Digital concrete: a review

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Digital Concrete: A Review

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Abstract

Digital fabrication techniques with concrete and cementitious materials have seen a large amount of research and industrial activity recently, with industrialization of techniques such as 3D printing becoming more of a reality. The potential to revolutionize construction is real, not only through reducing costs, but also bringing more sustainability and increased functionality. Material challenges are significant, chief among them understanding and controlling early age hydration and the link to rheology, incorporation of reinforcement, and overall, the link between processing, material, and performance, both from a structural and durability point of view. Interdisciplinarity is crucial, as the field brings together many disparate fields and has been driven by fields such as architecture so far. This article is a review of the state of the art in the newly forming field of digital fabrication with concrete, and aims to provide some direction in terms of the research challenges encountered thus far.

I. INTRODUCTION

The lack of innovation in the construction sector has been the topic of much discussion, especially in recent times. Compared to other sectors (e.g. manufacturing and agriculture) which have seen a marked increase in productivity over the past two decades, the construction industry's productivity has remained stagnant or even regressed. A recent detailed study by McKinsey noted several important steps that should be taken to address this lack of productivity, among them the infusion of digital technology, new materials, and advanced automation [1].

The construction industry has been slow to adopt many of the new innovations that have revolutionized other industries, but recent trends have indicated that digitization, new materials and technologies, and advanced automation are now making headway within the industry. For example, the relatively rapid adoption of building information modeling (BIM), especially in particular in East Asian locales such as Singapore, has demonstrated the potential for digital technologies to revolutionize the whole construction sector.

This has highlighted the potential for new innovations in digital fabrication technologies such as 3D printing with concrete and other additive manufacturing processes, the prospect of which was the primary impetus behind the organization of the 1st RILEM International Conference on Concrete and Digital Fabrication, or Digital Concrete 2018, in Zurich, Switzerland, in September of 2018. With 40% of the attendees from industry, the construction industry has taken note, and it appears that most observers and participants in this conference, as well as numerous other academic and industrial conferences on this topic, seem to agree that the march towards digitization seems inevitable [2].

In this paper, we reiterate the rationale for digital fabrication with concrete, followed by highlighting the state-of-the-art in the new and rapidly developing field of digital fabrication with concrete as they pertain to 1) materials and processing, 2) structure and performance, and 3) applications, which are driving the research.

A. Concrete and Digital Fabrication

Concrete is the most widely used construction material worldwide, and the most widely used material after water. This is due to the inherently useful characteristics of concrete: easily and globally obtainable raw materials, relative ease of processing and handling, and its ability to go from a fluid state, where it can fill a mold, to a solid state, where it can then bear a structural load. As was pointed out by Van Damme in a comprehensive, general analysis of the future of concrete in a digital context, there is simply no reason to expect that the demand for concrete will decrease in the future, as developing countries such as China and India grow their infrastructure, and developed countries refurbish their own [3]. This demand is placing a strain on the future in terms of climate change, with clinker production for Portland cement responsible for up to 10% of anthropogenic global CO₂ emissions [4]; in fact, if concrete were a country, it would be the 3rd largest emitter of carbon in the world. However, in spite of its reputation, concrete can be considered an ecological material, as was pointed out by Flatt et al. [5]. Compared to competitor building materials, concrete has a relatively low carbon footprint when normalized by volume: it is simply the enormous volume demands – 10 km³ per year in 2011 – that are responsible for its outsized impact on the climate. Thus, the possibility to reduce CO₂ emissions through better material efficiency by increased shape efficiency is one of the major potential benefits of digital fabrication. This is an argument that has been made in a number of reviews up to now [6–8], and is clarified and expanded in the following.

i. Decreased Costs

It is instructive to consider Figure 1, adapted from Ashby [9], when evaluating the potential impact that digital fabrication can have on concrete as a construction material. The figure illustrates the central problem of material selection in mechanical design, which is the interaction between function, material, process, and shape. There are, practically speaking, no alternatives to reinforced concrete as the backbone of our built infrastructure, and this is due to its ability to fulfill the required functions (to bear a structural load and be durable) with relative ease of processing (mixing and placement into molds) at the economic costs necessitated by the massive volumes of material required.

However, while structural engineers are able to design more materially efficient shapes through design tools such as graphic statics [10], their realization has been limited primarily due to the higher costs of custom formwork: that is, the processing has had a restrictive effect on shape freedom. The ubiquity of rectilinear walls, columns, and slabs is a consequence of the efficiency of easily constructed and reusable formwork. Digital fabrication processes fundamentally alter this by more effectively allowing construction without the use of traditional formwork. When examining Figure 1, it means the possibility of introducing curvilinear, and thus potentially more material-efficient and therefore more sustainable, shapes becomes more of a reality.

Figure 1. The fundamental problem in material selection for mechanical design: an object must fulfill a function, which requires a particular shape, into which a material must be processed. All four of these critical aspects are deeply interlinked. In construction, digital fabrication with concrete offers increased shape versatility by altering the process, as well as potential to add additional functionality, especially through integration of other materials, or functionally grading materials. Adapted from [9].

Figure 2 illustrates how digital fabrication and additive manufacturing make this possible. Typically, in manufacturing, the unit cost of a component increases quite substantially as the complexity of a component increases. This is true of conventional construction, where a complex geometry is difficult to produce economically with the use of wasteful, one-time-use formworks.

The complexity-cost curve for an additive manufacturing process, however, is much flatter: it has been said that additive manufacturing gives “complexity for free”. While not completely true, it almost certainly makes the cost of a custom component much, much lower than that of one produced via conventional methods. Where the complexity-cost curves of conventional construction and additive manufacturing intersect is where additive manufacturing “breaks even”, and becomes competitive with conventional methods. A case study of this from both an economic and environmental perspective was performed for the Mesh Mould process developed at ETH Zurich, showing how digital fabrication becomes more economical with increasing complexity [11,12]. Continued research and development will drive the additive manufacturing curve downwards, shifting the break-even point farther to the left, and making even less complex components economical to produce with additive manufacturing. Additionally, one would expect that the market volume, or market demand, for construction of complex geometries would increase as technology to produce them becomes more economical, and this is also illustrated conceptually in Figure 2.

Figure 2. Top curve shows unit cost versus complexity for both conventional construction and digital fabrication. The “break-even point”, where the curves intersect, is where digital fabrication (additive manufacturing) becomes competitive. Research drives the curve for digital fabrication down, shifting the break-even point farther to the left. The bottom plot is a conceptualization of market volume versus complexity, showing an expected shift in demand for higher complexities with digital fabrication (dashed line) versus the current status quo in conventional construction (solid line).

ii. Increased Functionality

In the field of value engineering, value is considered as a ratio of function to cost – thus, value can be increased by either reducing cost, as described in the previous section, or increasing function, which is described here, and the reader is referred again to Figure 1. While many of the arguments for digital fabrication focus on reduction of cost compared to conventional construction, the potential for added functionality offers probably a much greater rationale for the introduction of digital fabrication into construction. This point has been made by Buswell et al., in which a complex internal wall geometry was shown to have a significantly increased thermal performance compared to a standard concrete wall [13]. Bos et al. argued that local control of material placement at the printhead could lead to these sorts of complex designs with compositional variation; the authors dubbed it, metaphorically, as “colour” concrete printing [6]. This local composition control allows for tailoring material properties in specific locations of a monolithic component, better known as functionally graded materials (FGM) [14], and is one of the highest potential impacts of digital fabrication processes compared to conventional construction processes. Although functionally graded concrete components have been demonstrated in a non-digital context [15–17], the local material control at the printhead makes production of such components theoretically much simpler, much more versatile, and therefore is a very attractive feature of digital fabrication. Until now, while design concepts are abundant for FGMs at the architectural scale [18–20], only small-scale prototypes have been demonstrated with digital fabrication methods [21,22].

Similarly, local architecture control – allowing the control of material properties by control of meso-scale architecture – has been illustrated by researchers at Purdue University to have

potential to produce bio-inspired material behavior; by printing Bouligand architectures out of cement paste, the researchers mimicked the structure of the shell of the mantis shrimp claw, one of the toughest materials known [23]. In this case, precision placement at the resolution of the printhead allowed the creation of this complex local architecture.

Agusti-Juan et al. found that the digital fabrication processes themselves are negligible in terms of environmental impact; that is, the material embedded energy was the primary source of environmental impact [24]. Thus, through functional and material hybridization, one could lessen the overall environmental impact of a component. However, Agusti-Juan et al. later warned that a true life cycle analysis (LCA) must be done, as this sort of hybridization can have a negative impact on the service life or recyclability of a material [25]; the need for LCA has been pointed out by other authors as well [14]. A true cost-benefit analysis should be carried out when assessing if digital fabrication is truly bringing a more sustainable or cost-effective component [8].

B. Digital Fabrication Methods with Concrete

A brief review of the methods of digital fabrication with concrete follows. In general, the methods of digital fabrication with concrete can be classified on a process basis, but all show the common thread of concrete construction without the use of traditional formwork.

i. Extrusion

When one usually mentions “3D printing with concrete”, extrusion, the most popular method by far, immediately comes to mind. Extrusion is a process in which material is forced through a nozzle and placed by a print head in a specific location as the print head moves through space. An object is built up layer-upon-layer, in many ways similar to the well-known process of “fused deposition modeling” with polymers. The method was first pioneered by Dr. Berokh Khoshnevis and trademarked as Contour Crafting [26,27]; since then, many other academics, industrialists and hobbyists have followed suit. Various printer types have been demonstrated: gantry style printers, first shown in Contour Crafting, in which a printhead is controlled in 3 axes on a fixed rectangular frame [28]; robotic arms, in which the printhead is fixed to the end of a robotic arm, typically with both translational and rotational degrees of freedom [29]; and delta printers, which have a print head suspended by three retractable arms and thus an additional rotational degree of freedom compared to gantry style printers [30]. For a thorough examination of the current status of concrete extrusion printing and its challenges, from rheological to machining, the reader is referred to a recent paper from a special issue of Cement and Concrete Research on Digital Concrete [31].

ii. Formwork Printing

Many methods can be captured in the catch-all term “formwork printing”. One of the great challenges in digital fabrication with concrete is reinforcement (discussed in detail later in the paper) and often, 3D printing with concrete becomes essentially 3D printing concrete formworks, because of the need to add reinforcement and infill. For example, the startup XTreeE 3D printed a unique pillar geometry out of concrete and infilled with a UHPFRC [32]. The material used to 3D print the formwork need not be restricted to concrete, however; researchers at ETH Zurich used particle bed fusion to produce a 3D printed sand, topologically optimized formwork slab to infill with UHPFRC [33]. Of even greater interest is a 3D printed formwork that can add functionality. For example, the Mesh Mould process,

in which a robotic toolhead bends, cuts, and welds a steel mesh, creates a semi-permeable formwork that later serves as reinforcement [34]. Very high, immediate potential lies in these technologies, with a recent Boston Consulting Group study declaring that they are ready for the market now [35]. Indeed, the FreeFAB system of 3D printing formwork has already been used to produce custom concrete components for a London Tube station [36]. A last note on the topic of formwork printing, is that other materials than concrete may be used for this, which may then be followed by infilling with concrete, digitally or not. While interesting, this option is beyond the scope of the present paper.

iii. Temporary Supports

Similar to formwork printing, methods exist to generate a desired shape in space, which is then subsequently concreted. This includes the use of flexible formworks in particular to produce double curved concrete elements. Schipper demonstrated the possibility of using flexible, deformable molds to form a shape in space onto which concrete is cast in a precast context [37]. More recently, the use of knitted textiles, tensioned in space to form a particular shape, and upon which a series of stiffening layers of cementitious materials are added, has been demonstrated both on a small scale and a large scale, on-site context [38]. In these cases, the aspect of digitalization comes mainly through the design of the supporting structure in terms of shape and load bearing, while the application of concrete has up to now most often been done in more traditional ways.

iv. Slipforming

Slipforming is a method in which a vertically moving formwork has concrete placed in the top in the fluid state and exits in a hardened state. While this method is typically used to create large scale, usually constant cross sectional area structures such as silos, the Smart Dynamic Casting system developed by Lloret et al. [39] is an example of a scaled down version to produce columnar elements in a digitally controlled way. Due to the downscaling, hydration control is required, and is performed by the use of chemical admixtures. The system is suited to produce columnar elements of variable cross section through the use of a digitally actuated, deformable formwork [40], although it has also been demonstrated to be used to produce thin folded structures that are more buckling resistant [41]. A similar approach has been taken to produce a large series of twisted columnar elements, with the intent of using these in a variable shading façade [42]. Major advantages of slipforming compared to other techniques include the ability to slipform around conventional steel reinforcement, the relative absence of layer interface problems, and a high surface quality.

v. Particle bed fusion

Particle bed fusion (sometimes called powder bed printing, binder jetting, or sand printing) is a method of additive manufacturing in which a layer of particles is spread and a print head moves and selectively deposits a binder onto the particles. Another layer of particles is then spread and the process repeats, so a component can be built layer upon layer. The process is advantageous in that the particle bed serves as a temporary support structure, so that cantilevering is possible. In construction, the method has been pioneered by Enrico Dini of D-Shape who has produced large scale components initially with a Sorel cement binder [43] and more recently with a Portland cement binder. In the context of producing cementitious components, this process has been recently reviewed in depth in a recent Cement and Concrete Research Special Issue by Lowke et al. [44]. In the production of these components,

the binder can be water added to a bed containing cementitious materials, or the binder can be a paste injected into a bed of aggregate [45]. Besides being able to produce cantilevered parts or parts with undercuts, one of the primary advantages of this method is the high resolution afforded by it; theoretically, to the size of the largest particle in the bed. However, the method generally requires extended post processing to remove the unbound particles, which are very limited in recyclability in the case of systems with Portland cement. Alternative binder systems using geopolymers are currently being investigated, considering the recyclability of the unbound particles and the requirement of an enclosed system [46,47].

C. Major challenges

This paper aims to review the major challenges being faced by researchers, and guide future research in this new and dynamic field. Specifically, the next section will review the fresh state properties and challenges in processing concrete for digital fabrication, from mix design to admixture selection and dosing to rheological requirements for processed concrete. The section following this will then review the hardened state research challenges and possibilities, examining performance of digitally fabricated concrete components and addressing the problem of reinforcement. The final section will address the applications – the applications that have driven this field of research until now.

What is apparent is how each of these research areas – processing, performance, and application – have brought together somewhat disparate research areas into a single field. These research areas include materials specialists and structural engineers, who even until now have experienced a sort of “phase separation”. However, the eclectic group includes also roboticists, who are able to engage with challenges of their own in digital fabrication [48], as well as one of the most key components – the architects and structural designers, whose creativity and innovative design are pushing the field forward by leaps and bounds, allowing those who develop the process to see what it can be used for. This brings to light the interdisciplinary nature of this field, and the importance of teams being able to communicate across their disciplines to advance the field. Indeed, even greater potential may lie in bringing in even more disparate fields such as computer science and big data analysis, as Van Damme pointed out in his recent article [3], which can truly revolutionize the construction industry with machine learning, AI, and augmented reality.

II. FRESH STATE – MATERIALS AND PROCESSING

Most processes described in the previous section, no matter if they aim at printing an element or a mold, are far from being standard formative processes. Most of them do not use a mold or formwork able to sustain the weight of the fresh material without being deformed. From a fresh material requirements point of view, this translates into turning the typical fresh (in this case, self-compacting) concrete requirement from “being fluid enough to fill a mold of a given shape under the sole effect of gravity-induced pouring” [49] to “being able to be shaped and maintain this shape until setting”. This requirement often involves many contradicting features such as being fluid enough to be mixed and pumped while being consistent enough to maintain a shape without any support.

Digital fabrication with concrete is, in a way, a simpler process, as there is no need to build a form before shaping an element. As such, it is expected to allow for more freedom in design as described in section I. It has however to be kept in mind, and this will be emphasized further, that this enhanced simplicity comes at a requirement cost on the printable material [50]. The present section will go through the most recent state of the art on these new requirements along

with opened research questions that needs to be addressed to turn digital concrete into a commercial reality.

A. Fresh materials requirements

i. Deliverability or pumpability [51]

Concrete pumping is extensively used worldwide [52] and is a mandatory processing step in most digital concrete processes as it allows for the feeding of the printing system no matter the considered printing technology.

The flow typology within a pumping pipe is however complex and was shown to differ from the one of typical viscous fluids such as water or oil [53]. The primary reason for this difference comes from the fact that fresh cement-based materials are yield stress fluids (*i.e.* they flow only if the applied stress is higher than its yield stress). As a consequence, there exists at the center of the pipe (*i.e.* around the symmetry axis where the shear stress is equal to zero) a zone where concrete is not sheared [54]. Most approaches of concrete pumping in literature have taken into account this yield stress and the existence of this unsheared zone [53,55,56] by assuming that concrete behaves as a Bingham fluid or Herschel Buckley fluid. These approaches have, however, almost systematically failed to predict pumping flow rates correctly on a large range of concrete viscosities, as they ignore the fact that a lubrication layer exists at the interface between concrete and the pipe.

Indeed, the second reason for the difference between pumping of concrete and pumping of simpler materials comes from the fact that, under the action of shear, a redistribution of particles occurs within the pipe. This is a common feature of particle suspensions and initially well-mixed particles in concentrated suspension flows are shown to undergo migration from high shear rate regions to low shear rate regions [57–60]. This particle migration, in the case of coarse particles (*i.e.* particles with a characteristic size close to the characteristic size of the flow), can be increased by wall effect at the interface between the pumped material and the pipe [61]. During pumping, shear concentrates therefore in a fluid layer of material depleted from the coarsest particles of the concrete. Pumping of concrete is therefore considered today as the shearing of an annular layer of unknown thickness and made of a material with unknown rheological properties. This is why most recent studies focus on the assessment and prediction of this lubrication layer as a function of mix design [62].

ii. Extrudability [61,63–65]

Over half the printing processes under development employ extrusion, typically a small (~6 mm to ~50 mm diameter) continuous filament, pumped through a nozzle often mounted on a gantry or robotic arm that positions the material during the build process [66].

An overview of the extrusion techniques for cementitious materials was recently presented in [31]. This paper shows various technologies and applications based on extrusion, most prominently recent developments in 3D-concrete-printing along with their mechanical analysis. The extrusion flow of the cement-based materials is shown to be composed of the elongational flow near the contraction in the so-called shaping zone and the plug flow in the barrel. The first zone is driven by the material rheological behavior while the second is driven by the tribological behavior at the interface with the extruding nozzle. Attention is also drawn in that paper on the risk of water drainage and phase separation that may hinder extrusion flow and the extruded material final properties. It can be noted that there exist strong similarities between pumping and extrusion flow typologies. Extrusion is however associated to slower

flowing velocities and often involves a flow contraction, which induces some shearing of the bulk material.

iii. Printability

Although a rather undefined concept, printability in literature seems to relate to the ability of the material/nozzle combination to produce a well-controlled filament. In the case of extrusion-based techniques, two asymptotical regimes have been identified (see Figure 3). For stiff materials, the so-called “infinite brick regime” is reached where the filament section is the one of the nozzle and is not affected by flow or gravity (left figure). The yield stress of such printable materials can reach several thousands of Pa [67]. They often allow for a very good control of the filament geometry but their pumping and extrusion requires extremely high pressure. On the other hand, for extremely fluid materials, the so-called “free flow regime” is reached where the material has “forgotten” about its flow history. The filament section results from a competition between gravity and yield stress. It can be predicted using some of the theories and models used to predict slump or slump flow [49,68]. This type of extremely fluid materials requires the use of an accelerator to allow for the deposition of successive layers (see next section).

Figure 3. The two asymptotical extrusion/deposition regimes. The so-called “infinite brick regime” where the filament section is the one of the nozzle and is not affected by flow or gravity (left figure) and the so-called “free flow regime” where the material has “forgotten” about its flow history and the filament section results from a competition between gravity and yield stress (reproduced from [50])

iv. Structural buildup and buildability [63,69–72]

By successively depositing layers, gravity-induced stresses increase progressively in the growing object. In order to prevent collapsing, the structuration kinetics of the printed materials must be located in a process-dependent and object length-scale-dependent time-window [7]. Through this time window, the material increases both its strength (*i.e.* yield stress) and rigidity (*i.e.* elastic modulus). At the end of the process, when the height of material has reached the

printed object final height, gravity-induced stresses reaches its maximum value in the bottom layer. As a consequence, gravity-induced stresses in the bottom layer could be at the origin of yielding and printing failure when they reach the local yield stress value [7,50,68,73]. This means that, at the end of the printing of a typical wall of height 2.5 m, the yield stress of the material must reach values around 30 kPa in the bottom layer. This increase in stress with the rising height of the object imposes the value of the structuration rate [65] of the deposited material, *i.e.* the rate at which yield stress increases with time. The difficulty with such an approach is that the rising speed is not an input parameter but a parameter resulting from the nozzle velocity, the printed contour length-scale and the thickness of the layers. As a consequence, the required structuration rate is expected to scale with the various length scales of the printed object along with the extrusion length scales of the process and, although being a material requirement, it is fully process dependent [7].

It has moreover to be kept in mind that, as the gravity-induced stress on one given layer increases, the layer may slightly deform. Although stress in the layer may stay below yield stress and flow (and failure) shall not occur, the cumulative amount of strain in all layers could threaten the control of the printed element final geometry [31].

Finally, it was shown that, in addition to the compressive failure risk in the bottom layer or the geometrical non-conformity due to layers deformation, the dominating failure mode for the printing of slender vertical structures finds its origin in the buckling of the printed element [50,67,74]. This was shown to impose a requirement on the elastic modulus of the printed material. It is interesting to note that that this requirement on elastic Young modulus scales with the power 3 of the height of the printed object whereas the requirement on yield stress discussed above increases linearly with that height. It is therefore expected that, below a given height, strength-based failure in the bottom layer would be critical while, above this given height, buckling would become critical [50].

v. Fresh properties measurements and monitoring [50,64,70,71,75]

As discussed above, yield stress and structuration rate of printable materials are key features in most printing applications. When the material is deposited, it exhibits an initial yield stress and an initial elastic modulus. With rest, these rheological parameters evolve and experimental results show that both parameters are increasing function of time. The material becomes not only stronger (higher yield stress) but also more rigid (higher elastic modulus).

Up to now, protocols allowing for the measurement of the structuration behavior of cement-based materials are uncommon and more complex than the ones allowing for the measurement of steady state flow properties [63,76,77].

Most simple measurements imply the use of protocols that do destroy the inner structure of the material. They impose therefore the preparation of many samples that are left undisturbed at rest before being tested. Successive Vane test procedures on independent samples are therefore the most common structuration rate assessment techniques in literature [51,64,65,78].

When working on materials containing only fine particles, oscillation rheometry can prove useful as it assesses the material with oscillations, the amplitude of which is small enough to be non-destructive [69,70,79]. It is therefore possible to assess continuously the evolution of the elastic modulus as a function of time on one unique sample. Other non-destructive techniques exist and should be further studied in the future, as the need to assess structuration properties is required for concrete printing. They include ultra-sound measurements [71] and needle penetration (slow penetration or fast penetration of needles that only locally destroy the sample structure) [72]. Finally, it is important to keep in mind that the consistencies reached by printable materials after a few tens of minutes often reach the upper limit of most standard rheometers and enter the realm of hardened materials testing. Interestingly, some papers

dealing with printable materials characterization demonstrate the adequacy of standard compression and shear mechanical tests for printable materials [71,75].

B. Layer Interfaces

The rheology requirements described above mostly dealt with the ability of the material to turn, within an extremely short time-window, from a rather liquid pumpable suspension into a quasi-solid able to carry its own weight without any formwork or any support.

Several authors [7,50] however discussed the existence of a potential upper limit for this structuration rate. Such a discussion originates from the assessment of obvious weak interfaces or weak bonds between successive layers [31,80]. Such weak interfaces have been already studied in the case of standard fluid concretes [78]. They were described as so-called “cold joints” or as the consequences of a so-called “distinct-layers casting”.

Distinct layer casting was shown to find its origin in the absence of remixing at the interface between layers of Self Compacting Concrete [78]. This feature was said to occur when the thixotropic nature of the material generates a fast increase in the consistency of the first layer, which, in turn, prevents the flow of second layer from re-initiating a flow of the first layer at the interface. Other authors [80] recently showed that distinct layer casting could also occur when the consistency of the material is too high to allow for a proper smooth contact between the two layers. Such a reduced effective contact area may therefore, in turn, reduce the bond strength.

Recently, it was suggested that, in the specific case of extrusion based additive manufacturing, in contrast with the existing literature, a drop in interface strength could find its origin in a superficial extremely localized drying of the first layer [81]. These authors suggested that this localization finds its origin in the fact that, for low porosity fresh printable materials, the liquid does not have time to flow and replace the evaporated liquid at the surface of the deposited layer. As a consequence, a dry region of thickness of the order of a few hundreds of micrometers is developing from the drying interface and is propagating in the material. In this region, after this drying, there is not enough water left to hydrate the cement powder and the interface strength decreases. This and other possible processing parameters that can impact interfacial strength, as well as possible methods to address them, are addressed in much more detail in section III.A.

C. Mix design and admixtures

As shown above, the ability to build up a structure is a key feature of printable materials. It is the one that allows, on time scales of the order of a couple of seconds, for the control of the geometry of the extruded filament and the one that allows, on time scales in the order of minutes, for the printing of an entire object with a controlled geometry. These requirements on structuration are illustrated in Figure 4 for these two time scales. The first increase in yield stress involves some kind of fast flocculation process while the second one, on longer time scales and leading to large yield stress variations, mostly involves the nucleation of some hydrates at the contact points between the grains [50].

In practice, from a mix design point of view, there exist many potential strategies to reach the yield stress requirements from Fig. 4 [82]. These mix design strategies involve the use of either flocculation agents and/or accelerators.

Flocculation agents may be high molar mass polymers such as viscosity modifying admixtures [82–84]. They can also be nano-particles such as nano-clays [85], which adopt a preferred orientation at rest. Both additives allow for a faster and stronger increase of the printable material yield stress through and right after the deposition process.

Acceleration of cement hydration is achieved in different ways that can be divided into physical and chemical actions [82,86,87]. The first physical action involves the desorption of some retarders from the reacting surface, as in the case of sucrose in the presence of portlandite [88]. A second physical mode of acceleration was observed by Thomas et al. [89] after the addition of C-S-H seeds in cement paste. Specifically, this addition strongly increases the surface available for further hydrate precipitation, which leads to an earlier onset and a faster acceleration period. The list of most common products that chemically accelerate the hydration of cement is generally divided into two different types: soluble inorganic salts and organic compounds [86,90–92].

It was recently noted in [82] that accelerators targeting mainly silicate hydration might show some limitations as it would require very high quantities to achieve sufficiently fast strength gain for additive manufacturing, which could interfere with rheological or durability properties. Therefore, a category of accelerators that presents interesting features for printable concrete is shotcrete accelerators [86,93]. For sprayed concrete, they are usually added in the nozzle of the equipment during spraying, allowing a very quick setting as soon as the concrete is sprayed and applied on the wall surface. Silicate and aluminum salts are among the most commonly used types [94].

Finally, it bears noting that although the focus here has been on mix design solutions to meet strength buildup requirements, mix design can be targeted to solve other issues unique to digital fabrication with concrete, such as moisture retention to prevent layer interface formation from drying.

Figure 4. Yield stress requirement as a function of time. On short time scales, flocculation allows for the printing of a filament with well-controlled geometrical features while, on longer time-scales, hydrates nucleation allows for the printing of vertical slender objects. Adapted from [50].

D. Fresh properties - Outlook

Many of the challenges for fresh properties of concrete in digital fabrication are not really “new” at all – they are challenges that researchers are already addressing. Processes such as

pumping, placement, and early age structural buildup are well-researched topics within the concrete research community, with their own open research questions, both from a fundamental and practical level. From a fundamental research standpoint, understanding structural buildup, from both flocculation and hydration in the early age, is very important, and further research on this topic can only help in digital fabrication with concrete. This is coupled with the key questions of how microstructure during early age hydration impacts the rheology of concrete. Admixtures and their mechanisms of interaction, especially how they impact early age hydration, are also of key importance. In particular, how admixtures interact takes on added importance, because often contradictory rheological requirements for the material at different times in the process is controlled through admixture addition.

Most of the new challenges for fresh properties research are technological, and related to processing. Key among these are developing newer methods to monitor fresh state properties for digital fabrication, especially in the setting regime, wherein heretofore such tight monitoring was not a necessity. Understanding admixtures from a fundamental standpoint is key to their application in the process, which is primarily in set control, with set control needing to occur not on the time scale of cast concrete (hours) or shotcrete (milliseconds), but rather on the order of minutes. Thus, new methods of set control are required, with tighter boundaries. The lack of a formwork also removes the “skin” of the traditional formwork, making moisture loss and shrinkage more of a concern. The implications of moisture loss or poor layer intermixing in the formation of weak layer interfaces is also an interesting engineering problem. Finally, the processing itself is imposing new requirements, as the processing is continuous, with various unit operations to control material properties and requiring tighter processing boundaries than previously needed.

III. HARDENED STATE PROPERTIES AND PERFORMANCE

The growing popularity to use digital fabrication with concrete in actual construction projects, increasingly requires a level of performance (for instance, in terms of quality control and consistency, structural properties, and durability) that can compete with existing alternatives. As the applied raw materials and mixtures are not radically new and the commonly applied extrusion-based concrete printing also bears resemblances to existing manufacturing processes, the global behavior of additively manufactured concrete is not totally alien to the field. Nevertheless, the specifically adjusted material compositions as well as the characteristics of the various digital fabrication processes have such an influence on the hardened state properties that the performance of the printed objects in-use is not a trivial issue. With regard to the materials, noteworthy deviations from conventional concrete include the use of high ratios of cement and alternative binders, chemical admixtures such as retarders, accelerators and viscosity modifiers, as well as a lack of normal and large size aggregates (aggregates larger than approximately 2 mm are rarely used). On the process side, the filament deposition, the pressure versus print nozzle speed, the formation of distinct layers, the lack of compaction, as well as the incompatibility with traditional reinforcement strategies, are some of the remarkable differences to the well-known casting process. These topics are receiving ever more attention in ongoing research efforts.

A. Anisotropy and Layer Interfaces

The anisotropy of printed concrete has already been pointed out in an early stage by Le et al., 2012 [95]. It is uniquely attributed to the layered object structure that can occur both in vertical and horizontal direction. There are currently no studies indicating that the anisotropy exists in the deposited bulk material, but the number of layers can be so dense that effectively

anisotropic material behavior should be assumed, rather than that the reduced strength of the discrete layers should be considered. No considerations on how to approach this issue from a practical perspective have been published. It should be noted that a significant anisotropy primarily exists with regard to strength. Although it is conceivable that the material stiffness is also influenced by the interfaces, their thickness seems to be too thin to have a meaningful influence on the global scale. All existing studies focus on interface strength, often in relation to process parameters because due to the nature of adhesive bonds, it is likely they have an influence. Figure 5 demonstrates directionally dependent mechanical testing respective to layer orientation.

Figure 5. Directionally dependent mechanical testing respective to layer orientation of extrusion-printed concrete. Reproduced from [96], with permission.

As already introduced in Section II.B, interfaces in concrete are not an uncommon phenomenon of themselves, and are influenced by many factors [97]. However, they usually occur between a layer that has previously hardened and a fresh layer, whereas in concrete printing they generally happen between two fresh layers. Therefore, existing design codes [98,99] are not applicable for the majority of interfaces in printed concrete. Outside the field of concrete printing, the effect of interfaces between two fresh layers has been subject of only a few studies, as noted before, all related to Self-Compacting Concrete (SCC) [78,100–102].

After Le et al. [95], who found that both the compressive and flexural-tensile strength were directionally dependent, other studies resulted in similar findings: perpendicular to an interface the tensile strength is lower than in the other directions, whereas results with regard to the directional dependency of the compressive strength are inconsistent, but quantitatively seem to be limited [103].

Figure 6. The interface strength in extrusion-printed concrete is expected to relate to a number of process parameters. Available studies have considered the interlayer interval time, the print head speed, the print nozzle height, and surface moisture content.

As illustrated in Figure 6 and described in the previous section, the interface strength is expected to relate to a number of process parameters. Several studies have shown the tensile strength of the interfaces depends on the interlayer interval time (also referred to as the time gap or time interval, TI), with longer interval times leading to (in some cases dramatically) reduced interface strength [95,96,104]. The strength reduction is usually shown through simple macroscale mechanical destructive tests, but the findings are supported by microscopic studies on the interface microstructure by Van der Putten et al. [105] and Nerella et al. [93]. While most studies focus on the interlayer interval time, Panda et al. [106] investigated the interface bond in relation to the structuration rate of geopolymer mortars to find that there is a time window in which the interval time has negligible influence, while outside that window the reduction is significant. Similarly, Kim et al. [107] found that for a printable OPC-based mortar with an initial setting time of 90 minutes, no significant interface strength reduction occurs for 15 and 30 minutes interval time, but that it does for a 60 minute interval time, still notably below the initial set time.

It is important to note that quantitatively, the interface tensile strength degradation with increasing interval time is highly system and material dependent. Within a single study, this was shown by Nerella et al. [93] who used two different mixtures one with and the other without pozzolanic additives, and found that the former gave reductions of less than 25% even with a 1-day interval, while the latter resulted in a decrease of approximately 90% with the same interval time. When comparing studies, results vary significantly from one to the other.

Other influences on the interface strength to have been studied include print head speed and print nozzle height. Again, results are inconsistent. Panda et al. [104] found a strength decrease for an increasing print nozzle height, while Wolfs et al. [96] concluded neither a smaller nor a larger than default print nozzle height influenced the average bond strength significantly, although the scatter increased for both non-default situations.

As pointed out in the previous section, several researchers have found that the surface moisture content is an important parameter with regard to the interface strength. Marchant et al. [108] correlated the strength with the measured surface moisture content for 3 different interval times. Tensile splitting strength reductions of up to 50% were reported by Keita et al. [94] for uncovered specimens, compared to specimens protected from drying. Likewise, Wolfs et al. [96] presented strength reductions of approximately 33-50% for specimens left uncovered at longer interval times (24 and 4 h). The effect of surface moisture content is supported by findings outside the field of concrete printing [97].

Thus, a range of factors related to the respective processes and the material compositions have been shown to influence the interface bond strength in printed concrete. However, the different studies have also revealed the quantitative effects can vary significantly from one combination of system and material to another (ranging in some cases from 50% or more to none at all). Furthermore, it could be expected that more, still unstudied factors are relevant to the interlayer bond, and indeed to the bulk material properties as well – an area of research that due to the attention to the interlayer has yet received relatively little attention. More comprehensive research in this area is required in the coming years.

In particular, more fundamental theories should be developed. Current studies, by and large, have a phenomenological character: they seek to establish (and quantify) which process parameters have a significant influence on interface properties, but beyond general explanations are not yet proposing thorough hypotheses linking microscopic behavior to macroscopic structural performance. For instance, the relations between process and interface quality may be expected to depend on the material concept (no-slump, highly viscous versus low viscous with accelerator), as it results in either a fully sheared filament, or a non-sheared filament with a sheared lubrication layer (discussed in Section II.A.iii, and presented in Figure 3). Other aspects, including surface porosity, thixotropy and hardening, are also likely linked to interface properties, but such considerations are not yet elaborated in studies in this area.

Considering the tensile strength of the interface may be reduced in comparison to the bulk material, a few studies have also aimed at improvement strategies. Marchant et al. [109,110] proposed an additional layer of cement mortar in between the bulk material layers. Kho et al. [111] suggested to include a primer-applicator (spray) to the print nozzle (although no details were given). A method that was experimentally shown by Zareyan et al. [112] to be effective, was the introduction of an accentuated top surface of the filament. This can be achieved rather easily by adjusting the print nozzle opening geometry. In general, however, it should be noted that interface strength improvement technologies are still in very early stages of development.

B. Reinforcement

Printable cementitious mortars are inherently brittle. Their failure behavior is characterized by a low ratio of tensile to compressive strength, and low ultimate tensile strain compared to their fracture strain. To nevertheless obtain safe structural behavior, existing approaches from conventional concrete construction are being adapted and new innovative strategies are being developed [113]. The uncertainties associated with the quality of the interfaces between layers render this even more important for additively manufactured concrete as compared to conventional cast concrete.

i. Conventional to innovative

As noted in section I.B.ii., perhaps the most basic approach is to use the printed concrete not as the primary structural material, but rather as a formwork into which conventional steel reinforcement bars are positioned and which are subsequently filled with cast concrete [114]. This approach has been applied in projects by several commercial entities like WinSun, Cybe, and TotalKustom. Similarly, XtreeE constructed a column with concrete printed lost formwork, and filled with cast ultra-high performance fiber reinforced concrete (UHPFRC) [115] which significantly increased the form freedom due to the lack of steel reinforcement bars. As mentioned in Section I.B.ii, akin to this strategy is the combination of casting UHPFRC in a 3d printed formwork of another material, such as sand [33] or plastic [116], which is later removed.

Alternatively, in specific digital fabrication processes, it is possible to place the reinforcement first, and subsequently deposit the concrete around it. This approach has been applied rather crudely by contractor HuaShang Tengda, using a forked nozzle to print around pre-placed conventional reinforcement mesh, and in a more sophisticated manner in Smart Dynamic Casting [40,117] in which a dynamic formwork slip-forms the geometry around a pre-placed reinforcement element, or in the Mesh Mould process [34,118–120] where a free form reinforcement mesh is robot-welded and subsequently used as an open formwork for the application of a concrete.

Asprone et al. [121] proposed segmented printed elements with post-applied external reinforcement bars and tendons, as a way not only to overcome reinforcement but also connection issues.

A different strategy could be to avoid the need for tensile reinforcement altogether by designing structures so that they are purely compression-loaded by gravity. Liew et al. [122] showed this is possible for shallow concrete floors (although in that particular study not printed). Borg Costanzi et al. [123] presented a compression loaded dome structure from concrete elements printed on a double curved print bed. Recently, a bridge was unveiled in China [124] that seems to be based at least partially on compression-arch action. Nevertheless, the requirement to ensure gravity induced compression at all times, limits the applicability of this strategy considerably.

Another method to avoid tensile stresses is the application of active reinforcement, i.e. prestressing. Lim et al. [125] first applied this in a 3D printed concrete bench. It was later applied on a larger scale in a bicycle bridge in The Netherlands [126] showing that it is useful approach to create bending loaded structures of considerable size. A subsequent study on a topology optimized prestressed beam, by Vantighem et al. [127], showed that this strategy may allow minimal usage of material.

Other developments aim to create reinforcement methods that are integrated with the printing process. In 2017, Eindhoven University of Technology introduced an online method that directly entrains a high strength steel cable into the printed concrete filament [128,129] to obtain behavior comparable to conventional reinforced concrete. The performance benefits were confirmed by subsequent studies from other groups [130,131]. The obvious directional dependency can partially (but not fully) be overcome by the print path design. Detailed aspects of cable bond need further study. The application of textile reinforcement has also been suggested [132], but actual research has not (yet) been presented.

To, theoretically, be able to cope with the geometrical freedom involved in concrete printing, it has also been suggested to print the steel reinforcement too. An initial study on the behavior of printed reinforcement steel was presented by Mechtcherine et al. [133]. However, it remains yet unclear how the steel printing process is to be integrated with the concrete printing.

ii. Fibers

Given the complications involved in embedding continuous forms of reinforcement into printed concrete, it is not surprising that the application of fibers in the printed mortar to enhance tensile strength and ductility has received considerable attention.

It was first explored by Hambach & Volkmer [134] on a very small scale. Subsequently, a number of studies have been performed to assess the effect of basalt, glass, steel, PP and PVA fibers, on tensile strength, compressive strength, interface strength, and post-peak behavior [135–139]. Generally, a strong fiber orientation in the direction of flow is noticed. Parallel to the fiber alignment, a significant increase in tensile strength is found [134, 135, 139]. The compatibility of the applied fibers with the system (whether they can pass through the applied pump, transport hoses and nozzle) is an important point of attention.

Strain-Hardening Cementitious Composites (SHCCs, also known as High Performance Fiber Reinforced Cementitious Composites, HPFRCCs, or as Engineered Cementitious Composites, ECCs) constitute a specific group of fiber reinforced mortars of which the matrix composition, fiber performance, and matrix-to-fiber bond have been optimized to produce strain hardening failure behavior, under significant inelastic deformation and dense crack pattern development [140–142]. This leads to very favorable structural performance. Generally, they are applied as self-levelling substances, but printable variants are under development. Soltan & Li [143] applied considerations of extrudability and buildability to develop a printable mixture with polyvinylalcohol (PVA) fibers, although printability was simulated by extruding from a manually operated caulk gun. The same group later presented functionally graded ECC as a way to optimize fiber usage [144]. Yu & Leung [145] used a similar printing method to study the stress-strain behavior of a PVA-SHCC in different directions. Besides the expected strain-hardening behavior in the direction parallel to printing (i.e. longitudinal to the dominant fiber orientation), they even found some strain hardening behavior perpendicular to the print direction (albeit at much lower strain values). More extensive studies that included large-scale printing experiments were presented by Ogura et al. [146] (Figure 7), and Chaves Figueiredo et al. [147] using high density polyethylene (HDPE) and PVA fibers respectively. Both these groups used (different forms of) ram-extrusion to characterize the print mortar fresh behavior. Generally, SHCCs seem very promising for printed concrete in terms of structural performance. Their sensitivity to mixing procedures, on the other hand, may prove a challenge to overcome.

Figure 7. *Fracture patterns from uni-axial tensile tests, in printed (left) and cast (right) specimens of printable strain hardening cementitious composites (SHCCs). When the tension is applied parallel to the print direction, a very finely crack pattern develops due to the favorable fiber orientation. Reproduced from [146].*

With regard to reinforcement for printed concrete, it may be concluded that a considerable range of strategies is being explored, with varying degrees of success both in terms of structural performance and compatibility with the various additive manufacturing processes. Further studies will need to point out which approach is the most competitive in which situation.

C. Durability

With the issues of process-dependent strength and structural ductility requiring the most acute attention to allow application of additively manufactured concrete in practice, long-term effects have yet received significantly less attention. However, several authors have pointed out that aggressive chemicals, such as retarders and accelerators, applied in a significant number (but not all) processes, can have detrimental effects, particularly on the durability of reinforcement [117,148]. Some others have studied the effect of the process on the durability of the printed mortar itself. The interlayer interval time seems to be an important parameter, not only with regard to bond strength, but also with regard to the durability of the printed mortar. Increased interval times have been shown to lead to an augmented porosity [105], increased capillary water ingress [149], and higher chloride penetration levels [150].

D. Hardened properties – Outlook

Considering the state of development of the topics discussed in the previous subsections, it is clear much research needs to be done in order for the technology to mature into a generally accepted construction method. Besides the obvious developments required to address the issue of reinforcement, there is more fundamentally, a need to understand the relations between materials, processes, and (long term) object performance. This is essential to establish quality control methods that are needed for an industrial scale application. As suggested by Bos et al. [151], projects applying printed concrete in practice (particularly in a structural capacity), should be subject to intense scrutiny and large-scale testing (Figure 8) as long as quality control methods have not been fully established.

Figure 8. Large scale testing of a 1:2 scale prototype of a bridge from printed concrete. Reproduced from [151], with permission.

Specifically, a comprehensive characterization of materials and processes is essential to allow the comparison of experimental results and an assessment of the scope of applicability of those results. A complicating factor in this respect is that it is yet not fully known in what terms such a characterization should be defined. On the process side, it will likely include (but possibly not be limited to) factors such as batch vs. continuous mixing, pump pressure or frequency, material debit (range), system friction, nozzle geometry, print speed, and layer height settings. On the material side, factors may include rheological properties, thixotropy and time-dependent behavior, fresh mechanical properties, open-time and setting times, binder content and reactivity, and more. To determine the appropriate parameters for characterization should thus be a research priority. This will also allow the development of modelling approaches of the print processes, which in turn will pave the road for further improvements and optimizations.

IV. APPLICATIONS

Especially in recent times, growth in the field of digital fabrication with concrete has been driven, by and large, by applications. Architects have long been interested in producing unique, structurally informed shapes, but have largely been limited by construction methods, either in practical or economical terms [8,10,11,152]. Shells, parabolic arches, and other funicular forms that take advantage of the high compressive strength of concrete are not as commonly seen due to the required construction of scaffolding to support formwork, and again referring the reader to Figure 2, this shows that the primary area of interest for digital fabrication will be for components of complex geometry. However, as research progresses and digital fabrication unit costs are driven downward, less complex components, such as those that often find their place in concrete infrastructure, will also become competitive to produce with digital fabrication techniques. In this final section, we review the latest in applications of these fabrication methods.

A. Early pioneers

The dream of building an entire concrete house in one go was already hatched in the early twentieth century by Thomas Edison, with his patent for single-pour concrete houses actually

realized in the construction of several homes, but abandoned due to high costs [153,154]. In the 1990s, the Japanese were the true pioneers in robotics in construction, targeting the implementation of robots for specialized tasks such as bricklaying, welding, positioning of steel components, and finishing [155]. In fact, Obayashi Corporation developed an automated construction system for a high rise building (dubbed the BIG CANOPY), which in 1995 produced a 26 story high rise reinforced concrete building in the Tokyo Metropolitan area [156]. This building used prefabricated reinforced concrete parts, and the automation in the construction process mostly had to do with the assembly using a protected rising platform. This offered limited shape freedom, and the focus had most to do with reducing costs in response to Japan's aging workforce.

In 1997, the first major study to promote the use of digital fabrication to produce freeform cementitious components was published by Pegna [157], who utilized a particle bed fusion technique with Portland cement binder in a proof of concept study. In 2004, Prof. Berokh Khoshnevis then demonstrated a 1:1 scale production of a concrete wall using the Contour Crafting process [158]. Since this time, researchers (primarily architects) have then taken the view of using automated construction processes not as "simple task replicators" to improve efficiency, but rather as generic fabrication methods, in order to produce freeform architecture, structurally and aesthetically informed at the material level.

B. On site construction

Khoshnevis envisioned Contour Crafting as an on-site construction method, where a gantry printer, larger than the structure being printed, would produce the structure in a manner similar to how fused deposition modeling (FDM) printers operate [27]. In such a system, the printer would be constructed, produce the structure, and then be disassembled afterward. Some practitioners have turned this idea into a reality, notable among them the architect Andrey Rudenko's TotalKustom castle, printed in his backyard in 2014 [159], a villa printed on site by the Chinese company HuaShang Tengda in 2016 [160], and the R&Drone Lab, printed by the Dutch startup Cybe in Dubai in 2017 [161].

The problem of reinforcement was resolved by Rudenko and Cybe by using the printed concrete structure as a lost formwork, while HuaShang Tengda, as noted earlier, used a forked extrusion nozzle to place concrete around traditional steel reinforcement. Researchers from the University of Nantes have printed an inhabitable house on site by using a sprayed polyurethane foam as a functional (insulating) formwork, with the concrete cast inside, in a process called Batiprint3D [162]. The Mesh Mould process used a mobile robot to produce the Mesh Mould wall of the DFab House, an inhabitable structure in Dübendorf, Switzerland. The robot produced a double-curved steel mesh structure as a functional formwork, which was subsequently concreted. The tooling and positioning challenges of on-site construction with robots were detailed by Buchli et al. for this project [48], which showed that the field of robotics still has major challenges to overcome before practical on-site mobile robotics can be employed.

While the previous examples demonstrate the shape freedom that digital fabrication creates to produce custom architecture in structures, it has also been envisioned for other purposes. The Austin, Texas startup Icon has claimed to print a house in 24 hours at a price of less than \$4k USD, with the aim of providing affordable housing for developing countries [163]. US Army Corps of Engineers researchers have printed a barracks with a crew of four soldiers within 40 hours to demonstrate the battlefield potential of this technology, where speed and reduced labor is essential [164]. The ability to produce shelter quickly in the event of a natural

disaster has also been pointed out as a use for this technology on site. Nonstandard infrastructure parts, such as sewage connectors, have been proposed for onsite printing by Cybe and XTreeE [165,166]. Finally, current wind turbine heights are limited by the size of cranes for construction as well as transport of large base components, but a concept by Khoshnevis has been presented to increase this possible height to above 100 meters using concrete 3D printing [167]. This offers an on-site production alternative to the pre-cast production of concrete elements that then get post-tensioned on-site [168], and digital prefabrication, described in the next section, could also offer an alternative to traditional prefabrication processes for current tower segments.

C. Prefabrication

While on site construction is an attractive prospect, it seems most apparent that prefabrication is where most digital fabrication technologies have the current highest potential. Indeed, up to now robust fabrication processes have required a somewhat controlled environment to limit the impact of humidity and temperature sensitivity on mineral binders. Also, as most processes being developed are in enclosed environments, the components currently being produced can reach structural scales, but not entire structures. Nevertheless, production at this scale can demonstrate the potential of digital fabrication, and provide essential insight into upscaling challenges.

Prefabrication also allows to introduce a bit more flexibility in the construction process by expanding the options for the design and planning of the assembly process. It is worth noting here that Duballet et al. recently published a useful first study in analyzing various prospects for concrete 3D printing in terms of direct print, or print and assembly of building components, and mapped these out in terms of robot complexity [169]. Independently of this, it should not be forgotten that some processes, such as particle bed fusion, realistically can only be expected to be viable in the prefabrication context.

Buswell et al. at Loughborough University noted the possibility to use digital fabrication to incorporate functionality in concrete elements [13], a process also more easily facilitated in the prefabrication context. In 2011, they demonstrated this with their concrete 3D printing process, producing the “Wonder Bench”, the first 3D printed large scale concrete demonstrator with a complex geometry [170]. More recently and at a larger scale, Enrico Dini, working with Acciona, has produced a 3D printed pedestrian bridge installed in Madrid [171] using particle bed fusion to generate segments that were assembled onto a steel frame. and the research team at TU Eindhoven has produced a bicycle bridge in a similar manner using their concrete extrusion 3D printing process [172].

As noted earlier, 3D printing formworks offers an immediate impact, and this has been the focus of some work in the prefabricated context as well. Besides the pillar produced by XtreeE, the same group has also produced façade elements from concrete 3D printed formwork [166]. A key element in the previously noted DFab House is the “Smart Slab”, which was produced by 3D printing formworks using particle bed fusion [173]. This is a slab for an articulated ceiling, custom designed to fit atop the previously noted Mesh Mould wall, and topologically optimized to save material and embed functionality for facilities (water supply tubes for sprinklers and electricity cables). It allows the illustration of a concept that holds much potential for application of these technologies: integration of the design, construction, and the use phases of a building. This is especially key, as the use phase of a building represents up to 90% of its energy demand through its life cycle [174].

Schlueter et al. demonstrated the potential of performance gain through functional integration with their 3for2 concept (Figure 9). In a nutshell, this approach starts from recognizing that ceiling plenums in high rise buildings can take up to one third of the vertical space in order to accommodate all the required facilities of the building (air handling, water, etc.). What Schlueter et al. have proposed and realized is to design floors that integrate heat control and electricity supply, in order to dramatically reduce this inter-floor space. Along with a better design of the façades, this makes it possible to place 3 floors in a high rise that currently takes the same vertical space as 2 [175]. This approach has the very obvious economic impact of increasing rentable space in a high rise by 50%. With respect to digital fabrication, this example is particularly important, because it shows that a different constructive approach can lead to massive economical benefits that would override the question of the cost of producing new enabling elements, in this case the integrated floors. Whatever the most cost effective solution is in this case does not really matter here, what does matter is that “think-different, build-different” probably offers the greatest benefits for digital fabrication, making direct production costs a secondary issue with respect to new primary gains obtained by new approaches, ones that might not be possible with standard technologies. Identifying and exploiting such opportunities appears to us as a great prospect and very exciting challenge for digital fabrication.

Figure 9. “3for2” concept, showing possibility to place 3 high rise stories in the space normally taken by 2 conventional stories, through integrated design to save space normally required for facilities in ceiling plenums. Image from [176].

V. CONCLUSION AND RESEARCH DIRECTIONS

Digital fabrication with concrete has gained considerable prominence with the general public, the construction industry, and the concrete materials and structures research communities within the past five years. Still, however, there are many unresolved and interesting new challenges for research. If the technologies being developed are to grow to the point that they can truly revolutionize construction, we see the following research areas as those requiring attention.

From a fundamental research standpoint, the following research areas already have thriving communities, but with the advent of a “digital concrete” research community, they take on a new dimension:

- Rheology: fundamental rheological relationships during fabrication processes take on new meanings compared to traditional casting processes. In particular, stability and deformation during fabrication, as well as dynamic processes such as mixing.
- Processing-Material-Performance: the link between engineering performance (strength, ductility, durability) and processing must be fully characterized in light of the unique aspects of digital concrete processing.
- Early age hydration: from mixing until the onset of the acceleration period, a more global understanding of the dissolution, nucleation, and growth processes of hydrates is required. In particular, the link between early age hydration products, their microstructure, and rheological behavior.
- Chemical admixtures: an understanding of the impact of chemical admixtures on early hydration, as well as interactions between the numerous admixtures used in digital fabrication.
- Computational modeling: the modeling of concrete properties during early hydration will prove essential for designing digital fabrication processes in terms of optimal tool paths. Also, design algorithms in topological optimization are key for architects in creating more sustainable constructions. Finally, computational modeling at the molecular scale complements our understanding of early hydration and admixture impact.

The following areas are of importance in terms of technological development:

- Reinforcement: resolving, or simply rethinking, how to reinforce structures produced by digital fabrication is a key challenge, and how to incorporate this in a processing scheme somehow.
- Test methods: development of appropriate fresh state property testing methods for digital fabrication, especially for nebulous terms such as “printability” and “extrudability”, is essential for the proper process development. Additionally, development of standard test methods for hardened digital concrete, linking them to large scale testing of components.
- Reproducibility: As these test methods are generally custom-designed for now, it behooves the research community to share as openly as possible (understandably, some limitations are expected with industrial collaborators) the experimental and constructive designs so that research can be more easily reproduced and verified. Making use of supplementary information in submitted publications would be a very useful avenue for this.
- Set control: development of chemical admixture formulations to control setting in the necessary time scales for digital fabrication is essential for fast building rates, and chemical admixtures are anyway necessary for rheological property control.
- Processing: the continuous processing of concrete, while not a new topic in itself, is changed in digital concrete due to tighter processing boundaries, and thus development and characterization of continuous processes such as mixing is essential, and development of feedback control systems to respond to changing conditions.
- Moisture management: the loss of the “skin” of the formwork in many digital fabrication processes, as well as the evidence that superficial moisture loss creates weak interfaces, makes moisture retention an important technological issue to resolve.

Finally, other essential aspects include:

- Sustainability: Digital concrete mixes generally have higher paste contents due to processing requirements, which offsets the benefit of material-efficient designs. Additionally, durability of digitally fabricated concrete constructions has largely been ignored. To be sustainable, a more holistic view of digital concrete constructions must be considered.
- Functionality: using precision material placement to add or improve functionality is a key advantage of digital fabrication with concrete. This can be done through local architecture control, or local composition control to create a functionally graded material, and with multiple materials.
- Creativity: the creativity of architects and structural designers has been driving the field, especially as they find new and innovative applications of the developing technology. New applications drive technological development, making these processes more competitive with traditional construction in the long run.
- Interdisciplinarity: in light of the above statement, the importance of interdisciplinarity cannot be understated. Being able to communicate across disciplines such as materials, structural engineering, architecture, and robotics is essential to success in this burgeoning research field. An even longer term outlook sees the potential for the field of computer science to revolutionize the construction industry with Big Data analysis, AI, and augmented and virtual reality [3].

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