Geopolymer vs ordinary portland cement: review of the 3-d printing of concrete

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ABSTRACT

Due to the need of the construction industry to implement structures with special and complex designs, mass customization with the lowest cost, especially reducing the labor cost as well as the amount of waste and materials used, the use of concrete 3D printing can be the appropriate solution to these requirements fulfill these options. As a result, a comprehensive and practical study of the major 3D printing methods and their development in the construction industry was carried out in this study. In addition, the use of ordinary Portland cement-based materials and geopolymer-based materials were reviewed and compared due to the development of the materials industry and the advantages and disadvantages of using different types of cementitious materials in the 3D printing of concrete.

1. Introduction

3D printing of concrete has become a very popular research topic over the past several years. All industries are moving towards automation and the construction industry is expected to do the same. Concrete is the most common raw material; its raw materials are abundant throughout the world and its production is simple and relatively low cost. Over time, concrete resists forces as it hardens, making it an attractive material for 3D printing processes.

3D printing was first introduced in 1987 as a rapid prototyping tool known as stereolithograph [1] [2]. Then commercial 3D printers became available, which were able to transform numerical models into solid 3D structures with the help of computers. Initially, 3D printers could only print small structures, but with research and development, larger structures could also be printed. There are various methods, materials, and devices for 3D printing [3], which have evolved over the years and are widely used in various industries, including construction, biomechanics of jewelry, toys, and medicine [4]. In recent years, 3D printing has been used successfully in the building industry [5], [6]. In 2016, WinSun printed a series of relatively low-cost homes in China ($4,800 each) in less than a day [7]. Research indicates that architectural applications account for only 3% of the 3D printing industry. However, the zone was not created until 2014 when it was used for housing [8]. In the last few years, more attention has been paid to the automated design of structures using 3D printing technology. as it significantly reduces construction time and labor required, improves worker safety, and significantly reduces costs [9], [10]. Traditional methods used in the construction industry are very difficult to apply to some structures, while 3D printing in construction can be used in areas with limitations, including geometric complexity and hollow structures. The most important advantage of

3D printing concrete is its ability to quickly print layers with non-standard, complex and detailed geometries without the need for moulds. Therefore, with its high-precision production ability, it offers various opportunities for consumers [11].

Structures built today release large amounts of waste and pollutants into the environment [12], [13]. In addition, due to the high CO2 emissions and high energy consumption in the manufacturing process of Ordinary Portland Cement (OPC), there is a need to produce non-OPC materials suitable for 3D printing processes. So far, research on 3D printing has mainly focused on OPC. Efforts were also made to 3D print alternative binders and non-OPC [14], [15] including sulphur-based concrete [16]–[18], calcined clay limestone cement [19], calcium aluminate cement [20] and geopolymers (GPs) [21]–[29].

In this article, we would like to make a comparison between GP concrete and OPC concrete, as well as give an overview of the different 3D printing processes of structures with OPC concrete and GP concrete and evaluate the possibility of using GPs as an alternative to OPC.

2. Method

2.1. Story of the concrete 3D printing

Researchers from around the world are trying to improve the 3D printing of concrete. After water, concrete is one of the most common construction materials used on land [30]. In an effort to make 3D printing more accessible to the construction sector, the primary 3D printed homes were constructed in Netherlands in 2014 (see Fig. 1) [31].

Fig. 1. DusArchitects' first 3D printed house [31]

Fig. 2 shows the other two well-known examples of 3D printing projects: WinSun's 3D-printed five-story 3D apartment and the Big Delta Castle, which was printed on site [32]. Therefore, efficient building materials compatible with 3D printers are necessary to develop this innovative building technique.

Fig. 2. Grand Delta Castle [33] to the right, and a Winsun-printed apartment to the left [34]

2.2. Pros and cons of concrete 3D printers

The mass manufacture and customization of a variety of low-cost custom products represent some of the key benefits of 3D printing [35]–[38] and less construction materials are required [38], [39]. As a result, mass-producing customized goods might be just as economical as making many identical parts. Lattice structures and other geometrically difficult structures can be produced in large quantities using 3D printing. As a result, 3D printing can be employed in situations where conventional production techniques like molding are impractical or demand specialized equipment, a lot of time, and expensive costs [38]. An investigation by Boswell et al. [40] demonstrated that 3-D printing can reduce wall construction time by 35 hours.

At the same time, The size of the 3D printer is directly correlated with the dimensions and shape of the structural design, which is one of the key disadvantages of 3D printing concrete. Since one 3D printer cannot simultaneously print different structures, the cost of purchasing and setting up other 3D printers is very high. Moreover, the use of 3D printers on a larger scale destroys many jobs [38]–[41]. Nevertheless, new technologies always create newer jobs as well.

2.3. 3D printing procedures for concrete

The main process of any 3D printing method is additive manufacturing (AM), which means that materials are applied layer by layer, unlike traditional methods. AM processes typically use 3D and 2D computer-aided design models to print complex 3D designs in layers [42]. Different 3D printing methods have been developed for printing high-quality complex structures. Rapid prototyping, the ability to print massive structures, fewer printing errors, and better mechanical qualities are important developments in 3D printing technology [43]. The most popular method of 3D printing, known as fused deposition modeling (FDM), primarily makes use of polymer filaments. Inkjet printing, contouring, stereolithography, direct energy deposition (DED), laminated object manufacturing (LOM), selective laser sintering (SLS), selective laser melting (SLM), or liquid bonding are also some of the most crucial 3D printing processes that support AM of powders [44].

It is beyond the scope of this discussion to explain all of this and only the methods directly involved in concrete 3D printing will be discussed. These methods include powder bed melting, Fused Deposit Modeling (FDM), inkjet printing and contour crafting (CC).

2.3.1. Powder Bed Fusion (PBF)

The PBF consists of thin layers of very thin powders placed on a platform filled with powder. The powders from each layer are combined with the binder to form layers. The roller then applies a new coat of powder to the previous coat, which is mixed into the binder to adhere to the previous coat. That process continues until the complete printing of the structure. Then, the extraneous powders are vacuumed if necessary and used in a subsequent printing. The most important factors in this printing process are the size and distribution of the powder, which determine the print density, the rheology of the paste, and the powder-binder relation [45], [46]. Fig 3 illustrates the operation of the powder bed method.

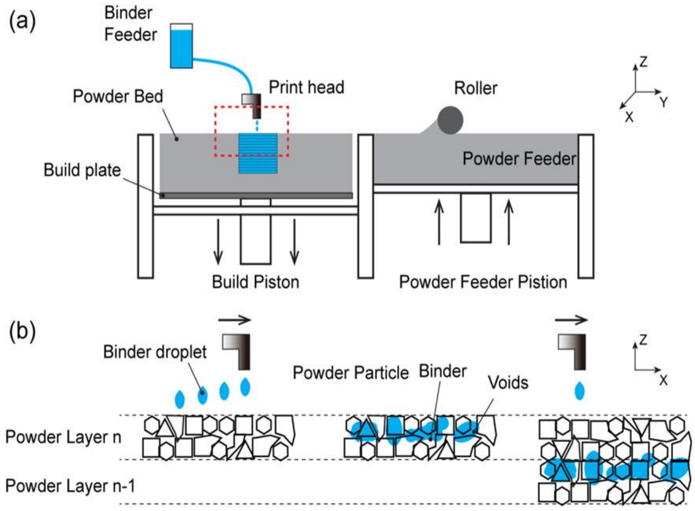

Fig. 3. Process of melting of a powder bed [26]

2.3.2. Fused Deposition Modeling (FDM)

FDM is one of the most widely used 3D printing methods due to its low cost, simplicity, and fast speed. Despite being first utilized for the 3D printing of polymers, this technique is also one of the most extensively used 3D printing methods because of its low cost, ease of usage, and rapidity; it may also be used to print objects out of many other materials, including concrete. Rapid prototype is where the FDM is most frequently employed. The primary production factors impacting the mechanical characteristics of printed objects are layer thickness, width, and direction as well as air gaps [47], [48] The three main benefits of FDM are its affordability, speed, and ease of printing. At the same time, the major disadvantages of FDM are poor mechanical properties and a stratified and lower appearance [49]. However, 3D printed items' mechanical characteristics are improved via FDM-based composites [50]. However, the biggest challenges in 3D printed composites include fiber orientation, fiber matrix composite and porous formations [46], [50], [51].

Fig. 4 shows the schematic of an FDM 3D printer. These printers are suitable for concrete, and the necessary structural and dimensional information is entered into a CAD file in part 0 and transferred to part 1, where it goes through a cutting procedure to be processed and split into several 2D layers. Cartesian coordinates of 2D layers are translated into machine-readable language together with printing parameters like print head rate and velocity of extrusion before being sent to the robot to begin printing [52], [53]. Part 3, the robotic arm, consists of the print controller (2) and the print head (4). Fig. 4 shows that in Part 8 a peristaltic pump uses the concrete that has been produced in the mixer to supply the printing head (7). Certain materials (e.g. quick setting agents) are often added to concrete to enhance its basic properties and make it suitable for printing before extrusion. These materials are processed in part 5 and pumped into the nozzle or the print head via a peristaltic pump.

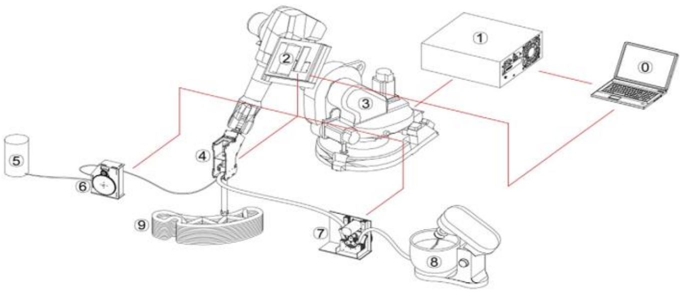

Fig. 4. The scheme of an FDM 3D Printer [54]

2.3.3. Contour Crafting (CC)

The technology known as "Contour Crafting" was developed in the middle of the 1990s and patented later in 2010 [55]. This technology was initially used to extrude ceramic paste [56], which was later used with cement and targeted large-scale printed structural elements. Today, huge constructions, such as buildings, are printed using contour crafts, which are based on the extrusion of concrete. A concrete reservoir, pipe, pumps, nozzle, and automated arm are the essential components of this technique. The automated arm directs the nozzle head in three different directions to print the structure in layers. Fig. 5 shows an automatic CC machine.

Fig. 5. The Schematic of An Automatic CC System [57]

2.4. Materials Used in 3D Concrete Printing

2.4.1. OPC-based Material

OPC is a substance that is frequently used in 3D concrete printing and serves as the fundamental component for this purpose. In this section, it has been attempted to explore several 3D printing techniques utilizing materials based on OPC.

2.4.1.1. Extrusion-based Printing

CC is AM's main method for large building structures. With larger and high-pressure nozzles, this process can extrude concrete paste, and a trowel-like machine connected to the printer head is used to achieve a flat finish rather than a layered appearance [58].

The performance of this technology during its lifetime has not yet been assessed because 3D printing technology for the building sector is still in its early phases. Recent research on the three-dimensional printing of concrete buildings has produced a number of approaches and materials, which will be reviewed here [59].

The most important aspect of contour craftsmanship is the primary characteristics of concrete when setting up. For 3D printing complicated shapes with extrusion, concrete must function well, and have a high initial strength to sustain the weight of the subsequent layers [60].

A mixed design that can last long before extrusion while having a high initial resistance to resist to subsequent layers without destruction requires good design materials and equipment. Several methods have been developed for this purpose [61]. Gosling et al. [54] developed a printing method in which the accelerator and mortar are pumped through separate pipes and then combined in the printing phase prior to extrusion. So that each subsequent layer may be effectively created, the physical properties of the paste can be regulated over an extended amount of time without impacting the initial rigidity of the layers [62]. Using an automated arm and carefully monitoring the material's behavior both before and after extrusion, this technique allows for the construction of more substantial and intricately shaped structures.

The rheological characteristics of pastes, in particular their thixotropic behavior, have been the subject of several investigations, and they have been shown to be crucial [63]. As the printing process requires constant material control, high-performance construction materials must be given priority [64]. Concrete with low to zero slumps is typically used to ensure that the substrate layers are not deformed. Concretes with non-zero slumps often have some accelerator added to achieve a faster initial setting and to prevent deformation in the lower layers. Utilization of a concrete with lower flowability requires crucial considerations, especially in the granulation of the aggregate, since the shape of the particles and their homogeneity affect the initial strength [65], [66]. As a result, a majority of 3D printing investigations have revealed that the largest possible concrete particle dimensions are under two millimeters [53], [67]–[69]. A settling test may also be used to subtly evaluate the shear stress of produced concrete [70], [71]. As a result, taking slump into account is crucial.

Controlling the qualities of the fresh concrete for adequate performance and open time for extrusion, as well as structural attributes including strength, interlayer bond, deformity, and craftability, are among the problems of concrete in 3D printing procedure. Printed structures should also undergo durability analysis [72]. For example, a 3-D printed structure may exhibit rapid water evaporation because the concrete is exposed to air due to the absence of mold. As a result, this element may raise the possibility of shrinking and fracture.

In terms of layer dimensions, printer head speed is also crucial. With a nozzle with a fixed material flow, the very slow print head movement can deposit excess material in an area and thicken the layer, making the layer larger than the nozzle orifice [73]. Similarly, too high velocity may deposit too little material and decrease the thickness of the layer. The printing speed chosen depends on the size and geometrical complexity of the item to be printed. At the same time, we also have to take free time into consideration. Nerla et al. [53] utilized a speed of printing of approximately 75 mm.sec-1. They significantly decreased the initial concrete installation time to 3 minutes by injecting accelerators into the concrete.

Prout et al. [67] developed a conceptual structure based on the flowability behavior of a paste to optimize the printing rate without destroying and distorting the lower layers. This conceptual structure is founded on the distinction between the stress placed vertically at the beginning layer and the stress at the critical point of the plastic strain, also known as the elasticity stress.

Lou et al. [60] 3D printed a mortar reinforced with high-performance polypropylene fibers from OPC, fly ash, silica vapors and sand (up to 2mm particle size). A 9 mm nozzle with a 100-minute open operation duration was able to achieve a suitable extrusion efficiency with the addition of accelerators and speed bumpers. Additionally, this combination has the capacity to create up to 61 layers, or around 400 mm.

Compared to concrete reinforced with traditional concrete, 3D printing concrete composites with reinforced fibers has the advantage of being able to control their direction in a printed structure [74], [75]. The unconstrained orientation of the carbon fibers along with different printing directions significantly boosts the bending resistance up to 30 MPa [76]. Another study used a mixture of hardener and polyvinyl alcohol (PVA) compound to print at higher resolution. However, this resulted in delamination and the formation of small pores between the layers, which decreased when the samples were cured in water [77]–[79].

In an experiment, Zhou et al. [16] studied a mixture of OPC-based cement mortar and sulphoaluminate cement (SAC) as feedstock. The duration of drying time was the primary distinction among the both compounds. Due to its properties, SAC cures quickly and has high initial strength, while OPC hydrates slowly and takes longer to cure. After analyzing these two materials, the authors suggested that SAC is a more suitable 3D printing mortar compared to OPC because of its properties, since when 3D printing, the bottom layers should be strong enough to withstand the top layers. Therefore, the initial curing time is considered essential for 3D printing. Furthermore, The printing direction may affect factors like the nozzle's form, which affects the samples' mechanical characteristics [63].

Interlayer bond is a major challenge in concrete 3D printing and is affected by grain size, the extrusion method, and the thickness of the layers [80], [81]. Zareian and Khoshnevis [82] found that the lower the maximum calibration, the higher the cement-grain ratios, the higher the resistance and bond between layers. Likewise, thicker layers and more time to print the next layers decrease the compressive strength of the printed structures despite better interlayer bonding. In addition, shorter curing times can increase cold bonding between layers [82].

Shape stability is the next thing to consider regarding printed structures. The printed layers' resistance to deposition and distortion brought on by the printing of further layers is what is meant when something is said to be stable in a printing form. Kazemian [83] demonstrated that the addition of silica and nanoclay vapours could dramatically improve the stability of 3D printed paste. This improves 3D printing because of the lack of proper support and external mould to produce high and complex structures [54].

2.4.1.2. Powder Bed Fusion (PBF)

The PBF technique has also been utilized and researched, despite the majority of attention being paid to 3D printing cement and concrete paste. In an attempt by Shakur et al. [20] the powder layer was created using a combination of OPC and calcium-based cement, and the binding agent was a water-based solution of lithium carbonate. After printing, they found compression resistance of approximately 8 MPa, considerable porosity of over fifty percent, and small hydration since there was little interaction with powder and water.

2.4.2. GP-Based Material

New GP building materials, including concrete, mortar and brick, may be produced with aluminosilicate and alkaline chemicals that pose a low risk to the environment. When it comes to greenhouse gas emissions, OPC is a building material that is harmful for environment. Production of each ton of OPC emits approximately one ton of CO2 [84]–[86]. GP building materials can replace certain building materials produced by OPC. A significant part of the globe's CO2 emission is caused by the cement industry [85], [87]–[91]. The substitution of GP concrete for OPC concrete has a chance to cut CO2 emissions from the cement industry by 80-90% [92]–[95]. GP concrete production emits much less carbon dioxide into the atmosphere than Portland concrete production [96].

2.4.2.1. Comparison of OPC with GP

Impacts on the environment: The cement sector accounts for around 5-8% of worldwide CO2 emissions [69]–[73]. Studies have shown that materials such as AF and BFS as alternative binding agents, unlike OPC, do not pose an environmental hazard [91], [97]–[99].

Energy Consumption: A study by Bennet et al. found that 94% of the energy used to produce Portland concrete is used to produce OPC, while 39% and 49% of the energy used to produce GP concrete is used for sodium hydroxide and water glass, respectively. In other words, it takes 40% less energy to produce GP concrete than OPC concrete [100]. Fig. 6 depicts the energy required to produce the materials required for OPC concrete and GGBS and fly ash GP concrete.

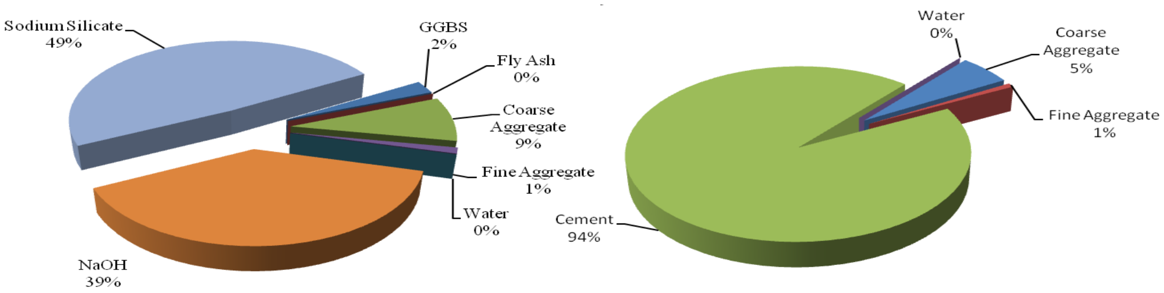

Fig. 6. Energy share of individual materials. Left: Fly ash GP concrete; Right: OPC concrete [100]

Compressive strength: GP concrete has higher compressive strength when processed at high temperatures [86], [101]–[104]. However, instead of high temperature, its strength can also be improved at room temperature by adding different amounts of slag to the GP concrete mix [105]–[107]. An experiment by Akhilesh et al. has proven that, in some cases, GP concrete has 1.5 times the compressive strength of OPC concrete [108].

Tensile and bending strength: In addition to its compression strength, GP concrete also has superior bending strength than Portland concrete. The higher tensile strength reduces the need for concrete reinforcing while avoiding cracks. The tensile strength of GP concrete is approximately 8-12% higher than for Portland concrete [109].

Density and Porosity: Besides the mechanical strength, experiments also indicate that the density of GP concrete is similar to that of OPC concrete [110], [111]. The porosity of GP concrete is also between 1% and 1.9%, well below that of Portland concrete (3% and 5.1%) [110]. Therefore, when these two concretes are placed in harsh environments, the destructive agents take longer to penetrate GP concrete. GP concrete is thus better able to withstand acid attacks, sulphates and chlorine [85].

Modulus of Elasticity: Nath et al. tested GP and OPC concretes at the same compressive strength after 28 days and found that GP concrete has a 25-30% lower elastic modulus than OPC concrete [111].

Heat resistance: Because of the properties of OPC concrete, if subjected to fire and extreme temperatures, it deteriorates. Also, GP concrete is heat resistant. According to the literature, GP concrete is more resilient than Portland concrete when exposed to a temperature of 500°C and also has higher mechanical resistance. This is because of the thermal dilation among the aggregate and the concrete paste [112]. Other tests of concrete samples at 800°C also confirmed this [113]–[116].

Creep: Due to the very low water consumption of the manufacturing process of GP concrete, it showed less creep than OPC concrete [97], [117]. Higher concrete compressive strength means less creep. An experiment reported a creep of 0.4 for GP concrete relative to 0.7 for Portland concrete [97].

2.4.2.2. Extrusion-based Printing

Not only the GPs are environmentally friendly, but they also have tunable properties specifically for extrusion-based printing [118], and their curing time is much less than OPC.

Zhong et al. [119] assessed a three-dimensional printed nanocomposite GP. The nanographene oxide GP system offered rheological properties appropriate for extrusion, a higher compression resistance of 30 MPa and improved electrical conductivity.

In another test, Paul et al. [63] employed three alternative mixing systems for flowability characteristics, two using cement as a binding agent and one with GP mortar (see Table 1).

Table 1. 3D printed concrete mixture [63]

Mix	Materials compositions (kg/m3)
Mix 1	Slag: 39, fly ash: 645, silica fume: 78, sand: 1168, actigel: 8, bentonite: 8, water: 47, K2SiO3: 250, KOH: 23
Mix 2	Concrete: 290, fly ash: 278, silica fumes: 145, sand: 1211, water: 285, sodium lignosulponate: 7.
Mix 3	Cement: 289, fly-ash: 277, silica fume: 145, sand: 1209, water: 284, sodium lignosulfonate: 9, glass fiber: 13.5 (density: 2.7, tensile strength: 1.5 N/m2, young's modulus: 74 GN/m2, failure strain: 2%)

Mixture 1 also consisted of fly ash and slag as binders. For improved performance and extrudability of Mix 1, Actigel has been used as a rheological modifier. Two alkaline solutions were applied to the alkaline solution, potassium silicate (K2SiO3) and potassium hydroxide (KOH). The results indicate that the plastic viscosity is 186 Pa.s. for mixture 1, which is superior to cement mixtures 2 and 3. Table 2 represents the rheological properties of mixtures [63].

Table 2. Rheology properties of mixtures [44]

Mix	Viscomat value				Using calibration coefficients		
	Static yield torque (N mm)	Dynamic yield torque (N mm)	The steep side of the curve (N mm/min)	Thixotropy (N mm rpm)	Static yield stress (N/m2)	Dynamic yield stress (N/m2)	Plastic viscosity (N.S/m2)
Mix 1	1370	358	6.3	11 273	13 522	3534	186
Mix 2	1401	367	4.8	13 756	13 828	3622	144
Mix 3	1767	303	3.8	17 947	17 401	2991	113

The reason for using Actigel is its ability to give a stable shape to the mixture. This material is a rheological modifier that minimizes shear stress and increases mixing capabilities within the extrusion process. It should be mentioned that the suitability of the offered techniques for testing the initial behavior of a printed GP is strongly reliant on the chemical characterization of the mixture and the instruments that are used to assess the characteristics [22].

The impact of varied mass ratios of the water glass to NaOH solution on the efficiency, structural retention, extrudability, and mechanical characteristics of printable GP mixes produced at room temperature was investigated by Bong et al. [28]. According to Fig. 7 and Fig. 8 and the direction of loading, the optimal 28 day compression strength of the mixture was 19.834.0 MPa and its bending strength was 6.37.1 MPa. In addition, the 28-day interline bond strength was 2.7 MPa. In addition, the GPs printed from Na2SiO3 solution with a SiO2/Na2O ratio of 3.22 had greater dimensional stability than the mixture of Na2SiO3 solution with a SiO2/Na2O ratio of 2. In addition, the increase of Na in the GP concrete blend also increases its compression strength.

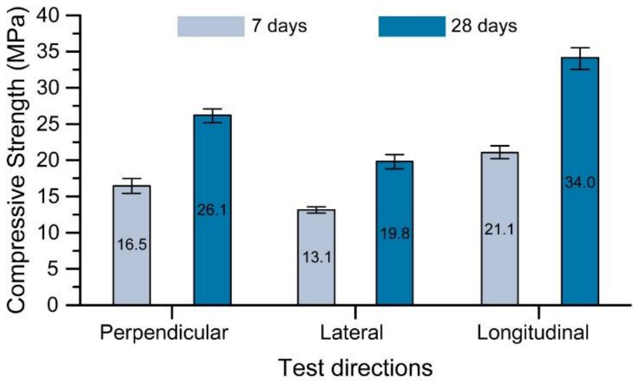

Fig. 7. Compression strength in different orientations obtained from the optimal blend for 3D printing [28]

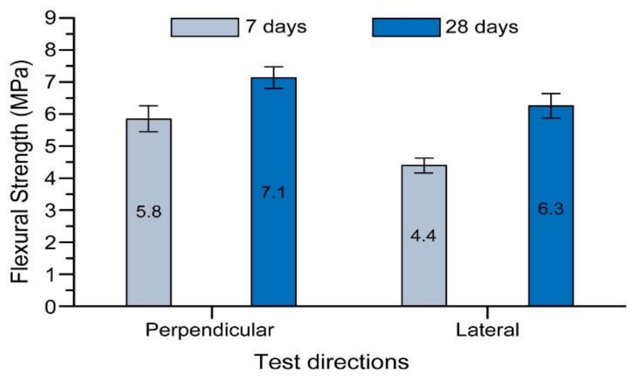

Fig. 8. Tensile Strength in Different Orientations Obtained from Optimum Mixture for 3D Printing [28]

2.4.2.3. PBF Printing

Xia and Sanjayan [26] studied 3D printing by PBF of GP, which contained molten iron slags, gravel and anhydrous sodium silicate (as an alkaline enhancer). The liquid paste was also a mix of water and a little of 2-pyrrolidone. After printing, the printed cubic shaped samples showed an extremely few resistance of 0.9 MPa and a subsequent expansion of under 4%. After curing the samples in a 60 °C alkaline solution, the resistance increased to 16.5 MPa. However, for large area 3D printed structures, curing in a hot alkaline solution is almost impossible or very difficult. To solve this problem, some GP properties and its mixing method are explained as an endeavor for future research, and a positive step is taken to improve the PBF process.

A similar experiment by Xia et al. [120] observed a 7-day compression resistance of 24.9 MPa at a slag/fly ash of 1 to 60°C. However, the printed samples with a slag/fly ash of lower than 1 did not reach an initial resistance sufficient for printing. In contrast, samples printed with only slag (no fly ash) achieved the highest durability.

Increasing temperature in GPs can effectively increase initial compressive strength and decrease setting time. Therefore, by increasing the temperature during early drying, high compressive resistance GP concrete is quickly supplied. A Nath & Sarker experiment [33] showed that GP concrete quickly reaches a high resistance when the temperature increases. In this experiment, Class F fly ash and 15M of NaOH were utilized to prepare GP samples that were cured at approximately 20-22°C using three composite designs with specific thermal properties. According to Fig. 9 and Case A, known as separate mixing, fly ash is first mixed with the NaOH solution for 90 seconds before waiting 30 seconds and adding Na2SiO3 and mixing for 90 seconds. In B, or the usual mix that most mixes follow, both NaOH and Na2SiO3 solutions are premixed, followed by the addition of fly ash. In C or pre-dry blending, NaOH, Na2SiO3, and fly ash are blended as solid, dry granules before water is added to the resulting homogeneous mixture (similar to PBF in 3D printing). This reaction is exothermic and heats the GP concrete.

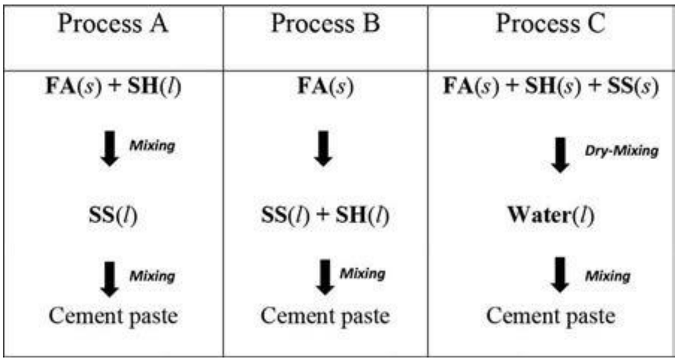

Fig. 9.GP Mixing Methods [121]

Fig. 10 shows that the C mixture achieves a temperature of about 53 °C in the initial minutes, which leads to the initial rapid curing of GP concrete.

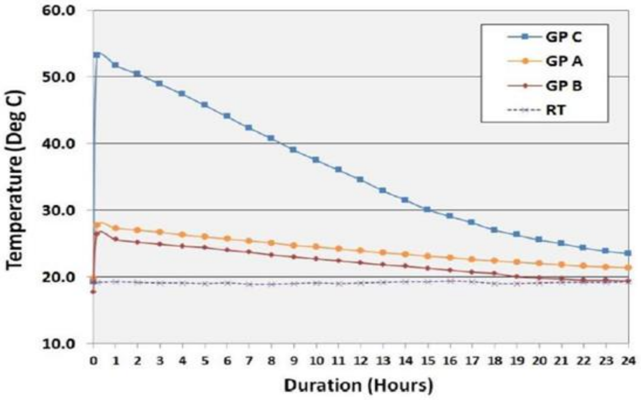

Fig. 10. Temperature changes of GP samples in different mixes [121]

In a similar test by Suwan & Fan [122], the C-case blending method was used to prepare GP samples. Referring to Fig. 11, the use of sodium hydroxide for preparing the alkaline solution generates more heat than sodium silicate. The heat generated by the 15M Sodium Hydroxide greatly strengthens the GP concrete in about an hour.

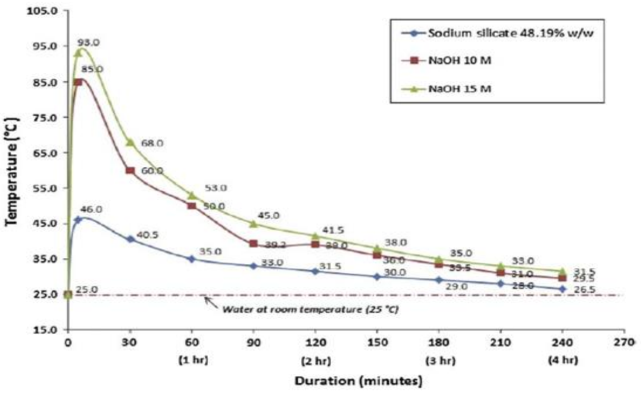

Fig. 11. The Effect of Alkaline Solution on Initial Curing Temperature [121]

Other studies [121] on this topic have analyzed the initial temperature of adding different amounts of OPC to the GP and its temperature changes with different mixing methods. Therefore, the various challenges of using these methods for the 3D printing of GP concretes should be considered.

3. Comparison

Concrete is the most often utilized synthetic material in the construction of structures worldwide. 3D printing is not as widespread in the construction industry, but its future is bright because of its benefits such as mass customization, formless design and automated construction. Despite the PBF technique has been investigated, but extrusion-based printing is the principal AM technology. The appropriate concrete for 3D printing may be quite different. Self-compacting concrete can also be inappropriate for 3D printing since it can lose its form after printing. The most pressing issues to fix are the layered look and the inadequate connectivity between layers. Notwithstanding these obstacles, architectural flexibility and the ability to build intricate and portable structures offer considerable potential.

The pressing problem with 3D printing is the creation of porosity between material layers. AM can create extra high porosity and reduce mechanical performance through the reduction in surface bonding inside the printed layers [46], [123]. The degree to which pores form is dependent on the 3D printing process and the materials used. Pinholes are more common in methods that use layers of material to print, such as CC and FDM, and are one of the main defects that degrade the mechanical properties [46], [82]. Pore formation can also result in stratification and damage among layers after printing [77]. In FDM 3D printing, increasing the thickness of the layer reduces the porosity as well as the bond between the layers, reducing tensile strength and increasing water absorption [124]. By increasing the depth of the concrete layers along with more delay to lay the next layers, one gets a better adhesion between the layers and forms less pores. At the same time, during the printing process of aluminum/glass composites, the porous nature of the AM may be greatly decreased resulting in the decreased depth of layers [125], [126].

A suitable nozzle is necessary to get the desired shape and the right construction on the underlying layers. The nozzle direction must be tangent with the extruder trajectory [127] to prevent the new layer from twisting or moving. The majority of concrete 3D printers have an extrusion mechanism that pumps precast concrete or mortar across a single printing head to create concrete layers. At the end of the printhead is a nozzle that creates layers of concrete of the desired form and size [127]. Extruding matrices are available in a range of forms, including round, oval, square, and rectangular. Auxiliary trowels may be used at the tip of the nozzle to increase surface quality [128]. Moreover, because of the full contact between the layers, rectangular nozzles generate less pores and a better surface area than cylindrical nozzles [56]. However, it is harder to 3D print complex forms with rectangular nozzles, especially joints [56].

A layered form is also a challenge because of the nature of AM. Fig. 12 illustrates a 3D printed concrete structure. As mentioned above, to remove the layered view, Khoshnevis [63] utilized a trowel-like device linked on to the outline printing head. The number of layers is dependent upon the thickness and height of the layer. By lowering the quantity of layers, it is possible to improve the look of the layers. 3D printing processes such as FDM and contour craftsmanship give a more stratified look than the PBF method, it cannot be used for large structures [26]. Despite many successful experiences in developing contours [53], [127], [129] and FDM on laboratory and industrial scales [130]–[132], there are several differences. CC printers are very easy to set up and can be adjusted to the desired size. However, robotic arms are usually fixed and unable to be adjusted. Nevertheless, the rate and degrees of freedom of an automated arm allow for many sophisticated tasks that would not be conceivable with the development of four-axis contours [133]–[143]. If the printed structure has a simple design, circumference manufacturing is preferable to robotic printing due to the higher cost. In addition, the CC method saves much more equipment than the FDM.

Fig. 12. Layered Appearance of a 3D Printed Concrete Structure [54]

4. Conclusion

This study gave a brief overview of concrete 3D printing and expressed the types of materials that can be printed. Among all the materials mentioned, GP concrete 3D printing showed greater potential than other materials. Among the many 3D printing processes, extrusion-based printing is the most suited and fastest alternative for 3D printing concrete on a large scale, but it has many drawbacks.

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