



3-D printing of concrete: Beyond horizons

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ABSTRACT

3-D printing is a disruptive technology that can have enormous social and economic impacts in years to come. The technology, which took shape in the 1980's and was initially limited to manufacturing small products, is moving to large scale construction applications, utilizing concrete and other cementitious and binder materials. This paper presents a state-of-the-art and state-of-the-practice of 3-D printing of concrete including a historical background and advances in equipment, materials, and computer modeling. Some demonstration projects are presented and opportunities and challenges associated with 3-D printing of concrete are identified. Formulation of ink utilizing local and in-situ materials is a major challenge and will continue to develop. Developments will also continue on large scale construction 3-D printers. The paper should be of value to both the seasoned researchers and beginners in 3-D printing, and also to those working on transitioning 3-D printing in construction from research to practice.

1. Introduction

3-D printing of concrete has lately received significant attention from the construction industry and researchers around the world. 3-D printing is poised to shake up the construction sector and has an impact on how architects, engineers, and designers are using concrete. Several reviews of 3D printing of concrete that cover the main 3D printing technologies employed, aspects of concrete mix design, and the effective properties of the printed concrete material have recently been published [1–4]. There has been, however, limited report in the literature on the topic of computational modeling in 3-D printing of concrete. One of the goals of this review paper is to address this gap and provide a review of the state-of-the-art and challenges of computational modeling and simulation in 3D printing of cement-based materials.

The paper first provides a historical background of 3-D printing in construction and discusses the evolution of the technology and recent advances in equipment for 3D printing of concrete for construction scale applications. After a review of the progress in cement-based ink development and printed material characterization, the paper focuses on advances and challenges in computational modeling for simulating the 3-D printing process and predicting printed cement-based material performance. A few demonstration projects are then presented, opportunities and challenges associated with 3-D printing of concrete are identified, and social and economic impacts are discussed. Finally, the

authors' view of the future of 3-D printing in construction is provided.

2. Historical background of 3-D printing in construction

The genesis and origins of 3-D printing in construction are in automated and robotic construction, which are not new to the construction industry. A mobile or stationary system, consisting of several robotic subsystems or components, is a 3-D printer and the construction materials (concrete, mortar, asphalt, etc.) serve as the ink of the printer. On a desktop printer, a digital image is sent to the printer, through a computer, to be printed on a piece of paper. Similarly, in construction, the intent is to send a digital model to the printer to create a facility at, above, or below ground surface. There are several established definitions of 3-D printing, in general, but not in the context of construction. Khan defines 3-D printing in construction as “transforming an imagination of a facility, in whole or in part, depicted through a computer model, into a real facility (bridges, highways, buildings, etc.), with least human involvement and most conservation of natural resources” [5].

To most, 3-D printing is an automated process of layer-by-layer creation of a product, similar to rock formation by acts and forces of the nature. This is opposed to creating a product by reducing a larger mass to a smaller mass of desired size and shape by progressively removing materials, as is done in creating a sculpture and numerous industrial products, and, thus, the technology getting the name “additive

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manufacturing.” Construction in buildings, bridges, highways, runways, marine structures, and almost any other facility, has traditionally been an additive or layered manufacturing process, unlike other industries. The only difference is that this additive or layered manufacturing in construction has traditionally been manual and extremely labor intensive, and uses formwork. Probably, one of the reasons the other industries did not realize the existence of additive or layered processes in construction is that construction and manufacturing have operated as separate industries.

Even when it comes to automation of additive and layered processes in construction, the concept is not new. For example, the use of slip forming techniques in construction started in the beginning of the 20th Century, and since then numerous offshore structures, towers, tanks, high-rise buildings, interstate highways, and runways have been constructed using slip forming where traditional construction techniques would have been too difficult and too time consuming. One of the recent examples is the expansion of a 0.42 m (16.5 in.) thick runway by 823 m (2700 ft.), using 3-D machine guidance, at the Fort Lauderdale-Hollywood International Airport in Broward County, Florida in 2016. This construction could have been easily labeled as 3-D printing. In slip form construction, the formwork is mechanized to automatically move vertically or horizontally as the material is continuously deposited in layers. Slip forming can also be cost-effectively and safely used in the construction of tall bridge pier columns and abutments.

Shotcreting is another example of additive or layered manufacturing in construction, and again the technology is a century-old technology. In shotcreting, the concrete is conveyed to a nozzle through a hose, and then applied to a surface under pneumatic pressure, layer-by-layer. In dry shotcreting, water is added to the dry concrete mix, coming through the hose, at the nozzle and the mixing and compaction of concrete take place at the applied surface. In wet shotcreting, the fluid concrete mixture, including water and any other admixtures, is pumped through the hose to the nozzle and then pneumatically applied to the surface. Shotcreting is used both in new construction and repair/rehabilitation of existing facilities. It has been extensively used in tunnels [6]. There are robotic machines available for shotcreting for quite some time that have automated the process significantly. Fiber reinforced concrete mixes have been developed for such applications [7].

3. Evolution of the technology

In the mid-1980's, 3-D printing gained popularity in industries like biomedical and industrial manufacturing, and commercial 3-D printers became available, which people could use to transform digital models into a solid three-dimensional object through their computers. Initially, these 3-D printers were limited to printing small objects, but the research and development efforts later led to printing large objects, as large as an automobile. Probably, this was the time period when people started thinking about construction on the lines of 3-D printing in these other industries, which was essentially an imagination of transforming a model or digital image to a constructed facility with the push of a “PRINT” button on a computer keyboard or screen.

In the mid-1990's, a technology named “Contour Crafting” surfaced, which is a modern-day additive or layered manufacturing in construction. The technology was later patented in 2010 [8]. This technology initially started as a ceramic paste extrusion method [9], but was later expanded to cementitious materials, aiming at large scale structural elements and even the entire facility, for example, a printed building. The novelty is that it utilizes guides to shape the material as it is deposited, without the use of formwork. The basic elements of this technology include a concrete tank, a hose, a pumping mechanism, a nozzle, and a robotic arm that guides the nozzle in *x*, *y*, and *z* directions. The nozzle deposits the concrete layer by layer, and the concrete layers cure and gain sufficient strength fast enough to support the new layers above them. One of the differences between contour crafting and shotcreting is that the shotcreting process utilizes pneumatic pressure to propel

material from a nozzle to the surface. The exit velocity of the material far exceeds that in the extrusion process, which is a piston-pump type of mechanism, similar to a syringe.

During the same time period of the mid-1990's, another additive or layered manufacturing technique “Selective Aggregation,” was introduced, which involved laying down a matrix of sand (silica) followed by selective deposition of cement on the sand matrix, and then activating the cement binder using steam. The process resulted in a strong and dense material, and could be automated by using computer-aided drafting and analytical modeling tools [10]. The technique was based on the premise that mountains could be created by joining sand, grain-by-grain. It appears that based on this principle of joining sand grains, a technology “D-Shape” was developed where sand grains were joined by selectively jetting a liquid binder on the sand matrix, which was initially a polymeric material and later modified to inorganic binder due to the problems associated with the stickiness of the polymer binder in the machine [11].

During the first decade of this 21st Century, another technology “Freeform Construction” or “Concrete Printing” came to attention, which is similar to contour crafting, with some differences in the design of the extrusion nozzle. The nozzle in this technique is capable of printing under different resolutions, both bulk and fine details. This technology was differentiated from others in that it focused on up-scaling additive manufacturing in construction in terms of large-scale structural elements. Also, the technology added functionality to its structural components such as acoustic, thermal, and ventilation [11,12].

It is about 25 years into the development of modern-day 3-D printing in construction, developments have been made, but still there is a long way to go before facilities can be printed by pushing “PRINT” button on a computer. For practical purposes, the 3-D printing is still in the laboratory or factory and efforts are continuing to improve the existing construction 3-D printers or develop new printers. Also, efforts are continuing to develop new construction materials (referred to herein as “ink”) for these 3-D printers.

4. Advances in equipment

To date, both gantry style [13–16] and robotic [17–19] concrete 3-D printers have been successfully implemented, both in research and real world applications. The advantage of gantry style printers is that they are relatively easy to scale up in size, whereas robotic arms typically have a fixed dimension. However, the speed and degrees of freedom of a six-axis robot allow many complex tasks to be performed that otherwise may not be achievable with a four-axis gantry printer [20]. The pay load on a gantry style printer is generally higher than that on a robotic arm. Fig. 1 shows different types of construction 3-D printers.

Fig. 1(a) shows the main components of a medium size four-axis gantry system at NASA's Marshall Space Flight Center (Huntsville, Alabama, USA). A gantry style printer is normally comprised of a gantry mobility system for *x*, *y*, *z* positioning, the concrete deposition system, and the concrete mixing and delivery system. The size of gantry printers currently in use varies from small tabletop laboratory versions up to large scale printers that may be used to print full size building components. The research team at Eindhoven University of Technology (TU/e) in the Netherlands developed a large-scale concrete 3-D printer with a four axis gantry robot and features an adjustable printing area of about 9 m × 4.5 m × 2.8 m (29.5 ft. × 14.8 ft. × 9.2 ft.) [13].

Although gantry style concrete 3-D printers were successful in scaling up additive manufacturing for construction, yet they have significant limitations. Mainly, gantry style printers are limited to vertical extrusion. Thus, gantry style printers do not yield true 3-D, rather 2.5-D topologies. To address this challenge, robotic arms have been developed as a means for large-scale 3-D printing research and development. The utilization of industrial robots with accessible software and scripting languages largely eases the planning and control of robotic

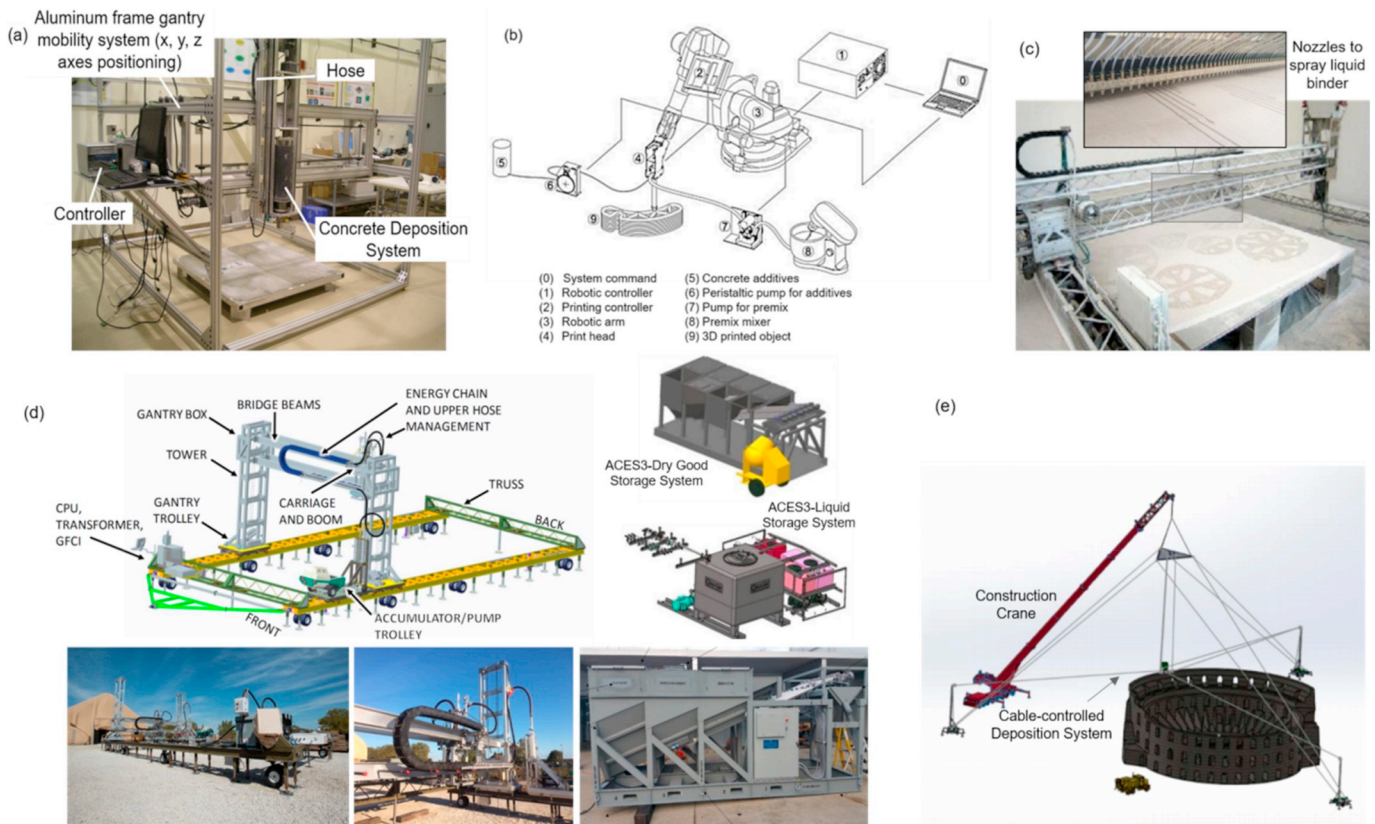


Fig. 1. Different types of construction 3-D printers: (a) Gantry style concrete 3-D printer at NASA's Marshall Space Flight Center (photo courtesy: Michael Fiske and Dr. Jennifer Edmunson (NASA MSFC/Jacobs)); (b) robotic concrete 3-D printer (adopted from [21]); (c) "D-Shape" printer (adopted from [22]); (d) the Automated Construction of Expeditionary Structures (ACES) system developed jointly by USACE and NASA (adopted from [23], photo courtesy: Dr. Robert Mueller, NASA KSFC); and (e) concept of ORNL's SkyBAAM printer (adopted from [24]).

trajectories, which, in turn, enables the printing of complex artifacts [25].

Most of the aforementioned concrete 3-D printers are equipped with an extrusion-type concrete deposition system, where concrete/mortar premixes are pumped to a printing head to form the concrete filament to be deposited. The end part of the printer head is the nozzle that forms the desired shape and size of the concrete layer [13]. Various nozzle shapes have been used as orifice of the extruder, such as circular, elliptical, square and rectangular shapes. For better surface finishing, side trowels can also be used in the nozzle orifice as that implemented by Contour Crafting [26]. D-shape printers, on the other hand, use a mechanism similar to the selective laser sintering (SLS) process, where the printer head is equipped with a number of spray nozzles that selectively spray a binding liquid on predefined areas of the sand layer during the printing process (Fig. 1(c)). D-shape has been proven to be effective in printing large scale structures [22].

Attempts have also been made towards the development of field deployable large-scale concrete 3-D printers. The Construction Engineering Research Laboratory of the United States Army Corps of Engineers (USACE), together with the National Aeronautics and Space Administration (NASA) Marshall Space Flight Center and NASA Kennedy Space Center, jointly developed the Automated Construction of Expeditionary Structures (ACES) system. The ACES has a mobile robotic gantry system and an automated material delivery system (MDS), which is comprised of a dry-goods delivery system (DGDS), and a liquid-goods delivery system (Fig. 1 (d)). The ACES is designed to be field deployable and requires relatively short setup time. This ACES prototype was effective in the 3D printing of a concrete Barrack (B)-Hut, the first habitat structure 3D printed with concrete using 10 mm (3/8 in.) aggregate for higher strength concrete [23].

Researchers at the Oak Ridge National Laboratory's (Oak Ridge,

Tennessee, USA) Manufacturing Demonstration Facility (MDF) are developing a hanging cable-controlled large-scale deposition system with the goal of allowing for full-scale automated construction of buildings – the Sky Big Area Additive Manufacturing system, known as SkyBAAM. The system is envisioned to be field deployable with conventional construction equipment. SkyBAAM is cable-driven by four base stations and suspended from a single crane. In contrast to gantry systems, found commonly in large-scale additive manufacturing systems, SkyBAAM can be set up quickly with minimal site preparation [27].

5. Advances in materials

The cement-based printing inks constitute one of the main pillars for the success of 3-D printing of concrete structures. The development of cement-based printing inks that have suitable flowability, extrudability, buildability, and can set rapidly enough to meet the 3-D printing process requirements remains a significant challenge in the application of 3-D printing in the construction industry and has been the subject of active research in the 3-D printing of concrete during the last few years. Compared to traditional mixing and casting, 3-D printing requires a greater control of the hydration kinetics, rheology, and structuration rate (i.e., the constant rate of increase in yield stress [28]) of the cement-based material to ensure buildability and shape stability of the stacked printed layers as a result of the elimination of the use of formwork. The material and processing challenges of designing cement-based printing inks are many, and recent progress has been discussed in several reviews of 3-D printing with concrete [4,29,30]. The new opportunities provided by additive manufacturing to optimize the cementitious binder are discussed in [31]. Rheological requirements for printable concrete change rapidly over the printing process timeline from the nozzle to the filament deposition, filament interface, and the

buildup of the printed element and appear contradictory to each other [32]. Designing and formulating effective printing inks thus requires understanding the relationship between mix design, selection of chemical admixtures and mineral additives, and the time-dependent cement-based paste rheological response (i.e., deformation and flow characteristics); correlating the fluid rheological properties (static and dynamic yield stresses) and hydration kinetics to the evolving plastic viscosity of the fresh cement-based paste under the influence of the printing process; addressing the inclusion of multiscale reinforcements within the cement ink; and understanding the relationship between fresh and hardened properties, including the material adhesion and bonding between printed layers. Other important challenges in formulating cement-based printing inks include requirements imposed by the size of the object under construction, the speed of the robot, and the vertical build rate.

Most research to date has focused on printing inks based on ordinary portland cement. A few studies have explored the use of non-portland binders, including sulfur-based cements [33–35], limestone calcined clay cements [36], calcium aluminate cements [37], geopolymers and geopolymer mixtures [38–42], and magnesium potassium phosphate cements blended with fly ash [43]. Available studies have examined the effect of different setting time controllers (accelerating and retarding agents), dispersing agents and superplasticizers, flocculation agents such as viscosity modifying admixtures and nano-particles (e.g., nano-clays and nano-silica), supplementary cementitious materials and pozzolanic additives (e.g., silica fume and fly ashes), recycled materials, and aggregate gradation and content [33,43–59]. An overview of potential admixtures and additives to control the rheological and hydration properties necessary for printable concrete is provided in [44] along with a discussion of potential candidates for the binding matrix as alternatives to ordinary portland cement. A few notable results reported in the literature include an increase in structural buildability and shape stability of fresh printing mixtures with the addition of small amount (less than 2%) of nano-clay [47,49,53] and nano-silica [54]; higher yield stresses (i.e., stronger material), lower plastic viscosity, and greater buildability with continuous gradation of sand particles [46], and a linear correlation between flowability and optimum aggregate content [48]. Additionally, the addition of 10% silica fume has been reported to be effective to adjust rheology for 3D printing and fly ash (60% replacement in magnesium potassium phosphate cement formulation) to increase working time of rapid hardening materials [43].

Efforts on cement-based ink development have also focused on improving the buildability and the adhesion between the printed layers. During the deposition process, the intermixing and bonding between layers are affected by the cement ink composition, age and moisture content of the extruded filaments, the printing time delay between deposited filaments, the water bleeding between printed layers, and the surrounding environment of the deposited filaments during curing. The surrounding environment can lead to drying, autogenous shrinkage, and carbonation of the printed filaments, thus affecting the bonding (adhesion) between the deposited layers. A few available studies have examined the influence of the printing process (e.g., head speed, printing time gap, and print nozzle height) on the interlayer adhesion [60–65]. Notably, a decrease in bond strength has been reported with increasing printing time gap between the layers [60,61,64,66]. However, inconsistent results have been reported with respect to the print nozzle height [60,64]. Weak interfaces have been reported to lead to significant mechanical anisotropy and to influence the mechanical integrity and load bearing capacity of the printed structures [1,59,67,68]. Adhesion enhancers (i.e., “glue”) have thus been explored to increase the contact between adjacent printed layers and decrease the voids formed between layers during the deposition. Examples include use of cement paste and polymer-based “glue” between printed concrete layers [59,69]. The effects of dosage of viscosity modifying admixtures, addition of retarders at the nozzle, curing methods, and interlocking on

interlayer adhesion and strength have also been investigated [59,69,70]. Particularly, the addition of viscosity modifying agents (VMA) has been reported to increase the contact between adjacent printed layers and to result in improved structural integrity [59], and the application of a cementitious “glue” paste between layer depositions to increase the bond strength up to 60% [69]. Furthermore, the use of interlocks between printed layers has been observed to increase the bonding strength by 26% [70].

In addition to the research effort on printability and buildability, recent developments in cement-based printing inks for the 3-D printing of concrete include the incorporation of discrete, short fibers (e.g., microfibers) within the cement-based ink as an alternative to traditional steel reinforcement (rebar). The issue of reinforcement for 3-D printing is discussed in [4,71]. Available studies have reported on the use of steel, glass, polymers, basalt, and carbon microfibers [71–84] and a recent study has reported on the use of carbon nanofibers [85]. 3-D printing with cement-based ink containing short fibers has been reported to produce printed structures that exhibit orthotropic mechanical behavior with superior performance than the conventionally cast counterpart as a result of preferential fiber alignment along the print path direction induced by the 3-D printing nozzle [72,74,75,85]. 3-D printed microfiber reinforced cement-based materials with ultra-high tensile ductility and tensile strain-hardening behavior have recently been developed [74,76,80,86,87]. The integration of fiber reinforcement directly within the cement-based printing inks thus offers new options for structural applications and opens a new design paradigm for the development of bio-inspired and functionally graded cement-based materials. Potential applications include the design of structures with improved resistance to seismic events, impacts, and blast loadings [88,89]. Other approaches to reinforcement of 3-D printed cement-based elements that have been reported in the literature include directly entraining a continuous micro steel cable during the filament deposition process [90,91] and directly printing of the steel reinforcement using gas-metal arc welding [92].

Another opportunity for cement ink development is the incorporation of functional inclusions that can provide the printed element with intrinsic smart properties (e.g., self-sensing, self-healing, and thermo-responsive properties), thus transforming passive 3-D printed elements into stimulus-responsive elements by adding functionality as a fourth dimension to 3-D printing, referred to as 4-D printing. 4-D printing enables shape and functionality evolution of 3-D printed materials in response to external stimuli (thermal, chemical, electrical, and mechanical). Recent advances, opportunities, and challenges in 4-D printing of multifunctional materials for applications in the aerospace, biomedical, and semiconductors industries are discussed in [93–96]. Possible smart characteristics for concrete and cement-based materials that have shown promises in traditional mixing and casting of cement include self-sensing of damage (e.g., nano-iron particles, carbon nanotubes, and steel and carbon microfibers), self-healing of cracks (e.g., capsules filled with chemical agents and super absorbent polymers), self-cleaning (e.g., nano-titanium dioxide), and self-adjusting to thermal parameters (e.g., thermal-responsive or phase change materials) [97–101].

6. Advances in material characterization

While 3-D printing of cement-based materials has progressed rapidly over the last years and new cement-based inks have been developed, the long-term performance and durability of the resulting 3-D printed materials and structures have received little attention and have yet to be fully investigated and demonstrated. In addition, there is a growing and urgent need for standard characterization and quality control methods to ensure consistent and reliable properties of the printed elements and compatibility with existing design codes for safe structural applications. The available studies have focused on methods for characterizing and quantifying the workability, extrudability,

buildability, and stability of cement-based inks [102–110]. The majority of the efforts on characterization of the hardened 3-D printed structures have been on the macroscale mechanical properties [52,66,73,74,76,78,84,111–114] and a few available studies have reported on the characterization of the microstructure of 3-D printed cement-based materials and the interlayer interface [68,72,75,85]. Recent advances in microstructural characterization of cementitious materials are discussed in [115] and include X-ray imaging and spectroscopy techniques, in-situ and high-pressure X-ray diffraction, and nanotomography.

7. Advances in computer modeling

The integration of computational modeling and additive manufacturing has emerged as a tool for creating and testing novel materials and interfaces in industries like biomedicine, aerospace, automotive, and energy. In these areas, computational modeling is typically used to assess the impact of process parameters and to help optimize conditions for producing 3-D printed objects with high dimensional accuracy, consistent microstructure in terms of grain size, morphology, and composition, and desired material characteristics and mechanical properties targeted to specific applications [116–119]. Computational modeling provides important insight into the multiple, multiscale, and multiphysics (chemical and physical) phenomena that lead to the final material properties and allows for exploring an infinitely large design space. The Virtual Cement and Concrete Testing Laboratory (VCCTL) software developed by NIST [120] is an example of computational materials science tools that allow a user to model microstructure, simulate hydration, and calculate physical properties and can be used in the development, testing, and quality control of cement and concrete materials. New modeling paradigms are emerging and a discussion of the new frontiers in computational modeling of material structures as a result of the emergence of the unprecedented capability offered by additive manufacturing is provided in [121]. However, it is currently impractical to simulate and predict the entire 3-D printing process and printed material performance based on physics-driven models. As a result, data-driven models are gaining significant interest. Artificial intelligence and machine learning are now fueling the next wave of 3-D printing to address the inextricable complexity of the relationship between process parameters and printed quality through pattern recognition and data regression analysis [122]. Applications of machine learning to cement-based materials are not new and have been used in the literature for phase analysis of cement, prediction of microstructure development, mix design of concrete, and prediction of fresh and hardened properties [31,123–129].

Most research to date on 3-D printing of cement-based materials is based on experimental investigations. Computational simulations of the 3-D printing process of cement-based materials remain limited [130]. Some of the main modeling and simulation challenges associated with the extrusion-based 3-D printing of cement-based materials were discussed during the Multiscale/3-D Printing Cement Workshop sponsored by the US National Science Foundation (NSF) and co-organized by Vanderbilt University, Purdue University, and Tennessee Technological University in 2015 [131]. These challenges are related to the complex nature and time dependent behavior of cement-based materials that are multi-size, multiphase materials and that evolve over time. During the extrusion-based printing process, cement-based materials undergo complex, time-dependent chemical reactions and rapid phase changes. They transform from a liquid paste that is flowable and can be extruded to a solid paste that needs to gain rigidity rapidly after being deposited to remain stable and withstand the load of subsequent layers. This transformation and the final 3-D printed product are strongly affected by the mix design (i.e., cement types, chemical admixtures and mineral additives, and water to cement ratio), reaction kinetics, the external environmental conditions (i.e., temperature and relative humidity), and the printing process parameters (i.e., extrusion pressure, printing speed,

layer thickness, and infill density). In addition, during the printing process, microscopic residual stresses can occur as a result of a mechanical mismatch between printed filament constituents and between printed layers, shrinkage of the printed layers due to fast evaporation of the mixing capillary water, and variations in printed filament age along the printing path and from the bottom filaments to the top filaments forming the 3-D printed object. This can lead to deformation and cracking of the 3-D printed object, eventually leading to premature failure. Models must thus span multiple spatial and temporal scales; incorporate multiphysics phenomena; be capable of integrating internal geometry architectures, multi-material configurations, and spatially varying internal material properties; and be capable of dealing with the evolution of the material microstructure and properties during the build process. The following provides an overview of advanced computational methods and approaches for simulating the process-structure-property relationships in additive manufacturing of cement-based materials.

7.1. Physics-driven computational modeling of the additive manufacturing process

Modeling the 3-D printing process of cement-based materials is complicated by the complex, dynamical physical and chemical transformations that occur over a range of length and time scales. During the extrusion-based 3-D printing process, particles are moving, interacting, and reacting inside the flowing cement paste. Particle scale with hydration kinetics and time-dependent rheology properties affects the microstructure development and the overall product macroscale behavior and performance. Different approaches are used to simulate the behavior of fresh concrete flow and include computational fluid dynamics (CFD) methods, the discrete element and particle method (DEM/DPM), and the multiphase suspension method. In CFD methods, the flow of concrete is modeled using the Navier Stokes equations, and the continuum-based partial differential equations are solved numerically using traditional grid-based methods (finite element, finite volume, and hybrid finite element-finite volume discretization) or grid-free techniques. As an alternative to the conventional continuous Navier Stokes solvers for CFD, the lattice Boltzman method models the fluid as a collection of particles propagating and interacting over a discrete lattice domain [132,133]. In DEM/DPM methods, particles are traced individually and characterized by their specific properties. The use of the CFD and DEM approaches to simulate the behavior of fresh concrete are reviewed in a RILEM state-of-the-art report [134] and are also discussed in [135–138]. The multiphase representation considers concrete as a suspension of interacting particles carried by a fluid. This particle-laden flow is modeled by an Eulerian-Lagrangian approach consisting of the continuum CFD method (continuum fluid phase) combined with the discrete DEM/DPM method (suspended, dispersed particles) [137,139]. These modeling approaches are computationally expensive and the coupling of the fluid and discrete particles is inherently complex in part because of the wide range of particles, the large volume fraction of the solid phase in concrete, and the presence of free-surfaces. Challenges associated with computational modeling of particle-fluid flows with free-surfaces and fresh concrete flow can be found in [137,138,140–142].

At this time, the majority of computational advances in 3-D printing of cement-based materials are yet to be published in archival forms; thus, much of the work is traceable only to presentation abstracts. Among these on-going works, researchers at Tennessee Technological University (Cookeville, Tennessee, USA) have developed a concept referred to as 2-dimensional stationary computational printing (2D-SCP) [143,144]. Dealing with the free surface flow problem presented by 3-D printing is computationally intensive in three-dimensions. To reduce computational time, yet capturing relevant insights regarding the effect of material rheology and scale, the 2D-SCP concept considers a 2-D plane in which the printed object is dynamically formed layer-by-layer.

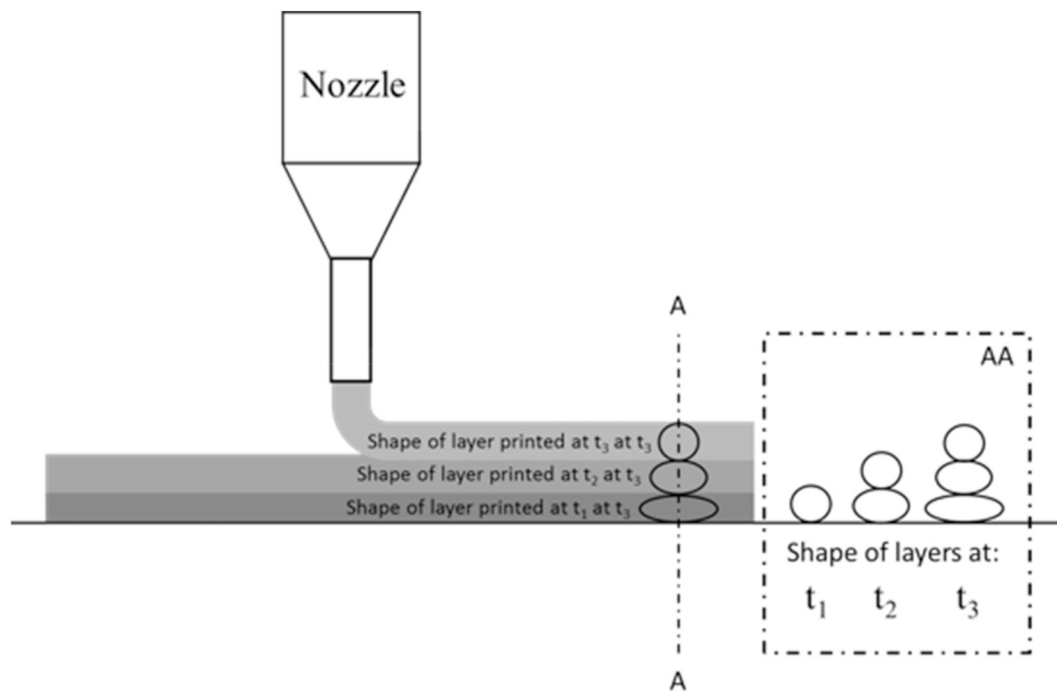


Fig. 2. Conceptual representation of a 2-D plane (AA) developing in time as layers are printed for $t_3 > t_2 > t_1$, (courtesy: Joseph J. Biernacki, Tennessee Technological University).

Diameter Size	1 st Layer	2 nd Layer	3 rd Layer
	Simulation Time (0 to 8 seconds)	Simulation Time (8 to 16 seconds)	Simulation Time (16 to 24 seconds)
3 mm			
6 mm			

Fig. 3. 2-D stationary computational printing results illustrating the effect of print scale on printing outcomes for a cement paste with yield stress of 350 Pa, (courtesy: Joseph J. Biernacki, Tennessee Technological University).

In this context, the first 2-D layer geometry is laid down at $t_1 = 0$, permitted to slump until t_2 when the next layer is stacked atop it and slumped to time t_3 . This process is repeated to form 2-D stacks that preserve the time-sequence of a print-job at a given point in a hypothetical structure (Fig. 2). Inferences based on this approach suggest

that material rheology must be tuned to the scale of the print job, i.e. a rheology that works well at scale A may not work well at scale B (Fig. 3) [145,146].

These computational modeling approaches, however, only provide an analysis of the fresh concrete in the dynamic (flowing) state during

the extrusion process. After extrusion, these computational approaches are, however, no longer applicable. Once deposited, the fresh 3-D printed concrete is “at rest” and transforms with time from a fluid to a solid, and different computational models are then needed. Numerical models describing the time-dependent development of the mechanical properties during the build-up process (i.e., during material deposition) and directly after printing have recently been proposed [130,147]. However, a fundamental understanding of the relationships between the extrusion process at the nozzle, the filament deposition, and the evolving properties of the printed material has yet to be developed.

7.2. Topology and microstructural optimization

Additive manufacturing offers new possibilities to design and create concrete and cement-based materials with desired properties by controlling their structures at different length scales. This includes optimizing the 3-D printed cement-based component in terms of weight, mechanical properties (e.g., stiffness), and integration of function such as self-adaptive thermal conductivity or tunable acoustic properties. Printing enables the creation of a hierarchy of structures and patterns over a broad range of length scales that is not possible with traditional mixing and casting. Researchers at Purdue University (West Lafayette, Indiana, USA) have developed 3-D printed cement paste elements with bio-inspired structural patterns and architectures such as honeycomb and boudin (helical) structures, which have demonstrated unique damage control mechanisms and are showing great promise for the creation of flaw-tolerant structural elements like beams or columns [148].

Computational modeling and topology optimization techniques provide for the possibility to design and optimize the 3-D printed cement-based element on a multitude of scales and materials and to achieve more sustainable and cost-effective designs. Topology optimization consists of the discretization of an object or structure into small elements and optimization of the material composition, volume fractions, and spatial distribution within each element to achieve functionally graded objects or structures with desired properties and/or functional performance. New computational frameworks for topology optimization with microstructures that supports design spaces of multiple dimensions are emerging and are being combined with 3-D printing in many fields [149–153]. For concrete, topology optimization techniques are being used to optimize the location and minimize the amount of material to create efficient 3-D printed concrete elements with less materials [154–158]. An example of the use of topology optimization combined with 3-D printing has been presented by researchers at Ghent University and collaborators, who realized the 3-D concrete printing of a topology-optimized bridge [159]. Another application of topology optimization techniques for concrete concerns the optimization of the cement binder itself by tuning the internal topology at different scales. Advances and challenges in this area are discussed in [151].

7.3. Computational materials modeling

The performance and chemo-mechanical behavior, including strength and durability, of 3-D printed structures across length scales (nano to macro) ultimately are linked to the early age hydration and development of the microstructure. Over the past two decades, computational modeling of cement-based materials has seen significant advances with the ability to model the material properties and performance over length scales ranging from nanometers to meters. Computational materials models have been developed from first principles of physics and chemistry to describe cement hydration and microstructure development, cement paste rheological behavior, and transport processes and to predict the material properties and long-term performance. An overview of the advances of material modeling of cement-based materials can be found in [31,160]. With the advent of 3-

D printing and the need for new cement-based formulations as printing ink, computational materials science modeling faces new challenges. Some of these challenges, related to the complexity of the cement-based formulations due to the use of a wide range of mineral additives and chemical admixtures, are discussed in [31]. The modeling and prediction of the structural performance of 3-D printed cement-based materials is, additionally, complicated by the anisotropic material behavior caused by the intrinsic 3-D printed layered architecture and print-induced inclusion distribution and reinforcement orientation. Other key challenges include appropriate description of the bond behavior between inclusions (aggregates and reinforcements) within the filaments and the matrix and bond behavior between filaments. As a result, the design of cement-based inks is, to date, essentially based on empirical approaches and testing. Some of the recent advances in computational materials modeling that are poised to provide new opportunities for the development of 3-D printed cement-based composites are discussed in the following.

At the molecular and nanoscale level, molecular modeling and computer-aided molecular design have emerged as tools for “*in-silico*” experiments to understand the relationship between the molecular structure and the mechanical and physico-chemical properties and to design materials from the molecular scale at a fundamental level [31]. A review of the use of molecular dynamics for the nanoengineering of construction materials is provided in [161]. Molecular modeling has provided insight into the main building block of concrete, calcium-silicate-hydrate (C-S-H), and concrete durability and has recently been successfully used to investigate the reinforcing mechanisms and tuning of the mechanical properties of C-S-H with graphene and graphene oxide [162–168] and the bonding between adjacent layers of 3-D printed concrete [169].

A recent trend in predictive materials modeling is the coupling between computational modeling approaches at multiple length scales and experimental characterization [170]. Data-driven and machine learning models have recently gained interest and are emerging as tools for designing new cement-based composites [31]. Commonly used machine learning algorithms in materials science are discussed in [171]. Machine learning models are based on pattern recognition in data to make new predictions and are providing alternative approaches to traditional physico-chemical and mechanical models for predicting hydration of complex cement mixtures and relating microstructure development to strength properties [127–129,172]. One of the challenges, however, in realizing the full potential of machine learning is the need for a highly diverse training dataset and sufficient representative data from detailed material characterization.

Other data-driven models that have been developed in recent years to describe damage evolution in cement-based materials and relate the microstructure to the material macroscopic properties include microstructure informed models coupled with multi-phase homogenization techniques. These models are informed by experimental data and take into account the underlying microstructure and the presence of inclusions to evaluate the constitutive response of the composite. For example, high resolution X-ray micro-computed tomography has been used to incorporate microstructure features such as volume fraction and size distribution of anhydrous cement grains and porosity and pore size distribution into the analysis of the material mechanical properties [173–175]. Recently, grid nanoindentation coupled with phase elemental composition and a combination of homogenization and area-averaging techniques [176] has been proposed for quantitative characterization of the intrinsic mechanical properties of the material constitutive phases as a function of chemical changes and provides an alternative to direct modeling of damage evolution.

7.4. Modeling the behavior of 3D-printed structures

Beyond the simulation of material behaviors during and after the 3D printing process, research efforts have been extended into the

experimentation and modeling of 3D printed structural components. Due to the complexity in geometry (one advantage offered by the technology), inherently weak interface bond between filament layers, and different reinforcing strategy, 3D printed structural members often show much different failure modes and mechanical behavior in comparison with conventionally cast concrete members [177]. As a results, there is still a lack of widely accepted design theories for 3D printed structural members. For the mechanical behavior analysis of structural components during the 3D printing process, Suiker and Wolfs [178,179] developed a mechanistic model for analyzing and optimizing the mechanical performance of wall structures in 3D printing processes. Two failure mechanisms - namely elastic buckling and plastic collapse, are considered in the analytical model. The model incorporates the process parameters including printing velocity, the geometrical features of the printed object, the curing characteristics of the printing material, as well as the presence of imperfections. This provides, for the first time, an analytical tool for engineers to gain in-depth understanding of the *in-operando* behavior of structural components during the 3D printing process.

8. Demonstration projects

A demonstration project by the Oak Ridge National Laboratory (ORNL) well depicts the current state-of-the-art of 3-D printing in construction. A small house has been 3-D printed using laboratory 3-D printed panels of polymeric materials, the house is remotely connected to a laboratory 3-D printed vehicle, and both the house and the vehicle power each other (see Fig. 4). The researchers at ORNL also show a timeline for their progress in Big Area Additive Manufacturing (BAAM) using freeform construction. In January 2013, they started with a prototype system with a build volume of $2.1 \text{ m} \times 2.1 \text{ m} \times 1.5 \text{ m}$ (7 ft. $\times$ 7 ft. $\times$ 5 ft.). Incrementally, in March 2017, they were able to increase the build volume to $2.1 \text{ m} \times 4.0 \text{ m} \times 2.4 \text{ m}$ (7 ft. $\times$ 13 ft. $\times$ 8 ft.) [180]. The deposition rate increased from 4.5 kg/h to 45.3 kg/h (10 lb./h to 100 lb./h). In their development efforts, the ORNL has partnered with a number of private and public organizations, including the Construction Engineering Research Laboratory (CERL) of the U.S. Army Corps of Engineers.

Researchers from Southeast University (Nanjing, China), Nanjing Institute for Green Intelligent Additive Manufacturing Co. Ltd. (Nanjing, China), and the University of Tennessee (Knoxville, Tennessee, USA) jointly designed a 3-D Printed concrete building with integrated green wall for building energy savings [181]. The prototype building is located at Jiangbei Kechuang Stadium, Nanjing, China. It has a steel frame structure enclosed with the 3D printed vertical green

wall system (3D-VtGW). 3D-VtGW is a living wall system assembled with 3D printed modular elements that can serve as the backbone for growing vertical greenery (Fig. 5). Each 3D-VtGW module is comprised of double-layer supporting wythes as well as a wave-shaped functional surface to grow greenery, as shown in Fig. 5 (b). The cavity between the two supporting layers can either be filled with reinforcements (e.g., rebar) and high performance concrete (e.g., UHPC) for load bearing, or thermal insulation foams to improve the building's energy performance. In addition, sinusoidal-shaped exterior wythe is integrally printed with the wall module such that the space enclosed by sinusoidal-shaped wythe and the supporting wythes can be filled with soil to grow greenery. The moist soil and vegetation serve as heat sink and shield to solar radiation. In combination with evapotranspiration within the 3D-VtGW module, the integrated vertical green wall will significantly reduce through-wall heat flux and save building energy use during summer months. For the 3D printing of 3D-VtGW module, a low-critical shear stress mortar premixed with fine aggregates was prepared with a rheological behavior appropriate for pumping and extrusion-based printing. Then, the printed and cured 3D-VtGW modular elements were assembled on-site around a load-bearing steel frame. The joints were grouted with a non-shrink cementitious sealant to prevent water intrusion and minimize air infiltration. After erecting the roof and placing fenestration components, such as windows and door frames, the envelope was painted with a water-proofing surface paint. Lastly, an irrigation system was installed and soil with growing vegetation was placed into each green wall module. This demonstration project highlights one of the most attractive features of concrete 3D printing of concrete – i.e., the flexible design space offered by concrete 3D printing technology allows the reconciliation of multiple architectural functionalities (other than load-bearing and space separation) into one single assembly.

The demonstration of 3-D printing in construction is slowly moving beyond laboratory. In December 2018, the 1st Marine Logistics Group of the U.S. Marine Corps 3-D printed a pedestrian bridge in Camp Pendleton, California (Fig. 6). The 3-D printing of the bridge was carried out in collaboration with the Marine Corps Systems Command Advanced Manufacturing Operations Cell (AMOC) and the Army Corps of Engineers. The bridge was 3D printed component-by-component, and then all the components were assembled together.

9. Challenges and opportunities

The development of ink is one of the most active areas of research on 3-D printing of concrete. Certainly, in the existing literature, very little has been revealed on the composition of the ink or the concrete



Fig. 4. 3-D printed vehicle by the ORNL, which remotely connects to a 3-D printed house (photo courtesy: Dr. Som Shrestha, Oak Ridge National Laboratory).

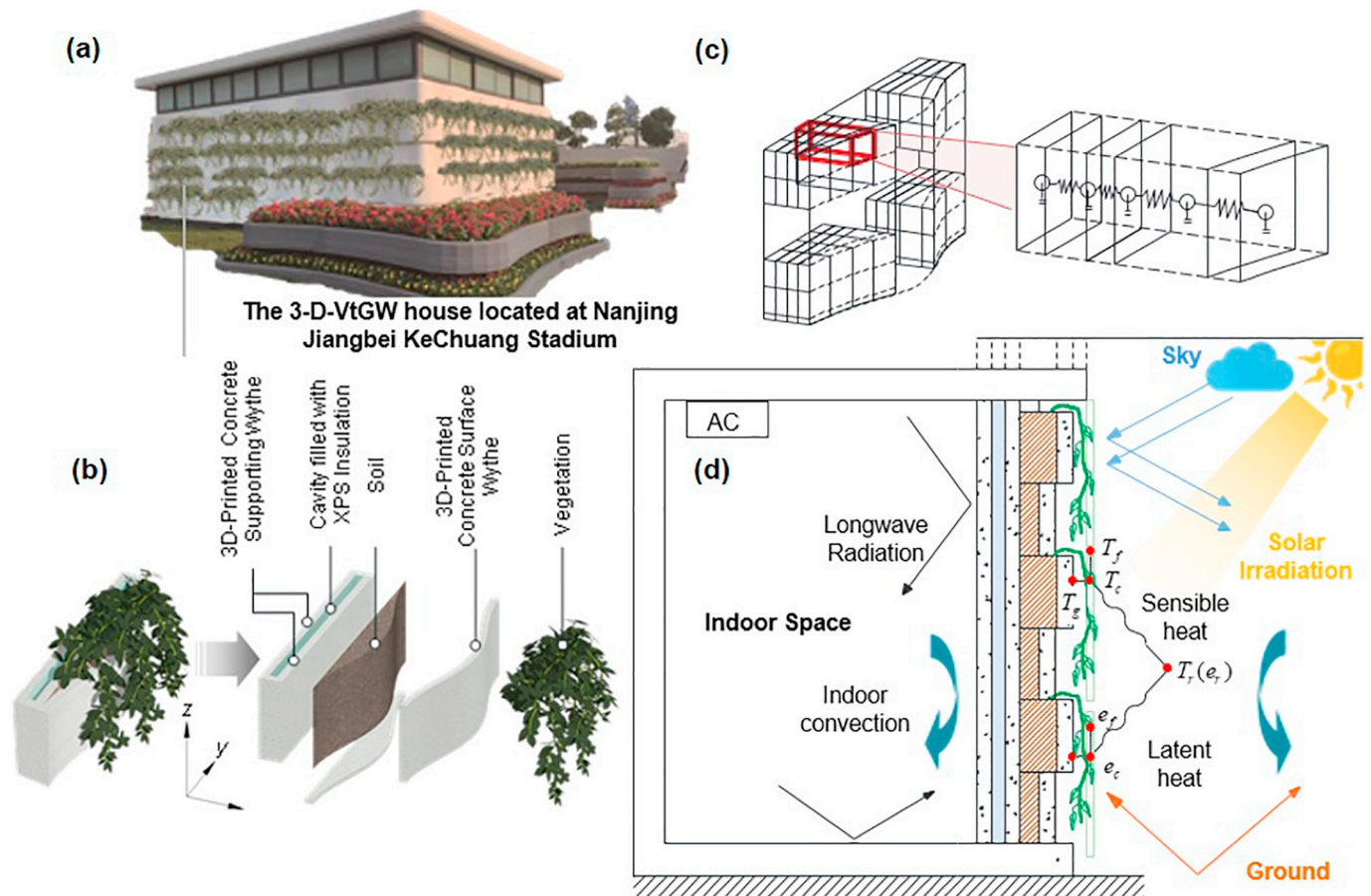


Fig. 5. 3-D printed concrete wall system with integrated vertical green wall (3-D-VtGW): a) The printed structure; b) geometric of the 3-D printed green wall and a representative unit; c) the thermal network model established for building energy simulation; and d) environmental processes acting on the 3-D-VtGW. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

mixture used in construction 3-D printers when it comes to proprietary ink formulations that have been used in some commercial applications. However, significant amount of information is available in the literature coming from academic institutions where research continues to optimize ink formulations [1,4,29–65,67–70,72–79]. These ink formulations include ordinary portland cement and a variety of alternate binder materials, including sulfur-based cements, limestone calcined clay cements, calcium aluminate cements, geopolymers, and magnesium potassium phosphate cements blended with fly ash [33–43]. The development of inks that have suitable flowability, extrudability, buildability, and can set rapidly enough to meet the 3-D printing process requirements remains a significant challenge, and presents an opportunity for further development and improvement in years to come. Furthermore, standard characterization and quality control methods and tools need to be developed, particularly for field applications, to ensure consistent and reliable properties of the printed elements and compatibility with existing design codes for safe structural applications.

The lack of design rules and guidelines to material formulation for 3-D printers, understandably, is a major challenge, considering the emerging nature of the technology. Concrete mixture optimization studies have been conducted for more than 100 years, and there are always new waves of studies when a new cementitious material (fly ash, silica fume, slag, etc.) or a new chemical admixture (superplasticizer, accelerator, retarder, etc.) is introduced. There is a good reason for these optimization studies because every time a new material is introduced, it changes the behavior and performance of the concrete mixture. One of the drawbacks of the mixtures used in 3-D construction is that it completely eliminates the coarse aggregates from the mixture, and increases the demand for cementitious materials by as much as

twice. A concrete mixture with a high cementitious material content is never a desirable option because, first, it increases the cost of the material, and, second, it increases the shrinkage and cracking potential of the material. However, this challenges also presents an opportunity. Now, the concrete materials scientists can come up with a completely new generation of concrete mixtures for 3-D printing applications incorporating non-portland cement binders and technologies such as nanotechnology [33–43,85,182].

Incorporating reinforcing steel is another major challenge in 3-D printing in construction, particularly in case of in-situ printing. This technology will have serious limitations if the reinforcing steel cannot be easily incorporated in the 3-D printing process and the structural and load bearing capacity of the constructed facility is not comparable to traditional construction. The current code of practice is based on a composite concrete-steel system and will remain so until a new material can offer the same balancing attributes of compressive strength and tensile strength. Alternative materials as a replacement to conventional reinforcing bars are being explored. These include microfibers and even, in some cases, nanofibers, composed of steel, glass, polymers, basalt, and carbon [72–76,85], and continuous micro steel cable [90,91]. Conventional reinforcing bars, but co-printed with the cementitious ink, using techniques such as gas-metal arc welding, are being considered [92].

Most of the research on 3-D printing of concrete has so far been experimental, with not much focus on computational simulations of the 3-D printing process, and even there is a lack of published information on simulation and modeling. Computational modeling would provide an opportunity to design and optimize 3-D printed cement-based elements on a multitude of scales and materials and achieve more



Fig. 6. 3-D printed bridge by the 1st Marine Logistics Group of the U.S. Marine Corps, in December 2018 (photo courtesy: Dr. Michael Case, U.S. Army Corps of Engineers).

sustainable and cost-effective designs. Advances will continue in computational modeling and linking the computational models with experimental investigations will help mature the 3-D printing technology in concrete.

10. Social and economic impacts

3-D printing, in simple terms, means more machine and less human involvement and the capability of the consumer to create products in a configuration and at a time and place of their own choosing. The manufacturing that was centralized and controlled by a few in the past would now be localized and controlled by many. The balance of the movement and consumption of ingredient materials versus finished products will be disrupted. This not only applies to industrial products, but also to construction materials and products. Portland cement, aggregate, and conventional reinforcing steel were the three primary concrete-making materials, which accounted for bulk of the construction cost. With advances made in the formulation of ink for 3-D printing, the use of these materials may be minimized or completely eliminated, and replaced by other materials. For example, portland cement may be replaced by non-portland binders, there may be less demand for coarse aggregates, and alternative reinforcement materials may be used in place of conventional rebars. Formwork is another significant component of the construction cost, which traditionally utilizes wood and skilled labor. 3-D printing eliminates the need for formwork and, if needed, can even print relatively inexpensive formwork by using recyclable materials such as engineered wax. Furthermore, all these new or alternative construction materials, used for 3-D printing, may be manufactured locally rather than being

imported from far away distances, which may be other regions, states or countries. NASA is even exploring the use of in-situ materials, as aggregate and binder, to 3D print facilities on the Moon and Mars [183–185].

In a survey conducted by RAND Corporation, it is predicted that additive manufacturing can wipe out about one-quarter of the cross-border trade by 2060. According to the survey, this is a conservative estimate and the impact could be even more disruptive; almost two-fifth of the cross-border trade could diminish by 2040 if the investment in additive manufacturing doubles every five years [186]. A diminished cross-border trade could have both positive and negative social and economic impacts.

A traditional supply chain typically consists of supplier, manufacturer, retailer, and consumer. With 3-D printing, this supply chain can reduce to 3-D model provider, 3-D shop, and consumer, or collapse to just 3-D model provider and consumer who has a 3-D printer. In a traditional supply chain, freight movement connects different elements of the supply chain (supplier, manufacturer, retailer, consumer) and accounts for a substantial portion of the cost of a product by the time it reaches to the hands of the consumer. 3-D printing can eliminate most of the costs associated with freight movement. Additionally, it can eliminate the costs associated with assembly, distribution, and warehousing. The shortened supply chain in 3-D printing can potentially result in a cost saving of 50% to 90% [187].

In traditional manufacturing, the cost of a product depends upon the complexity of its geometry, with products of complex geometry costing much higher than those with simple geometry. However, in 3-D printing, complexity of a product is not a factor in determining its cost. Once a digital model is created, it essentially costs the same to 3-D print

the product regardless of its geometry. Thus, significant cost savings can be realized in constructions where complex geometries are involved. Furthermore, if the shapes and geometries are too complex, they simply cannot be incorporated in traditional manufacturing and construction, but they can be incorporated in 3-D printing. Thus, with 3-D printing, more aesthetically pleasing facilities can be created.

11. Path forward

The path forward for 3-D printing in construction is bright and we can look beyond horizons on what transformational changes this technology can bring. Any challenges can be overcome collaboratively by involving and engaging all disciplines and bringing together concerned public and private institutions, including academia and research. The engagement of government organizations is particularly important in this journey because these are the institutions that rise above individual, group, or entity interests and look at national interests both in terms of near-term and long-term benefits of a technology.

The information and knowledge base on 3-D printing is expanding, and from this we can charter a path for the future, as follows:

- Continue building a platform, which can bring people and organizations together, and increase the diversity and inclusion of innovators, entrepreneurs, researchers, scientists, practitioners, and owners.
- Leverage and learn from the successes of 3-D printing in other industries such as automotive, aerospace, biomedical, energy, and industrial manufacturing.
- Leverage and learn from the successes of shotcreting and slip forming techniques in construction and bring this expertise into the fold.
- Integrate robotics with existing crane and Self-Propelled Modular Transporter (SPMT) technologies in the development of large scale 3-D printers for in-situ applications, such as SkyBAAM.
- Focus upon 3-D printing full-scale structural components in a plant setting and then transporting them to the site and assembling and connecting them, while the 3-D printing technology for in-situ applications matures.
- Continue developing and evaluating new generation concrete mixtures, incorporating the latest advances in the science and engineering of concrete, which can serve as a strong, durable, and long-lasting ink for the 3-D construction printers.
- Continue developing and evaluating reinforcing materials that can either be incorporated into the cementitious ink or co-printed with the cementitious ink, capable of providing the needed tensile and flexural attributes to the printed material for structural applications.
- Continue advancing the technology for 3-D printing of economical forms and molds, which accounts for substantial construction cost, where a formed construction might still be the most feasible and economical solution.
- Develop quality assurance/quality control (QA/QC) techniques that can work in tandem with the 3-D printing and are non-destructive and remotely controlled. A QA/QC check after the 3-D printing is complete would be too expensive in case of a defect.
- Develop academic curriculum at universities for 3-D printing in construction that combines all the needed knowledge and skills, including materials, structures, robotics, and computer software and hardware.

12. Conclusions

Construction industry is probably the only industry which has been doing additive manufacturing or 3-D printing since its inception. The only exception is that 3-D printing in construction was completely manual initially and then automated incrementally as we progressed through the industrial revolution. In this paper, 3-D printing in

construction is defined as “transforming an imagination of a facility, in whole or in part, depicted through a computer model, into a real facility (bridges, highways, buildings, etc.) with least human involvement and most conservation of natural resources.” Using this definition, we are at a stage where we can digitally transform a model into a constructed facility on a limited scale and on a component level, primarily in a laboratory or factory setting. However, from the advances this technology has made and the potential it exhibits, it is possible that by the middle of this century, we can 3-D print, at least some facilities, in-situ in a matter of hours or days by pressing “PRINT” button on a computer.

The coming years and decades will witness lots of development efforts on large-scale 3-D printers and ink (concrete mixtures) for these printers. This presents an opportunity for concrete materials scientists to develop new generation concrete mixtures, which are strong, durable, and long-lasting, by incorporating alternate binder materials and alternate aggregates, optimized through a combination of experimental research and computational modeling. The developments will also focus on incorporating alternate reinforcing materials in the cementitious ink and co-printing both the concrete and reinforcing steel in the same construction process to realize the full benefits of a concrete-steel composite system.

The 3-D printing in construction will require a workforce with integrated knowledge of materials, structures, robotics, and computer software and hardware. There is a need for a new academic curriculum at universities that can prepare a future workforce capable of overcoming the challenges of this technology.

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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