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Evaluation of durability performance for maintenance of tunnel structures due to repeated freezing and thawing

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Abstract. In this paper, the quantitative evaluation method is presented for the durability performance of mountain tunnel concrete linings experiencing freezing and thawing during winter season. To analyze the freeze-thaw characteristics of lining, the freezing time of the concrete lining was measured by the outside temperature. The heat flow analysis was conducted based on the freezing time measured through the indoor experiment, and based on this, the energy required to freeze the concrete lining by the temperature of the outside air could be analyzed. In addition, the temperature change during the winter season was measured through an instrument installed on the actual tunnel concrete lining, and based on the results of indoor and field experiments, criteria for freeze-thaw environment evaluation and progress evaluation were prepared. Also, an equation using the freezing index was proposed through regression analysis.

Keywords: criteria development; durability performance; freeze-thaw characteristics; Heat flow analysis; quantitative evaluation method

1. Introduction

Facility damage and quality deterioration due to freezing and thawing in winter can shorten the life of facilities and cause damage to human life and property. Jerzy Waqrzenczyk *et al.* (2017) confirmed through experiments the number of freeze-thaw repetitions that can cause cracks in concrete, considering the correlation between the increase in concrete mass and concrete cracks through repeated freeze-thaw cycles. Bassuoni and Nehdi (2005) analyzed that high-performance concrete with no air entrainment and a low water-binder ratio could not find weaknesses using a general freezing durability test, but complex deterioration mechanisms could occur under various environmental conditions in actual sites.

In the case of facilities constructed in the regions where cold waves or heavy snowfall frequently occur, tunnel concrete lining may be more damaged by repeated freezing and thawing. In addition, the degree of damage is likely to increase every year. Various researchers tried to find the failure mechanism of concrete due to freeze-thaw cycles. Jian *et al.* (2018) confirmed that the freeze-thaw repetition lowered the particle agglomeration and increased both the proportion of fine particles and the proportion of porous area through an experimental study. Liyun *et al.* (2020) compared the characteristics of the interface strength parameters during the freezing process and analyzed the differences between the interface shear characteristics and failure mechanisms during the frozen soil-structure interface freezing-thawing process. Jakobsen *et al.* (1996) found that the main factor of internal deterioration of concrete due to repeated freezing and thawing is the movement of water inside concrete, and there is a strong correlation between moisture absorbed in concrete and internal cracks. This confirmed that the crack volume corresponds to the mass of water absorbed into the concrete by observing the deteriorated concrete under a microscope

Changes in climatic conditions have a great influence on the deterioration of concrete. Especially in winter, concrete can cause severe durability degradation such as surface peeling and cracking through the action of freezing and thawing over a long period of time. Therefore, it is necessary to present clear standards and countermeasures that can quantitatively confirm the damage of freeze-thaw. Han *et al.* (2021) studied a quantitative evaluation method for maintenance effectiveness according to the degree of deterioration of tunnel lining. Assel *et al.* (2021) conducted a comprehensive laboratory work to assess the effect of the cyclic freeze-thaw action on strength and durability of CSA cement-treated sand. Gao and Chen (2019) conducted a study on a model to predict the service life of tunnel structures due to the decline in durability depending on the surrounding environment.

This study presented a deterioration environmental assessment and deterioration progress assessment method to evaluate the durability performance of tunnels. It is believed that if the evaluation criteria presented in this paper are used

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Table 1 Time(hour) taken for the temperature of specimens (NO. 1,2) to drop to -2.2°C

Division	surface of the specimen	75 mm	150 mm	225 mm	back surface of the specimen
Specimen No. 1 (Back temperature 5.5°C)	Immediately	10.42	17.42	25.75	30.50
Test Subject No.2 (Back temperature 6.5°C)	Immediately	10.17	18.58	28.17	32.58
Average	-	10.30	18.00	26.96	31.54

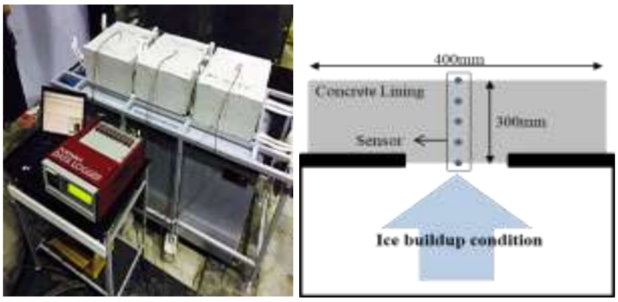

Fig. 1 Concrete specimen and experiment status

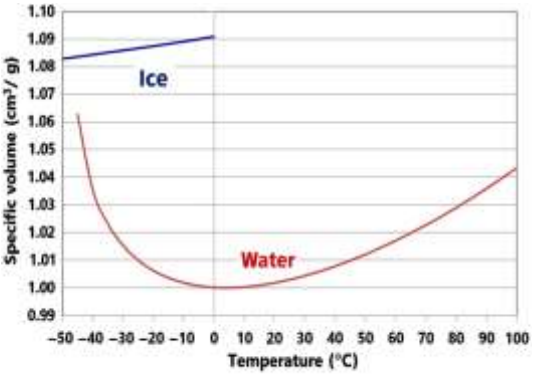

Fig. 2 Change in volume of 1 g of water at temperatures

when maintaining or designing a tunnel, it will be useful in establishing a tunnel maintenance strategy and selecting a tunnel construction method.

2. Analysis of concrete freezing properties

2.1 Indoor freezing experiment

An indoor experiment was conducted to find out the time required for the concrete lining to freeze. Tunnel linings in Korea are manufactured in accordance with the tunnel design standard. The minimum thickness is about 300mm as standard, and the minimum standard 28-days compressive strength of concrete is 21 to 24 Mpa. Therefore, the thickness of the concrete specimen produced for the indoor experiment was determined as 300mm, and the 28-days compressive strength of concrete was designed to be 36.4 Mpa. The concrete test specimen and experimental status are shown in Fig. 1.

2.2 Analysis of freezing time of concrete specimens

The indoor freezing experiment was conducted to measure the time taken for the concrete lining to go down to a constant temperature below zero due to the temperature of the outside air during the winter season. The temperature change of the concrete specimen was measured through temperature sensors installed inside and outside the concrete, and temperatures were measured at 5-minute intervals. The outdoor temperature conditions were set to -13 ~ -18°C, which is the average winter temperature (November to February) in Daegwallyeong, Gangwon-do, the coldest region in Korea, and a total of 5 sensors for temperature change measurement were installed on the surface of the concrete specimen and at intervals of 75 mm from the surface (lower surface, 75 mm, 150 mm, 225 mm, upper surface), as shown in Fig. 1.

The indoor experiment was conducted in 2 sets. The concrete specimen was maintained at a temperature of about 5.5°C and 6.6°C, and the time required for the temperature of the 300mm-thick concrete specimen to change to a temperature below -2.2°C was measured.

As a result of the freezing test, it was found that it took about 30.5 hours for the specimen No.1 at 5.5°C and 32.6 hours for the specimen No.2 at 6.5°C to change to -2.2°C, as shown in Table 1.

2.3 Analysis of temperature change by depth of concrete specimen

Power (1945) used hydraulic pressure theory to explain the freezing mechanism in which the freezing of water inside the capillary pores and the resulting volume increase increases the internal tensile stress. According to the hydraulic theory, when the water drops below 0°C, the water present in the concrete freezes, resulting in a volume change of about 9%. Therefore, if the expansion pressure is greater than the tensile strength of concrete when the expansion amount of water is greater than the voids in the concrete, defects such as cracks and scaling occur.

Fig. 2 shows the change in volume of water with temperature change. In general, water has a minimum volume at 4°C and a maximum volume after freezing at 0°C. In other words, it can be interpreted that the effect of the expansion pressure will be relatively large in the concrete from the time the temperature of the concrete is below about 0°C. It will take some time until deterioration progresses as concrete and water inside the concrete freeze. Therefore, in this paper, the temperature condition affecting concrete was selected as about -2°C.

Table 2 shows the average freezing time according to

Table 2 Average freezing time (hours) of concrete specimens

Depth from the surface	Measured temperature	Initial specimen surface temperature							
		5°C	4°C	3°C	2°C	1°C	0°C	-1°C	-2°C
75mm	0°C	5.79	5.04	4.08	3.04	1.71	-	-	-
	-1°C	8.08	7.33	6.38	5.33	4.00	2.29	-	-
	-2°C	10.25	9.50	8.54	7.50	6.17	4.46	2.17	-
	-2.2°C	10.83	10.08	9.13	8.08	6.75	5.04	2.75	0.58
150mm	0°C	10.13	8.42	6.67	4.54	2.33	-	-	-
	-1°C	12.79	11.08	9.33	7.21	5.00	2.67	-	-
	-2°C	15.79	14.08	12.33	10.21	8.00	5.67	3.00	-
	-2.2°C	16.79	15.08	13.33	11.21	9.00	6.67	4.00	1.00
225mm	0°C	11.88	9.63	7.38	5.00	2.79	-	-	-
	-1°C	16.83	14.58	12.33	9.96	7.75	4.96	-	-
	-2°C	22.58	20.33	18.08	15.71	13.50	10.71	5.75	-
	-2.2°C	23.38	21.13	18.88	16.50	14.29	11.50	6.54	0.79
back surface of specimen	0°C	17.17	14.75	12.46	9.79	5.92	-	-	-
	-1°C	22.17	19.75	17.46	14.79	10.92	5.00	-	-
	-2°C	26.38	23.96	21.67	19.00	15.13	9.21	4.21	-
	-2.2°C	27.33	24.92	22.63	19.96	16.08	10.17	5.17	0.96

the initial specimen temperature and depth of specimen. The temperature of each section of the specimen was measured every 1°C, and the freezing time was measured at various depth from the surface under various initial temperature conditions. It was found that the average time required for the concrete specimen to change from 5°C to –2°C was 10.25 hours at depth of 75mm from the surface, 15.79 hours at depth of 150mm, and 22.58 hours at depth of 225mm. It was found that it takes about 10 hours to freeze the surface if the outside air temperature of the tunnel is about -16°C. Therefore, the tunnel lining frequently freezes during winter season in Daegwallyeong, Gangwon-do.

2.4 Heat flow analysis according to Fourier's law

The heat transfer that works to freeze the concrete specimen means the flow of energy caused by the temperature difference between the surface and the back of the specimen, which is cooled due to the outdoor temperature maintained below zero. The heat flow phenomenon that occurs inside concrete can be known how much heat energy is transferred through Fourier's law, and the heat flow can be calculate using Eq. (1).

$$Q_{cond} = -kA\frac{\Delta T}{\Delta x} \quad (1)$$

where, Qcond = heat flow generated in concrete [W]; k = thermal conductivity of concrete [W/mT]; ΔT = temperature difference between the temperature of the surface of the concrete specimen and the temperature of the back of the concrete; Δx = thickness of the concrete specimen; and A = area exposed to the outside air.

In this study, the thermal conductivity of general concrete, 1.4, was used. The area of the concrete specimen used for the freezing test was 300 mm × 300 mm, and the thickness was 300 mm. The heat flow was calculated based on the results of measuring the temperature change and time of the concrete specimen through the freezing experiment, and the energy required to lower the temperature of the concrete back surface by about 1°C was calculated. The average values of heat flow and energy calculated through the experimental results are shown in Table 3.

As a result of the experiment, the average heat flow required to freeze all the concrete specimens to -2.2°C was about 7.05W, and the average heat energy generated at this time was calculated as 694,067J. Based on the thermal energy calculated in this way, the time for concrete to freeze when the outdoor temperature changes was predicted.

The temperature of the actual tunnel lining will vary depending on the outside temperature and the temperature of the surrounded rock or soil. Therefore, the outside temperature, the exposure time, and the temperature of the surrounded ground will be important factors in the condition in which all the concrete linings are frozen. The outdoor temperature in the indoor freezing experiment varied from about -13°C to -18°C, and the average was about -16.2°C. The temperature of the concrete back surface can be measured from 5.5°C and 6.5°C. Based on the freezing time analyzed through the experiment, Fourier's Law was used to calculate the energy required to drop the temperature of the back surface of concrete by 1°C. The average thermal energy required to lower the backside temperature of concrete by about 1°C was calculated as 72,592J.

Table 3 Analysis result of average energy required to change the temperature of a concrete specimen by 1°C

classification	surface (T2)	Back surface (T1)	time (second)	Qcond(W) (J/s)	Energy (J)
Average energy required for 1°C temperature change	-13.27°C	5°C	-	-	-
	-14.14°C	4°C	8,700	7.25	63,072
	-14.90°C	3°C	8,250	7.20	59,372
	-16.01°C	2°C	9,600	7.10	68,141
	-16.98°C	1°C	13,950	7.14	99,784
	-17.61°C	0°C	21,300	7.13	151,916
	-18.14°C	-1°C	18,000	6.98	125,507
	-18.45°C	-2°C	15,150	6.78	102,710
	-	-2.2°C	3,450	6.83	23,565
Average	-16.19	-	-	7.05	-
sum	-	-		-	694,067

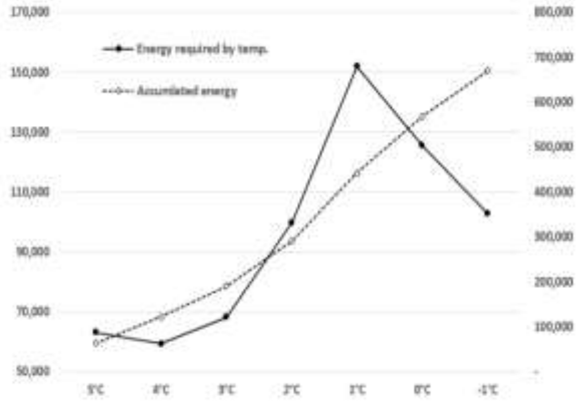

Fig. 3 Thermal energy consumption by temperature of concrete specimen

Table 4 Analysis of concrete lining freezing conditions by outside temperature

Outside Temp.	Concrete Temp.	Freezing Temp.	Duration (day)	Outside Temp.	Concrete Temp.	Freezing Temp.	Duration (day)
-20°C	2°C	-2°C	0.68	-11°C	2°C	-2°C	1.27
-19°C	2°C	-2°C	0.72	-10°C	2°C	-2°C	1.41
-18°C	2°C	-2°C	0.80	-9°C	2°C	-2°C	1.58
-17°C	2°C	-2°C	0.80	-8°C	2°C	-2°C	1.79
-16°C	2°C	-2°C	0.86	-7°C	2°C	-2°C	2.08
-15°C	2°C	-2°C	0.92	-6°C	2°C	-2°C	2.49
-14°C	2°C	-2°C	0.98	-5°C	2°C	-2°C	3.10
-13°C	2°C	-2°C	1.06	-4°C	2°C	-2°C	4.16
-12°C	2°C	-2°C	1.16	-3°C	2°C	-2°C	6.64

In addition, the thermal energy required to decrease by about 2°C from 1°C to -1°C was 277,423J, and the average thermal energy required to decrease the temperature by 1°C was calculated as 138,712J. As mentioned above, these results are believed to be related to the freezing time of the moisture inside the concrete.

Fig. 3 shows the average thermal energy required for the temperature change calculated as a result of the freezing experiment, and it can be confirmed that the required thermal energy increases as the concrete specimen approaches the freezing point of 0°C. When the moisture inside the concrete changes from liquid to ice, the molecular structure of water changes. Due to the heat generated at this time, it takes some time for the moisture to completely freeze. This phenomenon can be confirmed in this freezing experiment.

3. Concrete living freeze-thaw conditions

In order to select the temperature conditions required for freezing of concrete lining, the freezing time of concrete for each outdoor temperature was predicted using the thermal energy calculated based on the results of the freezing experiment. The freezing time of the concrete lining for each temperature of the outside air is summarized in Table 4. Actual tunnel linings are subject to highly variable temperature changes. Therefore, it is important to select the representative outdoor temperature and duration. In order to calculate the evaluation criteria using the daily average temperature, the duration was selected based on 24 hours. Among the temperature conditions and durations summarized in Table 4, the most representative freezing conditions were analyzed at -14°C for about 24 hours, -7°C for about 48 hours, and -5°C for about 72 hours.

Wawrzenczyk and Molendowska (2017) calculated the number of freeze-thaw cycles leading to deterioration in concrete durability through the correlation between the number of freeze-thaw cycles, the increase in mass, and the decrease in strength. The average number of freeze-thaw

Table 5 Freeze-thaw number related to concrete deterioration

Properties	Concrete A	Concrete B
Sample #1	133	132
Sample #2	108	133
Sample #3	116	138
Sample #4	124	140
Sample #5	133	143
Sample #6	-	158
Average	122.8	140.7

cycles required to reach the limited mass increase was 123 for concrete A and 141 for concrete B as shown in Table 5.

In general, since the minimum lifespan of a concrete structure is regulated to be about 30 years, structural damage may occur if the number of freeze-thaw repetitions exceeds about 4.7 times a year. These results are intended to be used when calculating the evaluation criteria for the number of freeze-thaw cycles to be presented in this paper.

4. Lining and back temperature analysis by on-site measurement

4.1 Temperature change of tunnel lining surface and back surface during winter

During the winter season (November to March) when freeze-thaw damage may occur in the tunnel, the temperature of the tunnel lining surface and back surface by depth was measured, and the correlation between the outside temperature of the tunnel and the back temperature was analyzed. As shown in Table 6 and Fig. 4, a total of 5 locations were selected for temperature measurement, including the surface of the lining, and a total of 3 sections up to 150 m inside the tunnel were selected to measure the temperature.

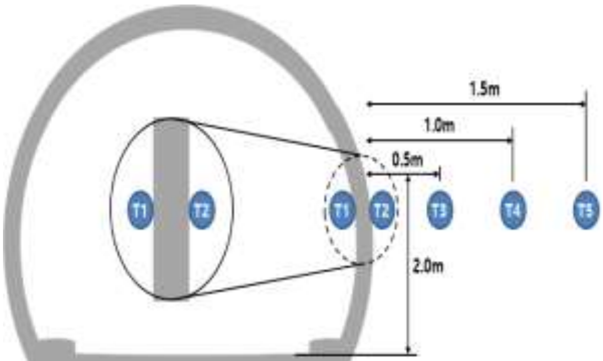

Fig. 4 Temperature measurement locations on the tunnel lining surface and back

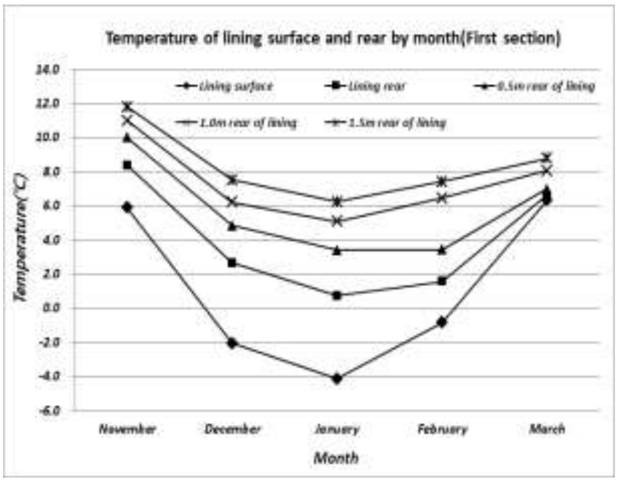

Fig. 5 Temperature measurement result graph by location in section 1

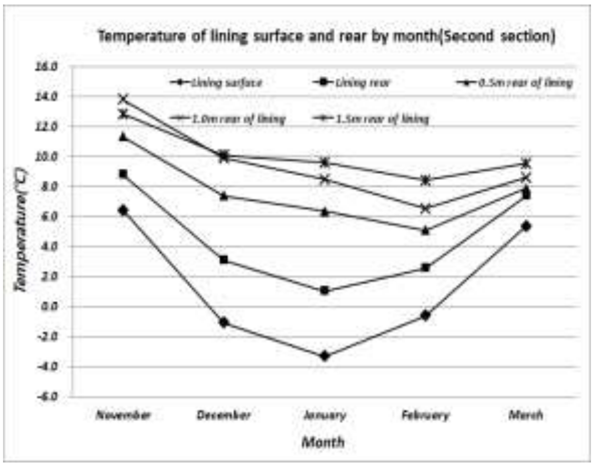

Fig. 6 Temperature measurement result graph by location in section 2

The average temperature of the winter season at the site where the temperature measurement was conducted was about 1.2°C, about 6.1°C in November, about -1.5°C in December, about -3.7°C in January, about -0.5°C in February, and about 5.5°C in March. Table 7 shows the outdoor temperature measurement results for each section.

Examining the temperature results by depth from the rear surface of the lining measured in Section 1 (30 m inside the tunnel) and Section 2 (90 m inside the tunnel), it can be seen that the outdoor temperature of the tunnel affects the temperature change of the back surface. It is found that the occurrence of freeze-thaw damage according to the outdoor temperature will be concentrated for about 3 months from December to February. The temperature measurement results of section 1 and section 2 are shown in Figs. 5 and 6.

Looking at the temperature measurement results measured in three sections as shown in Fig. 7, it can be seen that the temperature of the rear surface is maintained relatively constant at about 9.8°C and 5.9°C in November

Table 6 Tunnel lining temperature measurement location and sign

Division	Measurement range			Measuring position				
Location	Distance from tunnel entrance (m)			Depth from lining back side (m)				
	30	90	150	surface	0	0.5	1.0	1.5
Sign	Section 1	Section 2	Section 3	T1	T2	T3	T4	T5

Table 7 Outdoor temperature measurement result by section (November to March)

Division	Section 1	Section 2	Section 3	Average
November	5.9	6.4	6.0	6.1
December	-2.0	-1.1	-1.5	-1.5
January	-4.1	-3.3	-3.7	-3.7
February	-0.8	-0.6	-0.2	-0.5
March	6.3	4.5	5.7	5.5

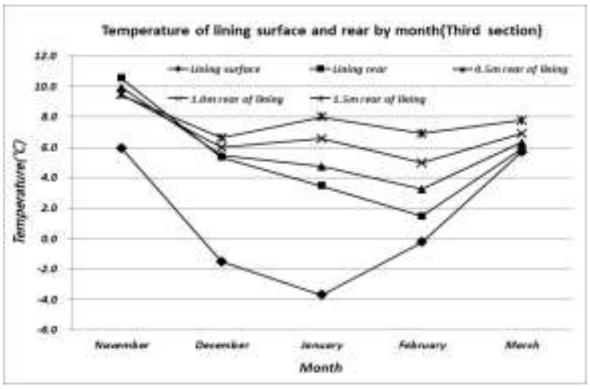

Fig. 7 Temperature measurement result graph by location in section 3

and December. However, from January, it was found that the temperature difference appears depending on the position of the back surface by depth. This means that the temperature change of the rear surface of the tunnel is relatively less affected by the temperature outside as it moves from the tunnel entrance to the inside. Additionally, damage due to freezing and thawing can be interpreted as being more concentrated on the lining surface as it approaches the tunnel entrance.

4.2 Tunnel lining freeze-thaw repetitions by section

Through the temperature measurement results of the surface and back of the tunnel lining conducted during the winter season (November to March), the number of freeze-thaw times of the concrete lining was analyzed according to the actual outdoor temperature. This is the temperature measurement result from December to February, when freezing-thawing is expected to be concentrated, and the temperature measurement time was set at 10 am. In consideration of the measurement time, when the temperature of the rear surface was about 0.1°C or less, it

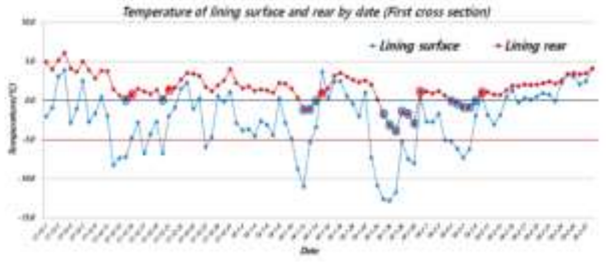

Fig. 8 the number of freeze-thaw repetitions of concrete lining in Section 1

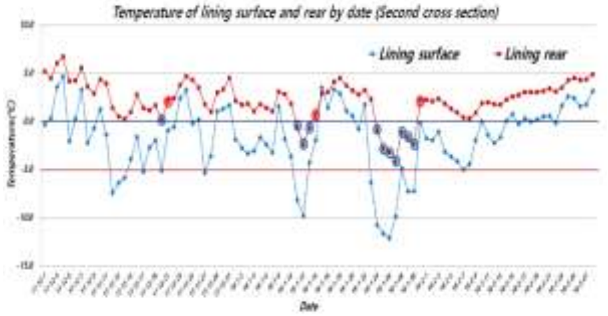

Fig. 9 the number of freeze-thaw repetitions of concrete lining in Section 2

Fig. 10 the number of freeze-thaw repetitions of concrete lining in Section 3

Table 8 Tunnel Freeze-Thaw environmental evaluation standard

Classification	Evaluation grade				
	a	b	c	d	e
Number of freeze-thaw repetitions(F)[1)] (F= Number of freeze-thaw repetitions per year)	F<1.5	1.5≤F<3	3≤F<4.5	4.5≤F<6	6≤F

The number of freeze-thaw repetitions (F) can be applied differently for each region, and typical conditions are as follows.
1. In the case of lasting more than 1 days at -14°C and then 1 day at 0°C or higher
2. In the case of lasting more than 2 days at -7°C and then 1 day at 0°C or higher
3. In the case of lasting more than 3 days at -5°C and then 1 day at 0°C or higher

was assumed to be the freezing condition, and when it was more than 1.0°C, it was assumed to be the thawing condition.

From Fig. 8 to Fig. 10, the point at which the concrete lining freezes is indicated by a blue circle, and the point at which it thaws is indicated by a red circle. As can be seen in the graph, there was a difference in the number of occurrences of freeze-thaw by section.

It was analyzed that freezing and thawing were repeated 5 times in section 1, 3 times in section 2, and 1 time in section 3. Assuming that the minimum lifespan of the tunnel is 30 years, it can be predicted that the freeze-thaw at the entrance of the tunnel will be repeated about 150 times. As summarized above, since the number of freeze-thaw repetitions is about 4.7 or more, it is found that this tunnel has a high possibility of structural damage due to freeze-thaw during its minimum lifespan.

However, since it is very difficult to measure the lining temperature of all tunnels subject to maintenance in Korea, it is necessary to determine the degree of freeze-thaw risk by region after selecting the conditions in which the concrete lining freezes and thaws in consideration of the temperature and duration of each region in the country. Therefore, it is intended to establish evaluation criteria based on the number of freeze-thaws, and the results of this field experiment will be used to determine whether the proposed freeze-thaw evaluation criteria are appropriate.

Looking at the temperature results measured at the tunnel site, it was confirmed that the concrete lining was thawed within about 24 hours when the temperature outside rose by 1°C or more after it was frozen. In addition, even when the outdoor temperature is about -2.0°C, it was confirmed that the temperature of the back surface of the lining recovers to 0°C or more. This is considered as a phenomenon that occurs as the effect of the outdoor temperature is important for the thawing of the tunnel lining, but it occurs in combination with the action of the geothermal heat of the tunnel back ground. Therefore, if the daily average temperature is about 0°C or higher, the concrete lining will thaw.

5. Freeze-thaw quantitative evqluation method

5.1 Selection of freeze-thaw environmental evaluation

In the first criterion, the freeze-thaw environmental evaluation standard, the evaluation criteria were selected based on the number of freeze-thaw repetitions (F). In the second criterion, the freeze-thaw progress evaluation criteria were selected based on the remaining time for deterioration progress due to freeze-thaw (T). Based on the freezing time of the concrete lining according to the indoor freezing test, the outside temperature conditions of the tunnel required to freeze the concrete lining are -14°C for 24 hours, -7°C for 48 hours and -5°C for 72 hours.

The thawing conditions of the concrete lining were selected when the temperature outside the tunnel was about 0°C or higher for 24 hours, and each freeze-thaw condition is as follows.

1) In the case of lasting more than 1 days at -14°C and then 1 day at 0°C or higher

2) In the case of lasting more than 2 days at -7°C and then 1 day at 0°C or higher

3) In the case of lasting more than 3 days at -5°C and then 1 day at 0°C or higher

The number of repetitions that tunnel lining can cause structural defects through freezing and thawing is about 123 to 141 times. Assuming that the minimum lifespan of the tunnel is 30 years, if it is repeated about 4.1 to 4.7 times per year on average, structural defects due to freeze-thaw may occur after 30 years. Tunnels in public use in Korea are maintained through periodic inspection and diagnosis, so it would be reasonable to select the maximum number of freeze-thaw repetitions that tunnel linings can overcome as a value of 141 or less for safety. Therefore, it was selected as the number of freeze-thaw repetitions that can cause structural defects when repeated about 140 times. The selected freeze-thaw environmental evaluation criteria are shown in Table 8. As the degree of freeze-thaw damage is determined according to regional climatic conditions, it is possible to classify freeze-thaw risk areas by region in Korea.

5.2 Selection of freeze-thaw progress evaluation criteria

It will be necessary to consider the period of use after the tunnel facility is completed. That is, by selecting the evaluation criteria including the concept of time, it will be possible to suggest whether to secure the durability against the occurrence of freeze-thaw damage at the time of evaluation. Therefore, it will be necessary to evaluate the freeze-thaw risk of the tunnel through evaluation of how

Table 9 Outdoor temperature measurement result by section (November to March

Evaluation grade	Remaining time before deterioration(T)	Calculation method
a	over 30 years	Calculate T after calculating the number of freeze-thaw repetitions (F) at the time of evaluation
b	20 years < T ≤ 30 years	
c	10 years < T ≤ 20 years	
d	5 years < T ≤ 10 years	
e	5 years or less	

Table 10 The effect of freeze-thaw repetition frequency (F) from freezing index and daily average temperature

Dependent variable	Independent variable	standard error	β	t	significance probability	tolerance limit
Number of freeze-thaw repetitions(F)	Constant number	6.658	-	-6.186	.000	-
	Freezing index	.28	1.197	14.571	.000	.157
	R=.967, R2=.934, F=439.894, p=.000, Durbin-Watson=1.550					

close it is to the maximum of 140 by calculating the number of repetitions of freezing and thawing from the time when the structure is completed to the time of evaluation.

In order to evaluate how much the tunnel lining secures the durability performance due to freeze-thaw, it is necessary to consider the period of use after the tunnel facility is completed. Since the damage caused by freezing and thawing is closely related to the number of repetitions, the durability performance will continuously decrease as the usage period increases

Therefore, it is necessary to select an evaluation criterion that includes the concept of time and present whether or not durability performance due to freeze-thaw is secured at the time of tunnel evaluation. The remaining time (T) until severe deterioration due to freeze-thaw was calculated as in Eq. (2), and the freeze-thaw progress evaluation criteria of the tunnel were selected as shown in Table 9.

$$\mathrm{T} = \frac{140}{F} - t \tag{2}$$

where, T is the remaining time for degradation due to freeze-thaw, F is the number of freeze-thaw repetitions at the time of evaluation, and t is the common life time

5.3 Freezing-thawing evaluation criteria verification through regression analysis

The depth of freezing of the ground depends on the temperature below 0°C and its duration, and the value obtained by integrating the daily average temperature during the freezing period is called the freezing index. The freezing index appears larger in colder regions, and is an index used to determine the depth of freezing of the ground.

In order to analyze the correlation between the number of freeze-thaw repetitions (F) and the freezing index and daily average temperature, the freezing index and daily average temperature of 67 regions in Korea were set as independent variables, and freeze-thaw in the same region for 30 years Multiple regression analysis was performed by setting the number of iterations (F) as a dependent variable.

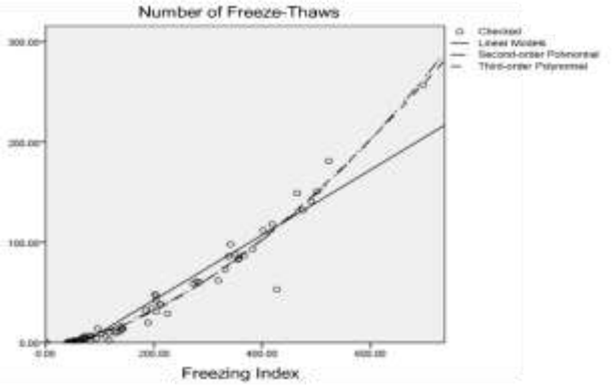

Fig. 11 the relationship between the number of freeze-thaw and the freezing index

As shown in Table 10, the F statistical value shows a value of 439.894 at p = .000, and R2 for the regression equation is .934, showing about 93.4% explanatory power. Durbin-Watson is 1.550, indicating that the regression model is suitable because there is no correlation between the residuals. The Durbin Watson test is a method to verify whether the error term satisfies independence, and is generally considered normal if it is between 1.5 and 2.5.

The equation for the regression model was calculated through curve estimation according to regression analysis. it was confirmed that the quadratic and cubic equations representing the relationship between the number of freezing and thawing repetitions (F) and the freezing index had a correlation of 96.5%. In this paper, an equation to calculate the number of freeze-thaw repetitions (F) for about 30 years, which is the minimum lifespan of a structure, was derived as shown in Eq. (3).

$$F = 0.00037x^2 + 0.116x - 5.807 \quad (3)$$

where, F is the number of freeze-thaw cycles over 30 years, and x is the freezing index for each region.

6. Conclusions

This study presents the quantitative evaluation criteria for freezing and thawing that can be used in tunnel design and maintenance. The main conclusions of this paper are summarized as follows.

1) Moisture inside the concrete increases in volume when it freezes, and the expansion pressure caused by the volume increase damages the concrete. This deterioration of concrete is further progressed by freezing duration and repeated freeze-thaw cycles.

2) It took about 11.25 hours for the temperature of the back surface of the concrete specimen to decrease by 4°C (from 5°C to 1°C). It was confirmed that it takes 10.92 hours for the temperature to decrease by 2°C, and an average of 5.46 hours was taken for a change of 1°C.

3) There is a large difference in the temperature decreasing rate with time at the freezing point, which can be explained by the release of heat caused by the change in molecular structure when water changes from liquid state to solid state.

4) As a result of heat flow analysis using Fourier's law, the average heat flow required to change the concrete specimen from 5°C to -2.2°C was analyzed as 7.05W, and the total required heat energy was analyzed to be 694,067J.

5) Based on the analysis results of the freezing time of the concrete lining, the freezing conditions of the concrete lining were analyzed for 1 day at -14°C, 2 days at -7°C, and 3 days at -5°C.

6) The freeze-thaw evaluation criteria presented in this paper are quantitative criteria for classifying domestic freeze-thaw risk areas. It can be reflected in the tunnel design, and the freeze-thaw progress evaluation can be used when securing durability performance and establishing a maintenance strategy.

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