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Technical Paper

Effect of initial curing conditions on air permeability and de-icing salt scaling resistance of surface concrete

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Abstract: Enhancing the surface quality of concrete is a key to improve the durability of reinforced concrete. Surface concrete can protect steel bars from corrosion due to the migration of gas, water and ion from the surrounding environment. Therefore, the influence of the initial curing on air permeability and the de-icing salt scaling resistance of surface concrete were investigated in this paper. Firstly, existing bridge structures in the cold region of Japan were surveyed with visual rating and non-destructive test (NDT) for the surface quality of concrete. Secondly, the concrete specimens were prepared for different curing conditions and methods including cold weather concreting, heat or non-heat-supply curing, extending demold period and water-retention sheet. These results showed that concrete curing with sheet or permeability formwork was better than curing in air. Especially, utilizing permeability formwork is greatly effective for the attainment of high surface quality of concrete. Simultaneously, focus on cold weather concreting, could evaluate the appropriate curing period combining with the surface air permeability and the de-icing salt scaling resistance of concrete. The surface concrete has better de-icing salt frost resistance, when the surface air permeability coefficient is below $1\times10^{-16}m^2$ or the initial curing period is more than three weeks.

Keywords: Surface quality, cold weather concreting, initial curing, surface air permeability, de-icing salt scaling.

1. Introduction

One of the most significant issues for concrete structures is to ensure long-term durability in severe conditions of the actual environment. Therefore, the surface quality of concrete cover has to be critical to attaining the durability of a concrete structure.

In the cold region of Japan, the de-icing agent has been used on the roads since early 1990s when using spike-tires on a car was banned, in order to secure the driving safety of the car in the winter season. The main component of the de-icing agent is sodium chloride, potassium chloride, calcium chloride magnesium chloride. The excessive spreading of these agents induced the acceleration of multiple deterioration (such as frozen deterioration of the concrete cover, corrosion of reinforcement due to chloride ion, and the alkali silica reaction of aggregates) [1] of concrete structures. The concrete cover has the function as mitigating layer for some deterioration factors (water, ion, gas and so on) that can be penetrate the concrete surface from the surrounding environment [2,3]. Therefore, if severe deterioration occurs on the cover concrete, the durability of concrete structures is probably affected by the degree of deterioration. Thus, it is important for concrete structures to ensure and improve the quality of the surface concrete. The initial curing of concrete is the greatest factor to ensure the quality of the concrete cover, which can make concrete obtain a sufficient heat of hydration and improve the strength [4,5]. The drying of cementation materials due to poor curing, particularly at the concrete surface, leads to restricted hydration in the surface layers and thus to higher porosity and permeability [6-9].

In addition, de-icing salt scaling resistance is another feature influenced by the surface quality of concrete. Research and surveys of the past showed

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that the spraying of de-icing salt on a concrete surface led to gradual deterioration from the surface into the inner part [10]. The higher and looser porosity of the surface concrete tended to markedly reduce the de-icing salt scaling resistance [11]. Thus, attainment of high surface quality is essential to make the concrete durable in a severe environment. However, the initial curing period of concrete which is necessary to attain the surface quality and the de-icing salt scaling resistance of concrete, would be not be clear enough, and has not been specifically indicated even in the standard specifications for the construction of concrete structures [17].

The purpose of this paper is to investigate the influence of some curing methods and mold-types on surface quality of concrete structures through a survey of on-site RC structures using NDT (testing of surface air permeability and water content) in cold regions. After the survey, concrete specimens were used for simulated cold weather concreting, the influence of a curing temperature, curing methods and additional curing or not on the surface quality of concrete was experimentally examined, and the durability of its concrete, especially freezing-thawing resistance with a sodium chloride solution (scaling resistance) was also evaluated via laboratory test.

2. Detail of Survey and Experiment

2.1 Survey of existing RC structure

Evaluating the effects of some experiments, in an attempt to ensure and improve the surface quality of concrete was conducted, existing concrete structures in Aomori and Iwate Prefecture in the northern part of mainland of Japan were targeted. The mold types, the additional curing methods, and the additional curing period were set as the parameters to survey the targeted structures with the surface air permeability test (Torrent method see Fig. 2(a)) [12,13]. Table 1 shows the information of the surveyed structures. The W/C used for these surveyed structures were in the range of 50 to 55%. Blast furnace slag

Table 1 – List of surveyed existing structures

Structures	Members	Ready-mixed concrete	Period of construction (Y. M)	Date of survey (Y. M)	Standard curing period (during formwork keeping)	Additional curing after demolding	Permeability formwork
Bridge A	A1, A2	24-8-25 BB	2014.01-2014.02	2014.06	14 days, 7 days	-(non)	—
Bridge B	A1, A2	24-8-25 BB	2010.06-2010.07	2013.11	10 days	-(non)	—
Box culvert B	Side wall	24-8-25 BB	2014.05-2014.06	2015.06	7 days	-(non)	—
Bridge C	P2	27-8-25 BB	2009.12-2010.02	2013.11	5 days	-(non)	—
Bridge D	P1, P2	24-8-25 BB	2014.01-2014.02	2015.01	P1: 8 days P2: 9 days	Sheet curing P1: 15 days P2: 11 days	—
Box culvert D	Side wall	24-8-25 BB	2014.06	2014.10	14 days, 7 days	-(non)	—
Bridge E	A1, A2	24-8-25 BB	2013.04	2014.11	A1: 10 days A2: 8 days	Curing agent	—
Box culvert E	Slab	24-8-25-BB	2016.06	2016.09	1 day	Water-supply curing (6-36 days)	—
Bridge F	P2, P3, P4	24-12-25 BB	2015.01-2015.04	2015.07	7 days	Sheet curing	○
Bridge G	A1	24-8-25 BB	2014.01	2015.06	7 days	-(non)	—
Bridge H	A1	24-8-25 BB	2015.04	2015.08	60 days	-(non)	—
Bridge I	A2, P2	24-8-25 BB	2017.03-2017.04	2017.08	A2: 9 days P2: 5 days	Sheet curing A2: 27 days P2: 68 days	—
Bridge J	A1, P1	24-8-25 BB	2016.12-2017.06	2017.08	A1: 9 days P1: 7 days	Sheet curing A1: -(non) P1: 25 days	—

※Ready-mixed concrete: design strength-slump value-maximum size of coarse aggregate / Blast furnace slag cement (BB). Pier: P1, P2, P3, P4; Abutment: A1, A2. (Y. M): (Year. Month).

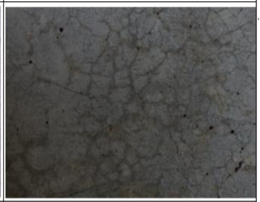
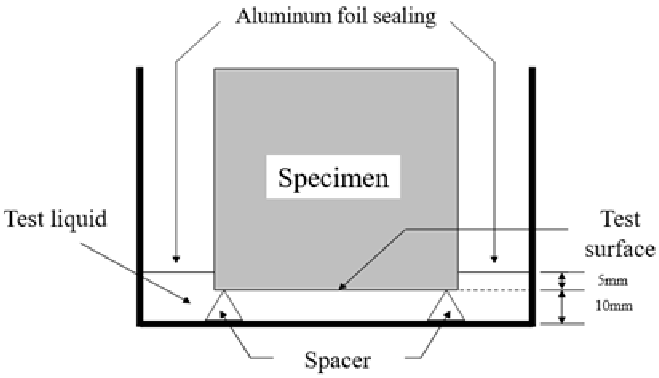
Visual rating of surface micro cracks				
Rating grade	**4(AAA)**	**3(AA)**	**2(A)**	**1(B)**
Observation method: 1. Polishing the surface lightly with sandpaper to remove dirt. 2. Wiping with a cloth of being impregnated with acetone.				
3. Evaluating the micro cracks of surface concrete, when acetone is completely absorbed into concrete.	Almost no micro cracks on surface concrete of survey-area.	Appearing slight micro cracks on surface concrete of survey-area.	Appearing moderate number of micro cracks on surface concrete of survey-area.	Appearing severe number of micro cracks on surface concrete of survey-area.

Fig. 1 – Visual rating of the existing concrete structures surface micro cracks

(a) Surface air permeability test



(b) Specimen of de-icing salt scaling test

Fig. 2 – Test set-up for the freeze-de-icing salt test and Torrent method

cement (BB) was used for such structures. Simultaneously, the visual rating of the existing concrete structures surface micro cracks were also conducted in the surveying with Fig. 1 [16,17], which will be presented in the results and discussion as follows.

2.2 Experimental outline

2.2.1 Preparation of materials and specimens

The mix proportions of the concrete were listed in Table 2. The ready-mixed concrete (24-12-25, target air content: 5.0 ± 0.5%.) with two types of cements (ordinary Portland cement (N) and blast furnace slag cement (BB)) were adopted in this experiment. N was used for reference specimens. The replacement ratio of blast furnace slag is 42% and its chemical composition is set according to JIS R 5211. The fine aggregates and the coarse aggregates used for the test were pit sand and crushed limestone respectively. Prism specimens of 150×150×530mm were produced in a laboratory that assumed cold weather concreting in a temporary snow covered enclosure under the temperature controlling (Temperature: 10℃, and Relative humidity: 60%).

2.2.2 Procedure

The curing conditions, additional curing methods, additional curing period and the application of a permeability formwork were set as experimental parameters, which are presented in Table 3. A heat-supply curing technique was used in this study, the curing temperature of concrete in cold weather conditions was exposed to be maintained at 5℃ or higher until the compressive strength reaches the values given in the JSCE Guidelines for Concrete structures [18]. Thus, the curing temperature at 5℃ was selected for entire the curing conditions until demolding of the specimens. After the demolding of the specimens, the heat-supply curing (15℃), the heat-supply curing (5℃) and the non-heat-supply curing (simulating an actual outside condition in winter: +8 ⇔-2℃) were executed as additional curing (extending demold period, wrapping with water-retention sheet, and in air conditions). After the additional curing period, specimens were kept in an air conditioned room (20℃, 60%) for 63 days, and then the surface air permeability test was conducted to confirm the quality of the surface concrete with NDT (Torrent method).

Table 2 – Mix proportion of concrete (unit: kg/m^3)

Types	W/B (%)	Air (%)	s/a (%)	Cement	Water	S1	S2	G	AE
N	54	6	45	288	156	620	270	1086	2.59
BB	54	6	44	281	152	605	262	1121	2.53

Table 3 – Experimental conditions

Curing conditions	Age of demold	Additional curing period	Additional curing	N		BB	
				Normal mold	Permeability formwork	Normal mold	Permeability formwork
Heat-supply curing (15℃)	N: 3 days, BB:5 days	7 days 21 days	Extending demold period	●	—	●	—
			Water-retention sheet	●	—	●	—
			Air (room condition)	●	●	●	●
Heat-supply curing (5℃)	N: 5 days, BB:7 days		Extending demold period	●	—	●	—
			Water-retention sheet	●	—	●	—
			Air (room condition)	●	●	●	●
Non-heat-supply curing (+8～-2℃)	N: 3 days, BB:5 days		Extending demold period	●	—	●	—
			Water-retention sheet	●	—	●	—
			High-adiabatic sheet ①	●	—	●	—
			High-adiabatic sheet ②	●	—	●	—

Measuring six positions on the two other surfaces except the casting surface side were done on every specimen (150×150×530mm).

Specimens with dimensions of 150×150×150 mm were cut from a prism specimen that came from measuring surface air permeability, then the de-icing salt scaling resistance test was conducted in accordance to JSCE-K 572(6.10)(see Fig. 2(b)). The testing surface of a specimen was the side surface perpendicular to the casting direction. The specimens were sealed on their surface except for the testing surface, and after the capillary suction period, they are kept for seven days at a temperature of 20 ± 2℃ with 3% Na Cl solution. Then, the specimens were exposed to freezing-thawing conditions (Temperature: 20 ⇔ -20℃, two cycles a day) [14,15]. The scaling amount of a specimen was measured every 6 cycles up to 60 cycles.

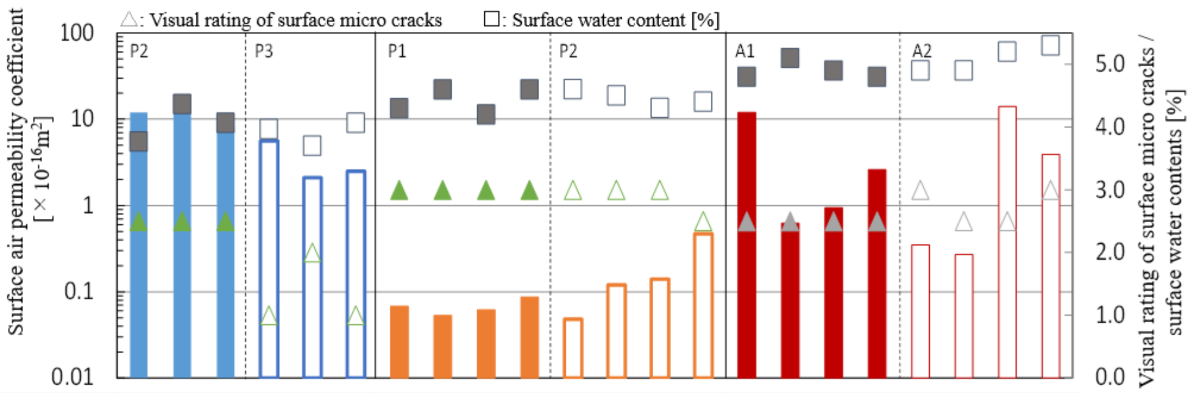
3. Results and Discussions

3.1 Evaluation of the effect of additional curing after demolding

The results of the surface air permeability coefficient, the surface water contents and the visual rating of surface micro cracks are shown in Fig. 3. Different methods of the additional curing after demolding were utilized. Bridge C is the case of a non-additional curing, Bridge D is the case of a heat-and-moisture retention curing via polyethylene sheet after demolding and Bridge E is the case of using the curing-agent (low drying shrinkage type) after demolding. Testing the air permeability coefficient requires the water contents of a concrete surface to be at a lower level [12,13]. From this figure, the water contents of all of the measurements are under 5.5%.

From these results, it is observed that the surface air permeability coefficient of Bridge D is lower than Bridge C and Bridge E. The surface air permeability of Bridge C indicated the range from 2.9~14×10^{-16}m^2 and Bridge E has a range from 0.3~1.2×10^{-16}m^2. The results are little different between Bridge C and Bridge E, although additional curing has not been conducted on Bridge C. On the other hand, the coefficient of surface air permeability of Bridge D indicated almost 0.1×10^{-16}m^2. The reason of this is considered that it is due to the effect of heat and moisture-retention by being sealed immediately after demolding with polyethylene sheet, and is due to the result of the improved surface quality of concrete by its positive effect. In addition, compared with the result of the case of another curing method, Bridge E has some fluctuation range of data in the same structural member. It may be due to non-uniform spray of the curing-agent on the surface of concrete.

Moreover, the results of visual rating of surface micro cracks are also shown in Fig. 3. It is showed that the visual rating of Bridge C and Bridge E have larger fluctuations in the same structural member. However, the visual rating and the surface



Structure	Bridge C		Bridge D		Bridge E	
Member	Pier (P2)	Pier (P3)	Pier (P1)	Pier (P2)	Abutment (A1)	Abutment (A2)
Ready-mixed concrete	27-8-25BB		24-8-25BB			
Construction period	2009.12 ~ 2010.2		2014.1 ~ 2014.2		2013.4	
Standard curing	5days		8days	9days	10days	8days
Additional curing	Non		15days (sheet curing)	11days (sheet curing)	Curing agent	

Fig. 3 – Effect of the additional curing on the surface air permeability of existing structure

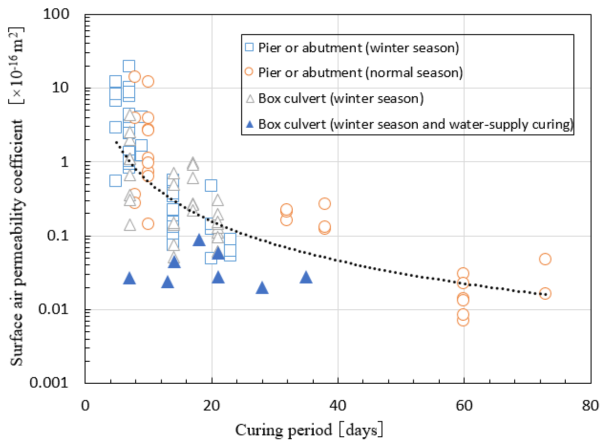


Fig. 4 – The relationship between the surface air permeability coefficient and curing period

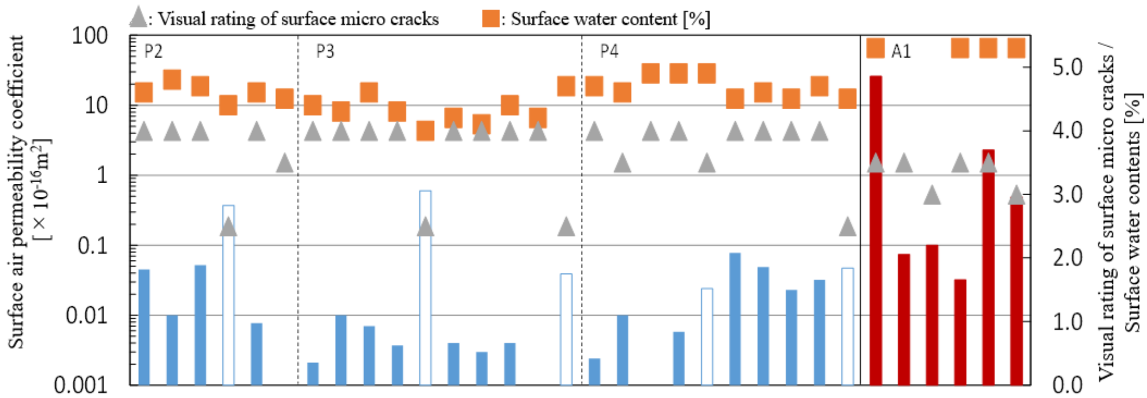
air permeability coefficient of Bridge D are relatively stable. Thus, the entirety of the concrete structures can obtain better quality via the sheet curing method.

Fig. 4 indicates the relationship between the surface air permeability and the entire curing period (including an additional curing period). This figure includes all data from the survey, which includes the results of the survey other than the structures described above, together (see Table 1). The data shown in this figure are (a) Cement type: Blast furnace slag cement (type B), (b) W/C: 50-55%, and (c) Mold types: ordinary mold (wooden type), and the additional curing methods are a case of sealed curing (extension of a demolded period, or using a water-retention sheet).

From this result, it was found that the surface air permeability decreased with the extension of the curing period which included an additional curing period. Especially, in the case of a curing period less than 10 days, the surface air coefficient change in a range from 0.024×10^{-16} to $19\times10^{-16}m^2$. A trend was recognized that has a large variation. It was considered that the reason was the density of surface concrete was decreased because the cement hydration stopped, and during drying of the concrete surface after demolding, some micro cracks appeared. In the case that the curing period was longer than 14 days, the surface air coefficient change was in the range from 0.007×10^{-16} to $1\times10^{-16}m^2$. A trend was recognized that has less variation, and the coefficient varied within a certain range. Moreover, it was observed that the method of water-supply curing could improve the air permeability of concrete better than others in winter.

3.2 Evaluation of effect of using permeability formwork

The development of a unique type of permeable formwork was proposed by researchers as a replacement for the conventional formwork used since 1987 in Japan [19]. Permeability formwork is the setting a permeability sheet on the face of the mold, and using this formwork, it was expected that the quality of surface concrete was improved by draining extra water and/or by reducing surface air void. Fig. 5 indicates whether the surface air permeability of structures (Bridge F, G) used the formwork with a permeable sheet or not. The pier of Bridge F is an elliptical shape, and the measuring results in the curved position shown with the white color bars in the figure, and the characteristics of this pier construction as



Structure	Bridge F			Bridge G
Member	Pier (P2)	Pier (P3)	Pier (P4)	Abutment (A1)
Ready-mixed concrete	24-12-25N			24-8-25N
Construction period	2015.1 ~ 2015.4			2014.10
Standard curing	7days			15days
Additional curing	28days (sheet curing)			Non
Permeability formwork	Using			Non

Fig. 5 – Effect of the permeability formwork on the surface air permeability of structure

follows:

(a) Large amount of bleeding water occurred during construction.

(b) It was not only using a permeability formwork but also conducting a sealed curing with a water-retention sheet for about 1 month.

A comparison of results between Bridge G and Bridge F revealed that the surface air permeability coefficient of Bridge F (about 0.1 to $0.01\times10^{-16}m^2$) was lower than Bridge G (about 0.1 to $10\times10^{-16}m^2$). Therefore, the effectiveness of utilizing permeability formwork was confirmed and indicated. Then, comparing the coefficient of different measuring positions, it can be seen that the surface air permeability coefficient in the straight position (blue bar less than $0.1\times10^{-16}m^2$) is lower than the curved position (white bar more than $0.1\times10^{-16}m^2$) on Bridge F. In addition, there were also some straight positions that showed a remarkable low coefficient (less than $0.001\times10^{-16}m^2$). This reason may be considered that is the influence of the excessive bleeding amount that was gathered the near surface of concrete in a curved position of the pier and lead to an increase in water to cement ratio.

Moreover, in the case of Bridge F, the results of visual rating of surface micro cracks were indicated that the visual rating increases with the decrease of the surface air permeability coefficient.

Table 4 – The surface air permeability coefficient ($\times10^{-16}m^2$)

Curing conditions	Additional curing	Cement	N				BB			
		Mold	Normal mold		Permeability formwork		Normal mold		Permeability formwork	
		Period	7 days	21 days	7 days	21 days	7 days	21 days	7 days	21 days
Heat-supply curing (15℃)	Extending demold period Water-retention sheet Air (room condition)		1.60	1.45	—	—	2.90	1.70	—	—
			1.90	0.80	—	—	1.77	0.87	—	—
			2.05	3.40	1.80	1.75	5.00	4.80	0.68	1.86
Heat-supply curing (5℃)			1.43	1.15	—	—	3.25	2.95	—	—
			1.50	1.21	—	—	3.25	1.18	—	—
			3.05	3.00	2.45	1.85	7.05	9.05	1.06	1.21
Non-heat-supply curing (+8~-2℃)	Extending demold period		1.35	2.20	—	—	2.65	4.45	—	—
	Water-retention sheet		1.90	2.00	—	—	2.55	6.05	—	—
	High-adiabatic sheet①		1.70	1.50	—	—	2.40	1.60	—	—
	High-adiabatic sheet②		2.35	1.40	—	—	2.05	0.88	—	—

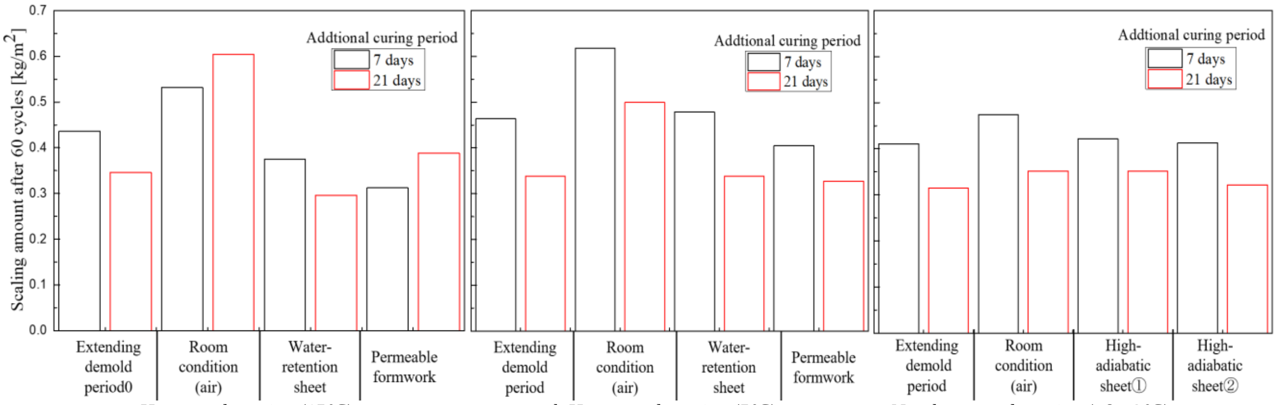


Fig. 6 – The scaling amount after 60 cycles of freezing-thawing action

3.3 Influence of curing condition on surface quality in laboratory

From the results of the survey targeting existing concrete structures, the importance of curing conditions for the improvement of surface quality was found. Therefore, the objective of this section is to evaluate the influence of curing conditions on surface quality of concrete, assuming the cold weather concreting, and the experimental programs were planned.

Results of the surface air permeability coefficient for all conditions are listed in Table 4. The moisture content was 4.2~5.1% at the time of measuring the surface air permeability. From Table 4, in the case of non-heat-supply curing, it was confirmed that the surface air permeability was decreased due to heat-protection curing with high-adiabatic sheet. Simultaneously, it was found that the surface air permeability was decreased with the extension of the additional curing period at the same temperature. Moreover, focus on the difference in mold types (normal mold / permeability formwork), it was found that the surface air permeability for the specimen which used the permeability formwork was a lower value.

Fig. 6 presents the scaling amount after 60 cycles of freezing-thawing action. From these figures, for the specimen assuming heat-supply curing (15 ℃ and 5 ℃), it was found that the scaling amount of specimen conducting air curing indicated the trend that large scaling amount occurred compared with that of specimens under other curing conditions. On the other hand, in the case of keeping the mold setting, using a permeability formwork or using a water-retention sheet, it was confirmed that the scaling amount was reduced. The influence of additional curing period revealed that the scaling amount was decreased with the increase of an additional curing period, except in some cases. For the case of no-heat-supply curing (+8~-2℃), the influence of the additional curing method on scaling amount was less, and it was found that the scaling amount was decreased with the increase of the additional curing period regardless of the difference in an additional curing method. Therefore, it was considered that the heat-retaining curing was enough to ensure the surface quality and the de-icing salt scaling resistance of concrete. It was not necessary to conduct heat-supply curing in cold weather concreting when the outside temperature was above -2℃, as the test result showed.

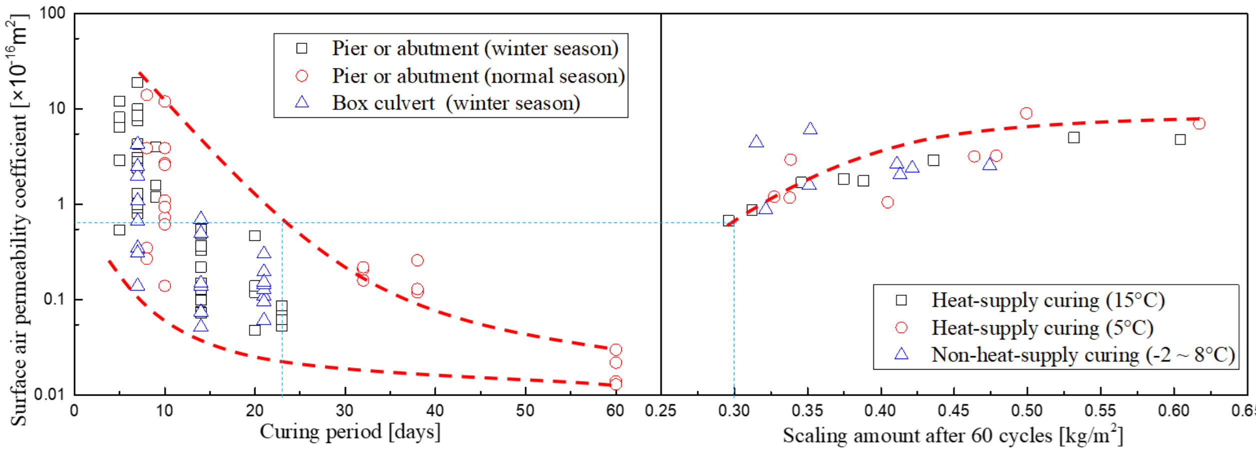


Fig. 7 – The relationship between curing period and the scaling amount after 60 cycles of freezing-thawing action

3.4 Expectation of curing period based on de-icing salt scaling resistance

Construction of concrete structures in actual engineering is not only to ensure the progress of the project, but also to provide better quality to ensure durability. The curing period of concrete is closely related to the progress of the project. Scaling amount is one of the parameters to evaluate the durability of concrete. Fig. 7 is the relationship between the surface air permeability coefficient with the scaling amount after 60 freezing-thawing cycles and a curing period including additional curing. The object of this figure is to play a guiding role to help the decision-makers of construction to select an appropriate initial curing period by combining with the results of the on-site surveys and the laboratory experiments.

From this result, it was found that the surface air permeability coefficient decreases with the increase of the curing period, and the scaling amount decreases with the decrease of the surface air permeability coefficient, regardless of curing temperature and curing method. In addition, it can be found that the range of the surface air permeability coefficient changes from large to small. In other words, the surface air permeability coefficient tended towards stability with the increase of the curing period (the surface quality of concrete is improving).

Furthermore, it is possible to consider an appropriate initial curing period according to the low scaling amount and surface air permeability coefficient in Fig. 7. From this figure, when an example of the scaling amount is 0.3kg/m^2, the safety curing period would need at least three weeks and the surface air permeability coefficient is about 1×10^{-16}m^2. It was decided that the concrete has better de-icing salt frost resistance, when the surface air permeability coefficient is less than 1×10^{-16}m^2 or the initial curing period is more than three weeks. Therefore, using NDT to test the surface air permeability of concrete is promising as an effective method for confirming the de-icing salt frost resistance of concrete.

4. Conclusions

In this investigation, the aim was to assess the surface quality of concrete through initial curing conditions and de-icing salt scaling resistance in field surveys and laboratory examinations. The following conclusions may be drawn:

1) The additional curing after demolding or extending the initial curing period can effectively improve the surface quality of concrete, and the surface air permeability coefficient was decreased with the increase of curing period. When the curing period was greater than about 14 days, there was the less variation of surface air permeability, and the variation trend and speed of the decrease of surface air permeability coefficient will reduce.
2) The results of visual rating of surface micro cracks show the relationship between the micro cracks and the surface air permeability that the visual rating increases with the decrease of the surface air permeability coefficient. Thus, it is possible that assessment of surface quality of concrete through visual rating of surface micro cracks.
3) By using the permeability formwork, the surface air permeability was greatly reduced. In particular, using the permeability formwork was effective for the concrete that have a great amount of bleeding.
4) It is helpful for the decision-makers in construction to consider an appropriate initial curing period based on the relationship between the surface air permeability coefficient with the scaling amount after 60 freezing-thawing cycles and curing period.

As a result, the experimental results play a certain role in choosing the initial curing period to meet the durability requirements of concrete. The relationship between curing period and anti-scaling performance needs to be further improved. Our investigations into this area are still ongoing to confirm our hypothesis.

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