PRELIMINARY REPORT ON THE AVAILABILITY OF MATERIALS FOR 3D PRINTING OF SUSTAINABLE HUMAN SETTLEMENTS

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1. Introduction

1.1 Background

For the past two decades, South Africa as a country have witnessed a steady increase in its population; incidental to this growth are challenges and problems beseeching for attention and solution. One of these challenges is the need to provide adequate and affordable housing and accommodation for its teeming population, despite the best efforts of the national, provincial and local level governments, as well as that of private, individuals and institutions, are yet to be fully solved. Some of the reasons associated with the latter are: the high cost of construction; and construction materials, which made it nearly impossible for the low and middle-income individuals, who constitute about 80% of the population, to afford their own housing and accommodation needs. Thus, it becomes imperative to evolve solution to the costliness of building and construction materials and possibly develop viable, cheaper, alternative materials and construction method to meet the goal of Fourth Industrial Revolution (4IR).

However, in order to solve the problem of cost and speed of construction, the use of three-dimensional (3D) printing additive technologies is believed to provide a cost-saving and fast method of construction. Hence, the Department of Science and Innovation of the Republic of South Africa through the University of Johannesburg has embarked on a pilot project to purchase the 3D printer for sustainable human settlements development.

In addition, it is well known that concrete/mortar is a composite and the most widely used material in the construction industry. Its primary constituents are cement, fine aggregate (sand), and water. However, the high cost of its constituents and environmental impact of its production have affected its availability for use. For example, Portland cement is obtained from cement clinker which is produced by heating powdered limestone and clay at temperature between $1400^{\circ}C$ and $1500^{\circ}C$. Furthermore, it has been reported that the production of 1 ton of cement is accompanied by the release of 1 ton of carbon dioxide into the atmosphere. Even the quarrying operation involved in the production of quarry dust is energy-intensive. In other words, the combination of high-embodied energy and overall environmental recklessness inherent in the production of concrete/mortar are important cases against sustainable development. Any measure aimed at reducing the embodied energy in concrete mitigates the harm to the environment and reduce the unit cost of concrete/mortar production. Such a measure is therefore sustainable and environmentally friendly alternative to cement and aggregates.

The highlighted problems with the use of traditional aggregates and Portland cement for concrete/mortar production have necessitated the research for alternative cost effective binding materials that could partially or wholly replace the traditional construction materials. However, the generation of huge quantities of construction and demolition (C&D), industrial, and agricultural wastes, is associated with the activities related to infrastructural development. Due to these huge quantities of waste, the disposal is one of the major problems all over the world. Hence, instead of using these wastes for landfill or burning, which may contribute to gas emission, the utilization of the same as a potential substitution of natural aggregate and cement is a sustainable option for 3D printing concrete production. This will not only convert waste to wealth, but also reduce its impact on the environment.

For this project therefore, it is envisaged that there is an abundance of different wastes that is available across South Africa particularly in Johannesburg for use as sustainable materials for 3D printing additive technology for human settlements. This document seeks to compile different mortar mixes as a partial replacement of cement in the development of new, durable, and low-cost self-compacting, recycled and geopolymer concrete/mortar, namely:

- Industrial wastes (i.e., sludge, blast furnace slag as a binder, recycled fine aggregate);
- Construction and demolition (C&D) wastes (i.e., ceramic tiles, recycled concrete aggregate, recycled mortar);
- Pozzolans from agricultural (i.e., Rice Husk Ash, POFA, Biogas fuel ash); and
- Other wastes (Fly Ash)

It is expected that the produced concrete/mortar from these waste will be cheaper and more sustainable alternative to conventional concrete. This is also expected to be environmentally responsible, sustainability-conscious and budget-responsive one.

1.2 Objectives

The objectives of this report are to:

- Identify materials used in 3DCP;
- Identify locally available 3DCP materials;
- Review of the costs of 3DCP materials; and
- Recommend the most appropriate material available for local 3DCP.

2. Methodology

2.1 Research Questions

The following questions were engaged for resolution:

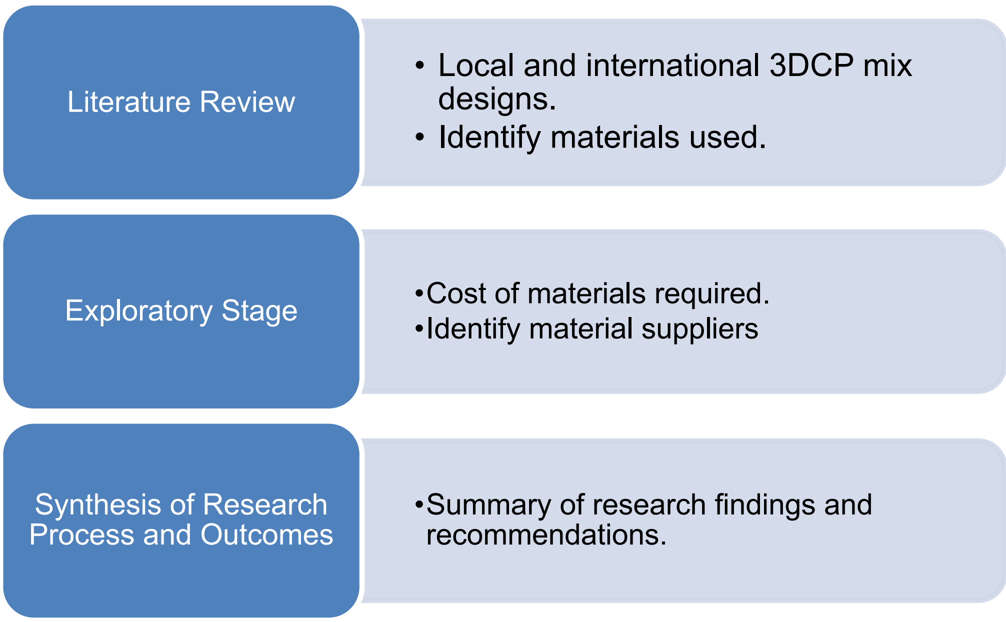
i) How and where can 3DCP material be sourced locally?

ii) Is the price of the identified 3DCP material financially viable?

iii) Where can 3DCP material be sourced?

The methodology was categorised into three stages as shown in Figure 2.1. The first stage was to critically review the literatures on available locally and international 3DCP mix designs. The second stage is to identify individual materials from the mix designs. In the third stage, cost of materials will be calculated, and suppliers identified. The final stage was to combine all the data, summarize and make recommendations.

Figure 2.1: Research Methodology



Source: Researcher's construct

2.2 Research Design

The report on the availability of the availability of materials for 3DCP used quantitative method to answer the research questions above. The following table summarises the methods used to answer each question:

Table 2.1: Methods used to answer research questions.

Research Question	Method Used to Answer Question
What are the mix designs used in 3DCP locally and intentionally?	This was done through critical literature review and Online search
Which materials are used for 3DCP?	This was done through critical literature review and Online search
What is the cost of 3DCP?	This was done by requesting quotations from suppliers and online search
Where can 3DCP material be sourced locally?	This was done by online search

2.3 Sample

The selection of materials and mix designs was based on literature review of published papers and information supplied by 3D concrete printer manufacturers.

2.4 Data Collection

The data was collected from published papers and various internet sources.

2.5 Data Analysis

The qualitative analysis was done by the application of the engineering judgement through prior knowledge/information.

2.6 Limitations

Report on the visitations to the suppliers was not included because of the travel restrictions as a result of the Coronavirus pandemic. Information on mix design by machine manufacturers is also very limited because they regard this as their intellectual property.

3. Results

This section will focus on the materials and mix designs that are currently being used for 3DCP applications.

3.1 High performance mix design by Le et al

The mix design has been one of the most commonly used designs for 3DCP and has broadly laid the foundation for 3DCP formulae as shown in Table 3.1 below (Le et al., 2012).

- 3:2 sand-binder (sand aggregate contains no particles larger than 2 mm).
- Binder: 70% cement, 20% fly ash and 10% silica fumes.
- 1.2 kg/m³ micro polypropylene fibres (12/0.18 mm in length/diameter).
- 0.26 water-cement (w/c) ratio.
- 1% polycarboxylate – based superplasticizer and 0.5% retarder (amin –tris, citric acid and formaldehyde).

Table 3.1:Composition of high-performance concrete(HPC) in weight %

Component	Composition (wt. %)
Sand	53.5
Cement CEM I 52,5 N	25.0
Class F Fly Ash	7.1
Silica Fume	3.6
Water	9.3
Polypropylene fibre	0.05
Superplasticizer	1.0
Retarder	0.5

Source: (Le et al., 2012)

3.2 Gantry system mix design

This mix design is viable but not limited for gantry-based systems. The mix below was developed by a 3D concrete printer manufacturer called COBOD that manufactures gantry based systems. Instead of a prepackaged material offering, they proposed a locally sourced material design shown in **Table 3.2**.

Table 3.2: Mix design developed by COBOD

Material	**Quantity (tons)**	**Percentage by weight**
Cement	6,12	32%
0-2 mm sand	3,5	18%
0-4 mm gravel	3,5	18%
0-4 mm recycled roofing tiles	4,36	23%
Water	1,66	9%
Glenium sky 631 - Superplasticizer	0,04	0%
Crackstop fibers	0,02	0%
Total	**19**	**100%**

Source: COBOD (2019)

3.3 Robotic arm mix design

This mix design is viable but not limited for Robotic arm systems. It appears that most robotic arm manufactures prefer pre-packed materials, this may be due to the fragility of the system. Below is an example of a pre-packaged mix design developed by Apis Cor. The prepackaged materials only require the addition of sand, Portland cement and water.

Table 3.3: Apis Cor's material cost per metric ton

MATERIAL	QUANTITY
Ordinary Portland Cement	300 kg
Dry Sand	630 kg
Apis Cor pre-blended additives	70 kg

Source: Apis-cor (2019)

3.4 Waste materials

Although there is limited research on the use of waste material for 3DCP applications, this section will focus on the possible use of waste material for 3DCP. The use of recycled material as a primary material in 3DCP could be game changing for the technology. This could drastically bring down the cost of materials used in 3DCP and make it very competitive in the industry.

3.4.1 Copper tailings waste

During the process of purifying of copper from the copper ores, there is solid waste material that is left behind; this waste material is referred to as copper tailing. The tailings are considered harmful to the ecological environment and are usually disposed. Copper tailing could be used in 3DCP and possibly reduce the cost of material (Ma, G. Li, Z. Wang, L 2018). Ma et al. (2018) conducted experiments that replaced sand in six proportions from 0% to 50% with waste copper tailings. The findings were evaluated using important 3DCP properties. Namely: extrudability, buildability, flowability, open time, fresh and hardened properties. The experiments showed that the optimum mix was when a substitution of 30% of copper tailing was used. This has displayed much higher mechanical properties and favourable buildabilty. The use of copper tailing could be used as waste material for 3DCP applications.

3.4.2 Recycled glass

Glass can cause bad adverse effects on the environment, and its disposal after usage has been a global issue. Research was conducted to assess the impact of recycled glass on 3DCP material as a substitution fine aggregate in the mix. Previous research has been conducted to analyse the use of recycled glass on concrete. Although concrete with recycled material displays better flow properties, it has been shown that recycled glass has lower mechanical properties compared to sand (Ting, G. Tay, T. Qian, Ye. Tan, M 2019). In the research, the river sand was replaced and compared against recycled glass. The design mix contained cement, fly ash, Silica fume, aggregate and water. The printing nozzle speed was 100 mm/s at a flow rate of 0.037 l/s and a layer printing height of 15mm.

Table 3.4: Mix design of both mixtures

Cement to binder ratio	Fly Ash to binder ratio	Silica fume to binder ratio	Aggregate to binder ratio	Water to binder ration
0.7	0.2	0.1	1.2	0.46

Source: Ting *et al, (2019)*

Previous research on 3DCP has shown that pumpability is related to dynamic yield strength and plastic viscosity. It also shows that the mix with recycled glass has a lower static inducing weaker, buildability. However, it is shown that the mechanical properties of the glass mix is lower than that of river sand. With results show, the replacement of sand with glass has not shown any helpful characteristics for 3DCP with the tests conducted.

3.4.3 Locally available materials in South Africa for use in 3D printing additive technology

This section deals with the survey of the locally available materials for use in 3D printing additive technology for sustainable human settlements in South Africa. Figure 1 shows some of the available local materials in South Africa. Majorly, wastes can be classified into three, namely construction and demolition (C&D), industrial and agricultural. Figure 2 provides the likely process involves in the use of waste for 3D printing.

It is well known that cement industry is a significant generator of greenhouse gas emissions (Kajaste and Hurne, 2015; Mikulčić et al. 2016; Cai et al. 2015). Since cement is the most polluting ingredient of concrete/mortar, its use is commonly reduced through partial replacement by industrial by products such as fly ash, blast furnace slag, and silica fume (Lothenbach et al. 2011; Snellings et al. 2012; Juenger and Siddique, 2015). However, the amount of these industrial by products is expected to reduce in the future due to, e.g., the closing of coal power plants. Furthermore, these materials are not available everywhere. Developing countries, need to rely on different sources of "green" pozzolanic materials. It is known that processed/incinerated waste can be used as a partial replacement of cement, if its composition contains sufficient quantities and ratio of CaO and SiO_2 (Carr 2019).

Research has shown that certain wastes available in developing countries such as South Africa, possess such properties. Therefore, this review provides state of art literature on the use of different agricultural solid waste such as palm oil fuel ash (POFA), rice husk ash (RHA), sugarcane bagasse ash (SCBA), and bamboo leaf ash (BLA) in concrete production. It provides a systematic evaluation of the properties of selected agricultural wastes with regards to their intended use as cement replacement or aggregate replacement and general production processes to make them ideal for use and some challenges towards promotion of their use in concrete production. It also provides possible solutions that can be implemented after further studies/research is undertaken. The information provided in this paper should help researchers to widen their perspective about the suitability of various agricultural wastes and their influence in the production of a sustainable and greener concrete. It also highlights the research gaps with regards to the promotion of agricultural wastes in concrete production for future studies.

It should be noted that agricultural wastes can successfully be used in combination with binders other than ordinary Portland cement, such as lime and MgO cement. For example, Stevulova et al. (2018) developed a biocomposite comprising 40% hemp hurds, 29% MgO cement, and 31% water. Other examples include using rice husk ash and flax for creating biocomposites in combination with inorganic matrices (Son et al. 2017; Brzyski et al. 2017). This is a promising field of research, but is outside the scope of the current review.

This research will assess the possibility of using 100% industrial solid waste such as laterite, FGD gypsum, Aluminum slag and carbide slag for the production of high performance cementitious materials.

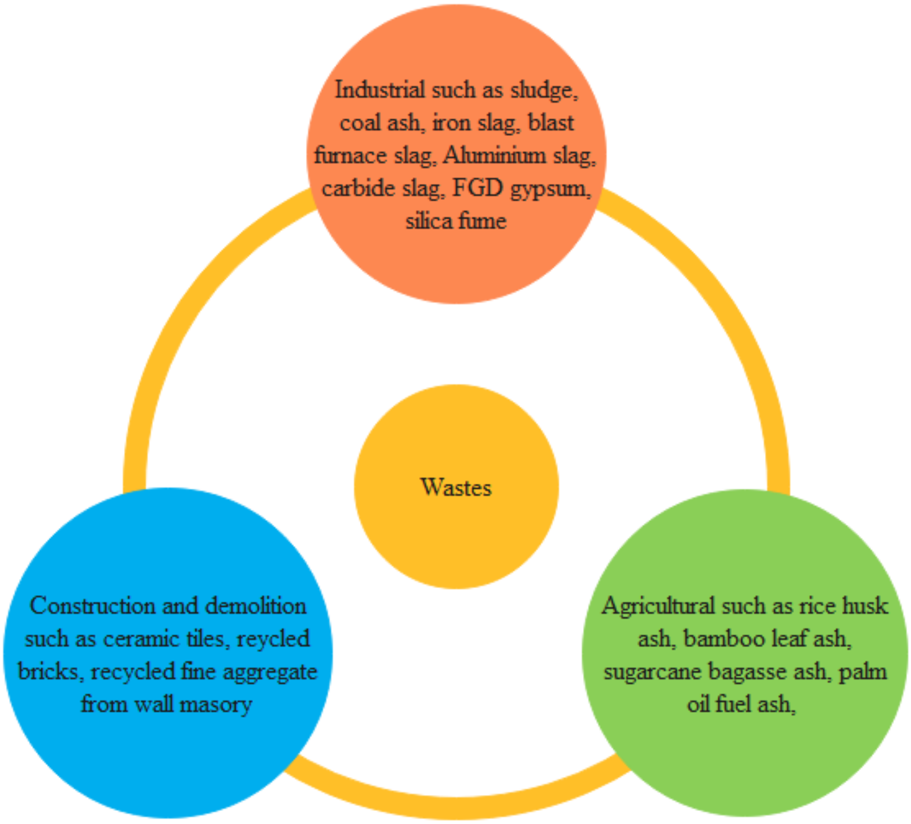


Figure 3.1: Some of the identified local materials in South Africa

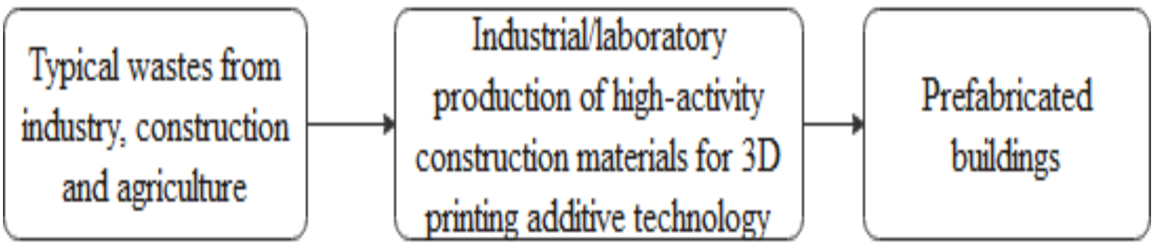


Figure 3.2: Typical process of using waste materials for 3D printing.

Some proposed mixes

Oil Sludge and Construction and Demolition Waste

From a nearby location, oil sludge is collected, dried to extract moisture, and then sieved to achieve a standardized particle size. In the laboratory, the consistency of the oil sludge will be checked and analyzed to achieve the number of pollutants initially available. To assess the metals found in the oil sludge, an atomic absorption spectrophotometer will be used. Then the oil sludge together with recycled aggregates which will be derived from construction and demolition waste (C&D) mixed with cement and water to get concrete.

Table 3.5: Mix for recycling oil sludge and C&D waste into building materials

Concrete	Aggregate	Cement
Conventional Concrete	Fine sand	Cement
Concrete from oil sludge and C&D materials	Oil Sludge	Cement

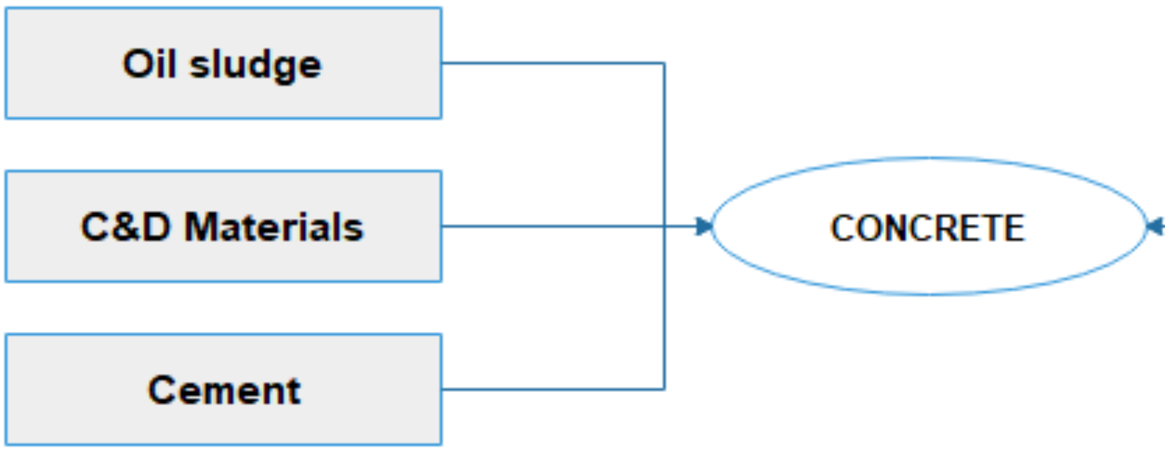


Figure 3.3: Recycling processes of oil sludge and C&D waste into building materials

Table 3.6: Mix group

	MIXING	MATERIAL CONSTITUENTS
1.	**MIX A**	Cement (1) + Fine sand (2)
2.	**MIX B**	Cement (1) + Oil Sludge Sand (2) + C&D (3) {as replacement for C&D from 0% to 100%}
3.	**MIX C**	Cement (1) + Fine sand (2) + Sludge (4) {as replacement for sludge from 0% to 100%}

The recycling process as shown in Figure 3 will be carried out using oil sludge and C&D waste as the main aggregates to replace sand. The recycled aggregates are mixed with water and cement. Conventional block production processes such as material batching, mixing, compaction, and, curing will have applied. The different mixing ratio used in the material rationing will be adopted. After mixing, the handle manual compaction will be applied to mould the cubes with sizes of 150 x 150 x 150 mm^3. The cubes produced will be cured for 3, 7, 14, 21, 28, 56, 90 days submersed in water. After which the cubes were taken to the Laboratory at the University to determine their compressive strength, density and water absorption ratio. Other test to be carried out on the concrete will be Slump test before leaving the batching plant, water permeability test, rapid chloride ion penetration test, initial surface absorption test and microstructural. This test will be carried out according to standard method as prescribed in British, Euro and South Africa standards. The Laboratory testing and analysis will be carried out according to standard methods as presented in Research Method Section.

4. Summary of Findings and Discussion

The table below summarizes the materials required for the design mixes. The costs and local suppliers are also included.

Table 4.1: Summary of results of obtained.

ITEM NO.	MATERIAL	SUPPLIER	COST
1.	Cement OPC 52.5 N	Builders Warehouse **Nationwide**	R 100 – R 150
2.	Fly Ash	MAPEI Chemical Products for construction **Johannesburg**	R 2 per kg
3.	Silica Fume	MAPEI Chemical Products for construction **Johannesburg**	R 5 per kg
4.	Sand/Gravel	Builders Warehouse **Nationwide**	R 500 per 1000kg
5.	Superplasticizer - Glenium	MAPEI Chemical Products for construction **Johannesburg**	R 38.78 per liter
6.	Retarder	MAPEI Chemical Products for construction **Johannesburg**	R 12.89 per liter
7.	Polypropylene Fibre	MAPEI Chemical Products for construction **Johannesburg**	R 789.98 per 6 kg

8.	Crackstop (Microfiber) Fiber	MAPEI Chemical Products for construction **Johannesburg**	R 62.00 per 600g
9.	Apis Cor Pre-blended additive mix	APIS COR **Unavailable locally**	R 2 200 per 70 kg

5. Conclusion and Recommendations

Based on **table 4.1** there are primarily nine materials required for 3DCP. Namely, Cement OPC 52,5N, Fly Ash, Silica Fume, Sand/Gravel, Superplasticizer, Retarder Polypropylene fiber, Crackstop fiber and Pre-blended additives mix.

These materials are fortunately readily available in South Africa. The suppliers identified locally are Builders Warehouse who have a national distribution footprint and Mapei chemical products for constructions who are based in Johannesburg. The only materials that are not available locally are the pre-blended additive mix from Apis Cor. This will only be an option if an Apis Cor robotic arm printer is procured. In conclusion, materials for 3DCP are available locally for 3DCP applications.

6. References

Addis, B. (1994). Portland cement and cement extenders. *Fulton's Concrete Technology,Midrand, South Africa.*, 2–7.

Addis, B. (2009). Concrete mix proportioning and Fundamentals of concrete. *By Cement and Concrete Institute. Midrand, South Africa*.

Airey, J, Nicholls, S, Taleb , H, Thorley (2012). Design Project Mega scale 3D Printing. *Masters*.

Apis-cor. (2019). *3D Printed Homes | Apis Cor | United States*. https://www.apis-cor.com/

Banfill, P. F. G. (2003). The rheology of fresh cement and concrete-A review. *11th International Cement Chemistry Congress*.

Blezard, R. G. (1981). Technical aspects of Victorian cement. *Chemistry and Industry*.

Bye, G. C. (2011). Portland Cement. *The French Institute of Science and Technology for Transport, Development and Networks*.

Chiesi, C W, Myers, D F & Gartner, E. M. (1992). Relationship Between Clinker Properties and Strength Development in the Presence of Additives. *Fourteenth International Conference on Cement Microscopy*.

Cobod. (n.d.). *BOD2 - Modular 3D Construction Printer available now*. Retrieved April 19, 2020, from https://cobod.com/bod2/

Feng, X & Clark, B. (2011). Evaluation of the Physical and Chemical Properties of Fly Ash Products for Use in Portland Cement Concrete. *World of Coal Ash Conference*.

Ferron, R P, Greogori, A, Sun, Z & Shah, S. P. (2007). Rheological method to evaluate structural buildup in self-consolidating concrete cement pastes. *ACI Mater J 104:242–250*.

Forrester, J. A. (1970). A Conduction Calorimeter for the Study of Cement hydration. *Cement Tech*, *1*, 95.

Gelardi, G. & F. R. J. (2016). Working mechanisms of water reducers and superplasticizers. *Sci. Technol. Concr. Admix*.

Gosselin, C., Duballet, R., Roux, P., Gaudillière, N., Dirrenberger, J., & Morel, P. (2016). Large-scale 3D printing of ultra-high performance concrete - a new processing route for architects and builders. *Materials and Design*, *100*, 102–109. https://doi.org/10.1016/j.matdes.2016.03.097

Gopalan, M. (1996). Sorptivity of fly ash concrete. *Cement and Concrete Research*.

Greszczyk, S. & K. L. (1991). The Influence of Chemical Composition of Cement on the Rheological Properties. *Rheology of Fresh Cement and Concrete*.

Güneyisi, M & Gesoğlu, Z. (2004). Eco-efficient concrete: Performance of self-compacting concrete (SCC) with high volume supplementary. *Cementitious Materials (SCMs)*.

Kellerman, J & Crosswell, S. (2009). Properties of fresh concrete. *Fulton's Concrete Technology, Cement and Concrete Institute Midrand, South Africa*.

Khan, M I & Siddique, R. (2011). Utilization of Silica Fume concrete. *Review of Durability Properties.*, *57*.

Khayat, K H, Omran, A F, Naiji, S, B. P. & Y. A. (2012). Field oriented test methods to evaluate structural build up at rest of the flowable mortar and concrete. *Materials and Structures*.

Khoshnevis, B. (2004). Automated construction by contour crafting - Related robotics and information technologies. *Automation in Construction*, *13*(1), 5–19. https://doi.org/10.1016/j.autcon.2003.08.012

Le, T. T., Austin, S. A., Lim, S., Buswell, R. A., Law, R., Gibb, A. G. F., & Thorpe, T. (2012). Hardened properties of high-performance printing concrete. *Cement and Concrete Research*, *42*(3), 558–566. https://doi.org/10.1016/j.cemconres.2011.12.003

Le, T T, A. S. A. & L. S. (2012). Mix design and fresh properties for high-performance printing concrete. *Materials and Structures*.

Longarini, N, Creapi, P, Zucca, M , Giodano, N. &Silvestro. (2014). The advantages of Fly Ash use in Concrete Structures. *Journal of the Polish Mineral Engineering Society*, p 141.

Msinjili, N. S. (2012). Use of innovative technology in cement production for Africa's available resources. *18th International Conference on Building Materials*.

Paul, S, Van Zijl, G, Tan Ming, G. I. (2018). A review of 3D concrete printing systems and materials properties:Current status and future research prospects. *Emerald Publishing Limited*.

Perrie, B. (2009). Strength of hardened concrete. *Cement and Concrete Institute*.

Perrot, A, Lecompte, T, Estelle, P & Amziane, S. (2013). Structural build-up of rigid fiber reinforced cement-based materials. *Material Structure*.

Price, H. W. (1951). Factors influencing concrete strength. *Journal of American Concrete Institute*.

Rao, A. (2003). Investigation on the performance of Silica – fume – incorporated cement pastes and mortars. *Cement and Concrete Research*.