Efficient maintenance method for water supply facilities focused on the carbonation of concrete

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Abstract

In water supply facilities such as distribution reservoirs, the inner surface of reinforced concrete (RC) tanks is often coated with resin paint or the concrete cover depth is increased to protect the concrete from surface deterioration. However, there is little published research on carbonation – one of the main causes of concrete deterioration – in relation to RC tanks, leaving room for improvement with regard to methods for preventing surface deterioration. This study discusses the impact of surface coating and environmental conditions on the carbonation rate of concrete based on a survey of the present state of RC tanks of the Sapporo Waterworks Bureau. Coating was found to have an inhibitory effect on carbonation. Because the carbonation rate of concrete used for the inside and outside of RC tanks was slow, the sufficient concrete cover depth to protect rebar from carbonation while in service was found to be 75 mm for RC tanks without coating.

Key words: carbonation of concrete, coating of concrete surface, reinforced concrete cover depth

INTRODUCTION

Since most of the water supply facilities in Japan were constructed around 1975, these facilities will require renovation in the near future. However, waterworks investment has decreased in recent years. If this tendency continues, the renovation requirements are expected to exceed the investment from around 2025, and the aging of facilities may become a concern. Meanwhile, the income of water utilities has decreased due to decreases in the population served since 2010, as well as increased awareness of water saving and the spread of water-saving consumer electronics. To ensure the survival of water utilities under such severe circumstances, it is important to reduce maintenance costs by quantitatively understanding and evaluating the soundness of existing facilities and by maintaining the performance of water supply facilities through rational renovation plans based on technical evidence. For reinforced concrete (RC) tanks of major water supply facilities such as pumping stations and distribution reservoirs (hereinafter referred to as 'tanks'), the Sapporo Waterworks Bureau (SWB) increased the net RC cover depth (the distance from the concrete surface to the reinforcing bar surface, hereinafter referred to as the 'cover depth') from 75 to 100 mm for concrete without coating on the inner surface in 1987. For existing tanks with a cover depth of less than 100 mm, coatings or other surface finishings have been applied. Surface finishing (including coating of concrete surface. hereinafter referred to as 'finishing') is effective in improving the stability and water-tightness of tanks. However, care must be taken when deciding whether to apply a finishing, since it requires

maintenance costs for repair and renovation in the long run to remediate swelling, cracking, exfoliation and other aging-related conditions. Soundness surveys on several tanks of the SWB found carbonation, which is one of the main factors for deterioration, to not be progressing as expected. Therefore, it has been considered that there is room for improvements in the implementation standards for the cover depth and finishing of tanks in terms of durability. To readjust the cover depth to a necessary and sufficient level, it is necessary to determine the carbonation depth quantitatively and to predict carbonation progression accurately. Although many research projects have been conducted for commonly used concrete structures, little research has addressed carbonation predictions or the effects of finishing for water supply tanks with the special purpose of storing chlorine-containing water for prolonged periods. Knowledge of actual facilities is especially scarce. According to The Design Criteria for Water Supply Facilities (JWWA 2012), effective carbonation countermeasures are to increase the cover depth and to apply a watertight finishing. However, the design criteria have no provisions on the specific cover depth. Furthermore, according to a survey conducted by the SWB on other water utilities in Japan, the presence or absence of finishing and the standard for cover depth varied by utilities, indicating that there is no unified technical view on the specifications of the inner surface of tanks.

In light of the above, this study focuses on carbonation, which is a major factor in concrete deterioration. It discusses how environmental conditions, residual chlorine and finishing affect the progression of carbonation by categorizing the results of a carbonation survey of tanks managed by the SWB, for the purpose of determining a necessary and sufficient cover depth for the protection of rebar from carbonation.

SURVEY METHOD

The survey targets were pumping stations, distribution reservoirs and purification plants, which are structures where water is stored continuously. As survey samples, 294 specimens in total were collected under several different conditions, as shown in Table 1, to confirm how environmental conditions (outside or inside of tanks, phases) and the effect of finishing impact the progression of carbonation. As shown in Table 1, the survey was conducted from 1992 to 2012, and the age of facilities at the time of the survey ranged from six to 56 years. Most facilities were buried underground and had covering concrete to protect against frost damage. The survey was conducted for the liquid and gas phases inside the tanks (bottom plates, side walls and upper slabs), and for the gas phase outside the tanks (e.g., piping galleries). The concrete surfaces inside the tanks were uncoated or were finished with resin paint, and the outside of the tanks was uncoated or was finished with mortar or other materials. Until around 1967, the SWB used waterproof mortar for finishing. Epoxy resin paint was

Table 1 | Targets and number of specimens

Classification	Survey year	Years elapsed at survey	Number of specimens					
			Inside tank				Outside tank	
			Liquid phase		Gas phase		Gas phase	
			Surface finishing		Surface finishing		Surface finishing	
			Presence	Absence	Presence	Absence	Presence	Absence
Pumping station 6 stations, 69 specimens	1992 to 1994	14 to 29	53	0	1	9	0	6
Distribution reservoir 7 reservoirs, 44 specimens	1992 to 1994	22 to 56	16	6	0	1	3	18
Purification plant 2 plants, 181 specimens	1992 to 2012	6 to 56	17	58	2	23	23	58
The total (294 specimens)			86	64	3	33	26	82

mainly used for new facilities or surface refinishing until 1987, after which time coating has not been used in principle. As a result, the approximate breakdown of finishings for the inner surfaces of tanks is as follows: 59% epoxy resin paints, 39% uncoated and 2% other resin paints. The carbonation test was conducted by breaking concrete core samples laterally, spraying 1% phenolphthalein solution on the broken surfaces, and measuring the distance between the concrete surface and the part whose color had changed with a vernier caliper, in accordance with JIS A 1152 (method for measuring the carbonation depth of concrete). However, tests implemented before the establishment of JIS A 1152 were conducted by making measurement holes of 27 mm in diameter and 50 mm in depth, spraying the solution and measuring one colored part in each hole.

RESULTS AND DISCUSSION

Years elapsed and carbonation depth

The carbonation depths of target facilities categorized by the number of years elapsed and the environmental conditions (gas and liquid phases inside the tanks and gas phase outside the tanks) are shown in Figure 1, which also shows the Kishitani carbonation prediction formula (w/c = 53%, 55%, R = 1.0) (Kishitani 1986), the Japan Society of Civil Engineering (JSCE 2013) formula (γ_{cb} = 1.0, W/B = 0.55), and the log approximation formula for each environmental condition. The minimum measured carbonation value at the time of the survey was 0 mm, which was found for 46 specimens (approx. 16%) from several facilities aged six to 29 years. The maximum value was 25.7 mm, which was measured outside of a 35-year-old distribution reservoir. The measured value of carbonation was smaller than the value predicted by the Kishitani formula for 274 of the 294 specimens (approx. 93%) when w/c = 53%, and for 278 specimens (approx. 95%) when w/c = 55%. All specimens with measurement values exceeding the value of the Kishitani formula (w/c = 55%) were from outside the tanks (14 specimens), except for two specimens in the liquid phase inside tanks. The carbonation values determined by the approximation formula (coefficient of determination: R^2 = 0.102 to 0.469) were about half those determined by the Kishitani formula and were almost the same as those determined by the JSCE formula.
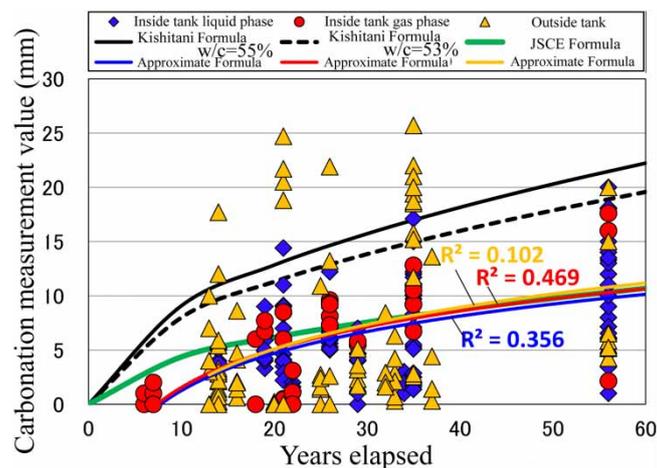

Figure 1 | Years elapsed and carbonation measurement value.

Carbonation rate coefficient

This section discusses how different phases and types of finishing affect the progression of carbonation of tanks in terms of the carbonation rate coefficient (hereinafter referred to as 'the

coefficient'). Under the assumption that carbonation, including that of surface finished concrete, progresses in accordance with the root t rule (JSCE 2013), the coefficients were determined by the equation below, based on the measurement values of carbonation found in the survey.

$$y = b\sqrt{t}$$

where, y: carbonation depth (mm),
b: carbonation rate coefficient (mm/$\sqrt{\text{year}}$), t: years elapsed.

The mean values (μ) and variations (standard deviation, σ) of the coefficients categorized by surveyed parts (bottom plates, side walls and top plates), phases (liquid or gas) and presence or absence of finishing are shown in Table 2. The distribution of the coefficients depending on phases and finishing conditions is as shown in Figure 2. It can be seen that, in this study, the carbonation rate tends to be slower for surface-finished concrete than for uncoated concrete, especially outside the tanks, by comparing Figures 2(a) and 2(b) or 2(d) and 2(e). The variation of the coefficients is also smaller under the condition with finishing for both inside and outside of the tanks (Figures 2 (a)–2(e)). This is thought to be because the finishing reduced the influence of external factors, such as the carbon dioxide concentration, temperature and humidity, which affect the carbonation progress rate.

Table 2 | Carbonation rate coefficient for each environmental condition

Survey part		Phase	Surface finishing	Cores (number)	Carbonation rate coefficient μ (mm/$\sqrt{\text{year}}$)	Standard deviation σ (mm/$\sqrt{\text{year}}$)
Inside tank	Bottom plate	Liquid	Presence	31	0.69	0.55
			Absence	21	1.12	0.87
	Side wall	Liquid	Presence	55	0.93	0.62
			Absence	43	1.47	0.59
		Gas	Presence	3	0.63	0.89
			Absence	4	0.84	0.53
	Top plate	Gas	Presence	–	–	–
			Absence	29	0.95	0.82
Outside tank	Side wall, floor slab	Gas	Presence	26	0.40	0.30
			Absence	82	1.43	1.50

A previous study indicated that there is little difference in the carbonation depth of tanks depending on the presence or absence of finishing (Shirakura *et al.* 1993). However, in the present study, the finishing (e.g., coating, mortar) seems to contribute to the inhibition of the progress of carbonation in water supply tanks as in the case of architectural and other outdoor concrete structures (Karasawa *et al.* 2007). Looking at the difference by phases, the coefficient in the liquid phase (1.36 mm/$\sqrt{\text{year}}$, Figure 2(b)) with little contact with the air is greater than coefficient in the gas phase (0.93 mm/$\sqrt{\text{year}}$, Figure 2(c)). Since the moving speed of carbon dioxide is considerably less in the liquid phase than in the gas phase, the progression of carbonation should be negligible when voids are filled with water (JSCE 2013). However, carbonation progresses faster in the liquid phase than in the gas phase in the present study. A laboratory experiment on concrete deterioration (Mashima *et al.* 1991) indicates that the progression of carbonation is affected by water pressure and that carbonation is faster in the liquid phase than in the gas phase. This study suggests that water pressure exerts an effect in actual tanks. However, in actual facilities, effects are exerted by water flow, reservoir water level fluctuations and other environmental factors peculiar to water supply facilities, in addition to water pressure. Since the possibility that factors specific to individual tanks, such as compressive strength or water cement ratio, affect carbonation and cannot be ruled out, further surveys on actual facilities are considered necessary. As described above, carbonation rates vary by environmental
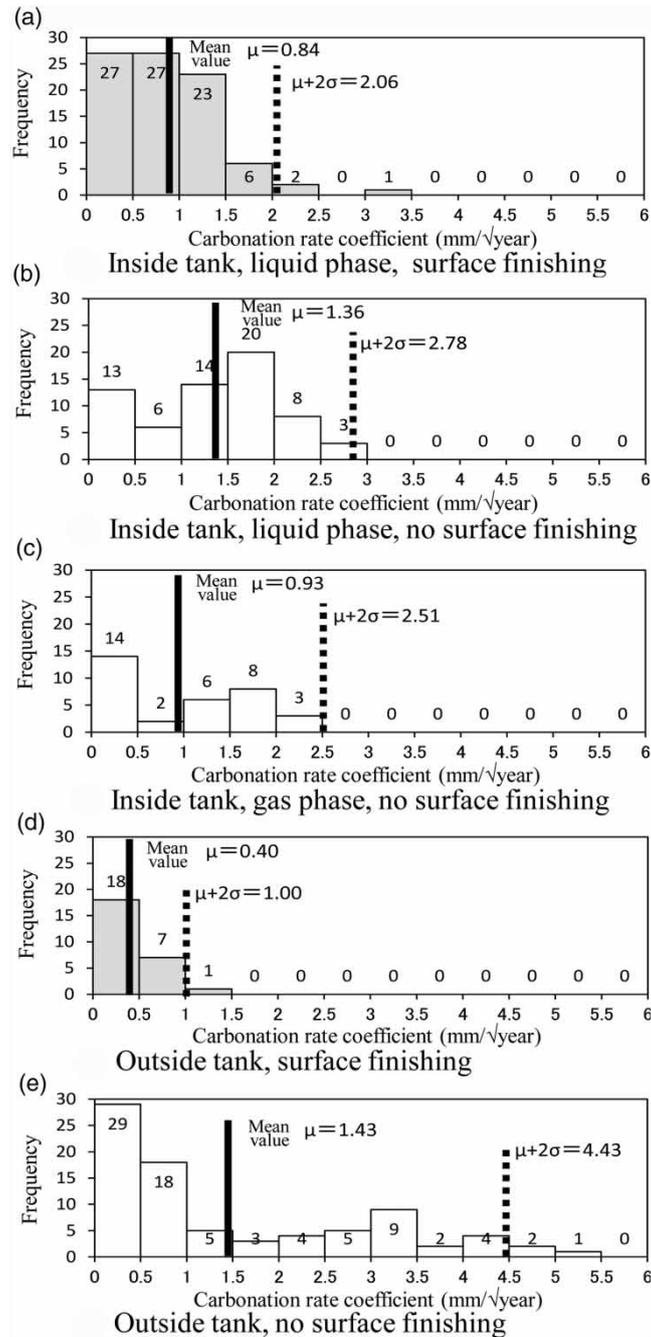
Figure 2 | Histogram of carbonation rate coefficient.

conditions and factors specific to individual tanks. Nevertheless, the maximum coefficient measured on the side walls inside a tank (liquid phase, no finishing) is 1.47 mm/$\sqrt{}$year (Table 2) and is less than one-third of the mean coefficient for ordinary residential buildings (4.71 mm/$\sqrt{}$year, $n = 441$, including the inside and outside of structures without coating) (Haruhata *et al.* 2011).

To summarize the above, it can be said that the carbonation rates of tanks vary by environmental and other conditions, and that the variation is relatively great (Figure 2). However, the progress seems generally slower than that for outdoor concrete structures. This is thought to be because the progress of carbonation is slow in certain wet environments in which tanks are usually located and because the facilities in this study were constructed using concrete with a low water cement ratio (w/c = 53% or under) that is supposed to hinder carbonation (Shimazoe *et al.* 1992). A study on the tendency of

concrete degradation conducted for tanks in 28 prefectures throughout Japan (approx. 120 facilities aged two to 91 years) (Fukuyama *et al.* 2013) also suggests that the carbonation rate in tanks is slower than in ordinary civil engineering structures. This also means that the results of this study show a tendency similar to that for tanks in the nationwide study.

Setting of the concrete cover depth based on carbonation progress prediction

This section determines the necessary concrete cover depth to protect rebar in the service period. A 100-year service period, which is designated in Japan as the design durable period for civil engineering structures requiring especially high durability (Endo 1991), was adopted.

Predictions were made for each section of tank by applying the root t rule in accordance with the JSCE specifications (2013). The carbonation depth of each part is the mean value for each part (bottom plate, side wall and top plate) calculated based on the measured values in Table 1 (294 specimens). For example, in the case of measuring carbonation depths at several parts of a side wall of a certain facility, the mean carbonation depth was used as the mean value for side wall values, and the wall was counted as one section for prediction. Figure 3 shows carbonation prediction curves for 100 years from the start of service life. The carbonation depth 100 years after the start of service life is predicted to be less than 30 mm in 86% ($n = 77$) of the survey locations ($n = 90$), and less than 40 mm in 94% of the survey locations ($n = 85$). The values are sufficiently less than the design cover depth (100 mm) for many facilities.
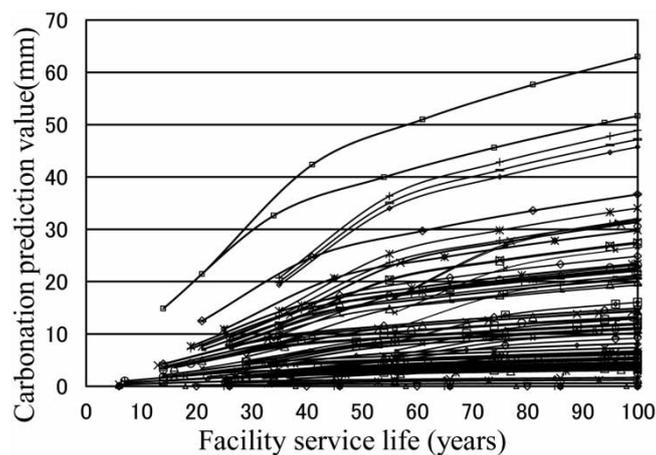

Figure 3 | Carbonation prediction curve.

From the viewpoint of rebar protection, a cover depth of approximately 50 mm is thought to be sufficient for more than 90% of sections. This depth includes the 10 mm from the surface of the remaining non-carbonated concrete to the rebar, at which rebar corrosion is supposed to begin (JSCE 2013). However, the root t rule used for this prediction is derived based on the diffusion process of carbon dioxide inside concrete in steady state, and carbonation rate coefficient is a complex function determined by many external and internal factors (Kishitani 1986). Thus, carbonation rates can vary as shown in Section 2.2, even under seemingly identical conditions. Construction errors (e.g., rebar swelling, deviation from the form position) may also cause variations in cover depth (Tanimura *et al.* 2003). If the variation is negative, the level of rebar protection becomes unsafe. At present it is also considered difficult to predict or manage such variations accurately. Therefore, it is desirable that the necessary and sufficient cover depth to protect rebar from carbonation be determined as the depth that can address the uncertainty caused by the variation of carbonation rate and cover depth in construction.

Figure 4 shows the distribution and variation of the predicted carbonation values 100 years after the start of the facility service life. Looking at the predicted carbonation values in the figure for after 100 years, the mean value μ is 14.2 mm, while $\mu + 2\sigma$ and $\mu + 3\sigma$, to which variations are added, are 40.8 and 54.2 mm, respectively. From this, the necessary cover depth to address the variation of carbonation is found to be approximately 65 mm, by adding the 10 mm to $\mu + 3\sigma$ (54.2 mm).
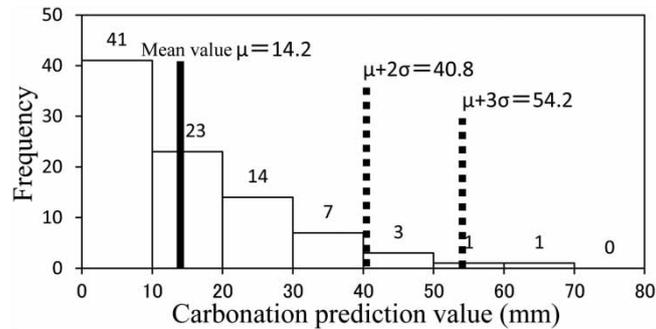

Figure 4 | Carbonation prediction value for 100 years.

According to a report on the actual measurement of construction accuracy of RC members, a negative error of concrete cover depth is the greatest on the underside of slabs, and the mean value for the underside of the slabs is −8.8 mm (1,362 samples) (Ito et al. 1994). Therefore, when determining the necessary and sufficient cover depth, it is considered possible to further ensure rebar protection by adding approximately 10 mm of thickness to address the variation in cover depth in construction to the above-mentioned 65 mm.

Based on the above results, it is assumed that 75 mm is the necessary and sufficient cover depth to address the above-mentioned uncertainty and to protect rebar from carbonation. Since this is the same as the value recommended for an environment with repeated wet and dry cycles in the Standard Specifications for Concrete Structures (JSCE), the value is considered appropriate for tanks.

Verification of the prediction

This section verifies carbonation values predicted in the previous section by using the results of a continuous survey on carbonation in the facilities shown in Table 1.

Table 3 shows the results of carbonation surveys conducted by SWB in 1994 and 2009 at an elevated reservoir of a water purification plant, and the predicted carbonation values for 2009 based on the results of 1994. Table 3 shows that in Condition 2, for example, the predicted value for 2009 is

Table 3 | Verification of predicted value

Condition (Inside tank only)	Surface finishing	1994			2009		
		Years elapsed	Measured value (mm)	The coefficient (mm/$\sqrt{}$year)	Predicted value (mm)	Measured value (mm)	The coefficient (mm/$\sqrt{}$year)
1) Liquid phase/ Side wall	Absence	7	1.00	0.38	2.52	1.90	0.40
2) Gas phase/ Top plate	Absence	7	0.67	0.25	1.67	1.40	0.30
3) Liquid phase/ Side wall	Epoxy	6	0.00	0.00	0.00	0.00	0.00
4) Gas phase/ Top plate	Absence	6	0.33	0.13	0.85	0.50	0.11

1.67 mm, while the measured value is 1.40 mm, which is close to the predicted value. Under other conditions, the predicted values are also the same as, or more than, the measured values. The coefficients calculated are also roughly the same under different conditions. Therefore, although the amount of data is small and the survey intervals are as short as 15 years, setting of the cover depth based on predictions by the root t rule is considered a necessary and sufficient or safe selection in terms of rebar protection.

Effect of residual chlorine

This section discusses the relationship between residual chlorine, which is an external factor peculiar to water supply facilities, and carbonation, focusing on specimens inside tanks in the liquid phase. Table 4 shows the names of facilities for which records of residual chlorine measurements were found in the Annual Report on Water Quality (SWB), as well as the residual chlorine concentrations and the coefficients by specimens. Figure 5 shows the relationship between the mean residual chlorine by facility and the coefficient, as well as the coefficients for raw water storage facilities that do not contain chlorine. Except in some facilities, residual chlorine was measured by the o-toluidine method for the most recent eight to 13 year period from the year of the survey. The measurement

Table 4 | Residual chlorine and the coefficient

| Objective Facilities		Residual chlorine of each facility (mg/L)				
PS: Pumping Station DR: Distribution Reservoir		Mean	Standard diviation	Data periods	Carbonation rate coefficient (mm/√year)	Survey year
Kiyota	PS	0.42	0.04	1981 to 1993	0.94 to 1.36	1992
Sumikawa	PS	0.49	0.06	〃	0.00	〃
Ishiyama	PS	0.53	0.09	〃	1.53 to 3.14	〃
Aoba	PS	0.46	0.05	〃	0.48 to 1.24	〃
Sakaigawa	PS	0.48	0.07	1984 to 1993	0.76 to 2.07	〃
Makomanai	DR	0.53	0.09	1981 to 1993	0.17 to 0.64	〃
Moiwa	DR	0.67	0.08	〃	0.23 to 0.96	〃
Elevated reservoir		0.81	0.06	〃	0.00 to 0.38	1994
Elevated reservoir		0.71	0.11	1981 to 2009	0.28 to 0.62	2010
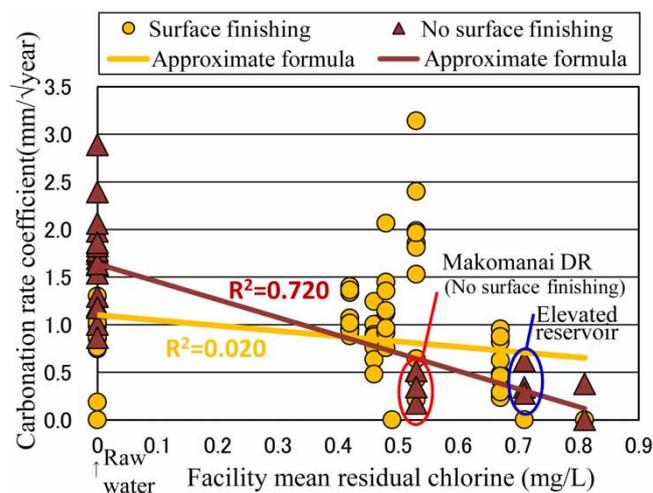
Figure 5 | Residual chlorine and the coefficient.

frequency was two to 12 times per month. From Table 4, the mean residual chlorine by facility is 0.42 mg/L ($\sigma = 0.04$ mg/L) to 0.81 mg/L ($\sigma = 0.06$ mg/L), almost the same values are maintained throughout the measurement period at the same facilities. Meanwhile, the coefficients differ considerably by survey section even in the same facility. According to a study that experimentally surveyed the effect of residual chlorine on carbonation (Mashima *et al.* 1991), it was supposed that carbonation progress tended to increase slightly with increases in residual chlorine. However, regardless of the presence or absence of coating, there was no positive correlation between the residual chlorine and the coefficient, as shown in Figure 5. Looking at specimens with coating in Figure 5, the residual chlorine and the coefficient have an almost flat relation (coefficient of determination: $R^2 = 0.020$), and no effect of chlorine is found. This may be attributed to the chlorine-suppressing effect of the coating. Looking at specimens without coating, a negative correlation ($R^2 = 0.720$) is found between residual chlorine and the coefficient. According to the results of an accelerated laboratory test (Mashima *et al.* 1991), a negative correlation between residual chlorine and carbonation depth is found when the residual chlorine is 0 to 50 mg/L in normal Portland and silica cement. The results of chemical analysis conducted for specimens immersed in chlorine reveal that the amount of carbon dioxide is great on the surface, and calcium carbonate is generated by carbonation. Furthermore, a careful reading of the analysis results reveals that only normal Portland and silica cement show a tendency for the carbon dioxide concentration inside specimens to decrease with increases in chloride ion concentration due to residual chlorine progress. In other types of cement, the carbon dioxide concentration inside specimens increased after the specimens were immersed in chlorine. As described above, in consideration of the results of this study and a previous report (Mashima *et al.* 1991), it is assumed that residual chlorine has a suppressive effect on carbonation under certain conditions and that this could be a reason for the slow progression of carbonation in tanks nationwide.

SUGGESTIONS ON SURFACE FINISHING FOR TANKS

From the results of this study on tanks of the SWB, it is presumed that a surface finishing suppresses carbonation under certain conditions (Figures 2 and 5). However, the measured carbonation values and the coefficients were adequately small regardless of environmental conditions and presence or absence of finishing (Figures 1 and 2). Therefore, from the viewpoint of suppressing carbonation, the necessity of finishing is considered to be low. In the tanks that are uncoated inside, it is considered possible to protect rebar from carbonation throughout the service life of a facility as long as a cover depth of 75 mm is secured (Figures 3 and 4). The study described in Section 2.3 (Endo 1991) presents the idea of using the cover depth to examine the durability of concrete structures, indicating that the maintenance of structural durability can be achieved by securing the appropriate cover depth. However, because of the intrinsic properties of concrete, structures made of this material cannot avoid cracking associated with drying-shrinkage, materials and loading. Cracks that occur on uncoated tanks may cause deterioration in water-tightness. According to The Water Supply Facilities Maintenance Manual (JWWA 2006), inspections for cracks and water leakage should be conducted regularly, since cracking has a significant influence not only on water-tightness, but also on structural durability. The JWWA also requires that sufficient earthquake resistance, durability and water-tightness be ensured as requirements for purification and distribution reservoir structures. Accordingly, this study presents a low-cost operation and maintenance method for maintaining the durability and water-tightness of tanks that are not coated inside by setting the cover depth, carbonation depth and leakage as indicators (Figure 6). For example, in the case of a tank with a deteriorated finishing, the cover depth at each section is first examined by non-destructive testing. If the cover depth is 75 mm or over, then subsequent carbonation testing may be omitted, and after the deteriorated surface is removed and it is confirmed that there is no leakage, it is appropriate to leave the inside of
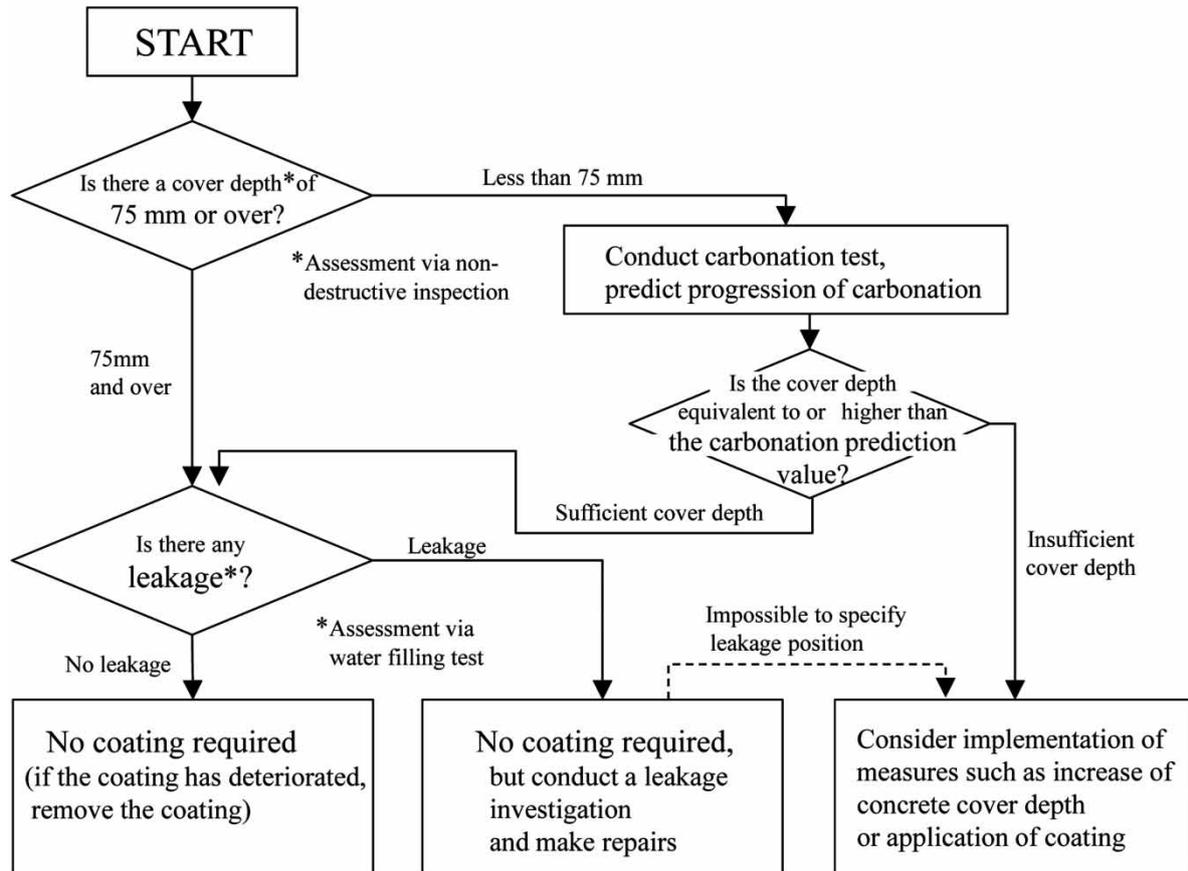
Figure 6 | Flow chart for selection of surface finishing method for existing tanks.

the tank uncoated. Meanwhile, if there is a section where the cover depth is less than 75 mm, then carbonation testing and progress prediction at this section should be conducted, and if the cover depth is less than the predicted carbonation progress value for the facility's service life, it is considered appropriate to take remedial measures, such as by increasing the cover depth or applying a finishing. Even if a cover depth of 75 mm or over is secured, a drawdown in tanks may be found in a water-filling test. In this case, it is considered appropriate to leave the inside of the tank uncoated after conducting a survey and repair for the leak location.

CONCLUSION

(1) Carbonation tends to progress more slowly in tanks than in ordinary concrete structures, but it may be affected by conditions unique to water supply facilities.

(2) It is assumed that 75 mm is the necessary and sufficient depth for protecting rebar while addressing variations in the carbonation rate and construction.

(3) In conducting maintenance on tanks whose inside is left uncoated, it is considered possible to use carbonation depth and leakage as indicators in order to ensure durability and water-tightness while reducing the longterm maintenance costs of tanks.

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