A REVIEW OF 3D PRINTABLE CONSTRUCTION MATERIALS AND APPLICATIONS

BING LU
Singapore Centre for 3D Printing and School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore, 639798, Singapore

MING JEN TAN
Singapore Centre for 3D Printing, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore, 639798, Singapore

SHUNZHI QIAN
Singapore Centre for 3D Printing and School of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore, 639798, Singapore

ABSTRACT: 3D printing, also known as additive manufacturing, is a technology using a layer-by-layer process to build three-dimensional objects. The developments of 3D printing in building and construction have seen great potentials during the recent years. Although this technology is still considered at its initial stage, its potential benefits such as quicker construction, low labor costs and less waste produced make it one of the most promising building technology in the future. This article surveys the researches and developments on 3D printable construction materials with corresponding 3D printing technologies to date. Fresh property requirements for 3D printable materials are discussed with the insights from sprayable and extrudable materials, followed by the discussion on hardened properties of structures printed with cementitious materials. The article also reviews various engineering applications of 3D printing recently emerged in building and construction sector. At last, the article hypothesizes the future developments of 3D printing for building and construction based on the reviews on plausible 3D printable materials and structural applications. The challenges from material and structural aspects are discussed in detail, followed by the potential applications of new functional materials. It is also possible to integrate the Building Information Modeling (BIM) and 3D printing in tomorrow's building and construction field for greater construction productivity, and the article will point out the feasibility and potential advantages of this combination.
KEY WORDS: 3D printing, construction material, structural property, engineering application, functional material.

1. INTRODUCTION

3D printing refers to an automated additive manufacturing process to create objects from digital models (Bogue, 2013). Compared with traditional manufacturing technology, 3D printing has high design flexibility and manufacturing efficiency with relatively low cost (Gao et al., 2015). In the past decades, the development of 3D printing is very fast and wide applications have been successfully achieved in many fields. Recently, this technology has been expanded to building and construction, with potential advantages include quicker construction, lower labor costs, and less waste produced (Wikipedia, 2015).

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The following sections of the article review the development of 3D printable construction materials and their potential engineering applications. Major large-scale 3D printing technologies are briefly introduced. The article discusses on the fresh property requirements of 3D printable construction materials with the insights from similar conventional construction materials. The hardened properties of 3D printed structures are also surveyed, followed by various engineering applications in the recent years. Future research directions of 3D printing in building and construction are envisaged, including challenges and potential applications.

2. MAJOR 3D PRINTING TECHNOLOGIES IN BUILDING AND CONSTRUCTION

Contour Crafting and 3D Concrete Printing are the successful practices of cementitious material printing system. Contour Crafting combines an extrusion process to form object surfaces and a filling process to build the object core in layered fashion (Khoshnevis, 2004). In the printing process, the rim of the structure is printed out first to form a closed section for a layer. Then the printing nozzle is lifted up to print another layer at the top of previous layer. At the end of printing process, fillers such as concrete may be filled in the closed section if needed (See Figure 1(a)). 3D Concrete Printing is also based on extrusion of cement mortar. Compared with Contour Crafting, it has a smaller resolution and ability to retain 3-dimensional freedom for better control when printing (Lim et al., 2012). However, 3D Concrete Printing lacks the surface-scraping so the structure has an obvious layered appearance (See Figure 1(b)).

(a) Structures printed by Contour Crafting (b) Structure printed by 3D Concrete Printing
Figure 1. Structures printed by Contour Crafting (Khoshnevis, 2004) and 3D Concrete Printing (Lim, et al., 2011)

Different from Contour Crafting and 3D Concrete Printing, another major large-scale printing technology D-Shape adds thin layers of binder to stone aggregates at predetermined slices (D-Shape, 2016). In the printing process, material is laid to the desired thickness and compacted, followed by the deposition of the binder to where the part is to be solid (Lim et al., 2012).

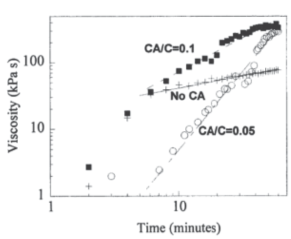
3. MATERIAL PROPERTIES OF 3D PRINTABLE CONSTUCTION MATERIALS

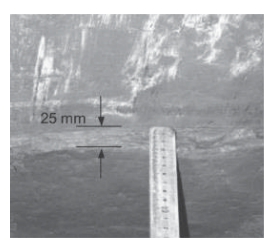
3.1 Fresh property requirements and insights from similar construction materials

In 3D printing, the structures are manufactured through a distinctive layer-by-layer process. It is noticed that each of the three major large-scale printing technologies does not need external mould or formwork. Hence, the printed layers should have enough strength to support the weight of itself, rather than dissipating the pressure to the side-formworks in conventional constructions. To meet this requirement, the printable construction material should set and harden very quickly after printed. In other words, the viscosity of printable construction material should reach a high level once the material leaves the printing nozzle. On the other hand, the viscosity of printable construction material should be kept at a relatively low level before printing to avoid the blockage inside the delivery hose or the printing nozzle. In addition, the printable construction material must possess enough adherence to assure the integrity of printed structure and alleviate the influence of weak bond resulted by layer-by-layer manufacturing process.

There are some similarities between sprayable construction material and 3D printable construction material, and the insight from sprayable material may provide a possible solution to achieve the requirements of 3D printable construction material. Shotcrete is one of the most used sprayable construction materials. In conventional construction, shotcrete is conveyed through a hose then pneumatically projected and gradually built up on a backup surface or substrate (Neville, 2002). The requirements of high performance shotcrete include relatively high very-early-strength, easy to be delivered through the hose and enough adherence to the substrate. However, the coarse aggregates used in normal shotcrete may not be used in the printable materials due to the limitation of nozzle size and requirement of printing resolution. In addition, shotcrete needs substrate while no external formwork is needed in 3D printing. With a high projected speed, shotcrete have rebounds, which should be avoided in 3D printing. So shotcrete must be modified to make it printable.

One of the key points in the design of high performance shotcrete is to achieve different rheological performances in pre-spraying stage and post-spraying stage effectively. In addition to the control of water/cement ratio, aggregate gradings are also suggested in the practice (ACI Committee 506, 1990). However, adjusting the gradings in the same way may not be suitable for 3D printing due to the lacking of coarse aggregates. Kim et al. (2003) proposed a solution through the design of a wet-mix shotcrete without coarse aggregate by introducing high-range water-reducing admixture (HRWRA) and hydroxypropyl methycellulose (HPMC). HRWRA serves as static dispersant for low viscosity in the pre-spraying stage, and HPMC helps maintain the cohesiveness. As Figure 2(a) shows, the viscosity increases as hydration continues, and the slight addition of calcium aluminate cement (CA) helps generate a rapid increase in viscosity over time. From the spray test, this shotcrete has great adherence (See Figure 2(b)) and high very-early-strength. The admixtures used in this shotcrete can be borrowed in the design of 3D printable construction materials, while CA should be substituted by other similar rapid-hardening materials due to its long-term strength decreasing effect (Odler, 2000).





(a) The change in viscosity over time with different proportions of CA and ordinary cement
(b) Spray test of shotcrete in the vertical direction
Figure 2. The rheological control and spray performance of shotcrete designed by Kim et al. (2003)

In addition to sprayable materials, extrudable materials can also provide insights for potential mix design of 3D printable construction materials. Currently the cementitious material printing system is mainly based on the extrusion process of cement-based mortar. In extrudable materials, the viscosity should be kept at a low level initially for better extrusion while increases rapidly after a certain time, which is referred as open time. Le et al. (2012) proposed a mix design of 3D printable concrete. In the mix design, the dosages of superplasticizer and retarder are carefully weighed considering the initial extrudability and open time. The mix is proved to build a certain numbers of layers without causing blockage in the nozzle or fracture in the printed layers.

It is also possible to improve the performance of printable concrete based on modified self-compacting concrete. The maximum layers the printable concrete can build is related to the green strength of this material as high green strength represents less deformation under mechanical operations or pressure in the fresh state. It is found that (Voigt et al., 2010) by adding fibers or clay, the green strength can be efficiently increased, especially for the clay composed of purified magnesium alumino silicate. The addition of fibers improves the workability while clay decreases the workability, which can be balanced by careful mix design.

3.2 Mechanical properties of 3D printable construction materials

The printed structures have obvious anisotropic mechanical behavior. Through mechanical experiments (Feng et al., 2015; Le et al., 2012), it is found that whenever the loading causes tension between the printed layers, the strength of printed structure is greatly reduced in any type of mechanical experiments. In comparison, the strength of printed structure is measured the highest whenever the loading causes tension parallel to the printed layers. This anisotropic mechanical behavior is considered to have a direct relationship with the layer-by-layer manufacturing feature, and lack of enough bond between layers leads to weak zones in the printed structures. Potential improvements in the bond strength include reducing the printing time between adjacent layers and adding fibers (Le et al., 2012; Christ et al., 2015). In the cementitious material printing, brittleness is clearly observed as in the conventional concrete, which may be addressed by adding fibers.

4. ENGINEERING APPLICATIONS

3D printing in building and construction is fast evolving and lots of engineering applications emerges recently. With the help of 3D printing, rapid construction is realized with considerably lower cost, less waste and reduced construction time (CNET, 2015). It is possible to print specially designed functional structures, which may be energy-efficient and environment-friendly.

One of the most important applications of 3D printing in building and construction is to make large-scale rapid construction. A Chinese company Winsun has constructed 10 houses using 3D printing technology in one day, where recycled construction materials were used in the 3D printing (Business Insider Singapore, 2014). Researchers from University of California, Berkeley have built an artsy pavilion through 3D printing (Engadget, 2015) for decorative use. The pavilion was created using dry powdered cement, which cannot be extruded through a nozzle like wet cement. In Amsterdam, the Netherlands, researchers are aiming at building a 3D printed steel pedestrian bridge (3dprint.com, 2015) to bear the traffic loading. This steel-printing system uses 6-axis robotic machines to create structures from steel literally in mid-air.

Besides large-scale rapid constructions, it is possible to construct more complicated functional structures by 3D printing. Cool Brick (Emerging Objects, 2015) is aimed at cooling the room temperature naturally. With its porous 3D printed structure, Cool Brick can easily retain rainwater and let the air flow at the same time, resulting in air-cooling effect by the evaporation of water. This can save the energy for air-conditioning, especially in hot and dry area. The Involute Wall (Emerging Objects, 2016) is constructed by 3D printing technology, and it can serve the purpose of dampening sound and heat. The involuted surfaces reduce resonance in the room, by absorption and redirection of sound waves. It can also serve as thermal mass while keeping much of the wall in shade, which is ideal for hot climates with extreme temperature shifts.

5. FUTURE PERSPECTIVE

While it is possible to achieve desirable rheological performance of printable material during different stage, however, the balance between long open time and high green strength should be carefully considered. Once printed, the material should harden rapidly to resist weight of the layers. However, this may lead to considerable differences in status of adjacent layers with lower adherence between layers, leading to lower bonding strength.

The development of functional construction materials can also be a future focus in 3D printing. For example, self-healing construction material can seal and heal the cracks by itself, which has the potential to improve the durability of the printed structures. Thermal-insulating construction materials can help reduce the heat transmission and save the energy used in regulating indoor temperature. Due to the freedom offered by 3D printing process, the creation of parts with functionally graded materials is possible (Gao et al., 2015). This multi-material printing can be borrowed in building and construction sector to print laminated multi-functional structure.

Building Information Modelling (BIM) is an inherently 3D modelling technology and associated set of processes to produce, communicate and analyze building models (Eastman et al., 2011). BIM can improve the collective understanding of design intent and overall project quality. It is possible to integrate BIM and 3D printing technology in the construction. Through the complicated geometry and structure details, provided by BIM, large-scale 3D printers can print the designed building with accurate mechanical controls. Hence, automated construction can be realized with the combination of advantages from BIM and 3D printing.

6. CONCLUSION

This article reviews 3D printable construction materials and their applications. Fresh property requirements of 3D printable construction materials are addressed in detail, and potential mixes to meet these requirements are discussed. Hardened properties of 3D printable construction materials are stated, followed by engineering applications from large-scale rapid constructions to 3D printed functional structures. At last, future challenges and potential research focuses of 3D printing in building and construction are addressed. The applications of functional construction materials are highlighted with the discussion of potential integration of inherently 3D BIM and 3D printing.

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REFERENCES

R.Bogue. (2013). “3D printing: the dawn of a new era in manufacturing”. *Assembly Automation*, 33(4), 307-311.

W.Gao, Y.Zhang, D.Ramanujan, K.Ramani, Y.Chen, C.Williams, C.Wang, Y.Shin, S.Zhang, P.Zavattieri. (2015). “The status, challenges, and future of additive manufacturing in engineering”. *Computer-Aided Design*, 69, 65-89.

Wikipedia. (Retrieved 24 Dec 2015). “Building printing”. https://en.wikipedia.org/wiki/Building_printing.

B.Khoshnevis. (2004). “Automated Construction by Contour Crafting – Related Robotics and Information Technologies”. *Journal of Automation in Construction – Special Issue: The best of ISARC 2002*, 13(1), 5-19.

S.Lim, R.Buswell, T.Le, S.Austin, A.Gibb & T.Thorpe. (2012). “Developments in construction-scale additive manufacturing processes”. *Automation in Construction*, 21(1), 262-268.

S.Lim, R.Buswell, T.Le, R.Wackrow, S.Austin, A.Gibb & T.Thorpe. (2011). “Development of a viable Concrete Printing process”. *The 28th International Symposium on Automation and Robotics in Construction*, Seoul, Korea.

D-Shape. (Retrieved 28 Feb 2016). http://d-shape.com/.

A.Neville. (2002). *Properties of concrete*, Prentice Hall/Pearson Education.

ACI Committee 506. (1990). *Guide to shotcrete / reported by ACI Committee 506*, American Concrete Institute.

Y.Kim, H.Kong & V.Li. (2003). “Design of Engineered Cementitious Composites Suitable for Wet-Mixture Shotcreting”. *ACI Materials Journal*, 6, 511-518.

I.Odler. (2000). *Special Inorganic Cements*. E & F Spon.

T.Le, S.Austin, S.Lim, R.Buswell, A.Gibb & T.Thorpe. (2012). “Mix design and fresh properties for high-performance printing concrete”. *Materials and Structures*, 45, 1221-1232.

T.Voigt, J.Mbele, K.Wang & S.P.Shah. (2010). “Using Fly Ash, Clay, and Fibers for Simultaneous Improvement of Concrete Green Strength and Consolidatability for Slip-Form Pavement”. *Journal of Materials in Civil Engineering*, 22(2), 196-206.

P.Feng, X.Meng, J.Chen & L.Ye. (2015). “Mechanical properties of structures 3D printed with cementitious powders”. *Construction and Building Materials*, 93, 486-497.

T.Le, S.Austin, S.Lim, R.Buswell, R.Law, A.Gibb & T.Thorpe. (2012). “Hardened properties of high-performance printing concrete”. *Cement and Concrete Research*, 42(3), 558-566.

S.Christ, M.Schnabel, E.Vorndran, J.Groll & U.Gbureck. (2015). “Fiber reinforcement during 3D printing”. *Materials Letters*, 139, 165-168.

CNET. (Retrieved 19 Jan 2015). “World’s first 3D-printed apartment building constructed in China”. http://www.cnet.com/news/worlds-first-3d-printed-apartment-building-constructed-in-china/.

Business Insider Singapore. (Retrieved 16 Apr 2014). “A Chinese company 3D printed 10 houses in one day”. http://www.businessinsider.sg/a-chinese-company-3d-printed-10-houses-in-a-day-2014-4/.

Engadget. (Retrieved 08 Mar 2015). “UC Berkeley 3D prints an artsy pavilion using dry powdered cement”. http://www.engadget.com/2015/03/08/uc-berkeley-3d-printed-pavilion/.

3dprint.com. (Retrieved 11 June 2015). “3D Printed Steel Pedestrian Bridge Will Soon Span an Amsterdam Canal”. http://3dprint.com/72682/amsterdam-3d-printed-bridge/.

Emerging Objects. (Retrieved 07 Mar 2015). “Cool Brick”. http://www.emergingobjects.com/projects/cool-brick/.

Emerging Objects. (Retrieved 24 Jan 2016). “Involute Wall”. http://www.emergingobjects.com/projects/involute-wall/.

C.Eastman, P.Teicholz, R.Sacks & K.Liston. (2011). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*, John Wiley & Sons.