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Review

Foam 3D printing for construction: A review of applications, materials, and processes

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ABSTRACT

Large-scale additive manufacturing for construction has gained momentum during the last two decades as a promising fabrication technology that can save materials, labor, and costs. Although foams are a significant material group in construction and explored in 3D printing (3DP) studies, no comprehensive review about this field exists to date. Consequently, the aim of this review is to define the field of foam 3DP (F3DP) in construction and provide an overview of relevant developments, challenges, and future research. Based on the analysis of more than 150 peer-reviewed articles and research reports, three major themes within the academic debate about F3DP could be identified: developments in material composition and material design, printing and processing technologies, and future challenges in application and material processing development. This review brings together promising advancements in F3DP for construction into a systematic overview and opens new horizons in research and development for sustainable construction processes.

1. Introduction

Large-scale additive manufacturing (AM) has become an increasingly researched field in architecture and construction engineering during the last two decades. Various review articles systematically presented the state-of-the-art, challenges, and future developments in this novel area of research [1–5]. Most advancements are documented in 3D printing (3DP) of cementitious materials, such as contour crafting and concrete 3DP. The latter dominates this research field and shows great potential for reducing waste and add value in construction through the formwork-free production of high-quality, multi-functional building components [6] and particularly through the optimal use of material in complex geometries [7]. To advance concrete 3DP further, the core interest in current studies focuses on printing systems and material design [8].

The motivation behind these research efforts are associated with the need for lean and sustainable construction, which refers to a more resource-efficient and environmental-friendly way of building [9]. However, universal statements about the degree of sustainability of 3DP technologies are debated among scholars and accurate assessment frameworks thereof are not yet sufficiently developed [10]. The applicability of construction 3DP in large building projects, the life cycle performance of printed building elements and their actual demand in mass-customized production remains uncertain [4].

More importantly, many reviews and empirical studies in construction 3DP emphasize the limited availability of suitable and sustainable printing materials. Labonnote et al. highlight that the dominant focus in research on concrete and more specifically on load-bearing properties of printing materials leave out many other critical aspects linked to the domain of building physics, such as insulation and vapor permeability [3]. Further efforts must be undertaken to develop new materials and 3DP processes that allow the fabrication of non-homogeneous building elements with differentiated material properties beyond structural strength.

This review addresses construction 3DP with another group of materials closely linked to sustainability in construction. Porous building materials with controlled densities, often in the form of solid foams, are particularly suitable for multi-performance applications, such as lightweight and energy-efficient construction. Despite their vast use in construction there exists only limited research about 3DP processes of foams in construction and no comprehensive overview and critical evaluation to date. Therefore, the aim of this review is to define the field of construction 3DP with foams and collate related work, challenges, and developments that are significant for future research. Ideally, it serves as a

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point of departure for exploring novel approaches to construction 3DP and an advancement of innovative material and fabrication systems.

1.1. *Methodology and structure*

In this review, foam 3D printing (F3DP) refers to any AM process that is relevant for construction and creates solid objects with cellular microstructure after consolidation. This can be achieved through the selection of the printing materials and the processing route or the design of printed micro-geometric features such as porous scaffolds [11], cellular lattice structures [12] or sparse infill patterns [13]. This review does not specifically cover these geometric strategies for 3D printing foam-like structures from arbitrary materials, although some of the presented studies make use of them. Instead, this review is grounded on the history and use of foams as a highly relevant material group in construction and focuses on AM with foams that result from specific material processes.

The first part of this paper provides a systematized overview of the significance of foams for construction 3DP. More specifically, this is achieved by contrasting the conventional use of foams in construction and resulting application challenges with the potential for fabrication automation and resource-efficient buildings through F3DP. The second part of this paper discusses the main challenges and questions in the field of F3DP, which were identified in an extensive literature analysis.

The literature used in this review originates from the domains of architecture, engineering, and material science. The analyzed publications cover more than 150 articles from conferences, peer-reviewed journals, book chapters, patents, and web pages that date from earliest 1989 with the majority being published between 2010 and 2021. The analysis synthesized three major debates in the literature about F3DP: developments in material composition and material design, printing technologies, and future challenges in application and process development. These topics are discussed in depth before all findings of this study are summarized in a conclusive outlook.

2. Foams in construction

In contrast to other material groups in the field of construction 3DP, foams have been used rather scarcely and no holistic understanding of their application in this field exists. To identify the role that F3DP could play in construction, this section covers conventional application methods with foams in construction today. An analysis on their shortcomings and challenges further expands the motivation to advance this area of construction through technological development.

2.1. *Conventional application methods*

Foams in construction are mainly used as insulation material due to their low thermal conductivity. Consequently, they play a significant role in reducing the operational energy consumption of buildings. Thermal insulating materials can be distinguished between their inorganic and organic types of raw source materials and their natural or synthetic processing [14]. The use of natural foam-like materials as insulation already dates back to our Neolithic ancestors, who cladded their dwellings with soil containing porous rocks such as clay and pumice. However, by the beginning of the 20th century a new group of synthetic organic materials revolutionized the building industry, commonly known as plastic foams [15].

Today, synthetic organic foams such as polystyrene (EPS, XPS) and polyurethane (PU) represent more than 41% of the European building thermal insulation market [16]. Also inorganic synthetic foams are available in various forms as insulation materials such as aerated concrete, cellular glass, foamed glass, calcium silicate foam, expanded perlite, and expanded clay [17]. Nonetheless, organic synthetic foams dominate the construction market due to their low cost and outstanding performance. Many natural materials such as wood wool, cellulose, hemp and flax are celebrating an industrial comeback, however they are not as performant as their synthetic competitors especially regarding their durability [18]. Typical applications of foams in construction are structural and non-structural insulated building elements that are subject to heat losses, such as internal and external walls, floors, and roofs. Moreover, foams are used as lightweight filling material and temporary or stay-in-place functional formwork.

2.2. *Shortcomings and challenges*

The most common way foams are used in construction, is in prefabricated elements such as insulation boards and modular blocks (Fig. 1a), sandwich panels (Fig. 1b), and custom-made elements (Fig. 1c). Additionally, they are also extensively used in on-site applications such as casting and spraying (Fig. 1d). Depending on the specific use-case, the processing route has a significant impact on construction efficiency and geometric properties of the foam element.

Insulation boards for example are prefabricated foam elements that can be made from organic foams such as EPS and XPS as well as from inorganic mineral foams. They are typically applied manually to load-bearing walls with mechanical fasteners or adhesives and can be covered with additional layers of coating, mesh, and finish render to form a unified exterior insulation finishing system (EIFS). In contrast, insulating concrete forms (ICFs) are modular formwork blocks made from organic foams for concrete casting and stay in place as lost functional formwork after the concrete has cured. Both applications are laborious, need to be handled by expert workers, and limit geometric complexity in custom structures.

Another example of prefabricated foam elements are sandwich panels, which were originally developed for cold storage in the 1960s [19]. They can be distinguished by the materials used for the foam core such as EPS, XPS or PU and the outer face layers such as concrete wythes or aluminum sheeting. Load-bearing concrete sandwich panels can be found today in commercial and residential buildings [20] and are produced in increasingly thin cross sections to achieve maximum insulation performance at a minimum spatial footprint and weight [21]. Sandwich panels are very effective multilayer composites which are produced in large sizes at very high accuracy. Their standardized nature though restricts geometric differentiation and makes any customization in the thermal envelope labor and cost intensive.

The last example of prefabricated foam elements are customized components that might be either used as temporary formwork for casting concrete into complex geometries or as building components, for example in facades [22]. Subtractive processes such as robotic milling and hot-wire cutting are used to produce tailored foam parts and significantly reduce costs compared to traditional machining methods. Moreover, robotic hot-wire cutting can achieve up to 80% reduction in machine time costs compared to CNC milling and therefore exhibits a greater production capacity [23]. However, customized foam components as temporary formwork for concrete are discarded after use and represent a significant volume of waste in the construction industry. Moreover, customized foam components in façade applications need to be surface treated for impact and weathering resistance, which makes their production very labor and cost intensive.

On-site applications such as casting and spraying differ from the previous examples in so far as the foam is created on the construction site and requires formwork or a substructure for application. Mineral foam and foamed concrete are used to cast monolithic wall and slab elements that exhibit a balanced relationship between moderate compressive strength and low thermal conductivity [24]. The requirements for the formwork are particularly high for water content and temperature control, which makes the on-site application laborious and dependent on highly skilled workers [25]. Similarly, spray insulation with expanding PU foam offers the possibility of fast on-site retrofitting and repair of geometrically complex thermal envelops but requires a high share of manual labor that is exposed to toxic fumes of the chemical

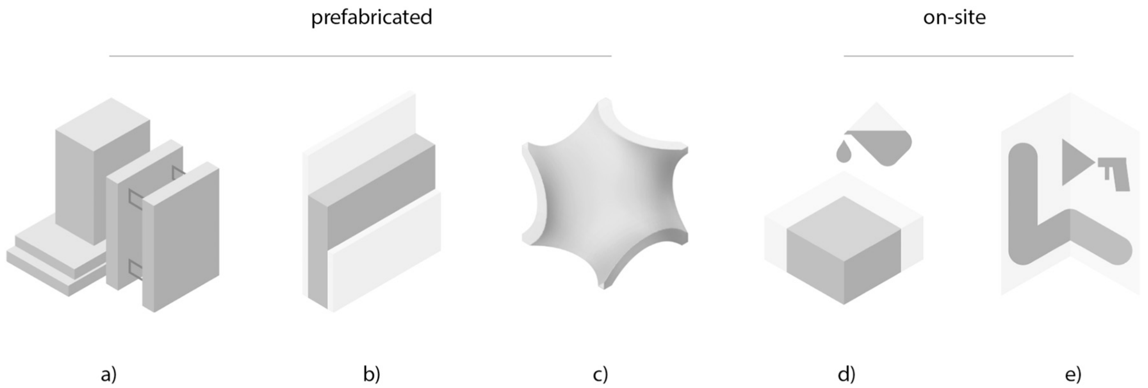

Fig. 1. Typical application methods for foams in construction. a) Boards, blocks, and forms, b) sandwich composites, c) custom milled forms, d) in-situ casting, and e) on-site spraying.

blowing agents. Expanding PU foam is also commonly used as sealant for manual application around windows and doors [26].

Major disadvantages of current application methods for foams in construction are either rooted in their serialized prefabrication or labor-intensive on-site processing. The first creates strict geometric limitations in standardized modules and prevents site-specific differentiation of foam elements in one-off construction projects. This leaves the potential of customization and material savings through locally optimized structures unexplored. On-site processing on the other hand is characterized by an inherently higher demand for skilled labor and relies on substructures and formwork, which produces unnecessary waste and increases construction costs.

3. Foam 3D printing

F3DP refers to AM processes that create solid objects with cellular microstructure. AM offers a lot of opportunities to the construction sector that can be transferred to building elements and processes using foams. In contrast to other fabrication processes, 3DP allows to materialize complex geometries without the need for formwork and production specific tooling. This has a significant impact on increasing material, labor, and cost efficiency. This section shows the advantages of 3DP in general and how specifically F3DP can be used differently than conventional application techniques. Furthermore, the chronological development milestones of F3DP are presented.

3.1. Advantages and benefits

The geometric complexity offered by 3DP enables the design of freeform building elements that are impossible or unfeasible to produce with other techniques [3]. This paves the way for a much higher degree of customization at no extra cost and enables unprecedented architectural details at building scale [27]. F3DP can extend the geometric design space of modular foam elements under light to moderate structural load such as boards, blocks and sandwich elements and make them suitable for a broader range of architectural freeform envelops. Especially construction projects with smaller quantities of custom foam elements can greatly benefit from the cost-efficiency of this approach.

Another difference of 3DP to conventional application techniques, is that geometric freedom allows to design building elements with well-established computational optimization processes which result in intricate shapes. A common type of optimization in manufacturing is topology optimization (TO) [28]. In this approach the material distribution in a given design space with defined loads can be optimized for specific goals such as minimizing weight and maximizing stiffness. Key algorithms to achieve this have been discussed [29] and their suitability for AM critically evaluated [30].

The potential of combining TO with large-scale 3DP for construction has been demonstrated by manufacturing the mold for an optimized geometrically complex concrete slab with binderjet printing and resulted in the use of 70% less concrete when compared to a conventional slab geometry [31]. Another project showed the applicability of TO on a segmented girder structure which was directly fabricated using concrete 3DP [32]. F3DP would enable innovative building elements with optimized shapes which are lighter and more material efficient. Specifically for F3DP an approach could be followed that uses multi-material TO with simultaneous thermal and structural optimization [33].

Furthermore, 3DP facilitates the integration of subsystems through geometric complexity without extra cost. Interface details, distribution channels and complex internal patterns can be easily provided for HVAC, water, lighting, fire prevention and other networked systems. Thus, by using F3DP, building elements in the thermal envelop and lightweight interior partitions can be manufactured with a higher degree of functional integration in contrast to conventional techniques, which rely on standardization.

Another key advantage 3DP offers to construction is associated to the absence of any formwork. This plays particularly a role in concrete structures, where formwork can result in 35–60% of the total concrete work cost [34]. Most importantly, concrete formwork is almost always made of foam for geometrically complex building elements, because it is easily machinable. The resulting amounts of waste from conventional subtractive machining processes can be avoided using F3DP for formwork production.

As a last point of great relevance, 3DP is an automation approach which can increase labor and cost efficiency and improve workers safety [2]. The evaluation of cost-effectiveness of AM is a complex assessment, since it also needs to account for comprehensive supply chain effects such as inventory and transportation costs [35]. However, a shortened supply chain and production on demand is significant in construction with limited lot sizes of building elements and production requirements that are unique to every project. In this case, F3DP can create added value in construction through the manufacturing of high-quality bespoke products which are impossible with any other technique.

3.2. Chronological development

Table 1 gives a chronological overview of experimental projects of large-scale 3DP with construction foams and indicates who conducted the study, which application method was employed, which application type was targeted, which printing material was used, and if print support structures were employed for increased geometric complexity. The very first experiments date already back to 1963. For instance, the University of Michigan in collaboration with Dow Chemicals demonstrated an XPS-based additive manufacturing system for a dome structure measuring 13.7 m in diameter [36]. Furthermore, in 1970 Bayer AG developed a rapidly deployable PU spray foam platform for relief housing after a

Table 1
Overview of precedent research in large-scale 3DP of construction foams.

Year	Author	Institution	Method	Application Type	Print Material	Print Support
1963	Dow Chemicals	University of Michigan	Extrusion from automated rotation boom	Roof structure	XPS	No
1968	F. Drury	Yale University	Manual Spray Foam on inflated temporary Support	Pavilion	PU	Yes
1970	Bayer AG	German Red Cross	Spray Foam on inflated temporary Support	Disaster shelter	PU	Yes
2007	Gramazio Kohler	ETH Zurich	Robotic Extrusion	Acoustic panel prototype	PU	No
2011	D. Pigram, W. McGee	TU Sydney, Univ. of Michigan	Robotic Spray Foam	Study exercises	PU	No
2011	P. Tighe	Sci-Arc Gallery	Manual Spray Foam & Robotic Milling	Spatial art installation	PU	Yes
2013	S. Keating, N. Oxman	MIT	Robotic Spray Foam & Machining	Dome prototype	PU	No
2015	E. Barnett, C. Gosselin	University Laval Quebec	Robotic Spray Foam	Sculptural prototype	PU, shaving foam	No
2017	B. Furret et al.	University of Nantes	Robotic Foam Printing	lost formwork for single-storey small house	PU	No
2017	E. Lublasser et al.	RWTH Aachen	Robotic Application of Foam Concrete on Walls	Thermal reinforcement of existing walls	Foamed Concrete	Yes
2019	V. Mechtcherine et al.	TU Dresden	Extrusion with robotic boom	Monolithic thermo-structural walls	Foamed Concrete	No

devastating earthquake in Gediz, Turkey.

Around the 2010s, academic research in digital fabrication started to revisit the early automation experiments of half a century ago. Pigram and McGee at the University of Michigan used PU spray foam deposition with a 6-axis industrial robot arm to print experimental building components [37]. Gramazio Kohler experimented with robotically sprayed PU foam for acoustic elements at ETH Zurich in 2007 (Fig. 2a). Moreover, Tighe designed and fabricated an immersive installation made of robotically layered and milled PU spray foam for the Sci-Arc Gallery in 2011. Another example at the University of Laval proved the printability of 2-component PU spray foam employing a cable-suspended robot and shaving foam as temporary support material [38].

Arguably the largest structures built with F3DP to date are the works of Keating [39,40] (Fig. 2b) and the BatiPrint project from the University of Nantes [41,42] (Fig. 2c). Both examples feature mobile robotic platforms for in-situ spray deposition of expanding PU foam (Fig. 2). Keating demonstrated a 14.6 m wide, double-walled, open dome structure, which was effectively printed in 13.5 h. The researchers in Nantes instead created molds for concrete casting of a 95 m^2, five-room house in about 54 h [43].

Latest research in F3DP for construction investigates the use of inorganic materials such as aerated concrete or ceramic foams. As a popular porous building material, foamed concrete was used in a robotic 3DP process, with the aim of insulation improvement of existing walls [44] (Fig. 3a). Furthermore, the potential for insulating façade elements motivates further research in improving material properties and the 3DP process for layered freeform construction [45]. Foamed concrete was also used for 3DP of monolithic walls that are insulating and sufficiently strong in compression, to be used as load-bearing structure [46].

Another approach of AM with porous concrete was achieved in layered spraying with varying lightweight aggregates [47]. Here the main objective was the fabrication of functionally graded concrete structures, with spatially varying material properties for a specific design case, e.g. structurally optimized, lightweight beams. For the first time this study showed the feasibility of this technique in an unprecedented scale that is relevant for construction. Functional gradation in foamed concrete was shown previously in smaller studies with graded porosities through foaming agents [48].

At a smaller scale, novel cement-free ceramic foams with unprecedented strength-to-weight ratio and tunable pore sizes were used for 3DP. Hierarchical porous ceramics were successfully tested in an extrusion-based printing process called direct ink writing (DIW) and resulted in differentiated layered lattices [49] (Fig. 3b). In a similar approach, researchers 3D-printed architected cellular ceramics with tailored microstructure, geometry and resulting mechanical properties that span over an order of magnitude [50] (Fig. 3c). The first study that used 3DP of cement-free ceramic foams for a construction scale application combined it with ultra-high-performance concrete in a lightweight composite façade shading panel [51].

4. Materials for foam 3D printing

Foams are a special class of composite materials, in which one of the components is a gas finely dispersed in an immiscible continuous phase. Foams are high surface area systems and therefore intrinsically thermodynamically unstable. To minimize the overall energy, a non-

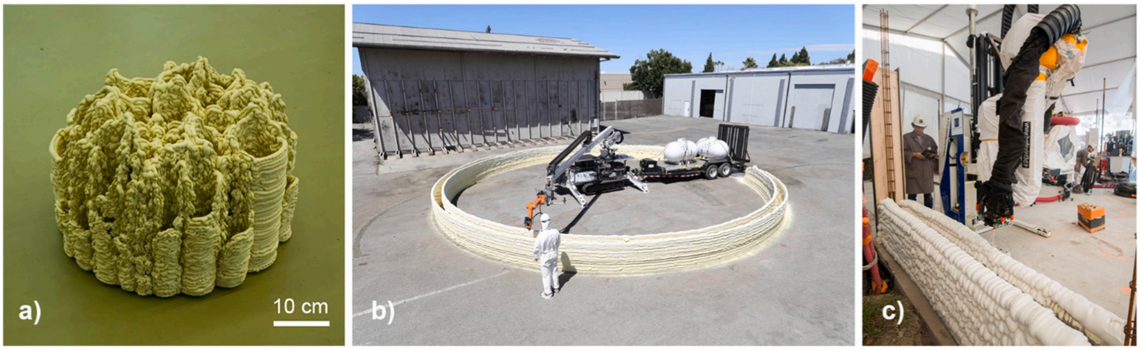

Fig. 2. 3DP of organic foams. a) for acoustic interior elements [52], b) lost formwork for dome structures [39], c) and social housing units [41].

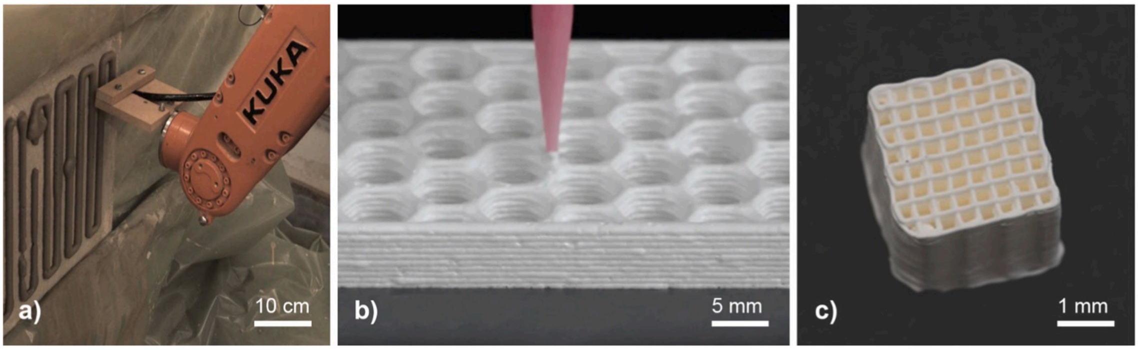

Fig. 3. 3DP of inorganic foams. a) foam concrete printed onto walls [44], b) and c) porous ceramics printed into 3-dimensional lattices [49,50].

properly stabilized system will eventually phase separate. A foam is considered stable if its density and microstructure remain unaltered within the considered time lag. The foam stability can be linked to the applied flow profile [53]. The latter can induce rearrangements in the microstructure increasing the collision event among bubbles, break liquid-air interfaces and overall speed up phase destabilization phenomena.

This point is particularly important for printing strategies where foams are subjected to shear forces. Additional source of instability can be induced by oscillatory deformations (e.g. vibrations) leading to shear thinning behavior and thus implying higher chances of foam drainage. Since foams are compressible materials, an excessive load can destroy bubbles. This pressure-associated stability must be considered when designing a layer-by-layer build-up of the 3D printed foam structure. If not supported by a strengthening contribution coming from the continuous phase, load-induced foam collapse can take place.

The nature of the continuous phase, the foam density, the bubble size, and the bubble morphology determine the final foam properties. These are also connected to the choice of the foaming method. In fact, many different strategies exist to introduce gas in a material. Depending on the nature of the continuous phase, the target bubble morphology, properties, and application, different foaming techniques can be used [54,55].

Direct blowing techniques are to date the most suitable for extrusion-printing and spray-printing. These foaming techniques can be divided into three categories: mechanical, physical, and chemical blowing. In mechanical blowing, air is incorporated by vigorously mixing the selected matrix with the gas. Alternatively, blowing agents are used which expand either upon decompression or react chemically releasing a gas. Typical blowing agents are nitrogen, carbon dioxide, water, air, pentane, hexane, dichloroethane and Freon [56].

A further method to create porous materials is the use of a sacrificial template that can be dissolved or burned out at a subsequent stage [55]. However, this approach requires an additional step and often leads to lower porosities as compared to the methods using blowing agents. In principle, the success of the foaming strategy does not rely on the chemical nature of the starting matrix. In practice, physical and chemical blowing are the most used for organic foams, while for inorganic materials chemical and mechanical blowing are typically the methods of choice [56–58].

In the following sections, possible foaming strategies for large scale 3DP are described for organic and inorganic foams. The suitability, the challenges, and opportunities of organic materials for F3DP are discussed, and the potential of different inorganic materials for F3DP is presented.

4.1. Organic foams

In organic foams, the continuous phase entrapping the gas is organic in nature, most commonly a synthetic petrol-based polymer. Typical matrix polymers used in industry are poly-urethane (PU), polypropylene (PP), phenolic polymers, and polystyrene (PS) [63]. These synthetic polymeric materials have inherently a low density and are mostly amorphous, making them suitable as thermal insulators.

Recently, many efforts were spent in optimizing their microstructure reaching even better insulating properties [64,65] (Table 2). Additionally, the experience acquired over the last 90 years in processing them, and the possibility to tune their properties depending on the application make them very attractive materials. Besides low thermal conductivities and sufficient mechanical strength, another important aspect to be considered in view of F3DP is the shrinkage behavior of organic foams during their processing and lifetime.

Materials for F3DP should ideally have minimal shrinkage, as it would result in an undesired reduction in porosity and is often source of cracking when not homogeneous. Therefore, the presence of significant shrinkage might pose limits on the design freedom of 3D printed structures. In case the dispersed phase is not effectively trapped in the matrix prior setting, the foam might shrink or even collapse.

Foam collapse can usually be avoided by tuning the composition and processing parameters [66,67]. While post-foaming shrinkage can be significant in elastomeric foams, it is less problematic in rigid polymeric foams, in which the degree of crosslinks is high enough [68,69]. However, most commonly used matrix polymers might undergo significant shrinkage if exposed to higher temperatures during their lifetime. In addition to the instability to high temperatures of organic foams, their most severe disadvantage is the intrinsic flammability.

Alternatively, other organic-based insulators are natural fibers such as straw, hemp, or typha. These are low cost and low environmental impact raw materials. However, their insulating capabilities are limited [70]. Consequently, to match the required thermal performances thick walls are needed. As compared to synthetic polymers, issues as durability, corrosion resistance, fire resistance, water vapor permeability, and fungal resistance remain unsolved [71]. Additionally to their lower durability and lower performance, the low environmental impact of natural sourced materials is strictly connected to their local availability [71]. Consequently, scalability can be a challenge in the case of natural resource-based materials.

4.1.1. PU foams

A scarce amount of literature is available describing F3DP of natural fibers. Oppositely, synthetic organic foams have shown to be very promising, as many large scale 3DP projects used expanding 2 component PU foams (see Table 1). In particular, the two main components of PU are multivalent isocyanates and polyols. These are blended with a catalyst and surfactants. The detailed chemical nature of both components may vary significantly. Depending on the chain length and the number of functional groups able to crosslink, mechanical properties, such as stiffness and strength, can be tuned significantly [72]. As a result, PU foams cover a wide spectrum, that ranges from soft sponges to hard wood-like foams.

Table 2
Typical material properties of construction foams.

Name	Type	Density kg/m^3	Thermal Conductivity W/mK	Compressive Strength kPa	Flammability DIN 4102	Reference
Polyurethane (PU)	Organic	30–100	0.024–0.030	20–30	B1, B2	[14]
Extruded Polystyrene (XPS)	Organic	28–45	0.027–0.036	300–700	B1	Austrotherm [59]
Expanded Polystyrene (EPS)	Organic	11–32	0.029–0.034	120	B1	Swisspor [60]
Foamed Glass	Inorganic	150–230	0.070–0.093	160	A1	[14]
Cement Foam	Inorganic	70–500	0.040–0.120	30–4000	A1	Airium [61]
Silica Foam	Inorganic	90–115	0.042–0.047	200–350	A1	Ytong [62]

In addition to the choice of the detailed chemistry, the amount and morphology of the gas phase is also a factor determining the final properties [66]. In the case of PU, isocyanates can react with water under release of CO_2. The released CO_2 is entrapped in the polymeric matrix forming a foam [72]. PU foams can be formed in-situ by mixing the two components and depositing the expanding mixture on the desired surface. The curing time for commercial products is typically within minutes and can be tuned. The potentially short curing time of PU foams is of advantage for 3DP, as often a fast strength buildup is required.

PU is a heavily used material in the construction industry; therefore, much experience was gained over the years and its durability and reliability could be demonstrated. It is easy to use, has high performances, tunable properties, and a fast and adjustable curing time. Consequently, there are many showcases where PU foams have been used for large scale 3DP [39,41]. However, challenges connected to the processing and to the material's nature remain unsolved. The resolution of extrusion based 3DP is determined by the filament size and its ability to retain its shape [73]. In the case of expanding PU foams, the material expands after deposition resulting in an unavoidable loss in resolution. This can be fixed by subtractive post-processing after printing such as milling [40].

A core problem that most organic foams have in common is their flammability and tendency to spread fires in buildings. Therefore, flame retardant and smoke suppressive additives are added [74]. This has an impact on their price, sustainability and sometimes toxicity [75]. In addition to the toxicity of fumes released when burning, it is common knowledge that isocyanates are toxic, and therefore PU foams can be considered as non-toxic only after complete curing of its precursors which makes their handling more complex.

In Switzerland it has been estimated that all plastic-based insulating materials installed between 1980 and 2015 contain brominated flame retardant (HBCD for polystyrene and PBDE for poly-urethane) [76]. These chemicals have been classified as a persistent organic pollutant and their production and use is forbidden [77]. Therefore, plastic-based insulators installed before 2015 cannot be recycled without a dedicated purification procedure to remove the hazardous chemicals from the insulation material. Consequently, only a negligible amount of the plastic-based insulation is currently recycled.

4.1.2. Opportunities for improvement

A recent modeling of the building stock evolution underlines the crucial role played by insulation materials. In particular, it has been predicted that the energy embodied in the production of conventional insulation materials will control the environmental impact of buildings [78]. Possible pathways to overcome this impasse have been proposed. In fact, the environmental impact of the building's insulation materials can be reduced through either increased recycling (−30%), replacement of oil-based materials (−32%), or more efficiently a combination of both (−44%) [79].

As alternative to the combustion for energy recovery, mechanical and chemical recycling strategies have been developed and are being constantly investigated. In the former, polymeric foams are mainly grinded into small particulate that is shaped and held together by a binder, while the latter relies on chemical processes to recover monomeric units [80].

An additional pathway to reduce the accumulation of waste is based on biodegradable and bio-based polymers. The former can even be achieved via microbially assisted degradation of organic foams. Both the chemical and physical properties of the polymer and the degradation conditions play an important role in the effectiveness of the microbes [81]. PBS, polyester based PU, PCL and PLA are examples of biodegradable polymers. Even though a large portion of bio-based polymers are also biodegradable, this is not always the case [82]. The main advantage of biopolymers lies in the fact that they are derived from renewable resources. Conversely, the majority of the polyols and isocyanates that are used to produce PU foams are derived from the petrolchemical industry.

Considering that oil is a finite resource, the search for alternative renewable and sustainable sources of polyols and isocyanates for polyurethanes has been pursued in the last years. In this regard, research in the chemical production of polyols from natural (e.g. vegetable oils) or recycled resources (e.g. PET and PU) has shown that petroleum-based polyols can be in part replaced [83,84]. Whereas bio-based polyols have been already scaled up to an industrial level [80], bio-based isocyanate sources are yet only a research topic and at an industrial scale most of them are still petroleum-derivatives [85].

Alternatively, research on cellulose-based nanostructured materials has shown promising results [86–88]. However, the processing includes freeze drying which makes these materials hardly scalable to the volumes required for construction applications and to 3DP. Despite the potential of bio-based and biodegradable polymer to reduce the environmental impact of construction materials, challenges connected to their price, mechanical properties, durability, and processing conditions remain unsolved [82].

4.2. Inorganic foams

In contrast to organic foams, all inorganic porous materials with negligible amounts of organic compounds are intrinsically nonflammable. Their flame-resistance strictly depends on the melting temperature of their components. In case of ceramic-based materials, it can easily exceed 1000 °C. Additionally, the use of inorganic materials allows to further decouple the growth of the building market from oil-based raw materials, conventionally associated to a high carbon footprint. Remarkably, the granular nature of inorganic solutions and the absence of persistent organic pollutants in their formulations simplifies their full recyclability. This last point is of great interest in a sector like construction, where only a small portion of materials is reused and recycled [79].

As for inorganic bulk materials, ceramic foams may be subjected to shrinkage upon drying. This is due to the capillarity arising between the foam building blocks upon the medium evaporation. The shrinkage stops when a sufficiently strong percolating network is formed within the sample [89,90]. The same line of thinking can be applied for foams. In this case, shrinkage stops when the foam skeleton is able to withstand the capillary pressure. For non-self-hardening systems (e.g. silica particles in aqueous medium) this is obtained when the colloidal particles in the foam wall form a closed-packed network [91]. For deformable bubbles (negligible interfacial rheology), bubbles can accommodate the macroscopic dimensional changes of the foam. Systems involving hydration products can form structures within the foam walls able to resist the action of the capillary forces and they may even suppress any dimensional changes [92]. As for any hydration process, autogenous shrinkage must be taken into consideration in the overall shrinkage analysis.

Hereafter, we propose examples of inorganic porous solutions mostly adopted in construction indicating their nature, state-of-the-art, and potential for F3DP.

4.2.1. *Concrete foams*

Foamed concrete is a porous cementitious material with a cellular structure obtained by the incorporation of air into mortar or cement paste [93–95]. It is deeply connected with the advent of air-entraining agents [93]. Different density levels have been proposed in literature spanning from 200 to 1900 kg/m^3 (concrete usually has a density of ~2500 kg/m^3). On an industrial scale, two main mechanisms are applied to introduce large volumes of air into the cementitious mixture. The first route relies on the use of gas-releasing agents such as aluminum powder that reacts with alkaline hydration products [58]. This process is at the base of autoclaved aerated concrete [96]. The properties of the latter can be considerably improved by autoclave high-pressure steam curing. This additional step greatly improves the properties of the material, but it also limits the versatility of these formulations.

Alternatively, the pre-foaming method is used. In this case, the foaming agents are used to prepare a wet foam that is subsequently intermixed with a separately formulated cement paste [57,97]. This method enables to target the desired density by blending the required amount of the foam to the base mixture [98]. Foam concrete has a lower thermal conductivity (~0.065 Wm^{-1} K^{-1} at ~250 kg/m^3) compared to regular concrete (~0.5 Wm^{-1} K^{-1}) [98]. This makes it possible to decrease the use of further insulation materials [79]. The possibility to reduce or even avoid extra insulation layers may significantly cut the time for transport and mounting on the construction site [57].

Despite the low cost and production scalability, the main downside of cement concrete is connected to the cementitious nature of the starting materials and therefore the unavoidably high CO2 emissions embodied in the final foam. A possible way to reduce the amount of cement consists in using blends [99–101]. Interestingly, an emerging research avenue takes advantage from the printability of foam concrete [57]. In particular, a protein foam has been mixed with a CEM II/A-M paste containing fly ash as secondary cementitious material (pre-foaming technique) and extruded with either a cavity pump or a 3D concrete printing device. This unchartered research line aims to expand frontiers for 3DP applications, while fulfilling both load-carrying and insulating functions. This new field is particularly challenging since it combines the technological hurdles associated to the printability of foams [50] and yield stress evolution required for the cement-based inks [102,103].

4.2.2. *Geopolymer foams*

Geopolymers form semi-crystalline 3D inorganic networks that are generated by the dissolution and reaction of a solid alumino-silicate source with an activating solution [104,105]. Interestingly, geopolymer foams have been the focus of a significant body of work in the field of porous inorganic materials because of their technologically promising combination of thermal and chemical stability, with excellent mechanical properties [106,107], low CO_2 emission and low energy use in their manufacture [108]. In fact, compared to the traditional ceramic processing routes, the use of geopolymers typically does not require any sintering or high temperature heat treatment steps. In general, sintering is a high energy step. At the same time, the synthesis of GP reactants is associated to marked environmental impacts. Therefore, only the exact formulation and processing parameters are eventually defining the ultimate environmental impact [109].

Porous geopolymers are typically fabricated via 4 main processing methods, namely: 1) direct foaming, 2) replica method, 3) sacrificial filler method and 4) additive manufacturing. Interestingly, each processing influences the bulk density, porosity, morphology, mechanical properties and thermal conductivity of porous geopolymers [105]. They are typically applied as catalyst supports or membranes, filtration units, adsorption and insulation materials [110–112]. Interestingly, the geopolymerisation reaction naturally involves a gelling phase which can be used to retain the shape of the wet material. This feature is pivotal and can be successfully used in case of additive manufacturing [113].

4.2.3. *Aerogels and sintered ceramic foams*

Among the inorganic porous materials, aerogels have become particularly popular as an alternative to conventional insulators due to their extremely low thermal conductivity and fire-resistance [114–117]. The remarkable insulating properties of aerogels mostly originates from their almost exclusive nanoscale porosity commensurable with the mean-free path of air (Knudsen effect). Depending on the overall porosity and pore size distribution, aerogels can show a thermal conductivity even lower than the one of air, i.e. lower than 0.026 Wm^{-1} K^{-1} [116]. For a detailed explanation of the physics ensuring the properties of aerogels we redirect the interested readers to specific literature reviews [116,118]. For these reasons, aerogels represent the cutting-edge in construction insulation.

Despite their exceptional performance, the multiple steps required for their fabrication are reflected in high costs and low production capabilities which are limiting their wider applicability. Additionally, to the knowledge of the authors, there is no evidence proving their production via additive manufacturing.

A possible way to tackle those issues consists in blending aerogels with a water based mineral binder, e.g. cement free plasters [118,119]. In this way, aerogels are used in form of granules and effectively applied as performance increasing agents. This utilization has become more popular than monolithic analogues due to lower costs. The use of aerogel granules in cementitious composites allows their printability. Nevertheless, only highly hydrophobic aerogels can be used in construction to ensure appropriate hygrothermal behavior of the final material. For this reason, coupling agents are needed allowing the blending in water-based binders. Those compounds are conventionally used in concrete technology as air entrapping agents and therefore they compromise both thermal and mechanical performances. Despite the intrinsic technological advantage offered by aerogels, their actual implementations are expected to lack the performance-to-cost trade-off [116].

A very promising way to combine non-flammability and the thermal performance of aerogels with the scalability and production flexibility of organic solutions is represented by inorganic foams [55,120–122]. They have been initially proposed using ideal colloidal suspensions composed by man-made and monodispersed nanoparticles eventually hardened via sintering. This combination of material choice and consolidation strategy reduces drastically the large-scale production and raises the costs considerably. Nevertheless, they have been proven to be suitable for 3DP [49,50].

5. Technologies for foam 3D printing

AM encompasses a broad range of process technologies from which only few are suitable for the use in large scale and with foam materials. This section provides an overview of three possible processing candidates, namely extrusion-printing (Fig. 4a), spray-printing (Fig. 4b) and binder jetting (Fig. 4c). They are briefly introduced with their definition, and details about their invention and applications in small and large scale are presented. Furthermore, their suitability for F3DP in

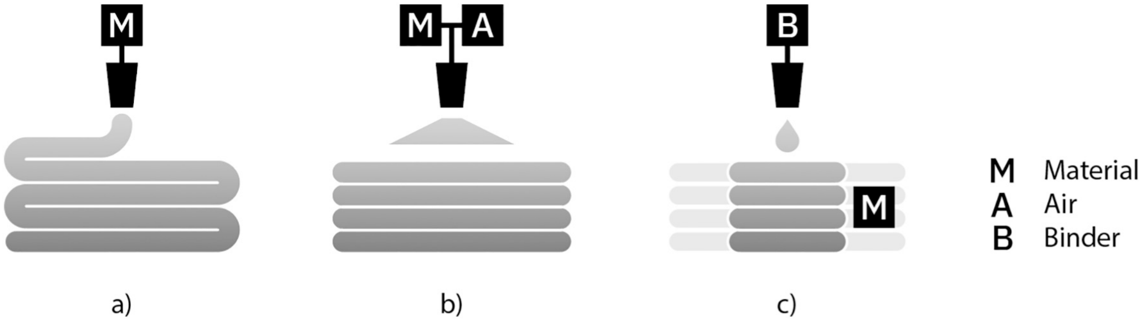

Fig. 4. Schematic illustration of 3DP processes for foams. a) Extruding, b) spraying, c) binder-jetting, whereas M stands for material, A for air, and B for binder.

construction is highlighted as well as their advantages and disadvantages.

5.1. *Extrusion-printing*

In general, extrusion-printing describes the process of forcing a material through a nozzle and depositing repeated layers of solidifying material until the three-dimensional object is created. The process has its origins in a 3DP technique called Fused Deposition Modeling (FDM). It was first patented in 1992 by Scott Crump and later commercialized by the company Stratasys [123]. The patent already addressed the use of any self-hardening printing material such as waxes, thermoplastic resins, two-component epoxies, foaming plastics, and glass. Today, FDM with thermoplastic polymers is the most popular and distributed 3DP technique on the consumer market.

Consequently, it is no surprise that early construction 3DP implementations followed the same path and developed large-scale FDM techniques with thermoplastic polymers such as the KamerMaker project [124] and the company Branch Technology [125]. Furthermore, these first steps matured and offer today scalable solutions for the production of secondary façade elements [126] or rapid manufacturing of complex molds for casting [127].

Additionally, extrusion-based 3DP techniques were also developed for other materials and scales. Similar to FDM, ceramic Direct Ink Writing (DIW, also known as robotic material extrusion or Robocasting) employs highly loaded ceramic slurries. In this process a paste-like material is forced through small nozzles, measuring between tenths of millimeters to several millimeters and is built up in layers to form small-scale intricate objects and multi-material composites [128]. In manipulating the rheology of the ceramic pastes during printing, studies showed the potential of DIW to achieve unprecedented microstructures and bioinspired multi-material compositions [129].

At a larger scale, the technique of DIW is also popularized under the term clay printing. Since many printing systems for clay printing are commercially available, accessible low-cost or even open source, many researchers leveraged this technology for their studies in construction 3DP. Projects investigated robotic clay 3DP of non-conventional wall components with the aim of optimizing print performance in a parametric framework and increasing material and machine time efficiency [130]. Other researchers looked into robotic clay 3DP of functionally graded structures in using low-cost co-extrusion nozzles for extruding two different clay substrates simultaneously [131].

These foundational approaches of extrusion-based 3DP such as FDM, DIW and clay printing greatly influenced the research in large-scale concrete 3DP. Because they are all based on the principle of forcing the material through a nozzle, researchers could focus on adapting them to material-specific challenges such as workability, pumpability, extrudability, and buildability and their relationship to the geometrical design space of the print object [6].

The advantages of large-scale extrusion-based 3DP for construction are the wealth of precedent research in printing systems, printing quality and efficiency, suitability for various robotic manipulators and a separation between printing material preprocessing or reservoir and print head. Although in commercial applications the printhead is the most confidential component after material design, different design approaches are available online and in literature as good points of departure.

Another advantage is that extrusion-based 3DP can achieve high degrees of precision due to the control with nozzle diameters and resulting layer dimensions of up to 40 mm × 10 mm [6]. Very fast printing can be achieved in concrete 3DP with print speeds up to 180 mm/s [132] and produced parts need little to no post-processing. The suitability of extrusion-based 3DP for robotic arms, gantry systems and cable-driven robots makes it versatile in on and off-site operations.

Disadvantages of extrusion-based 3DP can be seen in the visible layered surface texture of printed artifacts due to the 2-dimenional topology of print paths. However, in many studies with large-scale extrusion the emerging patterns of layered toolpaths are specifically designed. Moreover, other approaches to this problem have been demonstrated with non-planar toolpaths [133] or the use of secondary subtractive processes to improve surface and interface details [134]. Extrusion-based 3DP is also more limiting for the creation of overhang structures, which can only be overcome with additionally printed support structures.

5.2. *Spray-printing*

The technique of spraying describes the distribution of an atomized medium with compressed air in small droplets over an area. Naturally, many conventional applications in the construction sector that target to cover larger surfaces use this technique such as spraying of paint and coatings, concrete, and PU insulation foam. Concrete spraying, which is commonly known as Shotcrete, was first invented by Carl Akeley at the Smithsonian Institution to spray on molds of animals in the museum in the early 1900's. By 1930 it was used as a tunnel construction technique in Iran and later in Europe [135].

Today Shotcrete is a standard technique in tunnel construction worldwide and many improvements were achieved on automation of the spraying equipment and the design of the material composition. However, also Shotcrete 3DP (SC3DP), matured recently in scientific and commercial advancements. Robotic SC3DP was developed for spraying on permeable glass-fiber mesh for creating thin freeform reinforced concrete elements [136]. Moreover, a larger freeform reinforced concrete wall was presented and proved a significant decrease in risk for cold joints as well as the possibility of printing horizontal cantilevers [137] [138] (Fig. 5a). Recently a startup emerged from this research efforts and offers fabrication service and equipment for SC3DP [139].

Spray-based 3DP using PU insulation foam for construction has been developed based on modifications of conventional equipment available for in-situ processing [39]. Based on this work, an implementation as large-scale fabrication method was demonstrated with an autonomous on-site robot featuring a large hydraulic boom with a smaller electric

Fig. 5. Spray-based 3DP examples. a) SC3DP of reinforced concrete components [138], b) robotic additive plaster spraying [142],c) drone robot spraying for earthen monolithic shells [141].

arm as end effector [140] (Fig. 2b).

The biggest advantage of spray-based 3DP over other techniques is the speed of production because the printing material is spread over a larger area. Layer dimensions of 80 mm × 35 mm at a print speed of 150 mm/s are documented with PU F3DP which result in a very high volumetric output of 1.7 m^3/h. Furthermore, with shotcrete printing a volumetric output of up to 1 m^3/h is achievable.

The remote location of the spray nozzle allows the integration of reinforcement prior to printing and reduces the risk of collisions of robot and print object. Spray-based 3DP can achieve horizontal cantilevers and the cured printing material exhibits a very high mechanical bonding between the print layers – both features are difficult or unachievable e.g. in extrusion-based 3DP. Lastly, spray-based 3DP is suitable for a broad range of actuation systems on and off site such as robotic arms, gantries and cable-driven robots. Even the integration with aerial drones (fig. 5c) is feasible and was presented in small scale applications [141]. Disadvantages can be seen in applications that require a high degree of precision. Sprayed material is harder to control than extrusion-printed or binder-jetted substrates. Consequently, resulting print objects are either restricted to applications that require only poor surface quality or need to be post-processed on their later visible areas or precision interfaces.

5.3. *Binder-jetting*

The process of binder jetting (BJ) belongs to the group of particle-bed 3DP techniques, where bulk particles are evenly distributed onto a print bed and bound together by a binder to form the print object layer by layer. It was invented in 1993 at the Massachusetts Institute of Technology and commercialized shortly after [143]. Today several companies develop and distribute BJ printers successfully such as ExOne, Voxeljet and 3D Systems.

BJ is mainly used for the printing of casting molds and cores for machine parts. Here, it contributes significantly to reduce the geometric limitations and required lead time for complex mold patterns. Although it is much slower than traditional methods of mold fabrication, it adds value through enabling geometric features that improve the casting and cooling process, such as thin wall sections with rib-reinforcements, custom assembly, and handling details. More recently, using BJ for fabricating porous parts becomes an emerging topic in the medical field for denture framework, surgical implants, and pharmaceutics.

In large-scale construction applications BJ offers new opportunities to create geometrically optimized and material-efficient building elements, especially when combined with the strength of concrete or other cementitious materials [144]. As stay in place formwork it enabled the pre-fabrication of a topology optimized and highly material-efficient concrete slab [31]. Furthermore, BJ was used to produce the geometrically complex molds for a 78 square meter prestressed concrete slab that features an optimized rib layout and highly articulated visible surfaces [145].

For using BJ to directly print construction elements, researchers developed methods for the use of cementitious materials as early as 1995 [146]. Two distinct methods are known to date for large scale BJ printing of concrete elements, namely selective cement activation [147] and selective paste intrusion [148]. One of the first systems using BJ technology with non-cementitious materials for creating construction elements is known as D-Shape [149].

What makes BJ particularly attractive for F3DP in construction is its suitability for a wide range of materials which can facilitate the creation of foam-like structures with the use of porous particle materials such as sawdust or wood chips [150]. Furthermore, parts printed with BJ possess inherently porous qualities depending on the binder infiltration into the particle bed. This property was leveraged by researchers who developed an implementation for printing porous silicon nitride ceramics [151].

BJ was also used for manufacturing high porosity copper foam structures [152]. This was achieved by using a foaming copper feedstock for 3DP. The sintering and foaming processes were then staged in separate steps. A different approach was used to fabricate stainless steel metal foams of 40% to 60% porosity [153]. Here, a subsequent sintering process was coupled with a powder space holder technique. In this process, spherically shaped polymer powder is printed intermixed with the print particles and burned out during the sintering process, leaving a porous structure behind.

Further general advantages of BJ are that it can achieve the highest resolution details and highest degree of geometric complexity for printed parts. This stems from the process itself, where particles which are not infiltrated by binder encapsulate and support the printed part inside the particle bed layer by layer. This makes almost any kind of shape features possible, including overhangs and undercuts. Furthermore, BJ allows to control the particle and binder composition locally, which enables differentiated material properties for functionally graded print parts [154].

Disadvantages of BJ are that it is relatively slow when compared to other 3DP techniques. However, this is directly related to the print resolution which is determined by particle and binder droplet dimensions. When the resolution is decreased, the process speed increases. Another factor which decreases the efficiency of BJ is the extra work required to remove unbound particles after the print process is finished. Depending on the size of the printed part, this can require a significant amount of time.

6. Discussion and future challenges

This section discusses the last major topic identified in the literature debate: future challenges. First, novel applications beyond mere automation of conventional processes are discussed. More specifically the significance of F3DP for functionally graded building components is outlined. Second, the focus of future material and processing development is covered with focus on most promising avenues of research. Lastly, the importance of geometry processing is discussed with the impact that the printed material layout has on the performance of building elements.

6.1. Novel applications

Many research projects have been reported in this review about 3DP in the field of high-performance façade elements. Particularly with large-scale extrusion of plastic, researchers showed the benefits of using this technique for façade elements with high integration of energy subsystems [155], for harsh climatic environments such as the desert [156], and with complex internal geometry features for climate control [157]. Entire building envelops can now be manufactured with either F3DP as lost functional formwork with casted concrete infill [41] or foam as stiffening infill of 3D printed cellular scaffolds [125].

However, these attempts still use foams in combination with other materials to deliver composite structures. While demonstrating a significant advancement in automation and efficiency, they miss to leverage the opportunity of using 3DP with foams of different densities for creating monolithic and yet differentiated building components. The advantage of such an approach is a more effective and simplified mono-material manufacturing process that addresses the demands for varying material properties inside building components through material differentiation.

The concept behind such an approach is called Functionally Graded Materials (FGM) and constitutes a widespread technique in engineering applications, where two or more material properties are combined. Instead of merging different materials as a composite, FGM are designed to vary their properties from one local extreme to another without varying the nature of the material. As a result, they relinquish force concentrations between materials like in conventional composites, such as thermal and residual stresses [158]. FGM are very expensive when created with conventional manufacturing processes, which is a limitation that can be overcome with AM technologies [159].

Functional gradation can be observed in many biological structures such as sea urchins or human bones. The efficient use of material in complex arrangements inspired early research in architecture and design to describe novel material and fabrication models [160]. With advancing computational simulation and fabrication technologies, these concepts matured and fostered research in multi-material 3DP [161], designing with computational fluid dynamics (CFD) [162], fibrous architectural components [163], and many more.

Functionally graded components for buildings were first explored by the research group of Werner Sobek at the University Stuttgart in 2011 [164]. They systematically researched materials, process technologies and applications for FGM in construction, such as casting, spraying and 3DP of concrete, and layering of polymers, textiles and fiber composites. Furthermore, they developed weight-optimized, functionally graded precast concrete slabs [165] (Fig. 6a) and numerical design methods based on topology optimization for the internal material distribution [47]. Functionally Graded Concrete (FGC) is by now a research topic of considerable interest with the potential to contribute to a higher material-efficiency in construction.

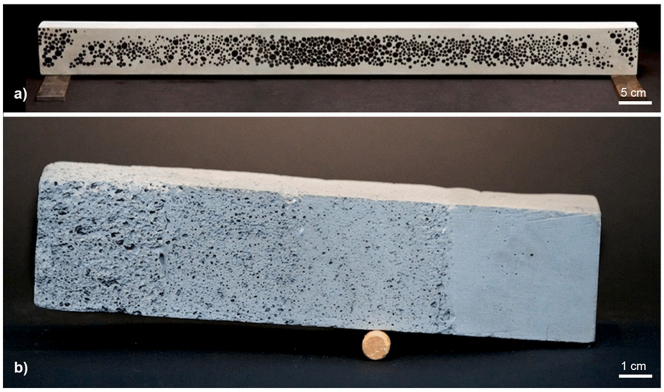

Fig. 6. Functionally graded concrete using a) lightweight aggregates [47] and b) chemical blowing agents [48].

Only few investigations were done with functionally graded foam materials. Small samples of cement foams with linear and radial density gradient were produced at MIT in 2011 [48] (Fig. 6b). However, foams are particularly well suited for functional gradation due to their inherent porosity. In tailoring this property throughout a 3DP process allows for printing parts with higher density in areas of increased mechanical stresses and higher porosity in areas that require a high thermal gradient.

Consequently, with 3DP of functionally graded foam it is possible to overcome the drawbacks of multi-material composites developed up to now. Building elements become feasible with unprecedented material-efficiency, because different densities can be manufactured throughout the print part. Dense skins for weather and impact resistance can be smoothly combined with internal structural scaffolds and porous infills with locally optimized geometries. Such an architected material layout further reduces resource consumption and part weight. The element performance can be greatly improved through this density transitions and omits problematic material interfaces and stress accumulations. Moreover, the resulting building elements would be superior in recyclability because they essentially consist of one material only.

6.2. Material development

The possible applications outlined above require a new understanding of foams as a material group. Particularly with inorganic solutions, several challenges in material development are still hindering their full adoption. More specifically, the main challenge is associated to their consolidation. To preserve a low carbon footprint, sintering and autoclave steps must be avoided, and the use of inorganic binders should be minimized, especially of cement. This poses several limitations and opens new challenges associated with the long-term durability of structures. Furthermore, the suitability of different foam densities for specific building applications must be studied through assessing their impact and weathering resistance.

With respect to the possibility to use AM technologies for the fabrication of porous inorganic material, the flow behavior of the inorganic ink and its evolution over time plays a crucial role. A precise synchronization of the complex and often not yet fully understood kinetic processes leading to the hardening of hydraulic binders is a necessary step for large-scale 3DP. Consequently, an understanding of the required material performance metrics and necessary experiments needs to be established for this specific material group.

Furthermore, to exploit the full potential of F3DP for automating a wide array of existing building processes and for truly novel applications, several challenges must be mastered in the printing technology. As shown in section 4, deposition methods such as extrusion and spraying are very suitable for foams and their drawbacks in precision can be mitigated. Depending on the chosen foaming method (mechanical, physical, or chemical) the process chain from raw material handling, to foaming and depositing needs to be tailored for the specific printing application. Additionally, the choice of the kinematic system of the printing platform need to consider the required process steps, their peripheral equipment and material handling systems. Depending on the scale of application, gantry systems, cable-suspended robots, and industrial robotic arms can be considered.

Finally, to be able to produce functionally graded mono-material structures, varying foam densities must be produced. Different strategies are possible: grading with at least two foams of different density in spatially varying patterns or grading with continuous variation of foam density. Both approaches allow for functional differentiation, however at different scale and resolution. Grading with two (or more) discrete densities could be achieved as hybrid fabrication with the combination of extrusion, spraying, and casting.

6.3. Geometry processing

For designing spatially informed and graded porous structures for F3DP, suitable design and representation tools must be developed. To describe material qualities such as density and porosity in 3-dimensional space, the concept of voxel-based modeling can be used [166]. A voxel is a discrete unit and the equivalent of a 2D-pixel but in 3 dimensions. Voxel-based models are also used in thermo-structural analysis and can therefore contain unit properties from optimization results (such as TO) or from functional material mapping [167]. Various voxel-based software developments aim at describing spatial qualities for fabrication purposes and to make them malleable for design workflows [168–170]. More advanced geometrical representations such as V-Reps allow to explicitly model the volume by non-singular trimmed trivariate B-Splines or non-uniform rational B-Splines (NURBS). Primitives of such representations may then also be combined using Boolean operations to construct very complex variations of material [5,171].

How building elements are printed with F3DP and more specifically how the material is arranged spatially can impact their early physical behavior during printing and their final physical properties such as density, thermal conductivity, and mechanical strength. Infill patterns play an important role and studies investigated the structural effect of bio-inspired designs [172] and varying infill parameter [173] for thermoplastic extrusion and the anisotropy of 3D printed concrete [174]. For concrete printing several techniques were developed to improve structural properties, such as increasing interlayer bonding through surface roughness [175] and introducing reinforcement during the printing process [176].

The optimization of print metrics for F3DP such as layer times and print speed influence the feasibility of possible infill patterns. Besides monolithic patterns with 100% infill, sparse patterns require a rapid strength development of the material to avoid buckling of thin walls. Furthermore, internal voids and meta-structures that are introduced through the toolpath design can further improve the thermal insulation performance of objects created by F3DP. Closed cellular structures can be designed and optimized for wall elements [177] and introduce substructures for increasing early built strength and active temperature control [157].

7. Conclusions

The building industry is facing significant environmental and economic challenges and is undergoing a transformation towards more sustainable and lean construction processes. However, despite the advancements in resource-efficient large-scale AM with cementitious materials, a broader perspective on using multi-performative construction materials is required. This review highlighted the significance of porous materials, in particular foams, for the building industry as high-performance, lightweight, and insulating material (Section 2) and the important role they could play in latest AM research for efficient construction processes and innovative building elements. Surprisingly, only few research projects investigated the potential of large-scale 3DP with foams until now (Section 3).

The few significant examples that reached construction scale print results used PU spray foam as lost functional formwork. Because organic foams are a long-standing material group in construction, they can be precisely tailored and adapted for 3DP applications. However, they remain highly problematic because of their flammability and petrochemical origin (Section 4.1). In contrast, inorganic foams are non-flammable and suitable for 3DP such as cement, geopolymer, and ceramic foams. Their inorganic origin and non-toxic processing make them a superior building material compared to organic foams (Section 4.2). However, only few examples of 3DP with inorganic foams exist in literature and are primarily small-scale results of material design research.

A variety of process technologies are possible for F3DP (Section 5). Among them, extrusion printing is the most accessible and very suitable for printing materials such as slurries, pastes and foams. This technique has proven to be reliable in small scale tests in the development of printable foams. Elevating this research into the scale of construction creates many challenges but rewards with manifold opportunities. F3DP would allow to automate labor-intensive applications and create novel lightweight, insulating building components.

Future challenges are the development of novel building components enabled through F3DP. Mono-material foam elements become feasible with highly efficient functionally graded porosity for thermo-structural applications (Section 6). Material formulations and processing routes for large-scale continuous F3DP must be developed for robust and reliable fabrication results. Furthermore, the effect of the toolpath layout on the final performance and durability of printed elements must be studied to meet the high requirements of the building industry.

In conclusion, F3DP has the potential to drive progress in the construction industry and enable highly efficient fabrication processes for innovative functionally graded mono-material building elements through the development of advanced inorganic materials and adaptation of existing printing and processing technologies. Thus, architects and engineers are offered the opportunity with F3DP to rethink monolithic building in terms of performance, resource circularity, and material expression for sustainable future construction.

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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