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Development of Concrete Extrusion Nozzle for Producing Free-Form Concrete Panels and Extrusion Test

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Abstract: FCP (Free-form Concrete Panel) is used to easily realize the huge and complex curved surfaces of free-form buildings, and research on FCP manufacturing technology is being conducted. However, as the concrete was extruded manually into the manufactured mold, the precision of the FCP was lowered and errors occurred. Therefore, this study developed concrete extrusion equipment that includes a nozzle part, an open/close part, and a control part, according to the required performance derived from previous research analysis. The mixing ratio of concrete was selected at an appropriate value of W/C 38% and extruded uniformly with a width of 60 mm and a thickness of 22 mm. Depending on the opening/closing function, it was possible to open and close at the desired position. The concrete extrusion nozzle for FCP production is the basic equipment, and miniaturization and automation of the nozzle are required in the future. This is expected to contribute to the development of new free-form construction technology and equipment.

Keywords: free-form building; free-form concrete panel production; extrusion nozzle

1. Introduction

With the recent development of scientific technology, various types of free-form buildings combined with digital technologies unique to existing architectural styles are manifesting [1]. Unlike regular buildings, free-form buildings have complex curves and streamlines, thus requiring high levels of construction capacity [2]. In particular, the exterior of free-form buildings requires different curves, and due to their massive size, it is difficult to manifest them all at a single time. Currently, the exteriors of buildings are created by panelizing shapes that can be easily manufactured [3]. Such free-form panels are used through the customized production of molds to configure different curves. In the past, wood or steel was selected as the material for free-form molds because they were easy to fabricate, but they have limitations in that they can only be used one time, and cannot be reused. Furthermore, because free-form molds are produced by hand, precision is determined by the workmanship of the technician, and this can lead to errors. Therefore, technologies that can design free-form molds precisely for any curves, while also being reusable, are required [4].

Various new technologies are being used to precisely configure free-form buildings [5]. Programs such as Revit, CATIA, Rhino, and BIM are typically used for designing free-form buildings. Such computer technologies can efficiently design free-form buildings composed of geometric shapes such as curves, twists, etc. In reality, Figure 1 shows the construction process of the Museum of the Future in Dubai, which was completed in 2021. This is a donut-shaped free-form building, and like (a), it designed the building's shape using 4D BIM (Building Information Modeling) technologies. At this time, the number of panels for use in the design was calculated, and a total of 1024 stainless steel panels were used in the museum's external area of 17,600 m^2. The molds used for producing the panels were manufactured precisely by processing polyurethane as shown in (b). Afterward, the stainless steel produced with the mold that was completed as shown in (c) was attached to complete. The completed stainless-steel panel was transported and attached to the frame to configure the donut-shaped exterior [5].

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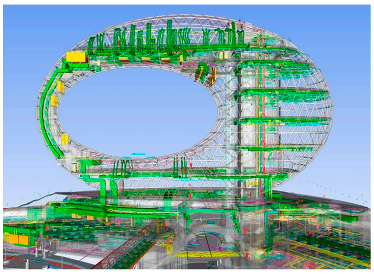
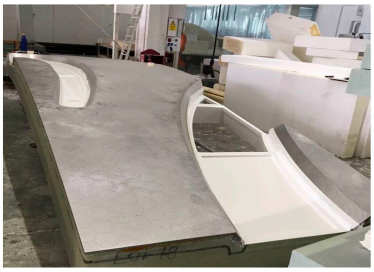


(a) 4D BIM design

(b) Polyurethane free-form mold production



(c) Stainless steel attached to free-form panel

(d) Panel transportation and attachment

Figure 1. Dubai Museum of the Future construction process [6].

Free-form building has social and economic effects, such as drawing in tourists with their unique exterior, which can help develop the city. However, the production time and cost of the molds used to configure free-form exteriors are great. Furthermore, molds that have completed their use become construction waste, thus posing many risks such as environmental pollution and additional costs. The Opera House of Australia has a shell-shaped roof structure, and it used approximately 10,000 free-from panels [7,8]. It was expected that construction would take four years and cost seven million USD. However, construction was delayed during the course of resolving the free-form roof structure, and it actually took 14 years and cost 102 million USD. The National Museum of Qatar used approximately 76,000 sheets of fiber-reinforced concrete to construct 316 cylindrical panels. It took longer than four months to complete one cylindrical panel, and about 3000 free-form molds were produced to build the roof [2]. Dongdaemun Design Plaza (DDP) in Seoul used a total of 45,133 aluminum panels. It was composed of 29% flat panels, 22% panels that curved in one-direction, and 49% panels that curved in two-directions, and the panel design period was 133 days, and it took about one year and six months from panel production cladding [9]. Furthermore, in the production, processing, design, and construction stages of panels that are difficult to manifest, errors, as shown in Figure 2, can occur [10]. Joint and round processing errors between panels as shown in (a), and errors due to panel specifications not matching can occur, as shown in (b). Such errors require repetition of the panel production processes, and it can cause various risks such as a delayed construction period and increased construction costs.

(a) Error in joint and round processing

(b) Error in panel specifications

Figure 2. Cases of construction errors in free-form buildings [10].

In order to precisely produce such free-form panels, FCP manufacturing equipment was developed, as shown in Figure 3. (a) is FCP manufacturing equipment and is composed of two-sided multi-point press equipment, and the side mold control equipment is made up of upper and lower CNC equipment. The rod installed on the upper and lower CNC equipment moves the silicone plate according to the design shape to configure the lower curve. There is a ball bearing in the rod that allows it to rotate, thus making it possible to produce a smooth, curved shape. The side mold control equipment is arranged cylindrically next to the upper and lower CNC equipment. This also sets the number and moving value of the supported rod according to the design shape, thus configuring the various side shapes of the panel. Concrete is injected into the completed FCP mold to cure [11].

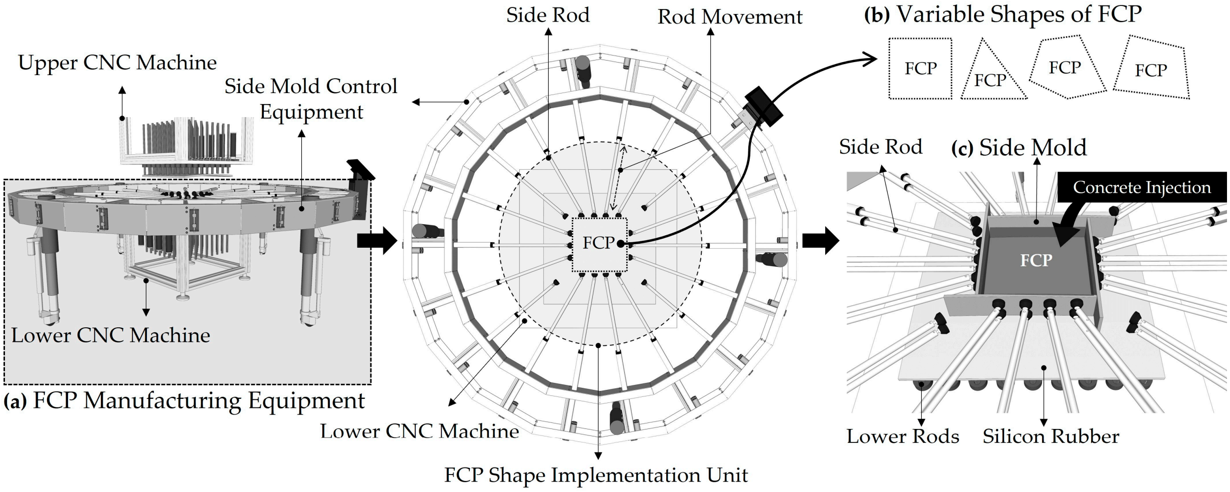


Figure 3. FCP manufacturing technology [11].

The FCP mold must configure various shapes, and therefore, the angle that makes up the side and bottom changes every time. If the FCP mold side angle is not a right angle, it will be weak against lateral pressure, and the manual placing method that has been used in the past decreases precision because the concrete is placed quickly as it aims to fill it. This causes construction errors, as shown in Figure 4, such as deformation or crumbling of the designed shapes of the side molds.

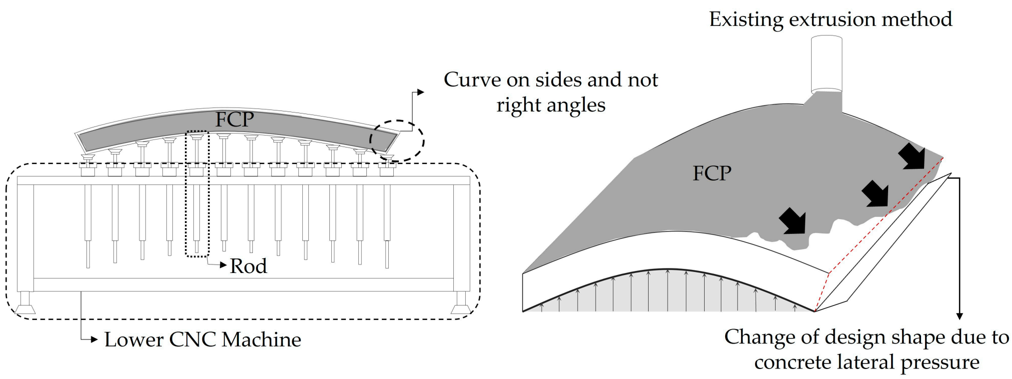
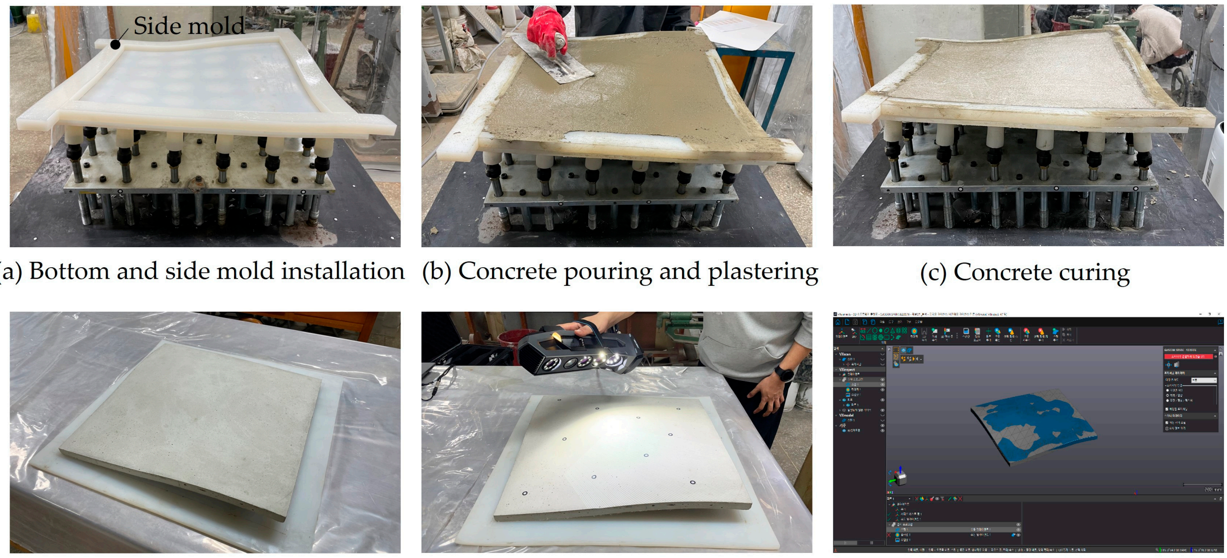


Figure 4. FCP mold construction errors when using existing extrusion method.

Therefore, in this study, extrusion equipment applicable to FCP manufacturing equipment is developed, and the methodology is as follows: existing concrete extrusion nozzles are used to print walls or structures, but the purpose of the concrete extrusion nozzle for producing FCP developed in this study is to precisely fill the inside of the molds produced by the FCP manufacturing equipment without deforming the shape. To develop equipment that meets this purpose, first, the preceding studies will be analyzed to determine the performance necessary for the extrusion equipment. Second, concrete nozzles, which are extrusion equipment, will be developed based on the deduced performance. Finally, the performance is verified through experiments. The study will be conducted with the goal of verifying the nozzle performance through concrete extrusion tests.

2. Literature Review

Yun (2022) conducted experiments, as shown in Figure 5, to verify the performance of the lower multi-point press equipment of the FCP manufacturing equipment [12]. The rod is raised according to the free-form design shape so that the silicone rubber configures the lower curve. In the past, variable side molds were used, but in this experiment, the silicone side mold, which had the same material as the bottom, was installed according to the side shape. Afterward, FCP was produced by placing and curing concrete, and in order to check for errors and the error rate in configuring the shape, a shape quality inspection was performed using a 3D scanner. As a result, the error rate of the lower shape satisfied the acceptable error presented in the paper at 3000 mm.



(a) Bottom and side mold installation (b) Concrete pouring and plastering (c) Concrete curing

(d) Removing mold (e) 3D Scanning of panels (f) Shape quality test

Figure 5. FCP manufacturing equipment lower multi-point press equipment performance test [12].

The side mold control equipment that configures the shape of the side on the FCP manufacturing equipment is shown in Figure 6. The side mold control equipment has an embedded ball bearing, and it is made up of a side rod with a magnet attached to the end and a side mold with variable steel plate material. The side mold control equipment has a round rod near the two-sided multi-point press equipment, and the rod in the necessary area moves according to the design shape. The rod is combined with the variable side mold with a magnet to resist concrete lateral pressure and configure the side shape. Yun (2021) produced a rectangular concrete panel using the side mold control equipment [13]. However, because the objective of the experiment was to verify the performance of the magnetic combination between the side rod and mold, a steel plate mold was used instead of a variable side mold. In addition, as it configured a rectangular panel instead of a free-form shape, verification for the free-form shape manifestation is needed.

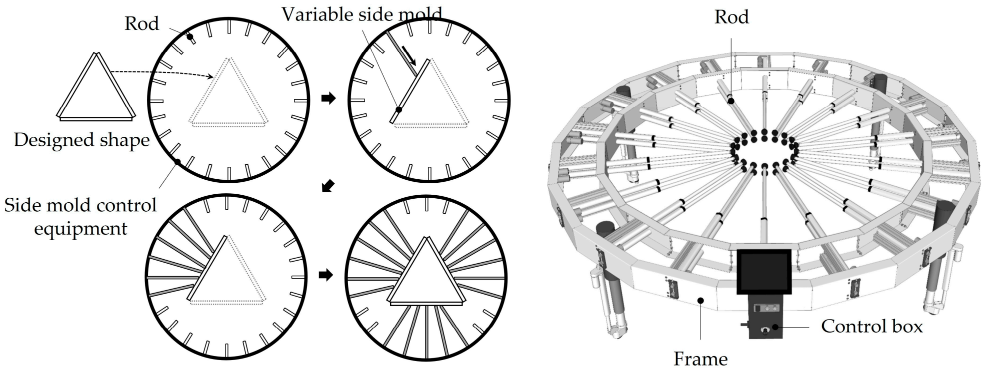


Figure 6. Concept of the side mold control equipment [13].

Youn (2022) performed experiments on the variable side mold as shown in Figure 7 [14]. An FCP panel was produced with the objective of checking the resistance of the variable side mold produced with steel plate materials against concrete lateral pressure. Lateral pressure applied to the side mold due to the free-form shape of FCP differed by area, and when there was sufficient resistance from the mold, errors had to be a value even or a value positioned within the acceptable range. Upon conducting 3D scanning on the side of the completed FCP, it was found that errors occurred in the center and at each end of the mold. However, this was found to be due to insufficient support, such as rods, and not a lack of resistance from the molds. Furthermore, it was determined that instead of extruding concrete precisely within the FCP mold, manual extrusion increased concrete lateral pressure, thereby affecting the error.

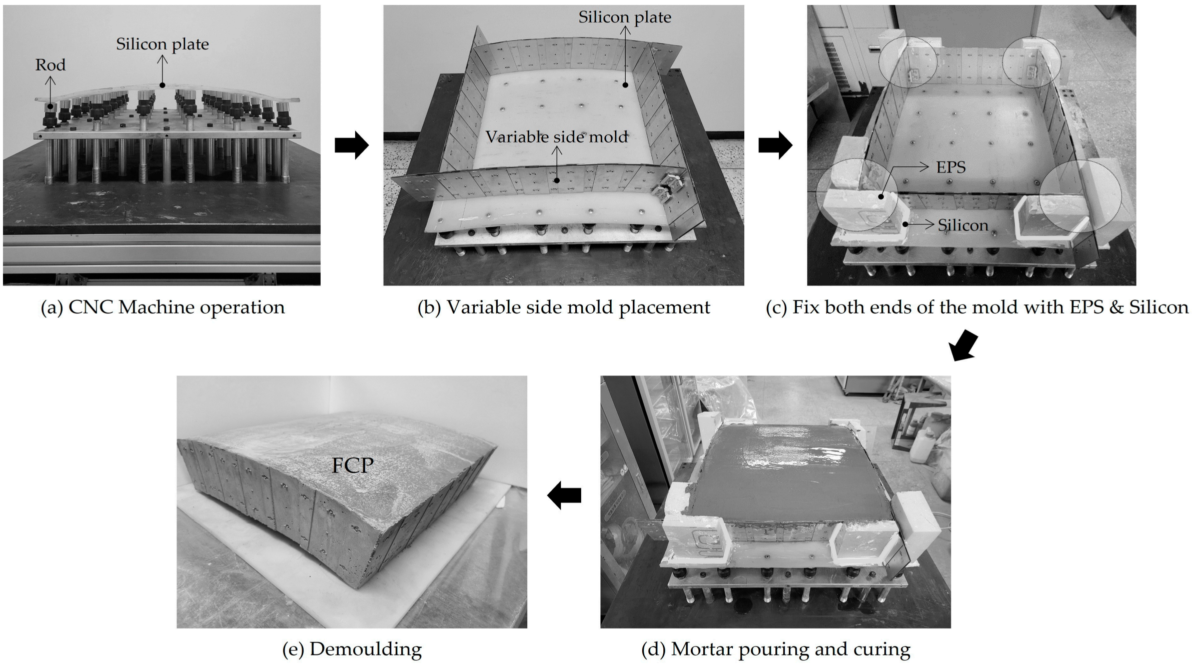


Figure 7. FCP production test process using a variable side mold [14].

In order to develop equipment that can fill the inside of such an FCP mold precisely, preceding studies on concrete extrusion nozzles were analyzed. 3D printing technologies are used in the equipment for automatically constructing elements or buildings based on 3D designs. This makes it possible to quickly and accurately construct complex-shaped structures, customized sub-materials, etc. in the construction sector [15]. These technologies are analyzed for studies applied to concrete extrusion nozzles. Khoshnevis (2004) generated a concrete structure using the contour crafting system [16]. There is a trowel on the end of the nozzle, which makes the modeling surface smooth. Additionally, the concrete was laminated precisely and smoothly according to the route set by the computer system based on 3D printing technologies to model it. This presented a concept for precise and automated construction equipment while minimizing waste. The Eindhoven University of Technology conducted a study of extruding and laminating concrete using 3D concrete printing (3DCP) technologies [17]. 3DCP supplies concrete mixed with water through a hose connected to the 3D printer head. The nozzle is a robot arm that operates vertically, and it moves to extrude and laminate concrete for each layer. This technology is flexible, and it is useful for configuring various shapes. However, in order to utilize 3DCP technologies, solutions for the extrudability of concrete, buildability, productivity, compliance of concrete open time, rapid hardening, and the ability to laminate are required. Recently, in the cases of Nan Zhang (2022) and Liming Yang (2023), 3D printing technology was applied to the nozzles [18,19]. However, these studies had different purposes from this study.

3. Deducing Required Performance of Concrete Extrusion Nozzle for FCP Production

3D printing nozzles are used for printing the walls directly or for producing the structure. However, nozzles used for producing FCP aim at precisely filling the inside of the free-form mold. The required performance of the concrete extrusion nozzle for FCP production was deduced as shown in Figure 8 for the preceding study analysis.

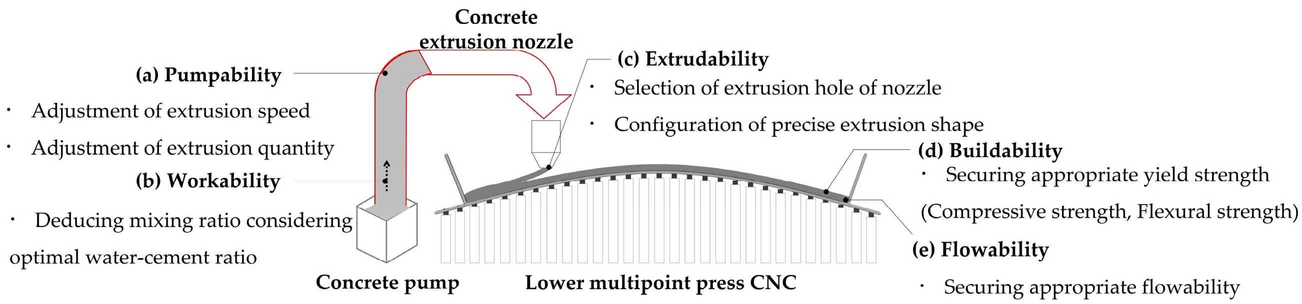


Figure 8. Analysis of required performance for the concrete extrusion nozzle for FCP production.

Pumpability refers to the transportability of moving concrete to the nozzle and represents stability and mobility [20]. The nozzle transports concrete using a pump, and therefore, pumpability is associated with the materials. Therefore, pumpability uses soft materials, and the thinner the concrete, the better. Even if soft materials are used, minimal concrete shape, concrete size, and density must be maintained, and hardness must be secured. If hardness is insufficient, it will cause material separation and quality will decrease while transporting the concrete. Therefore, a concrete extrusion nozzle for FCP production requires appropriate extrusion speed selection and extrusion quantity adjustment functions to prevent the separation of materials and thereby secure pumpability.

Workability is a factor that affects the buildability of concrete. This is determined by the concrete printing quality, stability of extrusion type, robustness of structures, printability, etc. [21]. When the ratio of water to cement increases, the workability of concrete also rises. The better the workability, material separation occurs less, and it is easier for laying and finishing. Therefore, it is necessary to select appropriate workability to prevent material separation around the nozzle, and this is determined by the mixing ratio of the concrete.

Extrudability refers to the uninterrupted and continuous extruding concrete supplied inside the nozzle, without stopping or clogging, to the desired location. This is a feature affected by the selected material, and extrudability is better when there is more flowability. Studies that developed 3D printing mortars to secure extrudability are currently mixing various compounds to conduct experiments [22]. These studies found that materials with a high yield stress had more difficulty with extrusion, and during extrusion it was not continuous, or there were disconnections. In addition, extrudability was highly impacted by the shape and size of the nozzle extrusion hole. Therefore, developed nozzles require a concrete mixing ratio where extrusion is easy and there are optimal nozzle extrusion holes. This is judged by the width and whether there are disconnections in the extrusion shape.

Buildability related to 3D printing technologies shows the quality of materials used for printing concrete. Used materials must secure flowability and yield stress after extrusion. Extruded concrete is laminated, layers are increased, and the structure is made in a zig-zag form, thereby improving the buildability of concrete. Buildability is thus measured with the yield stress of the concrete, and the shape and size of the concrete are categorized by buildability. When buildability is decreased, the usage years of the concrete decrease, which causes a decrease in quality, and therefore, it is a crucial feature for concrete printing. That is why it is necessary to secure the appropriate yield stress of the concrete used in the free-form concrete panel. In addition, it must have an intensity at which the developed concrete nozzle mixer can be tempered smoothly.

Flowability is a feature related to the materials used during concrete printing, and the aggregate content is determined according to flowability when selecting the appropriate 3D printing concrete mixing ratio. In the case of 3D printing concrete, unlike the concrete used in typical molds in the past, it has a high viscosity and is similar to a solid with almost no flowability; it also has outstanding extrudability and is easy for lamination. However, free-form molds have concerns about deformation in the design shape, thus making them impossible to lay, and they require good concrete liquidity. It is thus necessary to secure the flowability of concrete by measuring the slump value to use for printing.

4. Development of Concrete Extrusion Nozzle for FCP Production

Concrete extrusion nozzles for FCP production were developed to reflect the required performance derived above, such as pumpability, workability, extrudability, buildability, and flowability. This is composed of the nozzle part, open/close part, and control part, and its composition and function are shown in Figure 9 [23].

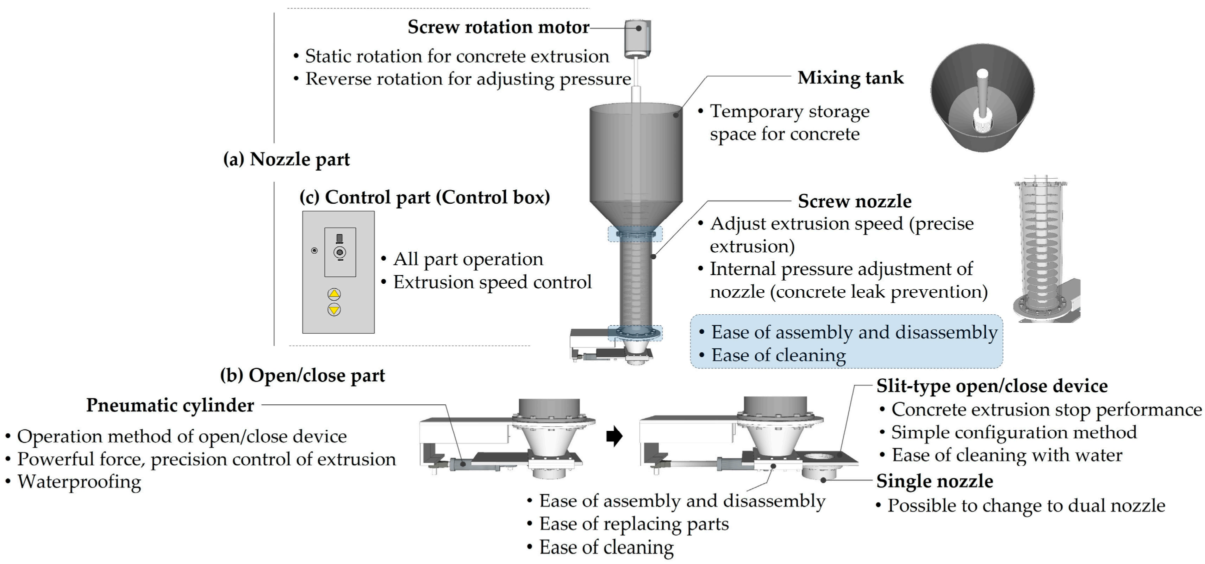


Figure 9. Components of a concrete extrusion nozzle for FCP production.

The nozzle part is made up of a screw rotation motor, concrete extrusion screw, and mixing tank, as shown in Figure 10. The screw rotation motor rotates the concrete extrusion screw and controls the extrusion screw's direction in a forward or reverse direction. It rotates forward during concrete extrusion, and because the nozzle is vertical, pressure is applied in the extrusion direction. When closing the extrusion hole after extrusion is complete, the concrete remaining in the mixing tape tends to leak due to the force that tries to exit through the extrusion hole because of internal pressure. At this time, the rotation direction of the screw is changed to switch the direction of pressure applied inside the nozzle to adjust the pressure. Therefore, when stopping concrete extrusion, the screw rotating in a forward direction is changed to the reverse direction to control the internal pressure and thereby prevent concrete leaks. The material of the concrete extrusion screws is stainless steel, which has good strength, does not rust as much as normal steel and is therefore a better material for concrete extrusion. This is rotated by a screw rotation motor, and it is used for extruding concrete. The screw rotation has eight speeds, and the concrete extrusion speed can be adjusted. This extrudes concrete precisely at an appropriate speed in the location where a single side or lateral pressure of free-form molding is expected to occur. It rotates quickly in the center of the mold or at a position where shape configuration is not needed to extrude the concrete quickly.

The mixing tank is where the concrete is supplied and stored. The supplied concrete is located within the mixing tank until the concrete is extruded in the mold, and the concrete located at the top will decrease in quality due to material separation or hardening as time passes. The continuous rotation of the mixing bar inside the mixing tank prevents material separation and hardening.

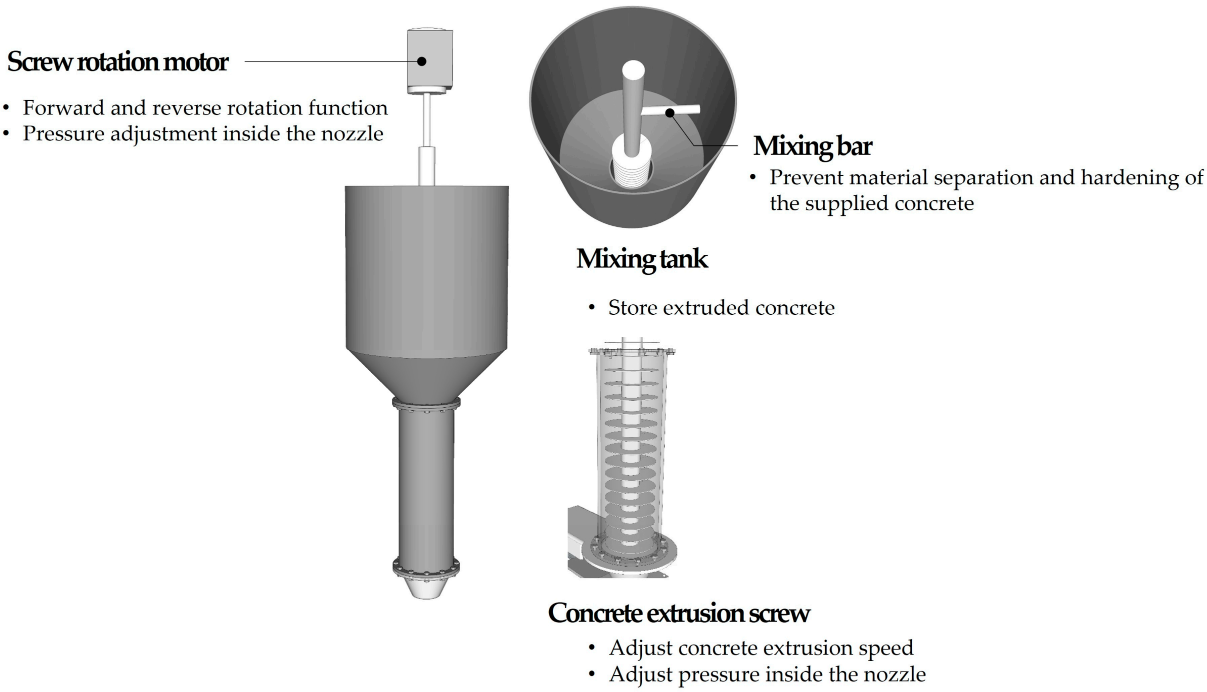


Figure 10. Components and functions of the nozzle parts.

The concrete extrusion nozzle for FCP production continuously extrudes to secure the concrete quality. The nozzle extrusion hole was designed in a vertical direction to continuously and uninterruptedly extrude. Valves and pumps are used to stop concrete from being extruded vertically and use methods to control with various software [24]. Free-form molds require precise extrusion as they have different shapes. Thus, it requires the operation and stop functions that adjust the extrusion quantity to extrude the fixed amount of concrete where the extrusion is located. This study installed a slit-type open/close device in the nozzle extrusion hole, as shown in Figure 11, to adjust the concrete extrusion quantity. The slit-type open/close device freely adjusts the concrete extrusion, stop, etc., and the slit moves according to the pneumatic cylinder to open/close the extrusion hole. The slit is fixed in the pneumatic cylinder, as shown in (a), to open the extrusion hole when extruding concrete. After extrusion ends, the pneumatic cylinder pushes the slit with a stronger force for the nozzle extrusion hole to open and close the extrusion hole, as shown in (b).

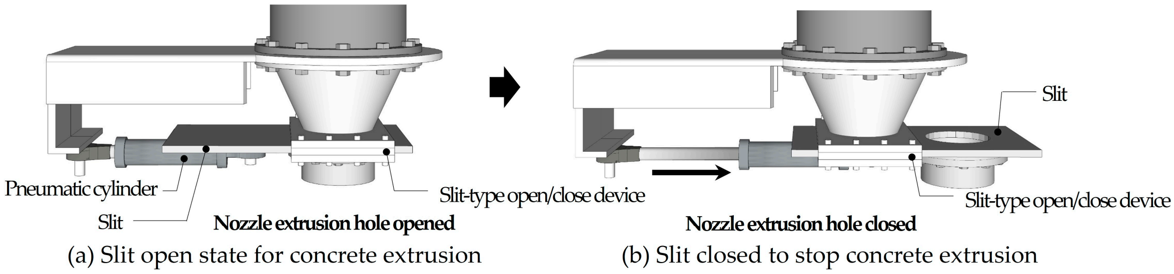


Figure 11. Slit-type open/close operation method.

The control part controls the functions of the manufactured concrete extrusion nozzle for extrusion and operation. This controls the aforementioned nozzle part and opens/closes the part using the control box. The extrusion speed adjustment function is made up of the operation switch and the speed adjustment function. The concrete extrusion field divides the mold into an end part and a central part, as shown in Figure 12a, to extrude with different extrusion speeds. The end part comes into contact with the mold, and therefore, it is very weak against lateral pressure and extrudes concrete precisely at low speeds. The central part has sufficient strength and therefore extrudes at faster speeds to fill. The rotation speed of the extrusion screw motor can be adjusted to 1–8 speeds, and this controls the mixing bar and the extrusion screw rotation speed. The open/close function opens and closes the extrusion hole with the on/off button for the slit-type open/close device. Existing concrete extrusion technologies cannot stop concrete immediately due to the strong pressure in the process of sending concrete from the pump. This extrudes concrete in excess of the fixed amount in the FCP mold, which requires precise configuration. In the case of the concrete nozzle for FCP production, the extrusion hole can be blocked for fixed quantity extrusion, as shown in Figure 12b.

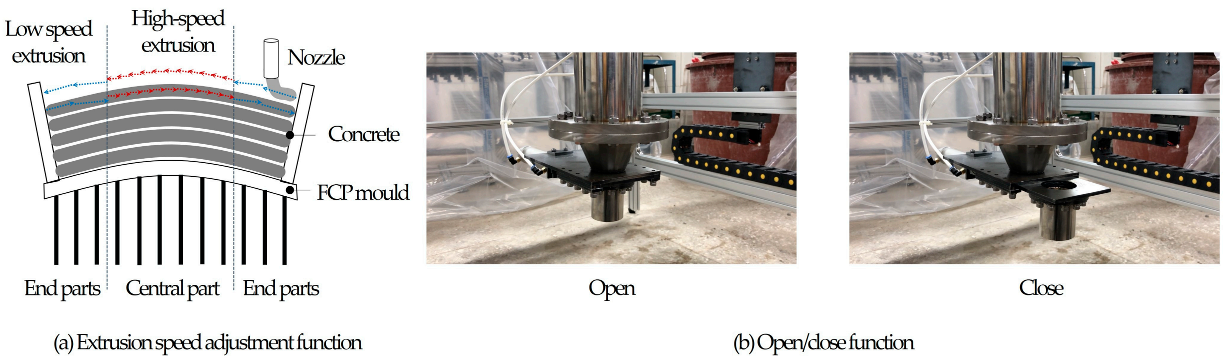


Figure 12. Functions of a concrete nozzle for FCP production.

In the slit-type open/close device developed in this study, a pneumatic cylinder pushes with a powerful force to close the extrusion hole. It is a new opening/closing method different from the existing nozzle, and it is possible to stop and operate the concrete at the desired time. However, the pumped concrete has a pressure that tries to push the closed slit plate inside the nozzle, causing leaks. This causes errors in the precise shape configuration of FCP. The process of opening/closing the extrusion hole and countermeasures for concrete leaks are shown in Figure 13. Concrete leaks are caused by the concrete pressure that tries to extrude from inside the nozzle. The extrusion screw rotates in a forward direction to extrude concrete. After completing extrusion, the nozzle is not stopped right away, but the rotation is changed to the opposite direction. At this time, the rotation direction is temporarily changed, and the inverse rotation of the vertical concrete pressure that occurs inside the nozzle is offset by the raising force. The extruded concrete is stopped at this time, and the open/close device completely closes off the extrusion hole.

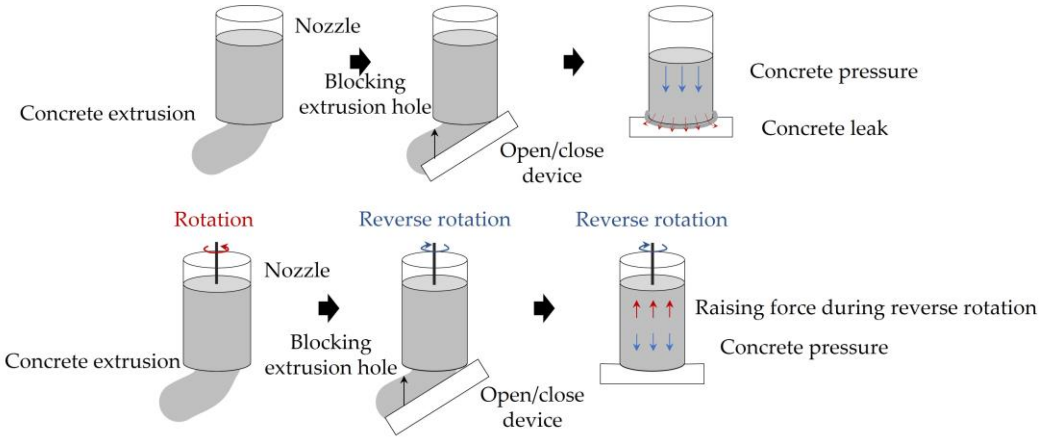


Figure 13. Process of opening/closing the extrusion hole and preventing concrete leaks.

The concrete extrusion nozzle for FCP production was developed based on this function and the nozzle order of operations are shown in Figure 14. Concrete is pumped to the mixing tank via the pump and the mixing bar rotates continuously until concrete extrusion to prevent material separation and hardening. After selecting the concrete extrusion location in the FCP mold, the slit-type open/close device is opened, and the extrusion is performed. The extrusion screw rotates in a forward direction and the appropriate extrusion speed is changed according to the position of extruding concrete, and it is precisely and quickly extruded to the FCP mold. After extrusion ends, the rotation direction is reversed to prevent concrete leaks, and the pneumatic cylinder pushes the slip to close the extrusion hole.

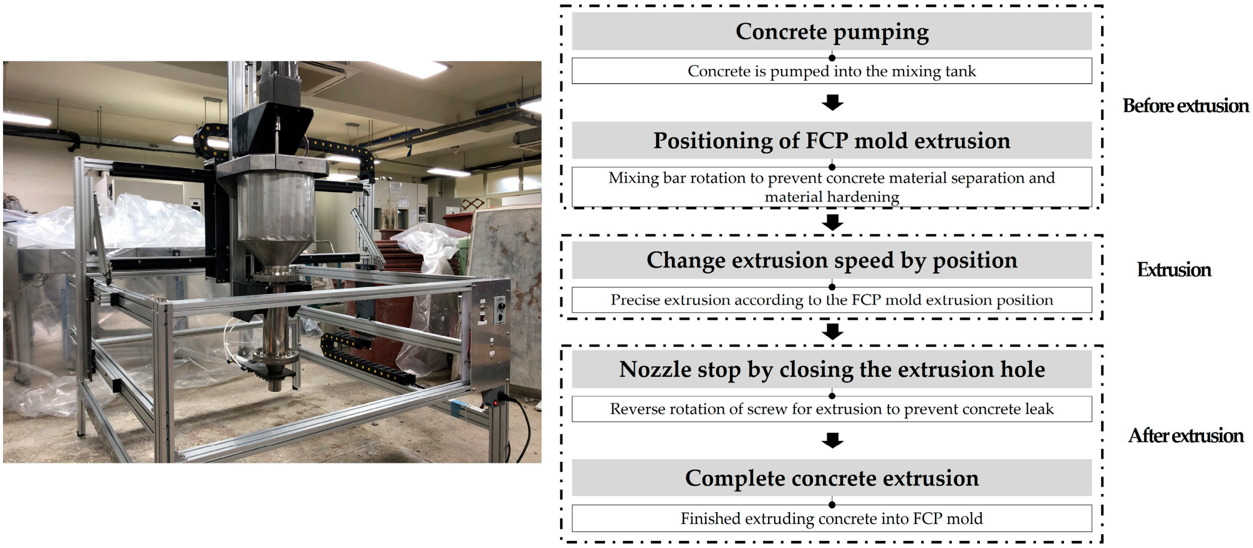


Figure 14. Concrete extrusion nozzle for FCP production and Nozzle operation order.

5. Concrete Nozzle Performance Test for FCP Production

The required performance for the concrete nozzle for FCP production developed in this study satisfied pumpability, workability, extrudability, buildability, and flowability. Nozzle extrusion tests were performed to check whether each required performance was satisfactory. During the mixing design of 3D printing concrete in the past, W/B, cement, aggregate, admixtures and compounds, fiber usage, printer nozzle size, printing speed, etc. were selected. In the case of W/B, it was found that there was a high correlation between flowability, hardening time, and the compressive strength of 3D printing [25]. In the case of the concrete nozzle for FCP production developed in this study, the appropriate mixture ratio standard was judged by compressive strength, flexural strength, and slump value to precisely fill the free-form molds with different shapes. Figure 15 shows the day-three compressive strength, flexural strength, and slump value at W/C 35, 36, 37, 38, 39, and 40%. Free-forms cannot perform laying, and it is thus crucial to secure flowability. Therefore, the mixing ratio was selected in the order of slump value, compressive strength, and flexural strength. The compressive strength was measured at its highest value when W/C was 35%, and it was found that as the W/C value increased, the compressive strength decreased. Flexural strength was measured at 5.4 MPa when W/C was 35%, but it was measured at similar values for other W/C values as well. There were no existing research results available for the standard of the slump value used in free-form concrete panels. So, we conducted preliminary extrusion experiments with concrete of W/C 30–45%. Through this, the range of standard values was narrowed, and an approximate interval was selected based on experience. The appropriate slump value for producing free-form concrete panels is 160 mm (±25) [26]. When the slump value is W/C 38%, it is 135 mm, and when it is 39%, it is 180 mm, thus satisfying the standards. Therefore, W/C 38% and 39% were selected as the mixing ratio to perform the extrusion tests.

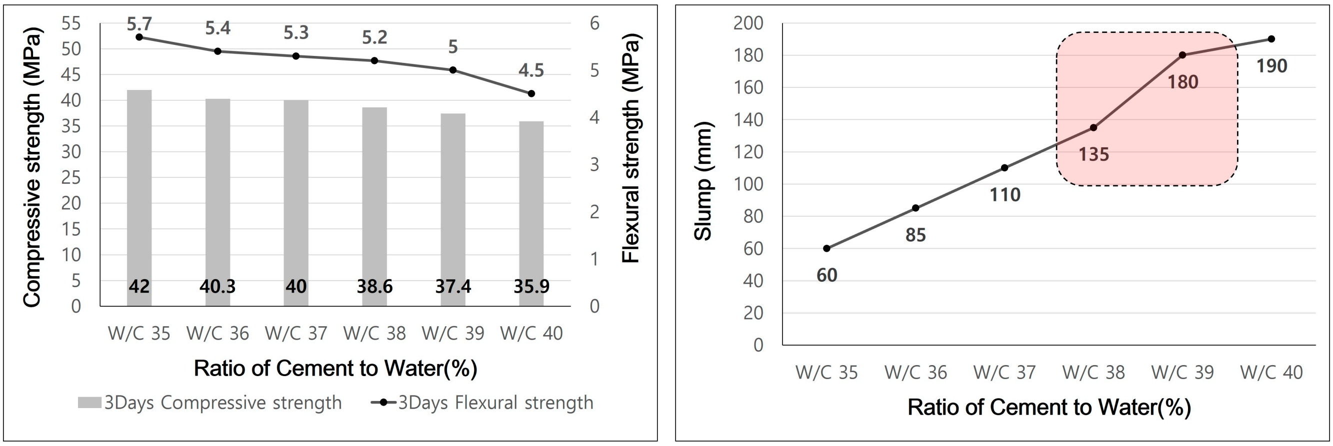


Figure 15. Evaluation item data according to W/C.

The extrusion test was performed at the previously selected mixing ratios of W/C 38 and 39%, when slump was insufficient at 37%, and when slump was beyond the standards at 40%. The experiment evaluated extrudability by having the concrete extrusion nozzle for FCP production and by checking the extrusion shape according to the slump value. Afterward, the mortar was extruded according to the path to check the open/close performance, which is the nozzle function. The extrusion shape according to slump is shown in Figure 16. There were fine cracks in the extrusion shape at W/C 37, 38%. When at 39 and 40%, it was found that the extrusion was performed evenly without cracks. However, during the extrusion process, extrudability and even thickness were possible according to the moving speed of W/C 38% and W/C 39%.

However, there were fine cracks in the extrusion shape at W/C 38%. Additionally, this lacked pumpability and extrudability because the nozzle extrusion hole shape was a vertical round pillar and had the same width for the insertion and extrusion hole. Furthermore, there were no concrete leaks during the open/close function operation in the extrusion process, but the slit was located higher than the extrusion hole, and therefore, residue was left, as shown in Figure 17, thereby reducing the density of the shape.

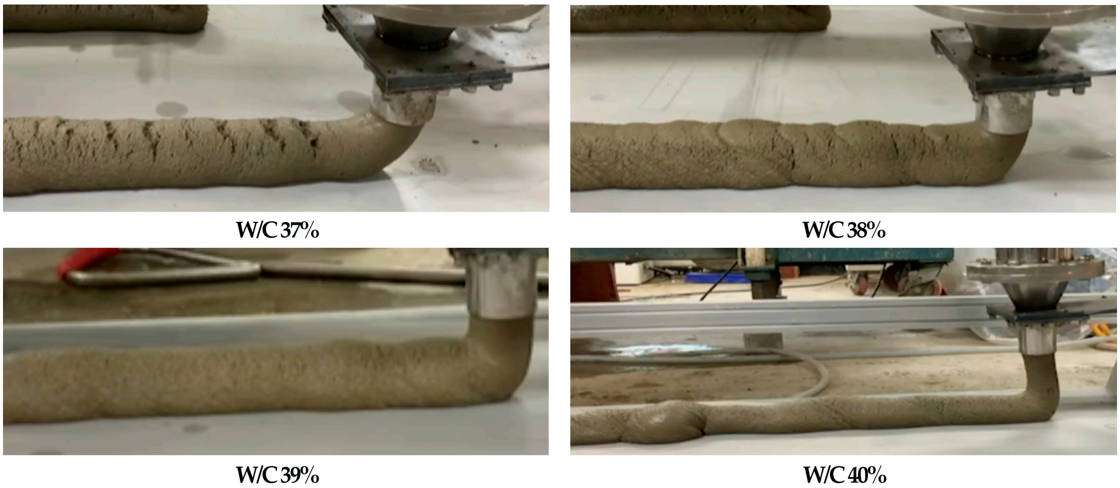


Figure 16. Extrusion shape according to W/C.

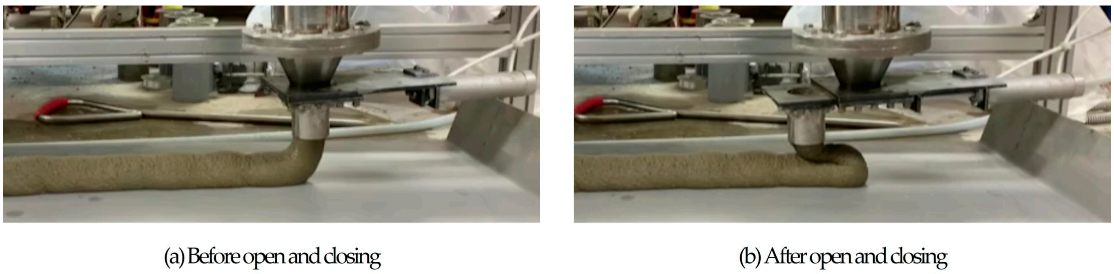


Figure 17. Problems of the open/close function.

In order to solve this, a new extrusion hole for the concrete extrusion nozzle for FCP production was selected to perform the extrusion tests. The width of the original nozzle extrusion hole that had similar width as the insertion hole was reduced in a rectangular shape to apply pressure inside the nozzle. This pressure generated inside the nozzle during extrusion, and when the force is applied to the concrete, it lumps up and extrudes the concrete evenly and precisely without any interruptions. Additionally, when using the open/close function, there is no extruded force, and therefore, complete stopping of the extrusion is possible. The improved extrusion hole is shown in Figure 18, and (a) is the rectangular extrusion hole model, and (b) is the model that was supplemented with a 3 mm half-elliptical shape on the two sides of the rectangular extrusion hole.

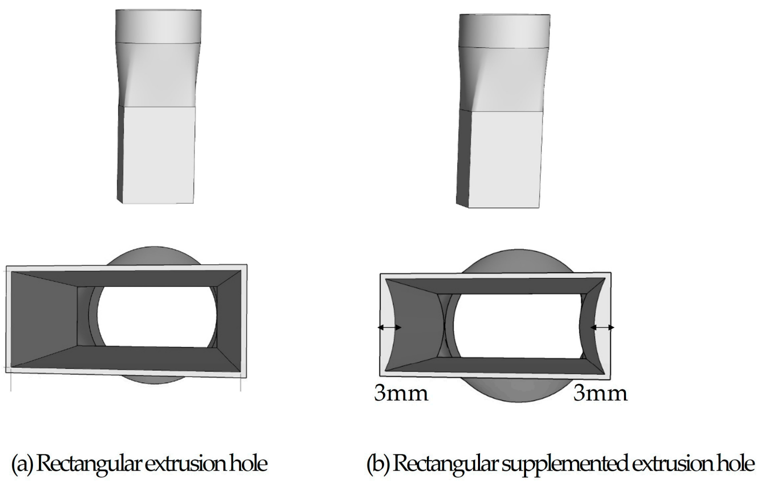


Figure 18. New nozzle extrusion hole modeling.

The new extrusion hole was printed using 3D printing to attach to the nozzle and perform the extrusion tests. The extrusion test aimed at verifying the performance of the previously selected mixing ratio and extrusion hole through the mortar extrusion shape. In addition, it aimed at checking the open/close performance and extrudability, which are the functions of the concrete extrusion nozzle for FCP production. The mortar extrusion test route was selected as follows: first, process ① performed the repeated extrusion, and changes were made to the extrusion direction to measure the width of the extruded mortar. The processes of ② and ③ performed the extrusion in one direction, and after completing process ②, the open/close device was activated. While the extrusion hole is closed, the nozzle was moved to ③ to perform the extrusion in a single direction. Through such a process, the thickness and width of the shape extruded by the new extrusion hole were measured to select the appropriate extrusion hole for the shape configuration. The rectangular extrusion hole of (a) extrudes mortar as shown in Figure 19. ① Disconnections improved in the straight-line sector for smooth extrusion. The width of the extruded shape was found to be 45 mm and the thickness was about 20 mm. However, extruding a constant thickness was not possible in areas where the directions changed. In the open/close sector from ② to ③, there was insufficient extrudability, thus making continuous placing impossible.

Figure 19. Rectangular extrusion hole extrusion shape and testing.

The rectangular supplemented extrusion hole (b) had a 3 mm elliptical shape located on the side of the extrusion hole to lay the mortar and extrude as shown in Figure 20. In the ① straight-line sector, thickness was not as even as (a), but extruded with less interruptions. The width of the extruded shape was found to be 60 mm and the thickness was about 22 mm. In areas where directions changed, thickness was maintained relatively well and even width was maintained continuously for extrusion. Residue was not extruded in the open/close sectors from ② to ③, but it was found that it extruded continuously even after opening/closing.

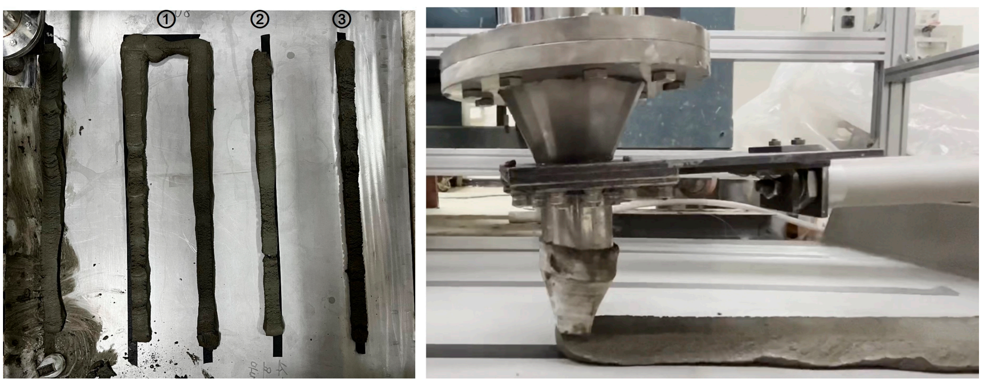


Figure 20. Rectangular supplementation extrusion hole extrusion shape and testing.

6. Conclusions

As studies to configure free-form buildings have been conducted as of late, there have been new technological developments and the development of new equipment. However, it is difficult to realize free-form shapes, so many studies are being conducted on how to manufacture them. Among them, research on technologies and equipment based on CNC technologies is being conducted, and FCP manufacturing equipment was developed as the most representative. However, FCP manufacturing equipment also uses manpower for extrusion inside the FCP molds. This requires the development of a precise extrusion method because design shape deformation occurs due to the lateral pressure of the precisely manufactured molds. Therefore, in this study, a concrete extrusion nozzle for FCP production was produced to develop technologies for more precise extrusion of concrete. Existing concrete extrusion nozzles are used to print walls or structures, but the purpose of the concrete extrusion nozzle for producing FCP developed in this study is to precisely fill the inside of the molds produced by FCP manufacturing equipment without deforming the shape.

(1) According to the purpose of this equipment, the required performances were selected as pumpability, workability, extrudability, buildability, and flowability through the preceding research analysis for application in FCP production equipment. Each required performance was satisfied, and the concrete extrusion nozzle for FCP production was composed of the nozzle part, the open/close part, and the control part, and they were produced with the purpose of filling the FCP mold. Its main functions are an open/close function for stopping concrete extrusion, extrusion speed adjustment functions for precisely extruding according to the free-form shape of FCP molds, and a reverse rotation function to prevent concrete leaks after stopping extrusion.
(2) Concrete extrusion tests were performed to verify the required performance of the concrete nozzles for FCP production. The appropriate slump value for producing free-form molds was 160 mm (±25), and the only mixing ratios satisfying this were W/C 38% and 39%. In order to judge this as an extrusion shape, it was experimented at W/C 38%, 39%, W/C 37%, where the slump value was insufficient, and W/C 40%, where the slump value was exceeded. As a result, the stable shape was checked at W/C 38% and 39%.
(3) There were fine cracks in the extrusion shape at W/C 38% because it is a straight-line structure where the nozzle pumps immediately from the insertion hole to the extrusion hole. This is judged to be due to insufficient pumpability and extrudability. For the open/close function, the slit location was higher than the extrusion hole, and therefore, the residue in the extrusion hole reduced the precision of the extrusion shape. Accordingly, extrusion holes for a rectangular model with a reduced width compared to the round insertion hole and a model with a 3 mm half-ellipse on the side of the inner part of the rectangle were produced. The rectangular extrusion hole and the rectangular supplemented extrusion hole all extruded smoothly without interruptions in the extrusion shape. However, in the case of the rectangular extrusion hole, it lacked extrudability, and continuous extrusion in the open/close sectors was not possible. In the case of the rectangular supplemented extrusion hole, it had a width of 60 mm and thickness of approximately 22 mm, did not have residue even in the open/close parts, and extruded evenly in continuous sectors.

Existing concrete extrusion nozzles are used to print walls or structures. but the concrete extrusion nozzle for producing FCP developed in this study is to precisely fill the inside of free-form molds. Testing the extrusion, the open/close performance, and extrusion speed adjustment performance were verified. However, constant extrusion in routes where directions changed was difficult, and therefore, to make possible precise extrusion in a constant shape for all directions, it is necessary to develop a new extrusion hole and an opening/closing device that does not thus cause residue. Concrete extrusion nozzles for FCP production are basic equipment, so they used mortar. Therefore, it is required to conduct concrete experiments (early shrinkage, plastic shrinkage, strength), and research on making nozzles smaller and automated for application in automatic FCP production equipment is needed. This study is expected to contribute to the development of free-form construction technologies and construction equipment, and it presented new open/close functions of concrete extrusion nozzles.

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