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2016

Tay, Y. W., Panda, B., Paul, S. C., Tan, M. J., Qian, S., Leong, K. F., et al. (2016). Processing and Properties of Construction Materials for 3D Printing. Materials Science Forum, 861, 177-181.

https://hdl.handle.net/10356/87936

https://doi.org/10.4028/www.scientific.net/MSF.861.177

Processing and Properties of Construction Materials for 3D Printing

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Keywords: Building and construction, Additive manufacturing, Concrete material, 3D printing.

Abstract. 3D printing (3DP), commonly known as additive manufacturing (AM), is a promising technology that can fabricate three dimensional complex shape prototypes directly from computer-aided design (CAD) model without any tooling and human intervention. Owing to its peculiar characteristics, AM is widely used in many industries to assist in the design, manufacture and commercialization of a product. More recently, this technology has been extended to building and construction (B&C) application in order to mitigate some of the critical issues such as shortage of skilled labour, high production cost and construction time, health and safety concerns of the workers in the hazardous environment etc. However for successful implementation, proper selection of materials and their mix design is highly recommended, which is a challenging task. This paper summarizes the current available 3DP systems from literature and the respective materials that have been used thus far by various experts, industries for B&C purposes. Finally, the benchmarking properties of theses material and potential research directions are briefly discussed.

Introduction

The building and construction (B&C) industry is one of the major business drivers, however in recent years due to the lack of skilled labour, automation and safety issues, it has been difficult to meet the targeted demand (less construction time, lower pollution and wastages). In this regard, 3D printing (3DP) seems to be a promising technology that can build complex 3-dimensional (3D) structures without the need of formwork and human intervention [1]. This process uses computer-aided-design (CAD) model as a blue print to fabricate complex 3D design in layer by layer manner. Early applications of 3DP was just for modelling and prototype purposes, but nowadays due to the development in the material science, it has been used in many industrial applications such as automobile, aerospace, defence and medical sectors. More recently, development of 3D printable construction material has evolved this technology to the B&C applications. This paper briefly describes three major 3DP processes such as contour crafting, D-shape, concrete printing and also some construction materials that have been used so far for manufacturing large scale 3DP construction object.

State-of-the-art of 3DP in B&C Systems and Materials

3DP in B&C started in 1997 with an innovative approach suggested by Pegna [2]. Currently three main categories of this technology are found in public domain. They are D-shape [3], Contour crafting [4], and Concrete printing [5]. All these three technologies have proven to be effective means of printing complex geometrical structures for B&C application [6]. Though the three processes are similar in the sense that they build the product in an additive manner, however, they are developed for different applications and materials. Both the D-shape and concrete printing are gantry based off site printing process whereas contour crafting is for on site, in-situ application.

D-shape uses powder deposition process, which selectively binds the powder by a chemical agent (binder) in the same way as of Z-Corp 3DP process [7]. Generally sand/stone powder (granular material) is used as the main processing material along with chlorine-based liquid (binder) for printing complex 3D structures and once printing is finished, excess material is cleaned away to unveil the 3D part. Though the produced part has good mechanical strength, more maintenance, cleaning and control instructions still remained as the biggest barrier for this process.

Contour Crafting (CC) has been in development for some years [8,9], and is based on extruding a cement-based paste against a trowel that provides smoother surface finish to the printed part. Literature reveals that several CC machines have been developed for research with various materials including thermoplastics, thermosets and various types of ceramics. Khoshnevis et al. used CC with speckling plaster compound and clay separately to produce 2.5 and 3D shapes having square, convex and concave features [10]. Easy availability, cheap and room temperature hardening motivated them to use this material and experimental results reveal a good quality of surface finish in the printed prototypes. In some cases, sand and waxes are used as supporting material for overhanging structures. Khoshnevis and his co-authors have also experimented cement based mortar in the CC system in order to fabricate a form wall with 5 feet long and 2 feet height [11]. The CC made concrete form wall is shown in below Fig. 1.

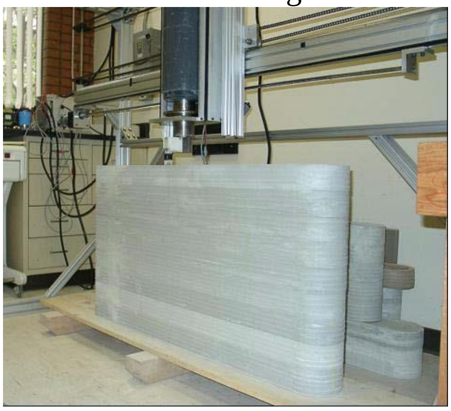

Fig. 1. Contour crafting (CC) made concrete form wall [10]

Like CC, concrete printing is an extrusion-based manufacturing process that fabricates complex part geometries layer by layer without the use of labour intensive formwork. Le et al. [12] from the Loughborough University, U.K used a cement-based mortar consisting of sand, cement, fly ash, silica fume and polypropylene fibre as main ingredients. As shown in Table 1, mix design 1 to 5 was used during the process to print a multi-cellular 3D curved bench.

Table 1 Materials compositions (kg/m^3) for 3DP used by Le et al. [12]

Mix Design	**Sand**	**Cement**	**Fly ash**	**Silica fume**	**Water**
1	1612	376	107	54	150
2	1485	446	127	64	178
3	1362	513	147	73	205
4	1241	579	165	83	232
5	1123	643	184	92	257

Out of these, Mix 4 was selected as the optimum mix design since this combination resulted shear strength in a range of 0.5-1.0KPa and according to the authors this range of shear strength is viable for successful printing without any difficulties and defects. Another study conducted by Lim et al. [13] from the same university used cement and gypsum mixed mortar as a source of printing material to build a wonder bench. The density of the mix design was found to be 2300 kg/cm^3 while experimental compressive strength was noted in the range of 100-110 MPa. Lim et al. [14] used two different materials, one as a prime printing material while another material is used for support to build over-hanging complex geometries. The support material is reported to be 100% recyclable, low strength and easy removal.

Maleb et al. [15] investigated the influence of superplasticizer on the flowability and buildability of a cement-based mortar. It was reported that in the mix with lower water-cement ratio, high superplasticizer (0.95% to 2.5% of water weight) content increases the compressive strength and flowability of the mix but it reduces the buildability capacity significantly. The optimum (better flowability and buildability capacity) water-cement ratio and superplasticizer content was found to be about 0.39 and 1.9% respectively, for a extruder with 2 cm nozzle diameter, which was used to build a 10cm height wall without any failure notification. Accelerator and retarder were also added to this mix design to control the rheology of mortar.

Fig. 2 displays a 3D printed tank, built in Singapore Centre for 3D Printing B&C laboratory, using low cost mix design as shown in Table 2. Superplasticizer (1.05% of water weight) was added to the mix design to increase its flowability. Although the developed material was found to have good extrudability and buildability, due to varying nature of flow from the outlet of the printer, layer thickness was inconsistent throughout the printing process. Further research is still going on in this direction to improve the quality of printing process as well as the stability of these printing structures.

Table 2 Mix proportions (kg/m^3) of the trial mix

Mix Design	Sand	Cement	Fly ash	Silica fume	Water
6	810	253	192	61	152

More recently, Le et al. [16] has conducted experiments on tensile bond strength (Since bond strength affects the overall structure strength) and reported that there is a reduced tensile strength with increase in time gap between printing layers. This reduction was expected as the adhesion reduces with increasing time gap in printing time.

Fig. 2. Experimentation of printing concrete using mix design 6

Future 3DP Materials for B&C

Green and sustainable materials: Cement based mortar has been used most frequently to investigate the potential of 3D concrete printing. But it is well known fact that cement production causes environmental pollution and also consumes lots of energy. Therefore there is a need of developing green construction materials (production required less energy and has minimum or no impact on environment) that can reduce this effect. Also the use of recycled materials as well as industrial by product such as fly-ash and slag should be encouraged to make the construction process cleaner and greener.

Functional construction materials: In addition, modern construction materials such as fibre reinforced concrete (FRC) and highly ductile engineered cementitious composite (ECC) can replace traditional concrete for sophisticated architecture design while assuring energy efficiency, sustainability and security [17]. Also, functional materials such as FRC and ECC may be beneficial to 3D concrete printing, since they have high tensile and flexural strength than conventional concrete and these properties are very crucial for stability of concrete structure.

Functionally graded materials (FGM): Other than functional materials, FGM may be applied to AM due to high complexity and conflicting property requirement [18]. For example, by altering the printing method, heavier and stronger material may be printed at the bottom and lighter materials may be printed at the top of the structure which may reduce the cost and materials required as compared to homogenous structure.

Benchmarking Material Properties

This section introduces and explains the importance of benchmarking properties that is needed to be considered while developing a new material for 3D concrete printing.

(1) *Extrudability* means the ease and reliability with which material is moved through the delivery system (nozzle). Since 3D concrete printing uses nozzle for extruding out the material, it is necessary for the material to flow smoothly without having any blockage issues. Uninterrupted flow should be the main concern while developing concrete printing materials. This property can be measured by visual inspection or conducting a shear stress test for the material [12].

(2) *Flowability* of a concrete mix is measured by performing the slump flow test. The time required for the mix to spread by a specific diameter is measured and the rate of flowing can subsequently be obtained. An easily expanding mix corresponds to a greater flowability and thus inappropriate for concrete printing.

(3) *Buildability* signifies the resistance of deposited wet material to deformation under load of newly deposited layer as shown in Fig. 3. High buildability is required for AM to prevent any deformation in each layer. If the material has low buildability, the individual layers may deform during printing causing the structure to collapse. Such deformation might also cause the final printed product to be out of shape.

Fig. 3. Testing of buildability of concrete [12]

(4) *Open time* is the period where the above properties are consistent within acceptable tolerances. This is an important criterion and has a relationship with its setting time. Vicat apparatus is usually utilized to measure it. With regard to a past investigation, open time for the mix design was found to be 100 minutes while keeping other properties consistent [13].

(5) *Layer adhesiveness* is a very important aspect of concrete printing as it would affect the structural integrity of the fabrication part. The bond between layers has to be high in order to withstand shearing load cause by environmental factor. Current research have lag on the study of the bonding between concrete layers and understanding this aspect could allow us to improve on the structural integrity.

Conclusion and Future work

3D printing (3DP) of full-scale construction components is gaining increasing attention since it eliminates the necessity of form work, reduces human labour, allows fabrication of complex 3D geometries and time saving etc. For successful implementation, not only the printing system but also the material must be designed appropriately, which is challenging. This paper has reviewed the available 3DP construction materials that have been applied so far for building and construction (B&C) applications. Although concrete printing has already been explored by some researchers, only limited materials have been used for this purpose, and there is no guideline or benchmark for the successful application of materials that can be used in 3DP. Also layered structures and the voids between the filaments are likely to produce anisotropic properties, which may weaken the structural capability. Therefore future work needs to be done on overall structural strength of the printed component via improving bond strength and contact surface area between layers. New B&C materials which will enable greater design freedom should also be incorporated for 3DP system in B&C applications that may not be achievable using conventional construction methods.

Acknowledgement

The authors would like to acknowledge the Singapore Centre for 3D Printing (SC3DP) and National Research Foundation (NRF), Singapore for funding and support for this research project.

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