THE EFFECT OF NOZZLE SHAPES ON THE COMPACTNESS AND STRENGTH OF STRUCTURES PRINTED BY ADDITIVE MANUFACTURING OF CONCRETE

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Abstract: In direct-extrusion based Additive Manufacturing of Concrete (AMoC), the compactness and the mechanical strength of printed parts can be improved by optimizing the shape of extrudate. The shape of extrudate is significantly affected by the shape of nozzle outlet because of the viscoelastic behavior of fresh concrete. In this paper, different shapes of nozzle were tested to find the nozzle design for the optimized printing quality. Three different nozzles were fabricated by Fused Deposition Method mounted on a mechatronic nozzle, which was plugged on a robotic arm. From the compression test of the specimen and the observation of cross-section of the specimen, the mechanical strength and compactness of the sample were obtained. The result could help to find the relationship between the quality of concrete printing and the shape of nozzle outlet.

Keywords: Additive Manufacturing 3D Printing with Concrete, Nozzle, Compactness, Compressive Strength

INTRODUCTION

3D Printing, which is also called Additive Manufacturing (AM), has grown very fast in many disciplines [1]. This method has a lot of advantages such as high automation, high complexity, customization and relatively low cost for building small quantity of products. Not surprisingly, applications of 3D printing in the construction industry are being heatedly studied because of the potential benefit in the reduction of labor cost, construction time and production cost [2, 3].

Despite of the rapid development, Additive Manufacturing of Concrete (AMoC) [4] still has many issues like low compactness [5]. Because of the property of fresh concrete, the concrete extrudate keep the similar shape to the nozzle outlet after extrusion, so the extrudate which cannot stack well will lead to low compactness printed structure. Low compactness will reduce the mechanical strength of the printed structure and in construction industry this is not acceptable. In the Contour Crafting and 3D Concrete Printing technology, optimizing the design of nozzle outlet was proved to be beneficial in improving the surface finish and compactness of the printed structure [4, 6, 7]. However,

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the existing studies is only limited to the visual observations of the printing quality. The relationship between the design of nozzle shape and the printing quality remains unclear as well.

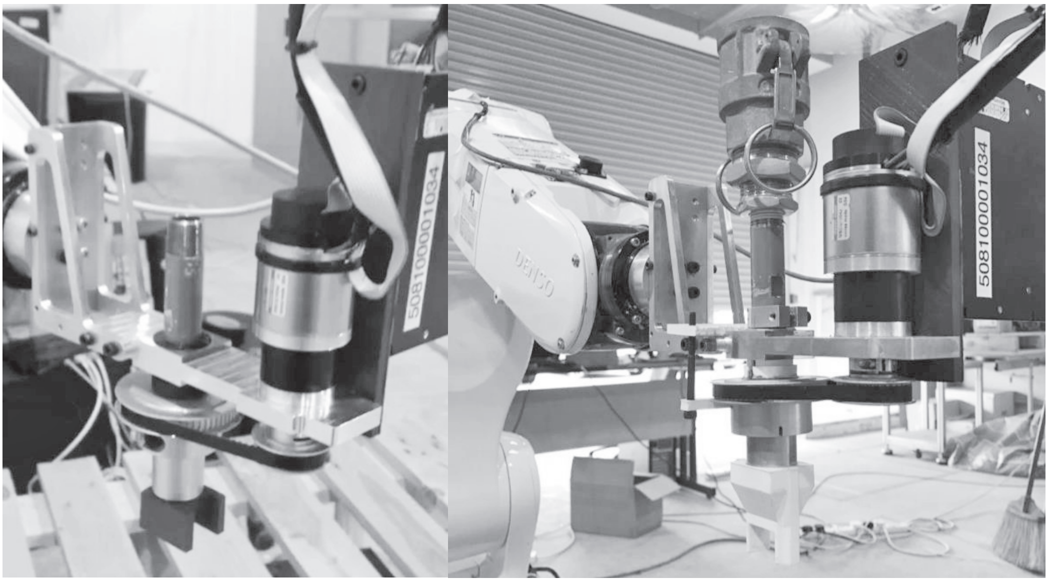
In this paper, printing experiments with various kind of nozzles were conducted and data representing the quality of printing was recorded. A mechatronic nozzle was designed and fabricated to provide a rotational degree of freedom (DOF) on the outlet of the nozzle. After that, different shapes of nozzle outlet were used in the printing experiment and the samples acquired were tested to get the mechanical strength and compactness. The data acquired was then utilized to analyze the printing quality for this experiment and the relationship between the shape of nozzle and the printing quality was found.

EXPERIMENTAL SETUP

To test different shapes of nozzle outlet, the nozzle assembly was required to have an extra degree of freedom in rotation at the outlet. If round nozzle was applied in the printing, the printer could simply move the nozzle along the designed path of deposition. However, if a rectangular nozzle was applied, simply moving the nozzle along the print path could ruin the printing completely, so controlling the facing direction of the nozzle outlet was needed.

A mechatronic nozzle assembly was designed to provide the rotational DOF at the nozzle outlet for nozzle experiments. In the nozzle assembly, the blue pipe was connected to the delivery system by an arm-locking coupler. Under the tube was a pulley which was connected to the pulley under the Maxon DC Brushless motor and the motion was transmitted from the motor to the other pulley by a timing belt. A connector clamped was designed to fit different nozzle outlets and firmly clamped by the pulley (Figure 1a). The nozzle assembly was connected to the DENSO robot which could move the nozzle along the printing trajectory (figure 1b) by an aluminum connector.

The cooperation between the robot and nozzle assembly was established through Robotic Operating System (ROS) [8]. During the experiment, the nozzle was connected to the concrete delivery system by an arm-locking connection and the concrete was forced to the nozzle by a MAI-Pictor pump. The robotic arm moved the nozzle along the printing trajectory and the nozzle assembly controlled the facing direction of nozzle outlet by receiving the real-time position information from the robot and control the Maxon motor by inputting calculated motor position command through the EPOS2 controller. The controller received command from the calculation node through the USB port connected to the laptop.



(a) (b)

Figure 1: Mechatronic Nozzle Assembly and DENSO Robotic Arm

The outlet part of the assembly was changeable, and the nozzle outlets used in the printing were printed by a Fused Deposition Method (FDM) 3D Printer, the Ultimaker 2+. As a result, nozzles with different shapes could be easily fabricated and tested in the printing.

With the aid of this experimental setup, the samples printed by three different nozzles were tested for the mechanical strength and compactness. The nozzles have three shapes including the elliptical nozzle, round nozzle and rectangular nozzle (Figure 2). All the three nozzle outlets have the same cross section area to maintain the same flow rate of concrete in the three experiments.

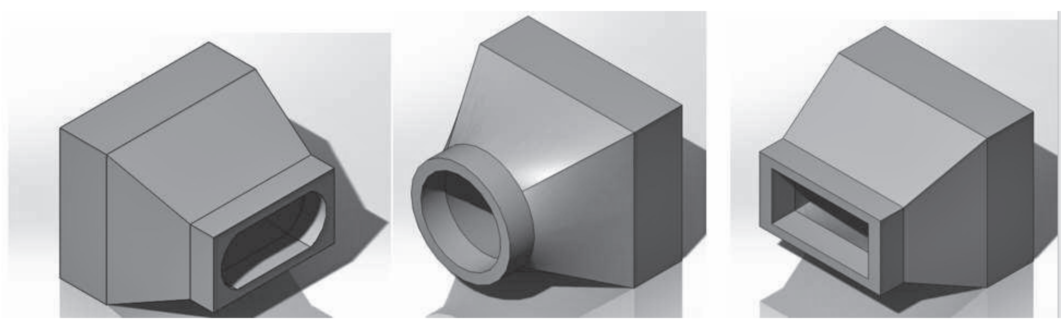


Figure 2: CAD Models for Different Nozzle Outlets

RESULT AND DISCUSSION

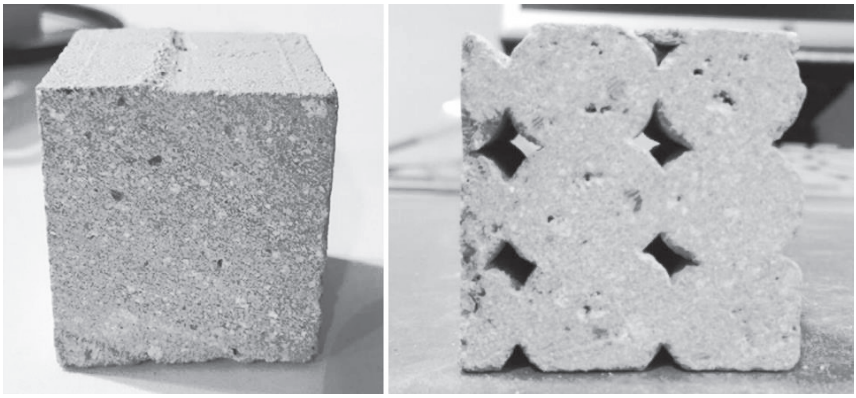
The printing trajectory was designed to form a part which was later cut into six samples of 50x50x180mm. Because of the trajectory-following function of the experiment setup, nozzle's facing direction was always parallel to the printing direction, so the width of the printing path was equals to the length of the facing direction of the nozzle outlet and the height of each printing path was equal to the width of the nozzle outlet.

The printing with different nozzles had different behavior. In the part printed by the rectangular nozzle (Figure 3a), the contact between different printing paths was better than the part printed with the round nozzle (Figure 3b). Comparatively, the round shape extrudate did not stack well between different print roads because the round shape extrudate had very low percentage of contact area comparing with its cross-sectional area. The cross-section of the extrudate from the round nozzle was very close to the nozzle's shape so the contact surface between printing path was much lower than rectangular and elliptical nozzles. Hence, the inter road adhesion in the printing with the round nozzle was quite weak and the stacking of print path was bad.

(a) (b)

Figure 3: Printing Test with Different Nozzles

The compactness of the specimen could be observed from the cross-section of the specimens. The comparison of part printed with round nozzle and rectangular nozzle had significant difference. The part printed with rectangular nozzle has very good contact between layers (Figure 4a) but the part printed with round nozzle has low compactness (Figure 4b).

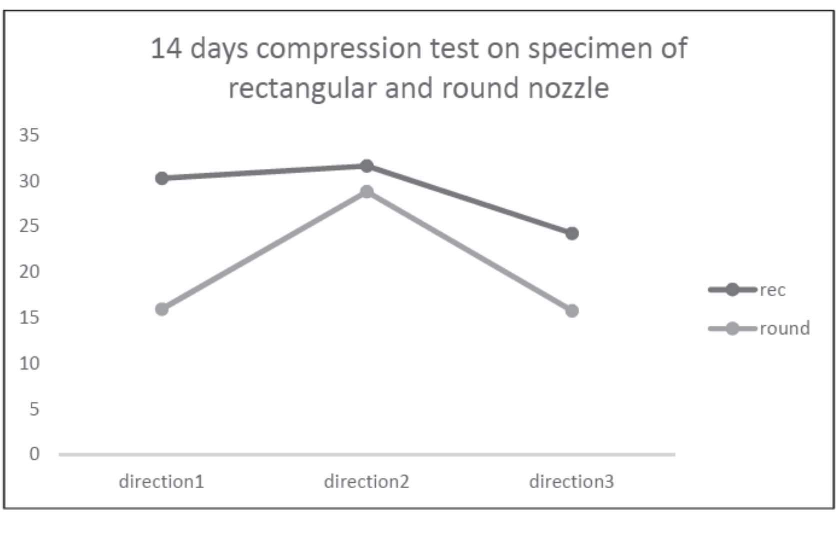


(a) (b)

Figure 4: Cross-Sectional View of Specimen Printed with Different Nozzles

Mechanical strength was also tested for the samples printed with different nozzles. The compressive strength of the cubic specimen printed with three different nozzles were tested.

The equipment used in the compression test was a Toni Technik Baustoffprufsysteme machine with a loading rate of 100 kN/min. The compression test of the samples including test of three loading directions on the specimen. The first loading direction was parallel to the direction of building higher. The second loading direction was parallel to the printing direction and the third loading direction was perpendicular to the layer height and the printing direction. For each direction, three samples were tested to minimize the experimental error. The result of the compressive strength samples printed with rectangular and elliptical nozzles were similar, so only the result of rectangular nozzle and round nozzle was showed here.



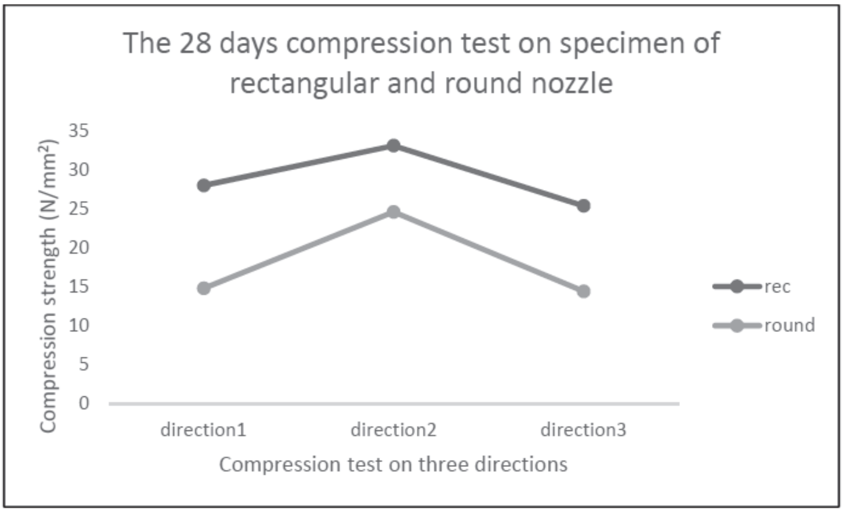


Figure 5: 14-days and 28-days Compression Test Result

The compression test showed that the printed specimen had obvious anisotropic behavior. The compressive strength was the strongest along the printing direction where the compression was supported by the continuous printed concrete. While in the other two directions the compression was also supported by structure of inter-road adhesion between printing path and the compressive strength was weaker.

Results on the compression test of part printed with rectangular and round nozzle showed significant difference (figure 5). Specimens printed with the round nozzle had weaker compressive strength all the loading directions than specimens printed with rectangular nozzle. The smaller contacting area between printing roads in the parts printed with round nozzle caused weaker inter-road adhesion in the structure, so the part printed by the round nozzle was easier to break in the compression test. In the AMoC, the shape of the printing nozzle was influential on the quality of printing because the quality of inter-road adhesion could be optimized by increasing the contacting area between print paths and the mechanical strength of the printed structure could also be increased.

Besides, even for the samples printed with rectangular nozzle which seem to be continuous and compact (figure 4a), the anisotropy phenomenon persists and compressive strength along the printing direction was significantly higher than other loading directions. The impact of the quality of inter-road adhesion was still significant to the mechanical property of printed part.

SUMMARY AND FUTURE WORK

While using the rectangular nozzle, the compactness and compressive strength of the part printed were better than the part printed with round nozzle. The great improvement in the compactness and mechanical strength would be important to the target of building safe accommodation structures and higher mechanical strength certainly plays an important role in raising the safety factor for this technology.

Because the design of nozzle shape has been proved to affect the quality of printing in AMoC, the next step is to control this relationship and improve the printing quality. The first target is to control the shape of the extrudate, so the well-organized print paths can improve the compactness and the quality of inter-road adhesion. The control of extrudate can be achieved by using simulation methodology or using experimental data and iterative improvement to get an empirical formula of the extrudate and the nozzle's shape.

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