Current challenges and Future potential of 3D concrete printing

Aktuelle Herausforderungen und Zukunftspotenziale des 3D-Druckens bei Beton

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Abstract: The emphases on reduction of construction time and production costs have profound influences on the construction process that has led us to investigate a new paradigm, known as 3D concrete printing. This technique can fabricate complex 3D building components directly from computer aided design (CAD) model without any tooling and human intervention. However, compatibility of the presently available materials has impeded its widespread application and commercialization. This paper introduces an overview of concrete printing processes and it's noteworthy potentials in the building & construction (B&C) sector. After sketching the potential, a novel fly ash based inorganic geopolymer is printed and characterized in terms of fresh and hardened properties with an aim for sustainable built environment.

Die Reduzierung von Bauzeit und Produktionskosten hat einen signifikanten Einfluss auf den Konstruktionsprozess, der dazu führt, dass ein neues Paradigma, bekannt als 3D-Druck für Beton, zu untersuchen ist. Mit dieser Technik können komplexe 3D-Bauteile direkt aus dem CAD-Modell hergestellt werden. Die Kompatibilität der gegenwärtig verfügbaren Materialien hat jedoch ihre Anwendung und kommerzielle Nutzung verhindert. Dieser Artikel gibt einen Überblick über konkrete Druckprozesse und deren Entwicklung im Bereich Bau und Konstruktion. Nach

Aufzeigen eines deratigen digitalen Konstruktionsprozesses wurde ein anorganisches thixotropes Material auf Flugasche-Basis gedruckt und in Bezug auf anfängliche und gehärtete Eigenschaften mit dem Ziel einer nachhaltigen Gestaltung charakterisiert.

Keywords: Digital construction, 3D Concrete printing, Geopolymer, Rheology and Mechanical properties

Stichwörter: Digitale Konstruktion, 3D-Druck für Beton, Geopolymer, Rheologie und mechanische Eigenschaften

1. Introduction

The construction industry has traditionally relied on two-dimensional (2D) drawings and scale models for the evaluation of the design process. Increasingly, 2D drawings and prototypes are being replaced by three-dimensional (3D) modelling in the virtual environment of building information modelling (BIM) [1, 2]. A benefit in the use of BIM in combination with digital fabrication methods allows architects, designers and engineers to investigate possible modifications due to changes in design intent or unforeseen circumstances.

Digital fabrication includes the use of 3D printing or additive manufacturing (AM) which uses a layer by layer deposition strategy to build complex 3D objects directly from the computer-aided design (CAD) model in a reasonable build time [3-5]. In recent years, this technology has shown the potential to be used in B&C applications due to significant advantages in terms of reduced build time, less wastage and less human resources invested when compared to traditional methods. 3D concrete printing has already been adopted for both structural and non-structural applications in many countries including Netherland, Dubai, Saudi Arabia and Spain. Some noteworthy examples are shown in Figure 1 [6].

[Insert Figure 1 here]

2. Potential of 3D Concrete Printing

There has been an increase in the usage of 3D printing process in the B&C industry and with the improvement of this technology, potential advantages such as faster construction, less human resources, increased complexity and/or accuracy, waste minimization and transportation savings are possible when compared to traditional construction methods [7, 8]. Here are some key benefits of concrete printing in the B&C sector:

Design freedom: One of the major benefits of 3D printing is that it allows architect and designer to be flexible in the shape of their designs. Using printable materials and composite mixtures, 3D printers can build these shape elements, which offers robust structural design, especially when compared to the traditional regular forms [9].

Low cost building components: The cost of 3D printed structures could be lowered because it is formwork less construction and requires less human resources at construction sites. The material is also deposited whereby it’s necessary, thus reducing the wastage of material. Thus, in future, cheap housing facilities can possible with 3D printing technology and it can benefit to the poor in the countries like India, South Africa etc.

Remote area construction: 3D printing does not need much labor work, instead it needs right material and a printer that can run continuously with minimal supervision. Therefore, 3D printing would be the best option for construction in a remote area where the environment is aggressive for humans. Fabrication of lunar and MARS habitat for the future astronauts can be considered as one of these target applications using locally available lunar regolith and 3D printing technique [10].

3. Challenges of 3D Concrete Printing

In 3D printing, the complete process is inter-dependent on *material*, *machine* and the *part design* and hence, it is necessary to maintain a proper co-ordination between these three components rather than optimizing individual components [14]. Despite of having significant potentials, concrete printed structures face a series of challenges, that need to be addressed for its successful implementation. The following sections discuss these challenges in more detail.

3.1 3D printable materials

Conventional concrete cannot be directly used for 3D printing applications since here no formwork is used for material deposition. For printing, material must possess sufficient yield stress to hold the subsequent deposited layers without any major deformation of the bottom layers. Simultaneously, it should be extrudable with good shape retention properties [11]. The main difference between the pumping of conventional concrete and 3D printing concrete is that in the former concrete is poured in a predefined formwork, where in later case, no formwork is used and therefore the shape of the objects is fully defined by the material rheology and other fresh properties. Recently, five key benchmarking properties such as extrudability, flowability, buildability, open time and layer adhesiveness have been introduced, in an attempt to benchmark the concrete materials for extrusion based printing process [12]. It was suggested that, thixotropic property of the cementitious material is very helpful in concrete printing application owing to their high yield stress and low viscosity properties [13]. Such behavior usually originates in the material due to colloidal flocculation and ongoing hydrates nucleation. Table 1 summarizes some well-known mix designs used by different authors and universities for 3D printing of concrete materials.

[Insert Table 1 here]

3.2 Structural integrity and anisotropic properties

For offsite printing, sometimes transportation of large scale objects is problematic. In such cases, the object can be built in multiple sections (modular construction) and later assembled to build the complete structure. However, proper care should be taken for structural integrity (especially in joining the multiple sections in one position), since shrinkage due to temperature change, or vibration in the structure from seismic action can cause tolerance errors in the structure. Also, the interfacial surface connection (bonding between the layers) must be strong enough for handling the printed part without any damages. Concrete layers should be deposited in such a way that they should stick to previous layers without any change of volume and later reinforcements (e.g. fibers, steel wires) can be added if necessary to improve the structural properties. The anisotropic behavior of the printed objects is also one of the unique properties for architects, to consider, during the building design phase. It has been found by few researchers that mechanical properties of 3D printed objects are mostly anisotropic due to layered deposition nature of the process [15].

3.3 Post-Processing

Poor surface finish (due to volumetric error) has been a limitation in concrete printing. Improper control and excess deposition of materials can cause poor surface quality in the part, which is not desired. Insufficient material may be even worse since voids may become trapped and incorporate weakness into the structure. Therefore, proper care needs to be taken during the printing as well as after the printing to improve the surface quality and dimensional accuracy. The integration of trowels in the nozzle orifice can significantly improve surface finish to some extent [16].

3.4 Reinforcement in the 3D printed structure

Concrete structures need reinforcements for improved mechanical properties as well as structural integrity. Therefore, there is a need of hybrid printing system that can print concrete along with the reinforcement in different arrangements which will eliminate the need of adding reinforcement to the structures [17]. Few possible ways of installing reinforcements in the 3D printed objects are shown in Figure 2 [18].

[Insert Figure 2 here]

It can be inferred from the above figure that in 3D concrete printing, reinforcement can be added during or after the printing process. Chinese company, Winsun has demonstrated the possibility of adding reinforcement bars in to the printed structures (figure 2(a)) and used a special extruder that can print the concrete around the pre-installed reinforcements (Figure 2 (c)). Alternatively, Dennis de Witte [19] proposed the idea of printing in-process reinforcement with concrete for improving ductility properties of printed parts. Recent applications of such process can be found in an experimental study of metal cable used as reinforcement in 3D concrete printing [20].

3.5 Printing of overhanging structures

Concrete printing has a limitation of not being able to fabricate significantly overhanging parts because of the material's low green strength properties after extrusion. However, using D-shape technology, it is viable to produce complex geometrical shape since in this process, unbonded powders are mainly used as support material [9]. Additionally, use of rapid hardening material can be opted to print these structures to some extent without compromising the bond strength between the deposited layers.

3.6 Standard for Concrete printing

For many applications, concrete must meet specific standards before it can be used. Therefore, as a new construction technology, 3D concrete printing must achieve certain levels of reliability before this technology can be used in real time application. In its simplest form, this might be achieved by bringing additional considerations and requirements to the attention of structural designers, analogous to precast construction, to which a separate chapter is devoted in Eurocode 2 for concrete buildings.

Despite the above challenges, concrete printing can improve the current fabrication methodology by automating the complete process. Automation also reduces the reliance on skilled labor and can increases in accuracy by lowering the potential defects due to human errors. However, considering the challenges, there is a need for intelligent system design as well as advanced material development that can lead to environment friendly affordable housing.

4. Fresh and hardened properties of a 3D printed green material

This section discusses the mechanical properties of 3D printed parts with respect to different loading directions and its comparative performance with conventionally casted part. It is well known that the 3D printing process generally induces anisotropic properties due to its layer wise nature of deposition and to reveal this unique property, especially in 3D concrete printing, our current study aims to develop and conduct directional compression tests on a 3D printable green construction material. The target material is a fly ash based geopolymer, that needs to exhibit thixotropic characteristics which can be described as time-dependent shear thinning property. Fresh property was studied using a rational rheometer (Viskomat XL) supplied by Schleibinger Testing Systems, Germany. The experiment was designed in such a way that the shear rate was gradually increased to 60 rpm in two mins, followed by a constant of 60 rpm for two mins and again gradual decrease to zero rpm in another two mins. The thixotropic behavior of printable concrete then can be obtained from the torque-rotation in rpm (T-N) graph (see Figure 3). Literature reveals that, the area held between up and down curve is a measurement of thixotropic property which is an essential property for extrusion based concrete printing processes [11]. The mix design for 3D printable geoploymer is tabulated in Table 2. Due to the limitation of nozzle size and grouting pump capacity, no coarse aggregates were used in the mix.

[Insert Figure 3 here]

As discussed before, for extrusion based printing, the material must possess high yield strength and low viscosity properties so that it can be easily extrudable, and once comes out of the nozzle, its shape can be retainable. Such a property is achieved here by adjusting particle grading and adding nano-clay to the primary (conventional) material followed by optimizing their combinations.

[Insert Figure 4 here]

Once the material is prepared, it is dumped into a hopper of the grouting pump and then printed accordingly to toolpath specified in the CAD model. A four-axis gantry printer developed at Nanyang Technological University (NTU), Singapore (Figure 4) is used for printing according to the design described in CAD model. Printed geopolymers are cured under ambient conditions prior to three directional mechanical testing. In order to conduct a comparison study between 3D printed and casted samples, 50 mm cubes are casted and cured using the developed printable material. After 28 days, nine 50 mm cubes are extracted from the printed part and tested in compression in three different directions. Experimental results of average compressive strengths (3 samples in each direction) for both casted and printed samples are shown in Figure 5a.

[Insert Figure 5 here]

It is anticipated from the above figure that the 3D printed parts are stronger than casting when load is applied on a plane perpendicular to the layers. However, the strength depends on inter-layer bond strength of the printed material and printing quality. Unlike casting, in concrete printing the possibility of variation in the compressive results are likely to be more due to some common problems like discontinuous flow, poor printing quality, voids/overlap between layers etc. Thus, it is recommended to the future building designers and architects to consider the printed part directional properties during different loading situations in order to utilize full potential of the concrete printing process [13].

7. Conclusion

3D concrete printing was introduced as a promising family of methods to address the current challenges of construction industry. It is acknowledged that this technology has been applied successfully in many demonstration projects and research laboratories. Tests to characterize both fresh and hardened properties of the printed parts are being explored by different universities that includes *viscosity recovery testing*, *structural built up testing*, *compressive strength testing*, *indirect tensile strength testing* and *interlayer bond strength testing*. In this paper, anisotropy property of geopolymer mortar were studied by loading the printed specimen in three different directions and later the results were elucidated by the additive nature of layer manufacturing process. Thixotropy property was also highlighted during the rheology test of geopolymer mortar.

The potential of automation, elimination of formwork, reduction of construction waste, geometrical precision and production of complex geometries render 3D concrete printing an exciting prospect for the construction industry. Though there are many challenges, concrete printing is believed to have the capacity to change or improve the traditional construction process to some extent. The need to abolish conventional methods completely may not be necessary. The future of construction is most likely to be an integrated process that allows organizations to take advantage of both conventional and 3D printing technologies at the same time.

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References

[1] H. Brad, D. McCool, *BIM and construction management: proven tools, methods, and workflows*, John Wiley & Sons, Indiana, USA **2015**.

[2] N.Č. Babič, P. Podbreznik, D. Rebolj, *Automat. Constr.* **2010**, *19 (5)*, 539.

[3] C.K. Chua, K.F. Leong, C.S. Lim, *Rapid prototyping: principles and applications*, World Scientific Publishing Co. Pte. Ltd. Singapore, **2010.**

[4] S.S. Mahapatra, B.N. Panda, *Int. J. Serv. Oper. Manag.* **2013**, *16(4)*, 460.

[5] B. Panda, M. Leite, B.B. Biswal, X. Niu, A. Garg, *Measurement*, **2018**, *116*, 495.

[6] F. Bos, R. Wolfs, Z. Ahmed, T. Salet, *Virt. Phy. Protyp.* **2016**, *11(3)*, 209.

[7] C. Gosselin, R. Duballet, P. Roux, N. Gaudillière, J. Dirrenberger, P. Morel, *Mater. Des.* **2016**, *100, 102-109.*

[8] B. Khoshnevis, *Automat. Constr.* **2004**, *13(1)*, 5.

[9] Y.W. Tay, B. Panda, S.C. Paul, M.J. Tan, S.Z. Qian, K.F. Leong, C.K. Chua, *Mater. Sci. Foru.* **2016**, *861*, 177.

[10] B. Khoshnevis, D. Hwang, K.T. Yao, Z. Yeh, *Int. J. Ind. Sys. Eng.* **2006**, *1(3)*, 301.

[11] S.C. Paul, Y.W.D. Tay, B. Panda, M.J. Tan, *Arch. Civ. Mech. Eng.* **2018**,*18 (1)*, 311.

[12] T.T. Le, S.A. Austin, S. Lim, R.A. Buswell, A.G. Gibb, T. Thorpe, *Mater. Struct.* **2012,** *45(8)*, 1221.

[13] B. Panda, S.C. Paul, L.J. Hui, Y.W.D. Tay, M.J. Tan, *J. Clean. Prod.* **2017**, *167*, 281.

[14] B. Panda, S.C. Paul, N.A.N. Mohamed, Y.W.D. Tay, M.J. Tan, *Measurement*, **2018**, *113*, 108.

[15] B. Panda, S.C. Paul, M.J. Tan, *Mater. Lett.* **2017**, *209*, 146.

[16] H. Kwon, S. Bukkapatnam, B. Khoshnevis, J. Saito, *Rapid Prototyping Journal*, **2002**, *8(3), 147-160.*

[17] Y.W.D. Tay, B. Panda, S.C. Paul, N.A.N. Mohamed, M.J. Tan, K.F. Leong, *Virt. Phy. Protyp.* **2017**, *12(3),* 261.

[18] Shanghai-based WinSun 3D Prints 6-Story Apartment Building and an Incredible Home, < https://3dprint.com/38144/3d-printed-apartment-building/ > access on May 2016.

[19] D. de Witte, *Ph.D Thesis*, TU Delft, The Netherland, **2015**.

[20] F. P. Bos, Z. Y. Ahmed, E. R. Jutinov, T. A. Salet, *Materials***,** **2017**, *10(11), 1314.*

[21] T.T. Le, S.A. Austin, S. Lim, R.A. Buswell, R. Law, A.G. Gibb, T. Thorpe, *Cem. Concr. Res.* **2012**, *42(3),* 558.

[22] Z. Malaeb, H. Hachem, A. Tourbah, T. Maalouf, N. E. Zarwin, F. Hamzeh, *International Journal of Civil Engineering*, **2015**, 6(6), 14-22.

[23] K. H. Jeon, M. B. Park, M. K. Kang, J. H. Kim, Presented at *ISARC*, Montreal, Canada, **2013**, pp. 1359-1365

[24] V. N. Nerella, M. Krause, M. Näther, V. Mechtcherine, Presented at 25th Conferences on *Rheology of Building Materials*. Hamburg, Germany: tradition, **2016**, pp. 236–246

[25] A. Perrot, D. Rangeard, A. Pierre, *Mater. Struct.* **2016,** 49(4), 1213-1220.

Figure 1. Noteworthy examples of concrete printing by (a) Counter crafting, USA, (b) University of Loughborough, U.K, (c) Winsun, China, (d) Xtree, France, (e) Apis-cor, France and (f) Mini-builder, Spain [6].

Abbildung 1. Beispiele für den Betondruck von (a) Counter Crafting, USA (b) Universität Loughborough, Großbritannien (c) Winsun, China (d) Xtree, Frankreich (e) Apis-cor, Frankreich und (e) Mini-Builder, Spanien [6

Figure 2. Reinforcing 3D concrete printed elements [17, 18]

Abbildung 2. Verstärkte 3D-Betonelemente [17,18]

Figure 3. Torque-speed (T-N) graph obtained from Rheometer

Abbildung 3. Drehmoment-Drehzahl-Diagramm (T-N), gemessen mit Rheometer

Figure 4. (a) 4 Axis gantry concrete printer at NTU, Singapore and (b) 3D printed geopolymer part.

Abbildung 4. (a) 4-Achsen-Portalbetondrucker an der NTU, Singapur (b) 3D-Geopolymer-Druck

Figure 5. (a) Comparison of compressive strengths of 3D printed geopolymer with casted samples and (b) different loading directions

Abbildung 5. (a) Vergleich der Druckfestigkeiten von 3D-gedruckten Geopolymeren mit gegossenen Proben (b) Verschiedene Belastungsrichtungen

Table 1. Different mix designs for 3D concrete printing

Tabelle 1 Verschiedene Mix-Designs für 3D-Betondruck

Table 2. 3D printable geopolymer mix formulation

Tabelle 2. 3D-druckbare Geopolymer-Mix-Formulierung

Table 1. Different mix designs for 3D concrete printing

Tabelle 1 Verschiedene Mix-Designs für 3D-Betondruck

Institute / Company	University of Southern California [10]	Yonsei University [23]	TU Dresden [24]	Loughborough University [12]	University of Southern Brittany [25]	XtreeE [7]	American University of Beirut [22]
Binder	CEM II cement (C/B: 1)	CEM I cement (C/B: 0.6) Fly Ash (FA/B: 0.3) Silica Fume (SF/B: 0.1)	CEM I cement (C/B: 0.55) Fly Ash (FA/B: 0.23) Silica Fume (SF/B: 0.22)	CEM I cement (C/B: 0.7) Fly Ash (FA/B: 0.2) Silica Fume (SF/B: 0.1)	CEM I cement (C/B: 0.5) Limestone filler (LS/B: 0.25) Kaolin (KC/B:0.25)	CEM I cement (C/B: 0.6 - 0.8) Limestone (LS/B: 0.1 - 0.2) Silica Fume (SF/B: 0.1 - 0.2)	Cement (C/B: 1) (unknown type)
Aggregate	S/B: 1.105	Fine aggregate and silica sand (0.1mm to 0.6mm)	S/B: 1.5897	S/B: 1.5 (Maximum particle size 2mm)	_	S/B: 0.8 - 1 (crystalline silica)	S/B: 1.92 (fine aggregate and sand)
Water	W/B: 0.505	W/B: 0.35	W/B: 0.23	W/B: 0.26	W/B: 0.205	W/B: 0.2 - 0.233	W/B: 0.39
Additive	SP/B: 0.084	_	SP/B: 0.0128	SP/B: 0.01 Retarder/B: 0.005	SP/B: 0.0015	_	Accelerator /B: ~ 0.008 Retarder/B: ~ 0.005

Other Materials / Remarks	_	3mm fibers Thickening agent and styren-acrylic polymer resin (each 0.1 wt.% of binder)	_	1.2 kg/m3 of 12mm length/ 0.18 mm diameter polypropylene fibres	Limestone filler had a particle size distribution ranging from 0.1 to 100 micron	_	_
Average compressive strength (Mpa)	18.9 Mpa	52 Mpa	80MPa (21days)	110 Mpa	No harden test result	120Mpa	42 Mpa

Table 2. 3D printable geopolymer mix formulation

Tabelle 2. 3D-druckbare Geopolymer-Mix-Formulierung

Materials	Weight percentage (%)
Class (F) Fly ash	22.42
Slag (GGBS)	3.27
Silica Fume	6.54
Fine river sand	49.0
Potassium Silicate (1.8 MR*)	13.25
Thixotropic additives	0.50

*MR stands for molar ratio