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A Study in Buildability Aspect Caused by Different Shape and Geometry of a Nozzle in Printing of Abrasive Materials

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Abstract: The 3D printing technologies is an eco-friendly variant and much easier, giving wider build customizability when compared to the traditional method, this paper focused on the buildability aspect that affected by the nozzles. The main objectives are to find the best nozzle size and geometry to print clay and a good buildability. Six types of nozzles will be used, three of them are in circular shape while the others are in rectangular shape and having different diameter. The study is using a clay admixture that are kept constants for all the testing and experiment, which are 600 gram of clay and 60 millilitres of water. From the observed data, rectangular shape nozzle gave the outcome and results. 3 mm nozzle with rectangular shape can 3D print clay up to 8 layers without collapse or bend on the contour. However, buildability can be affected on other aspects, such as printing speed, parameter setting, extrusion speed and the mixing design. For future work, aspect like mention earlier can be explored to achieve a good buildability.

Keywords: Buildability, Nozzle, Geometry, 3D-Printing

1. Introduction

3D printing is a new technology which consists of generating three dimensional solid objects from a digital file (Keep, 2020). The 3D printing process can be carried out using different technologies available on the market which are based on their own physical principles. Additive manufacturing (AM) is considered as one of the most well-known 3D processing method. In an additive process, an object is generated by laying down successive material coatings until the entire object is created. Each layer can be seen as a thinly sliced horizontal cross section of the ended object.

Nowadays, manufacturing market needs to be flexible and able to adapt to new available technologies in order to remain competitive. Talking about that, 3D printing has much to say at this point because flexibility and customization ability are two essential characteristics which can define

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this technology. 3D printing has slowly been adapting in new industry such as pottery, construction, and automotive. The uses of 3D printing in construction can reduce the cost of formwork as well in pottery making, it can reduce the labor cost as it fully automated.

There are few steps that must be fulfilled before it being printed. 3D printing's process is developed following three consecutive steps (Gilabert et al., 2016), as it is shown in figure 1:

1. Digital file's generation (designed or scanned)

2. File's conversion into a layered design in order to be printed as additive manufacturing

3. 3D printing application

As a final step, a post-processing can be carried out on the printed designs in order to give them the required characteristics requested by the customer.

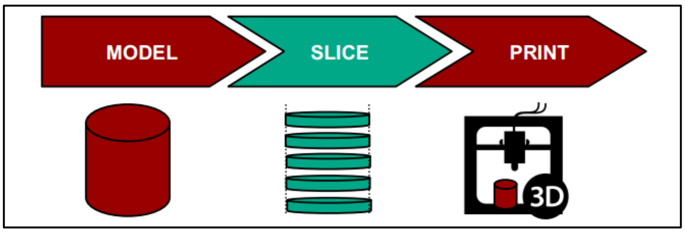

Figure 1: 3D Printing processes diagram (Gilabert et al., 2016)

With 3D printing, fewer parts need outsourcing for manufacturing. This equals less environmental impact because fewer things are being shipped across the globe and there is no need to operate and maintain an energy-consuming factory (MakerBot, 2021). In order to print the material to the desired model or shape, the person needs to understand the anatomy of the machine itself, which has relationship among the components. To obtain a good printing, the nozzle are the most crucial components that needs to be focused. Buildability is the aspect that crucial in 3D printing. Buildability of 3D print is the ability of the printed layers to sustain the dead loads due to self-weight of that layer and weight of subsequent layers. Buildability is considered in terms of both geometrical and material properties. The simplest measure of buildability is taken as deformation of lower layers (Bhattacherjee & Santhanam, 2020). To maximize buildability is by increasing the number of neighboring filament layers. Le at al 2012 describe that the influences of nozzle shape that affecting buildability in Figure 2 below.

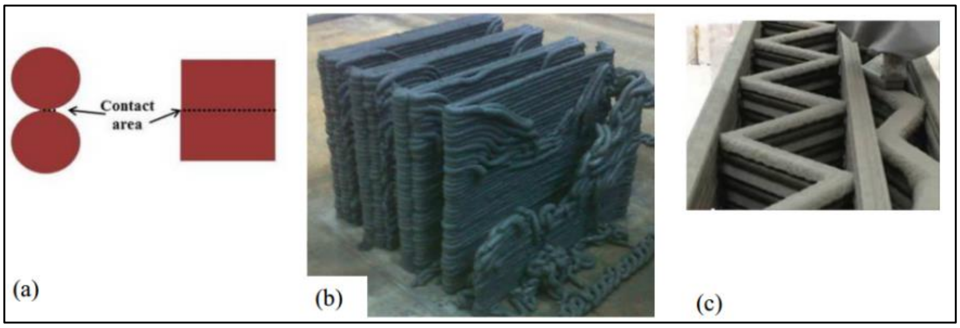

Figure 2: Nozzle geometry that influences buildability (Le et al., 2012)

1.1 Components

In a 3D printer, especially in clay printer or concrete printer, there are components that help to extrude and print the material such as, tank, pump, print-head and nozzle (Ji et al., 2019). Figure 3 shows the pump that push the material from the tank to the print-head. While Figure 4 describe the print-head that work as an optional component and Figure 5 shows the process of clay printing using direct nozzles.

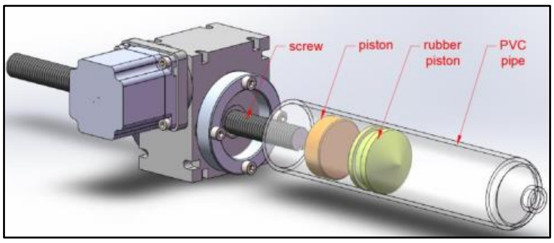

Figure 3: Piston pump

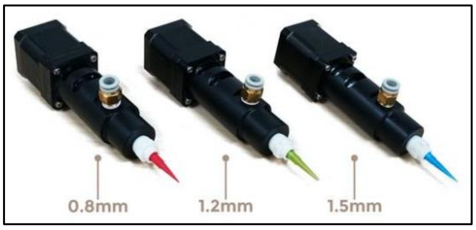

Figure 4: Print-head

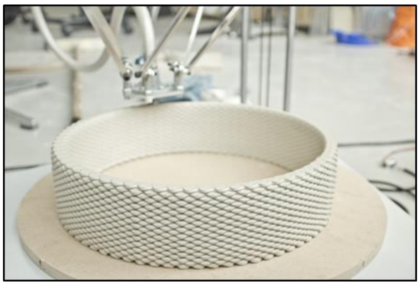

Figure 5: Clay printing

The nozzle is the part which is responsible for the flow of material at the desired size. Its design should aid in the process of achieving constant flow velocity at the outlet and there should be enough pressure build-up in the nozzle region to have continuous extrusion.

The most important aspect in printing of cementitious or clay material is the buildability and extrudability. The buildability and extrudability usually influences by the nozzle size and shape as well the materials. (Le et al., 2012) stated that, the buildability of fresh concrete was quantifying as the number of layers which could be built up, based on the shape used to evaluate the extrudability, without noticeable deformation of lower layers.

Illustration of good extrudability (Nerella & Mechtcherine, 2019) is often defined as a compound property which accounts not only for the ability of a material to pass through an orifice but also its shape stability (the ability of the material to retain its shape after the extrusion (Duty et al., 2018).

1.2 Nozzle

The nozzle size changes with the scale of the print. The nozzle size will also determine the amount of detail that can be obtained. A corner or edge can only be as sharp as the diameter of the clay extrusion (guide clay). In the 3D printing process, nozzle selection is crucial since a proper nozzle geometry can reduce the surface unevenness and the stair-casing effects.

The nozzle shape determines the shape of the filament, which further affects the contour of the construct (Karthick, 2020) uses larger nozzles and high pressure to extrude the concrete paste. In order to have a smooth finish instead of a layer-by-layer appearance, a trowel like apparatus has been designed that is attached to the print-head. Figure 6 show the standard size and shape nozzle.

Figure 6: Standard nozzle for clay printing

These nozzles are produced by Cerambot, this set contains four diameter needles, one for each aperture. Pink: 0.6mm. Gray: 1.2mm. Light green: 1.6mm. Light blue: 2.2mm. However, the nozzle has been modified to the maximum diameter, which is 5mm, as shown in Figure 7. Not only the size that contribute a great deal to the printing quality, but the shape also plays a big role in printability and buildability.

The nozzle diameter is directly related to the properties of the mix, precisely the mixture flowability. In short, as the diameter of the nozzle reduces, it is important to improve the flowability of the mix to accommodate for it, and vice versa (Malaeb et al., 2019). An analysis by Kwon showed that compared to an ellipse orifice, the surface finish produced with a square orifice is finer (Kwon, 2002). The ease of production is also stated to be greater with a square orifice than with an elliptic orifice (Anell, 2015)

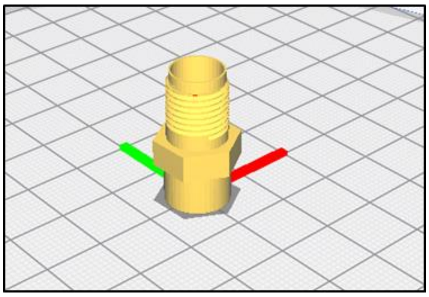

Figure 7: Modified nozzles

2. Materials and Methods

In this subtopic, materials that will be used and the method or procedure will be discussed thoroughly.

2.1 Clay

This study will be focusing on printing clay material. The parameter setting that being set will used as a reference or preliminary result for concrete printing. In this research, Ball Clay and Kaolin is used.

Recent works (Kuder & Shah, 2006; Voigt et al., 2006) show that use of clays sharply increases the shape stability and extrudability of the pastes at an early age and can substitute for cohesive and viscosity modifying admixtures (Chen et al., 2019).

This study will be fix and keep constant the mixing proportion of the Ball Clay and Kaolin. The mixture will be tested with different parameter setting nozzles size. Table 1 below describe the mixing proportions for printing the clay mixtures.

Table 1: The mixing proportion of Clay

Item	Materials	Amounts(grams)
1	Kaolin	300
2	Ball Clay	300
3	Water	60
4	Additive Substances	none

The materials being mixed manually for 10 minutes or until all the material mix homogenously. To avoid clogging the nozzle, the initial water content added to the mix was high to ensure extrudability (Malaeb et al., 2019). In this research all the material will be dry mix for 3 minutes and then slowly added to the materials and the mixing process was continued for further 10 min to obtain a consistent mixture. This method was suggested by (Bong et al., 2020) to obtain a homogenous mixture. By doing as suggested, the mixture will be mix completely and avoid any lump while adding the water.

2.2 Nozzle

To ease the extrusion process, the paste will be first pumped by a piston before it reached to the nozzle. Figure 7 shows the piston pump and the print-head attached with nozzles.

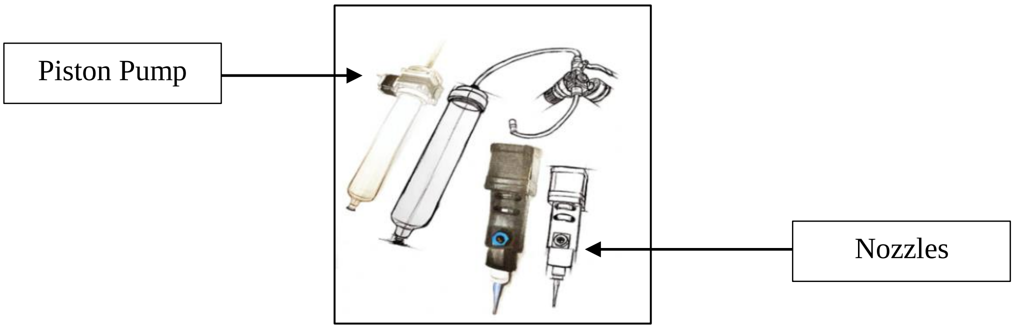

Figure 8: Piston pump with print-head that have auger screw

The end of the nozzle will be having few sizes, shapes and designs. As it will influence the printing quality. For instance, in case of a circular nozzle orifice the contact area between the two beads is less compared to a rectangular or square orifice (Paul et al., 2018).

(Jayathilakage et al., 2020) has conducted few trials using a 30 mm and 20 mm circular nozzles for printing and the layer height was kept as 10 mm in each case. Three trials were conducted for each nozzle size to achieve an average failure height. A printing speed of 2244 mm/min was used, which gives a 0.42 min time gap between two consecutive layers.

However, due to some limitation on the machine itself, this study will be printing at the speed of 15 mm/s. While the diameter of the nozzle will be having two designs, which is circular and square where the size varies from 4mm to 6mm.

Different parameter setting such nozzle size, layer height and line width will be printing the same design, so that it can indicates the variable that affect the most on the printing quality. Different size and shape of the nozzle will influence the layer height as well the line width.

2.3 Parameter Settings

The parameter setting of each experiment includes the nozzle size, layer height, line width, speed and clay to water ratio. However, some of the variables are kept to constant which is speed and the clay to water ratio. Table 2 shows the parameter setting for circular shape nozzles while Table 3 for rectangular shape nozzles.

Table 2: Parameter setting for circular shape nozzles

Nozzle Size (mm)	Layer Height (mm)	Line Width (mm)	Speed (mm/s)	Clay(gram): Water(gram)
3	2	2.5	25	600:60
4	3	3.5	25	600:60
5	4	4.5	25	600:60

Table 3: Parameter setting for rectangular shape nozzles

Nozzle Size (mm)	Layer Height (mm)	Line Width (mm)	Speed (mm/s)	Clay(gram): Water(gram)
3	2	2.5	25	600:60
4	3	3.5	25	600:60
5	4	4.5	25	600:60

3. Results and Discussion

In this sub-topic, few results have been obtained as a preliminary results or data. The data obtained, will further discuss as a benchmark and apply to the Cerambot printer in order to prints other materials such as concrete. All the test was printed the same design with different nozzle shape and geometry. The maximum layer that will evaluate are 5 layers and it will consider having a good buildability.

3.1 Circular Nozzle

Throughout the whole study, numerous designs have been printed in order to optimize the different variables affecting to the printing process. Some of the printed designs are shown below in Figure 8, Figure 9 and Figure 10.

Figure 9: Printed model using 3mm (circular and rectangular nozzles)

Figure 10: Printed model using 4mm (circular and rectangular nozzles)

Figure 11: Printed model using 5mm (circular and rectangular nozzles)

The parameter setting for each nozzle size has been stated as in Table 2. The printed model was printed using two different nozzles shape. Figure 11 shows the nozzle that being used in this study which circular and rectangular that varies in diameter from 3mm to 5mm.

Figure 12: Circular and rectangular shape nozzle

Observation was made on the buildability aspect as the material being deposited in layering manner. From the all the figures above, it is clearly demonstrating that nozzle give a significant impact on the buildability aspects. Critical element that has a high impact on the extruded paste properties is the nozzle. The nozzle diameter has a significant connection with the paste mix properties, specifically its flowability (Malaeb et al., 2015).

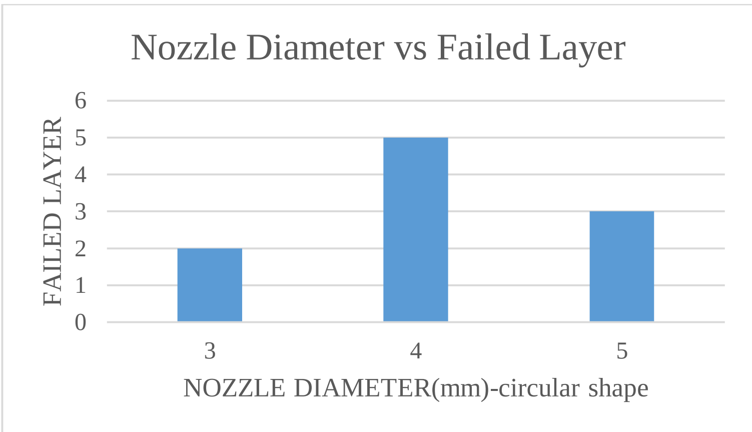

Figure 13: Buildability for circular shape nozzle

The buildability aspect was assessed by using the three different nozzles with different diameter but same in geometry. The mixture for each test were kept at constant which are 600 grams(g) of clay and 60 millilitres(ml) of water. As shown in Figure 12 circular nozzle with diameter of 3 mm start to failed at the second layer, while circular nozzle with 5 mm diameter failed at the third layer. Circular nozzle with 4 mm diameter completed the print without having any problem. This result may influence by the nozzle diameter as for the smallest nozzle have less contact surface while the largest diameter resulting the bottom layer cannot withstand it weight start to be failed.

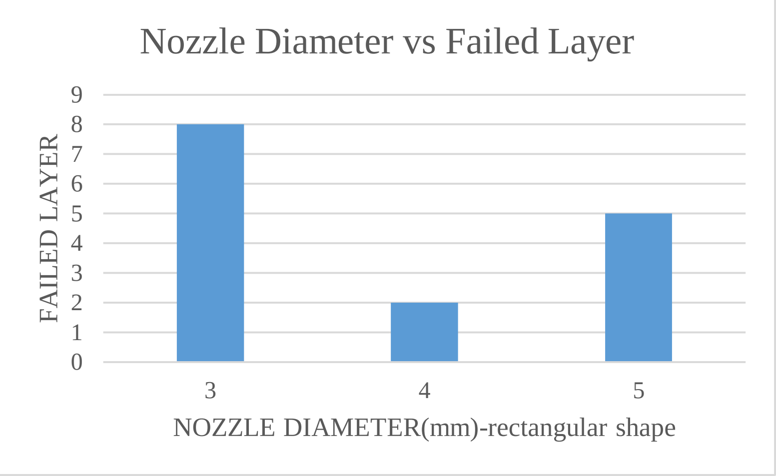

Figure 14: Buildability for rectangular shape nozzle

Figure 13 show the result obtained for rectangular shape nozzles. As mentioned earlier the mixture of the clay are kept at constant through the experiments. For the rectangular nozzles, the diameter of the nozzle are 3 mm, 4 mm and 5 mm. From Figure 13, the most success printing was obtaining through the 3 mm rectangular nozzle. The printing process was a success as it can go up to 8 layers without having deformation on the lower layer. Nozzle with 4 mm diameter failed at the second layer, while nozzle with 5 mm diameter failed at the fifth layers.

The buildability can be influence by many factors, such the nozzle, printing speed, extrusion speed and the mixing design. However, this study is focusing on the nozzle aspects, because according to Le et al, nozzle geometry and size gave a significant effect on the buildability of the printed models. As the data obtained, it is clearly shows, square nozzle will give a good buildability compared to circular nozzles.

4. Conclusion

To summarize the research, fresh clay mixtures were 3D printed and their flow properties were characterized with few types of nozzles that having different in diameter and geometry. The proportions of the admixtures in the clay are kept constant through-out the research.

In this nozzles study, the importance of the nozzle geometry has been identified which is the main reason why this research being conducted. The nozzle shape determines the shape of the filament, which further affects the contour of the construct. In the 3D printing process, nozzle selection is crucial since a proper nozzle geometry can reduce the surface unevenness and the stair-casing effects.

In comparison between the two types of nozzle geometry or shape, rectangular nozzle with 3 mm diameter gives the best result as it can 3Dprint up to 8 layers without any deformation and difficulties.

In the research work, for cylindrical constructs circular nozzle created twists in the layers and the square nozzle created even contour. Future work for this study will focus on shape fidelity and strength of the printed constructs with various print speed, nozzle geometries, and other additives such as plasticiser, fibre and cements.

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