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Use of 3D printing to create multifunctional cementitious composites: review, challenges and opportunities

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Abstract

Additive manufacturing has been a topic of interest in the construction industry for the past decade. 3D printing of concrete structures promises great improvements in construction efficiency, waste reduction, and shape optimization. Another field where additive manufacturing offers opportunities is on the material level of cementitious composites. Techniques developed in other fields can be used to create multifunctional cementitious composites beyond what is possible with conventional technologies. This letter reviews recent developments in the field. Different applications are discussed: creating reinforcement for cementitious composites, creating capsules and vascular networks, and cementitious composites with superior mechanical behavior. Challenges for further research and practical applications of such materials are also discussed.

Keywords: 3D printing; Cementitious composites; Self-healing; reinforcement

1 Introduction

A major possibility for innovation in the construction sector comes in the form of 3D printing. In recent years, development of additive manufacturing techniques is expected by many to lead to a “new industrial revolution” [1]. In general, 3D printing involves an additive manufacturing process whereby objects are made layer-by-layer following a series of two-dimensional slices. Complex objects and shapes, usually designed using CAD software, can be produced easily and with high accuracy. First approaches involved manufacturing of plastics [2], but at present also metals [3] and ceramics [4] can be used as base materials for 3D printing.

Initial focus of 3D printing technology was rapid prototyping and precise manufacturing, especially for use in mechanical and biomedical fields [5, 6]. In recent years, 3D printing of concrete structures has been undergoing rapid development [7]. Most approaches involve an extrusion-like process, whereby concrete is prepared and mixed as usual, and a concrete pump is guided to produce the desired structure [8-10]. Other, somewhat less developed approaches include shotcrete 3D printing [11] and powder bed concrete 3D printing [12]. Most studies of concrete 3D printing focus on development of large printing systems capable of producing entire houses and buildings. The expected advantage of using such technology compared to traditional construction methods is rapid construction and freedom of form. The emphasis is thus on construction speed and reduction in labor costs, not necessarily the improvement of the material itself.

Another possibility of utilizing 3D printing technology is on the material level of cementitious composites. Compared to 3D printing of concrete as described above, this field of research has been relatively less explored. Nevertheless, such approaches offer unprecedented opportunities. In many cases, we could directly use 3D printing technologies developed in other fields to enhance some aspects of cementitious materials. The main idea behind this development is that, *with 3D printing technology, we can develop cementitious composites that cannot be made using conventional methods*. This could lead to significant improvements in properties such as strength, toughness, or thermal properties. Furthermore, 3D printing could enable us more freedom in the development of multifunctional cementitious composites. This letter provides a short review of current developments related to use of 3D printing for creating cementitious composites. In addition, some opportunities for future developments are highlighted.

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2 3D printing of reinforcement

Cementitious materials are known to be quasi-brittle with high compressive but moderate to low tensile strength [13]. To overcome their low tensile strength, but also to control the cracking of the cementitious matrix, some form of reinforcement is necessary. Essentially, steel reinforced concrete and ferro-cement are cementitious composites with continuous reinforcement. The use of continuous reinforcement, however, requires careful placement and qualified labor, resulting in high costs. Although steel reinforced concrete is widespread, the labor-intensive placement of reinforcement was one of the limiting factors for the wide practical applicability of ferro-cement (although in recent years, an alternative in the form of textile reinforced concrete – TRC – with continuos reinforcement is becoming increasingly popular [14, 15]). To overcome this issue, cementitious composites with discontinuous reinforcement in form of discrete fibers have been developed. Fibers are added during the mixing process of concrete simply as another dry ingredient of the mix, resulting in their (presumably) random distribution when a reinforced concrete element is cast. This procedure results in minimal effort in terms of labor, but the developed composite is far from optimal in terms of material use and mechanical properties. In addition, unintended heterogeneities and weak spots may occur in fiber reinforced concrete as a consequence of the construction methods used [16].

In recent years, 3D printing techniques have been used as a way of optimizing both continuous and discontinuous reinforcement. In the following paragraphs, these efforts are described.

2.1 Discontinuous reinforcement

Recently, attempts have been made at creating reinforcement elements using 3D printing techniques. Different 3D printing techniques and base materials have been explored, and the influence of design and printing parameters has been highlighted. The studies focus on two groups of base materials which are also commonly used for concrete reinforcement: polymeric and metallic base materials. These two classes of materials are also on the opposite side of the spectrum in terms of mechanical properties: while both can have tensile strength that is significantly higher than that of cementitious materials, the elastic modulus of polymeric materials is lower while the elastic modulus of metallic materials is higher than that of cementitious materials.

One of the main advantages of using 3D printed reinforcement, compared to conventional reinforcement in this case, is the possibility to manipulate the bond between the reinforcement and the cementitious matrix. Bond between (discrete) reinforcement and the cementitious matrix is governed by adhesion, friction, and mechanical interaction. Additive manufacturing is especially suitable for manipulating the mechanical bond. Mechanical interlocking of the 3D printed reinforcement and the cementitious matrix can be tailored through creating different kinds of ribs, similar to the way ribbed reinforcement bars are different from plain bars (a very simple example is given in Fig. 1). However, additive manufacturing offers possibilities for creating much more complex rebars, as described below.

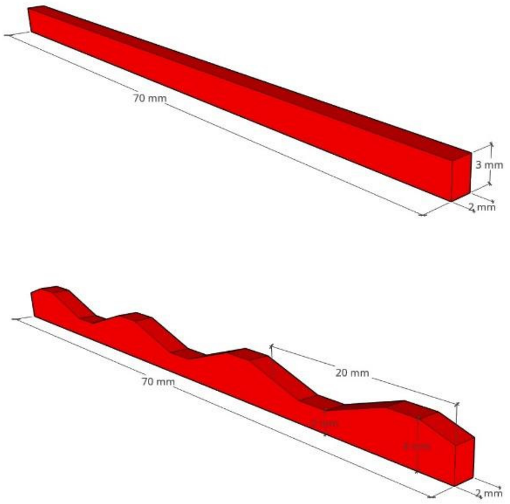

Figure 1. Examples of discrete 3D printed reinforcement bars: (top) with a rectangular cross-section; (bottom) with a "wavy" profile intended to increase mechanical interlocking [17] , in analogy to plain and ribbed steel rebars.

Farina et al. [18] investigated the possibility of printing discrete reinforcement bars using PolyJet 3D printing of liquid photopolymers through the Objet500 Connex printer. As a base material, they used a photopolymer transparent resin Fullcure 720, which has a tensile strength of 50-65 MPa, and a modulus of elasticity of 2000-3000 MPa. The 3D printed bars were then used as flexural reinforcement in mortar which was then tested in three-point bending. Reinforcement bars with a smooth and a rough surface were prepared. In case of the smooth reinforcement bars, actually, some roughness was also present on the surface as a result of the additive manufacturing process. On the other hand, reinforcement bars with a rough surface had an “engineered” roughness coating on the lateral surface based on the Koch snowflake (described in detail in Fig. 4). While reference specimens (i.e. non-reinforced) showed brittle failure after the crack initiation as expected (Fig. 2 left), the effects of 3D printed reinforcement were clearly visible. Specimens with smooth reinforcement showed an approximately constant residual load bearing capacity in the post-peak regime (Fig. 2 middle). On the other hand, specimens reinforced with rebars with a rough surface show a marked load drop after the peak load, followed by a hardening branch leading to a second peak, and finally a softening branch leading to specimen failure (Fig. 2 right). The failure modes were also different in these two cases: specimens with smooth rebars failed in bending, while specimens with rough rebars failed in shear.

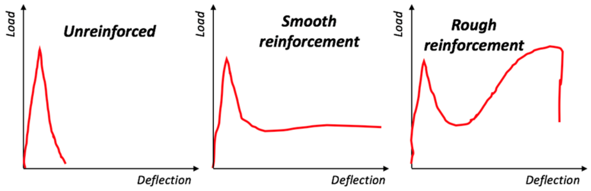

Figure 2. Schematics of load deflection curves of mortar bars reinforced with 3D printed polymeric bars subjected to 3-point bending (after [18]).

Stay-in-place formworks made using different materials for concrete elements have been proposed in the literature, including SHCC for crack width control [19], textile reinforced concrete for shear reinforcement [20], fiber reinforced polymer for column confinement [21], and knitted textile for shell bridges [22]. Building upon these developments and 3D printing technology, Katzer and Szatkiewicz [23] proposed a different approach: by means of 3D printing, a stay-in-place plastic formwork can be created, which would also function as flexural and shear reinforcement. The formwork could also contain additional reinforcing elements, such as ribs (Fig. 3). This formwork would then be filled with conventional or self-compacting concrete. The authors suggest that this approach is practically feasible in relatively short term since both technologies (i.e. 3D printing of plastics and casting of concrete) are very mature. In their preliminary study, they used a table top commercial 3D printer to print lab-sized molds using acrylonitrile-co-butadiene-co-styrene (ABS) plastics. These formworks (with different additional ribs) were then filled with regular mortar. Flexural testing of such composite specimens showed encouraging results, in certain cases resulting in doubling of the flexural strength compared to reference (i.e. unreinforced) mortar specimens.

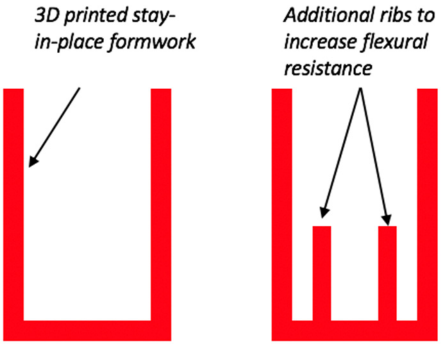

Figure 3. Concept of a 3D printed stay-in-place formwork which acts as reinforcement, after [23].

Farina et al. [18, 24, 25] also studied the effect of 3D printed metallic reinforcement in mortar. Their work involved the use of electron beam melting (EBM) to manufacture reinforcement using the titanium alloy Ti6Al4. In their earlier works, a studded surface was manufactured on the reinforcement to improve the physical bond [18, 24], which is in a way similar to using ribbed reinforcement in reinforced concrete. In their latest work, they manufactured metallic reinforcement with a hierarchical roughness pattern, i.e. a fractal Koch snowflake (Fig. 4). Such 3D printed reinforcements are aimed at inducing multiscale interlocking phenomena at the interface with the matrix material, due to their complex and multiscale geometry. The authors suggested that the bond strength between the reinforcement and the matrix will increase as the complexity of the Koch reinforcement increases, as a result of the increase in the reinforcement-matrix interface area. Furthermore, in the opinion of the authors of this work, this should result in a decreased thickness of the interface layer for increasing complexity of the Koch reinforcement and that the rough reinforcement surface will cause higher energy dissipation under external loading. Indeed, their results showed that increasing the reinforcement roughness embedded in mortars subjected to flexure resulted in higher first cracking strength and higher residual load (defined as the load that the specimen is able to bear after the peak, as seen in Fig. 2 middle). The authors note, however, that the level of complexity in Koch fibers is limited by the manufacturing technology used: in their case, fine features with a minimum size of around 0.4mm could be printed. Other additive manufacturing techniques could have higher resolution.

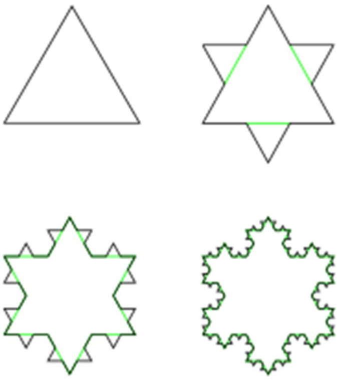

Figure 4. The first four iterations of the Koch snowflake (source www.wikipedia.org)[a].

While the studies discussed so far focused on creating reinforcement for cementitious composites with the matrix being cast in a conventional way, there is also interest in additive manufacturing of reinforcement to be used in combination with extrusion-based 3D printing. Mechtcherine et al. [26] performed a feasibility study on using gas-metal arc welding to create steel reinforcement. They manufactured vertical reinforcement bars with and without added surface

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[a] The Koch snowflake can be built up iteratively, in a sequence of stages. The first stage is an equilateral triangle, and each successive stage is formed from adding outward bends to each side of the previous stage, making smaller equilateral triangles. Consequently, the snowflake encloses a finite area, but has an infinite perimeter.

profiles, which should be comparable to ribbed and plain reinforcement bars, respectively. The manufactured bars had somewhat lower elastic modulus (152.22 vs 212.43 GPa) and yield stress (306.99 MPa vs. 424.86 MPa) compared to conventional steel reinforcement B500. However, additively manufactured rebars showed significantly higher ductility, with a strain capacity of 21.95%, compared to 6.28% of conventional steel reinforcement. Furthermore, printed steel bars showed satisfactory bond to printable fine-grained concrete. While this printing process of reinforcement cannot be simultaneous with the extrusion-based 3D concrete printing, due to high temperature involved and the slower printing process, this works provides a basis for a wider research on 3D printed techniques of steel reinforcement for extrusion-based 3D printing.

The studies presented so far focus on discrete reinforcement. Additive manufacturing, however, offers additional possibilities in creating complete reinforcement networks for cementitious composites (i.e. continuous reinforcement). This is discussed next.

2.2 Continuous reinforcement

Additive manufacturing has also been used to manufacture complete reinforcement meshes for cementitious composites. Compared to traditional reinforcement (fiber and discrete), 3D printed reinforcement offers many advantages. The principle is as follows (Fig. 5**Figure**): first, the reinforcement mesh is designed based on the specific needs; then, the complete reinforcement mesh is fabricated using additive manufacturing; further, it is placed inside of a mold, which is finally then filled with a cementitious matrix in a conventional way.

In their pioneering study, Nam et al. [27] suggested use of 3D printing for precisely controlling the distribution of fibers in FRCs and thus enhancing their mechanical properties. Actually, in their study, fibers are replaced by a continuous reinforcement mesh. This mesh was then infiltrated with a cementitious slurry, similar to the way SIFCON (slurry infiltrated concrete) is created. Additive manufacturing allowed the authors to create a simple functionally graded cementitious composite. Since 3 point-bending was used to test the composites, a functionally graded mesh was designed such that more reinforcement is present in the tension side of the beam.

Rosewitz et al. [28] brought this concept further and took inspiration from nacre, believing that it could lead to a new class of architected structural materials with superb mechanical properties. Bioinspired composites in their study were created by using 3D printed brick-and-mortar and auxetic polymer phases as reinforcement, cast in a conventional (albeit fine grained) mortar. These composites were then tested in four-point bending and uniaxial compression to quantify the effects of polymeric reinforcement on important mechanical properties, including strength, stiffness, toughness, and unit weight. Acrylonitrile butadiene styrene (ABS) polymeric reinforcement networks fabricated using fused filament fabrication (similar to that shown in Fig. 5) were used in their study. Three types of reinforcement architectures were tested (unit cells are shown in Fig. 6): a brick and mortar structure; a reentrant hexagon (i.e. bowtie structure); and a tubular structure with corrugations. Two of the reinforcement architectures (i.e. the bowtie and the tubular) have auxetic behavior, meaning that they have a negative Poisson's ratio [29]: if subjected to uniaxial tension, such architectures would expand laterally instead of contracting. This is seen a possible way of improving the mechanical behavior of cementitious composites.

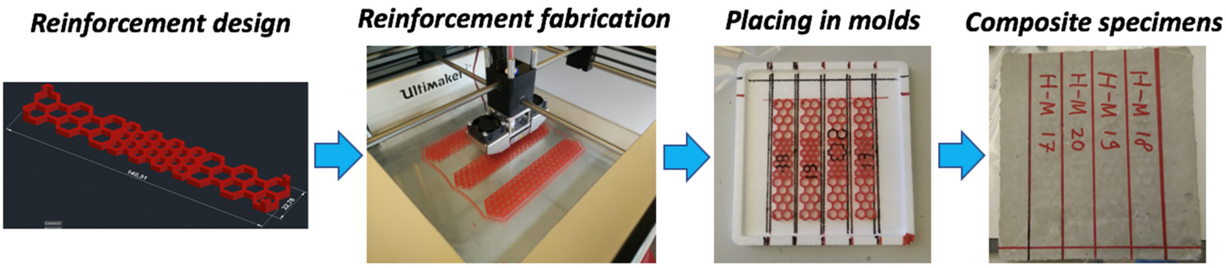


Figure 5. A process of creating cementitious composites reinforced with 3D printed reinforcement (author's photos).

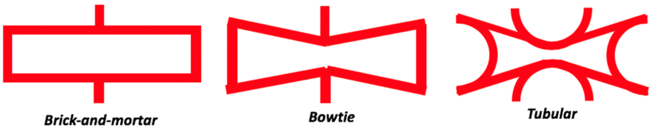
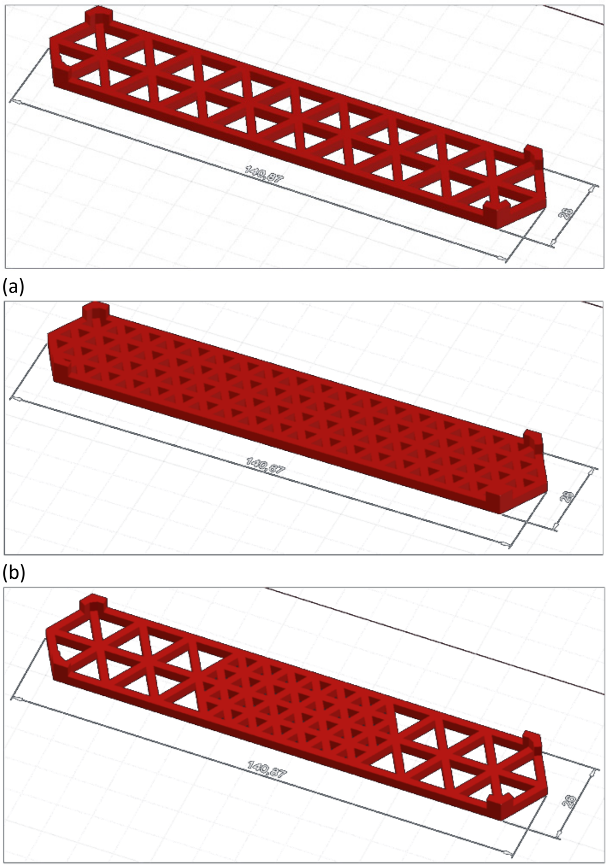


Figure 6. Typical unit cells of polymeric reinforcement used in the study by Rosewitz et al.[28]. Note that horizontal orientation of unit cells is shown, while other orientations were also tested.

Their study showed that composites reinforced with architected polymeric reinforcement are able to outperform control samples (i.e. unreinforced) as well as mortar samples with an equal volume of randomly oriented polymeric fibres, in terms of all mechanical properties measured. Note that not all reinforcement designs showed equal improvements in all aspects: highest compressive strength was achieved by the composite reinforced by the brick architecture, followed by the bowtie, while the composite reinforced with a tubular architecture was somewhat weaker than the reference. Even more impressive was the increase in specific compressive strength (i.e. strength per unit weight): since composites reinforced with polymeric architectures all had a lower unit weight compared with the reference mortar and (some of them) even higher strength, there was a significant increase in specific compressive strength. On the other hand, the composites all had a lower stiffness compared to both the reference and the fiber reinforced specimens. In terms of flexural resistance, composites with brick and tubular reinforcement were stronger than the reference mortar (as well as than the fiber reinforced mortar), while the composite with a bowtie reinforcement was weaker. However, all reinforced composites showed massive improvements in terms of deformation capacity: strain at fracture of composite specimens with architected reinforcement was 347%, 500%, and 426% higher compared to the fiber reinforced specimens for brick, bowtie, and tubular specimens, respectively. Furthermore, toughness was increased in all specimens by more than 200% compared to fiber reinforced specimens. This can be attributed to different energy dissipation mechanisms which occur in architected composites during deformation and cracking, which allows cracking to be distributed over large areas in the beam. This study showcases great potential for creating architected cementitious composites where reinforcement is “fit-to-demand” through use of additive manufacturing.

Xu and Šavija [30] used fused deposition modelling to create polymeric meshes to be used as reinforcement in strain hardening cementitious composites (SHCCs). In their study, ABS plastics was used as a base material for 3D printing of reinforcement using a commercial fused deposition modelling (FDM) 3D printer. Reinforcement meshes were then cast in a fine-grained mortar matrix. Small coupon specimens were tested in uniaxial tension (120 x 30 x 8 mm) and four-point bending (180 x 30 x 8 mm). For the reinforcement, simple triangular meshes with different triangle sizes were used (Fig. 7a and b), with an additional “functionally-graded” design (Fig. 7c) tested in four-point bending. The reinforcement in this design is denser in the middle, between the loading points, where the maximum bending moment is reached in the test. It should be noted that reinforcement percentages are not constant in these cases: specimens with small triangle reinforcement have a higher reinforcement volume percentage compared to specimens with large triangle reinforcement, while the mixed triangle reinforcement is between these two cases. Some stress-displacement and stress-strain curves of specimens tested at 7 days are shown in Fig. 8 and Fig. 9, respectively. It can be seen that all reinforcement designs increase the ductility and the energy dissipation capacity of mortar specimens significantly. As expected, reference (i.e. unreinforced) mortar specimens show brittle response in both bending and uniaxial tension. In bending, only the small triangle design and the mixed triangle design result in deflection hardening response (i.e. load carrying capacity after the first cracking is higher than the first cracking strength). The large triangle design does not show deflection hardening, Similarly, in uniaxial tension, while small triangle design shows strain hardening behavior, this is not the case for the large triangle design. Additive manufacturing of reinforcement does allow a lot of freedom in design, and designs can be optimized with the aid of experiments.



(a)

(b)

(c)

Figure 7. Designed polymeric reinforcement meshes used in SHCC by [30], defined as (a) large triangles, (b) small triangles and (c) mixed triangles.

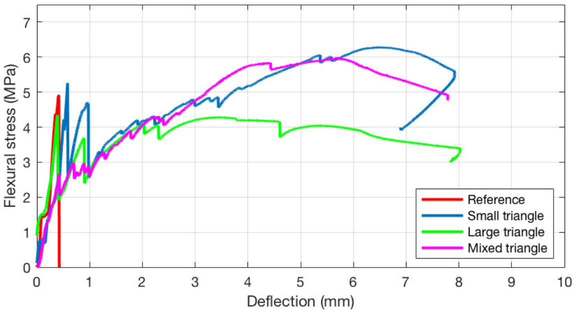


Figure 8. Flexural stress-deflection curves for specimens tested after 7 days.

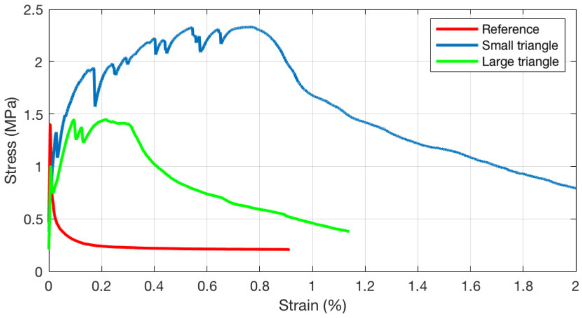


Figure 9. Stress-strain curves for specimens tested in uniaxial tension after 7 days.

3 3D printing for cementitious composites with added functionalities

3.1 Self-healing concrete

Self-healing concrete has the ability to close cracks occurring during the service life by itself, i.e. without human intervention. In the past 20 years, many different approaches for self-healing of concrete have been proposed [31, 32]. Typically, two types of self-healing systems can be distinguished: capsule based systems, in which discrete capsules filled with self-healing agent are (randomly) dispersed in the cement matrix; and vascular systems, in which a connected network of channels is introduced in the cementitious matrix, with or without self-healing agent already stored in the network. In the past three years, several interesting studies have focused on optimizing self-healing systems with the aid of 3D printing.

Studies on capsule-based self-healing utilizing 3D printing technology are relatively limited. Anglani [33] used FDM to print tubular capsules for self-healing concrete using different base materials: PMMA (Polymethyl methacrylate), PLA, PETG (Polyethylene terephthalate glycol- modified), and PET (Polyethylene terephthalate). In case of self-healing capsules, it could be beneficial to use different materials for two reasons: first, the long term stability of the capsule in contact with highly alkaline cementitious medium, as well as with the (internally stored) healing agent must be ensured; and second, the capsule must rupture upon cracking of the concrete to release the healing agent, which needs to be considered during capsule design depending on the base material [34]. In addition to using different base materials, Anglani et al. [33] also used techniques for improving the bond between the capsules and the matrix, for example by coating the capsules with epoxy and sand to increase the surface roughness. This study showed a proof of concept, and the results show a good potential of the proposed capsule-based system for structural applications.

De Nardi et al. [35] developed a so-called mini-vascular network system (MVN) for self-healing concrete. This system is, essentially, a compromise between the capsule-based and a vascular system: discrete tetrahedral MVNs are printed, filled with a healing agent (sodium silicate), and then distributed in the concrete mix. In their study, different types of PLA were used as base materials for printing the tetrahedral MVNs. Furthermore, ribs were created on the MVN's surfaces to improve bonding with the cementitious matrix. Their study showed great potential of such approach to add self-healing capability to concrete, without compromising the mechanical properties which are usually affected by vascular network systems.

In terms of vascular systems, two approaches have been proposed. Minnebo [36] utilized a 3D printed distribution piece that allows a self-healing agent to be pumped from the outside into a pre-placed vascular network (which, in their case, was not 3D printed). This is an extension of the concept proposed by Sangadji and Schlangen [37], who used a hollow core made of porous concrete to create a channel for pumping in a healing agent. A more elaborate 3D printed vascular system has been recently proposed by Li et al. [38]. Taking inspiration from nature, they utilized Murray's law for circulatory blood volume transfer to design a vascular network for concrete self-healing. They used 1D, 2D, and 3D structures (Fig. 10) printed with PLA as a base material. The authors suggest that 2D and 3D systems avoid blockages by providing extensive redundancy of flow paths to the critical region (i.e. the crack). Furthermore, by providing the self-healing agent from the outside, they ensure that its amount will be sufficient for healing of the crack. In principle, the proposed design approach could be used to design very fine vascular networks, which is limited by the resolution of the 3D printing technique and the viscosity of the self-healing agent used.

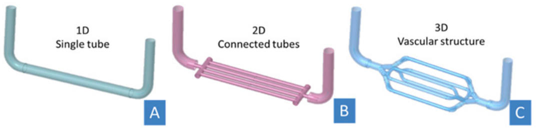


Figure 10. Vascular network systems for self-healing of concrete developed by Li et al. [38] (CC BY license).

3.2 Cementitious architectures with superior behavior

Approaches have been proposed for printing cementitious structures on the material (i.e. specimen size) level so that performance superior to that of cast cementitious materials can be achieved. Two techniques in particular stand out: direct ink writing and indirect 3D printing approach. So far, these approaches have been used for different purposes.

Direct ink writing technique as applied for cementitious materials is, in principle, very similar to extrusion-based 3D concrete printing. Typically, cement paste is extruded using a syringe which is mounted on and guided by a standard FDM 3D printer. Compared to extrusion-based 3D printing on the concrete/structural level, which mainly attempts to create large structures quickly or in shapes otherwise unattainable, the focus on direct ink 3D printing of cementitious materials has been different: the idea was to harness microstructural features that could not be achieved using cast specimens to improve certain properties of the specimen. While the mechanical properties of cast specimens are controlled by their composition, 3D printed specimens can also rely on their architecture (i.e. shape) and heterogeneities resulting from the printing process itself.

Hambach et al. [39] used direct ink writing to create hierarchical structures with fiber reinforced cement paste. The extrusion process results in preferential orientation and alignment of fiber reinforcement, thereby allowing higher strength to be achieved in the direction of the printing. The authors utilized this and, by optimizing the printing path, were able to create specimens with high flexural strength (>30 MPa).

Moini et al. [40] decided to take advantage of weak interfaces between consecutive filaments resulting from the 3D printing process. While the existence of weak interfaces between layers is commonly seen as a major drawback in extrusion-based 3D printing of concrete [9, 41, 42], Moini et al. [40] realized that, if utilized in a smart way, they can provide mechanisms for preventing cracking. They used direct ink writing of cement paste to create novel architectures in which heterogeneous interfaces were harnessed to increase resistance to cracking compared to brittle cast cement paste [43]. A typical architecture used in their study is the Bouligand architecture, a layered and rotated microstructure resembling plywood, which is commonly found in natural materials. Bouligand architecture consists of multiple lamellae, or layers, each one composed of aligned fibers. Adjacent lamellae are progressively rotated with respect to their neighbors. In their study, 3D printed architectures generated unique damage mechanisms which “transformed” the brittle hydrated cement paste to a flaw tolerant material. A combination of “weak” interfaces with carefully designed architectures promotes damage mechanisms such as e.g. interfacial microcracking and crack twisting, which leads to damage delocalization (i.e. more diffuse microcracking instead localized cracking), enhanced fracture resistance and damage tolerance. Their study showed that, in essence, crack paths in 3D printed elements could be controlled by varying the orientation of the filaments. This was also confirmed by Sajadi et al. [44], who tested different microarchitectures created using direct ink writing in uniaxial compression. Their results show that, while solid hardened cement paste is relatively brittle in uniaxial compression, ductility can be created by architecture design.

Other properties, such as permeability, could be controlled using a direct ink writing process as well. Recently, Luukkonen et al. [45] used direct ink writing of geopolymer pastes to create filters for water treatment. While ceramic filters have excellent properties, they tend to be costly so that in practice organic polymers are used. Filters made of organic polymers, however, have low durability. Luukkonen et al. [45] managed to create a water filter that satisfies requirements in terms of strength and porosity using metakaolin-based geopolymeric ink, based on an earlier study [46]. This study shows that direct ink printing of cementitious (or similar) materials could be used for many processes in which high chemical stability and strength in combination with controlled porosity is required.

Another option for creating cementitious architectures is to use an indirect 3D printing approach. As described by Xu et al. [47], this approach entails the following steps: first, the target shape is printed using an additive manufacturing technique such as e.g. FDM and any base material (e.g. PLA); then, this shape is used as a “negative” to create a mold by casting silicone around it; finally, the silicone mold is used to cast a cementitious material in it. This procedure allows creating cementitious architectures of arbitrary shape which do not have interfaces resulting from other printing processes (such as extrusion-based 3D concrete printing or direct ink writing), allowing more flexibility in terms of mix design used. So far, this technique has been used by Xu et al. [47, 48] to create cementitious architectures with auxetic behavior. As already described, auxetic materials have a negative Poisson’s ratio. This provides them with excellent shear resistance, high resistance to indentation, and impact resistance, among other properties. In the studies of Xu et al. [47, 48], chiral cells are used to create the geometry (Fig. 11). In these materials, auxetic behavior is achieved by rotation of unit cells under loading induced by the geometry of the structure. Since cementitious materials are brittle, cracking would typically occur under large rotations. Therefore, in their study, fine grained fiber reinforced mortar had to be used to allow for cracking induced cell rotation, which was identified as the mechanism behind the auxetic behavior.

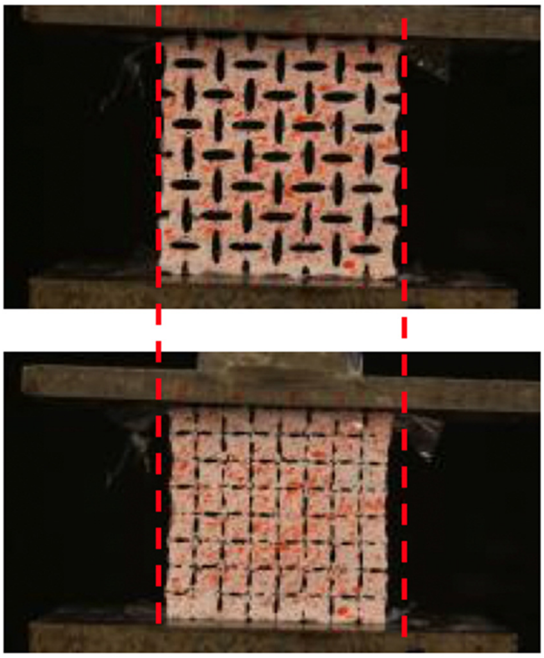


Figure 11. Cellular cementitious composite with auxetic behaviour. (top) unloaded; (bottom) under loading. Red dashed lines indicate that the specimen contracts laterally under vertical compressive loading.

4 Opportunities and challenges

Additive manufacturing techniques as described have significant potential in the construction industry. 3D printing could be used as an effective way to optimize the shape and the amount of reinforcement based on the specific loading case that a certain structural element is subjected to. For example, for shear reinforcement stirrups perpendicular to the main reinforcement are mainly used: although it is well known that this is not the optimal configuration, due to the labor costs it remains prevalent. Furthermore, 3D printing of reinforcement would enable creation of functionally-graded cementitious composites, with denser reinforcement in areas of higher stress [49, 50]. A simple functionally graded SHCC with 3D printed polymeric reinforcement has been shown to perform well (see Fig. 8). On the other hand, integrating structural reinforcement with a stay-in-place mold could significantly speed up construction. In developed countries in which the infrastructure is close to reaching its design service life, it is the speed of replacement of e.g. bridges that is the main design parameter, not (only) the cost [51].

Furthermore, additive manufacturing can be used to improve certain functionalities of concrete. For example, materials with negative Poisson's ratio (see Fig. 11) are known for excellent energy absorption, and could be used in protective and impact resistant structures. As described, different ways of 3D printing can be used to control cracking and significantly increase the toughness of cementitious composites. Similar approaches are well underway in other fields [52]. Other possible applications include tailoring of thermal or transport properties.

Although additive manufacturing offers many opportunities for development of multifunctional cementitious materials, there are several challenges that need to be overcome before these materials can be used in practice.

One of the main challenges is related to the scalability of the approaches: most studies were performed on laboratory sized specimens (mm to cm scale at most), due to several reasons. First, such specimen sizes are much easier to handle in the laboratory. Second, the additive manufacturing techniques used in the studies described can only produce specimens of limited size: for example, the FDM 3D printer used by e.g. Xu and Šavija [30] has a build volume of around 20 x 20 x 20 cm. This is much smaller than typical load bearing structural concrete elements. Although with present technology it may be possible to partly prefabricate elements and then "glue" them together, this would at least in part negate the benefits of the additive manufacturing technology. Developments in 3D printing technology will certainly overcome this problem if the need arises: once it is proven that it is useful for the construction industry, there will be a market for larger 3D printers.

Another issue is the anisotropy of printed parts. Depending on the technique used, 3D printed parts may exhibit significant anisotropy in terms of mechanical properties: in the study of Xu et al. [53] it was shown that small beams printed horizontally using FDM had about three times higher strength compared to beams printed vertically. The ductility of these elements was also significantly different. This anisotropy of material properties of 3D printed parts is at present a topic of significant research efforts [54-56]. At present, it seems that the material anisotropy is not only dependent on the base material and the printing technique used, but also on the specific printer properties used. This is very important if we are to use e.g. 3D printed reinforcement in cementitious composites: process dependence of material properties must be considered for reliable design. Furthermore, new base materials and printing technologies are rapidly developing. While this will provide new options for use in construction, much work will be needed to understand and characterize the physico-mechanical properties of these new materials.

In addition, the materials used so far in laboratory studies may be less than optimal. Developments in 3D printing of more common reinforcement materials such as FRP [57] and metals [58] could be very useful for creating reinforcement (either discrete or continuous) and stay-in-place 3D printed formworks. While these materials are known to be stable in highly alkaline environments present in concrete, this is not necessarily the case for some materials commonly used in 3D printing. Therefore, the compatibility of any material to be used with concrete, together with its long term stability, must be assessed.

The use of materials is also related to the cost, which is not an issue at present for laboratory scale testing. However, for large scale applications, cost of the base materials will certainly become an important aspect, and any increase in material costs will need to be offset by savings elsewhere in the supply chain.

5 Conclusions

Construction industry is facing major challenges. In terms of construction materials, and concrete in particular, issues such as CO_2 emissions, depletion of natural resources and waste landfilling are leading drivers of innovation. In recent years, this has led to significant developments in terms of e.g. new binder types and use of recycled materials as resources for concrete production. At present, technological developments in additive manufacturing present a great opportunity to further our efforts in development of better, stronger, and more optimal cementitious composites. In doing so, we do not need to start from scratch: we can build upon our knowledge of cementitious composite systems and use additive manufacturing to improve them in ways which were not possible in recent past. Although research is still in its infancy, many opportunities have been identified so far, some of which have been described in more detail in this letter. These can be summarized as follows:

- Additive manufacturing offers new opportunities for creating reinforcement for cementitious composites. Both discrete rebars/fibres and continuous reinforcement have been tested so far, showing certain benefits compared to traditional approaches.
- Additive manufacturing can be used to improve the design of multifunctional cementitious materials, such as e.g. self-healing concrete. Also in this field, it offers opportunities for optimization way beyond those possible with conventional means.
- Finally, additive manufacturing technologies may allow us to create cementitious composites with properties unattainable by conventional methods. Some examples

include crack resistant cementitious architectures and auxetic cementitious composites. With developments in the field, we may in the future be able to create designer construction materials, which are "fit for purpose", but without the associated additional cost. The benefits are not limited to mechanical properties, but may include thermal and transport properties, as well as additional functionalities such as self-healing. Similar developments are well underway in other fields where multi-material 3D printing is being used to enlarge the design space of multi-functional composites [59, 60].

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