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# Evaluation of durability of concrete for applying slipforming to construction of prestressed concrete outer tank for LNG storage

Shunsuke Ohnishi[1], Takeyoshi Nishizaki[2],

Kuniaki Sakurai[3] and Yuichi Yajima[4]

*[1,2]Osaka Gas Co., Ltd., Japan*
*4-1-2, Hiranomachi, Chuo-ku, Osaka, 541-0046, Japan*
*[1]sh-oonishi@osakagas.co.jp*
*[2]takeyoshi-nishizaki@osakagas.co.jp*
*[3,4]Obayashi Corporation, Japan*
*Shinagawa Intercity Tower B 2-15-2, Konan, Minato-ku, Tokyo, 108-8502, Japan*
*[3]sakurai.kuniaki@obayashi.co.jp*
*[4]yajima.yuichi@obayashi.co.jp*

## ABSTRACT

Slipforming was adopted for the first time in Japan for the construction of an outer tank of Osaka Gas aboveground LNG storage, which is now under construction. This is a method whereby concrete is continuously placed in thin layers in formwork, which is lifted using hydraulic jacks, while reinforcement is progressively assembled upward. It drastically shortens the construction period when compared with conventional methods.

Durability is a prerequisite for such an outer tank to contain an inflammable hazardous substance. However, slipforming exposes concrete at an early age, posing problems of controlling early strength development and ensuring durability. The authors therefore assessed the effects of early form removal on the durability of concrete.

This paper reports on the results of durability evaluation such as accelerated curing tests exposure tests conducted prior to the application of slipforming.

**Keywords.** LNG storage, Slipforming, Prestressed concrete, Durability, Model tests

## 1. Introduction

Osaka Gas constructs a new aboveground LNG storage tank in Senboku Receiving Terminal 1. The storage, which is scheduled to be completed in November 2015, is going to be the world’s largest aboveground LNG tank with a capacity of 230,000 m$^3$. Since such a large tank requires a long construction time, slipforming was adopted, for the first time in Japan, for construction of the outer tank for the storage to shorten the construction time and to reduce the construction cost. The fresh properties and early strength-developing properties suitable for slipforming were ensured for the application of this method. Slipforming requires early removal of formwork, which can adversely affect the qualities of concrete surfaces. The authors therefore conducted accelerated curing tests and exposure tests to investigate the effects of early form removal on the durability of concrete and formulated mixture proportions that meet the requirements for durability performance.

## 2. Outline of LNG aboveground storage with prestressed concrete outer tank

### 2.1 Structural summary

Figure 1 shows a structural drawing of the prestressed concrete LNG tank comprising the inner tank, outer tank liner, outer tank, steel pipe piles, base slab, insulation, and cold resistance relief. The tank currently under construction with a capacity of 230,000 m$^3$ is one of the world’s largest aboveground LNG storages. Its inner tank is made of 7% nickel steel to resist the extreme low temperature of LNG.

The prestressed concrete outer tank is a cylindrical shell structure measuring 89.2 m in inner diameter, 800 mm in wall thickness, and 43.65 m in height designed to contain the entire amount of stored LNG in case of accidental leakage. It is lined with a cold resistance relief made of polyurethane foam to protect the outer tank from the direct thermal shock of LNG. The compressive strength of outer tank concrete is varied in four levels based on the load (liquid pressure) to act under the different loading conditions of each level: 60 N/mm$^2$ for the top and bottom (0 to 9.5 m) levels, 40 N/mm$^2$ for the level of 9.5 to 15.5 m, and 30 N/mm$^2$ for the level of 15.5 to 42.85 m.

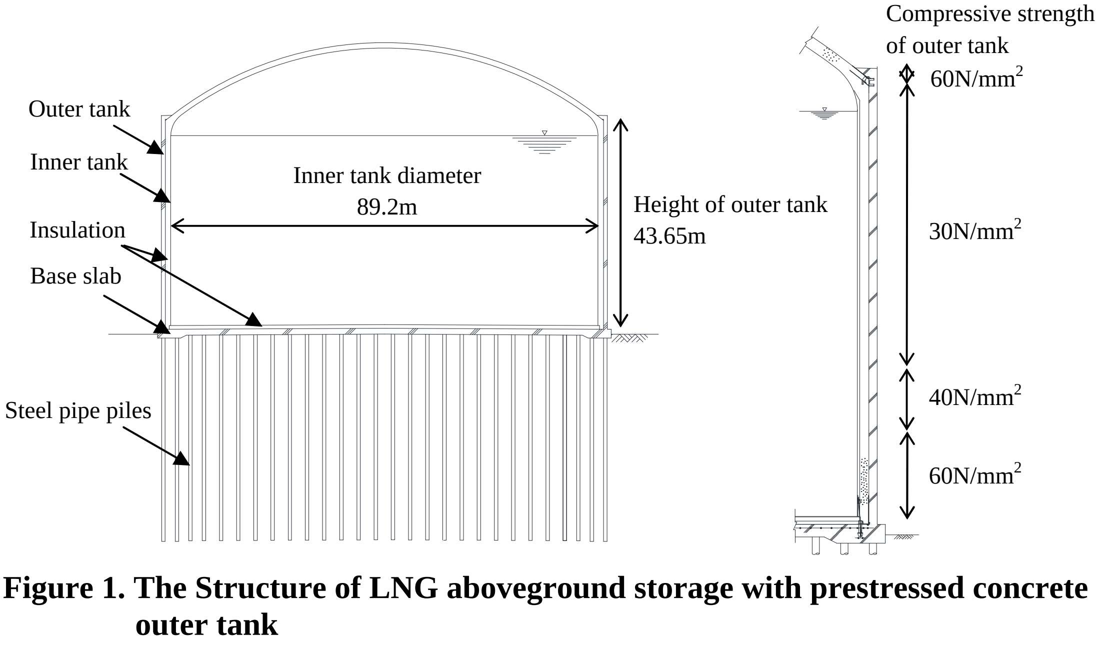

**Figure 1. The Structure of LNG aboveground storage with prestressed concrete outer tank**

Slipforming was adopted to construct the outer tank for the first time in LNG tank construction in Japan. Conventionally it takes 13 months to build an outer tank using large cranes to raise the scaffolding and formwork. Also, the process of re-constructing scaffolding and formwork account for approximately 50% of the total construction work for an outer tank. Slipforming enables a drastic reduction in the construction period to 6 months.

## 2.2 Required performance for prestressed concrete outer tank

Requirements for an outer tank include structural stability under loading conditions of normal operation, in the event of an earthquake, and in case of liquid leakage; durability throughout the service life; and liquid-tightness against leakage. When adopting slipforming, appropriate workability for concrete placing in thin layers should be ensured, and early strength development is required, as formwork is to be removed at early ages. Concrete for the outer tank should be proportioned to meet all these performance requirements.

Exposure of concrete at early ages in slipforming can make its surfaces vulnerable to outdoor air temperature and dryness and adversely affect microstructure formation, thereby altering the denseness of concrete surfaces. It is therefore vital to suppress chloride ion penetration and progress of carbonation in such circumstances to ensure the qualities related to durability.

## 3. Construction of outer tank by slipforming

### 3.1 Outline of slipforming

Figure 2 shows a photographic image and cross-sectional view of slipforming equipment. Figure 3 shows the steps of slipforming.

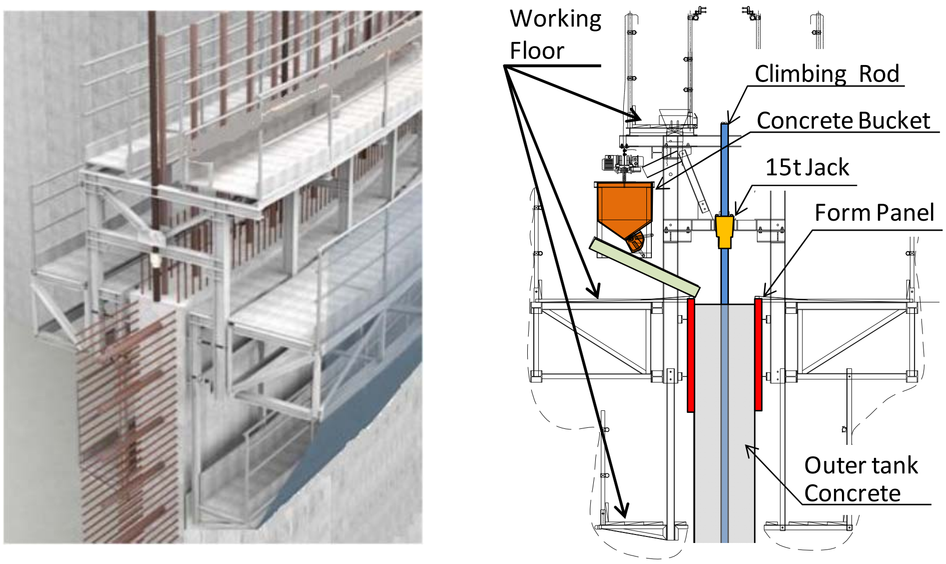

Figure 2. Image and of section map of slip-forming equipment

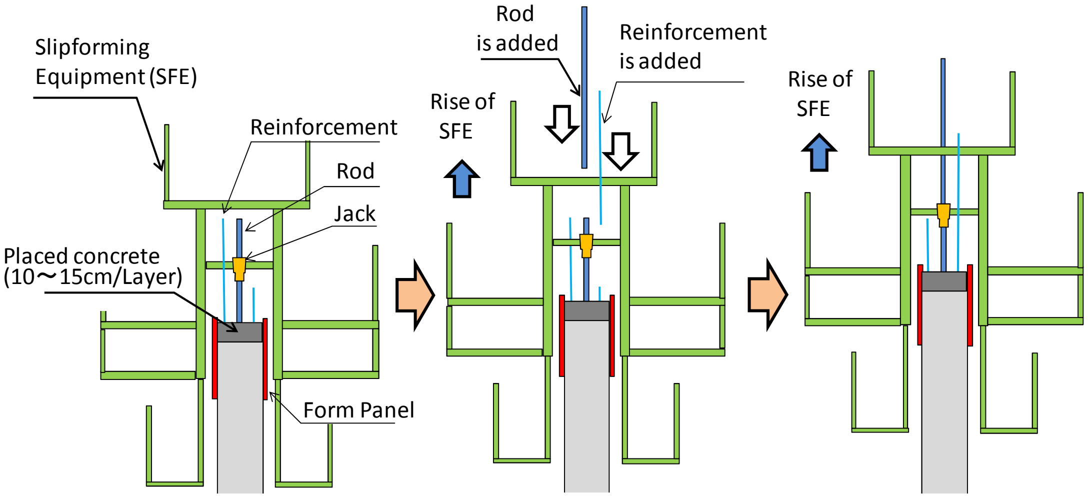

**Figure 3. Construction image of outer tank using slip-forming method**

Slipforming is a method in which a concrete structure is constructed by placing concrete in a continuous manner while continuously lifting the formwork. Special equipment incorporating formwork and scaffolding is used for this method. Formwork is jacked upward, sliding along the structural framing. Concrete is continuously placed in thin layers. Rods and reinforcing bars are sequentially spliced upward with the rise of the equipment. The structural framing can be constructed in a short time, as different types of work can be simultaneously carried out while no assembly or disassembly of scaffolding and formwork is necessary.

### 3.2 Construction procedure of outer tank concrete

In this project, the outer tank 40 m in height is planned to be constructed in 20 days by placing concrete at a rate of 10 cm per hour. The amount of concrete placement will be approximately 500 $m^3$ every day.

The outer tank is a cylinder with a wall thickness of 80 cm and perimeter of 280 m. Concrete for this huge structure is therefore planned to be placed in four separate blocks. Concrete is lifted up to the level of the slipforming equipment with a crane located at each block, transferred to a horizontal conveying bucket to convey it to the point of placing, and placed.

In slipforming, in which formwork is continuously lifted, concrete is left out of formwork at early ages. In the present project, in which the form removal time is 12 hours after placing, early strength development to allow form removal at this age is required. Meanwhile, excessive strength at the time of form removal causes a strong bond between the formwork and concrete, making it difficult to lift the equipment and formwork. It is therefore necessary to specify the upper limit of strength development as well.

## 4. Evaluation of durability of concrete

### 4.1 Performance required of concrete

Table 1 gives the qualities required of concrete when constructing an outer tank by slipforming.

#### (1) Qualities of fresh concrete

The outer tank is a cylinder with a wall thickness and perimeter of 80cm and 280m, respectively, while the concreting lift is as small as 10 to 15cm/hour. This requires concrete having high mobility. For this reason, the target slump flow for this project was set at 50cm. It was also decided to supplementarily consolidate concrete using vibrators after placing.

#### (2) Concrete strength at the time of form removal

In slipforming, concrete is stripped of formwork 12 hours after placing. It is required to develop a minimum strength necessary for standing on its own by this time. Meanwhile, high strength at an early age increases the bond between concrete and formwork, making it difficult to slide the formwork. It is therefore necessary to control the 12-hours compressive strength in the range of 0.1 to $0.3N/mm^2$.

#### (3) Durability

The service life of the LNG storage is required to be 50 years in terms of durability design, and inhibition of steel corrosion due to chloride attack and carbonation during service was selected as a performance requirement.

**Table 1. Required qualities of concrete for prestressed concrete outer tank constructed by slip-forming method**

| Item | Quality of characteristics and target range |
|---|---|
| Slump flow | 50±7.5cm |
| Air content | 4.5±1.5% |
| Compressive Strength | (1) With the time of stripping (at 12 hours of ages), 0.1～$0.3N/mm^2$ |
| | (2) With the 91days of ages, it is more than degign strength. |
| Coefficient of carbonation velocity[*1] | $< 8$(mm/$\sqrt{}$year) |
| Diffusion coefficient of Chloride ion[*1] | 30-50-20BB : $< 5.0$($cm^2$/year)<br>40-50-20M : $< 2.5$($cm^2$/year)<br>60-50-20M : $< 1.2$($cm^2$/year) |

[*1] A value required for durability reservation of design life (50 years) by this construction

### 4.2 Proportioning and qualities of fresh concrete

Table 2 gives the mixture proportions of concrete used in this project. Figure 4 shows changes in the slump flow of concrete over time. All concretes, when kept still, were proven to retain the target slump flow for 30 minutes after production.

**Table 2. Mix proportion of concrete**

| Kind of concrete | Design strength (N/mm$^2$) | Kind of cement | Target of slump flow (cm) | Target of air content (%) | W/C (%) | s/a (%) | Unit of weight(kg/m$^3$) | | | | | | Admixture (C × %) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | W | C | S1 | S2 | G1 | G2 | |
| 30-50-20BB | 30 | BB | 50 | 4.5 | 45.0 | 49.4 | 175 | 389 | 662 | 166 | 431 | 429 | 0.90<br>(VA) |
| 40-50-20M | 40 | M | 50 | 4.5 | 40.0 | 49.5 | 170 | 425 | 664 | 167 | 431 | 429 | 1.10<br>(SP) |
| 60-50-20M | 60 | M | 50 | 4.5 | 33.0 | 47.2 | 170 | 515 | 607 | 152 | 431 | 429 | 1.05<br>(SP) |

BB : Type B of portland-blastfurnace cement, M : Moderate-heat portland cement
S1 : Sea sand, S2 : Crushed sand, G1 : Crushed gravel 20-10mm, G2 : Crushed gravel 15-05mm
VA : Super plasticizer with viscosity, SP : Super plasticizer

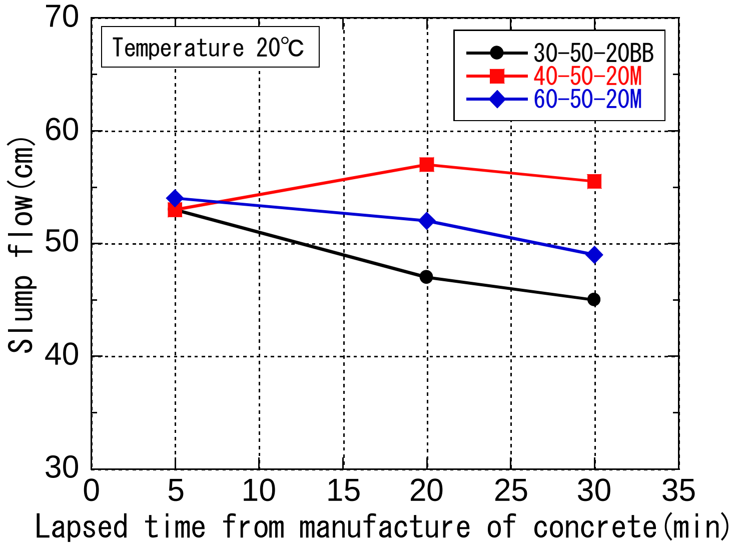

Figure 4. Elapsed time of slump flow

### 4.3 Control of early strength development of concrete

Figure 5 shows the early strength development of concrete proportioned to attain 30 N/mm$^2$ in relation to temperature conditions. The strength gains are found to widely vary depending on the temperature condition. A set retarder was therefore added. Figure 6 shows the relationship between the dosage of the set retarder and the compressive strength at an age of 12 hours. The 12 hours strength was found to be controllable within a target range of 0.1 to 0.3 N/mm$^2$ by adjusting the retarder dosage as shown in Fig. 7.

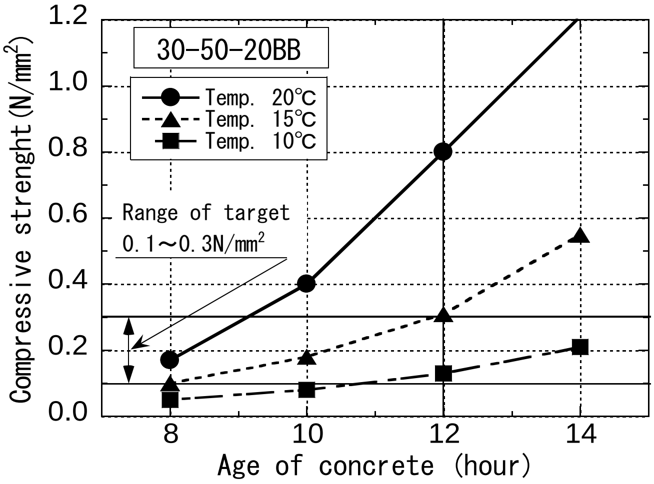

Figure 5. Compressive strength at early age

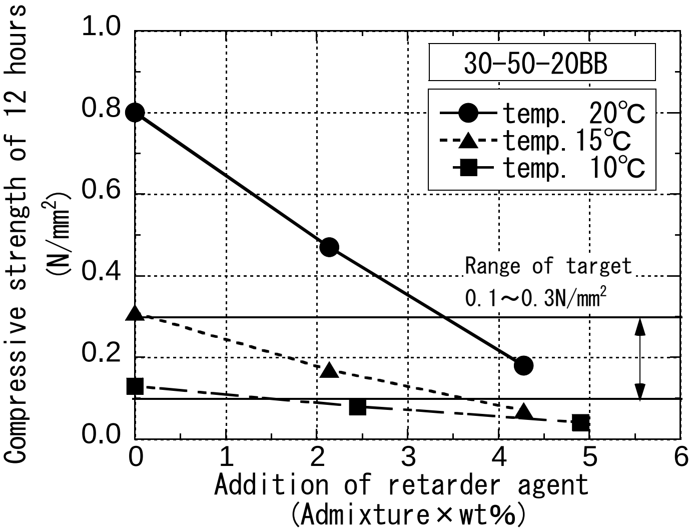

Figure 6. The change of compressive strength at 12 hours by retarder content

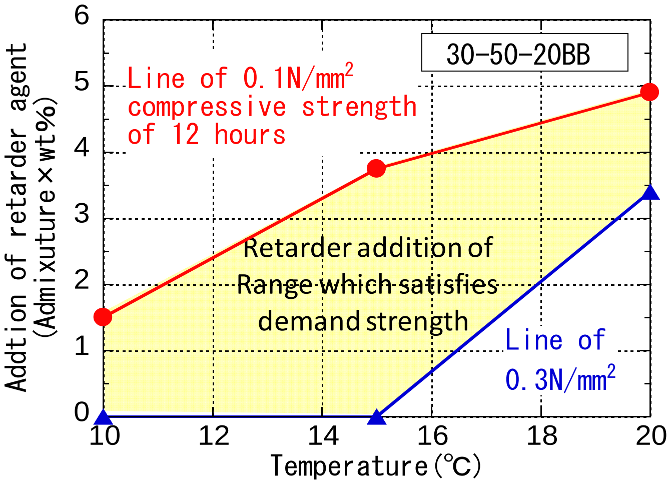

Figure 7. Required content of retarder to control the early strength of concrete on each temperature

### 4.4 Durability against carbonation and chloride penetration

Model specimens of the outer tank were fabricated to investigate the effect of early form removal on the durability of concrete (see Fig. 8). The formwork was removed at 12 hours similarly to actual slipforming. This was followed by seal curing, exposure to air (no particular curing after form removal), or coating with curing compound A (a glycolic surface coating type) or compound B (a silanic surface impregnation type). The specimens were exposed to the outdoor environment up to an age of 3 months. Cores were then drilled for compression tests, accelerated carbonation tests, and chloride penetration tests. Cylindrical specimens were also prepared and subjected to similar curing conditions. Only the results of mixture 30-50-20BB are reported in this paper.

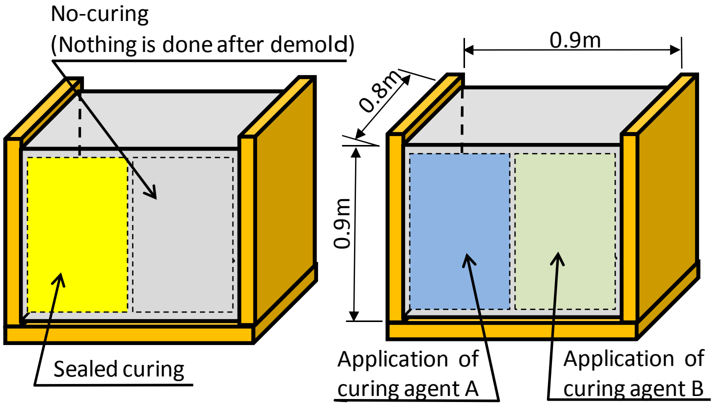

Figure 8. Exposure condition of wall block model

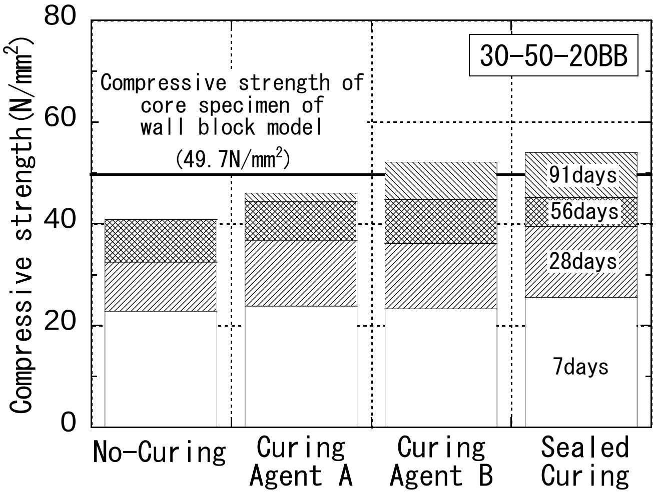

Figure 9. Difference of compressive strength by curing condition

Figure 9 shows the compression test results of different types of specimens exposed to the outdoor environment similarly to the model specimens. The compressive strength of cores drilled from the model specimens is comparable to that of seal-cured specimens. That of specimens exposed to the air is lower than that of seal-cured specimens. Those of specimens coated with curing compounds are nearly the same as that of seal-cured specimens.

Table 3 gives the carbonation rate coefficient and chloride ion diffusion coefficient obtained from accelerated tests. The carbonation rate coefficients are kept at low levels necessary for ensuring durability, or well below 8 (mm/√year), confirming that the possibility of causing carbonation-induced steel corrosion is very low despite early form removal.

The chloride ion concentration near the concrete surfaces varied depending on the curing method. Whereas exposure to the air led to high chloride ion concentrations, curing compounds were found effective in reducing the concentration.

Durability verification was conducted based on the chloride ion diffusion coefficients given in Table 3 and the chloride ion content near the concrete surfaces determined from cores drilled from an outer tank of an existing LNG storage. Typical results are shown in Fig. 10. Durability against chloride attack was ensured throughout the required service life of 50 years even when formwork was removed at early ages.

**Table 3. Evaluation of coefficient of carbonation velocity and diffusion coefficient of chloride ion (30-50-20BB)**

| Curing method | Accelerating test of carbonation (Accelerating period of 3 months) | | Coefficient of carbonation velocity in site (mm/√year) | Salt immersion examination (Accelerating period of 3 months) | | | | | Diffusion coefficient of Chloride ion ($cm^2$/year) |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Chloride ion concentration ($kg/m^3$) | | | | | |
| | | | | Range from the test specimen surface (mm) | | | | | |
| | depth of carbonation (mm) | Coefficient of carbonation velocity in accelerating test (mm/√week) | | 0～20 | 20～40 | 40～60 | 60～80 | 80～100 | |
| No-Curing | 4.7 | 1.3 | 0.73 | 9.2 | 0.2 | 0.2 | 0.1 | 0.1 | 0.35 |
| Curing agent A | 3.2 | 0.9 | 0.50 | 5.2 | 0.2 | 0.1 | 0.1 | 0.1 | 0.13 |
| Curing agent B | 12.1 | 3.4 | 1.87 | 5.6 | 0.2 | 0.2 | 0.2 | 0.1 | 0.15 |
| Sealed curing | 0.0 | 0.0 | 0.00 | 5.7 | 0.2 | 0.2 | 0.2 | 0.1 | 0.16 |

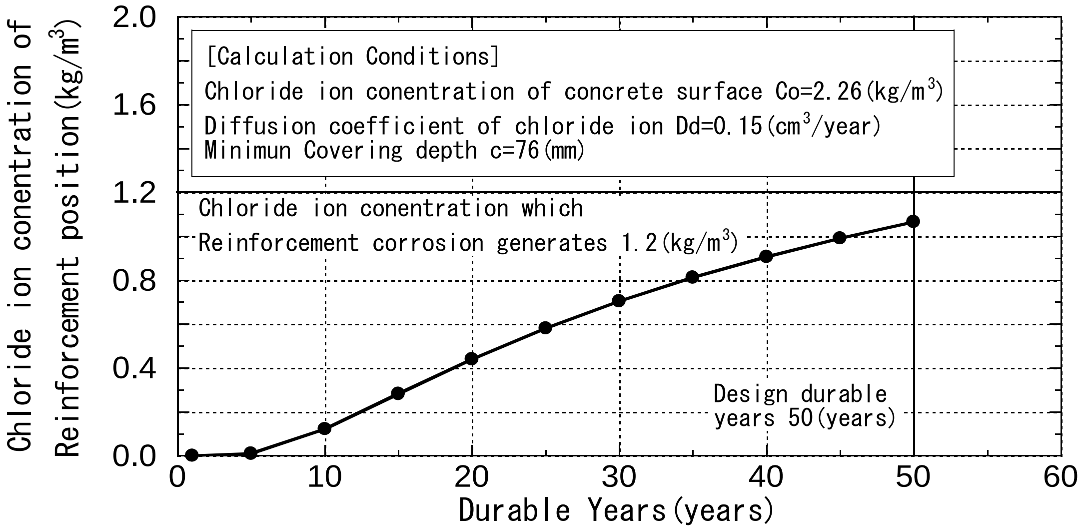

Figure 10. The durability collation result of reinforcement corrosion by salt

## 5. Conclusions

In view of the application of slipforming, concrete was proportioned to ensure the target slump flow suitable for placing in thin layers, while enabling control of strength development up to 12 hours, the age of form removal. The effects of early form removal were also investigated by accelerated curing tests and exposure tests. The performance requirements regarding durability were proven to be fulfilled.