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ISSN online 2545-2819
ISSN print 0800-6377

DOI: 10.2478/ncr-2022-0004

Received: March 31, 2022
Revision received: June 6, 2022
Accepted: June 23, 2022

Grading Material Properties in 3D Printed Concrete Structures



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ABSTRACT

Functionally graded materials (FGMs) describe composite materials with a gradual change in properties along one or several axes. A major advantage with this approach is the avoidance of discontinuities between different layers of material. 3D Printing offers the possibility to control

the material composition and spatial placement along the printing process to create structures with graded properties. However, there are very few examples of the application of this approach to 3D concrete printing (3DCP). This paper presents a review of the current approaches of and methods to grade the material properties of a 3DCP structure, as well as a review of similar methods used in other 3D printing processes. Finally, the potential applicability of these principles into concrete are presented and discussed.

Key words: 3D concrete printing, additive manufacturing, functionally graded materials, digital fabrication

1. INTRODUCTION

Concrete is typically graded in different qualities according to the requirements for each application. This gradation, however, is mostly restricted to discrete batches, making it increasingly difficult to include different values of the multiple properties in different parts of the same structure. In most cases, the low cost of the material makes the savings marginal when compared to the extra cost of multiple mixes and pours and the overall increased cost of logistics. This may no longer be the case when accounting for the environmental impact of concrete, as the assessment of the need to reduce the emissions associated with the material can make us reconsider the benefits of actively grading concrete structures [1]. Furthermore, automated construction techniques and digital building modelling technology have progressively enabled the implementation of advanced manufacturing technologies in concrete construction [2].

Nevertheless, the gradation of concrete has been studied in specific applications such as layered concrete where different grades of concrete are cast in discrete stages to optimise cement use and reduce the overall weight of the structure. The continuous gradation of material properties across the volume is known as functionally graded materials (FGM) and has been a specialised focus of research in aerospace and medical applications, where they serve specific requirements [3]. Current advancements in the field of digital fabrication with concrete allow the manufacture of non-standard forms with enhanced functionality at a lower cost when compared with conventional construction [2]. The introduction of Additive Manufacturing (AM), also known as 3D printing (3DP), in the concrete industry leads to the possibility to completely rethink the conceptualisation of the material [4] and represents an important opportunity for increasing the efficiency of the industry.

In recent years, several studies have suggested the possibility to introduce advanced fabrication methods into concrete technology. This paper seeks to situate and compare the state-of-the-art of the development of FGMs using AM and their applicability to concrete construction. The scope of this study is limited to extrusion-based additive manufacturing of cement-based materials, commonly referred as 3D concrete printing (3DCP), which is based on deposition of cement-based mortars that builds an object layer by layer using computer-controlled motion. The same precise movement can be used to actively control the composition and placement of concrete throughout the printing process. The application of 3DCP provides a framework to the development of functionally graded concrete, which can optimise the use of materials while providing extended functionality and therefore, can potentially reduce the environmental impact of concrete construction [5]. The research question for this study is therefore: How the concept of FGM can be applied into concrete construction using 3DCP? This review is organized in three

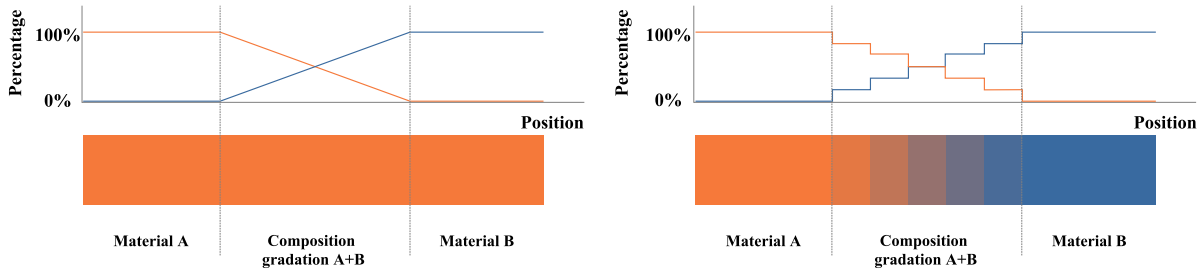
overlapping topics, and for each one, Scopus and Web of Science were searched for relevant papers. i) A general overview of the field of FGMs and associated methods using AM. Search terms for this section were "functionally graded materials, graded materials, material gradients, multi-material, microstructures, additive manufacturing, and 3D printing." ii) A specific review of the articles claiming the application of FGM to concrete. These articles included both "graded materials, multi-material, functional grading" AND "concrete printing, additive manufacturing concrete, 3D concrete printing, concrete technology". iii) The last section is a review addressing the challenges of modelling and simulating structures with variable properties . For this section, search terms were "3D printing, additive manufacturing, 3D printed concrete" AND "modelling, finite element, optimization". Section 2, below, provides an overview of FGMs and the use of AM to create them. Section 3 describes closely the concepts of microstructure and its applicability to different materials and processes. Section 4 depicts the state-of-the-art of the applications of FGMs in 3DCP. Finally, Section 5 identifies relevant methods and limitations for the design of FGMs.

2. FUNCTIONALLY GRADED MATERIALS

2.1 Definition of FGM

Functionally graded materials (FGMs) are advanced manufactured materials characterised by a continuous gradation of material properties through progressive changes in material composition or structure to achieve an intended function [6]. By embedding different qualities in a single material, further layering or assembly can be avoided, resulting in a superior performance and prevention of defects at the interfaces between different materials. First conceptualised as gradient composites in 1972, FGMs were defined as a continuous gradation of a certain characteristic of the composite material [7]. This concept was then extended to materials of varying composition across the volume of the object where a material grading is designed to perform a certain function. Grading refers to the gradual change of structural, mechanical, electrical, chemical, biochemical, and physical properties as opposed to layering of different materials on top of each other. Depending on the nature of the manufacturing process, this gradient can be continuous or discrete, where the latter has been considered a special case of FGM [7] also known as layered FGMs [6]. FGMs have long been observed in nature, where many natural structures exhibit spatial gradation of properties that respond to internal and external factors. For example, bone exhibits mesostructures that grow denser and change orientation in response to stress [8]. This is also the case of bamboo structures, where fibres grow progressively denser in response to stress [9].

The extensive field of FGMs emerges from early applications in the aerospace industry, but their use has extended rapidly into other research areas. Since the early development of FGMs has been related to high-performance requirements with very specific constraints, the high cost associated with these techniques has limited the scope to high-added-value industries. Across the multiplicity of definitions there are many nuances that change the scope of what is considered an FGM in different fields [10]. Accordingly, different classification schemes have been proposed depending on the manufacturing process [11], the materials involved [12], or according to particular features achievable with each technique [13]. Three main types of FGMs are described according to the type of gradient used: (i) composition gradients, (ii) porosity gradients and (iii) microstructure gradients.



a) Continuous gradient b) Discrete gradient

Figure 1 – Continuous and discrete gradients between two materials.

The first type of FGM is achieved by gradually changing the composition of the material along the spatial position. In this category it is possible to include all the processes that create progressive changes in material composition by changing mix ratios, adding particles or fibres. Figure 1a shows an example of a continuous material gradient between two materials while Figure 1b displays discrete stages. Porosity control is another common type of FGM where the size and distribution of pores can be designed to change the density or thermal properties of the material. In medical applications, for example in implants, porosity serves important physiological functions [14]. The use of microstructures has received a lot of attention in the last decades, as improved performance can be achieved by creating materials with lattices and small-scale features. This approach has been used to create structures with high strength and reduced weight. By successively changing the dimensions or shape of the microstructures the material properties can be seamlessly graded as a continuous object. A detailed discussion of this approach as well as its applicability to new fields will be further discussed in Section 3.

2.2 The use of 3DP to generate FGMs

Additive manufacturing (AM), commonly referred as 3D printing (3DP), is a manufacturing technology based on the precise deposition of material according to a digital model that enables the direct fabrication of complex geometries in an automated process. AM and 3DP can be used interchangeably in most contexts, but according to the ISO/ASTM 52900:2015 [15] AM refers to the layered placement of material according to a 3D model, while 3DP refers more broadly to any deposition-based fabrication process. AM is often preferred to refer to advanced systems used in the manufacturing industry while 3DP commonly refers to low-end systems, such as consumer grade Fused Filament Fabrication (FFF) desktop 3D printers. Accordingly, this paper uses the term AM when referring to the manufacturing industry whereas 3DP is used to refer to construction, as used in 3DCP.

From the early development of AM, the capabilities offered by the technology have been applied to the development of FGMs [16]. The use of digital control and the layering process enables the gradation of the material properties to be seamlessly incorporated into the manufacturing process, since the gradient arrangement is no longer directly constrained to a specific technique. This means that the desired material properties can be added to the digital model as an extra degree of freedom. AM-based methods for creating FGMs can be classified in (i) single-material FGMs that create density gradients by adjusting the porosity or spatial microstructures, and (ii) multi-material FGMs using different compositions in discrete phases or continuous gradients [17]. The application of digitally controlled materials has been extensively researched in the field of multi-

material AM [18, 19, 20]. In deposition-based 3D printing, the material is extruded through a nozzle that has to transverse the entire volume of the printed object, which can adapt the material properties for each location without interfering with the process. Some materials can be graded by controlling the parameters in the printing process, whereas the exact control method depends on the 3D printed method in use.

3. DEFINITION OF MACRO, MESO, AND MICROSTRUCTURE

The definitions of micro, meso, and macroscale depend on the field and material in use. These terms are relative and can overlap for different scopes within the same structure. In the development of FGMs, the use of microstructures refers, as in materials science, to the use of manufacturing processes to grade the internal structure of the material, such as the metallographic properties in different alloys [21]. Microstructures can strongly influence the properties of the material at the overall scale, and in this sense, the definition has been extended to larger scales than the microscopic structure usually meant in materials science. The creation of FGMs using AM establishes new processes that redefine the boundaries of these concepts. Some AM techniques can generate microstructural gradients at the scale of the grain of the material, such as in selective laser melting (SLM), where controlling the laser power and other parameters can produce different crystallographic structures with anisotropic properties [22]. For example, materials with a negative Poisson's ratio can be manufactured by 3D printing lattice structures that are called microstructures [23, 24, 25]. Extensions of this approach are also called engineered or architected materials which refer to the spatial placement of material and empty space designed to achieve performances not obtainable with existing materials [26] or specifically to the design of microstructures to improve the properties of the material [27].

Other applications extend the use of microstructures to the creation of infill lattices customised and distributed in the print volume to generate varying properties as shown in Figure 2. When contrasted with the types of FGMs described earlier (cf. Section 2), these techniques can be classified both as microstructure generation [28, 29] as well as porosity control [24]. In the scope of this paper, the distinction between porosity and microstructures is made in terms of geometry control. The use of porosity is reserved by the creation of density gradients resulting from material processes while the use of microstructures refers to spatial distributions achieved by the active control of the 3DP process.

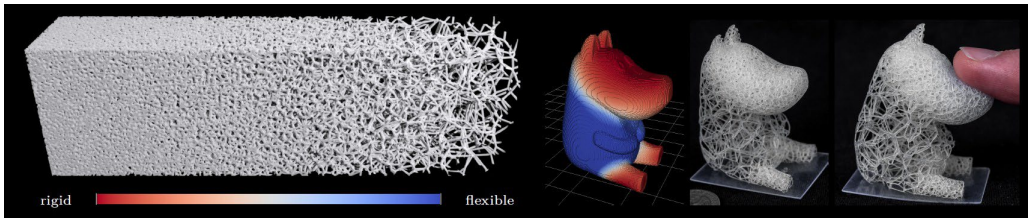


Figure 2 – An example of a 3D printed FGM by generation of variable microstructures to control flexibility. Reproduced from [28].

3.1 Applicability to concrete construction

Whereas concrete can be considered a homogeneous mass at the metre scale (10^0 m), its composite nature becomes evident at the millimetre scale (10^{-3} m) where its structure is

determined by the aggregate distribution in the cement paste matrix. In concrete material science, microscale commonly refers to the internal structure of the cement paste, normally at the micrometre scale (10^{-6} m) for which X-ray micro-computed tomography (μCT) and Scanning Electron Microscopy (SEM) are used [30, 31]. The introduction of 3DCP allows the definition of a mesoscale that refers to the scale of the printed filament, i.e., the extruded concrete strand, and their internal arrangement in the overall geometry [32, 33, 34], analogous to the use of the term in small scale 3DP processes [35, 36]. In 3DCP, the use of the macroscale can be defined to the overall shape of the object being printed, typically in the range of (10^{0} m); while mesoscale can be defined in the range of (10^{-1} m) to (10^{-2} m) and microscale in the range of (10^{-3} m) and below.

Mesoscale structures can be used to control a wide range of material properties along the overall geometry of the object. These properties include stiffness, strength, heat dissipation, heat transmission and others [37]. The introduction of mesostructures to the construction industry is aimed to fill the gap between the developments in materials science at the microscale and the work of structural engineers [38]. While developments in this scale have been reserved to specific applications such as metal trusses, new degrees of freedom offered by digital manufacturing can be used to create optimised substructures at different scales. The same approach can be applied to 3DCP with the use of mesostructures to control the mechanical properties of the printed component [33, 39]. The homogeneous infill structure can be graded to match the expected structural performance. Many authors have studied the adaptation of these internal infill structures to the different stresses along the print, although these studies are yet to be applied into full-scale construction [29, 32, 40].



Figure 3 – An example of controlled segregation by rotating the fresh mix on a lathe. Reproduced from [45]

4. FUNCTIONALLY GRADED 3D PRINTED CONCRETE

4.1 Current methods for functionally graded concrete

The initial development of FGMs is closely linked to the development of advanced manufacturing methods, and therefore their classification responds to the manufacturing industry and their applications into different fields. The use of concrete as a casting material limits the implementation of FGMs to different batches, by successive horizontal layering or specially

designed moulds with vertical separators for different mixes. A detailed overview of the methods for functionally graded concrete is presented in Torelli et al. [5]. However, this study does not include other AM methods based on the controlled addition of particles or fibres. Several studies have demonstrated the advantages of using functionally graded concrete to selectively improve the material properties of concrete to meet specific design requirements without over or under specifying the entire batch. This also allows solving conflicting requirements without making a compromise on either end. Applications for functionally graded layered concrete include fibre reinforcement for pavements [41], low-permeability layers for reinforcement protection [42], beams with layers of fibre-reinforced lightweight concrete [43], and beams with a layer of high-volume fly-ash concrete [44]. Additional methods include controlled segregation, in which fresh concrete separates in non-homogeneous properties by the application of external forces, as shown in Figure 3. Graded spraying offers another possibility to create gradients by using two nozzles simultaneously with different mixes and varying the mixing ratios [45]. This approach was further developed in [46] where functionally graded concrete beams were manufactured using a stepwise gradation of increasing porosity. This method can be classified today as 3D printing using material jetting (shotcrete) [47], which is beyond the scope of this paper.

4.2 Functionally graded 3D printed concrete

The introduction of 3DCP allows the creation of structural members with higher complexity without the associated costs of customised formwork. This increased complexity can be applied to the development of materially efficient shapes. Another fundamental advantage of the digitalised process is the possibility of automation. As the manufacturing instructions are fully contained on a digital description, the process can be driven seamlessly from the digital model, closing the gap between Computer-aided design (CAD) and manufacturing (CAM). 3DCP allows the generation of continuous gradation by digitally controlling the composition or disposition of fresh concrete during the printing process. Since concrete is a composite material, the mixing proportions for each of its components can be graded as the material is deposited in different parts of the print [48]. However, different mixes may result in very different rheological properties that can present a challenge to the 3DP process. Another constraint is that the methods for grading concrete should be compatible with the continuous extrusion required for 3DCP since additional steps can counteract the benefits of the automated process. In this section, a new classification is proposed to group different applications to functionally grade 3D printed concrete, divided in the following subsections: 4.3 “Variable mixing ratios”, 4.4 “Variable addition of particles”, and 4.5 “Varied densification”.

4.3 Variable mixing ratios

The properties of concrete can be specified by adjusting the mix proportions to meet particular requirements. Under this principle FGMs can be created by digitally controlling the material proportions to achieve a variable material mixture. This can be done by creating different mixtures with specific material properties that are combined during the extrusion process. By digitally controlling the mixing ratios the material properties can seamlessly transition between the individual properties of the starting mixes [49]. While some studies have mentioned the possibility of controlling the concrete mix in 3DCP [48, 50], only a few actual examples teams have been developed into actual applications. The use of multiple concrete mixes greatly increases the complexity of the system as specialised equipment is required to convey and control two different mixes simultaneously. This has been mostly developed by Craveiro et al. as a proof-of-concept

using other materials [51, 52], and then applied to 3DCP by combining two different mortars with different aggregates and controlling the mixing ratios along the print [53]. Although this is similar to the method presented in Section 4.4, here the lightweight aggregate is previously added to the mix and the gradation is made by controlling the mixing ratios of different materials.

Another example of this approach is the active rheology control developed by Reiter et al. [54] that changes the amount of accelerator in real time to control the setting time of concrete. This has been applied in different applications using digital fabrication with concrete by Anton et al. [55, 56, 57]. This approach enables the adaptation of properties of fresh concrete from casting to 3D printing material, which can be considered functionally grading. The challenge with this approach is maintaining a compatible rheology for different mixes to match the printing settings. Variations in the pumping ratios of the two mixes and their time dependency also create a challenge to ensure the consistency of the rheological properties of the two mixes.



Figure 4 – Functionally graded 3D printed concrete by variable addition of lightweight fillers within higher ratios of insulating material away from the centre. Reproduced from [62]

4.4 Variable addition of particles

The functional gradation of concrete can also be achieved by controlling the addition of particles during the printing process. This approach can be divided between two main types of particles: (i) the use of reinforcement fibres and (ii) the addition of lightweight fillers. In the case of reinforcement fibres, the base mix represents the lower bound of the material gradation, while a higher concentration of particles corresponds to improved tensile strength.

Selective addition of fibres has received the most attention, but the same principle can be potentially extended to the addition of steel fibre links or other discrete reinforcement units. Ahmed et al. [58] presented a comprehensive study where the effect of variable addition of reinforcement fibres and lightweight aggregates mixed with the printing material, and fibres added in between layers of freshly printed concrete. The results show a significant improvement in ductility, especially when adding glass fibres at the print head [58]. Gebhard et al. also studied the impact of interlayer fibres as secondary reinforcement for 3DCP beams [59]. Larger aggregates can also be added in varying quantities to improve the mechanical resistance of concrete. The effect of large aggregates in 3DCP has been investigated in [60], however this study did not consider any variable gradation. The implementation of an on-demand mixing system is

particularly challenging due to the differences in the pumpability of concrete mixes with different maximum particle sizes.

The second approach is the incorporation of lightweight fillers into the mix, a procedure that reduces the density of the print material. Duballet et al. [61] investigated this approach where the addition of lightweight aggregates reduces the density and improves the thermal insulating capabilities of concrete. The resulting sample shown in Figure 4 uses a core with pure mortar and uses increasing ratios of insulating material for each layer closer to the walls. Ahmed et al. presented an airborne system to transport particles to the mixing nozzle, which successfully graded the density of concrete samples, although a higher volume of particles is necessary to achieve significant reductions in density. The density reduction reduces the dead load of the structure and the mass needed to be transported and lifted in the case of prefabricated structures, which needs to be balanced with the negative impact in the compressive strength of concrete.

4.5 Varied densification

FGMs can be also achieved from a single source of material by controlling the deposition process to create structures with varying degrees of porosity or average density. As discussed in Section 3, 3D printing technologies offer the possibility to create structures at different scales: from random entrapment of air at the microscale to manufactured structures at different scales. 3D printed elements are most often manufactured as shells with internal infill structures, which can reduce the overall weight and optimise the use of material. The internal structure can be optimised to follow the expected loads in the print [23, 24]. By manipulating the print paths, a gradation of the material density can be achieved by creating mesostructures throughout the print. This enables the production of functionally graded 3D-printed concrete structures without the use of specialised equipment. In this approach it is possible to classify methods from the controlled generation of voids at the millimetre scale, to the introduction of variable infill patterns or mesostructures in the range of decimetres and potentially metres. The progressive introduction of air can be used to reduce the overall weight and material use in regions with lower stress requirements, as the air content reduces the strength of concrete.

Although there are examples of this approach in other materials [63], the implementation of single-material FGMs with varied densification has received little attention in the field of 3DCP. In Tay et al. [64, 65] an experiment is presented as functionally graded concrete by 3D printing using different extrusion parameters. Using topology optimisation, the model is divided in solid and void regions, which are then translated into solid and support parameters for 3D printing. Support regions correspond to the same print paths printed at a higher speed resulting in a thinner extruded filament. However, there is a limited range of variation in the filament dimensions that are limited by the extrusion speed [66].

4.6 Material limitations

The application of FGM methods to concrete construction increases the complexity of the 3DCP system that can extend the printing time or introduce points of failure in the system. Overall, the introduction of functionally grading concrete presents two main challenges for 3DCP: (i) The development of methods for efficiently varying the composition of concrete during the printing process, and (ii) ensure the compatibility of those methods with the time dependency of the mix. The rheological properties of fresh concrete can be affected by varying mix compositions or the

inclusion of fibres or particles which should be controlled to ensure the printing quality. Conversely, differential drying shrinkage maybe alleviated by the smooth gradation of material properties in functionally graded concrete, as sudden changes at the interfaces may be avoided. While many of the current methods show promising results, further development and standardisation is needed before they can become reliable methods for production. Currently, there are no standard procedures specifically developed for 3D printed concrete, and specialised equipment needs to be further developed for achieving functionally graded 3DCP. Although in a very early research stage, methods based on the varying densification by manipulating the print path and process parameters present the advantage of not requiring additional equipment.

5. DESIGN AND MODELLING OF FUNCTIONALLY GRADED CONCRETE

The existing methods for designing concrete structures have been largely shaped by the historical development of concrete as a casting material. Although optimisation methods allow the design of complex geometries for specific load cases [67, 68] the increased complexity is often constrained to what can be done with traditional building techniques, as the extra cost of customised fabrication can make the proposed optimisation impractical. Although some systems feature discrete deposition of multiple materials, they are not suitable for the production of spatially variable physical elements with gradual spatial change [69]. When referring to design, as in most 3DP structures, it is generally restricted to the overall geometry of the element. Furthermore, existing 3DP technologies are most commonly used to manufacture elements with uniform material properties. While structural optimisation is the most common design objective, the same tools can be set up to multiple goals, like considering structural and thermal performance at the same time [62, 32].

Hence, the introduction of advanced manufacturing technologies in the construction industry requires the broadening of the scope of the design to take advantage of the full potential of their application. As the design of FGMs respond to functional requirements, the integration of effective workflows between Computer-aided design (CAD) and Computer-aided engineering (CAE) software is critical to analyse and optimise the design objectives prescribed. The development of innovative manufacturing technologies requires higher control of the printing parameters that in most cases are specified in close relation with the design. Although analytical models have been developed for common structures and gradients [3] the application of FGM to concrete requires the adaptation of these methods. Additionally, the introduction of 3DCP allows for higher geometrical complexity that would limit the applicability of analytical models in favour of numerical simulations. Therefore, numerical simulations play a major role in the design of FGMs as the arrangement of gradients respond to specific functional requirements.

5.1 Numerical simulations

In order to prevent collapse, a proper assessment of material behaviour plays a critical role as it directly influences buildability. The rheological requirements for 3DCP involve low to zero slump and therefore special tests are required to characterise the printability. Several models have been developed to analyse the mechanical behaviour of fresh concrete during the printing process. An analytical model proposed by Rousell [70] is based on material rheology. A mechanistic model is developed by Suiker [71].

Numerical models have received the most attention, mostly based on the finite element method (FEM) that have become widely used for simulating the incremental printing process and the strength development of the material. In this approach, the mechanical behaviour of fresh concrete is most often modelled using the Mohr-Coulomb yield criterion with a time-dependent development of the material properties [72]. This requires an experimental characterisation of the mechanical properties, especially the early age properties of fresh material. Improvements of this method include a damping mechanism to increase the robustness of the simulation [73]. Furthermore, the modelling of 3DCP structures contains several challenges to translate the print paths into a model that allows the correct settings in the FEM software. Sharp edges and self-intersecting print paths create topological problems that impede the simulation. Voxel-based methods offer a simplified approach that create less accurate simulations but are robust against these issues [74]. The multiple forces and parameters involved in the deposition have also been studied with computer fluid simulation (CFD) methods that offer higher accuracy, but their higher computational requirements make them not suitable for full-scale simulations [75, 76]. Still, complex features such as material bridging or self-intersecting print paths have not been incorporated in the numerical models. By applying the results of finite element analysis and adapting the material properties according to the expected stresses it is possible to formulate optimised structures with increased complexity.

5.2 Software limitations

With the introduction of 3DP the material gradation can be specified independently of the geometry of the object. This implies a challenge to the use of boundary representation modelling to describe solids with non-homogeneous properties. These constraints have been addressed in multi-material printing, where the use of voxels allows the 3D representation of the different material properties using discrete spatial units [77]. Still, these tools are specialised and have not been developed beyond the experimental setups. Further development of digital tools is necessary to increase the availability of this technique.

6. CONCLUDING REMARKS

The introduction of 3D printing into concrete construction industry can facilitate the manufacturing of elements with extended complexity without the increasing the costs of custom-made formwork. This increased complexity can be used to create optimised structures with reduced material use or to deliver extended functionality. However, the complexity of the structure is generally limited to the geometry of the outer shell, to which a regular infill lattice is uniformly applied. The further inclusion of mesostructures and tool path generation to the design domain make the material properties another design variable to be considered. This is relevant for both optimisation goals and as an extension of the design possibilities of 3DCP elements.

This paper presents a review of the current methods for implementing functionally graded concrete through 3D printing. Although these studies are still in a very early stage, several development routes have been suggested to create 3DCP structures with functional grading, that could potentially take advantage of the digital process to create structures with optimised structural and thermal properties. In this study, several advancements in FGMs using 3DP are discussed as potential routes for further developments applicable to concrete construction. By controlling the composition or spatial disposition of the material throughout the printing process the design can be further extended to the gradation of material properties in different parts of the

print. The use of 3DCP to produce functionally graded concrete structures represents an opportunity to optimise material efficiency and enhance the digital modelling to prescribe material properties into the design. This study proposes a definition of what can be referred as micro, meso, and macroscales as well as a classification framework for different types of functional graded concrete. Although these studies are still in an early stage, several development routes have been traced to create 3DCP structures with functional grading that take advantage of the digital processing to create structures with special properties. Several advancements in 3DP to create FGMs are suggested as potential approaches applicable to concrete technology.

Moreover, the development of advanced concrete materials needs to be accompanied by corresponding development of appropriate methods for structural analysis to ensure their implementation in the industry. Prior studies have noticed the potential to apply FGM methods into concrete construction. However, further development of the technology should be achieved before the benefits can offset the additional costs of processing and equipment. Further research is also needed to evaluate the scalability of these technologies into full-size construction, as well as the development of standardised processes, before widespread use can take place.

ACKNOWLEDGEMENTS

The project has received support from Hesselmanska Foundation, the Development Fund of the Swedish Construction Industry (SBUF) and the strategic innovation program Smart Built Environment (2020-00257), which is part of the strategic innovation areas initiative funded by Vinnova – the Swedish Innovation Agency, Formas – a Swedish Research Council for Sustainable Development and the Swedish Energy Agency.

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