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Mechanical properties of layered geopolymer structures applicable in concrete 3D-printing

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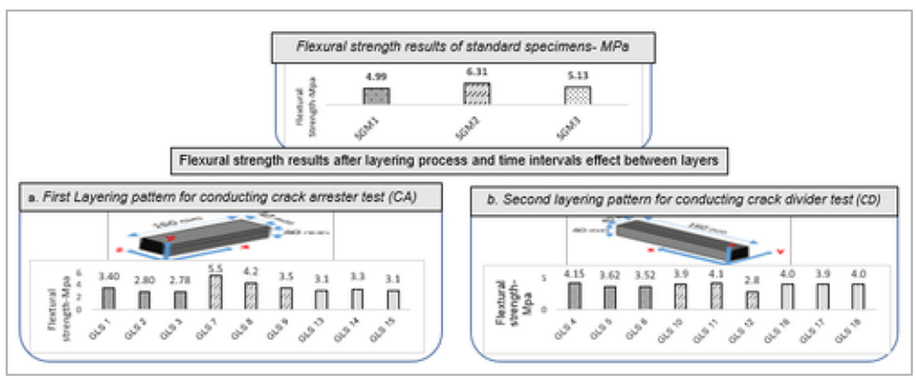
HIGHLIGHTS

- Using geopolymers in additive processes resulted in adequate flexural strength.
- Inclusion fibers involved negative effects on the bond strength between layers.
- Reducing time gaps between subsequent layers enhanced flexural strength results.
- Increasing thicknesses of objects' layers improved the flexural strength result.

GRAPHICAL ABSTRACT

The type of load application on layered concrete structure affects on the final mechanical properties of specimens.



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ABSTRACT

This paper focuses on inspecting the structural buildability of layered objects. Simulating extrusion method process was used to investigate three geopolymer mixes, three-time gaps, and two layering patterns through 18 layered samples. This paper also evaluates effects of the layering process on hardened properties of build-up materials through 9 standard specimens. The used materials were Gladstone fly ash, sand, 8 M sodium hydroxide solution, and D-grade sodium silicate. The weight ratio of sodium silicate to sodium hydroxide was 1, and activators to fly ash was 0.26. Mix 1, mix 2, and mix 3 contained 0%, 1% steel fibers, and 0.5% polypropylene fibers respectively. The structural buildability of layered samples and the influence of the layering process were assessed in terms of flexural strength through 3-point bending tests. Flexural strength results indicated that the layering process has negative impact on the mechanical strength of build-up materials. Also, mix 2 resulted in the highest flexural strength values in standard specimens and layered samples. However, the most bond separation issues between additive layers were achieved with layered samples produced with mix 2. Most layered samples produced with minimum time gaps recorded the highest flexural strength results.

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1. Introduction

Currently, additive manufacturing (AM) technology is regarded as one of the most studied emerging technologies. The terms 3D-printing and AM refer to the additive production process [1]. Typically, all current 3D-printing processes are mainly categorized into two systems including powder-bed fusion (PBF), and fused deposition methods (FDM) [1,2]. Both systems have broadly been applied to wide variants of ABS, rubber-like elastomers, and polycarbonate [3]. In recent years, 3D-printing processes, including contour crafting, concrete printing, and D-shape have been developed to deal with cementitious materials, aggregate, and fiber reinforcement to print large scale freeform constructions [4]. Consequently, they have been moving from an architectural modelling tool to the freeform construction [1]. Especially, the current conventional construction practice experiences numbers of issues related to the environment, health, economy, as well as the quality. For instance, the concrete production is not considered as eco-friendly, since it involves Portland cement as principal binder [5,6]. Specifically, intensities of average cement emissions ranges between 500 and 600 kg of CO_2 per clinker ton [7]. Also, the process of cement production includes detrimental effects on anticipated workers by causing irritant contact dermatitis and allergic occupational dermatitis [8]. Furthermore, formwork is another impediment faced in the traditional concrete industry. Specifically, current practices of traditional formwork involve sizable time and cost consuming as well as injury accidence [9,10]. Statistics have revealed that around 1/3 of the steel reinforcement cost and 15% of the construction cost are linked to formwork [9]. As a result, the current construction sector experiences the lack of the productivity and quality in comparison with other sectors. Consequently, there have been several attempts to replace the current construction method by alternatives with low cost and time consuming as well as high safety. Specifically, 3D-printing processes have been suggested in the construction domain to launch a new era of an efficient construction methodology. Precisely, AMC can result in increasing architectural freedom, saving construction time and cost, as well as eliminating the need of labors [10,11]. Typically, these automated processes are integrated with engineering function and adapted to the environment [12]. Especially, 3D-printing processes have been amid to deal with geopolymer concrete instead of OPC.

Geopolymers are alternative binders to OPC possessing aluminosilicate sources. Basically, each material involves silica and alumina bearing phases, is suitable for geopolymer production. Typically, aluminosilicate materials are produced from industrial natural aluminosilicates and/or by-products, like primary (kaolinite, illite, ...) or secondary (fly ash, red mud, steel slag, etc) raw materials [13,14]. Geopolymers can be made by the chemical reaction between alumino silicate and silica components in alkaline activator (NaOH and/or KOH) at ambient or elevated temperatures [14]. Geopolymers do not depend on calcium carbonate as a main component, and thus produce much less carbon dioxide emissions through the manufacturing process [13]. Therefore, due to its accessibility, energy efficient, eco-friendly production process, excellent mechanical property, and good durability, geopolymer cement has recently attracted significant considerations [14,15]. Thus, FDM and PBF should extent the application of green materials. Basically, both systems create three-dimensional physical objects from virtual CAD models divided into layer information. PBF is also known by selective modeling because each layer of fused powder is selected selectively to react constantly formulating a 3D-physical object. That can be achieved by variant printing processes, i.e. light, laser, or liquid jetting [1,2]. For instance, D-shape is based on the liquid jetting process and it is regarded as one of large scale additive manufacturing processes [1,11]. In PBF, powder properties are important to determine the printability and the structural buildability of a printed object. For instance, the shape and the size of powder particles size are significant to determine the deposit ability and the resolution of printed layers [16,17]. Powder deposition can be conducted with build powder in a wet or dry state based on particles size of prepared materials [17]. Particle size of 20 μm and even larger are preferred in the dry processing. Whereas, particle size lesser than 5 μm can be dropped in either the wet or dry state. FDM is also named by extrusion method and direct deposition method [1]. It means that materials are extruded straightaway from a nozzle onto the printing bed in subsequent layers. The most known examples of large scale processes in the construction field based on the FDM concept, contour crafting (CC), and concrete printing [1,2,18]. The procedure of these two processes involve data preparation excluded from a post-processing step, and material preparation. Then it is followed by delivery and printing procedures, which include extruding cementitious mix layer by layer through nozzles [1]. Typically, the printer head movement as well as constant flow of concrete lead to linear filament. The single filament dimensions are affected by a nozzle section, the speed of printer head, concrete flow, concrete slump and setting characteristics [1,19,20]. Since the printer and the mounting system of PBF and FDM are dissimilar, build up materials, dimensions and the appearance of final printed objects are different. Consequently, each method has variant advantages and disadvantages regarding to the feasibility, quality, and economy. For instance, contour crafting uses two passes of the deposition head mounted on a crane system [21,1]. The printhead of contour crafting process allows several additives to be printed such as gravel, sand, and reinforcement fiber. Consequently, this process has the sufficient ability to build large-scale freeform constructions on a site. While, concrete printing process is a gantry-based off-site process based on FDM and with no the need to trowels. Subsequently, a small resolution of material depositing (4–6 mm defined by layer depth) is demanded to attain better degree of 3D freedom [1]. Whereas, D-shape process involves a gantry frame system with several nozzles installed in series which demands a single traverse per each layer [1]. Therefore, the printer and the mounting system of this process can limit this process to print objects with a small or medium scale. However, even though FDM and PBF have several distinct favorable features, some challenges have been faced in both systems regarding to the strength and feasibility aspects. For instance, most printed objects had an orthotropic microstructure in the printing direction. Consequently, the bearing capacity of the printed structure has been substantially impacted [22,23]. As a result, some variations between the final printed geometry and the CAD model have been noticed, especially in the alignment of the vertical printed surface [1,18]. Specifically, the stacking force between printed filaments is usually not strong enough to sustain the weight of subsequent layers. Since FDM are in-between state, it totally depends on the setting time, print time, and layer interval time. As a result, it necessitates extensive developments regarding to material parameters, i.e. stiffness and strength overtime [24].

Therefore, this paper aims to inspect the structural buildability of layered objects in term of flexural strength. A simulating process was used to inspect some factors having effects on the layering process i.e. build-up materials, time gaps, and layering patterns. Therefore, three geopolymer mixes, three-time gaps of 5, 10, and 15 min, as well as two layering patterns were investigated through 18 layered samples. Meantime, this paper evaluates effects of the layering process on hardened properties of geopolymer based processes through 9 control samples. All samples have been prepared with fly ash (F), sand, and alkaline activator (a combination of sodium silicate and sodium hydroxide solution with concentration