

# Fabrication of RC Caissons Using the Slipform Method at Sea

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**Abstract** For the first time in Japan, rapid construction of an RC caisson offshore was carried out using the slipform method. To raise the formwork at a constant rate under conditions of large temperature fluctuations, we developed an application that automatically calculates the required dosage of retarder based on forecast air temperatures, enabling control of concrete setting time. In addition, because slipform formwork is open at the bottom, dewatering occurred from the lower edge of the form. To simulate these conditions, we produced formwork for cylindrical specimens and conducted strength tests to evaluate early-age strength. This paper reports the construction outline and concrete quality control.

Keywords: offshore caisson fabrication, slipform, early-age strength, retarder

## 1. Introduction

The slipform method (hereafter: the SF method) is a construction technique that rapidly builds structures with a constant cross-section by sliding the formwork upward, and it has been widely used for tower-like structures such as chimneys and prestressed concrete (PC) tanks. Overseas, there are many examples of its use in producing RC caissons for port facilities, including numerous projects in Singapore; however, in Japan, only one previous application is known, at the Shirashima Petroleum Storage Base 1.

With conventional RC caisson fabrication methods, building the wall portion of a 4,000 t-class caisson required 2 to 3 months on a floating dock (hereafter: FD). By applying the SF method, rapid construction becomes possible in about 8 to 9 days per unit.

In the SF method, the formwork is raised (stripped) as soon as the concrete reaches stripping strength. If stripping occurs too early, the concrete cannot support itself; if it occurs too late, the bond strength between the formwork and concrete increases, making it difficult to raise the formwork. Therefore, the formwork must be raised at the proper stage of strength development, and concrete strength control is critical.

This paper reports on a case in which RC caissons were fabricated offshore using the SF method in Kagoshima City, Kagoshima Prefecture, covering an overview of the SF equipment installed on an FD, the construction procedure, and quality control related to the concrete.

## 2. Overview of the SF Method

### 2.1 Equipment on the FD

Offshore RC caisson fabrication using the SF method is carried out using two of Japan's largest FDs—an 11,000 t-class unit and a 7,500

t-class unit. On the 11,000 t-class FD, a gantry measuring 35 m in width, 37.8 m in length, and 35.5 m in height was installed, and inside it a three-level SF system was built, consisting of upper, middle, and lower floors (Photo-1, Photo-2).

On the upper level, 28 hydraulic jacks for lifting are installed. These jacks support a suspended structure in which the upper, middle, and lower floors are hung below. The SF equipment was manufactured by



Photo-1 Offshore construction conditions

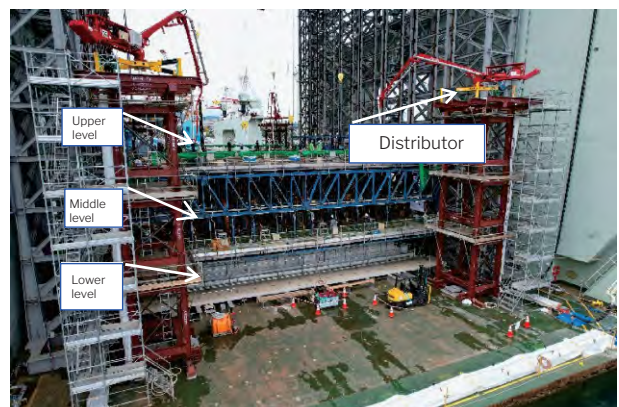


Photo-2 Equipment on the FD

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Byggin-Uddemann of Sweden, and the assembly of the gantry and related components on the FD, as well as installation of the SF equipment, were carried out at a domestic shipyard.

Eight Telpher cranes are installed along the gantry's ceiling, and they are used to hoist rebar up to the upper level, reposition the concrete pumping hoses, and move various materials and equipment.

The RC caisson being fabricated is divided into 24 cells by partition walls, and openings are provided on the upper level—aligned with each cell position—so that the concrete pumping hoses can be lowered to the middle level (Photo-3).

On the middle-level floor, 1 m-high formwork is secured using members called yokes, where rebar is assembled and concrete is placed (Photo-4).

The lower-level floor is a suspended scaffold structure, and as the formwork rises, a curing compound is sprayed onto the newly exposed concrete and finishing work is performed.

Four support frames were installed on the deck of the 11,000 t-class FD, and distributors were set on top of them. The distributors were connected to the pump truck delivery lines so that concrete could be supplied to the upper-level floor as the SF rose (Photo-2).

**2.2 Fabrication of the RC Caisson Base Slab**

For fabrication of the RC caisson base slab, rebar and formwork were first assembled on a pedestal installed on a 7,500 t-class FD.

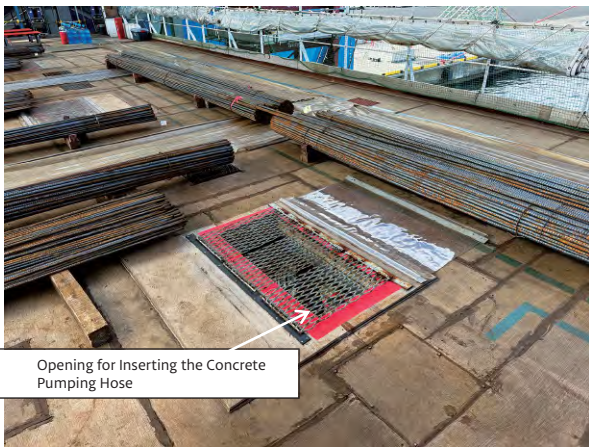


Fig.-3 Temporary Rebar Staging and Openings on the Upper Level

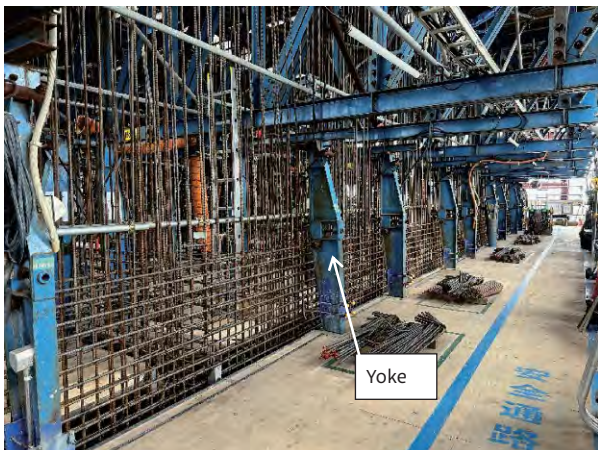


Fig.-4 Middle Level

Rebar and formwork were assembled on the installed pedestal. Then, the 7,500 t-class and 11,000 t-class FDs were docked, and a winch was used to tow the pedestal carrying the rebar and formwork over to the 11,000 t-class FD. After the pedestal transfer was completed, the base slab concrete was placed and the formwork was stripped, completing construction of the base slab concrete.

This pedestal transfer method using two FDs was adopted because there was no way to secure a work area on land, and because if the base slab concrete were placed on the 7,500 t-class FD, the resulting weight would make it difficult to move the unit to the 11,000 t-class FD. In addition, since the 11,000 t-class FD is equipped with SF facilities, operational constraints also prevent the use of a crane to assemble the base slab rebar and formwork.

**2.3 SF Construction**

After constructing the base slab, the SF equipment was lowered and the SF formwork was set on top of the base slab concrete.

Under the SF method, for an RC caisson wall height of 15.5 m, construction takes 9 days in winter (December–March) and 8 days in other seasons. However, concrete placement is carried out as a continuous 24-hour pour for 2 days; then, placement is halted for 1 day to hoist the main bars and distribution bars to the upper level and install the main bars, after which another continuous 24-hour concrete placement operation is carried out.

The workforce operated on a three-shift schedule with 9-hour shifts (8:00–17:00, 16:00–1:00, 0:00–9:00). In addition, because extended operation can cause the concrete in the pump truck hopper to begin setting, pump trucks were swapped out every 12 hours. A 5-inch delivery line was used, with a maximum lift of about 20 m and a total run of about 100 m.

The caisson being fabricated was divided into four zones across its 24 cells, and placement was shared by four pump trucks positioned on the quay (Photo-5). Work locations and pour sequences were set for each crew, and time blocks were assigned cell by cell so that each crew's start times were evenly balanced. In addition, the lift height was set to 20 cm per layer to ensure a uniform rise. This is because uneven lift heights cause differences in setting across the surface, which can interfere with the SF system's uniform upward movement.

Placement per layer (approximately 20 cm in height) took 2 hours in winter (December–March) and 1 hour 45 minutes in other seasons during construction



Fig.-5 Pump Truck Layout

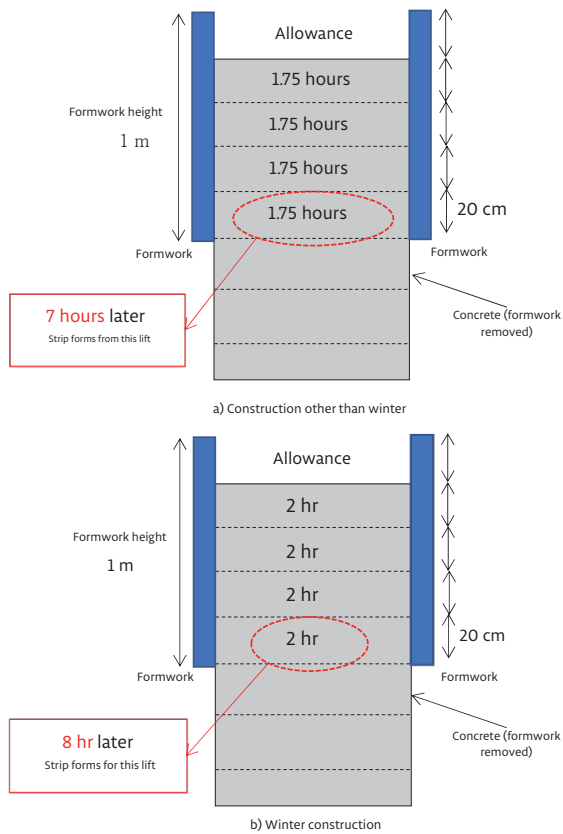


Fig.-1 Relationship between 1-lift placement time and form-removal time

was set. This duration was defined as the placement time for one lift based on the concrete setting time. With a 1 m form height, 20 cm was left as a margin, and the remaining 80 cm was divided into four lifts; in winter, the time to reach the stripping strength (0.06–0.1 N/mm<sup>2</sup>) was taken as 8 hours (8 hours ÷ 4 lifts = 2 hours), while in other seasons it was set at 7 hours (7 hours ÷ 4 lifts = 1 hour 45 minutes) (Fig.-1). The maximum re-vibration/overlap time between lifts was 2 hours; however, retarders were added to match temperature changes, and especially in hot-weather conditions, as described later, a super-retarder of 2 kg/m<sup>3</sup> or more was added to the concrete, so no cold joints were observed.

In the lower section, as the SF rose, the concrete surface stripped at a concrete age of 7 to 8 hours became exposed. However, because the scaffolding rose together with the formwork and sheet curing could not be applied, a membrane-forming curing compound was sprayed and worked into the surface during trowel finishing to help prevent the concrete surface from drying out.

## 2.4 Rebar Assembly

Rebar assembly was carried out during concrete placement by feeding the reinforcing bars (distribution bars) temporarily staged on the upper level down to the middle level in step with the SF's rise, using a rebar slider, and then assembling them (Photo-6, Photo-7). Because concrete placement and rebar assembly proceeded in parallel, a large number of workers had to be assigned to the middle level.

## 2.5 Launching / Temporary Staging

Remove equipment such as the working platform and distributor installed on the FD and cure for 10 days after completion of concrete



Photo-6 Supplying rebar from the upper level to the middle level



Photo-7 Rebar assembly on the middle level



Photo-8 Caisson tow-out

placement. After that, tow the FD to the designated location, launch the caisson, tow it to the temporary staging mound, and place it there; this completes the series of manufacturing processes (Photo-8).

## 3. Concrete Quality Control

### 3.1 Concrete Used and Mix Proportions

It was necessary to ensure a steady supply of ready-mix concrete for 24-hour operations

Four nearby ready-mix concrete plants were used so that each caisson would be supplied by three of those plants. For the first two placing days, concrete was supplied continuously for 24 hours from the same plant; after that, supply was switched to another plant and continued for two consecutive days.

As described above, this method sets the placing rate for each 20 cm lift to 1.75 hours or 2 hours. As a result, the pumping rate per pump truck is lower than for typical concrete placement: winter: about 1.9 m<sup>3</sup>/h; summer: 2.1 m<sup>3</sup>/h. In addition, with a maximum pumping distance of about 100 m and an elevation difference of about 20 m, a slump loss was anticipated, so concrete with a slump of 18 cm at discharge was used. Early in construction, pump-line blockages occurred in the upper lifts due to segregation; therefore, the mix was revised by increasing the unit cement content by 20 kg/m<sup>3</sup> to improve viscosity. Table-1 shows the mix proportions for Plant A before and after the improvement.

Across the four plants, the combinations of cement supplier, admixture supplier, and fine-aggregate source—as well as the mix designs—differed from plant to plant. As a result, the concrete produced at each plant differed in viscosity and early-age strength development, and variability was observed, such as 4-week strengths ranging from 39 to 46 N/mm<sup>2</sup>.

### 3.2 Weather Conditions

Figure-2 compares annual temperatures in Singapore—where many RC caisson projects using the SF method have been carried out—with those in Kagoshima City. Compared with Singapore, Kagoshima City (the project site) shows larger temperature swings over the year and tends to have greater day-to-night temperature differences. The bar chart in the same figure shows the number of days in 2021 when Kagoshima City's daily temperature range was 10°C or more. During winter (November through March), days with large daily temperature ranges tend to occur more frequently. To control the development of stripping strength (0.06–0.1 N/m<sup>2</sup>) in line with these temperature fluctuations, a retarder was added at the ready-mix plant to regulate the rate of hardening.

### 3.3 Managing Retarder Dosage

#### (1) Determining the Retarder Dosage

The retarder dosage must be set based on the air temperature at the time of production and the forecast temperature. In addition, because the materials and mix designs differ among the 4 plants used, the required retarder dosage varies even at the same temperature. Because manual calculations would require batch-by-batch computation and be time-consuming, an application was developed that automatically calculates the dosage on a tablet device (Figure-3). Tablets with the application installed were provided to the ready-mix plants so operators could refer to the displayed retarder dosage and apply it to the mix. Also, because the system that controls the plant mix design was kept offline for security reasons, the measured dynamic load value was printed on the concrete delivery ticket so that, upon delivery, the retarder dosage could be checked at the unloading point.

Table-1 Mix Proportions

	W/C (%)	s/a (%)	Unit Quantity (kg/m <sup>3</sup> )					High-Range AE Water-Reducing Admixture
			Cement	Water	Sea Sand	Crushed Sand	Coarse Aggregate	
Before Improvement	49.9	45.0	349	174	542	239	988	1.86
After Improvement	47.4	44.5	369	175	529	233	988	1.96

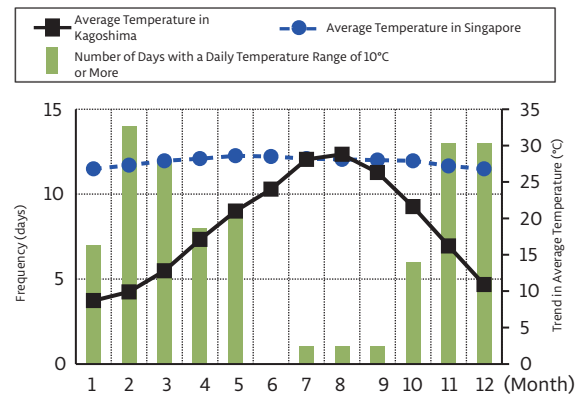


Fig.-2 Number of Days with a Daily Temperature Range of 10°C or More (2021, Kagoshima)

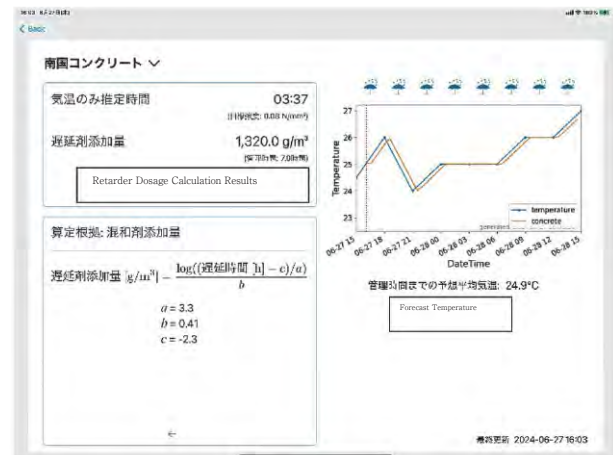


Fig.-3 Application Screen

For calculating retarder dosage, the time required to reach stripping strength without retarder (median: 0.08 N/mm<sup>2</sup>) was estimated using maturity (cumulative temperature), based on forecast temperatures obtained from online weather service (Figure-4). Using these results, retarder dosages were set for the four plants so that the stripping time would be 8 hours (December through March) and 7 hours (all other periods). The parameters for the prediction equation entered into the application were determined by delivering ready-mixed concrete produced in each plant's actual mixer to the site and conducting strength tests.

#### (2) Example of Retarder Dosage

Figure -5 shows the measured temperature trend from January 20 to 22, 2024, along with an example of retarder dosage. The temperature dropped sharply from around 19°C to around 4°C, and based on the weather forecast results

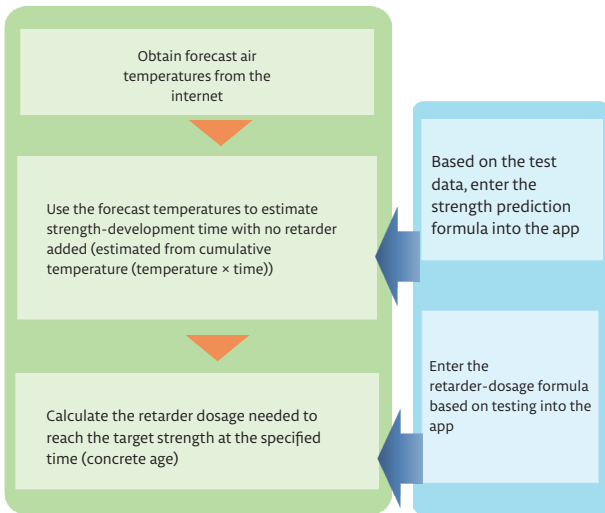


Figure-4 How to Calculate Retarder Dosage

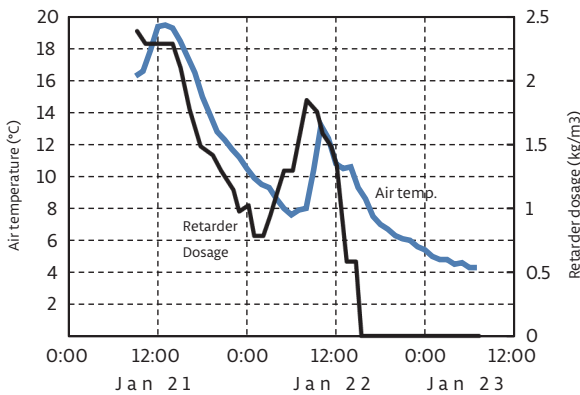


Fig.-5 Example of temperature trends and retarder dosage

The amount of retarder added was also reduced. However, when the air temperature drops to 3°C or below, there is concern that stripping the forms at a concrete age of 8 hours may result in insufficient strength; in that case, measures were taken to ensure the placement time was at least 2 hours per lift (i.e., form stripping at 8 hours or later).

Figure-6 shows the strength test results of cylindrical specimens measured on January 21 and 22, as indicated in Figure-5. Even with fluctuations in air temperature, at a concrete age of 8 hours the results fall within the managed stripping-strength range of 0.06–0.1 N/mm<sup>2</sup>, demonstrating that the retarder dosage can be controlled.

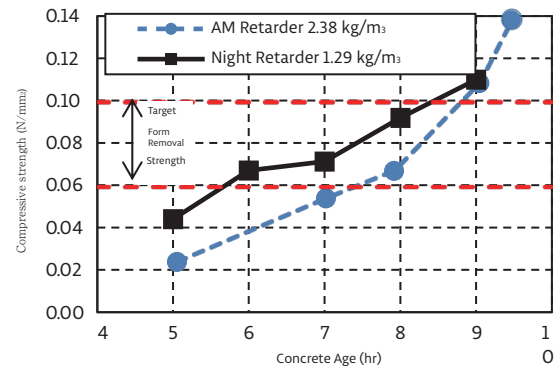
### 3.4 Strength Control

#### (1) Strength Control Method

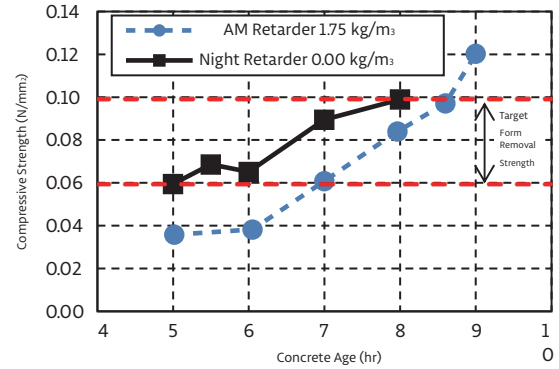
Strength development was monitored by inserting a reinforcing bar into the concrete and by testing cylindrical specimens.

For the reinforcing-bar method, a rebar was inserted into the placed surface and the hardness was judged by feel. Once stripping strength is reached, the rebar can no longer be inserted; therefore, strength control was performed based on measured insertion depth.

For strength control using cylindrical specimens, during SF work, specimens of  $\phi$  100×200 were made and tested twice per day. The strength testing machine could measure up to 2.0 kN for geotechnical testing, and tests were conducted in a temporary laboratory set up within the site yard.



a) Run on Jan. 21



b) Run on Jan. 22

Fig.-6 Example: Retarder Dosage vs. Strength Development

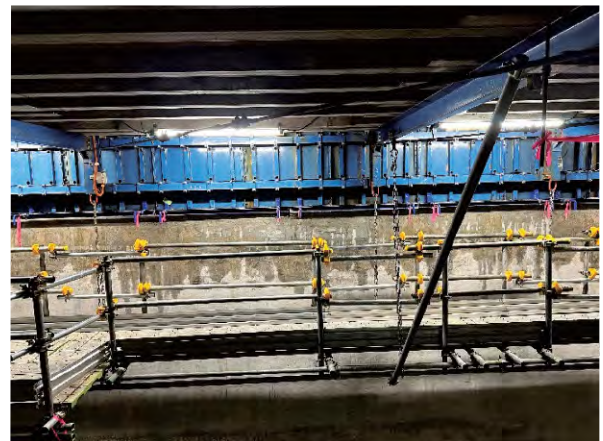


Photo-9 Dewatering from the Underside of the Formwork

#### (2) Impact of Dewatering on Strength Development

At the start of construction, the structure itself (confirmed by rebar insertion) tended to gain strength faster than the cylindrical specimens, and the strength development measured by cylinders and by rebar insertion was clearly different. Site observations confirmed that moisture was leaking from the underside of the formwork from the placed concrete (Photo-9). This is thought to be because the SF formwork is designed to widen downward in a V-shape by about 4–6 mm to make stripping easier, which makes dewatering more likely. Assuming this dewatering affected strength development, a mold for cylindrical specimens that can drain excess water—lined on the inside with a permeable sheet as shown in Photo-10—was fabricated and used for strength control. Figure-7 shows, under a 20°C environment, the same

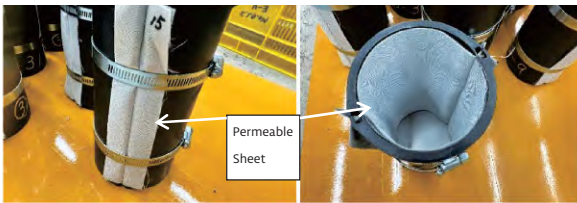


Photo-10 Cylindrical specimen mold that can dewater excess water

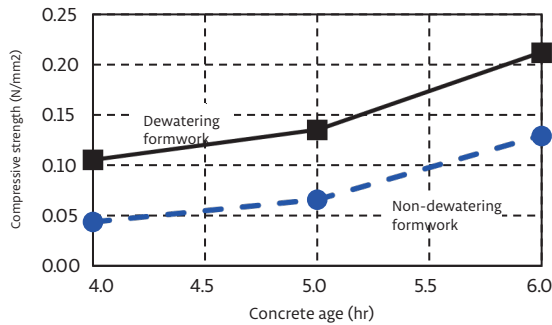
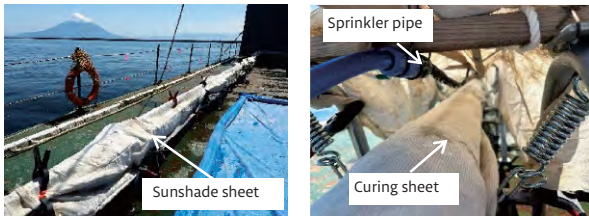


Figure-7 Differences in strength development with and without dewatering



a) Piping sunshade sheet b) Sprinkler pipe, curing sheet

Photo-11 Hot-weather measures for concrete pumping lines

This compares the strength of concrete cylinder specimens made with the same mix, using non-dewatering and dewatering molds. It was confirmed that dewatering shortens the time to reach 0.1 N/mm<sup>2</sup> by about 1.5 hours. Based on these results, strength measured using cylinder specimens with a dewatering effect showed a tendency to be consistent with measurements taken from reinforcing bars in the structure. A more detailed study of early-age strength development due to dewatering is planned by the authors in the future.

### 3.5 Agitator Truck Dispatch Management

Because the placing rate was slow, each agitator truck was loaded to 2 m<sup>3</sup>/truck, and dispatching was managed to minimize on-site waiting time.

Agitator truck dispatching was managed using IC tags: by scanning IC tags at dispatch from the plant, arrival at the site, and the start and end of unloading, each time was recorded automatically, enabling real-time tracking of shipment times and on-site waiting times.

### 3.6 Hot-Weather Concrete Measures

Because the placing rate was slow, in hot-weather conditions a slump loss due to rising pump-line temperature was a concern; therefore, the pump

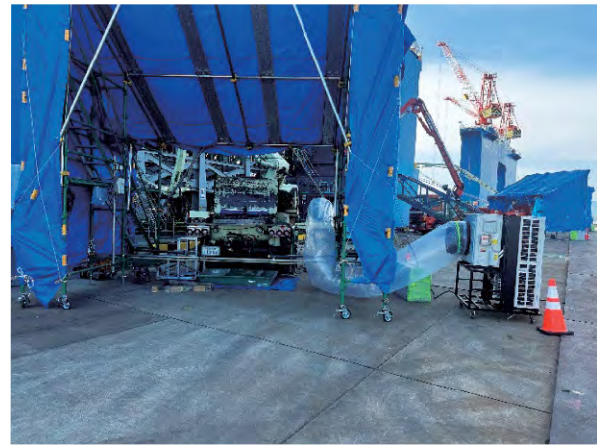


Photo-12 Installing a canopy over the pump truck hopper and cooling with a spot cooler

line was wrapped with a curing sheet made of non-woven fabric, automatic sprinkling was performed for 5 minutes per hour, and sunshades were also installed to suppress temperature rise in the piping as a countermeasure<sup>3)</sup> (Photo-11)

In addition, a sunshade tent was installed over the hopper of the pump truck, and to curb temperature rise of the concrete in the hopper, a large spot cooler was used to blow chilled air as a countermeasure (Photo-12)

## 4. Conclusion

For the first time in Japan, caisson fabrication using the SF method was carried out offshore, and the wall section was built through 24-hour continuous construction over eight days.

For concrete control, the dosage of retarder was calculated using an application on a mobile device, allowing the setting rate to be controlled even in Japan (Kagoshima) where temperature fluctuations are large, thereby keeping both the construction rate and the formwork climbing rate constant.

Going forward, we plan to clarify the mechanism of strength development due to dewatering and to examine more accurate methods for predicting strength development.

**Acknowledgments** This project was carried out with the cooperation of all parties involved, including the owner, the experts who provided technical guidance, those engaged in construction, and the material suppliers. We would like to express our sincere appreciation.

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