4. Results and Analysis of Indoor Freezing Experiment

4.1 Analysis of freezing time of concrete specimen according to indoor freezing test

A total of 2 sets of indoor experiments were conducted. The concrete specimen was maintained at about 5.5°C and 6.6°C. As shown in Table 5, the FHWA evaluates the freezing standards of concrete based on when the concrete changes to a temperature of -2.2°C or less. According to the FHWA standard, the time required to change the temperature of the concrete specimen to a temperature of -2.2°C or lower was measured. In addition, the amount of heat flow (W) required to freeze the specimen was analyzed based on the experimental results. Through heat flow analysis, the energy required to change the temperature of the concrete specimen can be calculated at the outside temperature, and if the conditions are the same, the freezing time according to the change of the outside temperature can be predicted according to the law of conservation of energy.

Table 5. Freeze-Thaw evaluation criteria of FHWA

Exposure Condition	Classification		
	a(N/A)	b(Grade 1)	c(Grade 2)
Freeze/Thaw Durability Exposure (x=F/T cycles per year[1)])	$x < 3$	$3 \leq x < 50$	$50 \leq x$

1) F/T stands for "freeze/thaw". A freeze/thaw cycle is defined as an event where saturated concrete is subjected to an ambient temperature which drops below -2.2°C (28°F) followed by a rise in temperature above freezing.

Through the freezing test, it was confirmed that it took about 30.5 hours and 32.6 hours as shown in Table 6 for the total temperature of specimen No. 1 at 5.5°C and specimen No.2 at 6.5°C to change to -2.2°C. The time taken to change from the surface of the specimen to -2.2°C or less by depth was reviewed as taking an average of 10.30 hours in the 75mm section, 18.00 hours in the 150mm section, 26.96 hours in the 225mm section, and 31.54 hours on the back of the specimen. Figures 1 show the temperature change patterns of specimens No.1 and No.2 according to the results of the freezing test, respectively.

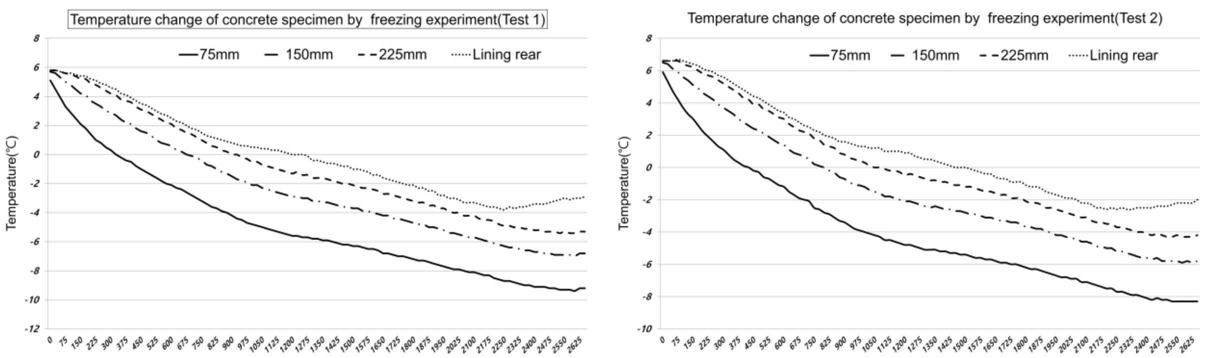

Fig. 1 Temperature change analysis result of concrete specimen(No.1, 2)

Table 6. Time for the concrete specimen(No. 1, 2) to change to -2.2℃

Division	surface of the specimen	75mm	150mm	225mm	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

4.2 Analysis of temperature change by depth of concrete specimen

In the indoor freezing test, the change in the internal temperature was measured at a depth of 75 mm from the surface of the specimen, and the time required to lower the internal temperature in each section to about -2.2 °C was measured.

The main cause of defects in concrete due to freeze-thaw is the expansion pressure generated by freezing of the water contained in the concrete. When water freezes, about 9% of volume expansion occurs, and when the amount of expansion of water is greater than the voids in the concrete, if the expansion pressure is greater than the tensile strength of the concrete, defects such as cracks and scaling occur.

In general, water has a minimum volume at 4°C, and has a maximum volume after freezing at 0°C. In other words, it can be interpreted that from when the temperature of the concrete is below about 0°C, the influence of the expansion pressure inside the concrete is relatively large.

Table 7 is a table that summarizes the freezing time according to the temperature of each section of the concrete specimen. The temperature of each section was measured at every 1°C from 5°C to -2°C, and the freezing time from the surface to the 75mm point was measured.

It took an average of 10.25 hours at the 75mm point for the concrete to change from the temperature of 5°C to -2°C at the temperature of the concrete specimen, 15.79 hours at the 150mm point, and 22.58 hours at the 225mm point on average.

When the outdoor temperature of the tunnel is about -16°C, it is judged that the time it takes for the surface to freeze is about 10 hours. In the case of winter, when nights are longer, it is judged that the surface of the tunnel lining will freeze frequently after the sun goes down.

4.3 Freezing time analysis according to the back surface of the concrete specimen

By analyzing the temperature change and time measured through the indoor freezing experiment, it was confirmed how the moisture in the concrete affected the freezing time of the concrete specimen.

It took about 11.25 hours for the back temperature of the concrete specimen to decrease by about 4°C from 5°C to 1°C, and it was confirmed that it takes an average of 2.81 hours for a change of 1°C. And it took about 10.92 hours to decrease about 2°C from 1°C to -1°C, confirming that it takes an average of 5.46 hours for a change of 1°C.

This is considered to be related to the time at which the moisture inside the concrete freezes. Through the experiment, it was confirmed that the time it takes for the concrete specimen to decrease by 1°C at the freezing point is about twice as long as the time it takes to decrease by 1°C at the freezing point.

Figures 2 are graphs showing the freezing time of the concrete specimen, and it can be seen that the cumulative freezing time increases as the concrete specimen approaches the freezing point of 0°C.

Table 7. Average freezing time of concrete specimens

Classification		Specimen 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

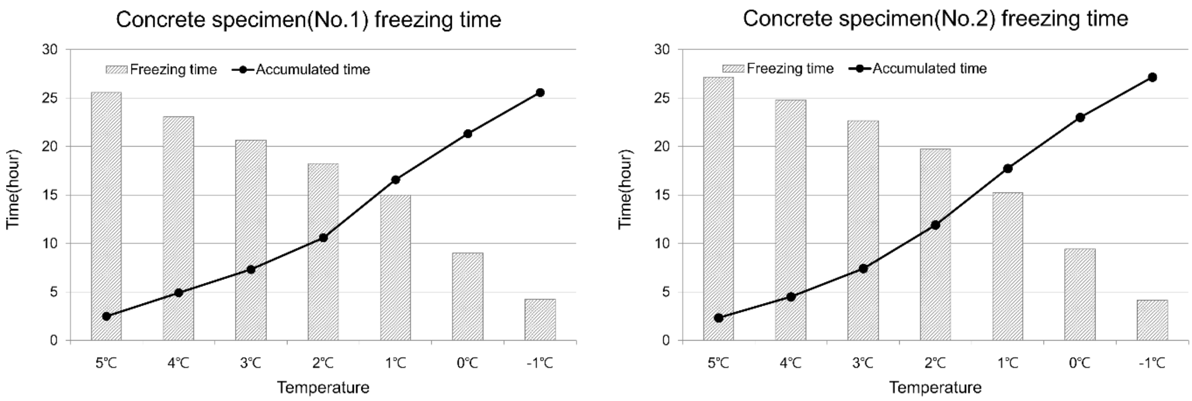

Fig. 2 Analysis of freezing time by temperature of concrete specimen(No. 1, 2)

4.4 Heat flow analysis according to heat conduction theory

The heat transfer acting to freeze the concrete specimen refers to the flow of energy generated by the temperature difference between the surface and the back surface of the specimen cooled due to the external temperature maintained below zero. The concrete specimen is frozen due to the convection phenomenon caused by the sub-zero outside temperature, and the lowered concrete surface is frozen through the inside of the concrete to the back side.

In the case of heat conduction occurring inside concrete, the amount of heat energy transferred can be known through Fourier's law. The equation used at this time is the heat flow (W) equation and is the same as Equation (2).

$$Q_{cond} = -kA\frac{\Delta T}{\Delta x} \tag{2}$$

Here, k is the thermal conductivity of concrete and the unit is . In this paper, the thermal conductivity of commonly used concrete of 1.4 was applied. ΔT is the difference (T1-T2) between the temperature (T1) of the surface of the concrete specimen and the temperature of the back of the concrete (T2), ΔX is the thickness of the concrete specimen, and A is the area exposed to the outside air in the specimen. Qcond is the amount of heat generated in concrete, and the unit is W (watt), meaning that 1J (joule) of energy is generated for 1 second.

The area of the concrete specimen used in the freezing test is 300mm×300mm, and the thickness is 300mm. The amount of heat flow was calculated based on the results of measuring the temperature change and time of the concrete specimen through the freezing test, and the energy required to lower the temperature of the concrete backside by 1°C was calculated. Table 8 shows the average values of heat flow and energy calculated through the results of two experiments.

According to the experimental results, the average heat flow required to freeze all concrete specimens to -2.2°C was about 7.05W, and the average heat energy generated at this time was calculated to be 694,067J. Based on the thermal energy calculated in this way, we want to predict the freezing time of concrete when the temperature of the outside air changes.

4.5 Analysis of energy required for freezing concrete lining

The actual tunnel lining temperature will vary depending on the temperature of the outside air and the temperature of the back ground. Therefore, the temperature of the outside air, the exposure time and the temperature of the back surface will be important factors in the condition that all the concrete linings are frozen.

The outdoor temperature in the indoor freezing test varies from about -13°C to -18°C, and the average is about -16.2°C. The temperature of the back side of the concrete can be measured from 5.5°C and 6.5°C. Based on the results of measuring the freezing time of all concrete specimens under these temperature conditions, Fourier's Law was used to calculate the energy required to lower the concrete surface temperature by 1°C.

The thermal energy required to lower the back temperature of concrete by about 4°C from 5°C to 1°C was 290,369J, and the average thermal energy required to lower about 1°C was calculated as 72,592J. In addition, the thermal energy required to decrease by about 2°C from 1°C to -1°C is 277,423J, and the average thermal energy required to lower the temperature by 1°C was calculated as 138,712J.

Table 8. Analysis result of average energy required to change the temperature of a concrete specimen by 1℃

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

These results are considered to be related to the time at which the moisture inside the concrete freezes. Figures 3 show the thermal energy required for the temperature change calculated as a result of the freezing test of specimens No. 1 and 2, and it can be seen that the required thermal energy increases as the concrete specimen approaches the freezing point of 0°C.

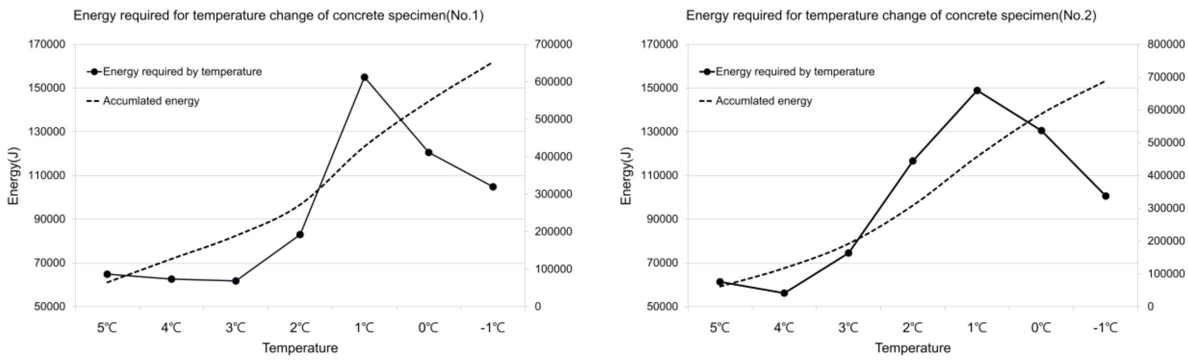

Fig. 3 Thermal energy consumption by temperature of concrete specimen(No. 1, 2)

5. Concrete lining freeze-thaw evaluation criteria

5.1 Selection of the required duration for freezing of concrete lining

In order to select the temperature conditions required for freezing of the 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 temperature of the lining of the tunnel will be distributed in various ways, such as the temperature of the outside air and the condition of the back ground. Therefore, the temperature condition of the back surface of the concrete was selected from 5°C to 1°C, and the freezing temperature of the concrete was selected from 0°C to -2.2°C.

The Korea Meteorological Administration observes the temperature every hour, and the average daily temperature is the average of the values observed every 3 hours.

When evaluating the temperature conditions required for freezing, it is judged that it is appropriate to use the daily average temperature of each region.

Table 9 is a table summarizing the temperature and duration required to freeze each concrete. In order to calculate the evaluation criteria using the average daily temperature, the duration was selected based on 24 hours (1 day).

In the case of Gangwon, the coldest region in Korea, the average annual temperature in winter is about -1.73°C, and it is assumed that the temperature of the backside of the concrete lining of the tunnel is used to maintain the backside temperature in the winter at about 1~2°C. The temperature condition is conservatively judged to be about 2°C. In addition, as a criterion for selecting the freezing temperature, the freezing point of water, 0°C, and the concrete damage mechanism due to the freezing of moisture in the concrete were taken into consideration, and a safety level of about -2°C or higher was selected.

Therefore, among the temperature conditions and durations summarized in Table 9, the most representative freezing conditions were analyzed when lasting for about 24 hours at -14°C, lasting for about 48 hours at -7°C, and lasting for about 72 hours at -5°C.

Table 9. Concrete lining freezing condition analysis result by outside temperature

outside temperature	concrete temperature	freezing temperature	duration (day)	outside temperature	concrete temperature	freezing temperature	duration (day)
-19°C	5°C	-2.2°C	0.99	-11°C	3°C	-1°C	1.10
-18°C	5°C	-2.2°C	1.05	-11°C	1°C	-2°C	1.04
-18°C	4°C	-2°C	1.03	-10°C	2°C	-1°C	1.05
-18°C	4°C	-2°C	0.98	-9°C	5°C	-2°C	2.02
-17°C	5°C	-2°C	1.07	-9°C	4°C	-2.2°C	1.98
-17°C	4°C	-2.2°C	1.03	-8°C	3°C	-2.2°C	2.09
-17°C	4°C	-2°C	0.98	-8°C	3°C	-2°C	1.98
-16°C	4°C	-2.2°C	1.09	-8°C	1°C	-1°C	1.02
-16°C	4°C	-2°C	1.05	-7°C	2°C	-2°C	2.08

-16°C	3°C	-2.2°C	1.01	-6°C	5°C	-2°C	3.08
-15°C	5°C	-1°C	0.99	-6°C	4°C	-2.2°C	3.08
-15°C	3°C	-2.2°C	1.08	-6°C	1°C	-2°C	2.10
-15°C	3°C	-2°C	1.03	-5°C	5°C	-2.2°C	4.00
-14°C	5°C	-1°C	1.06	-5°C	2°C	-2°C	3.10
-14°C	3°C	-2°C	1.10	-4°C	4°C	-2.2°C	5.07
-14°C	2°C	-2.2°C	1.04	-4°C	3°C	-1°C	3.06
-14°C	2°C	-2°C	0.98	-4°C	1°C	-2.2°C	3.98
-13°C	4°C	-1°C	1.03	-3°C	4°C	-2.2°C	8.10
-13°C	2°C	-2°C	1.06	-3°C	3°C	-2°C	7.02
-12°C	3°C	-1°C	1.01	-3°C	2°C	-2°C	5.96
-12°C	1°C	-2.2°C	1.01	-	-	-	-

Table 10. Concrete mixing ratio(Jerzy, 2017)

Constituent	Content, kg/m3 (%m.c)	
	Concrete A	Concrete B
Cement	360	400
Water	169	159
Sand	599	670
Coarse aggregate	1216	1117
Super plasticizer	0.58	1.00
W/C	0.47	0.39

In the case of concrete specimen A, it shows a periodic increase in mass from the start of freezing. This indicates the formation of cracks in the rapid deterioration process and the absorption of moisture accordingly. At this time, microcracks were observed on the surface of the specimen. Table 11 summarizes the number of freeze-thaw repetitions required to reach a limited mass increase.

The evaluation of the decrease in durability due to freeze-thaw is to measure the change in mass, and through this, it is possible to determine the number of freeze-thaw repetitions that can cause fatal damage corresponding to a decrease in strength of about 20%.

In general, the minimum lifespan of concrete structures is stipulated as about 30 years, so if the number of freeze-thaw cycles exceeds 4.1 to 4.7 times per year, structural damage may occur. These results are intended to be used in the evaluation of the evaluation criteria for the number of freeze-thaw repeated days presented in this paper.

Table 11. Number of freeze-thaws related to concrete deterioration(Jerzy, 2017)

Properties	Concrete A Number for Δm = 10g	Concrete B Number for Δm = 12g
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

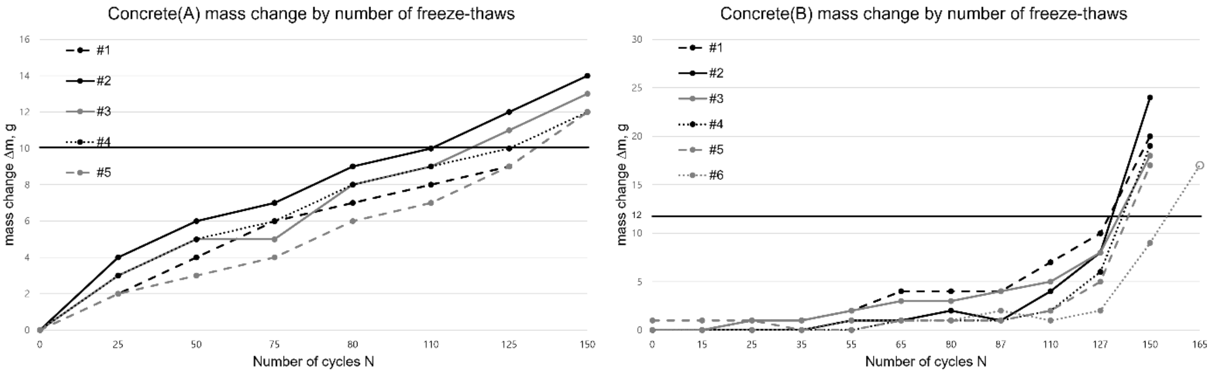

Fig. 4 Change in mass of concrete specimens(A,B) according to the number of freezing-thaws(Jerzy, 2017)

5.3 Selection of freeze-thaw evaluation criteria considering the climate

Based on the freezing time of the concrete lining according to the ambient temperature confirmed through the indoor freezing test, the temperature conditions of the outside air of the tunnel required to freeze the concrete lining are -14°C, -7°C and -5°C, and the duration of each is 24 hours, 48 hours and 72 hours.

The melting 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.

In addition, 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 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.

As the degree of damage from freeze-thaw is determined according to the climatic conditions of each region, it is possible to classify the freeze-thaw risk areas by region in Korea. The maximum number of freeze-thaw repetitions that cause deterioration in the tunnel structure is 140. Accordingly, the case where the concrete structure is repeated 140 times or more during the minimum lifespan of 30 years was calculated as d grade. The evaluation grade was selected based on about 4.5 times a year considering the safety side. The selected freeze-thaw environmental evaluation criteria are shown in Table 12.

Table 11. 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

6. CONCLUSION

In this paper, quantitative environmental evaluation criteria for freezing and thawing that can be used in the design and maintenance of tunnels are presented. The main conclusions of this paper are summarized as follows.

1. Moisture inside the concrete increases by about 9% when it freezes. Accordingly, when the pores are filled with water, the expansion pressure is generated due to the volume increase due to freezing, and the concrete is damaged. This deterioration of concrete is further progressed by freezing duration and repetition of freeze-thaw.

2. A freezing test was conducted to confirm the freezing conditions of the tunnel concrete lining, and as a result of the experiment, it took about 27.33 hours to freeze the temperature of the concrete specimen from 5°C to -2.2°C.

3. It took 11.25 hours for the temperature of the back surface of the concrete

specimen to decrease by about 4°C from 5°C to 1°C. It was confirmed that the time taken for a decrease of about 2°C was 10.92 hours, and it was confirmed that an average of 5.46 hours was taken for a change of 1°C.

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

5. While the temperature of the back surface of the concrete specimen decreased by about 4°C from 5°C to 1°C, the required thermal energy was 290,369J, confirming that an average of 72,952J of thermal energy was required for a 1°C change. In addition, the thermal energy required for a decrease of about 2°C from 1°C to -1°C was 277,423J, confirming that an average of 138,712J of thermal energy was required for a 1°C change.

6. 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.

7. Based on the research result that the deterioration of concrete proceeds rapidly when freeze-thaw is repeated about 140 times, the limit of the number of freeze-thaw repetitions was set. Since the service life of the tunnel is about 30 years, if you repeat freezing and thawing about 4.5 times a year in consideration of safety, damage to the tunnel structure will be possible. Using these conditions, the tunnel freeze-thaw environmental evaluation criteria were selected.

8. In areas where the freeze-thaw environmental evaluation grade is below grade c, it is necessary to design the tunnel to ensure durability during the period of use of the tunnel in preparation for freezing-thawing when designing the tunnel, and the freeze-thaw progress evaluation grade Tunnels of grade c or lower require establishment of a maintenance strategy against freeze-thaw damage.

9. The freeze-thaw evaluation criteria presented in this paper are quantitative criteria for the classification of freeze-thaw risk areas. In the future, through the freeze-thaw environmental evaluation criteria, it can be reflected in the tunnel design so that durability can be secured against freeze-thaw damage.

REFERENCES

Jin, H.W., Hwang, Y.C. (2017), “A study on current extent of damage of road tunnel lining in cold regions”, *KGES*, 18(1), 49-58

Jeong, H.M. (2013), “Degree of Damage Risk by Freeze and Thaw of Concrete Structures in Korea”, *Journal of the Korea Concrete Institute 2013*, 89-90

Bassuoni, M.T., Nehdi, M.L. (2005), "The case for air-entrainment in highperformance concrete", *Proceedings of the Institution of Civil Engineers, Structures & Buildings 158, Issue SB5*, pp. 311-319.

Federal Highway Administration (1998), “High-performance Concrete Defined for Highway Structures”, *High-Performance Concrete Committee Special Report No. 4*.

Jerzy Wawrzenczyk, Agnieszka Molendowska (2017), “Evaluation of concrete resistance to feeze-thaw based on probabilistic analysis of damage, *International Conference on Analytical Models and New Concepts in Concrete and Masonry Structures*, pp. 35-41.

Park, K. H., An, J. W., Park, S. H., Yoon, T. G. (2017), "A Study on the Development of Maintenance System for Tunnel with Freezing-Thawing Damage", *Geotechnical hazard Mitigations ; Experiment, Theory and Practice*, pp. 121-135.

Powers, T. C. (1945), "A working hypothesis for further studies of frost resistance." *Journal of the American Concrete Institute*, Vol, 16(4), pp. 245-272.

Zhang, X., YU, W., Wang, C., Liu, Z. (2006), "Three-dimensional nonlinear analysis of coupled problem of heat transfer in the surrounding rock and heat convection between the air and the surrounding rock in the Fenghuo mountain tunnel", Cold Regions Science and Technology, Vol. 44. pp. 38-51.