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Effect of printing parameters in 3D concrete printing: printing region and support structures

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Abstract

3D concrete printing can be used to build many complex structures. However, due to its material properties in the fresh state, it is difficult to construct overhanging structures without supports. In order to unleash the true capability of 3D concrete printing, a support structure is required to support any overhanging fresh material, which is usually removed during post-processing. This study demonstrates the feasibility of adjusting the printing parameters to print the main structure and support structure using a single type of building material. It was found that the solidity ratio, which is defined as the ratio between actual and expected filament sizes, was significantly affected by the nozzle travel speed and material volume flow rate. Furthermore, a gap distance characterisation test was carried out to find the maximum distance that the filament can cross over without a significant slump. The results were combined to determine the different printable regions for different operations. An overhang structure was printed to verify the results obtained for the different printing operations. This technique allows complex structure to be built without the need for human intervention throughout the printing process.

Keywords: Printing parameters, 3D printing, support structure, cementitious material

1. Introduction

Formwork has been extensively used in the building and construction industry. It is a labour-intensive process and most of the time complex designs are limited by the formwork. Hanna (1998) presented a breakdown of different cost categories for conventional concrete slab and wall formwork. It accounts for 40 to 60 percent of the cost of the concrete frame and approximately 10 percent of the total

building cost. This portion of the cost is related to the formwork labour cost. To reduce the cost of formwork, walls with simple design are preferred. Tay *et al.* (2017) reviewed the use of 3D printing to construct complex architectural design and reveals that 3D printing offer advantages such as reduction in time and labour involvement. These advantages, which translate to cost-saving, compel the exploration of using 3D printing in construction to increase architecture complexity.

3D concrete printing does not require formwork and thus the emphasis on the material behaviour and properties such as self-compacting, no-slump and pumpable capabilities are more prominent. Roussel (2018) discussed the fresh property requirement of 3D printable cementitious materials and confirmed that the rheological behavior requirements such as buildability and pumpability are contradicting which is a challenge for mix design engineer to get rid of the formwork. Although printing complex structure was demonstrated by Le *et al.* (2012), a major hurdle persisted for this application is to construct overhanging structures. Unlike the other popular B&C powder-bed fusion techniques which uses un-used powder to create the support required for overhanging structures as reported by Feng *et al.* (2015), a temporary physical surface to support the overhanging filament is required for extrusion-based printing which would otherwise be hanging over empty space.

For extrusion-based 3D concrete printing, some popular techniques that were used to accommodate for overhanging structures include support-less closed structure design and using supporting wood planks, as shown in Figure 1. Rudenko (2014) printed a closed structure design shown in Figure 1(a) has a maximum slope that can be printed without the structure collapsing. The maximum slope angle of the design is material-dependent. Even though using self-supporting design to support overhanging layer is a clever idea, it is limited by the slope angle. More recently, a house printed on-site by Arup (Carra *et al.*, 2018) with a portable robot to showcases the role of 3D printing can play in reducing construction waste, by minimizing inefficiencies during the building process. Wooden planks and scaffoldings were used to support the overhanging material as shown in Figure 1(b). Although the existing support technique as shown in Figure 1 is able to mitigate the overhang problem, human intervention and design constraint are still issues that need to be solved.

Figure 1: Different techniques used for printing overhangs. (a) support-less closed structure design to support subsequent overhanging layer (Rudenko, 2014) (b) wood planks with supporting scaffolding (Carra *et al.*, 2018)

To overcome the freeform issue, a method varying the printing parameters to produce support material is proposed. This technique can effectively build structures with overhanging components. In this paper, the gaps between the supports were exploited to determine the maximum distance of the bottom layer without the subsequent bridging layer slumping. By varying the flow rate and travel speed, it is possible to obtain the optimum range for the main structure and the support structure.

In section 2, other techniques to construct supports for overhanging structure used in additive manufacturing are discussed. Section 3 presents the methodology of the technique proposed in this study and the results in section 4 will be examined. Lastly, the discussion and conclusion in section 5 and 6 will review the advantages, limitation and recommend some future work for this proposed technique.

2. Related works

In this section, the existing technique that is used to print the overhanging structure for the extrusion-based technique are examined and classified into three main categories. In order to 3D print overhanging structures without changing part orientation, fabrication of support underneath is inevitable.

These sacrificial materials enable the overhanging segment to be integrated with the main structure instead of connecting modular parts.

2.1 Printing over existing surface

To print over an existing surface, the nozzle must follow the contour of the surface after they are mapped out prior printing. In most cases, this support is placed manually. Figure 2 shows a structure printed with an overhanging design. A support structure is erected to hold the subsequent layers as shown in Figure 2(a). Printing over a flat existing surface, such as a re-useable plank can be a cheap solution. However, since 3D printing can be used to print more complex structure, which may not necessary be a flat surface, this existing surface support need to be tailored according to the design. The tailoring of the complex surface support is time consuming and the labour intensive. Furthermore, the placement of support is disruptive to the printing process. This disruption can cause a longer time-gap between the subsequent layer and the current layer which the support is added. Tay *et al.* (2019) investigated the influence of time gap on the strength of the inter-bond layer and result revealed that a time gap of more than 5-minutes will have a significant decrease in the tensile strength at the inter-bond layer. Depending on the complexity of the overhang, longer time gap can be expected and will further reduce the bond strength. After printing, the support scaffolding cannot be removed until the material gains sufficient strength.

Support-less roof shown in Figure 3, inspired by ancient methods, is an example of constructing a support-less closed structure and was proposed by Khoshnevis (2004). The idea of this technique was borrowed from the vault construction, where bricks and mortar were used to construct parabolic-shaped roof at an angle approximately 20° to perpendicular along the longitudinal axis of the vault as reported by Dahmen and Ochsendorfs (2012). This angle allows the prior section of the roof to support successive sections without the need for formwork. Such technique integrates the supporting system with the main structure. By building the roof with this parabolic-shape, the arrangement of the bricks enables the

structure to be in compression. However, this parabolic shape does not benefit 3D concrete printing as the material extruded is still in its fresh state. The successive layer needs to be supported by the prior layer at an inclination of more than 20° to perpendicular along the longitudinal axis for the material to be stable during the printing process. With the adoption of such technique, rapid hardening property of the material are expected so that the load of the subsequent layer can be supported by the previous layer which is also an overhanging structure.

Figure 2: Printing of overhangs over existing support (a) manual insertion of support (b) printing over existing support.

Figure 3: Contour crafting approach to fabricate support-less structures (Khoshnevis, 2004)

2.2 Printing of supports with a support material

Generally, the generation of support starts by determining if the surface requires a support. Strano *et al.* (2013) explained that once a surface requires support, the support geometry is computed and is usually printed with a weak infill pattern. Some fused filament fabrication (FFF) (See Figure 4) and

jetting-based additive manufacturing technique use a dual-nozzle printer to print with primary material and a support material. The primary material is defined as the material used to print the main structure. The support material, on the other hand, is a temporary structure to be removed during post-process. Stansbury *et al.* (2016) presented a Multijet printing method that utilized a UV-curable material to produce smooth parts in highly complex geometry, wax or other gel-like support material that can be co-deposited for subsequent removal by heating. On the other hand, Fahad *et al.* (2013) utilized a different property for the support material. For FFF technique, support material such as polyvinyl alcohol, PVA, a water-soluble thermoplastic is used as it can be dissolved in water. For jetting-based technique, support material such as propylene glycols is preferred as high temperature is used to melt the support material. These printing techniques are usually used to print multi-piece assembly which careful consideration is given to the accessibility of the residual material between components. The dissolving and melting of the support materials also reduce the possibility of feature damage due to human error.

Figure 4: FFF dual nozzle system to print with support material

No printer setup with multiple materials has been reported in 3D concrete printing. However, using two robots to print a single piece structure was demonstrated as shown in Figure 5 by Zhang *et al* (2018). Each robot printer is attached to its own pump to print collaboratively. Although the materials used in the study are both primary material, support material such as clay can be put into one of the robots

to create the support structure. With this configuration, high precision on the robot control is necessary to prevent any collision and to ensure communication on the exact location for the support and primary material is properly executed. The use of two or more nozzle increases the complexity of the printing system drastically. Nevertheless, mortar is generally a cheap material to use. Thus, if the cost of the support material is higher than the primary material, it could potentially drive up the overall cost of manufacturing the component.

Figure 5: Continuous printing by two robot printers (Zhang *et al.*, 2018).

2.3 Printing of supports with the primary material

Using the primary material to print support structures for the “overhanging” problem has already been investigated in many publications with different solutions being proposed for the FFF technique. Dumas *et al.* (2014) exploited the ability of FFF printers to print bridges across gaps. Points to support for the overhangs were selected and optimised to print scaffolding composed of bridges and vertical pillars. Vanek *et al.* (2014) optimised the framework to reduce the amount of support structure required which resulted in the support structure to have a tree-like shape that effectively supports the overhangs. In general, the support structures fill the free space beneath the overhang in a densely or truss-like manner. The differences between the literatures are the quantity, suitability and reliability of the material used. Different support geometries were proposed to reduce the material wastage and reduce the contact point

between the support structure and the main structure to improve surface finish. Printing of chamfers support without vertical structures was demonstrated by Cacace *et al.* (2017), however, the proposed technique was designed for FFF and the material used has a rapid hardening property.

Concrete printing, on the contrary, is a brittle material and requires curing time. It is not possible to print truss-like supports with concrete material because the gap distance is too far apart and may result in the main layer to slump. The study done by Tay *et al.* (2019) has shown that a good mechanical mix at the interbond layer is important. Even though fast curing concrete may be able to achieve low slump with far gap distance support, if the curing or the stiffening time of the material is too rapid, it will weaken the bonding between the main layers.

Another approach for printing supports with the primary material is to vary the printing parameters. Although the support and the main structure may be the same material, the material properties extruded at different parameters will not be the same. Carneiro *et al.* (2015) characterized the printed specimen mechanically through varying the printing parameters. The objective is to print the support structure with a lower strength that can be easily removed during post-processing. To the best knowledge of the authors, there has been no literature which investigates the use of concrete as a feasible support material for concrete printing.

2.4 Overview of different support techniques

The three different methods of printing with supports were evaluated and the results were compiled in Table 1. Seven key factors were considered and were evaluated in three different classifications. The best performance for the key factor was highlighted in bold (e.g. low or high). As shown in Table 1, printing support with primary material is more beneficial than the other two techniques.

Table 1: Overview of the performance of the different support technique

	Cost	Bond strength	Freedom of design	Ease of removal	Wastage of material	Equipment complexity	Manpower
Printing over existing surface	Moderate	High	Moderate	Moderate	Low	Moderate	Moderate
Printing with support material	High	Moderate	High	Moderate	High	High	Low
Printing with primary material	Low	High	High	Low	High	Low	Moderate

In this paper, an experimental method for obtaining the optimised values of the printing parameters for different printing region will be presented. Two different print paths will be used to correlate the effect of the travel speed and the flow rate on the dimensional precision of the filament. Also, investigation on the dimensional parameters such as the top surface area of the filament and the slump in the bridging layer are investigated. Furthermore, through experimental analysis and designing appropriate benchmarks, the printing parameters are calibrated to print different types of filament for different structures (primary structure and support structure). The results obtained will be verified by printing an overhanging beam. Lastly, the advantages and limitations of this technique will be discussed.

3. Methodology

3.1 Materials and preparation

Tay *et al.* (2016) tailored a mix design to be able to withstand slumping under its own weight and can be pumped through a 25.4mm diameter hose. A similar mix design was used in this study that comprises of Ordinary Portland cement (OPC, ASTM Type 1, Grade 42.5), silica fume (undensified, Elkem), Fly ash (Class F) and river sand (diameter less than 2.36mm). The mix design has an initial setting time of 170 minutes. Although the material strength gain due to hydration plays an important role

in 3D printing, due to the small structure printed and the long setting time of the material, the hydration rate is neglected in this study. Table 2 shows the material composition.

Table 2: Material mix design composition

Cement to binder ratio	Fly ash to binder ratio	Silica fume to binder ratio	Sand to binder ratio	Water to binder ratio
0.7	0.2	0.1	1.7	0.495

The sieve analysis of the sand particles was shown in Figure 6. Panarese (1973) suggests that the aggregates gradation used for pumping should match the gradation requirements specified in the ASTM C33 (ASTM C33 / C33M-18, 2018). Fine aggregates are important in the design of pumpable concrete mix. The finer portion of the sand together with fly ash, silica fume and cement form the lubricating film inside the pump and pipeline prevents bleeding of the fresh concrete during delivery. On the other hand, excessive fine sand should be avoided, as it not only increases the water requirements, it affects other properties of the material in terms of durability and shrinkage. Crepas, (1997) explained that finer materials have more surface area to be coated with the cement-water paste. If there is too much fine sand in the mixture, more water will be needed to get the same workability.

A Hobart mixer was used to prepare the material where dry components were dry-mixed at 59 rpm for 5 minutes. Water was then added to the mixture for mixing at slow-speed (59rpm) for 1 minute followed by 7 minutes of high-speed mixing (198rpm). The mixed material was placed in the progressive cavity pump for printing immediately after mixing.

Figure 6: Sieve analysis of sand particles

3.2 Filament and gap distance characterization

A gantry printer coupled with a rectangular nozzle as shown in Figure 7 was used in this study. The rectangular nozzle has a dimension of 30mm by 15mm which forms a nozzle orifice area of 450mm² and the height of each layer was set at 15mm to match the width of the nozzle.

Figure 7: (a) Gantry printer (b) 30mm by 15mm nozzle used for printing

Two printing paths (See Figure 8 and Figure 9) were established to characterize the filament. The first printing path was used for filament characterization. As shown in Figure 8, the printing path was repeated for four different flow rates (37.9ml/s, 45.2ml/s, 48.0ml/s and 51.3ml/s) to print a single layer. Evaluation of the relationship between the printing parameters and the dimensional parameters of the filament was carried out by characterising with a dimensionless value $R_{m/i}$. It is the ratio of the measured top surface area divided by the ideal surface area of the filament.

Figure 8: Printing path for filament characterization

A support structure should be printed with sufficient top surface area to support the subsequent main layer. Therefore, to simulate the different breakage gap distance in the support filament, the printing path as shown in Figure 9 is established. The objective for this test is to evaluate the maximum gap distance on the support filament (first layer) before any significant slump in the bridging layer (second layer) that is in contact with the support filament is observed. A bridging layer is defined as the subsequent layer in contact with the support filament. This bridging layer is printed over the gaps of the support layer and it should not have significant slump or breakages. The flow rate and travel speed are kept constant for this investigation.

Figure 9: Print path for gap distance characterization

3.3 Solidity ratio and printing limits

The flow rate of the material and travel speed of the nozzle variation can affect the solidity ratio (SR) which is the expected filament size and is defined as:

$$SR = 1000 Q / A_p v \quad (1)$$

where A_p (mm^2) is the cross-section area of the nozzle, v (mm/s) is the nozzle travel velocity and Q (ml/s) is the flow rate of the material. Figure 10 shows the theoretical effect of the flow rate and the travel speed on the filament. In theory, when SR is less than 1, the printing process is operating within region D, where there are more discontinuities, more voids, lower filament strength and smaller filament width. On the other hand, when SR is more than 1, the printing process is operating in region A, where there are

fewer discontinuities, fewer voids, higher strength and larger filament width. Theoretically, the solidity ratio can also be calculated by

$$SR = W_f H_f L_f / A_p v \quad (2)$$

where W_f , H_f , L_f (mm) are the measured width, height, and length of the printed filament, respectively. Lao *et al.* (2017) revealed that the filament will deform during the printing process, the cracks and the fluctuation of flow rate will also lead to measurement error of filament width and length. Thus, further investigation is still necessary to study the relationship between solidity ratio and printing parameters.

Printing processes operating in region B and C, where SR is approximately 1, would produce the best filament. Printing in region B reduces the printing time and the time-gap in between the layers. On contrary, printing in region C increases the printing time.

Figure 10: Printing limits: effects of flow rate and travel speed on the printed filament

4. Results

4.1 Effects of flow rate and travel speed on the surface area of the filament

A total of 32 specimens of different flow rates and travel speeds were printed as shown in Figure 11. Large filament surface area was found in high flow rates and slow travel speeds (Region A). More material was extruded than expected thus causing the material to be squeezed on to the substrate pushing

material in the lateral direction. Although excess material deposited will improve the bonding between layers and thus leading to better mechanical strength, but it will also result in the poor surface finish and poor geometrical resolution. On the other hand, large breaks were found in low flow rates and fast travel speeds (Region D). These breaks were caused by the disproportionate slow flow rate of the material exiting the nozzle. The friction force between the substrate and the material that has been extruded causes a shear on the existing material at the nozzle thus resulting in breakages.

Figure 11: Filament printed with different flow rate (a) flow rate: 37.9ml/s (b) flow rate: 45.2ml/s
(c) flow rate: 48.0ml/s (d) flow rate: 51.3ml/s

A filament length of 400mm was cropped from Figure 11 for each respective flow rate and travel speed and was length of the nozzle of 30mm to obtain a dimensionless value ($R_{m/i}$)

$$R_{m/i} = A_s / 400 \times 30 \quad (3)$$

where A_s (mm²) is the printed specimen surface area. Basically, $R_{m/i}$ is the experimental measurement of SR.

The filaments shown in Figure 11 were classified into four different types as shown in Table 3. The filaments that were found to have a large surface area are shaded in the darkest shade of grey and are found to have an $R_{m/i}$ value above 1.4. Those filaments that have no breaks and cracks generally have the optimum filament width which is within the range of 1 to 1.4. Those filaments that have cracks but do not have any breaks are found in the range of 0.75 to 1. Lastly, those filaments that have breaks and cracks were below 0.75.

Table 3: Ratio of the measured surface area and ideal surface area of the filament ($R_{m/i}$).

		Travel Speed (mm/s)							
		60	80	100	120	140	160	180	200
Flow Rate (ml/s)	51.3	1.794	1.470	1.237	1.046	0.913	0.840	0.814	0.785
	48.0	1.523	1.380	1.093	0.999	0.860	0.772	0.681	0.621
	45.2	1.317	1.204	1.062	0.931	0.814	0.712	0.668	0.632
	37.9	0.990	0.860	0.661	0.574	0.480	0.470	0.424	0.398
Filaments that have thicker width									
Filaments that have no breaks and crack									
Filaments that do not have breaks but have obvious cracks									
Filaments that have breaks and cracks									

4.2 Factorial test result

In this study, a factorial test was performed to determine if the printing parameters have any statistical significance on the dimensional parameter of the filament. The velocity is inverse to support Equation 1 derived from the first principle and is denoted by s that $s = 1/v$. The formulas to obtain the

values in Table 4 can be found in the book written by Montgomery (2017). Larger F values indicate that the variation of the printing parameter is more significant on the dimensional parameter changes. From Table 4, the F-values of s and flow rate (Q) are 54.92 and 74.59 respectively, which is significant. It is also evident from the F-value that the flow rate (Q) is more significant than the inverse of travel speed (s). However, the interaction of the s and Q ($s \times Q$) does not have a significant effect on the dimensional parameter. On the other hand, low P-value reflects the there is a strong evidence that an effect is significant. The P-value of s and Q is lesser than 0.001, this means that these two parameters have a significance effect on the filament surface area.

Table 4: Analysis of variance (ANOVA) table

Source of variation	Degree of freedom	Sum of square	Mean Square	F-value	P-value
s	7	4.682	0.669	54.92	<0.001
Q	3	2.726	0.909	74.59	<0.001
$s \times Q$	21	0.460	0.022	1.8	0.065
Error	32	0.390	0.012		
Total	63	8.259			

The individual main effect of the travel speed and flow rate is shown in Figure 12. As the inverse of the travel speed increases, $R_{m/i}$ increases. This indicates that the filament surface area increases as the travel speed reduces. The effect is more significant when the s value is around 0.01 to 0.0167 which translates to the travel speed of 60mm/s to 100mm/s. It is less significant when the s value is around 0.005 to 0.0063 which translates to the travel speed of 160mm/s to 200mm/s. On the other hand, the effect of the flow rate is increasing for all values.

Figure 12: Main effect plot for $R_{m/i}$

A quadratic model expression was obtained through statistical software (Minitab). The quadratic model has a R-squared value of 0.95, indicating a good fit. In regions B and C of Figure 10, the difference between theory and experimental results is small. However, when the flow rate and travel speed are different, i.e. in regions A and D of Figure 10, the difference between theory and experimental results becomes larger. These differences, as discussed in Section 3.3, are mainly caused by the deformation of the filament when the solidity ratio is high, or the crack and voids when the solidity ratio is low.

$$R_{m/i} = -0.321 - 54.7/v + 0.0129Q + 2.773Q/v \quad (4)$$

where $R_{m/i}$ is the ratio of the measured surface area to the ideal surface area of the filament, v (mm/s) is the travel speed and Q (ml/s) is the flowrate.

Figure 14 is evolved from the theoretical chart shown in Figure 10 by using data in Table 3, which is differentiated by four different types of filament. As indicated in Figure 14, the filament surface area increased the most when the increase in flow rate and a decrease in travel speed are in the direction that is perpendicular to the lines separating the types of the filament (Direction A). Moving in direction A also increased the print time. On the other hand, the total print time can be reduced when the flow rate increases and the travel speed increases parallel to the lines separating the types of the filament (Direction B), while keeping the filament width consistent.

Figure 13: Solidity ratio from theory, experiment, and fitted model.

Figure 14: Contour plot of the ratio of measured surface area to the ideal surface area of the filament

4.3 Bridging vs supports

In FFF, Jin *et al.* (2015) optimized the number of support points which can reduce the total time needed for fabrication. However, the structural recovery of fresh concrete is not as rapid as a polymer material after extrusion, and it tends to slump if there is insufficient support surface underneath.

Therefore, it is not recommended to print support structures with large breaks. The following experiment was carried out with the 2nd print path to determine the maximum gap distance for the bottom support without significant slumping of the bridging layer. The different types of slump of the bridging layer at different gap distance are shown in Figure 15.

Figure 15: Effect of gap distance on the slump of bridging layer (a) 6mm (b) 10mm (c) 28mm

Figure 16 shows the relationship of the gap distance of the first layer to the slump of the bridging layer. An exponential model $y = 1.56[\exp(0.05x) - 1]$ was able to fit the experimental data with $R^2=0.9506$. The slump of the bridging layer should not be more than 15mm which is the thickness of the first layer. In order to maintain a level bottom surface of the bridging layer, a 2mm slump is determined to be within a

satisfactory limit (<13% of the layer thickness). This 2mm slump of the bridging layer is translated to a maximum 10mm gap distance of the first layer.

Figure 16: Relation of gap distance and slump

From Figure 11, it is observed that the filament having a gap distance of less than 10mm is the filament with the travel speed and flow rate of 140mm/s at 45.2ml/s and 160mm/s at 45.2ml/s, which has a $R_{m/i}$ of 0.814 and 0.712 respectively. Therefore, when the $R_{m/i}$ is less than 0.7, which is referred to as the failure region, the gap distance is larger than 10mm. To print the support layer that will cause a deformation of less than 2mm slump in the subsequent bridging layer, the $R_{m/i}$ should be within the range of 0.7 and 0.8. Figure 17 is the combine results of Figure 14 and Figure 16 to show the different region of the printing parameters.

A normal printing region was determined to have a $R_{m/i}$ range of 1 to 1.4. In this region, the filament appears to have high dimensional accuracy and minimum cracks appearing on the surface, as shown in Figure 11. The intermediate region is the region between the normal printing region and support printing region with a $R_{m/i}$ range of 0.8 to 1. This is not suitable for printing the main structure because of the cracks that appear on the surface of the filament which may reduce the strength in the main structure.

It is also not desired for printing supports because the gap distance is too narrow in this region. Printing supports in the intermediate region will use more material than required and it will increase the production time which is uneconomical in terms of time and cost.

The last region is the oversupply region. In this region, the flow rate of the material is significantly higher, which causes the filament to possess a thick and inaccurate dimension. The oversupply region has a $R_{m/i}$ range of more than 1.4. By using Figure 17, it is possible to determine the different region suitable for printing different application.

Figure 17: Characterization of the different printing region

4.4 Printing of supports for overhanging structures

A design as shown in Figure 18(c) that requires supports was printed to verify the results obtained from sections 4.1, 4.2 and 4.3. Figure 18(a) and (b) show the main structure and the supports printed using the primary materials only. Due to the configuration of the printer, it is easier to keep the flow rate constant throughout the printing process. Therefore, only the travel speed parameter is changing throughout the printing process. The printing parameters were selected based on the result shown in Figure 11 and Figure 17. For this demonstration, the flow rate was chosen as 45.2ml/s. The travel speeds were then selected within the respective region for the main structure and support structure as shown in

Figure 17. The travel speed parameter to print the main structure and the support structure for this flow rate are selected at 80 mm/s ($R_{m/i} = 1.2$) and 160mm/s ($R_{m/i} = 0.7$) respectively. During post-processing, the support structure was easily removed using a chisel and a hammer after a day of curing and the end result is presented in Figure 18(c).

Figure 18: (a) Printing with supports (b) before post-processing
(c) after post-processing

5. Discussion

Through the factorial test, it was ascertained that the travel speed and flow rate have a huge effect on the filament dimension and these two parameters are not dependent on each other. Furthermore, it was observed that the flow rate has a greater effect on the filament dimension. To better understand the slump of the subsequent bridging layer, the gap distance characterisation test was carried out to find the maximum distance that the filament can cross over without a significant slump. A slump of more than 2mm on the bridging layer was deemed as a significant slump, therefore the maximum gap distance was determined to be 10mm. To keep the support layer gap distance less than 10mm, the $R_{m/i}$ should be within 0.7 and 0.8.

The theoretical concept of the printing parameters region is shown in Figure 10. It indicates a fundamental guide to the effects of the filament dimension at different printing parameter region. However, after much research was performed and compiling the results in sections 4.1 to 4.3, the printing parameter region was remodelled and is presented in Figure 17. They were corrected in Figure 17 to the printing operations such as normal printing and supports printing. Although the graphs as shown in Figure 16 and Figure 17 are material-dependent, most cement-based material generally behaves in the same manner in its fresh state.

With the chart obtained shown in Figure 17, different printing operations are possible and were verified with overhang structure as shown in Figure 18. The oversupply region and the intermediate region can also be used for different printing operations. When a higher strength is required, oversupply region can be printed within dimensional limits to improve the strength as compared to normal printing region. On the other hand, if the strength requirement is not significant, printing in the intermediate region can help to reduce the time and material needed.

6. Conclusion

For 3D concrete printing, material extruded from the nozzle will retain its soft characteristic. Without the use of formwork, a temporary physical surface is necessary to support the overhanging filament. Based on the literature review in section 2, printing supports with the primary material can eliminate the complexity of a dual-nozzle system, as well as, eliminating the increase in the time gap between the bridging layer and the current layer where the support is added. In this study, the feasibility of adjusting the printing parameters to print the main structure and support structure using a single type of building material was demonstrated.

It was found that the nozzle travel speed and material volume flow rate significantly affects the solidity ratio of the filament. Additionally, a gap distance characterisation test was carried out to find the maximum gap distance that the filament can cross over without a significant slump. The combined results were used to determine the different printable regions for different operations. An overhang structure was printed to verify the results obtained. The main advantage of this technique is being able to complete the printing process with minimal human intervention and without much interference to the printing time gap. It also allows the complex structure with overhangs to be built.

In section 2, the use of primary material to print support structure was found to bring more benefits than the other two support techniques. However, this paper does not suggest that using the primary material as a support structure is the best method. Support structures are eventually sacrificed after the object is built. Furthermore, the presence of support structures increases both the manufacturing time and the post-processing operations. Since printing support with primary material has its own setbacks, the first rule of thumb is to decrease the use of support material to reduce waste.

With these printing region established, printing a functionally graded material (FGM) is possible. Future work such as printing with different travel speed and flow rate can create an optimised structure that possesses different material characteristics. Additionally, the effect of the material thixotropy with the printing parameters have on the filament as well as creating an explicit boundary between the main

structure and the support structure for ease of removal of supports during post processing can be investigated.

The proposed method as demonstrated can be used for small construction activities such as window openings, electrical, mechanical, and finishing work or holes. It is unwise to print a support structure that is twice or more than the amount of material required to print the main structure. Different support techniques can be combined to fabricate the main structure with the aim of reducing manpower, material waste and time required for production.

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Conflict of interest

The authors declare that they have no conflict of interest.

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