Ingeniería y
Competitividad
Vol 25 (suplemento) 2023; doi: 10.25100/iyc.v25i3.13236

Número Suplemento

ISSN
0123-3033
e- 2027-8284

Artículo de investigación

Edición especial 25 años del doctorado en ingeniería

3d printing applied to building development around the world: a systematic literature review

Impresión 3D aplicada al desarrollo de edificios en todo el mundo: una revisión sistemática de la literatura

Cómo citar: Vélez, S., Ortiz, A., Gómez, D., García, J.J., Thomson, P., Sandoval, E. 3d printing applied to building development around the world: a systematic literature review. Ingeniería y Competitividad. 25(3) ,e-21313236. doi: 10.25100/iyc.v25i3.13236

Sebastián Vélez[a], Albert Ortiz[a], Daniel Gómez[a], Jose Jaime García[a], Peter Thomson[a], Eimar Sandoval[a]

[a]School of Civil Engineering and Geomatics, Universidad del Valle, Cali, Colombia

Resumen

The construction industry is undergoing a transformation towards automation, and 3D printing is at the forefront of this revolution. However, to optimise 3D printing in construction, it is crucial to consider the printer's scale, the printing material's rheological properties, and the printed structure's mechanical properties. This paper provides an overview of the state of the art in this field, including the promising technologies, such as D-Shape and Contour Crafting, used in building applications. The paper also compares the use in 3D printing of conventional materials, like concrete, with non-conventional earth-based materials, such as sand, clay, and mud, or combinations with cementing materials. This review highlights the need for more research on alternative materials to concrete, particularly in developed countries. Nevertheless, earth-based materials offer significant potential for 3D printing in developing countries, where they are readily available. However, further research is necessary to improve the mechanical properties of 3D-printed elements, particularly for large-scale structures, to ensure their reliability and safety, making 3D printing a mainstream building method.

Palabras clave: Sustainable construction, building automation, contour crafting, building materials, concrete, soil.

doi: 10.25100/iyc.v25i4.13236

Introduction

According to international organisations and reports, there is an imperative global need to provide suitable housing for large populations in precarious set- tlements, marginalised communities, or unfavourable living conditions [1]. This necessity is particularly pronounced in underdeveloped or developing regions, like Latin America, where the governments are responsible for resolving these housing challenges [2]. Consequently, various treaties and agreements have been instituted by governments across the world, to prioritise urban development policies, thereby increasing housing options to enhance the quality of life for local communities [3]. On the other hand, the International Energy Agency (IEA) reports a huge carbon footprint due to the buildings sector [4]. In 2021, the operation of buildings accounted for 30% of global final energy consumption and 27% of total energy sector emissions [4]. Additionally, these emissions are growing concerning 2019 or 2020, making the building industry the sector with the lower change in CO2 emissions compared to other [5]. As explained by the [4]: "To align with the Net Zero Scenario, carbon emissions from buildings operations need to more than halve by 2030, requiring significant efforts to reduce energy demand through clean and efficient technologies in all end uses", to achieve this, the automation of the construction industry has obtained considerable attention and development in the last few years.

Current construction methods may be too expensive, slow, inefficient, or labour- intensive to meet the global demand for decent housing and clean technologies [6]. Among the emerging ones, 3D printing technology has demonstrated significant potential for building construction. Its main benefits are design freedom, mass process customisation, loss minimisation, the ability to fabricate complex structures, and rapid prototyping [7].

Over the last 25 years, extensive research has been conducted on the application of 3D printing in the construction industry, particularly in developed countries [8]. However, most of the research and reviews in this field have been focused on the application of 3D printing with concrete [9], neglecting the potential of non- conventional materials, even when it's demonstrated that earth-based materials are abundant everywhere [10].

To address this inequality, a thorough review examining the gap between 3D- printed concrete structures and earth-based 3D-printed buildings is crucial. This review should encompass technological advancements, material ratios, geometric considerations, reinforcement methods, and printing parameters. Therefore, the primary objective of this research is to provide a critical analysis and comprehensive systematic literature review (SLR) of the current state-of-the-art in global 3D printing for both conventional and unconventional construction materials. For this purpose, Section 2 describes the methodology used to conduct the research. Next, Section 3 delves into an exploration of 3D printing technologies implemented across various industries. Subsequently, Section 4 examines 3D printing applica- tions in building construction using concrete and unconventional materials such as soil. Finally, Section 5 provides a valuable discussion of the challenges that must be overcome to improve 3D-printed buildings in the coming years and offers a global perspective on innovation and research in this topic.

Methodology

This work presents a SLR on the application of 3DP technologies in building materials and development. The protocol used to collect and analyse the article database consisted of three phases: (1) data search, (2) data selection, and (3) data analysis. For the data search, 1141 were accessed through the Scopus web page [11]. The data collection and selecting method consisted

doi: 10.25100/iyc.v25i4.13236

of the items listed in Table 1. Then, the database was filtered, selecting only relevant documents based on their links and the number of citations, that were used as a more detailed source.

Table 1. PRISMA items used in this research

Item	Value
Source	Scopus web page
Keyword strings	(a) "Concrete" AND "3D printing" AND "building" (b) "Soil" AND "3D printing" AND "building" (c) "Clay" AND "3D printing" AND "building" (d) "Cob" AND "3D printing" AND "building"
Elegibility criteria	(a) Date: 2010-2022 (b) Document type: Journal papers, conference proceedings, books. (c) Language: English

Initially, the general keyword strings "3D printing" were used deliberately and the 1141 most cited papers were used as the raw database. The next step consisted of the delimitation of the results using the keyword method oriented to construction materials, exclusively, both conventional and non-conventional. For the keywords "Concrete" AND "3D printing" AND "building", 434 documents were selected. On the other hand, for the keywords related to non-conventional materials, such as "soil", "clay", and "cob", only 57 documents were selected. This database of 491 documents was used to extract information related to the most studied materials in 3DP. However, the final selection was based on papers with more than 10 citations.

A bibliometric approach known as network analysis was used. This method represents the complex links between papers and their citations across various journals in a simple visual way, giving weight to the total number of citations of any document. Consequently, it streamlined the information collection process and provided a clearer understanding of the knowledge structure by elucidating the interconnections between papers through the description of nodes and their interconnected network framework [12].

The VOSviewer software was used for the bibliometric analysis. It is a software application designed to create and visualize bibliometric networks. These networks can represent various entities such as journals, researchers, or individual publications, and can be built based on citation, bibliographic coupling, co-citation, or co-authorship relationships. Additionally, VOSviewer provides features to gen- erate and visualize co-occurrence networks, highlighting significant connections within a corpus of scientific literature [13].

Finally, research bias was avoided to the greatest extent possible by assigning different tasks to the researchers. Three were responsible for the literature search and selecting the most relevant articles according to the eligibility criteria. In contrast, the other three investigators reviewed the information to prevent duplication of data, information that did not meet the criteria, and to ensure high quality in the final database.

doi: 10.25100/iyc.v25i4.13236

Current 3D printing technologies

Efforts to improve building efficiency through technology have been made with additive manufacturing being a particularly promising solution. This is a massive production tool that allows process automation in different industries. It was first developed by Charles Hull in 1986 and is commonly referred to as stereolithography or photo-solidification [7]. Today, there are several 3D printing technologies available, such as Fused Deposition Modelling (FDM) [14], Powder Bed Fusion (PBF) [15], Selective Laser Sintering (SLS) [16, 17, 15], Selective Laser Melting (SLM) [16, 15], inkjet-based 3D printing or contour crafting [7], Stereolithography (SLA) [18], Direct Energy Deposition (DED) [19], and Laminated Object Manufacturing (LOM) [20]. Most of these technologies are developed for non- construction purposes.

Non-steel-based materials, such as plastic, ceramic, or glass, can be printed using FDM, SLS, SLA or LOM [16, 17, 14]. FDM utilizes a heated nozzle to melt a continuous thermoplastic polymer filament and deposit it onto a platform or previous layers. Parameters affecting the printed object's final characteristics include layer thickness, filament width and direction, and voids between layers or in the material. Adding fibres to the materials can improve their mechanical properties, but challenges such as distortion between layers, fibre orientation, matrix link, and voids development arise from composite 3D-printed parts [14].

SLS and SLM use powder deposition to create successive fused layers using thermic energy [16]. SLM needs more energy than SLS and can use metal alloys like aluminium, titanium, or stainless steel, but this high energy requirement is offset by high density in the final product [15]. Similarly, SLA exposes a precursor liquid to ultraviolet light, which induces polymerization and solidifies the exposed areas. Different industries have applied this method, from the aerospace and automotive industries to medicine. The mechanical properties of printed materials with SLA vary depending on the requirements [18]. Finally, LOM uses a CO2 laser to cut each layer of rolled material laminated with adhesive coating, allowing the attachment of parts. LOM can use plastic filaments, composite sheets, and paper [20].

The technologies described above are usually for non-construction purposes. For building applications, PBF or DED can 3D-print steel and inkjet 3D printing, D-shape, or Contour Crafting are commonly used to 3D-print concrete or earth- based materials. PBF works by compacting fine powder onto a printing surface, which is then fused using a laser or binding agent. The powder bed serves as a support structure and eliminates the need for support material, but the process is expensive and lengthy, and the printed material may have high porosity. PBF is used in various industries, including scaffolding for tissue engineering and regenerative medicine, lattice beams and columns, the aerospace industry, and electronic parts [15]. On the other hand, DED utilises energy lasers controlled by a computer to deposit steel powder and form each layer. It offers high prototyping speed, parts repair, metal components production, and smart-structures construction. How- ever, it requires high laser power, and the parameters that most impact the finished product are the powder supply rate, scan velocity, and powder mass flow rate [19].

On the other hand, inkjet 3D printing, D-shape, and Contour Crafting are used for manufacturing complex ceramic structures like scaffolding for tissue engineering and regenerative medicine, structural elements such as walls, beams, or decks, and whole full-scale structures such as houses. Their working principle lies in the constant pumping and layer-by-layer deposition of a building material (zirconium oxide into water or wax-based inks for inkjet-based 3D printing, and concrete or soil for Contour Crafting) or a granular material composed of a mix of sand and pulverised metal oxide (D-shape) through a single nozzle (Contour Crafting) or multiple nozzles (D-shape).

doi: 10.25100/iyc.v25i4.13236

Later, the solidification of the material must provide enough strength to support subsequent layers. The parameters that usually affect these technologies are related to either, the material, such as the number of solids, particle size and viscosity, or the extrusion process, such as the rate, nozzle trans- lational speed and distance between the nozzle and the latest deposited layer [21]. The last technologies mentioned have been adapted to multiple mechanisms, with the robotic arms [22, 23, 24, 25, 26] and the frame-like (gantry) mobile structures [27, 28, 29, 30, 31, 32] as the most used [33]. Fig. 1 shows the essential components of a 3D printing system with the mentioned mechanisms.

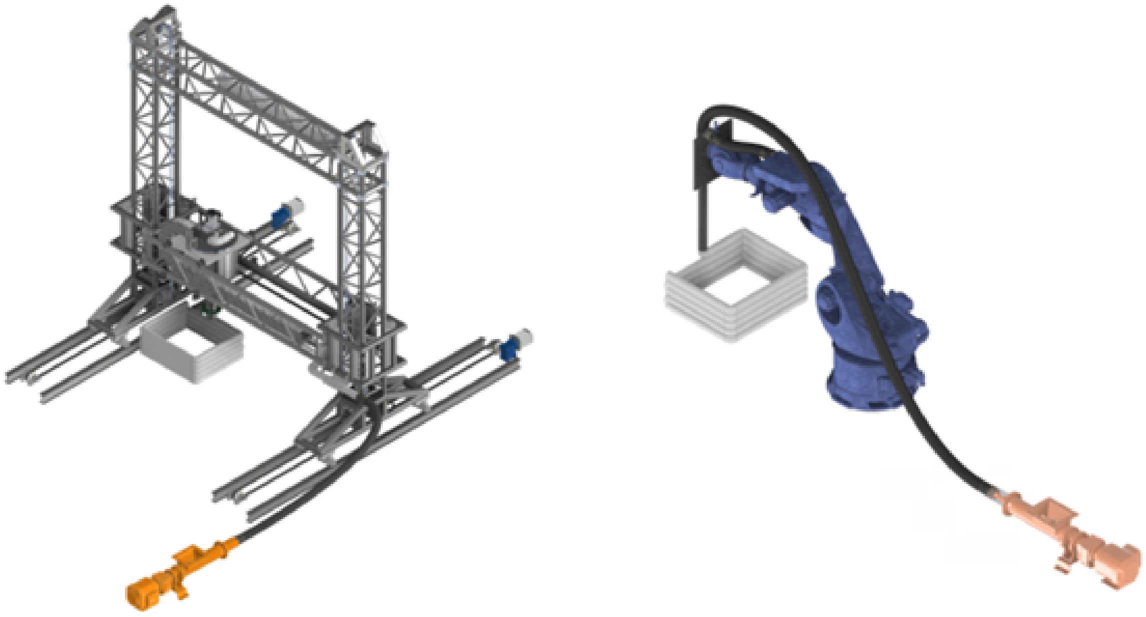

Fig. 1. Most used 3D printing Systems. (a) Illustration of a mobile frame 3D printing system. (b) Illustration of a robotic arm 3D printing system.

Building Applications of 3D Printing

Only 34 countries have 5+ published papers concerning building applications of 3D printing. Moreover, only two Latin American countries (Brazil and Chile) accomplish this minimum number. The five countries with the highest intellectual production are China, the U.S.A, Australia, Germany and the Netherlands, with 174, 157, 112, 112 and 74 published papers in top-level journals, respectively. It must be highlighted that the U.S.A. is the country with the most citations in 3DP, above 5500. Fig. 2 shows the global distribution of publications about building development using 3DP, considering all the data initially collected.

3DCP is a technology in its growth stage, with building applications representing only a small portion (3%) of the whole 3DP industry [7]. Fig. 3 presents the most used keywords in the literature concerning 3D printing technology applied to building development. Only 95 keywords occurring in more than 20 studies were considered. Under this condition, 4 clusters were identified, consisting of (1) keywords related to the fresh state of materials and to the mixtures

doi: 10.25100/iyc.v25i4.13236

themselves, in red; (2) keywords related to the technology and the industry: from the printers, modelling, and printing processes to the concrete industry, design, and digital fabrication, in green; (3) keywords related to the mechanical and structural behaviour of 3D-printed specimens, in blue; and (4) keywords related to geopolymers, in yellow. This research is focused on the first three clusters.

Moreover, Table 2 shows the top ten papers ranked by the number of citations and their links with other publications. It is evident that concrete is the most studied material, with only one paper among the top-cited studies exploring soil as a potential printing material. Mega-scale additive manufacturing or 3D printing technologies have been applied and developed for the last 25 years by more than 30 research groups currently active on these topics around the world.

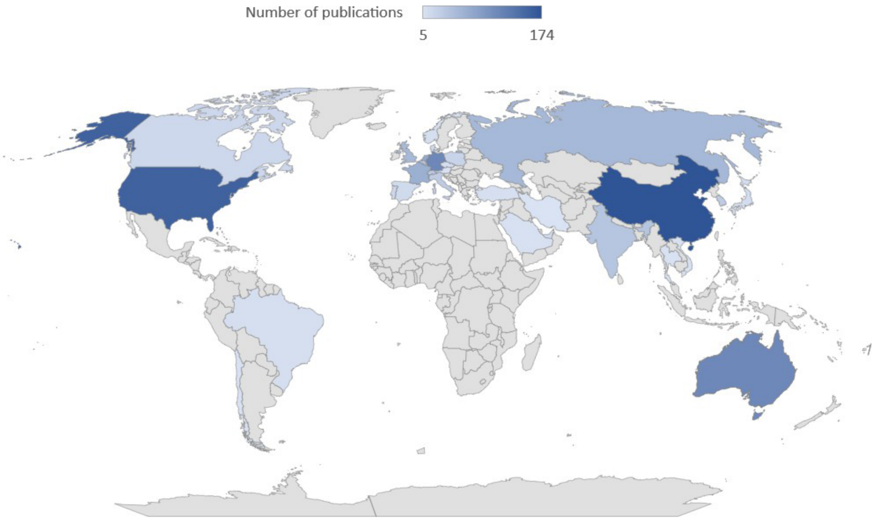

Fig. 2. Publications distributed by country

Table 2. Most cited papers regarding 3DP of building materials

Author (year)	Citations	Links	Studied or reviewed materials
Ngo et al. (2018)	2282	63	Metals and alloys Polymers and composites Ceramics Concrete
Cesaretti et al. (2014)	490	5	Regolith and lunar soil
Buswell et al. (2018)	419	222	Concrete

Bos et al. (2016)	416	202	Concrete
Gosselin et al. (2016)	390	159	Ultra-high performance concrete
Perrot et al. (2016)	357	178	Cement-based materials
Tay et al. (2017)	280	106	Ceramics Concrete Chopstick composites Natural composites Thermoplastic polymers Concrete
Schutter et al. (2018)	271	142	Concrete
Wolfs et al. (2018)	260	180	Concrete
Kazemian et al. (2017)	258	146	Cement-based materials
Panda et al. (2017)	225	124	Fiber reinforced geopolymer mortar
Paul et al. (2018)	210	112	Cement-based materials
Panda and Tan (2018)	183	94	Fly ash based geopolymer mortar
Panda et al. (2018)	182	86	Fly ash based geopolymer mortar
Sanjayan et al. (2018)	181	126	Concrete
Panda et al. (2018)	179	80	Fly ash based geopolymer mortar
Hager et al. (2016)	175	47	Concrete and eco-concrete
Buchanan and Gardner (2019)	171	13	Concrete Polymer Metal
Wolfs et al. (2019)	153	111	Concrete
Lowke et al. (2018)	149	72	Concrete

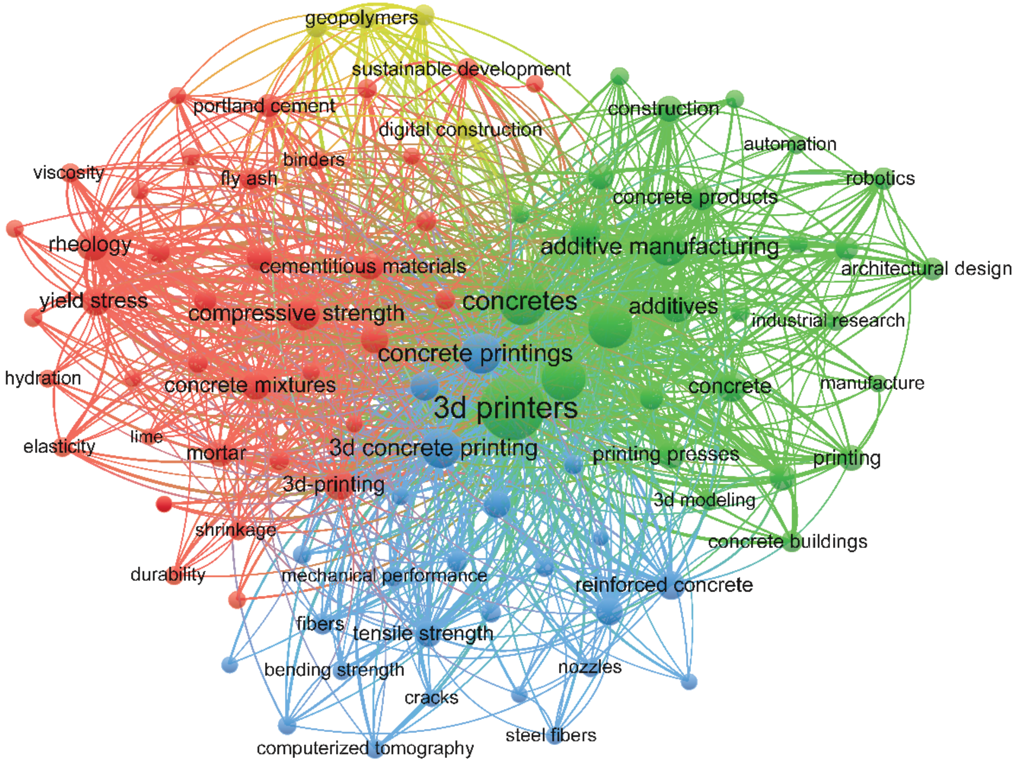

Fig. 3. Network of keywords with 20+ occurrences on literature regarding 3DP of building materials and its clusters, using VOSviewer software

According to Fig. 4, concrete has been widely studied as the main building material for 3D printing. However, other viable and sustainable options such as soil and recycled aggregates have not received sufficient attention in research. The following sections discuss various 3D printing applications and the challenges associated with different building materials. Although there are three types of materials used for 3DP construction: cementitious, metals, and polymers [50], this study analyses only cementitious materials, since they are the most developed and show the greatest potential of all.

doi: 10.25100/iyc.v25i4.13236

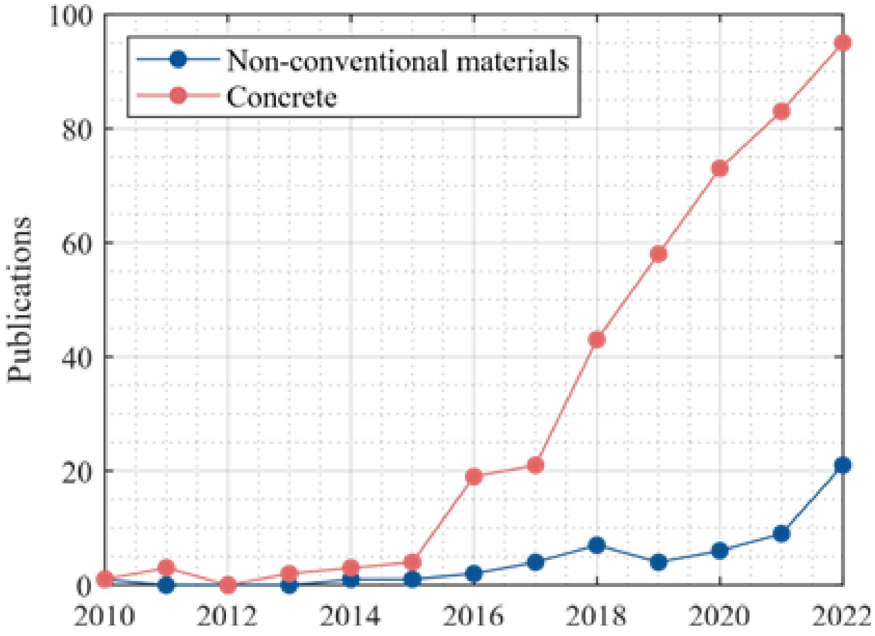

Fig. 4. Comparison between the research on concrete and non-conventional materials for 3D printing. The information was collected from the Scopus web page [11].

3D Concrete Printing (3DCP)

As mentioned above, concrete is a widely used building material, and has also become a popular choice for additive manufacturing applied to the building industry [7]. This technology has been developed since 1997, and the number of constructions carried out has increased exponentially in only two decades [35]. The breakthrough research on this scope was conducted in 1997 by Joseph Pegna [22]. He proposed a new process for building automation, manufacturing minor masonry structures using sand and Portland cement layers deposition. This process works with the premise that the continuous addition of some base material in a computer- aided way might build a complete structure. Additionally, Pegna managed to standardise geometry and other material properties in a lab-controlled condition.

In 2003, Khoshnevis patented the first technology for additive manufacturing of full-scale structures and construction [51]. The technology was called Contour Crafting, an additive manufacturing technology that originated in Southern California. This technology utilises computational control of trowels to produce plane surfaces with fine textures, resulting in improved surface quality, faster productiospeeds, and a wide range of usable materials compared to other manufacturing processes [51]. Using Contour Crafting allows the construction of various types of structures, including conventional buildings, as well as brick, adobe, or dome constructions that do not require external support elements. Furthermore, 3D printers can use non-conventional materials, as discussed in Section 4.2.

One of the Contour Crafting's first lab applications for structural elements was developed by Hwang and Khoshnevis in 2004. They built a concrete wall with a compressive strength of 18.90 MPa using the freeform concept, i.e., they printed the form and then filled it with fresh concrete

doi: 10.25100/iyc.v25i4.13236

[27]. Fig. 5(a) illustrates this process, and the wall is showed in Fig. 5(b).

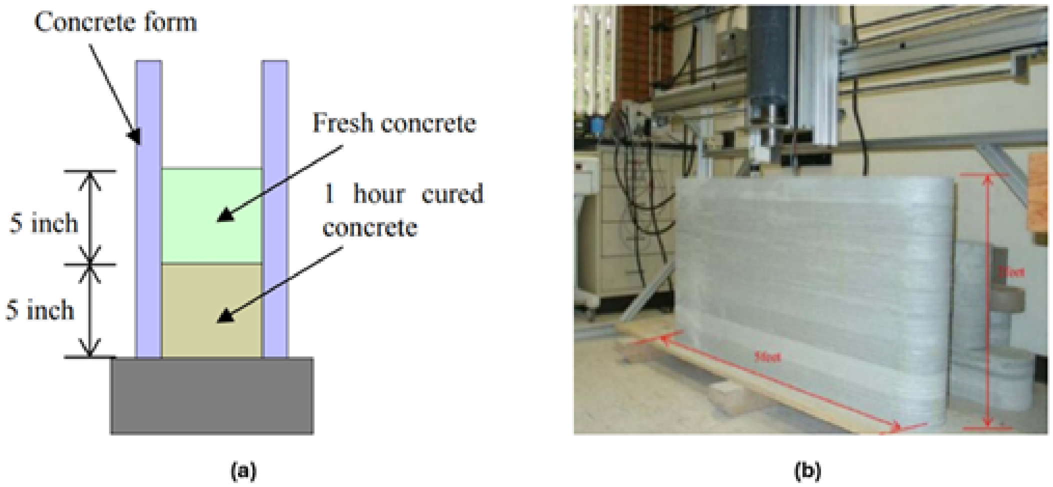

Fig. 5. Contour Crafting applied to concrete wall fabrication (a) Form and fill scheme. (b) Concrete wall and form [27].

After the free-form construction concept, in 2007, [52] introduced the concept of printing an entire structure, allowing efficient mega-scale manufacturing. They analyzed the parameters that affect the additive manufacturing of full-scale buildings and the viability of 3D-printed forms. They mainly evaluated the cost, operating time, available geometry freedom, and the value added by this technol- ogy [52]. By 2012, three acceptable processes for mega-scale additive manufacturing applied to construction and architecture were developed: Contour Crafting, D-Shape (patented by Enrico Dini), and concrete printing [53].
One of the first applications of D-Shape was carried out in 2008 by Andrea Morgante, who produced an architectural sculpture known as Radiolaria with a 1.8 m height, as shown in Fig. 6. Three years later, James B. Gardiner manufactured a big-scale Radiolaria [54].

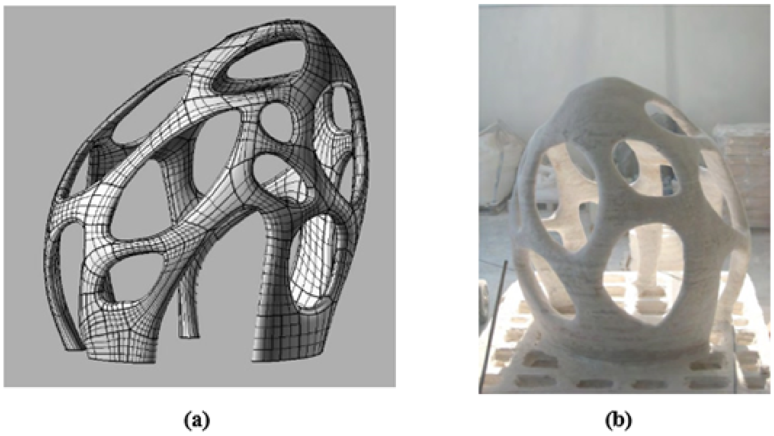

Fig. 6. Radiolaria printed by Andrea Morgante. (a) 3D Radiolaria model. (b) Radiolaria scale prototype [54].

doi: 10.25100/iyc.v25i4.13236

Research on 3D concrete printing has primarily focused on its potential for new building construction. In recent years, a significant challenge has emerged in understanding the physical and mechanical behaviour of 3D-printed structural elements and their load conditions. In addition to the solid-state characteristics, the fresh-state properties of the mix are critical to the 3D structural printing of cementitious materials, as highlighted by [55].

To successfully print fresh materials, four properties are needed: (1) high workability for extrusion, also known as extrudability or open time; (2) high early strength to resist subsequent layers, known as buildability; (3) controlled fluidity, known as flowability, affected by factors such as the water/cement ratio, size distribution, morphology, absorption capacity of the particles, and adequate mix dosage; and (4) the right time for material setting, while also preventing shrinkage through the use of mineral additions in the mix, a low water/cement ratio, a higher amount of fine aggregate, and the addition of reinforcing fibres [55, 56]. Developing a good mix design that ensures a perfect match between the properties mentioned above is one of the main challenges in current research on new 3D printing materials.

A good approximation to the behaviour of 3D-printed materials can be obtained from the relationship between forces and deformations, i.e. constitutive equations [57]. The study of these properties of materials is known as rheology and has been the subject of research by various authors worldwide in 3D-printed concrete [25, 31, 43, 58, 59, 60]. One of the postulates of rheology relies on the existence of materials which are not described by the Newton-Stokes and the Hooke laws, i.e. non-Newtonian and non-Hookean materials [57]. Mathematical approximations toreality, such as the Bingham model for non-newtonian materials, have allowed the calculation of parameters like the plastic viscosity or the expected shear stress of mortars [25]. Other studies have also examined the potential of different aggregates and additives to enhance concrete properties [29, 61, 62].

For instance, [23] developed a printing process that utilizes an accelerating agent and a pre-mix mortar, which are pumped through separate pipes and mixed in a printing head before extrusion. This method controls the pre-mix mortar’s rheology for a longer period without sacrificing the initial strength of the printed layers, thus enabling the construction of larger structures with complex geometries without the need for temporary support. The process uses a 6-axis robotic arm where the material’s behaviour during and after extrusion is controlled.

In a study by [28], a high-performance 3D-printed fibre-reinforced mortar was created using a mix of Portland cement, fly ash, silica fume, sand with a maximum aggregate size of 2 mm, and polypropylene fibres. The mix was enhanced with superplasticizer and retardant to improve its workability. The mixture built up to 61 layers, with a height of approximately 400 mm. The extrusion head had a 9 mm diameter nozzle and an open time of 100 minutes. Compared to traditional fibre-reinforced concrete, 3D-printed fibre-reinforced concrete composites offer the advantage of controlling fibre orientation. Carbon fibres printed parallel to the x-y plane along different printing paths significantly increase flexural strength up to 30 MPa [63].

Another research on 3D-printing mix design was carried out in 2017 by [61]. They used OPC (Ordinary Portland cement) and SAC (Sulphoaluminate cement) as raw materials for two different mortar mix designs with different setting times. SAC had a short setting time and high initial strength, while OPC had slower hydration and a longer setting time. They concluded that SAC is a better 3D printable composite due to its properties. Early setting time is crucial for 3DP in the layer-by-layer printing process, allowing lower layers to hold superior layers with enough strength [55].

doi: 10.25100/iyc.v25i4.13236

The mechanical properties of 3D-printed samples are significantly influenced by printing parameters, such as nozzle shape and direction [64]. Many researchers have tested specimens under different directions [42, 44, 25, 48, 65, 66]. They have found that strength and Young's modulus are higher when they test the specimens under stress parallel to the layer deposition direction, i.e., the nozzle travel path, and lower when stress is perpendicular to the layer deposition direction or matches with the joints between layers. [29] investigated the effects of particle size, extrusion speed, and layer thickness on bond strength between layers, and found that the maximum particle size of aggregates and the highest cement content, compare with the aggregate content, results in a strengthening due to better layer binding. Although better for binding, the shortest layer thickness with more elapsed time between posterior layers reduces compressive strength. Nonetheless, a longer setting time may increase cold joint formations on the layer interface. In addition, the form stability of printed layers is critical, as it measures the resistance of the layer against settlement and deformation caused by posterior layers. [41] demonstrated that adding silica fume and nano-clay can enhance the form stability of 3D-printed cement paste to overcome one of the major challenges of building higher and more complex 3D-printed structures: the lack of external support. Furthermore, [67] compared the quality of 3D-printed specimens with conventional mould-casted specimens, in terms of their mechanical properties, through compressive strength and ultrasonic pulse velocity tests. The material used was cement mixed with concrete waste, ceramic waste and red clay brick waste from construction and demolition activities, activated with Industrial grade sodium sulphate (Na2SO4). They obtained very similar properties of 3D-printed specimens to that of conventional specimens.

The number of completed 3D printing projects is growing rapidly, showcasing the technology's potential for construction. One early example is an urban micro home printed in Amsterdam in 2014 with plastic, using the FDM method. This project, driven by DUS Architects, aimed to demonstrate the mobility of printers and minimal waste and material costs, paving the way for automated construction. The structure was built in a former industrial area and required only 25 m^3 of material (Fig. 7(a)) [68].

In the same year, the Chinese architectural firm "WinSun" printed houses on a massive scale in Shanghai, completing the project in just 24 hours (Fig. 7(b)). At that time, traditional 3D printers were limited in size, making their application in the construction industry challenging. However, WinSun's project utilized a 3D printer with dimensions of 150 m in length, 10 m in width, and 6.60 m in height, and printed cement and glass fibre. Despite the project's success, the WinSun team encountered several challenges during its execution, including brittleness issues and integrating building services with indirect printing [9]. In 2015, this company built a 6-story structure (Fig. 7(c)) in Shanghai using recycled concrete derived from waste in the construction industry, such as concrete, glass fibre, and sand, mixed with accelerant additives [69]. In 2016, the Chinese construction company HuaShang Tengda, one of the major competitors of WinSun, printed a 400 m^2 two-story house in only 45 days totally on-site, the house is shown in Fig.7(d) [70].

doi: 10.25100/iyc.v25i4.13236

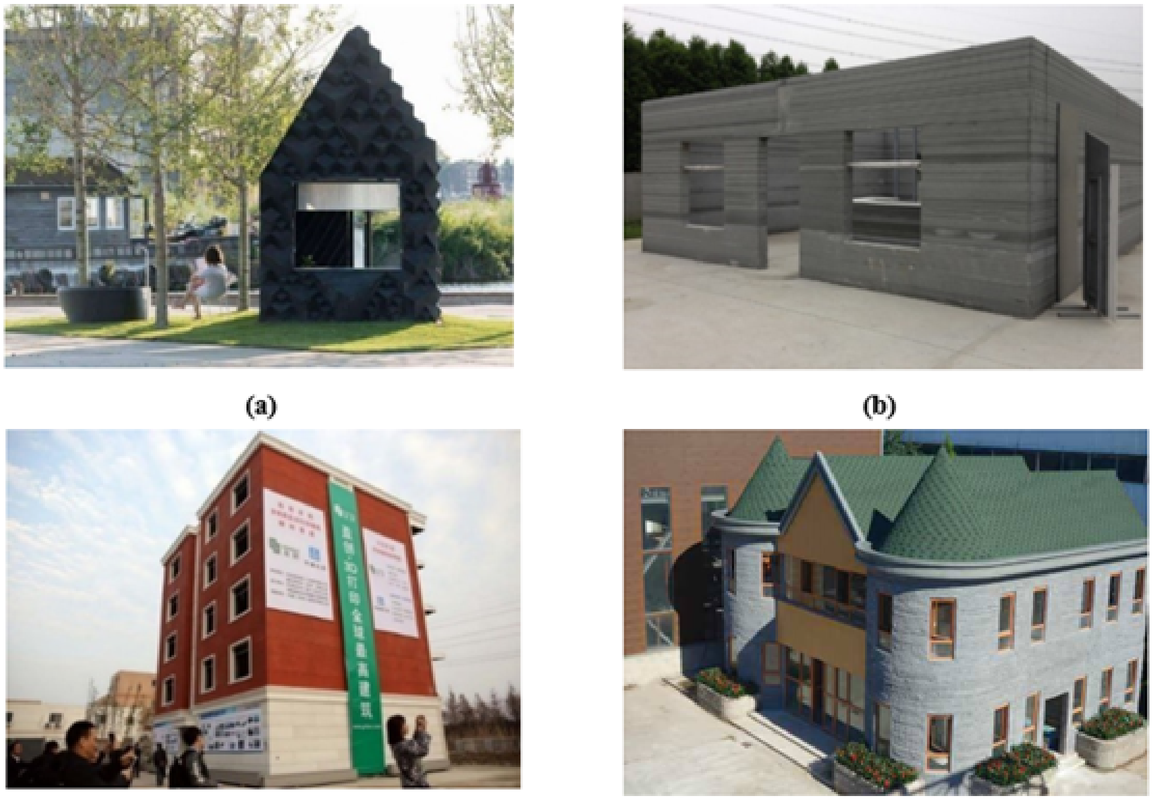
(a) (b) (c) (d)

Fig. 7. 3DP applied in construction. (a) Canal house, printed by DUS Architects [68]. (b) Standard house printed by WinSun in a village construction [9]. (c) Building printed by WinSun [69]. (d) Two-story house 3D-printed by HuaShang company [71].

In 2015, the first-ever hotel fully 3D-printed was built by TotalKustom enter- prise in the Philippines. One of the aspects to highlight was the architecture in different structural elements, like the columns (Fig. 8(a)). The following year, at the Delft University of Technology (TU Delft), 3DCP and flexible modelling were used to manufacture pre-fabricated elements for a concrete deck (Fig. 8(b)) [72]. In recent years, 3DCP technology has advanced significantly, allowing for the creation of elements with more complex shapes. For instance, XtreeE, a French construction company, built a sinusoidal-shape wall in just five and a half hours, with 2.5 m in length and 2 m in height using 3DCP technology, as depicted in Fig. 8(c) [73]. In a related study, researchers at the Zurich ETH University explored the use of computational design and 3D printing techniques to create columns with complex shapes, as shown in Fig. 8(d) [74]. The study revealed that the optimal material deposition mainly depends on high horizontal processing speeds, which distinguishes this process from other 3D printing methods. Furthermore, the researchers developed a project called Smart Dynamic Casting, in which they filled a numerically controlled form with mortar that was automatically activated immediately after extrusion [75].

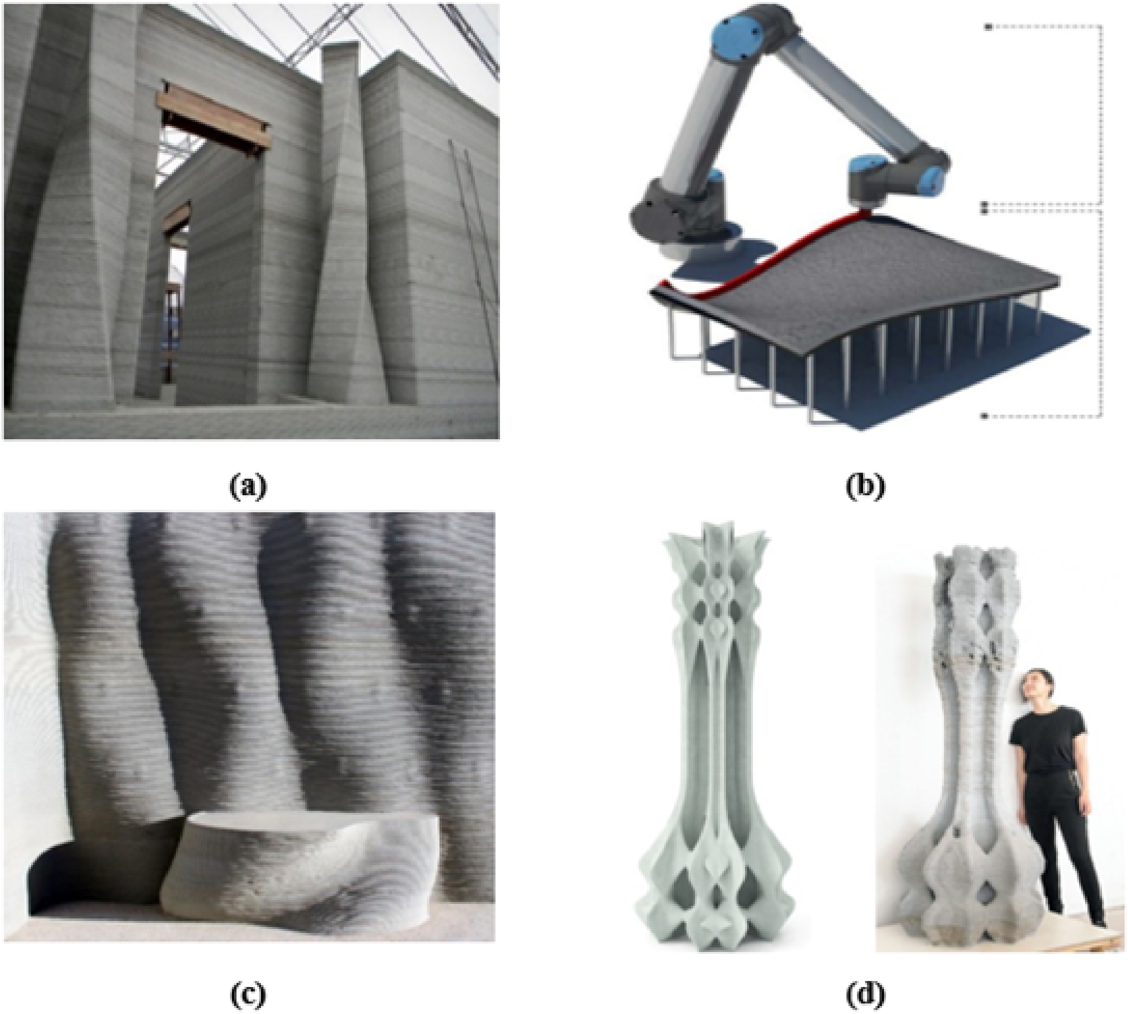

Fig. 8. Printed structures with non-conventional shapes. (a) Printed complex-geometry concrete structure by TotalKustom [76]. (b) Printer and deck model made by the TU Delft [72]. (c) Sinusoidal wall, printed by XtreeE company [73]. (d) Complex shape column [74].

Besides the structures and housing-adaptable elements, another application for 3DCP is related to infrastructure, such as vehicular or pedestrian bridges. One of the first 3D printings of a pedestrian bridge was the Alcobendas - Spain concrete bridge that measures 12 meters in length and 1.75 meters in width [77]. One year later, another bridge was inaugurated at Tongji University in Shanghai, China at the Digital Future 2017 Workshop, which was fabricated using modified plastic [78]. Another 3D-printed bridge was made with steel in the Joris Laarman labs in Amsterdam [79].

Subsequently, in 2018, researchers at the Eindhoven University of Technology (TU/e) designed and printed a prestressed concrete bridge [80] (Fig. 9(a)). This bridge had a span of 6.5 m and a cross-section of 3.44 x 0.92 m. The prestress and assembly of several precast elements printed in the lab were executed on-site (Fig. 9(b)). Finally, a load test was carried out with full water containers, as

doi: 10.25100/iyc.v25i4.13236

shown in Fig. 9(c) [80]. Similarly, between 2018 and 2019, [81] studied the behaviour of a post-tensioned concrete girder to be used as a pedestrian bridge. They made a design using topology optimisation, obtaining complex geometries and decreasing the required material amount. Other researches have focused on using optimisation for different parameters [78, 82, 83, 39, 81]. The latter applied optimisation to the tendon and the topology of the printed element [81]. Figs. 9(a) to 9(f) show optimised prototypes of 3DCP structures.

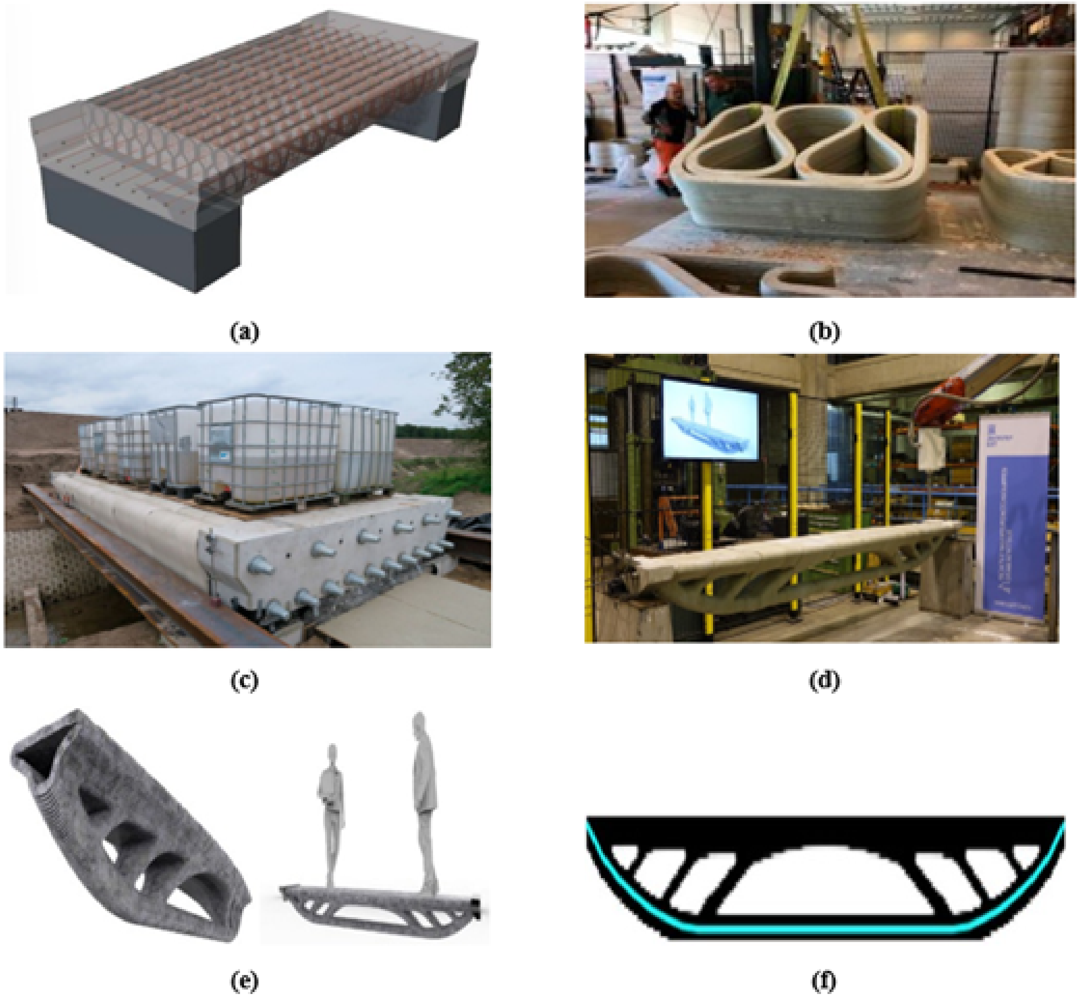
(a) (b) (c) (d) (e) (f)

Fig. 9. Optimised prototypes of 3DCP structures (a) TU/e Bridge model [80]. (b) prefabricated elements printed in the TU/e printing lab [80]. (c) TU/e Bridge load test on-site [80]. (d) A 3D-printed prestressed concrete girder in Magnel laboratory for concrete research - Ghent University [81]. (e) 3D modelling of the girder [81]. (f) Topology optimisation of the girder by Technion - Israel Institute of Technology [81].

3DCP technology has also been applied to military structures. The ACES (Automated Construction of Expeditionary Structures) program was launched by the U.S. Navy Research and Development Center in 2015, in collaboration with the Construction Engineering Research Laboratory at Urbana-Champaign, Illinois. The program's goal was to build durable and resistant structures using less material, which would reduce demand for workers, logistics, and suppliers [84]. The prototype, with a printable volume of 1 m x 1 m x 1 m, was designed for tests for different

doi: 10.25100/iyc.v25i4.13236

kinds of reinforcement and materials. Within a year, the program had successfully built a real-scale structure measuring 1.8 m x 1.8 m x 2.4 m. The following year, they scaled up their prototype to construct a barrack hut measuring 9.75 m x 4.9 m x 2.4 m, which can house up to 16 soldiers at a time [85]. Fig. 10 illustrates the construction of the barrack hut.

Fig. 10. 3D-printed barrack Hut, a mega-scale concrete structure built by the U.S. Army [86].

3DP with non-conventional and earth-based materials

The availability of some resources such as cementitious materials is sometimes limited, such as in the case of building in marginal areas with poor accessibility or in the construction of extraterrestrial habitats. In such cases, it is necessary to improve the actual 3DP technologies and to develop multi-functional, dynamic, and recyclable materials from natural sources to ensure that the number and amount of non-available materials used are reduced [87].

On the other hand, international space agencies such as NASA have turned their attention towards building automation using technologies such as Contour Crafting based on the advancements achieved in 3D printing. However, these "terrestrial" technologies require some adaptations to be functional in lunar or Martian environments in order to build extraterrestrial habitats for future human settlements. To achieve this, they have developed different kinds of tests on non- conventional building materials, primarily concrete composed of regolith-based aggregate, which is abundant on the lunar surface [85, 88, 89]. NASA developed the ACES-3 printer for space applications (Fig. 11(a)), which is the first machine capable of printing concrete with aggregates up to 3/8 in, resulting in high-strength concrete [88].

Simultaneously, [85] designed and created a prototype for a printing head (ZLM printing head) to be used on the Mars mission projected for 2030 by NASA (Fig. 11(b)). The main issue was the exposure of the printer components and the human operating the machine to destructive agents such as vacuum pressure, radiation, thermal changes, micrometeorites impacts, the rocket blast-off explosion and other effects present on take-off and landing, sand storms, flying sand, martian climate, topography, among others [85]. The lack of a commercial printing head for a

doi: 10.25100/iyc.v25i4.13236

composed material, such as concrete, geo-polymer, and regolith, was the reason for the ZLM project, developed in Kennedy Space Center Swamp Works labs [85]. [34] investigated possible applications of 3D printing of regolith on lunar settlements with the aid of two autonomous rovers: one collects and deposits material and the other removes waste outside and inside the structure (Figure 11(c)). They used two methods based on D-Shape technology, one for on-site building and the other for printing precast bricks to be assembled even with reinforcement.

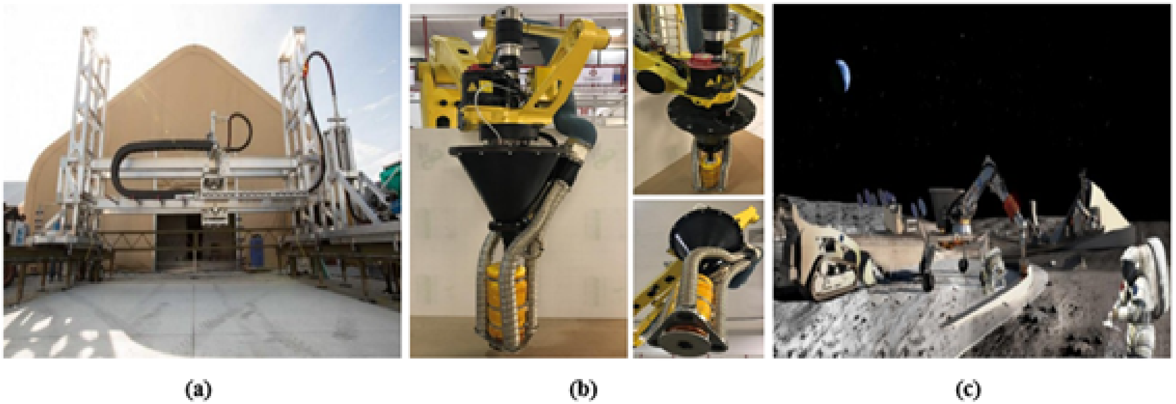

Fig. 11. 3DP with non-conventional materials for non-civil applications (a)ACES-3 printer [88]. (b) ZLM printing head, developed by NASA [85]. (c) Illustration of a robot printing a lunar habitat [88].

Back to earth applications, some researchers have proposed the use of soil or earth-based materials using Digital Manufacturing of Earth Construction (DMEC) technologies as an alternative to concrete for environmental sustainability reasons [8]. Given that the traditional construction industry (using concrete) is the cause of about 40% of greenhouse gas emissions all around the world [90], building with soil may reduce these numbers due to its environment-friendly properties and the use of local raw materials from the places where the work is going on. Base materials used for earth construction are soil, water, and fibre mixes [91]. Some cultures had used rammed earth as an ancient technique for building. However, nowadays, this technology is widely spread around the world and its use is not related to a country's economic or development level. That is evidenced in some examples of rammed earth around the world: a) the NK'Mip desert cultural Centre in the U.S.A, a developed country (Fig. 12(a)); b) a fortified city in Morocco that was the hub of the clay printing system of the company WASP [8] and demonstrated that it could be a massive construction technology (Fig. 12(b)); and c) houses built with rammed earth in Ghana, a developing country, by the Hive Earth company [92, 91, 93] (Fig. 12(c)).

doi: 10.25100/iyc.v25i4.13236


(a) (b) (c)

Fig. 12. Rammed earth buildings around the world. (a) Rammed earth wall, built on NK' Mip desert [91]. (b) Ksar from the city of Bereber A¨ıt Ben Haddou [93]. (c) Rammed earth built in Accra, Ghana, by the Company Hive Earth [92].

Finally, regarding Digital Manufacturing of earth-based structures, there are more than 50 projects carried out until now, of which, those related to building development are discussed herein. One of the companies with more projects worldwide concerned with 3DP of soil is WASP [94, 95]. Their first incursion was the GAIA project, which evolved into TECLA (Technology and Clay), whose houses are honeycomb-based structures (Figs. 13(a) to 13(c)). Their latest project was Travessera de Gràcia, a tall structure located in Gràcia-Barcelona [96].

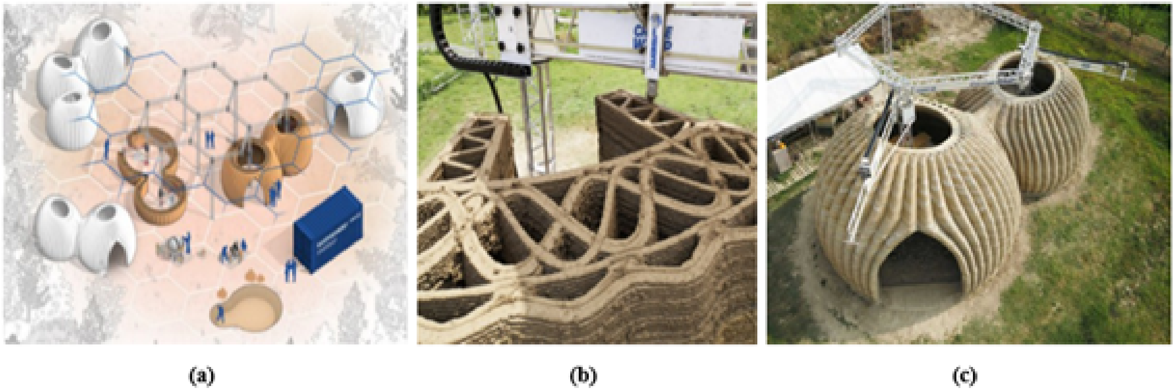
(a) (b) (c)

Fig. 13. Additive Manufacturing of earth-based structures by WASP [97]. (a) Housing conception. (b) The geometry of some 3D-printed structural elements. (c) Dome-shaped houses 3D-printed.

doi: 10.25100/iyc.v25i4.13236

Also, in Barcelona, members of the Institute for Advanced Architecture of Catalonia (IAAC) built clay columns named Pylos, with up to 1 m in height (Figs. 14(a) and 14(b)). To advance in mega-scale elements and structure manufacturing based on materials like clay [98], researchers of the same institute developed TerraPerforma in 2017. They built a real-sized clay wall with prefabricated printed elements (Fig. 14(c)) [99].

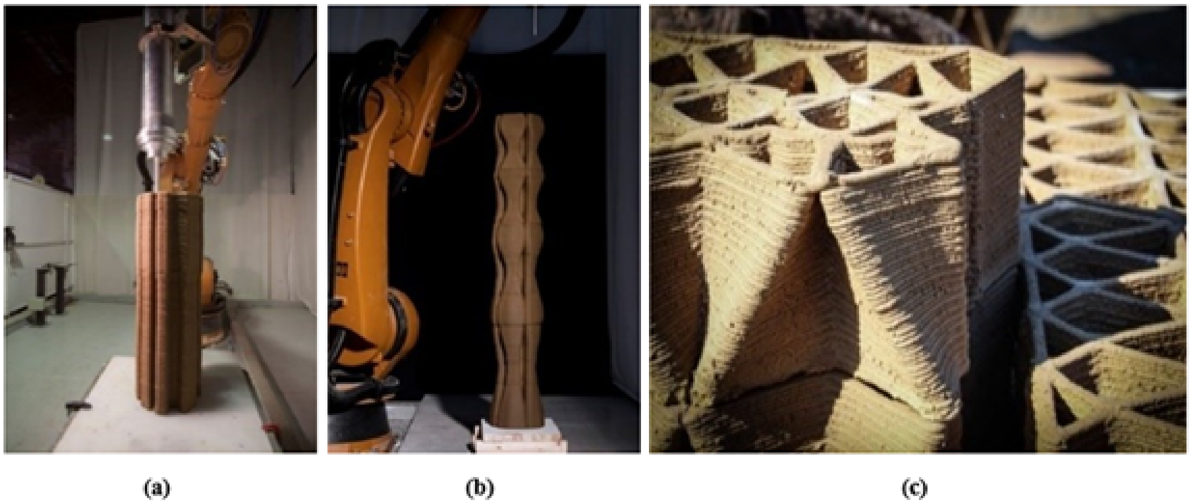

Fig. 14. Additive Manufacturing of earth-based structures by the IAAC. (a) PYLOS column during printing [98]. (b) Full-printed PYLOS column [98]. (c) Prefabricated elements for TerraPerforma Wall [99].

Discussion

As seen in previous sections, different parameters may affect a 3D-printed structure. This technology has proven to be multidisciplinary, combining advanced development in multiple research areas. The printer selection simplifies several processes but makes others more complex. As shown in Section 3, robotic arms have the advantage of requiring less space and attaining complicated printing geometries. Nonetheless, they could be expensive and inefficient for mega-scale buildings. In contrast, mobile frame 3D printing systems are less complex and allow massive buildings, with the drawback of printing less refined structures. Even so, the last mechanism is the most used for buildings.

On-site building requires some lab validations regarding geometry, viscoelas- tic properties, and printing speeds, among others. These are some of the most important parameters affecting the mechanical behaviour of elements or structures. Geometry's importance is evident in topology optimisation applied in many structural element designs, especially on beams, bridges, and walls. The analysis of the physical and mechanical behaviour of 3D-printed elements, starting from concrete extrusion until the setting process, allows the control of their rheological properties. In turn, these properties affect the strength, ductility, and durability of the printed elements. Finally, the printing speed affects the supply or building capacity, stability, and overall strength of the building. Thus, understanding and optimising these factors is vital for achieving desired performance and quality in 3D-printed structures.

doi: 10.25100/iyc.v25i4.13236

According to the literature review, more than 15 countries (Fig. 15) have developed full-scale buildings. While the global count of such projects exceeds 30, the numbers remain small, when considering the potential of this automated manufacturing technology. The countries with more 3D-printed full-scale active buildings are the U.S.A, China, Italy, and Spain. These countries are also home to the most renowned companies working in this emerging technology.

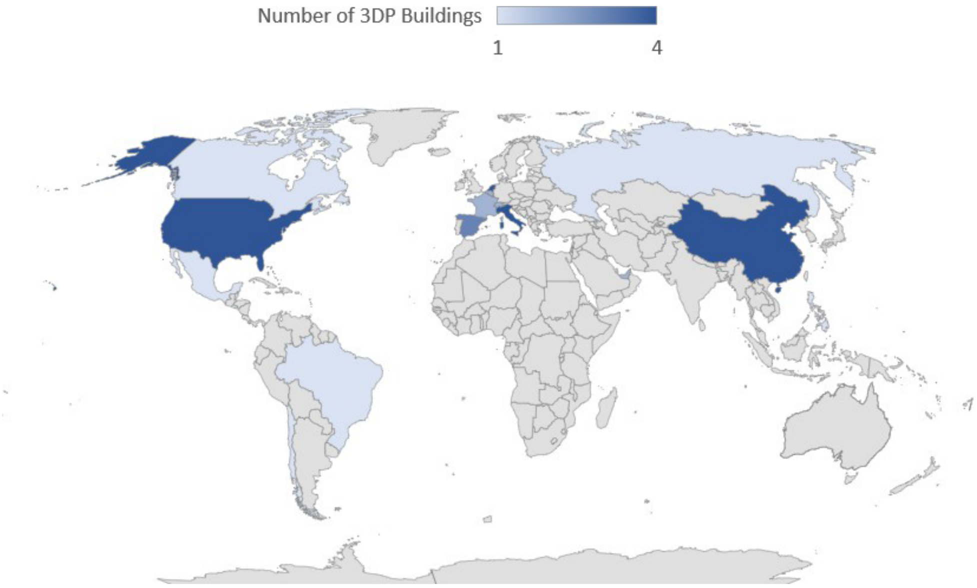

Fig. 15. Worldwide distribution of Full-scale 3DP buildings

Most of the 3D-printed building projects have utilised concrete as the primary material, while there is a lack of research on earth-based or non-conventional materials (Fig. 4). Nevertheless, Fig. 16 illustrates that rammed earth construction is a promising alternative that is being explored, particularly in countries undergoing development in Central America, South America, and Africa. This fact demonstrates that this type of structure may address issues related to forced dis- placement and inadequate housing in countries with high poverty levels. Despite this advancement, the number of functional full-scale structures built with these alternative materials represents only about 15% of all 3D-printed buildings.

doi: 10.25100/iyc.v25i4.13236

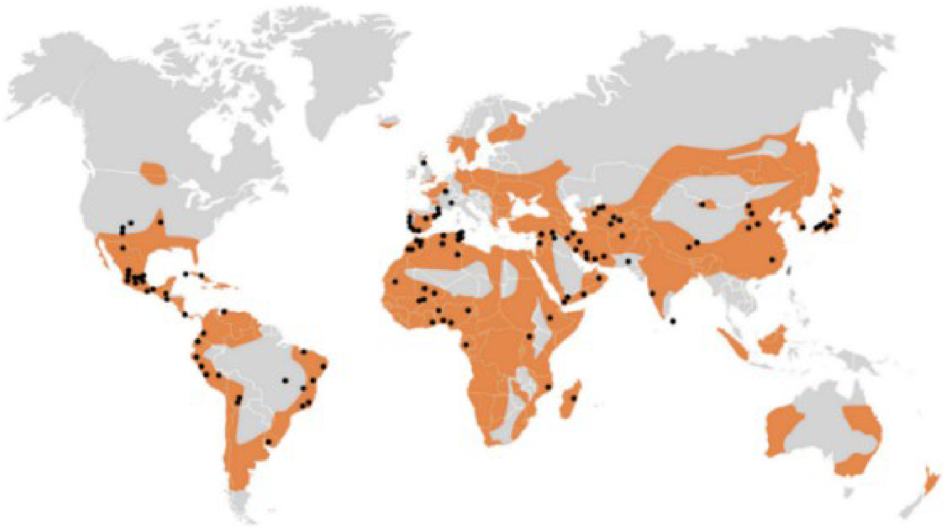

Fig. 16. Buildings with earth-based materials around the world (orange) and historical heritage buildings with earth-based materials (black dots) [100]

Conclusions

3D printing has revolutionized traditional building methods by making processes more efficient. Technologies such as D-Shape and Contour Crafting show great promise for printing full-scale structures. Automating building construction has significant potential for space and terrestrial applications, promoting low-cost and high-quality housing projects with advanced technology and the potential construction of human habitats on the Moon and Mars.

The evidence has demonstrated that concrete is the most common material for 3D-printed buildings. However, one of the current challenges in science is reducing the carbon footprint, and concrete is one of the most polluting materials. Even though it is necessary to study and develop non-conventional building materials based on local soil from different regions or on recycled aggregates, the gap between concrete and alternative materials research is still remarkable. Despite having some alternatives to concrete (e.g., earth-based materials), high-income countries are less engaged in using them for conventional construction or 3D printing. The relevant research on the 3DP of building materials and the highest number of full-scale 3DP constructions are still mainly devoted to concrete. In contrast, countries with abundant natural resources like sand, clay, straw, and mud have adopted these materials in a substantial portion of their constructions. Although research on non-conventional materials has increased in the last seven years, a knowledge gap must be filled. It is crucial to sustain this trend and ensure that the developing technologies in 3DP are fully adaptable to printing such alternative materials.

Even though the 3DP technology has the potential to offer significant benefits in construction, including cost savings, optimised material use, and environmental sustainability, further research is still needed to enhance the structural behaviour of elements for large-scale

doi: 10.25100/iyc.v25i4.13236

structures. Improving the mechanical properties of these elements is crucial to ensure their reliability and safety, and to make 3D printing a mainstream building method, especially for earth-based materials. Thus, continued investment and innovation can help 3D printing technology to revolutionise the construction industry offering a more efficient, sustainable, and affordable alternative to traditional building practices and materials.

Acknowledgments

This work was supported by the Ministry of Science Technology and Innovation of Colombia (Minciencias) using the General System of Royalties, which has provided financial support for the project where this paper comes from, titled “Development of a 3D printing system of sustainable non-conventional materials for the advancement of rural infrastructure in the department of Cauca” (BPIN 2020000100625).

References

1. UN-Habitat . World cities report 2022: Envisaging the future of cities. Publisher: United Nations Human Settlements Programme (UN-Habitat) 2022;
2. Acevedo P, Vera F, Zambrano-Barraga´n P, Poskus MA, Alonso Pastor L, Azcona G, et al. Informing the informal: strategies to generate information in precarious settlements 2021;doi:10.18235/0003784.
3. Afolabi A, Ojelabi R, Omuh I, Tunji-Olayeni P. 3d house printing: A sustainable housing solution for nigeria’s housing needs. In: Journal of Physics: Conference Series; vol. 1299. IOP Publishing; 2019, p. 012012.
4. IEA . Buildings - sectoral overview. 2021. URL: https://www.iea.org/ reports/buildings; (accessed Jun. 22, 2023).
5. IEA . Global energy review: Co2 emissions in 2021 – analysis. 2021. URL: https://www.iea.org/reports/ global-energy-review-co2-emissions-in-2021-2; (accessed Jun. 22, 2023).
6. Tabassum T, Mir AA. A review of 3d printing technology-the future of sustainable construction. Materials Today: Proceedings 2023;.
7. Ngo TD, Kashani A, Imbalzano G, Nguyen KT, Hui D. Additive man- ufacturing (3d printing): A review of materials, methods, applications and challenges. Composites Part B: Engineering 2018;143:172–196. doi:10.1016/j.compositesb.2018.02.012.
8. Gomaa M, Jabi W, Soebarto V, Min Y. Digital manufacturing for earth construction: A critical review. J Clean Prod 2022;338(January):130630,. doi:10.1016/j.jclepro.2022.130630.
9. Wu P, Wang J, Wang X. A critical review of the use of 3-d printing in the construction industry material finished. Autom Constr 2016;68:21–31,. doi:10.1016/j.autcon.2016.04.005.
10. Vyncke J, Kupers L, Denies N. Earth as building material–an overview of rilem activities and recent innovations in geotechnics. In: MATEC Web of Conferences; vol. 149. EDP Sciences; 2018, p. 02001.
11. Scopus . Scopus. Elsevier 2022;URL: https://www.scopus.com/home. uri; (accessed Feb. 14, 2022).
12. Zˇ ujovi□ M, Obradovi□ R, Rakonjac I, Milo□evi□ J. 3d printing technologies in architectural design and construction: a systematic literature review. Buildings 2022;12(9):1319.
13. VOSviewer . Welcome to vosviewer. Centre for Science and Tech- nology Studies - Leiden Universiteit 2021;:22–24,URL: https://www. vosviewer.com/.
14. Vyavahare S, Teraiya S, Panghal D, Kumar S. Fused deposition mod- elling: a review. Rapid Prototyp J 2020;26(1):176–201,. doi:10.1108/ RPJ-04-2019-0106.

doi: 10.25100/iyc.v25i4.13236

15. Mehrpouya M, Tuma D, Vaneker T, Afrasiabi M, Bambach M, Gib- son I. Multimaterial powder bed fusion techniques. Rapid Prototyp J 2022;28(11):1–19,. doi:10.1108/RPJ-01-2022-0014.
16. Kruth J, Mercelis P, Vaerenbergh J, Froyen L, Rombouts M. Binding mechanisms in selective laser sintering and selective laser melting. Rapid Prototyp J 2005;11(1):26–36,. doi:10.1108/13552540510573365.
17. Wang X, Laoui T. Lasers and materials in selective laser sintering. Rapid Prototyp J 2006;23(4):357–371,. URL: https://www.emerald.com/ insight/content/ doi/10.1108/13552549710191836/full/html. doi:10.1108/13552549710191836.
18. Schmidleithner C, Kalaskar D. Stereolithography - chapter 1. In: 3D Print. 2018, p. 1–22,. doi:10.5772/intechopen.78147.
19. Shim D, Baek G, Seo J, Shin G, Kim K, Lee K. Optics & laser technology effect of layer thickness setting on deposition characteristics in direct energy deposition (ded) process. Opt Laser Technol 2016;86:69–78,. doi:10. 1016/j.optlastec.2016.07.001.
20. Park J, Tari MJ, Hahn HT. Characterization of the laminated object manu- facturing (lom) process. Rapid Prototyping Journal 2000;.
21. Travitzky N. Additive manufacturing of ceramic-based materials. Adv Eng Mater 2014;16(6):729–754,. doi:10.1002/adem.201400097.
22. Pegna J. Exploratory investigation of solid freeform construction. Automa- tion in construction 1997;5(5):427–37.
23. Gosselin C, Duballet R, Roux P, Gaudillie`re N, Dirrenberger J, Morel P. Large-scale 3d printing of ultra-high performance concrete - a new processing route for architects and builders. Mater Des 2016;100:102–109,. doi:10.1016/j.matdes.2016.03.097.
24. Panda B, Paul S, Hui L, Tay Y, Tan M. Additive manufacturing of geopoly- mer for sustainable built environment. J Clean Prod 2017;167:281–288,. doi:10.1016/j.jclepro.2017.08.165.
25. Paul S, Tay Y, Panda B, Tan M. Fresh and hardened properties of 3d printable cementitious materials for building and construction. Arch Civ Mech Eng 2018;18(1):311–319,. doi:10.1016/j.acme.2017.02.008.
26. Zhang X. Large-scale 3d printing by a team of mobile robots. Autom Constr 2018;95:98–106,. doi:10.1016/j.autcon.2018.08.004.
27. Hwang D, Khoshnevis B. Concrete wall fabrication by contour crafting. Proc 2004;doi:10.22260/isarc2004/0057.
28. Le T, Austin S, Lim S, Buswell R, Gibb A, Thorpe T. Mix design and fresh properties for high-performance printing concrete. 2012. doi:10.1617/ s11527-012-9828-z.
29. Zareiyan B, Khoshnevis B. Interlayer adhesion and strength of structures in contour crafting - e ff ects of aggregate size , extrusion rate , and layer thick- ness. Autom Constr 2017;81(March):112–121,. doi:10.1016/j.autcon. 2017.06.013.
30. Lim S, Le T, Webster J, Buswell R, Austin A, Gibb A, et al. Fabricat- ing construction components using layered manufacturing technology. In: Global Innovation in Construction Conference. Loughborough University Leicestershire, UK; 2009, p. 512–20.
31. Panda B, Unluer C, Tan M. Investigation of the rheology and strength of geopolymer mixtures for extrusion-based 3d printing. Cem Concr Compos 2018;94:307–314,. doi:10.1016/j. cemconcomp.2018.10.002.
32. Yuan P. Smart dynamic casting: Slipforming with flexible formwork - inline measurement and control. Autom Constr 2018;16(1):165–185,. doi:10. 1108/13552540510573365.
33. Bici A, Yunitsyna A. Analysis of 3d printing techniques for building con- struction: a review. Construction Robotics 2023;7(2):107–23.
34. Cesaretti G, Dini E, Kestelier X, Colla V, Pambaguian L. Building compo- nents for an outpost on the lunar soil by means of a novel 3d printing tech- nology. Acta Astronaut 2014;93:430–450,. doi:10.1016/j.actaastro. 2013.07.034.

doi: 10.25100/iyc.v25i4.13236

35. Buswell R, Silva W, Jones S, Dirrenberger J. 3d printing using con- crete extrusion: A roadmap for research. Cement and Concrete Research 2018;112:37–49,. doi:10.1016/j.cemconres.2018.05.006.
36. Bos F, Wolfs R, Ahmed Z, Salet T. Additive manufacturing of concrete in construction: potentials and challenges of 3d concrete printing. Virtual Phys Prototyp 2016;11(3):209–225,. doi:10.1080/17452759.2016.1209867.
37. Perrot A, Rangeard D, Pierre A. Structural built-up of cement-based ma- terials used for 3d-printing extrusion techniques. Mater Struct Constr 2016;49(4):1213–1220,. doi:10.1617/s11527-015-0571-0.
38. Tay Y, Panda B, Paul S, Mohamed N, Tan M, Leong K. 3d printing trends in building and construction industry: a review. Virtual and Physical Proto- typing 2017;12(3):261–276,. doi:10.1080/17452759.2017.1326724.
39. Schutter G, Lesage K, Mechtcherine V, Nerella V, Habert G, Agusti-Juan I. Vision of 3d printing with concrete — technical, economic and envi- ronmental potentials. Cement and Concrete Research 2018;112:25–36,. doi:10.1016/j.cemconres.2018.06.001.
40. Wolfs R, Bos F, Salet T. Early age mechanical behaviour of 3d printed concrete: Numerical modelling and experimental testing. Cem Concr Res 2018;106:103–116,. doi:10.1016/j.cemconres.2018.02.001.
41. Kazemian A, Yuan X, Cochran E, Khoshnevis B. Cementitious materials for construction-scale 3d printing: Laboratory testing of fresh printing mixture 2017;145:639–647,.
42. Panda B, Paul S, Tan M. Anisotropic mechanical performance of 3d printed fiber reinforced sustainable construction material. Mater Lett 2017;209:146–149,. doi:10.1016/j.matlet.2017.07.123.
43. Panda B, Tan M. Experimental study on mix proportion and fresh prop- erties of fly ash based geopolymer for 3d concrete printing. Ceram Int 2018;44(9):10258–10265,. doi:10.1016/j.ceramint.2018.03.031.
44. Sanjayan J, Nematollahi B, Xia M, Marchment T. Effect of surface mois- ture on inter-layer strength of 3d printed concrete. Constr Build Mater 2018;172:468–475,. doi:10.1016/j.conbuildmat.2018.03.232.
45. Panda B, Paul S, Mohamed N, Tay Y, Tan M. Measurement of tensile bond strength of 3d printed geopolymer mortar. Meas J Int Meas Confed 2018;113:108–116,. doi:10.1016/j.measurement.2017.08.051.
46. Hager I, Golonka A, Putanowicz R. 3d printing of buildings and building components as the future of sustainable construction? Procedia Engineering 2016;151:292–299. doi:10.1016/j.proeng.2016.07.357.
47. Buchanan C, Gardner L. Metal 3d printing in construction: A review of methods, research, applications, opportunities and challenges. Eng Struct 2019;180(January):332–348,. doi:10.1016/j.engstruct.2018. 11.045.
48. Wolfs R, Bos F, Salet T. Hardened properties of 3d printed concrete: The influence of process parameters on interlayer adhesion. Cem Concr Res 2019;119:132–140,. doi:10.1016/j.cemconres.2019.02.017.
49. Lowke D, Dini E, Perrot A, Weger D, Gehlen C, Dillenburger B. Particle-bed 3d printing in concrete construction–possibilities and challenges. Cement and concrete research 2018;112:50–65.
50. Ali MH, Issayev G, Shehab E, Sarfraz S. A critical review of 3d printing and digital manufacturing in construction engineering. Rapid Prototyping Journal 2022;28(7):1312–24.
51. Khoshnevis B. Automated construction by contour crafting — related robotics and information technologies. 2004. doi:10.1016/j.autcon. 2003.08.012.
52. Buswell R, Soar R, Gibb A, Thorpe A. Freeform construction : Mega-scale rapid manufacturing for construction. 2007. doi:10.1016/j.autcon. 2006.05.002.

doi: 10.25100/iyc.v25i4.13236

53. Lim S, Buswell R, Le T, Austin S, Gibb A, Thorpe T. Developments in construction-scale additive manufacturing processes. 2012.
54. Gardiner J. Exploring the emerging design territory of construction 3d printing – project led architectural research rmit exploring the emerging design territory of construction 3d printing – project led for the degree of doctor of philosophy. 2011.
55. Robayo-Salazar R, Mejía de Gutie´rrez R, Villaquira´n-Caicedo MA, Del- vasto Arjona S. 3d printing with cementitious materials: Challenges and opportunities for the construction sector. Automation in Con- struction 2023;146:104693. URL: https://www.sciencedirect.com/science/article/pii/S0926580522005635. doi:https://doi.org/ 10.1016/j.autcon.2022.104693.
56. Guama´n-Rivera R, Martínez-Rocamora A, García-Alvarado R, Mun˜oz- Sanguinetti C, Gonza´lez-Bo¨hme LF, Auat-Cheein F. Recent developments and challenges of 3d-printed construction: A review of research fronts. Buildings 2022;12(2):229.
57. Malkin A, Ya A. Isayev. Rheology 2012;2.
58. Soltan D, Li V. A self-reinforced cementitious composite for building- scale 3d printing. Cem Concr Compos 2018;90:1–13,. doi:10.1016/j. cemconcomp.2018.03.017.
59. Zhang Y, Zhang Y, Liu G, Yang Y, Wu M, Pang B. Fresh properties of a novel 3d printing concrete ink. Constr Build Mater 2018;174:263–271,. doi:10.1016/j.conbuildmat.2018.04.115.
60. Panda B, Ruan S, Unluer C, Tan M. Improving the 3d printability of high volume fly ash mixtures via the use of nano attapulgite clay. Compos Part B Eng 2019;165:75–83,. doi:10.1016/j.compositesb.2018.11.109.
61. Jianchao Z, Zhang T, Faried M, Wengang C. 3d printing cement based ink, and it ' s application within the construction industry. 2017.
62. Nerella V, Hempel S, Mechtcherine V. Effects of layer-interface properties on mechanical performance of concrete elements produced by extrusion- based 3d-printing. Constr Build Mater 2019;205:586–601,. doi:10.1016/ j.conbuildmat.2019.01.235.
63. Hambach M, Volkmer D. Properties of 3d-printed fiber-reinforced portland cement paste. Cement and Concrete Composites 2017;79:62–70,. doi:10. 1016/j.cemconcomp.2017.02.001.
64. Paul SC, Van Zijl GP, Tan MJ, Gibson I. A review of 3d concrete print- ing systems and materials properties: Current status and future research prospects. Rapid Prototyping Journal 2018;.
65. Nerella V, Mechtcherine V. Studying the Printability of Fresh Concrete for Formwork-Free Concrete Onsite 3D Printing Technology (CONPrint3D. Elsevier Inc; 2019. doi:10.1016/B978-0-12-815481-6.00016-6.
66. Feng P, Meng X, Chen J, Ye L. Mechanical properties of structures 3d printed with cementitious powders mechanical properties of structures 3d printed with cementitious powders. Constr Build Mater 2022;93:486–497,. doi:10.1016/j.conbuildmat.2015.05.132.
67. Robayo-Salazar R, Martínez F, Vargas A, Mejía de Gutie´rrez R. 3d printing of hybrid cements based on high contents of powders from concrete, ce- ramic and brick waste chemically activated with sodium sulphate (na2so4). Sustainability 2023;15(13):9900.
68. Watkin H. Dus architects build 3d printed urban cabin in amsterdam. 2016. URL: https://all3dp.com/ dus-architects-3d-printed-urban-cabin/; (accessed Jun. 25, 2022).
69. Svenson B. Shanghai-based winsun 3d prints 6-story apartment building and an incredible home. 2015. URL: https://3dprint.com/38144/ 3d-printed-apartment-building/; (accessed Jun. 25, 2022).
70. Scott C. Chinese construction company 3d prints an entire two-story house on-site in 45 days - 3dprint.com: The voice of 3d printing / ad- ditive manufacturing. 2016. URL: https://3dprint.com/138664/ huashang-tengda-3d-print-house/; (accessed Jun. 12, 2023).
71. Augur H. This on-site 3d printed house took only 45 days. 2016. URL: https://all3dp.com/21776-2/; (accessed Jun. 25, 2022).

doi: 10.25100/iyc.v25i4.13236

72. Costanzi C. 3d printing concrete onto flexible surfaces. TU Delft; 2016.
73. XtreeE . Double sine wall. 2016. URL: https://xtreee.com/en/ project/mur-sinusoidal/; (accessed Jun. 25, 2022).
74. Anton A, Bedarf P, Reiter L, Wangler T. Vertical modulations: Computa- tional design for concrete 3d printed columns. 2019. doi:10.52842/conf. acadia.2019.596.
75. Lloret E, Reiter L, Wangler T, Gramazio F, Kohler M, Flatt R. Smart dynamic casting: Slipforming with flexible formwork - inline mea- surement and control. Second Concr Innov Conf 2017;doi:10.3929/ ethz-b-000219663.
76. TotalKustom . 3d concrete house printer. URL: http://www. totalkustom.com/; (accessed Jun. 25, 2022).
77. printer D, printing news D. Spain unveils world's first 3d printed pedes- trian bridge made of concrete. 2016. URL: https://www.3ders.org; (accessed Nov. 07, 2022).
78. Yuan P, Chen Z, Zhang L. Form finding for 3d printed pedestrian bridges. 2018.
79. MX3D . Mx3d bridge. 2018. URL: https://www.jorislaarman.com/ work/mx3d-bridge/; (accessed Jun. 26, 2022).
80. Salet T. Design of a 3d printed concrete bridge by testing. 2018. doi:10. 1080/17452759.2018.1476064.
81. Vantyghem G, Corte W, Shakour E, Amir O. 3d printing of a post- tensioned concrete girder designed by topology optimization. Autom Constr 2019;112:103084,. doi:10.1016/j. autcon.2020.103084.
82. Perrot A, Rangeard D, Pierre A. Structural built-up of cement-based ma- terials used for 3d-printing extrusion techniques. Mater Struct Constr 2016;49(4):1213–1220,. doi:10.1617/ s11527-015-0571-0.
83. Lei Y, Zhou H, Lai Z. A computationally efficient algorithm for real-time tracking the abrupt stiffness degradations of structural elements. Computer- Aided Civil and Infrastructure Engineering 2016;31(6):465–480,. doi:10. 1111/mice.12217.
84. Jagoda J, Diggs-mcgee B, Kreiger M, Schuldt S. The viability and simplicity of 3d-printed construction : A military case study. 2020.
85. Mueller RP, Gelino NJ, Smith JD, Buckles BC, Lippitt T, Schuler JM, et al. Zero launch mass three-dimensional print head. In: Earth and Space 2018: Engineering for Extreme Environments. American Society of Civil Engineers Reston, VA; 2018, p. 219–32.
86. Post N. Army researchers refine 3d-printed concrete bar- racks. 2018. URL: https://www.enr.com/articles/ 45002-army-researchers-refine-3d-printed-concrete-barracks; (accessed Jun. 25, 2022).
87. Dixit M. 3-d printing in building construction: a literature review of opportunities and challenges of reducing life cycle energy and carbon of buildings. In: IOP Conference Series: Earth and Environmental Science; vol. 290. IOP Publishing; 2019, p. 012012.
88. Mueller RP, Fikes JC, Case MP, Khoshnevis B, Fiske MR, Edmunson JE, et al. Additive construction with mobile emplacement (acme). In: 68th International Astronautical Congress (IAC). Space Industry Association of Australia Adelaide, Australia; 2017, p. 25–9.
89. Scott A, Oze C, Hughes W, Matthew S, Wisbey C. Performance of a magne- sia silica cement for martian construction. Earth and Space 2018;:629–636.
90. Soto B. Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall. Autom Constr 2018-08;92:297–311,. doi:10.1016/j.autcon.2018.04.004.
91. Cao L. How rammed earth walls are built. 2020. URL: https://www. archdaily.com/933353/ how-rammed-earth-walls-are-built; (accessed Jun. 25, 2022).
92. Donelly E. Is rammed earth construction the answer to ghana's housing crisis? 2019. URL: https://www.azuremagazine.com/article/ rammed-earth-housing-ghana/; (accessed Jun. 25, 2022).

93. Kratzer C. A¨ıt ben haddou. 2020. URL: https://www. sientemarruecos. viajes/blog/kasbah-de-ait-ben-haddou/; (accessed Jun. 25, 2022).
94. Perrot A. 3d printing of concrete: state of the art and challenges of the digital construction revolution 2019;.
95. Alhumayani H, Gomaa M, Soebarto V, Jabi W. Environmental assessment of large-scale 3d printing in construction : A comparative study between cob and concrete. J Clean Prod 2020;270:122463,. doi:10.1016/j.jclepro. 2020.122463.
96. Coutinho B. 152 travessera de gracia. 2020. URL: https://www. iaacblog.com/programs/152-travessera-de-gracia/; (accessed Jun. 26, 2022).
97. Chiusoli A. Tecla. 2019. URL: https://www.3dwasp.com/ casa-stampata-in-3d-tecla/; (accessed Jun. 26, 2022).
98. Giannakopoulos S. 3d printing with soil and natural materials. 2015. URL: http://pylos.iaac. net/main.html#material; (accessed Jun. 27, 2023).
99. Chukkappali S. Terraperforma 3d printed performative wall. 2017. URL: https://iaac.net/ project/terraperforma/; (accessed Jun. 26, 2022).
100. Asal A. Building with Earth - Sustainable Stabilization and Additive Man- ufacturing for Rammed Earth Construction. Ph.D. thesis; HTWG Konstanz- University of Applied Sciences Civil; 2021.

doi: 10.25100/iyc.v25i4.13236