. It is important to note that such challenges are common during the early stages of the evolution of any new technique.

Despite the obstacles encountered in the realm of digital fabrication, research institutions, laboratories, universities, and companies are diligently working to expand their knowledge of the topic. Their efforts are focused on promoting the utilization of this technology for the benefit of communities and the environment. The chosen case studies have been selected to illustrate three distinct approaches through which this technique can be applied, each yielding different outcomes. For instance, one approach involves the 3D printing of Adobe bricks off-site in a laboratory setting, followed by their storage and transportation to the construction site. Another approach maintains the traditional technique while updating the mold outline through parametric design, a method that cannot be achieved using traditional means. These examples showcase the potential for new designs and improved performance. These case studies also offer potential solutions to the challenges associated with manufacturing technologies and the availability of large-scale printers for building projects. Furthermore, the last example demonstrates the use of large-scale printers to construct buildings on-site, providing a viable solution to the challenges faced in this field.

The research presented in the experimental case study aims to enhance the structural capabilities of adobe bricks through the incorporation of intricate infill patterns not commonly seen in traditional adobe brick construction. The results of the compression test indicate that these complex infill patterns can achieve compressive strength levels similar to standard bricks, with the potential to even double the strength of the bricks. Additionally, the study highlights that these intricate patterns enable easy printing without distortions, reduce material waste, and improve thermal efficiency, all of which are crucial factors in enhancing the overall structural integrity of the adobe bricks. Interestingly, the research suggests that samples with a layer height of 2.5 mm outperformed those with a layer height of 3 mm, emphasizing the importance of layer height in determining structural performance. The findings underscore the significance of exploring innovative approaches to traditional sustainable construction methods, with a focus on digital fabrication techniques like the impact of infill pattern, nozzle size, and layer height. Ongoing efforts within the DMEC community are dedicated to overcoming challenges and promoting the widespread adoption of these advanced construction methods in the industry, paving the way for more sustainable and efficient building practices.

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