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Method of formulating geopolymer for 3D printing for construction applications

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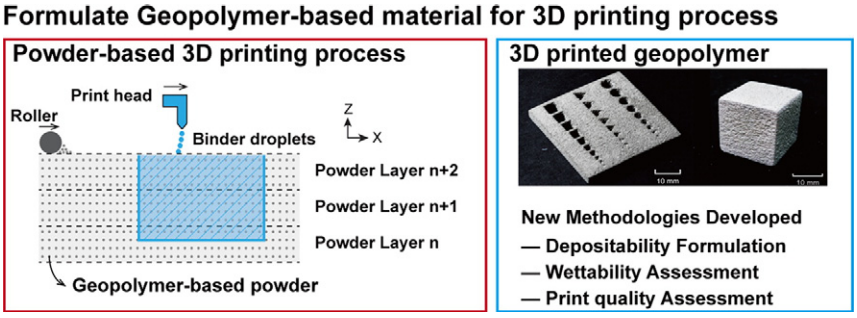
HIGHLIGHTS

- A new methodology is presented for formulating geopolymer for 3D printing process.
- The study identified the essential characteristics for printability and dimensional accuracy.
- Identified parameters for assessing the quality of the geopolymer printed shapes.
- A new post-processing method for geopolymer to gain strength for construction application.

GRAPHICAL ABSTRACT



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ABSTRACT

An innovative methodology is presented for formulating geopolymer-based material for the requirements and demands of commercially available powder-based 3D printers. Different key powder parameters such as particle size distribution, powder bed surface quality, powder true/bulk densities, powder bed porosity, and binder droplet penetration behavior were used to quantitatively evaluate the printability of prepared geopolymer-based material. Results indicated the prepared geopolymer-based material achieved sufficient printability to be used in a powder-based 3D printer. 3D printed specimens from the geopolymer were assessed for printing accuracy, apparent porosity and mechanical property. All printed cubic specimens exhibited an anisotropic phenomenon in dimensional accuracies and mechanical properties. Before further post-processing, the printed cubic structure gained compressive strength of up to 0.9 MPa with an acceptable low dimensional expansion of <4%. Post processing by immersion in saturated anhydrous sodium metasilicate solution at 60 °C gained compressive strength of up to 16.5 MPa.

1. Introduction

Additive manufacturing (AM) is a group of emerging techniques for fabricating three-dimensional (3D) structures directly from a digital model. Unlike conventional industrial manufacturing processes, AM processes build a finished structure in successive layers with less waste material. Since its emergence 30 years ago, AM technologies have been successfully applied in a wide range of industries including aerospace, automotive, biomedical, consumer and food [1].

AM is also now gaining popularity in construction industry. When compared with conventional construction processes, the application of AM techniques in construction industry may (1) reduce the labor requirements which would result in a decreased construction cost and

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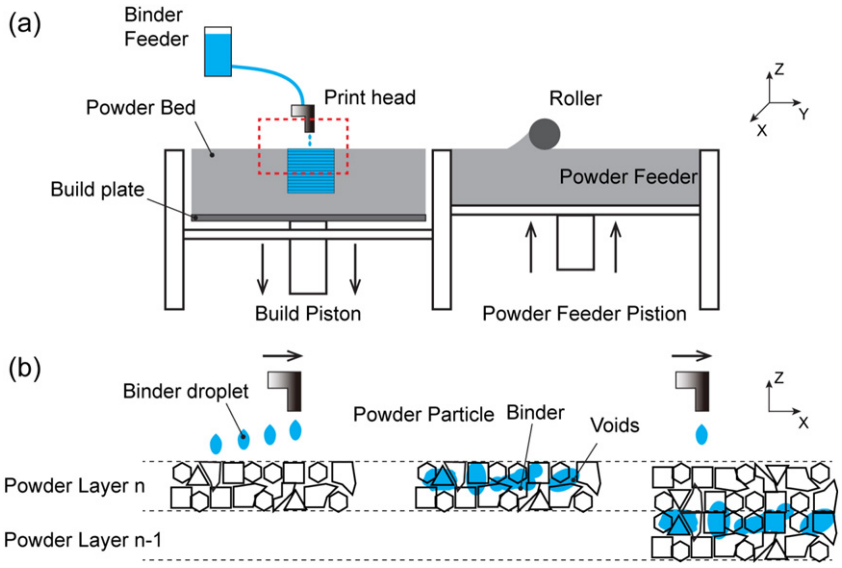

Fig. 1. Schematic illustrations of the 3DP process: (a) 3DP inkjet printing system, (b) Enlargement of the area in red rectangle: powder/binder interaction between adjacent layers.

an increased level of safety, (2) reduce on-site construction time by operating at a constant rate, (3) minimize the chance of errors by highly precise material deposition, and (4) increase architectural freedom which would enable more sophisticated designs for structural and aesthetic purposes [2,3].

In the last few years, a variety of technologies has been developed to adopt AM in construction industry. These techniques can be divided into two forms.

1.1. Extrusion printing

The extrusion printing technique is analogous to the Fused Deposition Modelling (FDM) method by extruding cementitious material from a nozzle mounted on a gantry to print a structure layer by layer. Examples such as Contour Crafting, developed by Khoshnevis [4,5] and Concrete Printing, designed by Lim et al. [6,7].

1.2. Powder printing

The powder printing technique, also named powder-based three dimensional printing (3DP), is another typical AM process that creates accurate structures with complex geometries by depositing binder liquid (or "Ink") selectively into to powder bed to bind powder where it impacts the bed [8]. Two typical examples are the D-shape technique developed by Cesaretti et al. [9] and Emerging Objects [10].

Both of the two techniques are designed for construction purpose and have many similarities. However, each technique has distinct features in construction industry. The extrusion printing technique has been aimed at on-site construction applications such as large-scale building components with complex geometries, while the powder printing technique is an off-site process designed to manufacturing precast components. It is the authors' belief that powder-based 3DP technique is highly suitable for small-scale building components such as panels, permanent formworks and interior structures that then can be assembled on site.

The work presented in this paper focuses on powder-based 3DP technique as this method is capable of producing building components with fine details and intricate shapes. There is a demand in construction industry for such components which can only be made with expensive formwork systems with the currently available construction systems. Powder-based 3DP technique needs to be developed so that they can produce robust and durable components at a reasonable speed to satisfy this industrial demand. Hence the urgency for research in this area.

A schematic of the powder-based 3DP process is illustrated in Fig. 1. At the start, a roller, mounted together with a print head, spreads a layer of powder to cover the base of the build plate. The base layer is about 3 mm in thickness. Then, according to the layer thickness setting of the 3D printer, a thin layer of powder (approximately 0.1 mm) is spread and smoothed by the roller over the powder bed surface. Once a layer is completed, the binder solution is delivered from binder feeder to the print head and jetted by nozzles mounted in the print head. The mechanism of controlling the binder solution is a non-continuous approach called drop-on-demand (DoD) technique [11] which has been widely used in contemporary desktop printing systems. In the print head, the binder solution is pushed out through nozzles either thermally by a thermal bubble or mechanically by a piezoelectric actuator. Then binder droplets are formed and are selectively applied on powder layer, causing powder particles to bind each other (Fig. 1b). Repeating the described steps, the built part is completed and removed after a particular drying time and unbound powder is removed by using an air blower.

Powder-based 3DP is a versatile AM technique characterized by a wide range of potentially suitable materials in powder form, including ceramics, polymers, metals and composites [12,13]. Powder-based 3DP technique has a great potential to make a significant and positive contribution to the construction industry. There are mainly two

Table 1
The chemical composition of slag (wt%).

Chemical	Al_2O_3	SiO_2	CaO	Fe_2O_3	K_2O	MgO	Na_2O	TiO_2	SO_3	L.O.I.[a]
Component	12.37	32.76	44.64	0.54	0.33	5.15	0.22	0.51	4.26	0.09

[a] Loss on ignition (unburnt carbon content).