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REVIEW

A road map to find in 3D printing a new design plasticity for construction — The state of art

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Abstract Recent years are showing a rapid adoption of digital manufacturing techniques to the construction industry, with a focus on additive manufacturing. Although 3D printing for construction (3DPC) has notably advanced in recent years, publications on the subject are recent and date a growth in 2019, indicating that it is a promising technology as it enables greater efficiency with fair consumption of material, minimization of waste generation, encouraging the construction industrialization and enhancing and accelerating the constructive process. This new building system not only gives an optimization of the building process but provides a new approach to the building design materiality. The direct connection between design and manufacturing allows the reduction in the number of the various construction phases needed. It is opening a new and wide range of options both formal and chromatic in customization, avoiding complex formworks, reducing costs and manufacturing time. The creative process has a strict and direct link with the constructive process, straightening design with its materiality. Cement-based materials lead the way, but new alternatives are being explored to further reduce its carbon footprint. In order to leverage its sustainability and enhance the system capacity, initiatives are being pursued to allow the reduction of the use of PC. Geopolimers are taking the first steps in 3DPC. Construction and Demolition Waste (CDW) materials are used to substitute natural aggregates. Even soil is being explored has a structural and aesthetic material. These research trends are opening a wider range of possibilities for architecture and design, broadening the spectrum of color, texture, and formal

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variations. The concern about textures and colours is not yet evident in many the structures already printed, opening the opportunity for future research. More can be done in the mixture and formal design of this building system, "discovering" other raw materials in others waste. This article aims to make a critical review of technologies, materials and methodologies to support the development of new sustainable materials to be used as a plastic element in the printed structure. A roadmap of 3D printing for construction is presented, and an approach on mix design, properties in the fresh and hardened state, highlighting the possibilities for obtaining alternative materials are pointed. With this review possible directions are presented to find solutions to enhance the sustainability of this system discovering "new" materiality for architecture and design.

Contents

1. Introduction

Using the construction materials three-dimensional aesthetics as part of the architectural design expression, has been pursued by many architects since modernity to define the buildings' tectonic (Giada et al., 2019; Kucker, 2002; Owens, 2001; Radford and Oksala, 2007; Vandenbulcke, 2011). Le Corbusier used concrete rawness obeying form to follow its function (Croft, 2004). Alvar Aalto found in different textures the sensorial space characterization (Radford and Oksala, 2007). Frank Lloyd Wright, with his holistic architectural perception, explored in each project different materials from the construction unity to composing building modulation (Kucker, 2002). In the 70s, Alison and Peter Smithson discovered shapes and textures in the vernacular architecture's variety to design the House of Future (Owens, 2001). Nowadays, Peter Zumthor uncovers in building characterization in different construction technologies (Vandenbulcke, 2011). Smiljan Radić crossbreeds architecture and sculpture through tectonic materials. In the work of each of these architects, there is a clear need to explore matter as form of architectural expression. What if they had the ability to print the construction elements to unrestrictedly explore the materials organicity? 3D Printing (3DP) seems to be the solution to design daring forms and optimizing the construction process. The creative process is directly linked to the construction process, bringing design and its materialization together (Craveiro et al., 2019; García de Soto et al., 2018; Gaudillière et al., 2019; He et al., 2019). Matter responds to form and form conveys the matter potential. This integrated process acknowledges the possibility to quickly change design without having to wait for calculations correction or new moulds creation. If Gaudi had in his time

3DPC he would probably use it as a fundamental tool to explore the materials capacity as part of his design process.

Automation is a powerful tool used in several industrial sectors to improve productivity and efficiency. In the last two decades, 3DP was developed to be the key to automation in civil construction, helping the sector in the transition to a low carbon industry improving architectural design freedom. Although it is a technology that could enhance construction for Industry 4.0, optimizing construction processes and therefore reducing costs, time and execution phases (Craveiro et al., 2019; García de Soto et al., 2018; Gaudillière et al., 2019; Weller et al., 2015; Weng et al., 2020), it is not yet widespread. The commercial response is not competitive due to its high price and the lack of response to building and environmental performance, particularly the Portland cement (PC) environmental performance. Chen et al. (2022) mentions that compared to mold-cast concrete, 3D printable cementitious materials may require a much higher amount of OPC, being its proportion more than 20 wt%. An alternative for producing an appropriate 3D printing material that improves performance while reducing material consumption, which is important for minimize CO_2, is alkali-activated materials that are substitutive binders to OPC (Amran et al., 2022).

In this perspective, alternative materials such as soil or clay, started to be studied by few architectural researchers in partnership with 3DP industry suppliers: IAAC (Institute for Advanced Architecture of Catalonia) in Barcelona explored 3D printing complex geometries with clay (IAAC, 2021) and WASP used soil to print small experimental houses (WASP, 2021a) (Fig. 1 a). Gomaa et al. (2022) mentions that the modern construction in earth is supported the digitally manufactured construction. The authors present cases constructions in sand, clay, adobe, cob, rammed earth using digital fabrication. The cases demonstrate great potential of earth construction as a modern construction method and provide many benefits to the environment and economy.

Other experiments used Supplementary Cementitious Materials (SCMs) like mineral additions or industrial by-products, such as fly ash, silica fume (Lediga and Kruger, 2017; Lim et al., 2018; Long et al., 2019; Ma et al., 2018; Nerella et al., 2019; Nerella and Mechtcherine, 2019; Suvash Chandra Paul et al., 2018; Tay et al., 2019; Ting et al., 2019; Weng et al., 2018), blast furnace slag (Askarian et al., 2019; Gao et al., 2019; Reddy et al., 2018; Subathra Devi, 2018), limestone filler (Chen et al., 2020) or nanoclay to reduce the PC content (Kazemian et al., 2017; Yuan et al., 2019; Y. Zhang et al., 2018) has been studied. Chen et al. (2022) mentions two strategies for developing low OPC-content cementitious materials: insertion of SCMs or other types of low carbon cement to substitute a high volume of OPC and reduce the binder content by increasing the proportion of aggregate (the binder composition is fixed). The addition of SCMs can significantly influence the rheological behavior of fresh mixtures. However, for different SCMs, the impacts on fresh properties may not be the same, varying according to type, morphology, fineness, chemistry compositions and others. Physical and chemical characteristics of SCMs were generally believed as the main reason for influencing the rheology of fresh mixtures (Chen et al., 2022). In 3D printing, one of the major challenges is the existing scarcity of printable concretes. To produce printed concretes that meet their important fresh characteristics a thorough understanding of the rheological criteria is required.

Another major challenge is incorporating reinforcement into 3D printing technology for reinforced concrete structure construction (Amran et al., 2022). Wu et al. (2022) discuss the possible ways to reinforce printed concrete to be suitable for large-scale construction, and to increase the tensile capacity of concrete members and reduce temperature and shrinkage cracking.

Chen et al. (2022) mentions that compared to mold-cast concrete, 3D printable cementitious materials may require a much higher amount of OPC, being its proportion more than 20 wt%. An alternative for producing an appropriate 3D printing material that improves performance while reducing material consumption, which is important for minimize CO_2, is alkali-activated materials that are substitutive binders to OPC (Amran et al., 2022). There is a variety of studies in this direction for a better understanding of alkali-reactive cements.

Apis Cor printed the world's largest building using a gypsum-based material (Cor, 2019). Twente Additive Manufacturing (TAM) explored highly complex geometries and textures in several 3D printed structures, showing the aesthetic potential of layered construction (Twente Additive Manufacturing B.V., 2021) (Fig. 1 b and c). In 2016, Bruil, a Dutch company, exhibited chromatic studies on a 3DP mortar, printing a structure with a chromatic gradient. The company intended to captivate the interest of designers and architects (Fig. 1 d) (Bruil, 2021; Bruil and MaterialDistrict, 2016). The development of new compositions with alternative materials or a lower PC rate may not only improve the sustainability in 3D Printing Construction (3DPC) but allow the exploration of new textures and colours.

A strong inclination towards innovation in architecture and construction is foreseeable due to vast changes in the realms of computational design and advanced fabrication tools. These elements are transforming the socio-economic and cultural conditions of our contemporaneity and have a strong impact on the design disciplines.

3DP have been receiving most of the attention in modern industry due to its wide applications, in addition to its technical and environmental benefits to several industries. Main opportunities of applying 3D printing in construction: reduction of material waste enabling a lower carbon footprint, use of recycled and environmental-friendly materials, minimisation of human labour necessity, minimisation of operation costs with formwork or temporary structures, complex and customised shapes, striking architectural forms, higher control process, better efficiency as construction time is reduced (Pessoa et al. 2021). It is important to point out that customization is gaining greater relevance, both at the concept phase and the preliminary design development, and in the production and construction phases. Advanced customization allows the introduction of highly specific architectural solutions linked to the ability to utilize flexible digitally controlled machinery and the increasing industrial capacity to change production patterns.

Fig. 1 Structures printed with different materials and technologies: a) "Tecla" printed with soil by WASP and designed by MC A — Mario Cucinella Architects (WASP, 2021b); b) and c) Structures printed by TAM, using 3DP to explore new textures and geometries (Twente Additive Manufacturing B.V., 2021); and d) colour gradient mortar explored by Bruil, in the Material Xperience exhibition in Rotterdam (Bruil, 2021; Bruil and MaterialDistrict, 2016).

Furthermore the use of 3D printing could reduce 35%—60% of the entire cost of concrete construction due to the elimination of formwork, 50%—80% of labor costs, and 50%—70% of production time (Amran et al., 2022). Agustí-Juan and Abert (2017) remark that the construction sector is already responsible for almost 40% of the energy consumption and greenhouse gas emissions globally, while 5—8% of global CO_2 emissions are generated from cement production. There is an urgent need for alternatives to Portland cement which are associated with high CO_2 emissions, high embodied energy and depletion of natural resources. However, it is essential to expand knowledge about 3DP to choose the best alternatives. Fontana and Leite (2021) observed that the subject of additive manufacturing received more attention from researchers in 2019, thus being a very recent field of research and lacking results and evaluations to expand its application in civil construction.

2. Research methodology

The main objective of this study is to gather information to support the research for the development of a sustainable material to be used in additive manufacturing technologies for construction as an aesthetic element. The printing system and its relation with the mortars development will also be studied. Therefore, a state-of-the-art of each, materials and technologies, will allow us to answer the following questions: i) Which technologies are being used? ii) Where and how are these technologies being applied? iii) Which are the steps to develop a 3DP material with a lower PC rate? iv) What kind of alternative compositions are being developed? v) What is their role in the structure plasticity?

The study of 3DPC is divided into two distinct but complementary vectors: the commercial vector focused on technology development and the research vector on the material development. Hence, the literature review is divided in two different parts: 3DP technologies and 3DP materials with two types of resources. For the commercial vector, the most important 3DP technologies in construction were identified, using web media as the main source of information. Now that the printing system knowledge is almost fully developed, the commercial sector is starting to implement some projects in experimental buildings. As this technology is currently the mainstream to upraise construction for the Industry 4.0, a strong press coverage is done throughout the world with projects and the best practices of collaborations between industry and architecture or design studios. For the scientific research on materials development, a typical systematic literature review was made in the main databases as Scopus, Web of Science and Science Direct. In this study the search was programmed to find the keywords in articles' titles and abstracts. The keywords "3D Printing" and "Construction" were restricted by the following filters: i) article type (research, reviews, and book chapters); ii) dated from 2015 to 2021, inclusive; iii) written in English. All the results were reviewed and selected with support of "Start" bibliographic review software (Fabbri et al., 2016). Duplicates were removed as well as the ones that did not contain in the title, abstract or keywords list the words: material, mix, mortar, ink, mix design, mortar design, design, fresh properties. The final selection was made analysing the title and abstract. This research methodology led us to the latest publications related to the 3DP materials development.

3. 3DPC materiality in architecture and design

The new digital technologies brought by I4.0 in construction are pushing the sector to explore interactive methodologies connecting design with production. The biggest change in the design process is made in the objects drawing process. Instead of describing the form with a set of 2D drawings of the various views of the of the object, the design is made form the beginning with a 3D digital BIM model with its technical information attached. The design starts not only with the sketch but also with a set of rules and assumptions that will generate the form, the Parametric Design (PD) and Generative design (GD). These rules and parameters that will define the form, are set by the production capacity granting the communication between design and building process (Bertling and Rommel, 2016). PD and GD are currently part of design process to achieve detailed and functional structures with deeper definition to be passed to the building process This process improves the interaction between architects, designers, engineers and production, creating greater innovation and faster and collaborative working processes between all stakeholders. Directly, the 3D model gives the machine the information to make the product or even manages each element of the product throughout its life cycle through Product Data Management (PDM) (Kyratsis, 2020). This approach is changing architecture, and its methodology, making the technical issues part of the design process since the beginning.

These technologies are obviously changing the design processes and forms in architecture. In the 90ties CATIA software, used only by the aerospace industry offered Gehry the possibility to make his sculptural architecture buildable ("Frank O. Gehry: The Complete Works", 1999). Zaha Hadid's architecture studio has been using PD and GD to find the rules to create designs inspired by nature, with extremely efficient solutions and highly complex geometries (Hadid and Schumacher, 2011). Currently, the Robotic Fabrication Laboratory (RFL), a multi-robotic system in ETH Zurich, is one of the best examples of the research in the use of robotics for architecture and 3DPC (Anton et al., 2020). Composed by four six-axis robots, assembled in a gantry system, this structure allows the use of the four robots throughout the building, a complete system that allows the study of different projects related to digital fabrication (Piškorec et al., 2019). This great diversity of projects has contributed with innovative approaches, using robotic systems, to develop digital construction, are examples: Eggshell, Mesh Mold Prefabrication, Timber Assembly with Distributed Architectural Robotics, etc (Falamarzi and Correa Zuluaga, 2019). The Eggshel project is an approach that allow the fabrication of non-standard reinforced structures, printing a 3D recyclable formwork using a Fused Deposition Modeling (FDM) 3D printer (Burger et al., 2020). This technique requires the synchronization of the two processes: printing and casting. Since it occurs simultaneously, the inclusion of 3D printing with a recyclable material in formwork fabrication allowed to reduce waste and costs, when compared with milling and cutting systems. Several types of structures (houses, bridges, reefs, urban furniture, panels, sculptures, etc.) were printed, proving its potential for future applications (BuiltWorlds Voices, 2016; Cor, 2019; Twente Additive Manufacturing B.V., 2021; XtreeE | the large-scale 3D, 2018). Although some approaches treat this texture as a defect, we believe that it is an element that should be explored aesthetically, working as a differentiating element of 3DP and following the thought of Le Corbusier and Peter Zumthor that a building must show the materials and methods by which are built. An example of this strong connection between research, industry and design is the 3D printed house studied by TU Eindhoven, developed by Saint-Gobain and designed by Houben & Van Mierlo Architecten, for Project Milestone (Guimarães et al., 2021) (Bos et al., 2020).

In recent years, the tendency to have nature as a source of inspiration and reference in the face of human challenges has grown considerably. The attempts to recreate organic forms in architecture, as well as the concern to achieve sustainable processes and an optimal use of materials, lead us to one of the topics that has been on the rise of these experiences in the last decade and that transversally affects all fields of knowledge, which is biomimicry (Benyus and Peters, 2011). Biomimicry in architecture can be applied at many scales: urban metabolism, energy systems, passive design, optimized structures, new materials development (du Plessis et al., 2021). 3DPC and biomimetics in the texture of the material itself. The study developed by Peeks and Badarnah examined the impact of surface texture on heat loss capabilities of concrete panels through evaporative cooling using morphological adaptations found in Nature. This study analysed the potential of concrete 3D printed tiles with complex geometries to improve the thermal performance in building envelopes, focusing on the air flow characteristics occurring near the outer surface of the tile (Hershcovich et al., 2021).

As seen in these analyses, the impact of the digitalization in the construction industry together with the advances in technology are opening a new paradigm in terms of processes and product development arising from the relation between the design conception and the building matter (Cangelli and Conteduca, 2018). Shortening the gap between design and production is opening new opportunities to create and manufacture complex forms both in architecture and design, particularly with 3DPC technologies. As a building is not a typical industrial product easily reproduced, mass customization can be considered as a win—win strategy that benefits both customers and companies increasing the construction process sustainability. Moulds are exempted, the construction process shortened, the used materials reduced and, as a result, the all-process waste severely diminished.

Now that the structural issues are solved and digitalization offers tools and methodologies to ground the design process, is time to explore the materiality of this system particularly in its colour and textures. Both can be crafted not only with the materials exploitation but also with the printing rhythm.

4. 3DP for construction world roadmap

3DP is an Additive Manufacturing (AM) process that produces automatically complex shapes from a 3D CAD model without any tooling or fixtures (Chua et al., 1998; Pham and Gault, 1998; Yan and Gu, 1996), avoiding the usual preparation processes or formwork (Gibson et al., 2010; Hull, 2015). The 3D CAD model is broken into several 2D layers (STL file) and translated to the 3D printer through a G-code file that builds the object layer by layer (Gaudillière et al., 2019; Gosselin et al., 2016; Malaeb et al., 2019; Xiao et al., 2020). Since its inception in 1983 (Hull, 1986, 2015), 3DP has developed a wide range of types and processes of manufacturing (Chua et al., 1998; Dimitrov et al., 2006; Gibson et al., 2010). Currently, the ISO/ASTM 52900-15 ("ISO/ASTM 52900:2015 Additive manufacturing — General principles — Terminology," 2015) features 3DP in seven process categories: Binder Jetting (BJ), Directed Energy Deposition (DED), Material Extrusion (ME), Material Jetting (MJ), Powder Bed Fusion (PBF), Sheet Lamination (SL) and Vat Photopolymerization (VP). All these processes use different types of materials which results in different textures, colours, and geometry possibilities. The most associated with 3DP is material extrusion essentially a large-scale implementation of the fusion deposition modelling, a manufacturing process massively disseminated being the process that better fits the rheological properties of cementitious materials (Pessoa et al., 2021). Research and industry are working together to further enhance the technology. Universities study mortar's compositions and technologies developments. Commercial companies, in collaboration with architects, designers and engineers, are trying to spread it out in various projects as buildings, bridges, prototypes of space habitats, reefs, and urban furniture (Table 1).

To provide a wider view of these two areas, a roadmap to identify the progress of 3DP in the construction industry together with the main projects developed around the world is proposed (Fig. 2). Analysing the map and timeline together allows to conclude that the commercial growth of companies such as CyBe, Apis Cor, Contour Crafting, ICON and WinSun has become more significant since 2014. Research actions on 3DP for the Construction Industry is stronger in German, French, Dutch, Swiss, Australian, Chinese, Singaporean and American universities. Despite the existence of other materials on the market (CyBe Construction, 2021a; Sika, 2018; SQ4D, 2021; WASP, 2021c), concrete is the most commercialized and studied. Its development concerning constituents, dosages, and characterization tests is mostly released by the scientific community (Chen et al., 2020; Lim et al., 2018; Ma et al., 2018; Nerella and Mechtcherine, 2019; Suvash Chandra Paul et al., 2018; Tay et al., 2019; Yuan et al., 2019).

For the building construction, BJ and ME methods are the most commonly used, but Spray-based 3D Printing (SB3DP) is now being explored by the Technical University of Braunschweig (Herrmann et al., 2018) and Nanyang Technological University (Lu et al., 2019) (Table 1). The BJ method, was developed to use a liquid binder sprayed over a powder bed (typically $<$1 mm sand layer), generating a layer by layer object with high levels of detail (Cesaretti et al., 2014; Pegna, 1997) (Fig. 3 a). Examples of this technology are the Joseph Pegna (1997) and Enrico Dini's sculptures, bridges, urban furniture and reefs (Cesaretti et al., 2014; D-Shape, 2010; Lowke et al., 2018). With ME technology, material (usually 3D concrete mortar) is extruded in layers, able to support its own weight as well as that of the following. Its resolution (detail level in 3D printed structure) depends on the materials particle size and nozzle diameter. In this case, higher resolutions usually allow better layer definition. HuaShang Tengda, a Chinese construction company, developed an extruder with two nozzles that allows printing a Class C30 concrete, using a large opening to process coarse aggregates that result in low detail resolution (C, 2016). The use of this technology with concrete, known as 3D Concrete Printing (3DCP), has been the preferential 3DP method in construction in the past two decades, resulting in a higher investment from the industry in technological research in universities. Most of them use robotic arms or gantries systems (Fig. 3 b) but it is possible to find other equipment concepts. Minibuilders (MB) developed by the Institute for Advanced Architecture of Catalonia (IAAC), print pieces larger than their size, using three mini robots for the material deposition (Institut d'Arquitectura Avançada de Catalunya, 2020); Apis Cor (apis cor, 2017), in a 132 m^2 printing area, uses a crane instead of a robotic arm to increase the printing range; and finally, Wasp's printers, Crane and Big Delta use a Delta type 3D printer (WASP, 2021a) (Fig. 3 c). The SB3DP process is similar to the ME process, but the material is sprayed rather than extruded.

These three processes, BJ, ME and SB3DP, offer different finishes and geometry possibilities: i) BJ increases geometric freedom and printing resolution due to the use of a fine material as final finish and support. It requires more time during and after printing and is suitable for highly complex structures (Cesaretti et al., 2014; Pegna, 1997) (Fig. 4 a); ii) ME, the industry's choice, is the fastest and the most economical system, hence with less geometric freedom than BJ due to its lack of support material (Bos et al., 2016; Cor, 2019; ICON, 2021; SQ4D, 2021) (Fig. 4 b); iii) finally, SB3DP allows better bonding of the layers due to its greater moisture, but less quality of finish (Herrmann et al., 2018; Lu et al., 2019).

Table 1 shows information of the most well-known printers and technologies and the respective developer, technology type, construction site and applications, as well as collaborations with Architects/Designers. It is possible to gauge that 52% of technologies have an on-site printing offer for buildings. The Gantry system is the most used, representing 48%, while the robotic arms represented 31% of all technologies, both of which are used mainly in the printing of buildings.

The 3DP materials development for construction, mainly for ME method, has allowed to print more buildings and increasingly complex structures. WinSun is printing houses off-site since 2013. The city of Dubai has committed to printing 25% of all the new buildings until 2025, a construction strategy announced in 2016 with the

Table 1 3DP technologies in the construction sector (printers, construction type, projects and architectural collaborations) (Contour Crafting, 2020; Khoshnevis et al., 2006; Koshnevis, B., Russell, R., Kwon H., 2001; WinSun, 2020; Cesaretti et al., 2014; Lowke et al., 2018; Lim et al., 2016; University, 2018; BetAbram (2021); CyBe Construction (2021b); DUS Architects (2021); Rudenko (2021); Keating et al. (2014); MX3D, 2021; WAAM, 2021; Gaudillière et al., 2019; Gosselin et al., 2016; XtreeE, 2021; Constructions-3D (2021); ETH Zurich (2021); COBOD (2021); Mighty Buildings (2021); ICON, 2021; Story, 2017; AI SpaceFactory (2021); Panda et al., 2018; X. Zhang et al., 2018; Herrmann et al. (2018); Twente Additive Manufacturing B.V. (2021); SQ4D (2021); WinSun, 2021).

Technology / Printer	Developer	Technology type	Construction site	Construction applications	Collaborations with Architects/Designers	References
Contour Crafting	University of Southern California	Gantry	On-site	Buildings; Space Buildings	-	(Contour Crafting, 2020; Khoshnevis et al., 2006; Koshnevis, B., Russell, R., Kwon H., 2001)
WinSun	WinSun	Gantry	Off-site	Buildings; Bridges	Killa Design	(WinSun, 2020; WinSun 3D, 2021)
D-Shape	Enrico Dini	Gantry	Off-site	Buildings; Bridge; Sculptures; Reefs; Space Buildings	Zaha Hadid Architects, Foster + Partners	(Cesaretti et al., 2014; Lowke et al., 2018)
Concrete Printing	Loughborough University	Gantry	Off-site	Building components	-	(Lim et al., 2016; University., 2018)
BetAbram	BetAbram	Gantry	On-site	Buildings	-	(BetAbram, 2021)
Pylos	IAAC	Robotic arm	Off-site	Building components	-	(IAAC, 2021)
Minibuilders	IAAC	Group of small robots	On-site	Building components	-	(Institut d'Arquitectura Avançada de Catalunya, 2020)
Cybe	CyBe	Robotic arm	On-site	Buildings; Urban furniture	Arup, CLS Architects	(CyBe Construction, 2021b)
Big Delta/Crane	Wasp	Delta	On-site	Buildings	Mario Cucinella Architects,	(WASP, 2021a, 2021b)
KamerMaker	DUS Architects	Gantry	On-site	Buildings; Urban furniture	Urban furniture	(DUS Architects, 2021)
Total Kustom	Andrey Rudenko	Gantry	On-site	Buildings	-	(Rudenko, 2021)
Digital Construction Platform	MIT	Robotic arm	On-site	Buildings	-	(Keating et al., 2014)
Apis Cor	Apis Cor	Crane	On-site	Buildings; Space Buildings	SEArch+	(Cor, 2019)
WAAM	MX3D	Robotic arm	Off-site	Bridges; Building components; Urban furniture	Joris Larman	(MX3D, 2021; WAAM, 2021)
XtreeE	XtreeE	Robotic arm	On-site	Buildings; Sculptures; Urban furniture; Reefs	Emmanuel Coste, Coste Architecture, Marc Dalibard, Myriam Garouachi	(Gaudillière et al., 2019; Gosselin et al., 2016; XtreeE, 2021)
Bruil	Bruil	Robotic arm	Off-site	Building components	Kokon - Architectuur & Stedenbouw	(Bruil, 2021; Bruil and MaterialDistrict, 2016)
Constructions-3D	Construction - 3D	Robotic arm	On-site	Buildings; Reefs; Urban furniture	-	(Constructions-3D, 2021)
3D Concrete Printing	Eindhoven University of Technology	Gantry	Off-site	Buildings; Bridges	Houben / Van Mierlo architects	(3DPRINTEDHOUSE, 2018; Bos et al., 2016; Wolfs et al., 2019, 2018)
Robotic Fabrication Laboratory	ETH Zurich	Gantry; Robotic arm	Off-site	Buildings; Building components	-	(ETH Zurich, 2021)
BOD 2	COBOD International	Gantry	On-site	Buildings	-	(COBOD, 2021)
Mighty Buildings	Mighty Buildings	Gantry	Off-site	Buildings	-	(Mighty Buildings, 2021)
Vulcan	ICON	Gantry	On-site	Buildings; Space Buildings	SEArch+, BIG - Bjarke Ingels Group	(ICON, 2021; Story, 2017)
AI SpaceFactory	AI SpaceFactory	Robots	On-site	Space applications	-	(AI SpaceFactory, 2021)
Team of mobile robots	Nanyang Technological University	Group of small robots	Off-site	Building components	-	(Panda et al., 2018; X. Zhang et al., 2018)
Shotcrete 3D Printing	Technical University of Braunschweig	Robotic arm	Off-site	Building applications	-	(Herrmann et al., 2018)
Berlim-1/ Tilikum-1	Twente Additive Manufacturing (TAM)	Gantry; Robotic arm	Off-site	Buildings	-	(Twente Additive Manufacturing B.V., 2021)
Autonomous Robotic Construction Systems (ARCS)	S Square - SQ4D	Gantry	On-site	Buildings	-	(SQ4D, 2021)

aim of reducing labour by 70% and cut costs by 90% (Forum, 2018). In 2017, small 3D printed buildings on-site started to appear across Europe and America (COBOD, 2021; Story, 2017). The New Story project, a neighbourhood of low-cost houses for extremely poor areas of Mexico is being developed with ICON technology since 2017 (Story, 2017). The Milestone Project started in 2017, is an Eindhoven Municipality project with TU Eindhoven and other local and international companies that pretends to print a set of 5 energetically efficient houses (2018) (Fig. 5). The projects diversity proves that 3D printing in construction is being used for the most diverse purposes, from high quality to low-cost constructions.

Each project poses different research challenges: in Dubai, technology must combat labour shortages, and follow the complex geometry of local architecture; the New Story Project needs construction speed and low cost to offer the largest number of houses in the shortest period; and in Milestone Project, 3DP seeks to fulfill the comfort requirements of European housing and to print the entire housing structure.

Even though printers have now developed to an extent that allows to build the projects stated above, further study is needed in materials development to enhance not only building performance and final plasticity but also the mortars environmental performance. To make this happen, it is mandatory to understand the printable material specificities. The materials used by ME technology for the construction industry, range from earth-based materials to PC-based ones, however they all need to meet the same fresh 3D printing properties. A material is printable if it has adequate rheology, i.e., it must be fluid during deposition and stiff right after, creating non-deformable layers able to support the subsequent ones (Kazemian et al., 2017; Lediga and Kruger, 2017; Ma et al., 2018; Malaeb et al., 2019, 2015; Y. Zhang et al., 2018). In large-scale 3DP, the walls assume a structural and self-supporting support function, as the system is free of forms. Thus, the success of the printed

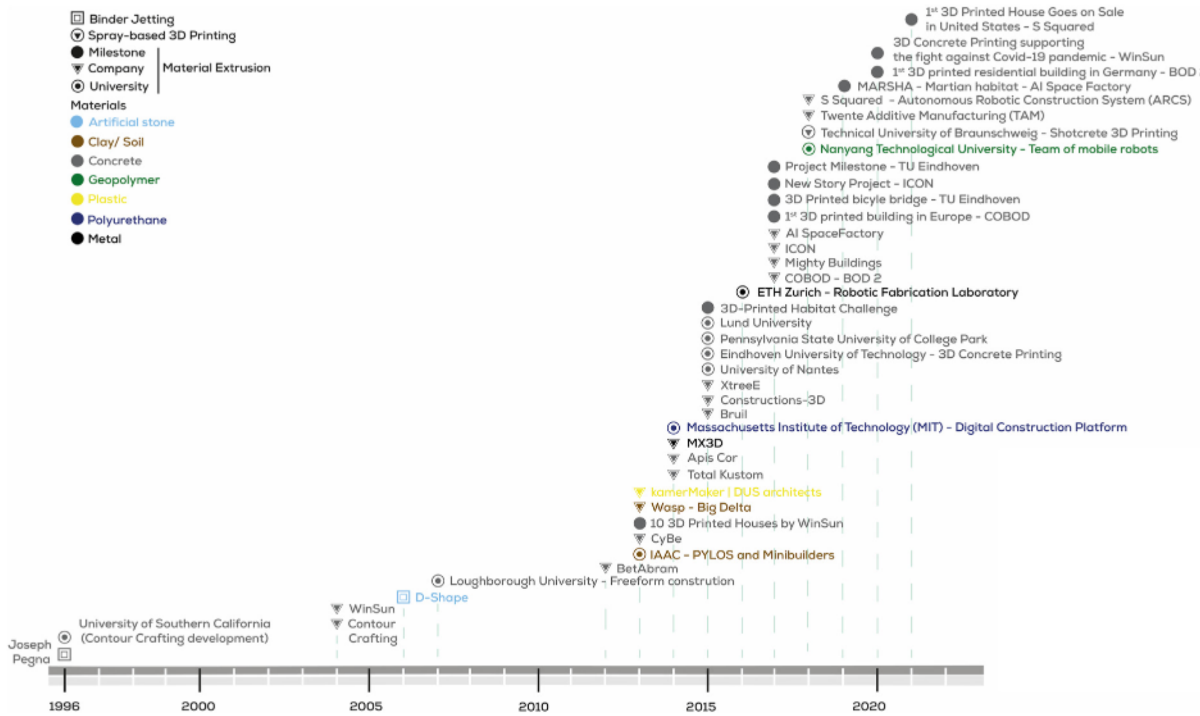

Fig. 2 Evolution of 3DPC: companies, universities, and some of the most important milestones. Note that some technologies can print with more than one material, but the figure only shows the most frequently used material by each one.

structure depends on proper properties of the material in the fresh state (Pessoa et al., 2021).

When defining its composition, printers' characteristics need to be considered (namely pump capacity, hose diameter, nozzle geometry and size, extruder type and printing speed) which will define the constituent's dosage and its granulometry (El Cheikh et al., 2017; Lediga and Kruger, 2017; Ma et al., 2018; Malaeb et al., 2015, 2019; Xiao et al., 2020). The extrusion nozzle is too narrow for the passage of coarse aggregates, therefore, to overcome this limitation, printing mortars normally contain water, cement and a large amount of fine aggregates, that with a suitable particle distribution, ensure adequate mechanical strength (Pessoa et al., 2021). The review presents in Teixeira et al. (2021) shows that most studies for 3D concrete printing use aggregates with a maximum diameter of 2.4 mm. However, from the experimental study in Teixeira et al. (2021), ensure that that is possible to apply aggregates with a maximum diameter of 4 mm, this possibility being totally dependent on the diameter of the extruder nozzle. It concludes that the maximum diameter of aggregate is 5 times the diameter of the extrusion nozzle. This conclusion corroborates the study by Kazemian et al. (2017) propose a maximum aggregate size no bigger than 4.75 mm.

Cement-based mortars are the most often used material in 3DP. Additives and admixtures eventually are added to control and optimize specific properties in fresh and/or hardened state (Pessoa et al., 2021). The paste consistency is also of the utmost importance during extrusion. It will serve as a coating for aggregates acting as a lubricant during the extrusion, filling the voids between aggregates, as Tay, Qian and Tan (Ting et al., 2019) mentioned. This reduces friction between aggregates and improves the mixture workability (El Cheikh et al., 2017; Ting et al., 2019; Weng et al., 2018).

The extrusion system is determinant for the printing success. Literature shows that rather than pistons, Archimedes' screw is the most effective extruder for high

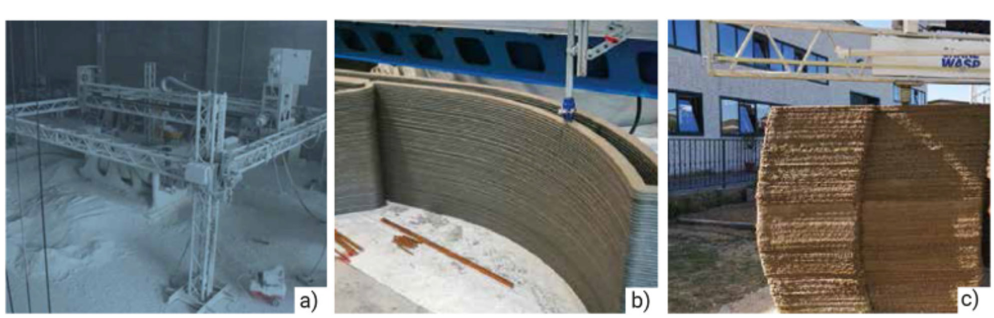

Fig. 3 3DP process types used in construction: a) D-Shape technology, BJ method (D-Shape, 2010); b) ME method, robotic arm printer by TAM (Twente Additive Manufacturing B.V., 2021); and c) ME method, Crane printer by Wasp.

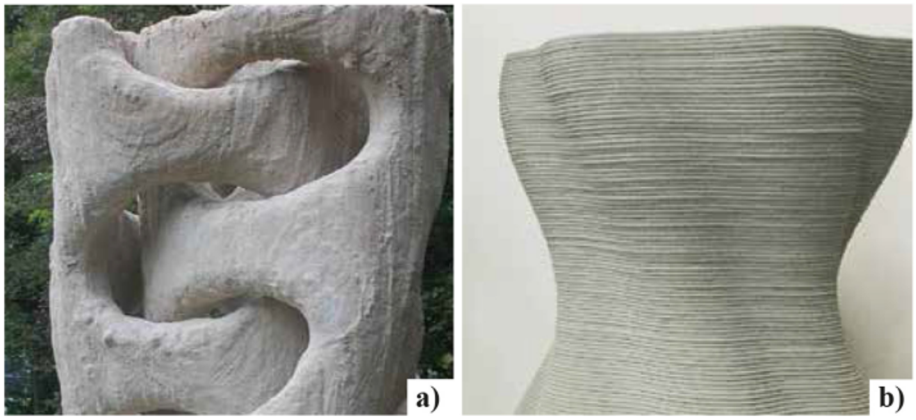

Fig. 4 Examples of different textures made by two types of 3DP processes: a) Sculpture printed through the D-Shape process, with a complex geometry and without layers texture (D-Shape, 2010); b) "Strand Vase à Dubai" printed with XtreeE technology, using a circular nozzle (XtreeE, 2021).

thixotropic materials (Albar et al., 2019; Chen et al., 2020; Jo et al., 2020; Ma et al., 2018; Malaeb et al., 2019). The authors (Teixeira et al., 2021), reported difficulties in extruding these materials with a piston-type, so they used pneumatic actuators near the nozzle to assist in the extrusion process. Ma et al. (2018) used a screw type extruder with a 8 × 30 mm nozzle opening to print a PC mortar with high powders content, chemical additives and fine aggregates (1 mm maximum particle size). This type of extruder, increase the extrusion capacity and can be used with a pumping system for large-scale 3D printings, while a piston type extruder only allows to use the amount of material present in the extruder body. Behind the extruder, other components like the mixer and pumping system need to be suitable for the material to be printed. For example, Wasp needed to develop its own mixer to allow the mixing of a 3D printable earth-based material, otherwise it was impossible to reach a 3D printable composition (WASP, 2018).

5. Fresh properties for a 3D printable material

In order to make a mixture printable, some characteristics have to be fulfilled. **Workability**, **flowability, pumpability, extrudability, buildability, shape retention, open-time, interlayer adhesion, and printability**, that work all together to allow the printing. Definitions and proposed tests are listed below. Most of the information refers to PC-based materials, however all materials developed for 3D printing need to meet the same properties (Fig. 6):

Fig. 5 3D printed house project designed by Houben & Van Mierlo Architecten for Project Milestone (2018).

- **Workability (W)** is a characteristic that makes pumping and extrusion easier but increases the possibility of layer deformation or collapse (Arunothayan et al., 2020; Chen et al., 2020; Kazemian et al., 2017; Nerella et al., 2019).
- **Flowability (F)** represents the material ability to flow through the printing system, controlled by measuring the material's workability with the following tests: flow table (Ma et al., 2018; Malaeb et al., 2019; Sun et al., 2020; Y. Zhang et al., 2018), slump flow (Chen et al., 2020) and V-funnel (Lafhaj et al., 2019; Ma et al., 2018)
- **Pumpability (P)** is the ability of the material to be pumped from the mixer to the nozzle (Nerella et al., 2019; Ting et al., 2019; Zhang et al., 2019). Similarly, to flowability, this property is related to the plastic viscosity and the material flow limit. Zhang et al. (2019) relate pumpability to the spreading diameter value obtained on the flow table.
- **Extrudability (E),** directly related to workability, is the ability of mortars to be extruded by a nozzle into continuous, uniform and stable filaments without blocking the system (Arunothayan et al., 2020; Chen et al., 2020; Kazemian et al., 2017; Nerella et al., 2019). Is usually measured visually by controlling the quality of the filaments (Kazemian et al., 2017; Nerella et al., 2019).
- **Buildability (B)** is the concrete ability to support an extruded layer weight as well as the following ones without changing its geometry; the more layers it can stack without deformation, the higher its buildability (Sun et al., 2020). This property is dependent on the material static yield stress and shape retention (Panda et al., 2019b; Ting et al., 2019): the static yield stress of the material provides initial stiffness. This stiffness is related to the shape retention capacity after extrusion, necessary even before the material's structural development. Structural development

depends on the binder's rate of flocculation and hydration. There must be a balance between the structural development of concrete and the speed of deposition to achieve buildability (Chen et al., 2020; Ma et al., 2018). If the deposition of stacked layers is faster than the printed material's rate of strength, they will collapse (Arunothayan et al., 2020; Kazemian et al., 2017; Panda and Tan, 2018). To evaluate buildability, B. Papachristoforou, Mitsopoulos and Stefanidou (Papachristoforou et al., 2019) printed five stacked layers and analysed the quality and dimension of the first and the last one. To consider a mortar printable, the relation between both must be close to 1.

- **Shape Retention (SR)**, (important to buildability) also called green strength by Zhang et al. (Y. Zhang et al., 2018), is the ability to maintain the layers' geometry after extrusion (Arunothayan et al., 2020; Kazemian et al., 2017; Panda and Tan, 2018). Tests with cylindrical moulds are proposed to assess it (Arunothayan et al., 2020; Chen et al., 2020; Y. Zhang et al., 2018). When filled cylinders are demoulded, their weight must be supported in the first few seconds. Thereafter, weight is applied and increased over time, simulating the subsequent layers. The weight that the material can withstand without deformation is the SR capacity. To remain stable with its own weight, slump tests can also be used when the material has low workability (low slump) and greater static yield stress. High static yield stress can result in high SR but it can also result in system blockage, therefore it must be controlled (Chen et al., 2020).
- **Open time** (also called printable window (Papachristoforou et al., 2019)) represents the time the material must have the necessary workability to be extruded and stacked in layers without deformations, but with enough workability to maintain good interlayer adhesion (Chen et al., 2020; Ma et al., 2018). Measuring it gives the time-period with the best conditions to be printed. Printed filaments over time (Chen et al., 2020; Ma et al., 2018) can also be measured with a Vicat apparatus (Lafhaj et al., 2019; Le et al., 2012a; Ma et al., 2018). The opening diameter value evaluated with a rheometer is inversely proportional to the dynamic yield stress (Paul et al., 2018).
- **Interlayer Adhesion,** crucial for mechanical performance and durability, is the material's ability to bond into subsequent layers (Lafhaj et al., 2019; Panda et al., 2019a; Sanjayan et al., 2018; Jolien Van Der Putten et al., 2019).
- **Printability**, influenced by rheological properties and shape retention, is the ability of a mortar to be deposited in stacked layers, keeping its geometry without deformations during the extrusion and other pathologies that could decrease its durability in hardened state (Arunothayan et al., 2020; Chen et al., 2020; Ma et al., 2018). Its evaluation is made with the combination of all previous properties and respective results.

To evaluate the printed mortars, some parameters like **rheology**, **shear stress, static yield stress, dynamic stress, thixotropy** are observed:

- **Rheology**, strongly related to workability, is the fresh state fluidity capacity and respective deformation level. It is a critical parameter to make the printing satisfactory from the mixer to the printing table (Long et al., 2019; Panda and Tan, 2018). Static yield stress, plastic viscosity (μ) and thixotropy are necessary to achieve buildability and segregation resistance (Long et al., 2019). Thus, the extrusion capacity evaluation of a 3D printable material can be supported by the study of its rheology.
- **Shear stress** indicates good extrusion quality and reversible behaviour, contributing to the mortar reconstruction after printing (Long et al., 2019). In the study of rheology, Bingham's model equations are used for a non-Newtonian material to determine the shear stress and plastic viscosity (Panda and Tan, 2018; Ting et al., 2019).
- **Static yield** stress is the maximum stress required for the material to flow from the resting condition. Grain size, aggregates' geometry, specific surface, paste/aggregates ratio regulates yield stress and plastic viscosity of 3DP material. Materials with high static yield stress are difficult to extrude and can present discontinuities in the extrusion process (Suvash Chandra Paul et al., 2018; Ting et al., 2019; Zhang et al., 2019). In 3DP, there is a yield stress increase over time, affecting directly the material workability and often causing extrusion blocking (Panda and Tan, 2018). Panda and Tan (2018) concluded that higher levels of sand in the mixtures lead to a static yield stress increase causing extrusion difficulties.

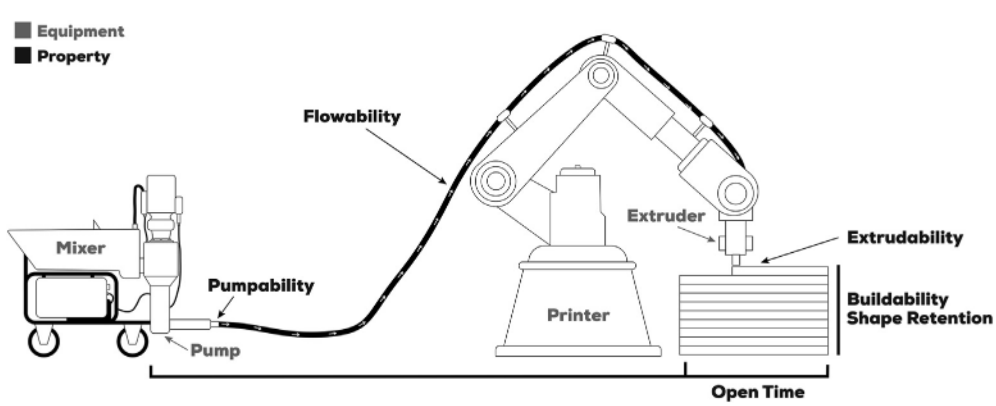

Fig. 6 Properties and equipment required for 3DP with material extrusion.

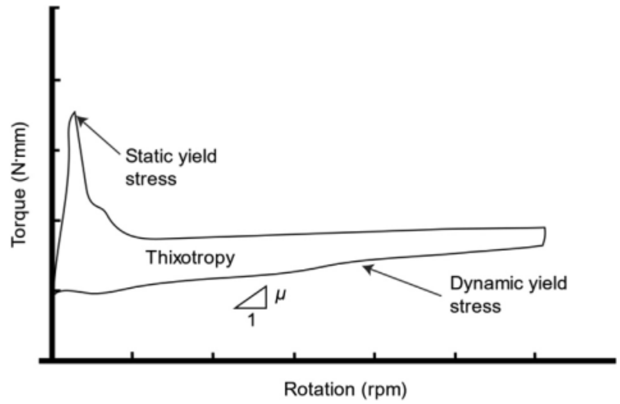

Fig. 7 Thixotropy of materials adapted from (Suvash Chandra Paul et al., 2018).

- **Dynamic stress** is defined as the minimum stress required to maintain workability.
- **Thixotropy** is the term given to the reduction in viscosity of a fluid with increasing shear rate, being the difference between static stress and dynamic stress (Long et al., 2019). The high thixotropy results in the deformation capacity of the materials, necessary for them to be extruded, and in their reversible behaviour, necessary to be stacked in layers. Fig. 7 shows the relation between thixotropy with static yield and dynamic stress.

Table 2 resumes the fresh properties required for 3DP materials and shows how they can be improved and validated.

6. Characterization in the hardened state

6.1. Mechanical performance

Quality requirements for the extruded material are the inexistence of defects in the printed surface, for instance tearing, the dimension of the component's conformity and consistency with the design throughout the print path, the mixture's strength, the quality of the aggregates, the introduction of additives and admixtures, and the shrinkage control, which has a significant effect on the dimensional accuracy and structural integrity of the printed components (Pessoa et al., 2021).

The main characteristic to analyse mechanical performance in 3DP materials are anisotropy in compressive strength, flexural strength, and interlayer adhesion.

Anisotropy, the mechanical performance according to the printing orientation, is of extreme importance in 3DP. Several studies show greater compressive strength with the load being applied parallel to the printed layers (Y direction) (Nerella and Mechtcherine, 2019; Özalp and Yilmaz, 2020; Suvash Chandra Paul et al., 2018; Wangler et al., 2019; Wolfs et al., 2019). Fig. 8 shows the printed layers' orientation according to the load applied. To evaluate 3DP materials, mechanical performance tests on moulded and printing samples are performed, using 50 mm or 40 mm cubes for compressive strength and 40 × 40 × 160 mm prisms for flexural strength.

Several authors show mechanical performance differences in the various test directions (Le et al., 2012b; Marchment et al., 2019; Nerella and Mechtcherine, 2019; Özalp and Yilmaz, 2020; Suvash Chandra Paul et al., 2018; Wolfs et al., 2019; Zareiyan and Khoshnevis, 2017). Paul et al. (Suvash Chandra Paul et al., 2018), and Nerella and Mechtcherine (2019) found that there is about 15% higher strength in the D3 direction, when compared to the moulded specimens. Paul et al. (Suvash Chandra Paul et al., 2018) also mention that, when a single layer is performed, mechanical properties may be greater than moulded samples. This great resistance can be explained by the pressure applied during the extrusion process. However, in 3DP this phenomenon is not dominant and other factors such as the nozzle (height during extrusion, geometry, and size), printing speed, interlayer interval time, the complexity of the printed objects can influence the mechanical properties (Nerella and Mechtcherine, 2019; Özalp and Yilmaz, 2020; Suvash Chandra Paul et al., 2018; Wolfs et al., 2019). It is also referred that the reason for D1 being the worst direction in mechanical performance, may be related to the fact that the load positioning requires a good interlayer adhesion. Test samples in this direction can be a good methodology to assess interlayer adhesion (Le et al., 2012b; Marchment et al., 2019; Zareiyan and Khoshnevis, 2017). To improve density, Manikandan et al. (2020) proved that printing with square nozzle can increase the compression strength.

When the geometry is more complex, there is a need to increase the tensile strength. In traditional processes, it would be solved with steel reinforcement, however, in a 3DP process this possibility would decrease the automation level. The steel reinforcement is placed manually inside a concrete mold printed which works as formwork for the final concreting, decreasing the process's automation level. It is an effective solution but increases construction time and cost (Asprone et al., 2018; Cor, 2019; WinSun 3D, 2021). Some alternatives have been explored: Classen et al. (2020) presented a system able to construct the steel reinforcement at the same time of the printing. HuaShang Tengda used a forked nozzle to print the walls over the steel reinforcement (C, 2016; New China TV, 2016). Asprone et al. (2018) proposed to segment the element to be printed in modules, later connected with tendons and/or bars. Serving not only as reinforcement but also as a connection form, this solution can be effectively applied in 3D printing façade panels. Perrot et al. (2020) suggested a reinforcement by applying steel nails after deposition of several layers, this investigation tested samples with 10 layers high printed with two different mortars, an approach that can be easily automated promoting the concept of digital construction. Freund, Dressler and Lowke (Freund et al., 2020) proposed for Spray-based 3D Printing (SB3DP) technologies a similar method where rebars were screwed through the fresh layers, a promising method that deserves to be studied for material extrusion technologies. The fibres inclusion in the material's composition has been widely used. The literature shows studies using various types of fibres: metallic (Arunothayan et al., 2020; Teixeira, 2018), polymeric (Rahul et al., 2019; Soltan and Li, 2018), carbon, glass (Lim et al., 2018), and natural (Kontovourkis and Tryfonos, 2020a; WASP, 2021b), typically used with a binder volume content of 2% (Arunothayan et al., 2020; Soltan and Li, 2018).

Table 2 3DP properties, validation tests and constituents that can improve printability.

3DP fresh property	Accepted conditions	Validation tests	Constituents that can improve printability	Constituents that can decrease printability	References
Flowability	It needs to flow from the mixer to the printing table.	Flow table, slump flow, V-funnel.	Limestone filler, superplasticizer, VMA, glass wastes.	Setting accelerators, nanoclays, metakaolin, sand content.	(Chen et al., 2020; Lafhaj et al., 2019; Ma et al., 2018; Malaeb et al., 2019; Sun et al., 2020; Y. Zhang et al., 2018)
Pumpability	It needs to be pumped from the mixer to the printing table.	Rheometer, slump flow.	Limestone filler, superplasticizer, VMA.	Setting accelerators, nanoclays, sand content.	(Nerella et al., 2019; Ting et al., 2019; Zhang et al., 2019)
Extrudability	It needs to be extruded by a nozzle into continuous, uniform, and stable filaments without system blocking.	Visually evaluating the filaments quality.	Powder's content.	Sand (grain size and geometry).	(Arunothayan et al., 2020; Chen et al., 2020; Kazemian et al., 2017; Nerella et al., 2019)
Buildability	It needs to be able to support the weight of an extruded layer and the following ones, maintaining its geometry.	Printing at least 5 stacked layers without deformations.	Nanoclays, setting accelerators, VMA.	Setting retarders.	(Panda et al., 2019b; Sun et al., 2020; Ting et al., 2019)
Open Time	Represents the time that material presents the necessary workability to be extruded and stacked in layers with good interlayer adhesion.	Measuring flow over time, Vicat apparatus.	Blast furnace slag, fly ash, setting retardants, VMA.	Setting accelerators.	(Chen et al., 2020; Lafhaj et al., 2019; Le et al., 2012a; Ma et al., 2018; Papachristoforou et al., 2019); Suvash Chandra Paul et al., 2018
Shape retention	It is the ability to maintain the layers' geometry.	Slump flow, cylindrical moulds tests.	Nanoclays, setting accelerators.	Setting retarders.	(Arunothayan et al., 2020; Kazemian et al., 2017; Panda and Tan, 2018; Y. Zhang et al., 2018)
Interlayer adhesion	It is the materials' ability to bond to subsequent layers.	Compressive and flexural strength, capillary tests.	Setting retarders, binder content.	Setting accelerators, lack of binder, fibres.	(Lafhaj et al., 2019; Panda et al., 2019a; Sanjayan et al., 2018; Jolien Van Der Putten et al., 2019)

Table 3 resumes the hardened properties required for 3DP mortars and shows how they can be improved and validated. In addition, aesthetic parameters such as colour and texture are presented that are related to the constituent materials and extruder nozzle in 3DP and can inevitably affect the mechanical performance.

6.2. Durability

Several studies report that 3DP increases the material porosity due to the layered manufacturing process, decreasing the material's durability (Li et al., 2020; Schroefl et al., 2019; J Van Der Putten et al., 2019). This

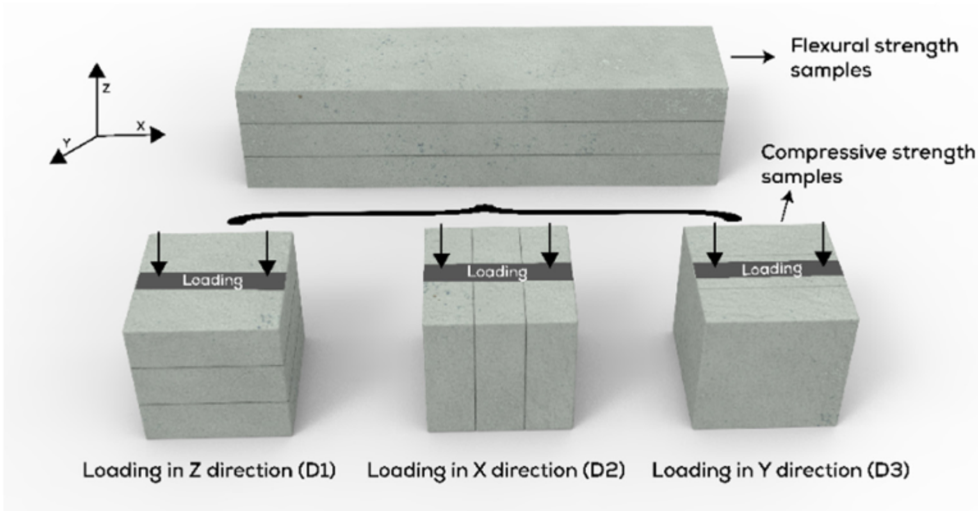

Fig. 8 Directions in which 3D printed samples should be tested (Suvash Chandra Paul et al., 2018).

problem results mainly from: i) the lack of formwork that enhances the contact area between air and the material, accelerating the curing time and increasing the shrinkage probability (Mohan et al., 2021); ii) poor interlayer adhesion, and iii) printing parameters, time gap between printed layers (Schroefl et al., 2019) and printing speed (J Van Der Putten et al., 2019), that increase material porosity.

Putten et al. (J Van Der Putten et al., 2019) measured the durability using Mercury Intrusion Porosimetry (MIP) tests (ISO 15901—1:2005) and concluded that lower printing speed reduces bigger pores (with low time gap between printed layers) improving the interlayer adhesion, mechanical performance, and durability. Using Capillary Water Intake (CWI) test, Schroefl et al. (2019) proved that a time gap between printed layers higher than 2 min, results in a bad interlayer adhesion, decreasing its durability. Despite these studies, the long-term study needs more attention from researchers, mainly because durability loss can be a problem for the material sustainability.

6.3. Textures and colours

When the printed texture is assumed, the surface finish quality is an important aspect in 3DP process, but it can result in structural and aesthetic problems, since the choice of materials can affect the printed pieces' texture and colour (Ma et al., 2018; Manikandan et al., 2020; J Van Der Putten et al., 2019; Xiao et al., 2020). The aggregates' size, powders' content, fibres' inclusion, nozzle geometry and printing speed affect the surface roughness (Manikandan et al., 2020; J Van Der Putten et al., 2019), with the nozzle specifications (geometry and opening size) being the most influential parameter (Kim et al., 2019; Kwon et al., 2002; Lao et al., 2020a; Manikandan et al., 2020). To control the finishing, Khoshnevis (2004) developed an extruder with trowels capable of moulding the surface finish. Manikandan et al. (2020) showed that cylindrical structures printed with a square nozzle have higher roughness than circular ones. Lao et al. (Lao et al., 2020a, 2020b) proved that, by optimizing the nozzle geometry, it is possible to achieve better dimensional and geometric quality of the printed part. The same authors developed a geometry-variable nozzle (Lao et al., 2021) which, through an algorithm, shapes itself according to printed element structure's geometry, reducing roughness and improving print quality. Kwon et al. (2002) concluded that surfaces of pieces fabricated with a square nozzle were smoother and have more noticeable cracks than pieces printed with an ellipsoidal nozzle. Putten et al. (J Van Der Putten et al., 2019) studied the effect of printing speed in roughness and observed that increasing the printing speed also increases roughness.

Sometimes the texture of the layering process is seen as a defect in 3DP. However, when controlled and properly studied, it can be assumed as an architectural mark expressive of the plasticity of technology in the printed structure. When the form of a building exhibits a sculptural presence, it is said to have plasticity. This characteristic is associated with architecture and construction and can be related to the final appearance in 3DP.

Colour, determinant to surface finish, does not have significant interference in the structural behaviour. In 3DP for construction, such as in traditional concrete construction with grey PC, it is common to get materials with grey shades (Cor, 2019; TAM, 2021; XtreeE, 2021). However, some projects have shown that colour in 3DP can be interesting in the plastic definition, as Bruil illustrates with the colour gradient mortar potential, in the Material Xperience exhibition in Rotterdam (Bruil, 2021; Bruil and MaterialDistrict, 2016). Sika developed mortars with a natural brick and yellow shades (Sika, 2018), colours similar to the printings with soil or clay (IAAC, 2021; WASP, 2021b). Some studies used white cement in the material, making it lighter, and closer to white colour (Özalp and Yilmaz, 2020).

Fig. 9 summarizes the colour palette currently used in 3DP for construction with these products.

7. Trends in the developing of more sustainable mortars for 3DP

The technologies and materials development has been a sustainable innovative tool for promoting energy conservation and reducing carbon emissions. 3DP has the potential

Table 3 Hardened properties in 3D printing materials and printing conditions that can improve each one.

3DP hardened property	Purpose	Printing conditions that can improve printability	Printing conditions that can decrease printability	Validation tests	References
Compressive strength	Structural	Square nozzle, low printing speed.	Circular nozzle, high printing speed.	Compression tests.	(Nerella and Mechtcherine, 2019; Özalp and Yilmaz, 2020; Suvash Chandra Paul et al., 2018; Wangler et al., 2019; Wolfs et al., 2019)
Flexural strength	Structural	Decrease the time between each printed layer.	Increasing the time between each printed layer.	Bending tests.	(Nerella and Mechtcherine, 2019; Özalp and Yilmaz, 2020; Suvash Chandra Paul et al., 2018; Wangler et al., 2019; Wolfs et al., 2019)
Durability	Structural	Low printing speed, decrease the time between each printed layer.	Increasing the time between each printed layer.	[a]MIP and CWI tests.	(Li et al., 2020; Schroefl et al., 2019; J Van Der Putten et al., 2019)
Texture	Structural | Aesthetic	Choose the nozzle according to structure's geometry, small nozzle openings.	Larger nozzle openings.	Visually	(Kim et al., 2019; Kwon et al., 2002; Lao et al., 2020a; Manikandan et al., 2020; J Van Der Putten et al., 2019)
Colours	Aesthetic	Only related with constituents.	Only related with constituents.	Visually	(Bruil and MaterialDistrict, 2016; IAAC, 2021; Özalp and Yilmaz, 2020; Sika, 2018; WASP, 2021b)

[a] Mercury Intrusion Porosimetry (MIP) and Capillary Water Intake (CWI) tests.

to improve sustainability in construction (Alhumayani et al., 2020; Weng et al., 2020), although some optimizations need to be done, particularly in the mortars constitution. Pessoa et al. (2021) says that 3DP will make construction more efficient while creating sustainable growth and stimulating circularity principles, emphasizing the use of recycled and environmentally friendly materials. The material can be extruded only where needed, hence saving on material consumption, which provides an optimisation of the construction components and lowers the industry's environmental impact. PC-based materials have proven to be suitable for 3DP but are one of the biggest responsible of the construction environment footprint, due to its high energy consumption and CO_2 emissions during clinker production (Costa and Ribeiro, 2020). Researchers have been looking for less aggressive alternative materials to minimize the PC negative effects overuse, and several approaches have emerged for 3D printable alternative materials. Behind environmental reasons, these materials can be used as final finish in 3D printed structures, allowing the exploration of new textures and colours. Fig. 10, summarizes the alternative materials studied in literature for 3DPC. Only materials with similar properties to concrete have been studied, other materials such as polymers, metals and foams were excluded from this study, in addition to alternative materials, options to turn PC-based materials more sustainable are presented.

7.1. Options to improve sustainability in PC-based materials

PC-based materials are the most used in 3DP for construction (Teixeira et al., 2021). There are two options for improving sustainability in PC-based materials: i) replace PC by Supplementary Cementitious Materials (SCM), they interact chemically and physically with the hydration products of PC, modifying the microstructure of the paste and bringing advantages in technical, economic and sustainable aspects; ii) the replacement of natural sand by recycled aggregates reduces the need for virgin raw materials, by allowing the incorporation of waste.

7.1.1. Supplementary cementitious materials in 3D printing

A large amount of powders is required for a 3DPM (Ma et al., 2018; Ting et al., 2019; Weng et al., 2018), so using Supplementary Cementitious Materials (SCM) is essential to reduce PC content. SCM are mineral addition that interact chemically and physically with cement hydration products, modifying paste microstructure and enabling the PC reduction (Kazemian et al., 2017; Panda et al., 2019b). These materials provide technical, economic and sustainability advantages: i) durability is improved, particularly with pozzolans, silica fume (SF), metakaolin (MTK) and fly ash (FA), due to enhance pozzolanic reactivity; ii) mineral additions can be by-products more economic than PC; iii) PC consumption reduction minimizes CO_2 emissions (Askarian et al., 2019; Chen et al., 2020; Gao et al., 2019; Kazemian et al., 2017; Lediga and Kruger, 2017; Lim et al., 2018; Long et al., 2019; Ma et al., 2018; Nerella et al., 2019; Nerella and Mechtcherine, 2019; Suvash Chandra Paul et al., 2018; Reddy et al., 2018; Subathra Devi, 2018; Tay et al., 2019; Teixeira et al., 2021; Ting et al., 2019; Weng et al., 2018; Yuan et al., 2019; Y. Zhang et al., 2018).

Fly ash (FA), generated from coal combustion, silica fume (SF), obtained from the silicon and ferrosilicon alloys

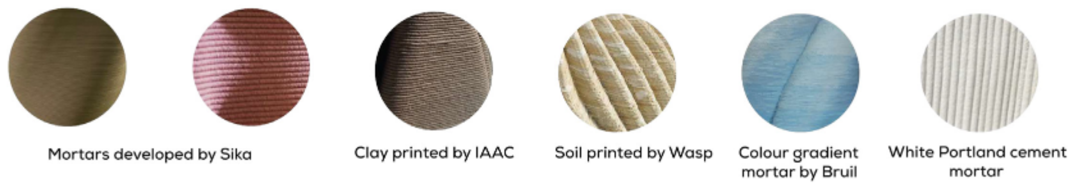

Fig. 9 Colours provided by the materials used in 3DP for construction sector (Bruil and MaterialDistrict, 2016; IAAC, 2021; Özalp and Yilmaz, 2020; Sika, 2018; WASP, 2021b).

production, (Lediga and Kruger, 2017; Lim et al., 2018; Long et al., 2019; Ma et al., 2018; Nerella et al., 2019; Nerella and Mechtcherine, 2019; Suvash Chandra Paul et al., 2018 Tay et al., 2019; Ting et al., 2019; Weng et al., 2018), blast furnace slag (from metallurgical industry) (Askarian et al., 2019; Gao et al., 2019; Reddy et al., 2018; Subathra Devi, 2018), limestone filler (LF), fine grinding of limestone (Chen et al., 2020; Teixeira et al., 2021), and nanoclays (NC) nanoparticles of layered mineral silicates (Kazemian et al., 2017; Yuan et al., 2019; Y. Zhang et al., 2018) can also improve 3DP mortar workability, mechanical performance, durability, dimensional stability and reduce hydration heat (Askarian et al., 2019; Chen et al., 2020; Gao et al., 2019; Kazemian et al., 2017; Lediga and Kruger, 2017; Lim et al., 2018; Long et al., 2019; Ma et al., 2018; Nerella et al., 2019; Nerella and Mechtcherine, 2019; Suvash Chandra Paul et al., 2018; Reddy et al., 2018; Subathra Devi, 2018; Tay et al., 2019; Teixeira et al., 2021; Ting et al., 2019; Weng et al., 2018; Yuan et al., 2019; Y. Zhang et al., 2018). FA and SF are the most used SCM combination in 3D printing (Lediga and Kruger, 2017; Long et al., 2019; Ma et al., 2018; Nerella et al., 2019; Nerella and Mechtcherine, 2019; S C Paul et al., 2018; Tay et al., 2019; Ting et al., 2019; Weng et al., 2019). FA is normally used in greater amounts, about 20% wt of the paste (Dedenis et al., 2020; Lediga and Kruger, 2017; Ma et al., 2018; Tay et al., 2019; Ting et al., 2019). Dedenis et al. (2020) showed that using a combination of PC, FA and metakaolin (MTK) increased the yield stress, cohesion, stability and printability, being more effective than using just one of them in combination with PC. Zhang et al. (Y. Zhang et al., 2018) have proven that replacing 4 wt% PC with 2 wt% SF and 2 wt% NC provides greater buildability than compositions with just SF or NC. The study of Kazemian et al. (2017) showed that the inclusion of 0.3 wt% NC allows a buildability similar to a mortar with 10 wt% SF. Bohuchval et al. (2021) studied the inclusion of FA, LF and MTK in 3DPM, and noticed that replacing 24 wt% of PC by LF increase the material's workability making the mortar unsuitable for 3D printing. In other hand, replacing PC by 22 wt% of FA and 12 wt% of MTK showed appropriated properties for 3D printing.

The literature reviled that fly ash appears in most compositions as the main SCM, however several countries plan to closure their coal-fired power stations to meeting the Paris Agreement targets about CO_2 emissions (Council, 2015). Since these stations are the producers of this industrial by-product, the break in their supply will be inevitable in the coming years, being mandatory to search for SCM with similar properties.

7.1.2. Alternative aggregates

As previously mentioned, experiments with mineral additions have been made to minimize PC content. Nonetheless, other mortar's constituents such as aggregates, also need to be replaced by more sustainable solutions, respecting the concepts of circular economy (Benachio et al., 2020; Kirchherr et al., 2017). Xiao et al. (2020), recently, presented mortars produced with recycled Construction and Demolition Waste (CDW) aggregates, replacing natural sand in the printing of a 2.5 × 2.5 × 3 m room. The recycled "sand" was obtained by crushing and screening concrete waste. The authors mention that recycled materials might be advantageous for a 3DP material, improving the mortars' shape retention without decreasing the mechanical properties. Results have shown that replacing natural sand with 25% of recycled sand does not result in disadvantages for the material produced (composed by graded river sand, recycled sand, PC, hydroxypropyl methylcellulose (HPMC), high-efficient

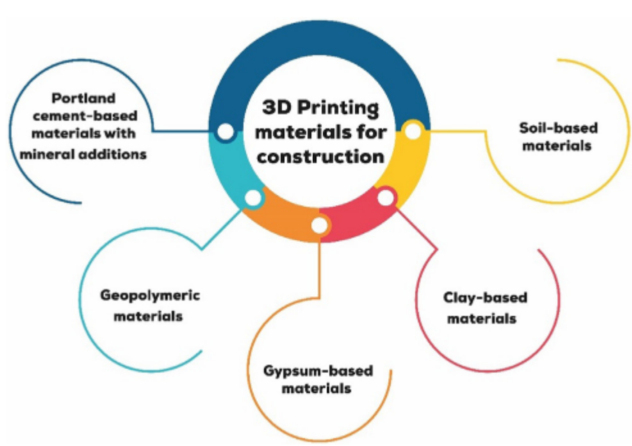

Fig. 10 Approaches followed by literature in the development of more sustainable 3DP materials.

polycarboxylate-based superplasticizer and NC). Ground glass waste has been used as fine aggregate for cementitious materials, while glass powders are used in PC replacement. Ting, Tay and Tan (Ting et al., 2019) explored the use of recycled glass as recycled fine aggregate, and concluded that compositions with recycled glass waste had lower dynamic yield stress and plastic viscosity, improving material's flowability, but decreasing material's buildability. This problem was solved using a nano-attapulgite clay and setting accelerators in mortar's composition. Ma, Li and Wang (Ma et al., 2018), developed 3DP mortars replacing 30% of natural sand by copper tailings. Contents above this value significantly affect the printing stability.

Despite the existence of studies with alternative aggregates, the research on mortars for 3D printing is focused on the replacement of PC. The literature demonstrates that the inclusion of aggregates from industrial and construction and demolition waste has been a way to environmentally improve the material for 3D printing, according to the principles of circular economy. However, we believe this inclusion can not only improve this performance but also offer new aesthetic possibilities, increasing the palette of colours and textures in 3DP. Assuming the texture of the manufacturing process in layers with the material colour, will allow to differentiate 3D printing from traditional processes.

7.1.3. Chemical admixtures

Chemical admixtures did not belong to the batch of sustainable materials, although they improve the performance of 3D printable materials, making them more durable, which is also one parameter of sustainability. Superplasticizers (included in most of the PC compositions found in the literature) allows the material to stiffen quickly, minimizes the shrinkage probability, and increases the workability even reducing the water dosage (Chen et al., 2020; Kazemian et al., 2017; Long et al., 2019; Ma et al., 2018; Malaeb et al., 2019; Nerella et al., 2019; Yuan et al., 2019; Y. Zhang et al., 2018). The types of superplasticizer are: lignosulfonic acid (LS) (Suvash Chandra Paul et al., 2018), melamine formaldehyde sulfonic acid (SMF), naphthalene formaldehyde sulfonic acid (SNF) and polycarboxylic acid (CE) (Chen et al., 2020; Kazemian et al., 2017; Long et al., 2019; Ma et al., 2018; Malaeb et al., 2019; Nerella et al., 2019; Yuan et al., 2019; Y. Zhang et al., 2018). The water content reduction that each one offers is 15—30%; 12—20%; 9—11% and 25% for SMF, SNF, LS and CE, respectively. The production of 3DP mortars with superplasticizer uses a water/binder ratio between 0.17 and 0.43 in composition (Chen et al., 2020; Kazemian et al., 2017; Long et al., 2019; Ma et al., 2018; Malaeb et al., 2019; Nerella et al., 2019; Yuan et al., 2019; Y. Zhang et al., 2018) and between 0.36 and 0.5 without it, which can result in better mechanical performance for compositions that used superplasticizers (Jo

Fig. 11 Structures printed using clay or soil-based materials: a) 3DP house "Gaia" printed by Wasp using soil-based materials (WASP, 2018); b) Project for a future 3D printed school by Studio Mortazavi; c) Printing process using a circular nozzle and a soil-based material developed by Perrot, Rangeard and Courteille (Perrot et al., 2018); and d) Structure printed by Kontovourkis and Tryfonos (Kontovourkis and Tryfonos, 2020a), using an extruder developed by 3D Potter.

et al., 2020; Lafhaj et al., 2019; Marchment and Sanjayan, 2019; Tay et al., 2019; Ting et al., 2019).

Setting accelerators are important to shorten the setting time allowing to achieve enough consistency for supporting subsequent layers, Usually, moments before extrusion to improve buildability and shape retention (Long et al., 2019; Malaeb et al., 2019) are used. In other hand, setting retarders are included in the mixture to avoid blocking problems during the transport phase. These chemical admixtures, when embedded in the cement particles' surface produces an insoluble layer, delaying hydration that increase the extrusion time (Lediga and Kruger, 2017; Y. Zhang et al., 2018) and can improve interlayer adhesion. Viscosity modifying additives (VMA) and water-soluble polymers are used to control workability and rheology decreasing segregation probability and improve dimensional stability (Arunothayan et al., 2020; Chen et al., 2020).

7.2. Geopolymeric materials

Geopolymers are considered a promising solution for replacement of PC-based materials in some applications, as industrial waste is used as raw material. In terms of environmental impact, geopolymers are known to generate 80% less CO_2 than PC (Panda and Tan, 2018), and produce better mechanical and durable performance (Panda and Tan, 2018). By-products rich in aluminosilicates (fly ash, blast furnace slag or silica fume), and alkaline activators (sodium (Na) and potassium (K)) are used to create a chemical reaction, allowing the material to achieve stiffness and bonding. Aiming at printing a 60 cm-high structure, Panda and Tan (2018) produced a 3DP geopolymer composed of fly ash class F, blast furnace slag, microsilica, river sand, a mixture of potassium silicate solution with 24.32 wt% SiO_2, 18.71 wt% Na_2O, and a NaOH solution in 45 wt% that was used as an activator. After obtaining the best mixture in extrusion tests, glass fibres (4 mm wide) and nano-attapulgite clay were incorporated to improve buildability and then the final structure was printed. Panda et al. (2019c) tried to verify the fresh properties such as yield stress, viscosity and thixotropy in geopolymers produced with fly ash, blast furnace slag and potassium activators (49.50 wt% SiO2, 42.54 wt% K_2O and remaining H_2O) together with potassium hydroxide (KOH) powder. The increase in blast furnace slag led to a higher yield stress and viscosity in mixture, important for shape retention and buildability. The researchers also concluded that the activators used lead to the development of rapid resistance without using accelerating additives. Paul et al. (Suvash Chandra Paul et al., 2018) produced a geopolymer with blast furnace slag, silica fume and fly ash, rheology modifiers (actigel bentonite and sand), and potassium oxides and silicates that were used as activators and polymerizers.

Despite promising studies in literature, the commercial use of these materials is still not well implemented, proven by the lack of prints with these materials outside of research projects.

7.3. Soil and clay-based materials

Soil and clay-based materials have been implemented in construction as low-cost recyclable materials with low environmental impact (Alhumayani et al., 2020; Kontovourkis and Tryfonos, 2020a; Perrot et al., 2018). Earth architecture, as a branch of vernacular architecture, is an architectural style based on local materials, local needs, and local builders' skills, where buildings are made from mixtures of soil and water, with occasional addition of fibres. Digitally manufactured earth construction is considered a modern construction type. Most of the current research and application of digital earth construction are concentrated on 3D printing technology, which is similar to the well-developed technology in digital cement-based construction (Gomaa et al., 2022).

Wasp has been printing small buildings using soil, straw chopped rice, rice husk and hydraulic lime (WASP, 2021b, 2019) (Fig. 11 a). IAAC, with Pylos project and TerraPerforma revealed the materials' possibilities, printing large-scale geometric complex elements (IAAC, 2021, 2016). These materials can be found anywhere, enabling construction in remote areas, as example the school designed by Studio Mortazavi that will be printed in Madagascar (Joyner, n.d.) (Fig. 11 b). All these projects have been motivating the scientific community to study soil and clay-based materials as 3DP materials for construction (Alhumayani et al., 2020; Kontovourkis and Tryfonos, 2020b; Perrot et al., 2018). Perrot, Rangeard and Courteille (Perrot et al., 2018) developed a 3DP material using a clay composed by quartz, kaolinite, illite, smectite and a commercial biopolymer called alginate, the last one used to increase the material's shape retention and buildability. A 3 m-high wall was printed, and the material offered a smooth finishing when printed with a circular nozzle (Fig. 11 c). Kontovourkis and Tryfonos (2020a) used two different open-source extruders: one developed by Wasp (WASP, 2021c) and the other by 3D Potter (Potter, 2021 and five different soil and clay-based materials to optimize the 3DP parameters through a parametric approach (Fig. 11 d). One of the materials it is commercially available, and was developed by Wasp (WASP, 2021d), the remaining compositions were developed, using body clay, sand, water, lean clay soil, straw fibres, calcarenite sand and sodium hexametaphosphate (Kontovourkis and Tryfonos, 2020a).

These type of materials appear as one of the most sustainable and economical alternatives in the construction sector (Alhumayani et al., 2020; Kontovourkis and Tryfonos, 2020a; Perrot et al., 2018). The "Maker Economy Starter Kit" is a WASP commercial option which explores the advantage of printing with local materials (WASP, 2021e), one of the main advantage of this materials. Although, when is not possible, the container is equipped with all the necessary equipment to print with other materials, namely mortars or recycled materials. Also, the company offers support and knowledge sharing through an online platform, an advantageous offer for construction in remote areas where access to construction materials and tools is extremely difficult. As it is a type of material associated with low-cost constructions, the layer texture is kept as the final finish, being the most illustrative structures of the use of layered manufacturing process as a plastic element in the structure.

7.4. Gypsum-based materials

The gypsum-based materials are one of the oldest building materials, present inclusive in the Greek age. Some

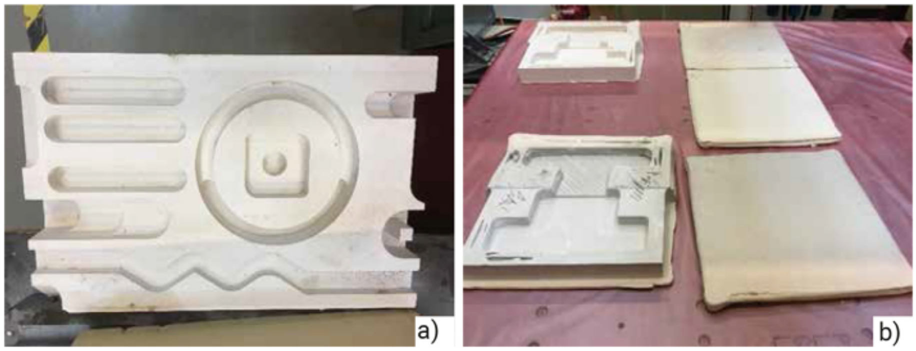

Fig. 12 3DP with gypsum-based materials, samples printed by the technology developed by Neto et al. (Neto et al., 2017).

Table 4 Resume of the main properties of 3D printable materials presented previously.

3DP material	Fresh properties	Mechanical performance /durability	Why are they being used in 3D printing?	Texture	Colour possibilities	Ref.
PC-based materials	They can be optimized using SCM and chemical admixtures. When used glass waste and copper tailings as aggregates the buildability and shape retention can be decreased.	It can be improved with the use of SCM and chemical admixtures.	Enables the development of high-performance materials for 3DP.	They allow a great freedom of textures, that can be controlled by aggregates granulometry and the nozzle geometry.	Greyscales mostly, although, when used white PC it is possible to achieve several colours.	(Dedenis et al., 2020; Lediga and Kruger, 2017; Ma et al., 2018a; Özalp and Yilmaz, 2020; Tay et al., 2019; Ting et al., 2019)
Geopolymeric materials	Just as in PC materials nanoclays can be used to optimize shape retention and buildability. They do not need setting accelerators to develop rapid resistance.	They reach better mechanical performance and durability than PC materials.	They generate 80% less CO_2 than PC.	They allow a great freedom of textures, that can be controlled by aggregates granulometry and nozzle geometry.	Greyscales.	(Panda et al., 2019c; Panda and Tan, 2018)
Soil and clay-based materials	Biopolymers like alginate can be used to improve shape retention.	The material achieves similar mechanical performance to conventional cob earth material.	They are low cost and recyclable materials with low environmental impact.	They are smother when printed with a circular nozzle.	Brown and yellow shades.	(Alhumayani et al., 2020; Kontovourkis and Tryfonos, 2020a; Perrot et al., 2018).
Gypsum-based materials	Polycarboxylates are needed to delay setting time, otherwise blockages may occur during printing.	Lower than PC-based materials.	They are low-cost materials, with lightweight, acoustic insulation and low environmental impact.	They can be machined to improve the final finish.	Greyscales.	(Krejsová et al., 2019; Liu et al., 2018, 2021; Lushnikova and Dvorkin, 2016; Zhu et al., 2018)

properties like fire resistance are similar to Portland cement-based materials but others have the opposite behaviour such as lightweight, acoustic insulation and low carbon character (Krejsová et al., 2019; Liu et al., 2018, 2021; Lushnikova and Dvorkin, 2016; Zhu et al., 2018). The energy demand for gypsum production is well below the energy demand for clinker production and can even be produced by raw materials (natural gypsum rock) or by industrial by-products (Krejsová et al., 2019; Lushnikova and Dvorkin, 2016). Apis Cor used a gypsum-based material to print the world's biggest 3D printed building (Cor, 2019), which proves the material capacity. Liu et al. (2018) study the gypsum-based material rheology for 3DP, and concluded that polycarboxylates can be used to delay material's setting time, without it the mortar would harden rapidly and block the printing system. Caetano et al. (2017) studied the development of a gypsum-based material to use in hybrid equipment composed by AM and machining processes (ADIMAQ Project) to produce low-cost models and moulds with good surface finish. Neto et al. (2017) reported the development of the printer technology as well as several compositions for 3D printing (Fig. 12). Despite not having applications in construction, it is an example that proves the capacity of gypsum-based materials to be printed and machining, an option that could be very interesting for the manufacture of high complex ornamental pieces.

All the materials presented provide different possibilities and advantages, making difficult to conclude that one is better than another without being inserted in a certain context. PC-based materials are used in more demanding structures, such as bridges, as they are high-performance materials and well known in construction industry. The inclusion of industrial by-products and waste in 3DP materials can be a way to improve their environmental performance and explore new textures and colours, further increasing the technology's customization capacity. Geopolymers have a great potential, however the existing knowledge about these materials is much lower than the existing knowledge about PC-based materials, which hinders its commercial use by the construction sector. Soil and clay-based materials are abundant on our planet, being a good option to print low-cost houses in remote areas. They can provide the construction of houses using local materials, avoiding costs and CO_2 emissions with the transport of materials like sand, bricks and PC. Gypsum-based materials offer lightweight, acoustic insulation, low cost and the possibility of being machined. They allow the printing of ornamental pieces, or an interior insulating layer. Table 4 resume the main characteristics of each material.

7.5. 3D metal printing

Metallic materials are widely used in the construction industry through traditional techniques. This leads to structural elements that are prismatic owing to their ease of manufacturing. Metal Additive Manufacturing (MAM) methods can be adopted for greater flexibility in the geometry of structural elements. MAM offers numerous benefits over conventional manufacturing methods, such as greater structural efficiency, geometric freedom, customization and reduced material usage. MAM can enable highly optimized, lightweight, efficient structural forms that would be excessively time consuming and costly to manufacture with traditional forming techniques. Furthermore, the use of waste and the recycling are applicable to metallic construction. Due to the high residual value of scrap and economic incentive for recycling, especially for high-value metallic materials which can be recycled completely and indefinitely. Another important factor for the growth of additive manufacturing of metals in construction is offsite manufacture. The offsite manufacture allows the manufacturing equipment to be used in a controlled environment and reduces the time and labour requirements onsite (Buchanan e Gardner, 2019).

8. Conclusion

The need to undertake a comprehensive literature review on the current status of 3DP for architecture and construction applications to clarify the extent reached by this technique the limitations, future perspectives and what should be done to improve this is substantial. The systematic review of the literature on 3DP for construction was presented in this article with the objective of supporting the development of new and more sustainable mortars. A review of the technologies and materials was made and the conditions to make a mortar printable were settled. It is shown that the Material Extrusion method is the most often used in the development of 3DP for construction systems, making it possible to print large buildings and complex structures with high efficiency. Countries like the United States, the Netherlands and China dominate the printers manufacture and the supply of printing services. However, the most productive printable mortars do not follow all the environmental efficiency that 3DP can provide, particularly in its PC dependence. Now that the technology is getting more mature and technological structural aspects are stabilized, more can be done respecting the systems' sustainability and aesthetical characterization.

It was understood that a high dosage of cement is used in 3DPC mixtures in order to provide printability. It was observed that supplementary cementitious materials are used in order to reduce the cost and increase the performance of 3DPC. Furthermore, minimizing cement consumption promotes the production of a more sustainable material. on a laboratory scale, it was observed that the fineness of the materials, especially the aggregates, is limited. This is due to the size of the extrusion nozzle, the most used being small. In addition, larger particles could degrade the nozzle. 3DPC mixtures should have different rheological behaviors during and after extrusion. The inclusion of some materials (limestone filler, VMA, nanoclays, blast furnace slag, and others) can improve the printability and this can and should be validated with tests, both in the fresh and hardened state. SCMs are suitable alternatives for developing sustainable cementitious materials in the longer term. To ensure sustainability and contribute to the circular economy, the focus should be on investigating the use of geopolymer, gypsum, earth, recycled aggregates or waste materials in 3DPC mix design.

For characterizing the fresh properties of printable cementitious materials during the extrusion processes, methods like flow-table, slump-flow, v-funnel, vicat, rheometry tests can be employed. In addition to qualitative visual essays. In the hardened state, the compression performance is the most referenced.

There are several strategies to develop a more sustainable 3DP mortars. However, the requisites and properties must be fulfilled to pledge its printability. This study features the most important printing properties, methods and laboratory tests to evaluate those properties, as well as the most used constituents. For a good printing, the mortar's constituents and the geometry of the structure to be printed need to be adapted to the characteristics of the printing process, providing a better structural and aesthetic performance.

The use of texture as a final finish has been clearly used in 3D printed structures with soil and clay-based materials. The companies TAM and Bruil have examples of texture and colour studies in 3D printing with concrete, however, this concern is not yet evident in many of the constructions already printed with this material. The lack of this type of studies creates the opportunity for architects, designers and engineers to explore texture as a mark of the construction process in the materiality of the structure.

3D printing can be a vast field for the application of biomimicry in architecture at scale of new materials development mainly. 3DPC can bring design and the production process closer together, creating identity, identifying new ways of exploring architecture.

Despite the printing of several buildings, 3DP is not yet a competitive option in the construction sector, not only for economic reasons, but also for its limited plastic options and weak building and environmental performance. The additive manufacturing could enhance the pre-fabrication industry to answer the market high demand for customizable products. To provide this, shape, colour and textures customization can be provided not only from raw materials but also by the industry's leftovers or Construction and Demolition Waste from working sites.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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