3D Printing in Construction, Mixture Characteristics, Strength, and Thermal Performance-Review

Amaal Al Shenawa and Poonam Mahadev Karoti
Construction Management Department
College of Architecture and Construction Management
Kennesaw State University
Marietta, GA
aalshena@kennesaw.edu; pkaroti@student.kennesaw.edu

Abstract

All industries have embraced three dimensions printing, which is shown to offer several advantages. This article examines the use of 3D printing in the construction industry. Concrete is the primary component when using 3D printing in a building; reinforcements are either seldom employed or not used at all. Although having many advantages, this building approach has some drawbacks. The substance utilized to make the printable paste combination is currently being researched because this is a novel technology. To meet the needs of 3D printing, material use, and mixing proportions have considerably different qualities from those of conventional building methods. As a fundamental need, three-dimensional printed concrete(3DPC) demands that an object be printed, buildable, resilient, and consistent. Knowing that 3D printing seldom uses reinforcement to increase strength, durability, or stability is crucial. This article offers a concise overview of all the applications, difficulties, and prospects for 3DPC. The article starts out with defining 3D printing before going on to discuss its prerequisites and challenges. It also examines the fundamentals of 3D printing in concrete, including its background, uses, and advantages. In this article, printing techniques and materials are thoroughly examined, and a material that is optimum for sustainability is suggested.

Keywords
3D concrete printing, Additive manufacturing, Construction, printability, mechanical properties

1. Introduction
The development of 3D printing in construction as a manufacturing technique has made it possible to manufacture complex structures and architectural ideas rapidly and precisely. Although the concept of additive manufacturing (AM) and 3D printing(3DP) has existed since the 1980s, it wasn't popular until the early 2000s that academics and builders began to take the technology seriously (Venkata Siva Rama Prasad 2022). In the field of construction, 3D printing has advanced quickly during the last ten years. Prior to 2014, 3DP was still in its infancy, and only a small number of significant demonstration projects were built using the technology. Most often, 3D concrete printing was used for landscape architecture, street decor, and other non-load-bearing maintenance buildings. The revolutionary progress of printing projects is as anticipated as the distinctive attributes of 3D concrete printing, even if several excellent engineering projects have been released since 2016 (Kazadi et al. 2022).
3D printing has a wide range of possible uses, from minuscule medical devices to massive infrastructural projects. It has already been used to create homes, bridges, and buildings, and it has a lot of potential for the future of design and construction (Pessoa et al. 2021). Computational modeling is widely used to assess the effect of process parameters to manufacture 3D printed items with high dimensional precision, consistent microstructure in terms of grain size, shape, and composition, and desirable material characteristics and mechanical qualities tailored to specific applications (Khan et al. 2020). The adoption of functional architecture and pre-assembly, the design and manufacture of pieces with complicated geometries, increased productivity, lower labor demand, sustainability and greater energy efficiency, and reduced construction and demolition waste generation are some of the most notable benefits of 3D printing (Robayo-Salazar et al. 2023).

A 3D design model can be created by stacking 2D printed planes using a technique called three-dimensional printing (3DP), which operates on a similar premise as 2D printing (Zhang et al. 2019). The development of concrete printing techniques and products, which slice and represent the object to be printed as multiple two-dimensional layers, typically uses 3D modeling software. Layer by layer, this data is transferred to a printing equipment to print the components (Strohle et al. 2023). A construction route must be created in the first phase of 3DP using a 3D-to-2D slicing tool to ensure the implementation of the technology. It initially creates flat, thin layers of a specific thickness out of the object's three-dimensional geometry, after which it plans the course of each layer. Each of these paths is built on a filling pattern and a contour line (Gosselin et al. 2016).

2. Current Progress

The traditional construction industry has demonstrated its effectiveness and dependability in constructing a diverse array of structures. Despite advancements in knowledge and technology, construction techniques have largely remained unchanged, resulting in a high environmental impact, reliance on labor during times of labor scarcity, and significant time and financial investments. As a result, residential housing costs have escalated in response to a growing population (Malaeb et al. 2019).

Modern additive or layered manufacturing in the building industry, known as contour crafting, was first invented in the late 1980s. Construction of buildings or structural components may be completed much faster and more effectively by implementing cutting-edge technology and 3D printing techniques (such as the use of computer guided grid structures) (Venkata Siva Rama Prasad 2022). Its distinctive layering manufacturing method also makes it possible to build components with a rather smooth surface finish. The innovation is that it shapes the material as it is placed using guides rather than formwork. The basic elements of this method are a concrete tank, a pipe with hose, a pumping system, a nozzle, and a robotic arm that points the nozzle in the x, y, and z directions (Khan et al. 2020).

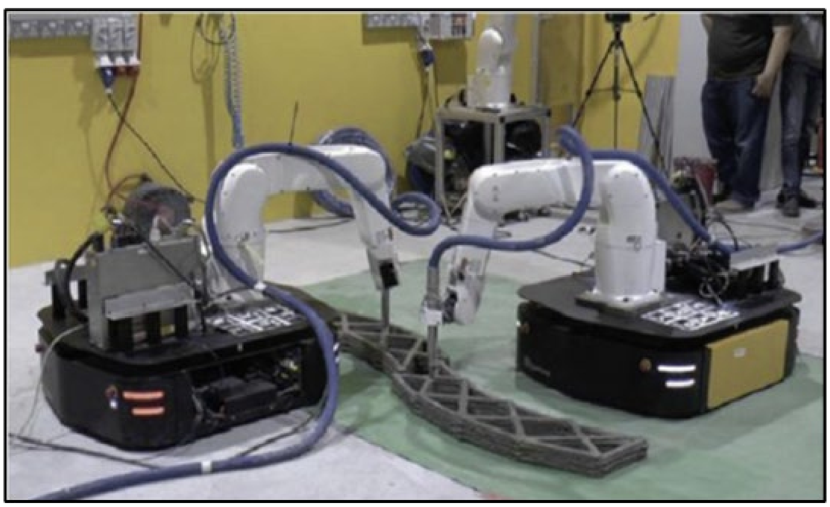

Figure 1: Robotic arm 3D printing of concrete (Prasad and Lakshmi, 2018; Rollakanti and Prasad, 2022).

To implement the additive manufacturing technology in concrete applications, many 3D concrete printing technologies were created. These technologies are classified into two categories: extrusion-based methods and powder-based approaches. Examples of extrusion-based manufacturing processes are Contour Crafting, Concrete Printing, and CONPrint3D, whereas D-shape Technique, Emerging Things, and Emerging Things are examples of powder-based manufacturing processes (Şahin, H. G. and Mardani-Aghabaglou 2022). For printing architectural models, D-shaped prints are frequently employed. These prints use powder deposition, which is selectively hardened to compact with the necessary thickness by adding layers of binder and fine aggregate. The roughly 300 preliminary shells that make up a fully assembled D-formed printing unit are installed on an aluminum box. During the building process, the printer goes over the printed area and applies binding materials. Once done, a few pieces of a loose precipitate deposit are dug. To react to the applied fluid binder, ground materials must first be mixed with powdered metal oxide (Venkata Siva Rama Prasad 2022). In a manner identical to the Z-Corp 3D printing technique, the powder-based D-Shape technology precisely deposits a binder over the powder or a sizable sand-bed. Sand plus magnesium oxychloride cement are the binding materials used in the D-shape approach. Figure 1 depicts the configuration of an extrusion-based 3D printer with two robotic arms (Rollakanti and Prasad 2022; Prasad and Lakshmi 2018).

3. Data collection

With the use of cutting-edge technology of 3DCP, the construction industry has potential for vast development. In this study, the aim is to thoroughly evaluate the most recent developments in 3DCP, its methodology, mechanical characteristics, strength, and thermal properties. A systematic search on Scopus using the TITLE-ABS-KEY option was conducted. Permutations and combinations for key words, "3D printing, concrete, additive manufacturing, properties, construction" were used and a total of 60 relevant papers were selected. These papers were selected by categories consisting of review papers, papers discussing the printability and mechanical characteristics, and also the thermal performance of 3DPC as shown in figure 2. The data gathered is thus explained in the paper.

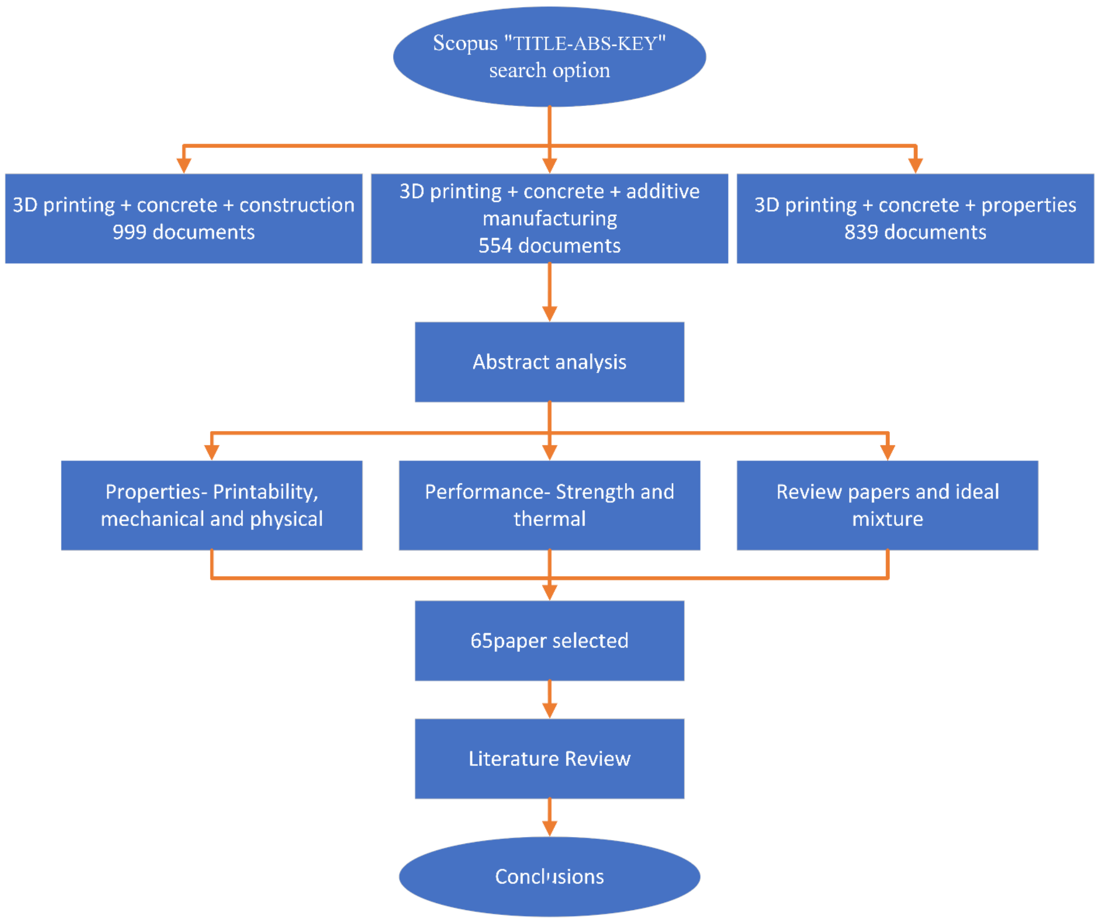

Figure 2: A schematic of data gathering methodology.

3.1 Key findings

The study and adoption of 3D concrete printing (3DCP) were initially documented in papers on Scopus dating back to 2010. However, research in this field experienced a significant surge starting from 2018 and has since been extensively explored in conjunction with other 3D printing materials and disciplines. As shown in figure 2, the principal topics discussed are the characteristics, strength, and mixture. Moreover, the research scope extends beyond these aspects to encompass areas such as strength enhancement, convenient printing, sustainability, experimentation, and standardization, among others. Literature review highlights the lack of resources for large scale printed structures and their study. Many challenges lie before developers and researchers to create a sustainable, durable, and printable mixture suitable for all kinds of weather.

4. Characteristics of 3D printed concrete

The creation of the ideal concrete mixture is essential to the success of 3D printing concrete, and it entails fulfilling a number of printing-related parameters. In order to create the ideal concrete mixture for 3D printing, (Robayo-Salazar et al. 2023) designed a step-by-step procedure, which is depicted in Figure 3 as a point of reference. The procedure entails figuring out the end structure's needed strength, choosing the right aggregate, figuring out the water-to-cement ratio, and altering the mix to make it operational. By using this procedure, it is feasible to produce concrete that is both pumpable and strong enough to support the necessary load. For 3D-printed constructions to have the accurate workability, strength, and durability, the right percentages of water, cement, and aggregate must be used. In the end, it is feasible to completely optimize the potential of 3D concrete printing to alter the construction sector by following the procedure described by them.

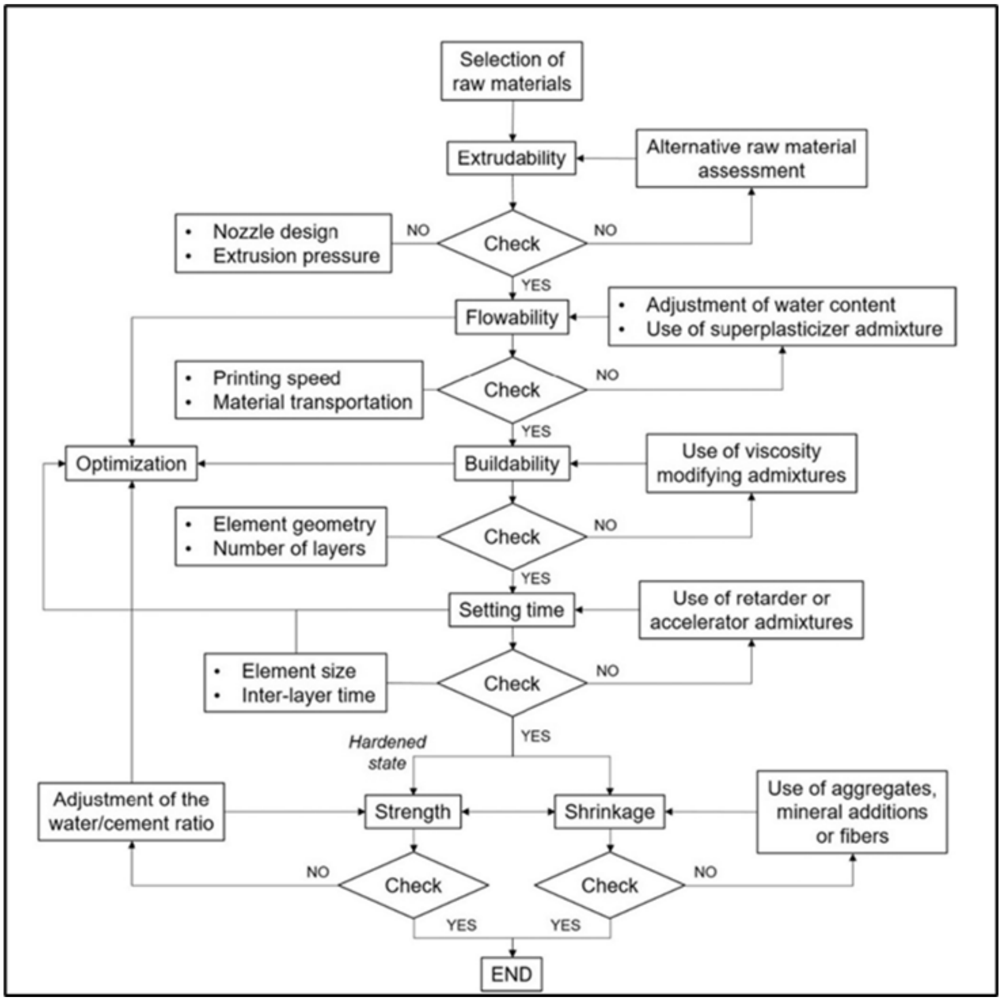

Figure 3: Design and optimization techniques for cementitious materials for 3D printing (Robayo-Salazar et al. 2023).

4.1 Physical characteristics

For the evaluation of ideal printable mixtures, the physical characteristics play a huge role in determining. These physical characteristics involved understanding the flow, extrusion, and layers strength of 3D printed concrete. The tests conducted by researchers to determine the printable range included flowability, extrudability, buildability, interlayer bonding and shrinkage tests. I) Flowability is the property of concrete mixture to maintain a constant physical state for easy extrusion. II) Extrudability is a test conducted to determine the appropriate extrusion range. III) Buildability explains the binding strength in the mixture to withstand its self-weights when layers are extruded on top. IV) Inter-layer bonding tests explore the adhesion of layers and the ability to form a bond without losing its shape and gaining strength. V) Shrinkage tests determine the amount of shrinkage in the printed mixture after extrusion. Water

content in the mixture contributes into understanding the outcome of shrinkage on the strength (Robayo-Salazar et al. 2023; Malaeb et al. 2019; Xiao et al. 2021; Şahin et al. 2021; Papachristoforou et al. 2018a).
One of a mixture's most crucial properties for 3D-AM is its extrusion capability, which is the capacity to convey easily and reliably from the delivery system while being pushed from a nozzle with the least amount of energy (Şahin, O., İlcan, Ateşli, Kul, Yıldırım, and Şahmaran 2021). The buildability of a cementitious mixture can be impacted by design features of the element, such as shape and/or the number of layers (height), hence this must be considered while evaluating a mix (Robayo-Salazar et al. 2023; Malaeb et al. 2019; Xiao et al. 2021). Extrudability and buildability are shown to be the most important fresh qualities, and these properties interact mutually favorably with workability and open time. The mix proportions, as well as the presence of superplasticizer, retarder, accelerator, and polypropylene fibers, have a considerable impact on these qualities (Robayo-Salazar et al. 2023; Malaeb et al. 2019; Xiao et al. 2021).

The concrete flowability and pumping parameters should be created for 3D printing technology to suit the needs of an adequate, unblocking concrete supply. To guarantee that concrete can be sufficiently fed to the printer without clogs, several test techniques for assessing the pumpability have been studied (Xiao et al. 2021). The kind and amount of superplasticizer admixtures used also significantly affect this feature, with these variables being the most important ones (Robayo-Salazar et al. 2023). Pumpability, extrudability, and buildability are all subsets of the broader concept of printability. Fresh printed concrete should have different rheological characteristics than regular concrete to meet these requirements (Robayo-Salazar et al. 2023).
The open time and flowability over specified time periods are measured using the slump flow test (Malaeb et al. 2019). The buildability of the material would be compromised by an extremely long setting time, resulting in the object slipping and collapsing during printing. Accelerating or retarding admixtures are used, respectively, to shorten or lengthen the time that cement mixes take to set (Robayo-Salazar et al. 2023). In order to ensure a constant flow of material through the pipes and rapid modeling of the item, the setup time must be long enough. After being deposited, the material needs to solidify fast in order to become sturdy enough to hold the upper layers. When altering the mix setting time, the size of the piece that will be printed and the time between layers are considered (Robayo-Salazar et al. 2023).

4.2 Mechanical characteristics

The mechanical properties of the concrete utilized in 3D concrete printing are crucial. The solidity of the concrete becomes essential since the printing method demands layering the building components rather than pouring it together at once. It is vital to choose a concrete mix with great compressive strength and strength development considering the setup time is expected to be quick and the printing process requires minutes to complete. By performing thereby, it is ensured that the 3D-printed construction will endure and remain capable of supporting the necessary load and keep its structural integrity as time passes. As a result, while creating the ideal concrete mix, the mechanical properties necessary for 3D concrete printing must be carefully considered. Nowadays, several lab studies on the mechanical characteristics and printability of 3DPC have been conducted (Malaeb et al. 2019; Xiao et al. 2021). To prevent deformations of deposited concrete, buildability must be attained after delivery and extrusion of the concrete. The resolution and printing efficiency in 3D PC technology are constantly determined by the size of the filaments being printed; smaller printed filaments can produce greater resolution but less efficient printing (Papachristoforou et al. 2018a).

The elapsed time, print time, and delay time needed for a layer of concrete mortar to harden sufficiently to support the weight of the top layers make up the construction time in 3DPC. Its strength increases mostly as a function of printing speed, the material's workability (or fresh characteristics), and the time elapsed before printing the subsequent layer (Nodehi et al. 2022; Diggs-McGee et al. 2019; Moelich et al. 2021). The materials utilized and their amounts must be carefully examined in order to obtain the appropriate toughened and fresh qualities. Both fresh and hardened concrete performance criteria must be met by a mixed design. There are numerous requirements that must be satisfied for the 3D concrete to have an "ideal" mix design, depending on whether the mix is designed for workability or compressive strength. For compressive strength, concrete's flowability and setting rate are maximized; nevertheless, for workability, pourability is prioritized and a sufficient setting rate is maintained (Malaeb et al. 2019; Strohle et al. 2023).
The mechanical characteristics of the printed structure in 3D concrete printing are essential for ensuring its structural soundness and capacity of sustaining the desired load. The mechanical qualities of a 3D-printed structure are significantly influenced by the strength of the concrete mixture used in printing. In order to establish the strength that a 3D printed construction can resist, researchers have carried out several investigations. Compressive strength, flexural

strength, 4-point bending, shear strength, and tensile bond strength were among the strength-related mechanical parameters that were examined (Asteris and Mokos 2020; Khan, M. A. 2020). The ability of an item to endure compression when an external force is applied is referred to as compressive strength (Şahin, H. G. and Mardani-Aghabaglou 2022). Given the fact that the structure created by 3D printing must be able to carry weight without collapsing or deforming, which is a crucial quality of the concrete utilized in the process. The ability of an item to withstand deformation under load is known as flexural strength. In essence, the 4-point bending test is a 2-point flexural strength test with added support. This test is frequently used to evaluate the 3D-printed structure's flexural strength. A material's ability to withstand twisting or shearing pressures is referred to as shear strength (Khan, M. A. 2020).

The strength of the bond between the layers of the printed structure is measured by tensile bond strength. In order to ensure that the printed structure maintains its structural integrity over time, a strong tensile bond strength is required. With the objective of supporting and retaining a building, the 3D concrete mixture used in printing must possess the required mechanical qualities. To make sure that the 3D printed construction can bear the necessary load and keep its structural integrity over time, the compressive strength, flexural strength, 4-point bending, shear strength, and tensile bond strength must all be carefully evaluated and tested.

5. Literature Review

A 3D-printed concrete structure's strength is a key aspect in evaluating whether it can sustain and hold up a building. Several academics have looked at the mechanical characteristics of 3D printed concrete structures throughout the years. The output of strength is explored in many evaluations that writers have conducted using 3D concrete mixtures, which will be included in this literature study. To ascertain their outcome on the strength of 3D printed buildings, many elements including mix design, printing parameters, curing conditions, printing speed, layer thickness, and fiber reinforcement have been investigated.

5.1 Strength in 3DPC

A recurring pattern in this research, however, shows that compressive strength of 3D printed concrete is significantly lower compared to cast concrete. This can be attributed to several factors, including interlayer bonding between layers printed, suboptimal water/binder ratios, and lack of reinforcement. These aspects have been the subject of several investigations to ascertain how they affect the compressive strength of 3D printed concrete (Ma et al. 2022; Yang, H., Che, and Shi 2021; Liu et al. 2021; Papachristoforou et al. 2018; Alghamdi et al. 2019). The following discussion includes examples of such research.

To reduce the 3DPC composites' setting time and boost their early age compressive strength, it is advised to utilize chemical admixtures (accelerator and viscosity modifying agents (VMA)) as well as mineral additives (silica fume and metakaolin). It is advised to employ the materials at their ideal rates without jeopardizing the interlayer adhesion and pumpability (Şahin, H. G. and Mardani-Aghabaglou 2022). For example (compression) based on water ratio, binder ration. In contrast to traditional cast fiber-reinforced concrete, the benefit is substantial. This is caused by a weakening of the bond between the printed layers in the case of steel fibers. By including fibers, the new concrete's yield stress is increased, improving buildability (Khan, M. A. 2020). Ilcan et al. (2022) used van shear tests in their research to assess the open-time performance as well as early rheological properties of mortar mixes in their fresh condition. Due to the variation in particular yield stress values brought on by the category and dimensional parameters of the handheld vane shear tool, the trial was conducted to assess the shear yield stress readings for geopolymer mortars.

In research by Papachristoforou et al. (2018) the workability of new concrete employed as an ingredient for additive manufacturing was assessed using four distinct trials. The compressive strength of hardened concrete was assessed on 40 mm cubes following a 28-day curing period in the humidity chamber. The category as well as the amounts of raw elements in the combinations have a substantial impact on compressive strength and ultraviolet protection, as was anticipated. The highest strength of 70 MPa was attained along a water-to-binder ratio of 0.4. Compressive strength decreases as the ratio of water to binder rises. When the Water/Binder ratio was maintained, the mixture with limestone and river sand filler generated the greatest strength values, accompanied by the mixture with 100% river sand. At the time portion of the cement was substituted with Fly Ash or Ladle Furnace steel Slag, the compressive strength decreased by 30%. UPV, a non-destructive strength estimation technique, was also evaluated and linked to the outcomes of the compressive strength testing.

Established by the extrusion technique of 3D printing, Chen et al. focused their study on the mechanical and rheological characteristics of hydroxypropyl methyl cellulose (HPMCI) water-reducing agent (WRA) with lithium carbonate Li2CO3 altered sulphoaluminate cementitious ingredients. The results of the research depict that HPMC significantly improves the viscosity and stress of cement paste, and that 3D structures must be built with plastic viscosities ranging from 1.650 to 2,53B Pa.s. In contrast, the cement paste combining WRA and Li2CO3 showed reduced apparent viscosity and shear stress. The setting time and rheological properties of 3D-printed cement paste along composite mixtures are also looked at utilizing response surface methods (RSM). The ideal hybrid admixture inclusions may give the 3D printing paste an improved deformation rate along with increased compressive strength. In summary, the use of mixtures offers a large capability for producing sulphoaluminate cementitious building materials that can be carefully regulated in terms of their rheological behaviors and printable qualities (Chen et al. 2018).
Liu et al. (2021) conducted a study on foam concrete to examine the effects of adding two substances, silica fume (SF) and hydroxypropyl methylcellulose (HPMC), as thixotropic and viscosity-modifying agents. The study found that adding HPMC and SF to foam concrete had advantageous benefits. HPMC helped the foam maintain its shape, and SF boosted the material's density, enhancing its tensile strength and durability. Overall, the study implies that the performance and usability of foam concrete in building projects may be enhanced by the combination of HPMC and SF. The volume water loss of the foam concrete was greatly decreased by HPMC and SF, which stopped the water from the concrete mixture from separating. The static yield stress, plastic viscosity, and dynamic yield stress of the foam concrete escalated as the dosage of HPMC and SF increased and as the resting period prolonged. While SF had a more substantial influence on the static yield stress, HPMC had a greater effect on the plastic viscosity and dynamic yield stress. These results imply that SF and HPMC possibly enhance foam concrete's stability, density, and rheological characteristics, thereby making it more appropriate for 3D printing applications. It is suggested to combine the material's tan and stack height in order to gauge the constructability of 3D printed foam concrete. The optimum static dynamic yield stress, yield stress, along with plastic viscosity ranges are 1113-1658 Pa, 66.4-230.1 Pa, as well as 2.08-3.71 Pa s, correspondingly, for 3D printed foam concrete along a wet density between 1550 and 1850 kg/m3. The compressive strength of the 1815 kg/m3 dry density 3D-printed foam concrete was 19.9 MPa, 28.5 MPa, and 24.6 MPa in testing directions Z, Y, and X, respectively.

Yang et al. (2021) conducted a study to investigate how the addition of nano-CaCO3 (NC) affects the freshly mixed and cured characteristics of 3D printed cementitious materials (3DPC) that use limestone powder (LS). The study aimed to understand the impact of NC on the properties of 3DPC, which could potentially enhance the performance of cementitious materials in the construction industry. The LS was replaced with 15% of the NC, and the remaining NC was added at rates from 0 to 3%. According to the results, adding NC improves the nucleation process, which speeds up Portland cement's hydration reaction. The strength and durability of the 3D printed cementitious materials may be enhanced by this acceleration. The study also discovered that the 15% LS addition reduced the yield stress and green strength while increasing its fluidity and vertical displacement of the freshly mixed 3DPC. These findings suggest that the inclusion of LS could enhance the material's handling and workability during 3D printing. The addition of NC significantly enhanced the fresh-state performance of 3DPC due to its high particular regions. However, mixtures with 15% LS exhibited lower compressive strengths & flexural compared to standard mixtures at all times. Combinations with 14% LS and 1% NC demonstrated superior strength properties at all durations compared to those comprising 15% LS.

Ma et al. (2022) researched the characteristics of uncured as well as cured aerogel-integrated concrete that are ideal for 3D printing. The most advantageous range for replacing aerogel for silica sand with a cementitious mixture range from 0 and 20% by volume in order to achieve the optimum printability, according to extensive testing. Three alternative approaches were used to evaluate how anisotropy influences the mechanical, physical, and thermal insulation characteristics in hardened concrete. The results showed that the cast specimens' compressive strength, which was 24.90 MPa on average, was moderately greater compared to the 3D-printed specimens, 3DCP-X, Y & Z, which were 23.63 MPa, 20.77 MPa, and 20.40 MPa on average in the specimen along X, Y, and Z directions, respectively. The thermal conductivity of the exemplar along the X-axis of the 3DCP-X was greater compared to those of the cast specimens (0.330 W/mK), while those along the Y-axis of the 3DCP-Y and the Z-axis of the 3DCP-Z was lower.

Ding et al. (2020) investigated the properties of the hardened material and used recycled/repurposed sand as an alternative to natural sand to print 3D concrete. The significance of repurposed sand substitute ratio, nozzle height, curing age, and anisotropic performance were examined using compressive testing, tensile splitting tests, as well as flexural tests. Additionally, the failure pattern and behavior of the layered and printed concrete under stress were documented using the digital image correlation (DIC) methodology. Significant quantities of unhydrated cement paste were present in the 3D-printed concrete using recycled sand. In comparison to specimens without recycled sand, this unhydrated cement paste was bonded to the recycled sand and produced a more moderate flexural strength. The 3D printed concrete with recyclable sand was also produced using an internal curing technique. As a result of this procedure, the recycled sand concrete's flexural and compressive strengths were lessened than those of the specimens without recycled sand. The flexural strengths, tensile splitting, as well as compressive of 3D-printed concrete developed with recyclable sand demonstrated a definite anisotropy. The strength of a material under pressure that causes it to bend or get squeezed from various directions was not significantly affected by the use of recycled sand in the manufacturing process. It did, however, have an impact on the material's resistance to pressures that pull it apart in various directions, making it less resilient in that regard.

The stress and viscosity precondition for 3D printing are varied from those for conventional cement-based materials; they show that the materials require to possess low yield stress as well as good flowability through the charging barrel via the nozzle, and that of freshly printed mixture requires to have a high viscosity and a quick setting time. Liu et al 202 developed the relationship between the components of cementitious materials and the materials' rheological characteristics (dynamic yield stress, static yield stress), formulating the relationship using the mix design technique, and identifying the best material composition to attain an equilibrium among high cementitious materials low dynamic yield stress and static yield stress. Slump test is a straightforward experiment used by researchers to examine the flowability as well as internal strength of a concrete mixture (Panda et al. 2019; Şahin et al. 2021; Ilcan et al. 2022; Giridhar et al. 2023).

5.2 Reinforcement in 3D printed concrete

When 3DPC building is compared to conventional construction, the lack of a strong integration approach for reinforcing is evident. A reinforcement system that can effectively manage automated printing while fulfilling the rheological requirements for simple concrete extrusion, buildability, and binding with the reinforcement is in great demand. Further exacerbating the requirement for an efficient reinforcing solution is concrete's propensity for brittleness and its poor mechanical performance in terms of tension and flexural strength. As a result, developing the engineering applications of 3D printing, development, and testing of reinforcing techniques appropriate for process automation and flexibility. Several research papers have shown that the strength of 3D concrete printing can be substantially enhanced through the incorporation of reinforcement. Various types of reinforcements have been employed for 3D printing, such as steel micro cable, U-nail, mesh, vertical insertion of bars, and short fibers, among others. Studies have reported positive results after the insertion of reinforcement, demonstrating significant improvements in compressive strength (Kazadi et al. 2022; Mechtcherine et al. 2019; Alonso-Canon et al. 2022; Nodehi et al. 2022; Lim et al. 2020). Examples of such studies and the observed strength changes after the insertion of reinforcement are discussed below.

The investigation conducted by Kazadi et al. (2022) over the course of 10 years looked at ten distinct reinforcing techniques utilized in 3D concrete printing. The usage of steel micro cable was discovered to boost the tensile outcomes by 290% among all the techniques utilized to make the blended components stronger. The interlayer shear performance would still be worse than other approaches, though. The interlayer shear strength may be escalated by 220% using the interlaminar U-nail. They do not interfere with one another when the two techniques are used with the proper fibers. This ought to be the most thorough method of enhancing the mechanical qualities of components made of 3D-printed concrete.

Use of fiber-reinforced polymers or wrapping steel tubes to boost performance may be an efficient strategy, 3D-printed concrete structural parts may encounter challenging stress states. Therefore, study has been undertaken on the triaxial mechanical characteristics of 3D-printed concrete. Ultra-high-performance fiber-reinforced concrete (UHPFRC) that is incorporated in the Z-direction, 3DP-UHPFRC, was examined for its triaxial behavior by (Yang, Y. et al. 2022). Mold-casting with UHPFRC was employed to create the reference sample. Using test results as a base, the failure criteria were evaluated as well as the mechanical properties and failure mode of the 3D-printed specimens. The experimental results displayed that MC-UHPFRC and 3DP-UHPFRC had identical mechanical properties, failure criteria, and triaxial failure processes. All three specimens of 3D printed 3DP-UHPFRC showed diagonal cracks when they were put under a triaxial load. The Mohr-Coulomb failure matrix was not particularly adept at predicting the outcomes when testing research samples produced without steel fiber. This is due to the fact that when specimens made by 3D printing were subjected to confining pressure, there was a definite nonlinear rise in strength that did not

agree well with the linear dependence of the Mohr-Coulomb criteria. However, for all 3D printed specimens, the Willam-Warnke along with Power-law failure criteria were more appropriate.
A potential strategy for creating concrete combinations that are both effective and ecologically beneficial is sustainable 3D printing of concrete. In this method, construction demolition debris and recycled aggregates are used as the initial raw materials for making concrete. By doing this, it encourages the effective use of natural resources and diminishes the environmental impact of the manufacture of concrete. Investigating the mechanical performance of sustainable concrete mixes made by 3D printing has significance in this instance.

Christen et al. (2022) developed a sustainable 3DPC-(RBA) by substituting the natural aggregate with reprocessed brick aggregate in a concrete mixture. Mechanical characterization examinations were conducted on both the selected RBA mix and the corresponding 3D printed mix for comparisons. The mechanical character development tests include direct tensile tests, compressive cube strength tests, and uniaxial compressive trial on 3D printed samples. The outcome of the mechanical characteristic's tests depicts that when RBA substitutes 64% of the natural aggregate in the mix, interlayer tensile 3DPC strength, the compressive cube strength, compressive 3DPC strength, and compressive 3DPC strength in two directions were each lowered. The interlayer tensile strength along with the captivity of compression of 3DPC specimens are axially dependent since there is inadequate fusion between printed layers. Ambient, print, material, and test factors can have an impact on compression's orientation dependence.
The effects of using recycled and natural coarse particles in 3D printed concrete compositions were studied by Rahul et al. (2022) Cube and beam samples prepared from carved from printed wall components were used to evaluate the mechanical properties. The analysis of mechanical properties demonstrates that the addition of coarse aggregates to both 3-D printed and mould cast samples partially decreases both flexural and compressive strength because of a substantially larger interfacial transition zone. Layer interactions result in printed samples having lower compressive strengths than mould cast samples, regardless of aggregate size.

5.3 Thermal performance in 3DPC

The thermal performance qualities of 3DCP have not received as much attention as its printability and workability, even though they are boosted in performance. It was discovered that the thermal performance depends on the binding strength and the gap between the printed layers. Concrete's density and porosity are strongly associated with its thermal conductivity (Ma et al. 2022).
An on-site test was carried out to evaluate the thermal overall achievement of an actual 3D printed concrete structure, as described in (Sun et al. 2021). Its capacity defects were identified along the infrared thermography technology. Thermal homes of the primary wall frame of the examined residence were intended with on-site tracking data. The effects picked out a noticeably non-uniform temperature dispensation at the exterior wall floor of the 3D printed concrete examined residence, that's in particular because of versions of printing direction and cross-phase design.
Suntharalingam et al. (2021) used Finite Element Models (FEM) in their study to examine the fire behavior of multiple categories of 3D printed concrete walls. In order to evaluate the fire suppression effectiveness of a variety of 3DPC wall designs (cavity, solid, and mixed) with typical fire circumstances, validated heat transfer FEMs have been expanded. The findings demonstrated that the solid 3DPC wall outperformed the 3DPC hollow wall without load bearing in terms of standard fire resistance. Despite the fact that the new 3DPC composite walls with Rockwool cavity insulation have better fire resistance.

6. Ideal Printable mixture

It was the objective of numerous authors to discover the optimum 3D printed concrete. These researchers conducted experiments using various compounds and different ratios. Use of components is not limited to the conventional concrete mixing ratios. Cement, fly ash, limestone, reclaimed brick waste, ordinary Portland cement, and other materials were used as binders. Superplasticizers were occasionally employed to speed up the cure process. The nozzle diameters of printers changed along with their size and kind.
Malaeb et al. (2019) discusses 3D concrete printing by examining how it has affected several engineering fields. The article primarily targets the construction materials industry by developing a concrete mixture that is satisfactory for 3D printing. It investigated the required printing strategy and offered an appropriate design to feed the printing device. The study team's 3D printer was capable of producing a sample consisting of a 77-centimeter wall and eventually varied structural shapes by changing on all three dimensions. The nozzle to print is one of the most crucial components, which developed to facilitate the process of extruding concrete. The 2 cm broad nozzle is connected to the top trowel and the side trowel, which trails behind it. Extensive testing with numerous materials led to the creation of an optimum blend that was ideal for 3D printing for a particular proportion. This combination had 125 g of cement, 80 g of sand,

and 160 g of fine aggregates, 0.39 ratio of water/cement. Additionally, 0.625 mL of a retarder and 1 mL of an accelerator were added to the mixture.

7. Conclusion

- An interesting new process called 3D printing in concrete is now the focus of a lot of investigation. Despite the advances made in the lab, the number of successfully completed large-scale efforts is still quite low. One of the main issues with this technology is the lack of standardization in terms of material combinations, equipment, and essential features.
- For successful 3D printing of concrete, the mixture should satisfy physical, rheological, and mechanical properties. These properties can be satisfied by making the mixture extrudable, buildable, flowable, open time, optimum strength, and strong adhesion.
- The choice of material, material strength, and interlayer bonding all affect the way 3D printed concrete conducts heat. The increased air concentration in foaming agent material mixes results in better heat resistance. The printed wall or structure, however, fails the thermal test because of the gaps in the layers if the interlayer connection is weak.
- Creating the ideal mixture for 3D printing is a huge challenge that depends on taking into consideration a number of factors, including strength, rheology, and thermal properties. If this technology is used to its maximum capacity, it might drastically reduce risks and costs associated with the construction industry while speeding up projects.
- Researchers undertook several tests to create a combination distinct from conventional concrete compositions. Researchers introduced or eliminated components like retarders, superplasticizers, additives, etc. depending on the desired qualities. Many researchers have also looked at creating 3D printing mixtures utilizing building debris. Despite studying several mixes, it is challenging to identify the one perfect composition. Every mixture fits the conditions of the experiment and fails for others. Therefore, standardization is essential to knowing the optimum needed features and materials.

References

Alghamdi, H., Nair, S. A., & Neithalath, N., Insights into material design, extrusion rheology, and properties of 3D-printable alkali-activated fly ash-based binders*, Materials & Design*, vol. 167, pp. 107634, 2019.

Alonso-Canon, S., Blanco-Fernandez, E., Castro-Fresno, D., Yoris-Nobile, A. I., & Castañon-Jano, L., Reinforcements in 3D printing concrete structures*, Archives of Civil and Mechanical Engineering*, vol. 23, pp. 25, 2022.

Asteris, and Vaseilios G. Mokos., Concrete compressive strength using artificial neural networks*, Neural Computing and Applications*, vol. 32, pp. 11807-11826, 2020.

Chen, M., Li, L., Zheng, Y., Zhao, P., Lu, L., & Cheng, X., Rheological and mechanical properties of admixtures modified 3D printing sulphoaluminate cementitious materials*, Construction and Building Materials*, vol. 189, pp. 601-611, 2018.

Christen, H., van Zijl, G., & de Villiers, W., The incorporation of recycled brick aggregate in 3D printed concrete*, Cleaner Materials*, vol. 4, pp. 100090, 2022.

Diggs-McGee, B. N., Kreiger, E. L., Kreiger, M. A., & Case, M. P., Print time vs. elapsed time: A temporal analysis of a continuous printing operation for additive constructed concrete*, Additive Manufacturing*, vol. 28, pp. 205-214, 2019.

Ding, T., Xiao, J., Zou, S., & Wang, Y., Hardened properties of layered 3D printed concrete with recycled sand*, Cement and Concrete Composites*, vol. 113, pp. 103724, 2020.

Giridhar, G., Prem, P. R., & Kumar, S., Development of concrete mixes for 3D printing using simple tools and techniques*, Sādhanā*, vol. 48, pp. 16, 2023.

Gosselin, C., Duballet, R., Roux, P., Gaudillière, N., Dirrenberger, J., & Morel, P., Large-scale 3D printing of ultra-high performance concrete–a new processing route for architects and builders*, Materials & Design*, vol. 100, pp. 102-109, 2016.

Ilcan, H., Sahin, O., Kul, A., Yildirim, G., & Sahmaran, M., Rheological properties and compressive strength of construction and demolition waste-based geopolymer mortars for 3D-printing*, Construction and Building Materials*, vol. 328, pp. 127114, 2022.

Kazadi, B., Yao, L., & Wang, L., In-process reinforcement method for 3D concrete printing: Status, potentials and challenges, *Proceedings of the 2022 International Conference on Green Building, Civil Engineering and Smart City*, pp. 394-402, 2022.

Khan. M. A., Mix suitable for concrete 3D printing: A review, *Materials Today: Proceedings*, vol. 32, pp. 831-837, 2020.

Khan, M. S., Sanchez, F., & Zhou, H., 3-D printing of concrete: Beyond horizons, *Cement and Concrete Research*, vol. 133, pp. 106070, 2020.

Lim, J. H., Weng, Y., & Pham, Q., 3D printing of curved concrete surfaces using adaptable membrane formwork, *Construction and Building Materials*, vol. 232, pp. 117075, 2020.

Liu, C., Wang, X., Chen, Y., Zhang, C., Ma, L., Deng, Z., Banthia, N., Influence of hydroxypropyl methylcellulose and silica fume on stability, rheological properties, and printability of 3D printing foam concrete, *Cement and Concrete Composites*, vol. 122, pp. 104-158, 2021.

Ma, G., Ruhan, A., Xie, P., Pan, Z., Wang, L., & Hower, J. C., 3D-printable aerogel-incorporated concrete: Anisotropy influence on physical, mechanical, and thermal insulation properties, *Construction and Building Materials*, vol. 323, pp. 126551, 2022.

Malaeb, Z., AlSakka, F., & Hamzeh, F., 3D concrete printing: Machine design, mix proportioning, and mix comparison between different machine setups. *3D Concrete Printing Technology*, pp. 115136, 2019.

Mechtcherine, V., Nerella, V. N., Will, F., Näther, M., Otto, J., & Krause, M., Large-scale digital concrete construction–CONPrint3D concept for on-site, monolithic 3D-printing, *Automation in Construction*, vol. 107, pp. 102933, 2019.

Moelich, G. M., Kruger, P. J., & Combrinck, R., The effect of restrained early age shrinkage on the interlayer bond and durability of 3D printed concrete, *Journal of Building Engineering*, vol. 43, pp. 102857, 2021.

Nodehi, M., Aguayo, F., Nodehi, S. E., Gholampour, A., Ozbakkaloglu, T., & Gencel, O., Durability properties of 3D printed concrete (3DPC), *Automation in Construction*, vol. 142, pp. 104479, 2022.

Panda, B., Lim, J. H., & Tan, M. J., Mechanical properties and deformation behaviour of early age concrete in the context of digital construction, *Composites Part B: Engineering*, vol. 165, pp. 563-571, 2019.

Papachristoforou, M., Mitsopoulos, V., & Stefanidou, M., Evaluation of workability parameters in 3D printing concrete, *Procedia Structural Integrity*, vol. 10, pp. 155-162, 2018.

Pessoa, S., Guimarães, A. S., Lucas, S. S., & Simões, N., 3D printing in the construction industry-A systematic review of the thermal performance in buildings, *Renewable and Sustainable Energy Reviews*, vol. 141, pp. 110794, 2021.

Prasad, V. S. R. and Lakshmi, T. V., Effect of bacillus subtilis on abrasion resistance of bacterial concrete, *International Journal of Applied Engineering Research*, vol. 13, pp. 12663-12666, 2018.

Prasad, V. S. R., 3D concrete printing technology current progress and future perspective: A state-of-the-art review, *Recent Advances in Civil Engineering: Proceedings of the 2nd International Conference on Sustainable Construction Technologies and Advancements in Civil Engineering (ScTACE 2021)*, pp. 27-39,2022.

Rahul, A. V., Mohan, M. K., De Schutter, G., & Van Tittelboom, K., 3D printable concrete with natural and recycled coarse aggregates: Rheological, mechanical and shrinkage behaviour, *Cement and Concrete Composites*, vol. 125, pp. 104311, 2022.

Robayo-Salazar, R., de Gutiérrez, R. M., Villaquirán-Caicedo, M. A., & Arjona, S. D., 3D printing with cementitious materials: Challenges and opportunities for the construction sector, *Automation in Construction*, vol. 146, pp. 104693, 2023.

Rollakanti, C. R. and Prasad, V. S. R., Applications, performance, challenges and current progress of 3D concrete printing technologies as the future of sustainable construction–A state of the art review, *Materials Today: Proceedings*, 2022.

Şahin, H. G., & Mardani-Aghabaglou, A., Assessment of materials, design parameters and some properties of 3D printing concrete mixtures; a state-of-the-art review, *Construction and Building Materials*, vol. 316, pp. 125865, 2022.

Şahin, O., İlcan, H., Ateşli, A. T., Kul, A., Yıldırım, G., & Şahmaran, M., Construction and demolition waste-based geopolymers suited for use in 3-dimensional additive manufacturing, *Cement and Concrete Composites*, vol. 121, pp. 104088, 2021.

Strohle, M., Sadique, M., Dulaimi, A., & Kadhim, M. A., Prospect and barrier of 3D concrete: A systematic review, *Innovative Infrastructure Solutions*, vol. 8, pp. 21, 2023.

Sun, J., Xiao, J., Li, Z., & Feng, X., Experimental study on the thermal performance of a 3D printed concrete prototype building, *Energy and Buildings*, vol. 241, pp. 110965, 2021.

Suntharalingam, T., Gatheeshgar, P., Upasiri, I., Poologanathan, K., Nagaratnam, B., Corradi, M., & Nuwanthika, D., Fire performance of innovative 3D printed concrete composite wall panels–A numerical study, *Case Studies in Construction Materials*, vol. 15, pp. e00586, 2021.

Xiao, J., Ji, G., Zhang, Y., Ma, G., Mechtcherine, V., Pan, J., Du, S., Large-scale 3D printing concrete technology: Current status and future opportunities, *Cement and Concrete Composites*, vol. 122, pp. 104115, 2021.

Yang, H., Che, Y., & Shi, M., Influences of calcium carbonate nanoparticles on the workability and strength of 3D printing cementitious materials containing limestone powder, *Journal of Building Engineering*, vol. 44, pp. 102976, 2021.

Yang, Y., Wu, C., Liu, Z., & Zhang, H., 3D-printing ultra-high-performance fiber-reinforced concrete under triaxial confining loads, *Additive Manufacturing*, vol. 50, pp. 102568, 2022.

Zhang, J., Wang, J., Dong, S., Yu, X., & Han, B., A review of the current progress and application of 3D printed concrete, *Composites Part A: Applied Science and Manufacturing*, vol. 125, pp. 105533, 2019.

Biographies

Amaal Al Shenawa is an Assistant Professor at Construction Management Department, College of Architecture and Construction Management, Kennesaw State University. Dr. Al Shenawa has more than seven years' experience in the academia and more than fifteen years' experience in the Construction Industry. She obtained her Doctorate degree in Mechanical and Energy Engineering from the University of North Texas and master's degree in civil engineering. Dr. Al Shenawa has more than 10 publications in international journals and national and international peer-reviewed conference proceedings. She is providing a review for several international journals and conference proceedings. She is the Principal Investigator and Co-Principal Investigator of multiple projects. Her research focuses one construction materials, sustainable materials, a save energy in construction.

Poonam M. Karoti is a recent graduate of the master's in construction management program from Kennesaw State University, GA, with a background in architecture from India and five years of experience in the field. Her goal is to bridge the gap between architects and engineers to create more effective and aesthetically pleasing building projects. Her research interests include novel technologies in the construction industry, such as 3D printing of concrete and virtual reality (VR), which she believes can revolutionize the industry and lead to more effective, cost-effective, and sustainable building projects. Poonam is excited to apply her knowledge and expertise to the field of construction and make a meaningful contribution to the industry's ongoing evolution.