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MYTHS AND REALITY OF IMPLEMENTING THREE-DIMENSIONAL TECHNOLOGY IN CONSTRUCTION

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Abstract: Due to the increased demand for more sustainable building environments, and the excessive need in building field to meet the designer's requirements such as irregular,complex shaped structures, the utilization of three-dimensional technology (3D printing or additive manufacturing *(AM)*) by engineers in construction sector is increased globally. The key-advantages of use 3D printing method over traditional building methods are: low labor cost, less waste materials, freedom in design, faster construction, no need for formwork and reduce the risk and safety issues in construction sites. In theory, the printing is based on using 3D computer-aided-design (*CAD*) to materialize the whole building structure by just pressing a button in the 3D printer that brought to the construction site while the reality is not like that. This paper presents most recent developed innovative methodology used for 3D printing, possible printed building materials and the existed 3D printed structures in reality towards spotting the light on the most high-tech applications in construction and the possibility to adopt such technology in Iraq to overcome the challenges in design with faster building methods towards develop the country in construction sector.

Keywords: *3D printing, Construction, Building materials, Additive manufacturing.*

خيال و واقعية تنفيذ تكنولوجيا ثلاثية الابعاد في البناء

الخلاصة: بسبب زيادة الحاجة على بيئات البناء الأكثر استدامة ، و الحاجة الى تلبية متطلبات المصمم مثل الاشكال المعقدة والغير منتظمة ، فان هنالك زيادة على مستوى العالم في استخدام تكنولوجيا ثلاثية الأبعاد (الطباعة ثلاثية الأبعاد أو التصنيع المضاف (AM)) من قبل المهندسين في البناء. ان المزايا الرئيسية لاستخدام طريقة الطباعة ثلاثية الأبعاد على طرق البناء التقليدية هي: انخفاض تكاليف العمالة ، وتقليل النفايات ، والحرية في التصميم ، والبناء الأسرع ، وعدم الحاجة إلى قوالب الخرسانة ، و تقليل من مخاطر العمل في مواقع البناء و تحسين امور السلامة و الامان. من الناحية النظرية تعتمد الطباعة على استخدام التصميم ثلاثي الأبعاد بمساعدة الكمبيوتر (CAD) لتجسيد بنية المبنى بالكامل عن طريق الضغط فقط على زر في الطابعة ثلاثية الأبعاد التي تم جلبها إلى موقع البناء في حين أن الواقع ليس كذلك. في هذا البحث يتم استعراض : أحدث التقنيات المبتكرة و المتطورة لاستخدم للطباعة ثلاثية الأبعاد ، مواد البناء الممكن طباعتها في الواقع ، و المنشات المطبوعة بتقنية ثلاثية الأبعاد والموجودة في الواقع و ذلك لتسليط الضوء على أكثر تطبيقات التكنولوجيا المتقدمة في الإنشاء وإمكانية اعتماد هذه التكنولوجيا في العراق للتغلب على التحديات في التصميم مع أساليب بناء أسرع نحو تطوير البلاد في قطاع البناء.

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1. Introduction

The rapid growth in technology which reflects its impact on many aspects of life and construction sector, is one of these aspects such as medicine, automotive and aerospace [1,2]. Three-dimensionally technology, particularly 3D printing in construction industry received great attention by construction-based companies and researchers in universities due to the advantages of utilization of 3D printing techniques (3DP) over traditional building method (TBM). The latter limits the freedom of design the structures and needs for repeated formworks on-site which increases the overall cost by increase the labour cost. Additionally, more injuries are expected during TBM which made such method less safety. In terms of sustainability, TBM is associated with more waste in materials at the construction site which may increase the cost of any project [3].

The above drawbacks of TBM inspired the owners of companies as well as researchers to find solutions to overcome such drawbacks and enhance the construction. One of the solutions was the implement of 3DP. The latter provides various benefits over TBM. These benefits are various among time reduction, new degree of freedom in design, functional structures, environmental and economical benefits. The printing process involves the usage of software, hardware and printable material [4]. In theory, printing is based on using 3D computer-aided-design (*CAD*) to materialize the whole building structure by just pressing a button in the 3D printer that brought to the construction site while the reality is not like that.

The objective of this paper is to address the most recent developed innovative methodologies used for 3D printing, possible printed building materials and existed 3D printed structures in reality towards spotting the light on the most high-tech applications in construction and the possibility to adopt such technology in Iraq to overcome the challenges in design with faster building methods towards develop construction sector.

2. Concept of 3D Printing

The American society for testing and materials (ASTM- F2792-12a.) defines 3D printing as the fabrication of objects through the deposition of a material using a print head, nozzle, or another printer technology [5]. In reality, some principles need to be followed for 3D printing. These principles are: modeling, printing and finishing. In order to obtain the desired 3D object or item, a computerized 3D image is designed using model is designed using computer-aided-design (*CAD*) software program or animation modeling software [6]. The CAD model is then sent to the printer which reads the design and starts to form the 3D object by depositing the material in layers starting from the bottom to the top then these layers are joined either automatically or using additional process in order to form the desired shape. The deposition of the layers may be carried out using various printing techniques such as extrusion, sintering, polymerizing, etc.

3. Classification of 3D Printing Processes

Many techniques are developed to produce 3D structures with the desired shapes and properties. The classification of additive manufacturing (AM) processes, or 3D printing technologies, in accordance to American Society for Testing and Materials (ASTM F42) may represented by seven categories: material jetting, binder jetting, material extrusion, powder bed diffusion, sheet lamination, direct energy deposition and VAT Photopolymerisation [7,8]. Table (1) summarizes the main advantages and disadvantages of using each of these techniques with the possible materials. The description of each technique is shown below:

3.1 ***Material Jetting*****:** in this process, either a Drop on Demand (DOD) or continuous approach of jetting material is used. The parts are printed layer by layer by deposit of droplets of material which will be solidified (cured) using UV light. The commercially developed techniques presented by this process are :Polyjet, Smooth Curvatures Printing (SCP) , Multi-Jet Modeling (MJM) and Projet.

3.2. ***Binder Jetting*** **:** a thin layer of powder-based material is deposits layer by layer. These layers are bind via liquid binder agent. The latter could be based on organic or inorganic material. After printing, parts that are made with some types of powders; namely metal and ceramics, are expose to post process (firing) to achieve the required strength for the printed parts. The 3D printing (3DP), ExOne and VoxelJet are the common commercially developed techniques for the binder jetting process.

3.3. ***Material Extrusion*****:** a printable material is pulled in this process via a nozzle or beads or orifice in tracks. This materials is deposits into layers to form the desired shape. An example of commonly developed commercially techniques are Fused Filament Fabrication (FFF) and Fused Deposition Modeling (FDM).

3.4. ***Powder Bed Fusion*****:** a selective powder-based materials are melted and fused together using different such as laser or electron beam. Various commercially developed techniques for the powder bed fusion are available such as Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM), Selective Heat Sintering (SHS) and Multi-Jet Fusion (MJF).

3.5. ***Sheet Lamination*** **:** the required object is formed by shaping sheets and bonding these sheets via various methods such as adhesives or ultrasonic welding or brazing depending of the material used for the sheets. Laminated Object Manufacture (LOM), Selective Deposition Lamination (SDL) and Ultrasonic Additive Manufacturing (UAM) are examples of commercially developed techniques for sheet lamination.

3.6. ***Direct Energy Deposition*****:** this process is used to repair or add other feature to existed objects. In this process, wire-based material or powder-based material is deposits through a nozzle onto a surface of the existed object. The depositing process is associated with the application of heating sources such as laser or electron beam. Examples of commercially developed techniques for direct energy deposition are : Laser Metal Deposition (LMD), Laser Engineered Net Shaping (LENS), and Direct Metal Deposition (DMD)

3.7 *Vat Photopolymerization*: liquid-based resin (photopolymer resin) is used in this process. This resin is hardened using a laser. Stereolithography Apparatus (SLA),Digital Light Processing (DLP), Scan, Spin, and Selectively Photocure (3SP) and Continuous Liquid Interface Production (CLIP) are examples of techniques that developed commercially

Table (1): Summary of AM Techniques

Category of AM techniques	Advantages	Disadvantages	Materials
Material jetting	*Low waste. *High accuracy and speed *Allows printing multiple material parts and colours *Homogenous mechanical and thermal properties	*High cost *Need for supportive material. *Limited materials	Polymers and plastics.
Binder jetting	*Usage of various materials. *Faster than other methods. *Different mechanical properties as well as various binder-powder combination could be achieved.	*Need for binder material *Not always suitable for structural parts. *More time is required. *Additional post process is needed	Metal, polymers and ceramics
Material extrusion	*Cheap process. *Allows for multiple colors *Good structural properties. *Office sized machine.	*Nozzle radius affect the final quality. *Lower accuracy and speed. *Need for constant pressure of material to increase the quality of finishes	Polyers and plastics.
Powder bed diffusion	*Suitable for visual models and prototypes *Office sized machine *Powder acts as an integrated support structure *Wide options of material	*Materials with no structural properties *Limit sizes *Need higher usage of power	Any powder based materials
Sheet lamination	*Low cost, *Very fast cutting *Permits combination of metal foils, including embedding components.	*Variation in the finishes *Need for post processing	Any sheet material capable of being rolled
Direct energy deposition	*Effective for repairs with high quality. *Not limited by direction or axis *Capable of controlling the grain structure to a high degree	*Variation in finishes. *Post processing is required.	Metal Wire and Powder, with Ceramics
VAT Photopolymerisation	*High level of accuracy. *Good finish surface. *Relatively quick process *Suitable for large build areas	*Expensive. *Long process *Limited materials *Need supportive structures. * Post curing is required.	Plastics, Polymers, Liquid resins

4. Available 3D Printing Methodologies in Construction

Different 3D techniques are employed in building sector to construct unusual designed structural parts. Such techniques are based on extrusion or powder-based techniques. The following sections address various techniques that was developed by researchers.

4.1 D-Shape

This technique is based on binder jetting process and one of gantry –based offsite processes which used in civil engineering applications to produce 3D printed complex structures. The D-shape technique (Fig.1) was developed by an Italian engineer (Enrico Dini). The printing with the D-shape technique involves the use of powder-based materials such as sand or blinder of cement and sand to be bind with a liquid chemical binder during printing. The printing process starts with deposits layers of powder on bed printing in the 3D printer. The binder then is applied on the top of these layers in order to solidify these layers. After printing, the non-solidified powder, which is a temporary support material, is removed. This process made the D-shape technique a slow process to produce the 3D parts in addition to the need for further cleaning and maintenance for the 3D printer. However, the D-shape technique is the suitable method to 3D printing different complex parts or elements than the conventional building method [9].

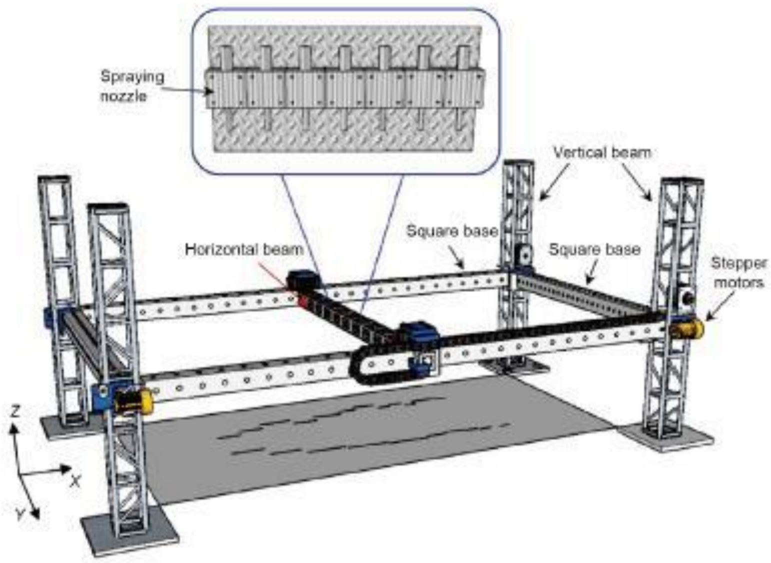

Figure 1. D-Shape Technique [9]

4.2 Contour Crafting

This technique is one of the available 3D printing systems that based the 3D fabrication process using material extrusion method (refer to section 3.3). The desired 3D element is constructed by printing layers of the material. The control crafting (CC) technique is a preferable method over others due to its suitability for construction large on-site structures with complex geometries with superior quality of surface finishing with an enhanced speed of fabrication [10]. Also, CC technique permits printing walls with embedded conductors (for electricity and plumping) in addition to reinforcement imbedding [11]. The main elements in CC are illustrated in Fig.2.

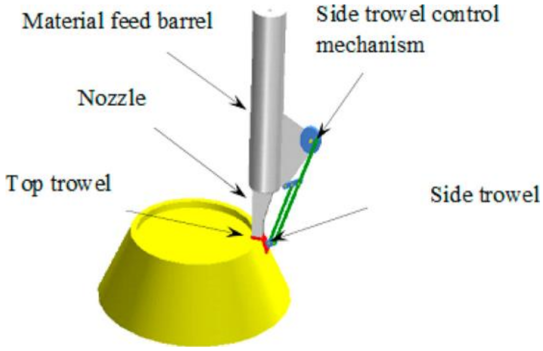

Figure 2. Contour crafting technique [11]

The printing process using CC method involves two systems: extruding and filling (Fig. 3). The material is extruded from a nozzle (or two nozzles) while the trowel guides the printed materials to produce the desired shaped with smooth surfaces. The computer controls the movements of the side trowel in the required angles (vertically and horizontally) to achieve the designed structure. The side trowel permits the deposition of thicker material which reduces the time that required for manufacturing. The maximum thickness of the deposited material is governed by the trowel height. Following the extrusion process to produce the boundaries of the layers, the internal volume of the structure is filled manually with the material by pouring layer by layer of the same extruded material or other material [12].

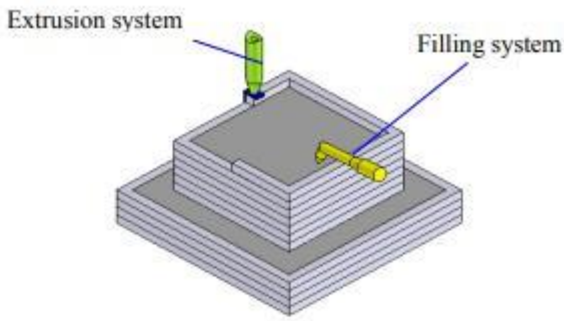

Figure 3. Extruding and Filling systems in Contour Crafting Technique [12]

However, some limitations are associated with CC printing system. This is due to the suitability of CC for vertical extrusion only in addition to the weak interfacial zones between the printed layers due to the weak mechanical properties of the material. The complexity to utilize the initial formwork and towel systems for the production of the printed object with the desired size and shape is also consider part of the limitations of CC technology [12].

4.3 Concrete Printing

This 3D printing process is similar to CC process in which printing of the material is based on extrusion-based technique to construct structures with complex geometries. However, 3D concrete printing (3DCP) technology differs from CC technology in many aspects. The internal and external geometries of the printed structure is greater control when using 3DCP. The latter also preferable over CC process since there is no requirement for labout intensive formwork [13].

The 3DCP is utilized for printing large-scale structural elements. The principle of 3DCP technology is illustrates in Fig. 4. A tubular steel beam (TSB) is connected to concrete depositing system (CDS). The latter consists of printing nozzle which is connected to pump via output pipe. The pump is attached as well to delivery pipe. The movement of the printing nozzle is control via a software in various directions (X, Y and Z). Many researchers in different universities developed their own 3DCP system to achieve the desired properties and design requirements [10].

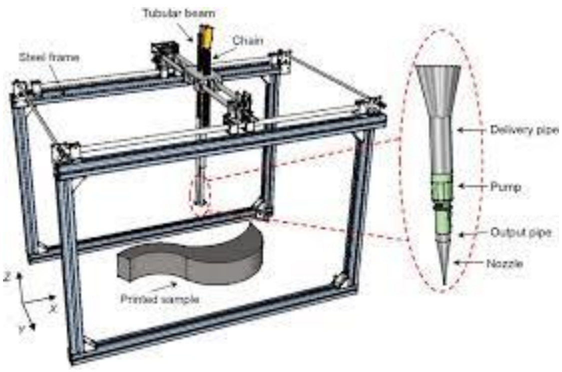

Figure 4. 3D Concrete Printing Technique [10]

5. Aspects of 3D printed Mixture

During the designation of the mix for three-dimensional printed materials via extruded-based techniques, specific printability properties must be considered. This is due to the nature of the printing process which involves many steps. These may categorized into: mix the ingredients in tanks, transportation of the mixture via pipes and pumping to the printing nozzle. The following present the commonly aspects of properties that considered during the mix design to obtain the desired properties for the 3D printed structural element [14,15]:

5.2. Extrudability refers to the ability for the transpiration of fresh printing mixture through pipe and nozzle

5.3. Flowability: refers to a continuous easy-flowing mix from the source to the printing nozzle. related to the concrete extrusion, flow, and workability

5.4. Buildability : refers to self-supporting ability of the printing layer as well as the ability of to hold other printing layers above it without collapsing. Such ability is related to the adhesion and cohesion between or within other printed layers.

5.5. *Strength*: printed mixture must also be of a certain suitable compressive strength.

5.6. *Open time* : refers to the change of mixture flowability with time and maintain sufficient workability for the mixture.

6. 3D Printed Construction Materials

Various materials may three-dimensioned printed. The states of printed materials are various among liquid, powder, solid or sheet material. Extensive work by researchers to develop materials for 3D printing using various techniques was reported in the literatures as shown in the following sections.

6.1 Cement-based Mortar

Kazemian *et al* [16] studied the workability of fresh 3D printed cement-based mixtures using proposed framework. Tree different workability aspects of a printing mixture were developed in this investigation. These aspects were print quality, shape stability and printability window. The compositions of the printed mixtures were consist of Portland cement (Type II), commercially available manufactured sand of 2.36 mm maximum aggregate size, polycarboxylate-based high-range water reducing admixture (HRWRA) and viscosity modifying admixture (VMA)), polypropylene fiber with 6 mm in length and 415 MPa tensile strength, densified silica fume with 2.2 in specific gravity ,and nano clay with highly-purified attapulgite of 2.9 specific gravity and with 3 nm in diameter and 1.75 mm as an average particle length.

These compositions were used to produce four different printed mixture and these were (PPM, SFPM, FRPM and NCPM). The water-to-binder ratio was kept constant (0.43) for all mixes for comparison purposes in addition to 600 kg/m^3 which refer to the ratio of the cementitious materials content which was kept constant as well. A drum mixer was used in their study for mixing the above compositions for 8 mins. In terms of the mix that contains naoclay (NCPM), the latter was dispersed in water prior to mixing by the mixer.

Test procedures were conducted in using different criteria conventional and new developed testing methods. In the conventional test which involves the measurements of unit weight, flow and compressive strength. The flow of the mixtures and the compressive strength at different curing ages (7 and 28 days) were determined in accordance to ASTM C 1437-15 and ASTM C109 respectively. The new developed test methods involves *print quality, shape stability and printability window.* The print quality for specific printing mix is related to the surface quality and dimensional conformity of the printed layer. In order to measure the ability of the printed sample to resist deformations during layering , two different tests methods (layer settlement and cylinder stability) were carried out. The layer settlement test was obtained by analyzing photos (Image J software) that taken via a camera during printing two layers on the top of each other with two different time gap (0 and 19 mins).

Another test to evaluate the shape stability was cylinder stability test which employed an apparatus that consists of 3D printed parts made from ABS plastics. This apparatus allow the application of load (5.5 kg) for the freshly printed cylindrical samples with 30mm× 60 mm in dimensions. The deformation of the printed sample was measure. In terms of the printability window test, the interval time that required to printing an acceptable quality mixture was defined via two time limits: printability limit and blockage limit. Different new mixes that based on PPM mix were developed for this test by the addition of different concentrations of $CaCl_2$ (1, 2 and 3%) and the setting time for these mixes was obtained in accordance to ASTM C403 using penetrometer. It was concluded that the proposed framework that used to 3D printing different mixtures was efficient to produce layers with 25.4× 38.1 mm in dimensions. The shape stability of the printed samples were enhanced with the utilization of nanoclay (NCMP) and silica fume (SFMP) when compared with other mixes.

Feng *et al* [17] studied the mechanical properties of 3D printed plaster cementitious powder in addition to the microstructure of the printed samples. The mixture that used for 3D printing was ZP150 with a binder (ZB60) of 21.8% of volume friction. The ZP 150 consists of plaster, vinyl polymer and carbohydrate while ZB60 containing humectants and water. The printing process was carried out using Spectrum Z510 3D printer with a nozzle HP 4810A 11. The dimensions of the objected that could be printed via this printer are up to 356 mm (length)×254 mm (width) ×203 mm (height).

The mechanical properties of the printed specimens were conducted by means of compression and flexural tests. The microstructure of the printed samples was conducted as well as using 3D high-depth stereo microscope and high resolution digital camera. The 3D printed shell structure of the samples was obtained using finite element analysis. The compression samples were fabricated to obtain the compressive strength as well as the modulus of elasticity. The dimensions of cubic samples were 70.7 mm specimens and 50 mm samples. In terms of flexural tests, small beams samples with 40× 40× 160 mm in dimensions were 3D constructed Some of these samples were tested in Z-direction and others in X-direction. Regarding the microstructure of the 3D printed samples, a layered orthotropic microstructure was identified. Same failure mode was obtained for all tested 3D printed samples and it was hourglass-shaped cracking on opposite sides of the samples when the load was applied in X-, Y- and Z-directions. Higher values were recorded for the compression strength and elastic modulus when the load was applied in the X-direction (printer head travel direction). The effect of the printing direction on the load bearing capacity of the structure of the sample was confirmed through the proposed finite element analysis.

An approach was developed by researchers [18] where a new powder-based materials was used for commercially 3D printer (Z-Corporation’s 3D printer). The actual powder of such printer was (Z-printer150, Z-Corporation, USA) and its consists of plaster, vinyl polymer and carbohydrate. The developed powder was base on mixing two types of cement; namely Ordinary Portland cement (OPC) and calcium aluminate cement (CAC). These cements were blended together using (1:0.475) mixing ratio for (CAC:OPC). The CAC was sieved on 150 μm to 75 μm sieves prior to mixing process. The mean particle size (D10, D50 and D90) for Z-powder, OPC and CAC was measured. The values for z-powder were 1.48, 23.07 and 70.12 μm for D10, D50 and

D90 respectively. The measured values for D10, D50 and D90 were 3.38, 79.93 and 127.11μm for OPC and for CAC were 0.19, 8.93 and 38.46 μm, respectively.

The mixing of developed powder involves using Hobart mixer to blend OPC and CAC. An accelerator agent (lithium carbonate) was used as a replacement in some mixes. The percentage of replacement was 4.5% of the total weight of the mixture. Various mixes were prepared for 3D printing and these were samples with and without the accelerator agent as well as mixes with hand manual mixing. During the printing, the powder-based mixture was used to build the 3D sample and Zb60 was used as a binder. Humectant and water were the components of Zb60 (the binder).The 3D printing process involves the usage of a commercially 3D printer that composes of various elements: container, roller, printing nozzle, feed bin and build bin. The powder of (CAC and OPC) is placed in the 3D printer container which connected to the feed bin. The 3D sample is created in the build bin by spread a layer of the powder in the build bin using a roller. The liquid binder is released via the printing nozzle. These steps were repeated till the whole 3D sample is constructed. The printing process was carried out in the x-direction and the saturation level of the 3D printed object were between (75-170%) and (150-340%) for the shell and core respectively.

Various tests were conducted to evaluate the properties of the 3D printed specimen. These tests were porosity analyses, Microscope imaging, 3D profiling Veeco (Dektak) and Scanning Electronic Microscope (SEM) an the compression test. The latter was conducted by testing 3D printed samples of 20 × 20 ×20 mm in dimension for various curing environments (no curing, curing with water and curing with both $Ca(OH)_2$ and water). It was concluded that maximum compressive strength was 8.26 MPa at the saturation level of 170% for both the shell and core. In terms of the porosity, the minimum porosity was 49.28% at the saturation level of 170% and 340% for the shell and the core, respectively. The hand mixing method was found to commit different concepts.

6.2. Geoploymer-based Mortar

A printable geopolymer-based material was prepared using different powders [19]. These were slag-based (GP) and plaster-based (ZP) geoploymeric powder. The geoplomer-based powder (GP powder) was a mixture of slag, activator (beaded anhydrous sodium metasilicate) and fine sand (70 Grade sand with 184 μm median size). The preparation of GP powder involves dry mixing of the above ingredients using Hobart mixer. Prior to the mixing process, beaded anhydrous sodium metasilicate was milled using ball mill for 5 mins. In order to bind the dry mixture during the process of 3D printing, an aqueous solvent (Zb® 63, Z-Corp, USA) with viscosity similar to pure water was utilized.Prior to 3D printing process, various key parameters such as particle size distribution, powder bed surface quality, powder true/bulk densities, powder bed porosity, and binder droplet penetration behavior were investigated in order to evaluate the printability of geopolymer-based material. After printing, the mechanical properties such as printing accuracy and apparent porosity were evaluated. The compressive strength for printed samples was conducted into 2\x- direction and z-direction.

In the printing stage, two different structural samples (based on two digital models) were printed using commercially 3D printer (ZPrinter® 150, Z-Corp, USA) with an HP11 print head (C4810A). The printed samples were with cubic and plate structures with 20 × 20 × 20 mm and 40.4 × 40.4 × 4 mm in dimensions respectively. The printed layer of the structure was 0.1016 mm. The binder-to- volume ratio was 0.24 and 0.14 for the shell and core sections respectively. Some printed cubic structures were subjected to a new post-processing technique. The latter was involves placing the printed cubic samples in a solution of saturated anhydrous sodium metasilicate for various periods (1 and 7 days) at 60°C.

It was concluded that the geopolymeric material that prepared in their investigation showed sufficient printability properties for 3D printing that based on powder-base materials. An anisotropic phenomenon in dimensional accuracies as well as mechanical properties was observed for all printed cubic specimens. The 3d- printed samples showed a compressive strength in x- direction and z-direction of 0.9 MPa and 0.76 MPa respectively for green samples (without post-curing). When the developed post-curing method was used, the compressive strength of 3d-printed specimens was increased. The recorded compressive strengths in x- direction were 10.3 MPa and 9.2 MPa respectively at 1 day post-curing and 16.5 MPa and 15.7 MPa respectively at 7 days of post-curing.

Another investigation was conducted by Panda *et al* (2018) [20]. In their study, the influence of some printing parameters on interfacial tensile bond strength between the layers of fly ash-based geopolymer mortars that printed using 3D technique was explored. The printing parameters were printing speed (70,90 and 110 mm/s), printing time gap (1 min, 5mins, 10 mins,, 15 mins, 20 mins, 35 mins, 3 hrs and 6 hrs) and nozzle standoff distance (0,2 and 4 cm). The mixing proportions of the ingredients of geopolymer mortar were 572.34, 35.52, 101.86, 1219.74,140.74,144.09 and 10.05 kg/m^3 for fly ash, slag, silica fume, sand, K-silicate, water and thixotropic additives respectively. The printing process was carried out using four-axis automated gantry system with working place of 1 ×1 ×1.2 m using two different nozzles with dimensions of 30× 15 mm and 20× 20 mm. A 70 mm/s was set as a gantry speed with 1.5 liter/min for flow rate of the pump. The bond strength was conducted for specimens of 50 mm in length after fixing two steel plates of both sides of the sample.

No significant effect was found on tensile bond strength using three different printing speeds except slight reduction in the bond strength when 110 mm/s was used as a printing speed which was attributed to the effect of size and cross section strain gradients due to printing with different speeds. In terms of the time gap, it was concluded that the bond strength reduced with the increment of the gap time and up to 1 hr due to the phenomena of moisture exchange.

Conversely, higher bond strength was recorded for samples that prepared with 35 mins of gap time and this was related to the freshness of the deposited material. Regarding the nozzle standoff distance, it was reported that higher bond strength was obtained when the distance was lowest (i.e zero) and some variations in the reported bond strength were observed for distances 2 mm and 4 mm. These variations were attributed to the increment of the original standoff distance of the nozzle due to the deformation caused by the slump of the bottom layer when a new layer was placed on the top of the bottom layer.

6.3. Printable Concrete

An attempt was recorded [21] to produce a printable concrete mix with enhanced surface quality towards building small-scale objects such as angular walls. The concrete mix consists of cement (Rapid cement CEM II A (Type 42.5R), flyash, silica fume, filler, water, superplasticizer (Glenium 51), natural granite aggregate. The grading of sand comprises of three sizes : 30% of R1-2mm, 24% R 0.5-1mm and 24% of R 0.1-0.6 mm. The mixing ratio was (1: 0.29:0.05:0.45) for (cement:flyash, silica fume and filler). The water-to-binder ratio is 0.27 and sand-to-binder ratio is 0.94. The superplasticizer was added by 0.64% by weight of cement.

The printing process was carried out using modified contour crafting method. In this technique, three additional axes of rotation were added to the printing system. The benefit of these is to set the angle for the trowels that shape and smoothen the edges and rotates the nozzle head around the Z-axis. Due to these additional axes, the original software was modified to control the added axes. Smoother surface was achieved for printed concrete using the new setup of the printer. The measurements of the indentations appearing between each printed layer showed that less depth (3.4 mm) was recorded for three-dimensional printed layers using contour crafting method when compare with those obtained for pieces printed without using the above printing method.

Another goup of researchers [10] designed concrete mix to be three-dimensional printed using printing system which was designed as well by the same researchers. In their investigation, various trial mixes were conducted to obtain the optimum concrete mix which meet the requirements of fresh properties of printed concrete. The basic concrete mix design includes cement (Type I), sand and fine aggregate (maximum aggregate size= 2 mm). The optimum control mix was achieved after various trials and it was with mixing ratio of (1:0.64:1.28) and minimum water-to-cement ratio was 0.48 for extruded concrete throw the printing nozzle. In order to enhance the workability and reduce the water-to-cement ratio, various dosages of superplasticizer (Viscocrete) (0, 0.4, 0.8,0.88 and 1.04 %) by weight of cement was used. Prior to pouring the concrete, various dosages (0.5-1%) of a retarder was added to avoid the setting of concrete during printing process. Additionally, an accelerator with different concentrations (0, 0.4, 0.8, 0.88 and 1.04% by weight of cement) was added immediately before pouring the mix to accomplish the required setting and gain of strength after printing.

The three-dimensional printing was conducted using designed printing system which was designed by the authors. The system was designed to print structural wall with length of 77 cm, width of 2 cm and distance between the walls of 10 cm. The main elements in the printing system are: concrete tank, pump, nozzle and motion control system. The latter allows the printing machine to move in three axes (x, y and z) to produce 3D object. Regarding the nozzle, various diameters were tested before finalize the design of the nozzle which affect the flowability of the mix. The optimum nozzle was with 2 cm in diameter thus the selection of maximum aggregate size of fine aggregate was set to 2 mm to obtain extruded mix. The nozzle has two trowels (side and top trowels) and it was connected at the bottom of the tank. The designed printing system includes designed pump which was connected directly to the cylindrical mobile tank.

Various test procedures were carried out to evaluate the required properties for the printed layers. These tests were the extrudability, flowability, buildability, open time and the compressive strength. The latter was conducted in accordance to BS 1881-116:1983 as well as 5×5 concrete cubes. The buildability of the printed layers was measured by printing 5 layers continuously with no collapse. In terms of the flowability, it was evaluate via slump flow test which was conducted in accordance to ASTM Standard C1611/C1611M-14. During the slump flow test, an open time for specific interval was calculated. It was concluded that the optimum concrete mix was specified with best extrudability, flowability and buildability. The mixing ratio of the optimum mix was (1:1.64:1.28) for (cement:sand: fine aggregate) with water-to-cement ratio of 0.39 with 0.8% and 0.5% by weight of cement for the accelerator and retarder respectively. The printed concrete with this mix proportions showed compressive strength of 42 MPa.

6.4. Special Concrete

6.4.1 High-Performance Concrete

Structural components were made by extruding layers of high-performance fibre-reinforced fine-aggregate concrete using novel digitally-controlled additive manufacturing method [15]. The mix was designed to achieve compressive and flexural strengths over 100 MPa and 12 MPa respectively. Various trial mixes were conducted in order to obtain the optimum mix. Each mix consists of 70% cement (Type I 52.5), 20% fly ash, 10% undensified silica fume, water and sand with maximum aggregate size of 2 mm. A polypropylene fibrer 12/0.18 mm length/diameter was added as well. The five trial mixes were varies in sand:binder ratio and water:binder ratio . Different dosages of superplasticiser, retarder and accelerator were added to the five trial mixes to achieve the optimum mix with the desired fresh printed properties (extrudability, flowability, buildability and open time). Excluding the percentages of the superplasticiser, retarder and accelerator, the water-to-binder ratio was 0.28 for Mixes 1 and 2 while it was 1.86, 1.50 and 1.22 for Mixes 3 , 4 and 5 respectively. In terms of sand-to-binder ratio, it was 3, 2.33, 1.86, 1.5 and 1.22 for mixes 1,2,3,4 and 5 respectively without taking into consideration of the added percentages of superplasticiser, retarder and accelerator.

It was concluded that Mix 4 presents the optimum mix with proportions of 3:2 and 0.26 for sand:binder ratio and water:binder ratio respectively. The 0.26 ratio includes the added dosages of 1% superplasticise and 0.5% of retarder. The proportion of polypropylene fibres was 1.2 kg/m^3 as recommended by the supplier. The tested properties for the printed concrete using Mix 4 showed shear strength of 0.5-1.0 KPa and compressive strength of 110 MPa with open time of 100 mins. This optimum mix was found to be suitable to print up to 61 layers in one session without association of any deformation in the bottom layer.

6.4.2 Ultra-High Performance Concrete

Group of researchers developed a processing route that based on FDM technique to print layers of 3D ultra-high performance concrete (UHPC) [22]. The concrete mix was premix cement-based materials supplied by LafargeHolcim. The mix was designed to facilitate the printing process. The premix consists mainly of 30-40wt% of Ordinary Portland Cement (CEM I 52.5N), 40-50wt% of crystalline silica , 10wt% for each of silica fume and limestone filler. Low w/(C+S) ratio was used (water/(cement+sand) ratio= 0.1). In order to enhance the quality of the interfaces between the layers, a gripping polymeric resin was added to the mix. Another agents (accelerated and thresholding agent) were added to the mix to achieve the desired properties of the printed material; particularly rheology and a setting time of the material. The printed samples were cured for 90 days at ambient conditions. The prepared UHPC mix was printed layers by layers using 6-axis robotic arm which contains a special print head for extrusion purposes.

Examples of 3D printed large –scale structural walls which were achieved in their study are shown in Figure (5 left). One of these elements is Multifunctional walls (Figure 5 left). The shape of these walls consists of two parts which were connected via two straight plates to form waves of bi--sinusoidal shell. The printed 139 layers were deposited to form the multifunctional walls with dimensions of 1360 × 1500× 170 mm. The printing process took half day. Some of these walls were left hollow for further installations of pipes or electrical wires. Fiber-reinforced UHPC was used to fill the formwork or insulation material might be poured instead.

The other printed structural element was acoustic damping wall (Figure 5 right). The printed walls of 26 layers were constructed within 2 hours with dimensions of 650× 650× 300 mm. Depending on the properties of the material as well as the geometry of the wall cell, soundproof properties were improved within this shape which result in damping acoustic waves from passing through.

Figure 5: 3D printed large-scale structural elements with complex geometries [22]

After printing and curing processes, mechanical properties were conducted in flexural and compressive tests. These tests were carried out using prismatic samples with 40×40×160 mm in dimensions. These samples were obtained from 3D printed layers. The latter were cut to the required dimension and tested in accordance to ASTM C1161. It was concluded that the adoption of such 3D printing developed rout permits the production of complex structures with large-scale. The produced 3D printed walls were achieved via the use of tangential continuity method for slicing and it is possible to produce walls with various thicknesses.

6.4.3 Metal cables -Reinforced Concrete

An experimental investigation was carried out by group of researchers [23] to reinforce three-dimensional printed concrete beams with metal cables using reinforcement entrainment device (RED). The latter was developed by the authors in order to directly entrain the metal cables into the concrete during printing process. The concrete mix consist of Portland cement (CE, I 52.5R), siliceous aggregate (maximum aggregate size of 1 mm), limestone filler, specific additives, rheology modifiers and small amount of polypropylene fibres. Some concrete specimens were printed and others were conventional casted. Two sets of tests were carried out and these were pull-out and 4-point bending tests.

Three different types of cables (A, B and C) were used as reinforcement for cast and printed concrete beams.. These cables were high-strength steel Bekaert Syncrocord® with different diameters. These were (0.64, 0.94 and 1.21 mm) for cables (A, B and C) respectively. Various lengths (15, 25 and 35 mm) of these cables were embedded in the concrete samples. In terms of printed beams, the cables were entrained into the concrete filament during printing process to the bottom layer. It was concluded that the usage of the developed reinforcing technique (RED) for printed samples provides similar performance the traditional method for reinforcement for cast samples. High scatter in the results of bond strength was recorded for samples that reinforced with cables type B and C. However, better strength properties were observed for cables type A but not sufficiently strong to use in practical applications.

6.4.4 Fiber -Reinforced Concrete

An experimental study [24] was recorded to explore the drying shrinkage of 3D-printed fiber-reinforced concrete (3D-printed FRC). In their work, the obtained experimental results were compared with FIB model. The mix consists of normal strength cement (42.5R), fine sands with particle size of (2-5 mm), steel fibers (0.5% volume friction) and water. The water-to-binder ratio was 0.4. The FRC was 3D printed layer by layer to produce prismatic samples with dimensions of 200×80×80 mm. Another set of FRC cubic samples of 28 days curing were fabricated in traditional method (casting) with 200 x 200 x 200 mm in dimensions. Two sets of tests were conducted and these were compression test and drying shrinkage. Cylindrical samples with 200×80 mm in dimensions were drilled from the cubic samples. In terms of drying shrinkage, eight selected samples were placed in curing rooms (20°C and 90 –100% relative humidity) after 3 days of casting and printing. Polymeric binder was used to glue two surfaces of shrinkage samples with points set. A 150 mm was distanced between two points. These samples were moved to another curing room (20°C and relative humidity of 60%±2%). Measurements of the shrinkage were obtained for various periods (1,7,14,30 and 60 days). Higher porous structure was observed for 3D-printed FRC than casted FRC. The present cods needs to be revised in term of the values of drying shrinkages for 3D-printed FRC. It was also concluded that since the workability is influenced by the drying shrinkage cracks, the mix design of 3D-printed FRC needs to be optimized. A proposal of consecutive pore model was made in this study.

6.5 Printable Reinforcement

Various types of reinforcement (reinforced rebars, aligned reinforcements, and fibers) were 3D printed [25]. The 3d printing was conducted in order to study the arrangement, distribution as well as direction of such reinforcement when used in Fiber Reinforced Cementitious Composites (FRCCs) in order to overcome the problems that associated when using traditional reinforcement and fibers.A photopolymer was used in their study instead of other traditional materials such as metal, and PVA. Depending on the size of the printer, a specimen of interior dimensions of 220×50×50 mm was fabricated and prepared for reinforcing with various types of 3D printed reinforcement (Fig. 6).

For printing thick frames of rebas with stirrups and aligned-fiber models, an FDM printer with low resolution was used. This was not possible for randomly distributed fibers which required high resolution printer (PolyJet printer) was used. Layers of printed material were deposited from bottom to top. Further supporting structure were also printed to avoid the collapse of overhanging geometries whenever available. Regarding printing process, two methods were employed to generate two points. One of these methods was used to make sure the surface of the specimen is free from sticky fibers during printing, The other method was employed to support the previous method by distributing the fibers without the need for a boundary condition. After printing , cement mortar that prepared traditionally was poured. It was reported that further investigations are need to explore the effect of such 3D printed fibers on fracture behavior of FRCCs.

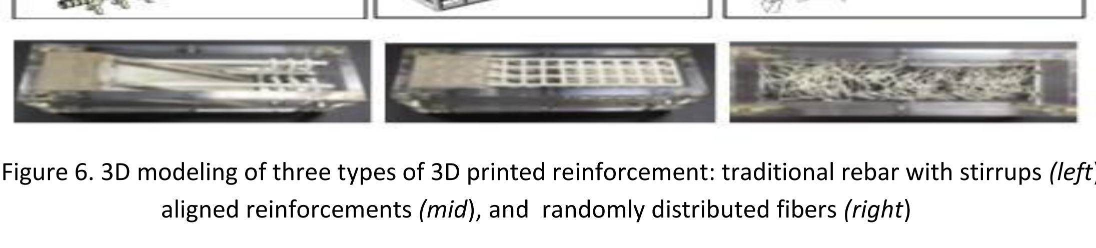

Figure 6. 3D modeling of three types of 3D printed reinforcement: traditional rebar with stirrups *(left*), aligned reinforcements *(mid*), and randomly distributed fibers *(right*)

7. 3D Printed Structures in Reality

Nowadays, many complex large-scale structures were constructed using 3D technology due to the advantages the associate the usage of such technology in terms of saving time required for construction and reduction in overall cost and wastes. Examples of such 3D printed structures which are available in service.

7.1 Residential House in Russia

An unusual designed single-story residential house (Fig.7) [26] was 3D printed located 60 miles south of Moscow, Russia [27]. The house of 37 m^2 was printed within 24 hours and the printing was carried out via he company Apis Cor with a total cost of 10,134 $ [28]. A concrete-based mixture was used as printing material. A mobile 3D printer (Figure 8) [29] was employed to print the whole house on-site. The printed structural elements are walls, partitions, and building envelope. As soon as the printing process is finished, a crane-manipulator was utilized to remove the printer. Following this process, a roof is then added. The roof was designed to resist heavy snowfalls [26]. A white decorative plaster was used for finishing the exterior part of the house following by the application of layer of paint. A combination of solid elements and liquid polyurethane were added on site as well to provide heating insulation. Since the printing process of the house at very low temperatures (-35°C) is associated with problems related to the concrete mixture itself (unprintable mixture u< 5°C), a tent was used to surround the house during printing to overcome the drawbacks of printing in such conditions [28].

Figure 7 .3D printed residential house in Russia [26]

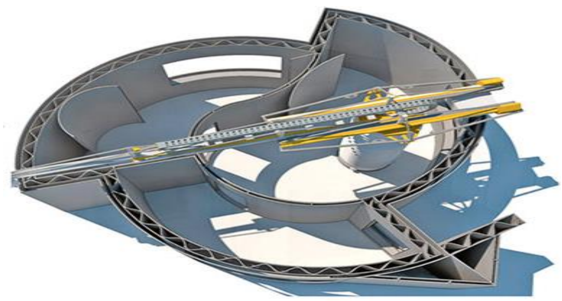

Figure.8: 3D printer used to construct residential house in Russia [29]

7.2 Apartment Building in China

A five-story apartment building (1100 m^2) (Fig. 9) was constructed in Suzhou Industrial Park, China using 3D technology [30]. The work was conducted via WinSun company which is one of the Shanghai-based construction firms [31]. The building is made of printed recycled mixture which consists construction waste materials such as glass fibers, concrete, sand [31,32] in addition to the use of hardened agent. This leads to reduction in waste of construction of about 30 and 60 % [33]. In terms of printing process, a giant printer with length of 40 m , width of 10 m and height of 6.6 m was used to print the building. The latter was printed into parts in the company facilities and then transported to the site to be assembly. Further installations such as steel reinforcements and insulations were carried out later in order to meet the requirements of standard buildings with a particular design [33]. The construction of such apartment building using 3D technology was found to be faster than the traditional method by 30%. Also 3D printing was recoded reduction of about 80% of the labour cost when compared with the traditional building method to construct such type of buildings [32].

Figure 9. 3D printed Five-story apartment in China [30]

7.3 Office in Dubai

The first 3D printed office in the world is constructed in Dubai (Fig. 10). This office of future have unique design to facilitate the work environment by making it more suitable and functional during the work time [34] .The 3D office was printed off-site in China by WinSun Global in only 408 hours and then the printed frames were cut in pieces to ship to Dubai to be assembly in only 48 hours. A giant printer with an automated robotic arm was used for 3D printing. The printer was with length of 36 m, width of 12 m and height of 6 m. The mixture that used for printing is made of special designed cement-based building materials which were brought from United Arab Emirates and United State. The total cost of the project was 140000$. As a comparison with the traditional building methods, the project shows around 80% cut of construction costs as well as 60% on waste. The labour costs of the project was also reduced by more than 50%. This reduction was achieved by using just one employee for monitoring the printer. The installation process of the constructed components required 7 employees.

Another ten of electricians and specialists were hired to support the engineering issues [35].

Figure 10. 3D printed Office in Dubai [35]

7.4 Villa in China

An exquisite 400 m^2 villa (Fig. 11) was 3D printed in Beijing, China in only one and half months via Shanghai-based company (WinSun). If such villa was constructed using traditional building method, then the project will need twice the time that needed when 3D printing technique is used. The printed house was designed to resist earthquakes. The printing process was carried out on-site using 20 tons of printed material which was C 30-grade concrete. Each printed wall of the villa was 250 mm in thickness. Prior to printing, frames of building, plumbing as well as rebar supports were installed by labours. A 3D sturdy construction was printed using a printer with special nozzle which was designed to split out the concrete on both sides (interior and exterior) of the rebar supports [36-39].

Figure 11. 3D printed Villa in China [36]

7.5 Concrete Bridge in Spain

The first 3D printed concrete bridge in the world was constructed in urban park of Castilla-La Mancha in Alcobendas, Spain (Fig. 12)[40]. The design of the bridge with length of 12 m and width of 1.75 m was carried out via Institute of Advanced Architecture of Catalonia (IAAC) in Spain. Eight different pieces that made of micro-refined concrete which reinforced with thermoplastic polypropylene were used to made the bridge. The 3D printing involves the usage of huge 3D printer to deposit layers of material [41,42].

Figure 12. 3D printed Concrete Bridge in Spain [40]

7.6 Hotel Suite in Philippines

A building of 2 bedrooms with a living room and Jacuzzi was 3D printed in Philippines [43,44]. The building was part of Lewis Grand Hotel in the Philippine. Fig. 13 illustrates the interior 3D printed hotel suite. The project was cooperation between the owner of the hotel (engineer Lewis Yakich) and the 3D printer designer (Andrey Rudenko). The hotel suite was 3D printed with dimensions of 12.5 × 10.5 × 3m. The printed mixture was made from local materials in Philippines. These materials were sand and volcanic ash. A 60% of building cost was reduced with 3D printing such building. The project was printed within 100 hours but the total time interval was longer than that due to various factors such as testing, assemble of 3D printer on site, installation of reinforcing bars, etc. These factors affected the 3D printing for the first project. Only few weeks was estimated for 3D printing another hotel suite.

Figure 13. 3D printed Hotel Suite in Philippines [44]

8. Conclusions

Three-dimensional technology is proven to be an effective building method to facilitate the construction of irregular shapes which meets the new requirements for design with less waste and cost. Initially, 3D printing (3DP) may replace partially the traditional building method until the challenges of using 3DP are omitted. Various techniques are available to be used for 3D printing depending on the different printing parameters such as printer type, details of the design and materials. The latter mix design should meet specific requirements to be ready for printing and these are extrudability, flowability, buildability, strength and open time. Some aspects still need to be explored for 3D printed structures such as structural analysis of the printed parts, improve the quality of the printed surfaces and develop hybrid system to facilitate the reinforcement.

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