Design and Construction of Shell-shaped Bench using a 3D Printer for Construction

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Abstract –

One of the problems in the practical use of 3D printers using cement-based materials is how to withstand the tensile force. In general, cement-based materials can withstand compressive forces. Therefore, reinforced concrete structures are applied as composite structures with steel materials such as reinforcing bars that can withstand tensile force.

In this study, we developed a composite structure, in which the outer part was laminated with mortar exclusively for 3D printers, and the inner part was filled with ultra-high strength fiber-reinforced concrete as a substitute of reinforcing bars. When the test piece was manufactured and its mechanical properties were tested by experiments, it was concluded that the desired strength had been obtained. Then, a large shell-shaped bench, whose outer dimensions comprised a width of 7 m, depth of 5 m, and height of 2.5 m, was manufactured. The design used topology optimization that derived a shape with high structural rationality; the total weight was reduced by approximately 60%. The shape derived by topology optimization would have been difficult to construct with a formwork, and we were able to exploit the advantages of using a 3D printer.

Keywords –
3D Printer; Automation; Laborsaving

1 Introduction

A 3D printer using cement-based materials (hereinafter called "3D printer") ejects special mortar (hereinafter called "3D mortar") from a nozzle attached to a mobile mechanism, such as a robot arm, and laminates the mortar to construct a structure. We have developing a 3D printer, which we refer to as a 3D printer for construction. Since the structures could be constructed automatically without using a formwork, freedom in design and laborsaving ways of construction could be realized.

One of the problems in the practical use of 3D printers is how to withstand the tensile force generated in the structure. In general, cement-based materials can withstand compressive forces. Therefore, reinforced concrete structures are applied as composite structures with steel materials such as reinforcing bars that can withstand tensile force. To solve this problem, the following methods have been devised: a) inserting a steel material such as a reinforcing bar during the 3D printing process [1], b) manufacturing a piece with a hollow using a 3D printer, and inserting a PC steel bar into the hollow to introduce a prestressed force [2], and c) using a cement-based material capable of withstanding the tensile force such as ultra-high strength fiber-reinforced concrete (hereinafter called "UFC") [3].

Therefore, we developed a composite structure in which the outer part was laminated with 3D mortar and the inner part was filled with UFC as a substitute to reinforcing bars. In this study, basic structural experiments were conducted to confirm that an actual structure could be constructed using this composite structure. And, we designed and constructed a large shell-shaped bench with outer dimensions comprised a width of 7 m, depth of 5 m, and height of 2.5 m; this experiment demonstrated the use of the composite structure.

2 Development of Composite Structure

2.1 Composition of Composite Structure

We developed a composite structure by using 3D mortar and UFC. In order to construct the composite structure, first, the outer portion of the structure was laminated with 3D mortar so that the portion that was to be reinforced by a reinforcing bar became hollow. Then, the UFC was placed into the hollow. The filled UFC could withstand the tensile force generated in the structure.

2.2 3D Mortar and UFC

For the 3D mortar, mortar premixed with a hardening accelerator was used, and the hardening speed was adjusted by setting up a retarder. In addition, polyvinyl alcohol (PVA) fiber was mixed to increase the bending strength. It had a compressive strength of 60 N/mm^2 and a bending strength of 3.5 N/mm^2.

UFC [4] is a room-temperature-hardening-type mortar, developed by the Obayashi Corporation that can achieve a compressive strength of 180 N/mm^2, tensile strength of 8.8 N/mm^2, and bending strength of 32.6 N/mm^2. This material has a high tensile strength, bending strength, and tensile toughness; thus it can function as a structure in itself. This slump flow was approximately 600 mm and had a self-filling property. Therefore, the placement work was easy, and the automation and mechanization will be easy as well, compared to the manual arrangement of reinforcing bars.

2.3 Verification of Mechanical Performance

2.3.1 Outline of Experiment

Figure 1 shows the cross section of the test piece. The width and thickness are 500 mm and 120 mm, respectively, and the UFC parts with a width of 50 mm and a thickness of 70 mm, are evenly arranged in five different positions.

Photo 1 shows the manufacturing status of the test piece. First, the 3D mortar was laminated with a 3D printer until the height was 1 m. Next, as shown in Photo 2, the UFC was placed in the hollow. The UFC, which was placed in the hollow, was constructed without being spliced.

A three-point bending test was conducted to confirm the bending properties of the test piece (No. 1) manufactured with the composite structure. For comparison, a bending test was also conducted on a test piece (No. 2), which was not filled with UFC, as shown in the cross-section of Figure 1.

2.3.2 Methods of Loading and Measuring

Photo 3 shows the device loading for the bending test. The left end of the test piece was supported by a pin, the right end was supported by a pin roller, and the distance between the supporting points was 800 mm. In order to maximize the bending moment at the center of the test piece, a hydraulic jack and ball seat were attached to the upper center part of the span, and the load was applied vertically downward. Since the width of the test piece was as large as 500 mm, a vertical load was applied through a beam with a height of 200 mm. The applied force was a monotonic load that was pushed in one direction. The vertical load at the center of the test piece was measured with a load cell. The displacement in the vertical direction at the center of the test piece was

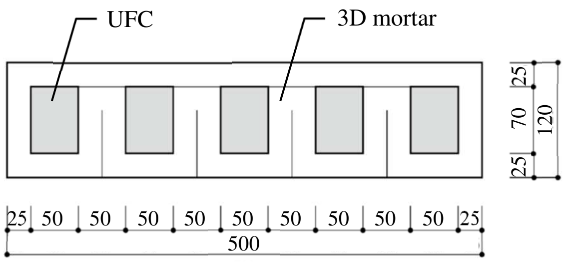


Figure 1. Cross section of the composite structure

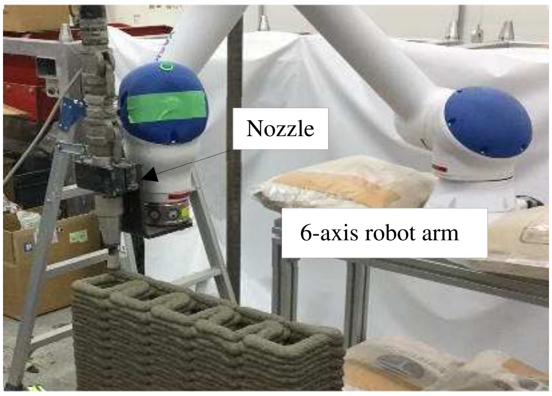


Photo 1. Printing of test piece

Photo 2. Placing UFC

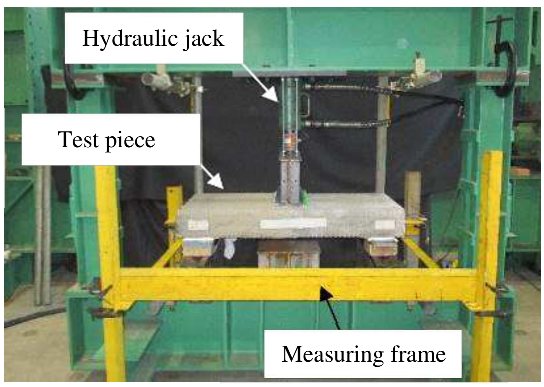


Photo 3. Loading device

measured with a displacement meter, and the downward direction reflected the positive values. The displacement was the average of the values measured at the front and at the back of the test piece.

2.3.3 Result of Experiment

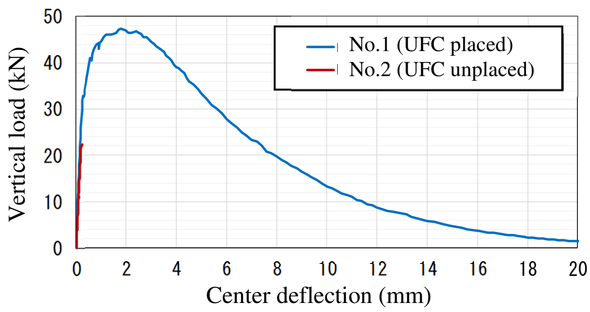
Photos 4 and 5 show the final destruction status. Photo 4 shows the final fracture of No. 1. Photo 5 is an enlarged photograph of the fractured surface of No. 1. In both No. 1 and No. 2, cracks were found near the lower end of the center of the test piece, and finally a fracture surface was formed almost in the center of the test piece. Many steel fibers protruded from the portion of the UFC on the fracture surface of No. 1. It was also confirmed that the hollow was filled with the UFC without any gaps. In both the test pieces, there were no evidences that the mortar at the compression edge had undergone compression failure.

Figure 2 shows the relationship between the vertical load and the center deflection. The maximum load of No. 1 was 47.4 kN. On the other hand, the maximum load of No. 2, which was not filled with the UFC, was 22.5 kN. No. 1 shows a maximum load of more than twice the maximum load of No. 2, because the UFC withstood the tensile force. Moreover, in No. 2, brittle fracture occurred after the maximum load was applied, and the yield strength decreased sharply. However, in No. 1, due to the tensile toughness of the UFC, the yield strength gradually decreased.

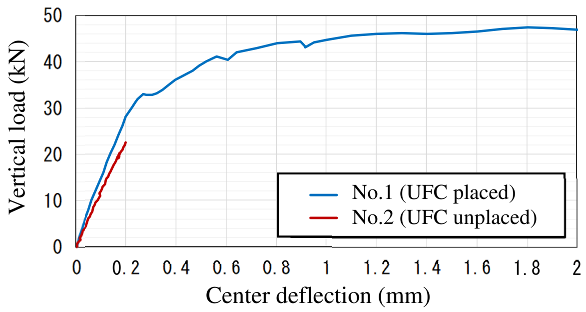
From the above, it was found that the developed composite structure improved both the maximum load and the toughness performance, because the UFC was placed in the hollow and could withstand the tensile force.

Photo 4. Final fracture (No.1)

Photo 5. Detail of the fracture surface (No.1)



(1) Entirety



(2) Initial loading

Figure 2. (Relationship between) vertical load and center deflection

3 Design of Shell-shaped Bench

3.1 Outline of Design

To verify the practicality of the developed composite structure, the shell-shaped bench, which is shown in Figure. 3, was manufactured. The design included a cantilever shape that produced a large tensile force and incorporated a curved surface that 3D printers were good at.

The outer shape was manufactured by laminating the 3D mortar, but if the entire interior was filled with the UFC, as shown in Figure 4, the weight increased and the structural rationality decreased. Therefore, the internal structure of the shell-shaped bench had a hollow part, as shown in Figure 5, to reduce the weight. Therefore, in order to determine the morphology of the internal structure, we applied topological optimization that gradually removed the stress and derived the optimum morphology by Finite Element Method (FEM) analysis. Figure 6 shows the design flow of the internal structure.

Since a 3D printer could manufacture pieces without using the formwork, it was suitable for manufacturing complex shapes that had hollow internal structures derived by topology optimization.

3.2 Topology Optimization

In topology optimization, the ratio of the reduced weight to the initial weight was set as the target value. Then, a form in which the stress was minimized in a range satisfying this target value was derived. The target value for weight reduction was set at 65% of the initial weight. Only the long-term load (self-weight) was used as the load condition in the FEM analysis, and the short-term load (horizontal force) generated during use was not considered. The reason for this is that shell-shaped benches have a cantilever shape and are easily affected by their own weight. As shown in Figure 7, topology optimization was performed by assuming a thin plate with a width of 30 mm in the cross-sectional shape of the center position of each piece obtained by dividing the total bench width of 7 m into 1 m intervals. For fixing the conditions, both the ends of the bottom of each piece were fixed.

Figure 8 shows an example of the result of topology optimization. The result of topology optimization of each piece divided into seven parts was truss-shaped, similar to that shown in Figure 8. The truss-shaped portion derived by topology optimization was made visible as a shell-shaped bench design. Therefore, as a design adjustment, the position of the bundle was adjusted finely so that the positions of the holes could be seen continuously from one end to the other.

3.3 Checking Allowable Stress

Topology optimization does not check whether the stress calculated in the morphology derivation process is within the allowable stress level of the material used. Therefore, the static stress analysis was performed on the design adjusted form, and the allowable stress level was checked. At that time, in addition to the long-term load, the horizontal force (0.2 G) was also considered as a short-term load that was generated during the use. The structural designer manually corrected the cross-sectional shape till the allowable stress level was cleared. Structural experiments have suggested that in the composite structure, 3D mortar and UFC behave as a unit. However, since the mechanism is still unclear, we used a design so that it could be established only for the cross section of the UFC.

3.4 Final Design

Figure 9 shows the final design of the shell-shaped bench. The shell-shaped bench was divided into 12 parts.

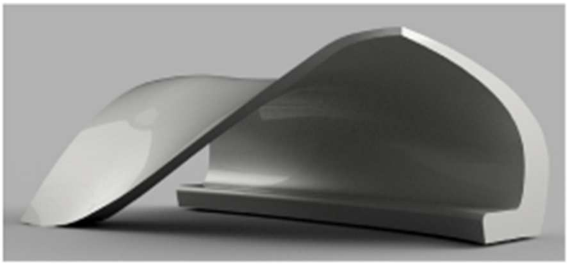


Figure 3. External design of shell-shaped bench

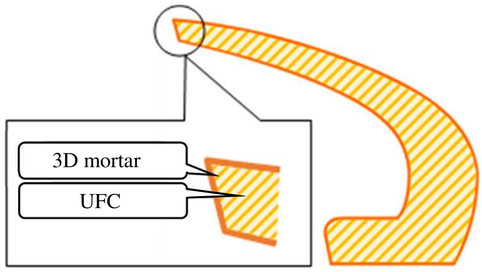


Figure 4. Layout of 3D mortar and UFC (Fully filled)

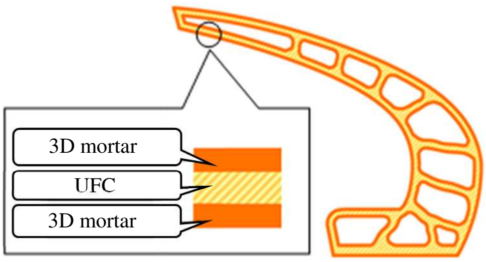


Figure 5. Layout of 3D mortar and UFC (Structurally rational)

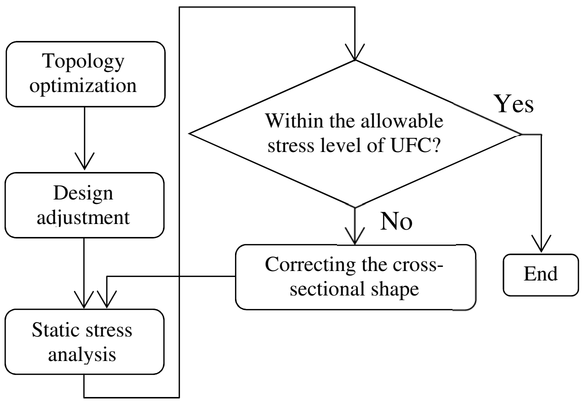


Figure 6. Design flow

The reason for this was that the time required for printing 3D mortar (working time per day) was limited, and transportation and erection after manufacturing became safe and smooth. The divided width of the 12 pieces was 500 mm at both ends and 600 mm at the other parts. Each piece was installed by a crane, with a joint width of 10 mm from the adjacent piece, and then sealed without connecting to the adjacent piece. The final design was approximately 60% lighter than the structure fully filled with the UFC.

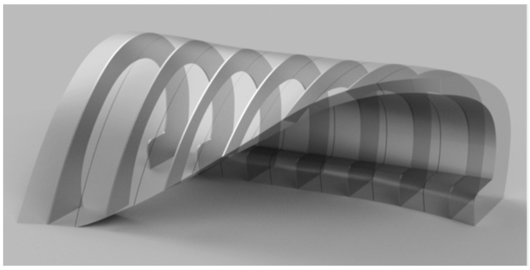


Figure 7. Sections to apply topology optimization

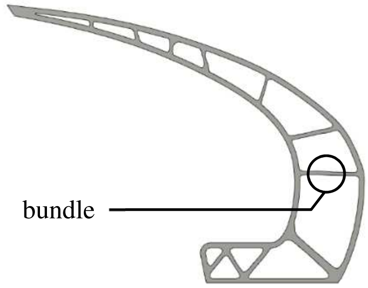


Figure 8. Example of applying topology optimization

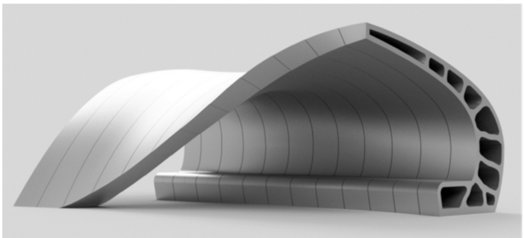


Figure 9. Final design

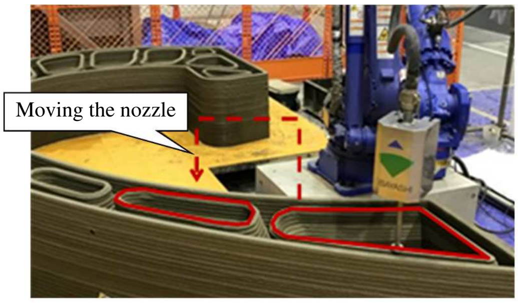


Photo 6. Example of jump in the print path

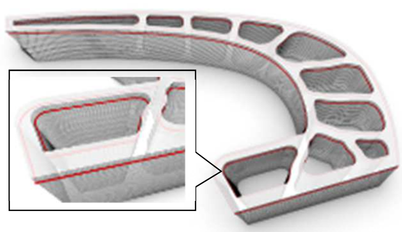


Figure 10. Automatic generation of the print path

4 Development of Elemental Technology for Printing 3D Mortar

4.1 Development of Valve

If the material ejection cannot be stopped in the printing 3D mortar, the print path must be a one-stroke and a non-intersecting path. Since the shell-shaped bench had a hollow, it was necessary to print the outer and the inner peripheries separately. Therefore, as shown in Photo 6, it was necessary to intermittently move the nozzle from the outer periphery to the inner periphery and from the inner periphery to the other inner peripheries. Therefore, we developed a valve that worked with the pump so that the ejection of the mortar could be stopped temporarily.

4.2 Automatic Generation of Print Path

We developed a software that automatically generated print path data from a 3D model. The 3D model was prepared in a format that represented a solid with a triangular mesh called the stereolithography (STL) format. In 3D modeling software, the STL format is a standard output format. Figure 10 shows an example of automatic generation. The 3D model was cut with the laminated thickness of the mortar, and the coordinates of the obtained intersections were classified into "outer periphery" and "inner periphery ". A print path was generated from the classified intersections and converted into a robot language used to control the robot arm.

5 Construction of Shell-shaped Bench

5.1 Outline of Construction

The 3D printer was installed in the building for experiments using concrete. Figure 11 shows the manufacturing process of the shell-shaped bench pieces. Manufacturing is a 5-day process. On the first day, the outer shape of the composite structure was manufactured using a 3D printer. The second day was a curing day and was used for developing the strength of the 3D mortar. The third day was the placement day of the UFC. The fourth day was also a curing day for developing the strength of the UFC. On the fifth day, the piece was moved from the 3D printer to the installation location.

5.2 State of Construction

5.2.1 Printing 3D Mortar

Photos 7 and 8 show the condition of the printing 3D mortar. The width and thickness of the 3D mortar lamination could be controlled to a designated size by adjusting the ejected amount of the 3D mortar and the moving speed of the nozzle. These were adjusted in advance to obtain a mortar width of 30 mm and a mortar thickness of 5 mm.

The piece was printed, laid down, and was divided into three layers in the direction of the height. The net time required for printing the 3D mortar was approximately 5 h. To lift the piece during construction and connect it to the foundation, a hole with a diameter of 24 mm was drilled, and an insert with an inner diameter of 20 mm was attached before the 3D mortar hardened. After printing the 3D mortar, it was covered with a wet curing mat. Water was sprayed till evening before the day of placing the UFC.

5.2.2 Placing UFC

UFC was placed at once without any jointing, using a concrete bucket with a capacity of 0.3 m^3. Photo 9 shows the UFC condition. The UFC is self-filling. Therefore, the UFC could be placed without any problem even if a 3D printer complicated the shape. In addition, because it has the characteristic of being hardened at room temperature, special curing methods such as heat curing was not required. However, after the placement was completed, a sheet curing was performed, after spraying a surface curing material, in order to prevent the dry shrinkage cracks on the top surface.

5.2.3 Moving Pieces

After the curing day of the UFC, the piece was moved from the 3D printer to the installation location. Lifting was performed under balanced conditions based on the position of the center of gravity calculated from the 3D model of the piece. After moving the piece, the 3D printing yard was cleaned to prepare for the next piece.

5.2.4 Erection and Installation of Pieces

First, the laid-down piece was raised. Gradually the roof side of the piece was lifted with a crane. When the piece was raised, the level was adjusted using the level gauge. Next, the piece was moved to the installation position, as shown in Photo 10. Support was installed to the bottom side of the roof to temporarily receive the piece. Then, the piece was anchored to the foundation with an insert attached to the bottom of the bench seat.

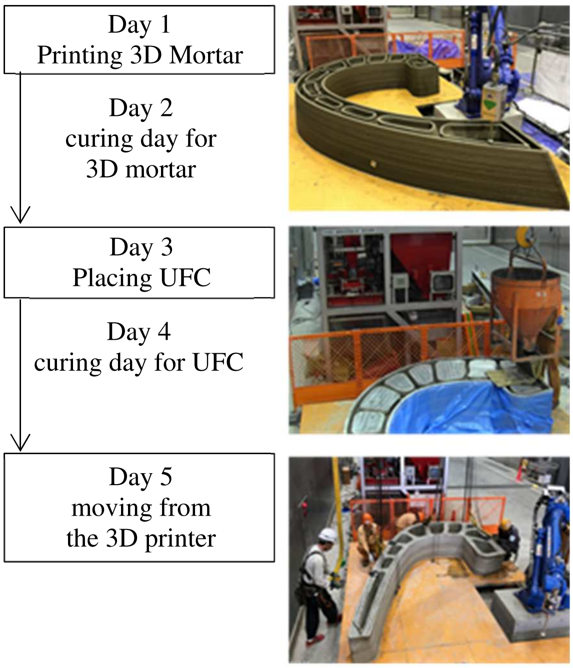


Figure 11. Manufacturing process of shell-shaped bench

Photo 7. Printing of 3D mortar (at the start)

Photo 8. Printing of 3D mortar (at the finish)

This support was removed after the foundation was established.

5.2.5 Finishing Work

A modified silicone sealing material for construction was applied to the joints between the pieces. In order to perform an exposure test on the coating performance on the 3D mortar surface, an aqueous fluororesin-based paint and a weak solvent-type two-component silicone-based paint were applied half by half. Photo 11 shows the completion of the shell-shaped bench.

Photo 9. Placing UFC

Photo 10. Erection and installation of the pieces

Photo 11. Completion of the shell-shaped bench

6 Conclusion

We developed a composite structure in which the outer part was laminated with 3D mortar and the inner part was filled with UFC, as a substitute for reinforcing bars. In this study, basic structural experiments were conducted to confirm that a structure could be actually constructed with this composite structure. In this paper, we have described the design and the construction of a large shell-shaped bench with outer dimensions comprised a width of 7 m, depth of 5 m, and height of 2.5 m, respectively, which were conducted as a demonstration experiment for this composite structure. The findings obtained are as follows:

1. In the developed composite structure, the UFC withstood the tensile force and the maximum load, and toughness performance improved. Using this composite structure, it was possible to manufacture a shell-shaped bench having a complicated shape that generated tensile force.
2. By topology optimization, the overall weight of the shell-shaped bench was reduced by approximately 60%. In addition, the hollow part consisting of curved surfaces, generated by topology optimization, had a shape that was difficult to construct with a formwork, and we were able to exploit the advantages of manufacturing with a 3D printer.
3. Since UFC has a self-filling property, it was possible to place it into a complicated shape manufactured by the 3D printer without any gaps.

Acknowledgments

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References

[1] apis cor. The biggest 3d printed building. On-line: https://www.apis-cor.com/gallary, Accessed:18/8/2020.

[2] bam. A World First: the first fully 3D printed, structurally pre-stressed concrete cycle bridge in the world. On-line: https://www.bam.co.uk/media-centre/news-details/a-world-first-the-first-fully-3d-printed-structurally-pre-stressed-concrete-cycle-bridge-in-the-world, Accessed:18/8/2020.

[3] Nadja G., Romain D., Charles B., Alban M., Philippe R., Mahriz Z., and Justin D. Large-scale 3D printing of ultra-high performance concrete – a new processing route for architects and builders, *Materials and Design*, Vol. 100, pp. 102-109, 2016.

[4] Takayoshi H. "SLIM-CRETE": DEVELOPMENT OF UFC FROM WHICH HIGH STRENGTH IS OBTAINED AT AN EARLY AGE IN NORMAL TEMPERATURE ENVIRONMENT (in Japanese). *CEMENT and CONCRETE*, JAPAN CEMENT ASSOCIATION, Vol.782:24–28, 2012.