EVALUATION OF FREEZE AND THAW DURABILITY OF DAM CONCRETE BASED ON A LONG-TERM EXPOSURE TEST

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ABSTRACT

To ascertain the durability of dam concrete, the long-term exposure test of large-scale concrete blocks at the Okutadami Dam have been conducted. During this study, the frost deterioration depth of the core specimens of the large blocks and the dam body were evaluated by microscopic analysis such as Electron Probe Micro-Analyzer and pore volume distribution. Moreover, the relation between the elapsed years and the frost deterioration depth was summarized in figures, and the method of forecasting deterioration by the $\sqrt{t}$ formula like the carbonation was shown.

INTRODUCTION

The deterioration of frost damage, which advances inwardly from the surface of concrete, causes phenomena such as scaling, peeling of the aggregate and the corrosion of steel, all of which impair the structural performance. For the appropriate maintenance, the depth of deterioration caused by frost damage must be evaluated to predict the progress of deterioration. But there is little research which evaluated the depth of deterioration corresponding to the exposure environment, exposure period, mix proportion conditions and others. To obtain the knowledge on the deterioration caused by frost damage, this report evaluate the freeze-thaw resistance of aging concrete by estimating physical properties such as the frost deterioration depth.

The investigation was conducted on four large blocks and the dam concrete core. The large concrete blocks were exposed to the freeze-thaw environment, while the concrete core was collected from the dam body and the large blocks for comparison.

SUMMARY OF LONG-TERM CHANGE IN THE LARGE BLOCKS

Outline of the Large Blocks

Okutadami Dam is a concrete gravity dam completed in 1960 and located in an area of heavy snowfall, within the mountainous Tohoku region. Its location is shown in Figure 1, while the yearly average temperature and the snow depth at the dam location are shown in Figure 2. The specifications and mix proportion of the large blocks are shown in Table

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1. The large blocks are composed of four mix proportions, including that of the external concrete of Okutadami Dam as standard, and those with differing entrained air, water/cement and fly ash replacement ratios respectively. These large blocks (one cubic meter per side) were fabricated two pieces per mix proportion, and have been exposed in the air near the dam site since 1963.

Measurement method and results

On-site measurements have been implemented annually since 1964(e.g., Nagataki et al. 2012). The pulse velocity of the ultrasonic waves, propagating through concrete one meter thick, is measured at the nine traverse lines on each of the facing surfaces of the large block, namely at a total of 18 traverse lines, whereupon the dynamic modulus of elasticity is converted from the average of the lines.

Setting a value of one year after establishing the initial value of blocks, the ratio of the measured dynamic modulus of elasticity to the initial value (percentage of the dynamic modulus of elasticity) is regarded as indicating the degree of soundness.

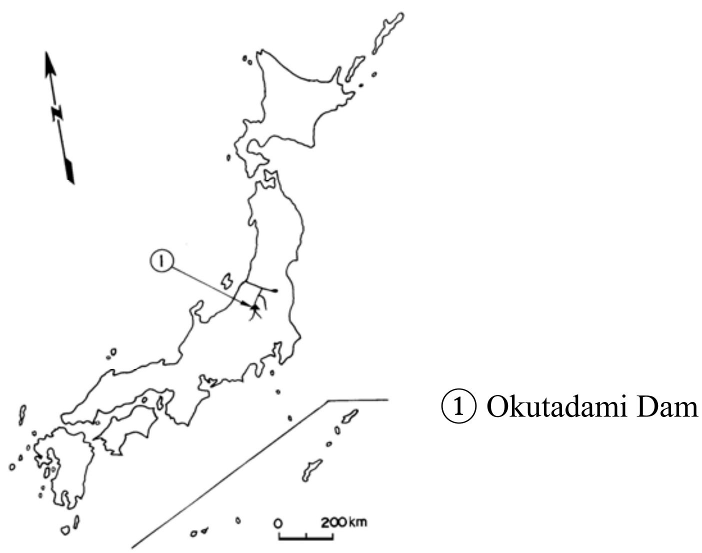
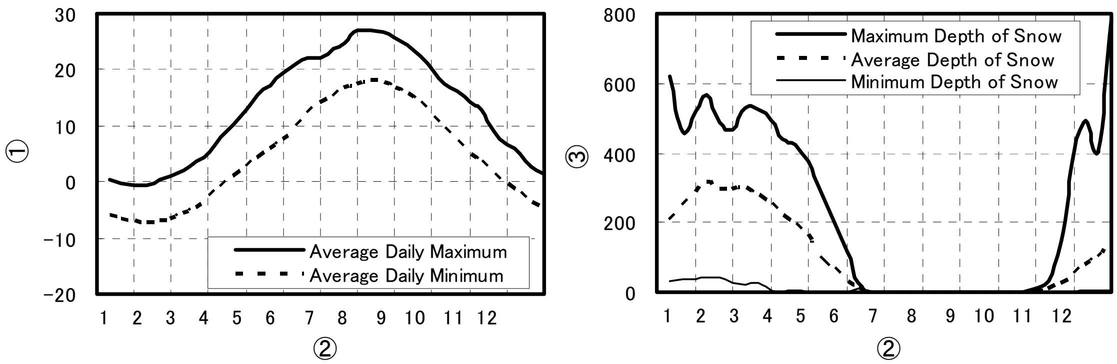


Figure 1. Locality of the Okutadami Dam.



① Air Temperature (^oC) ② Month ③ Snow Depth (cm)

Figure 2. Air Temperatures and Snow Depth at Okutadami Site (1963-2011)

Table 1. Concrete Mix Proportion (Okutadami)

		Dam body	Block Specimens			
Mix Proportion		----	A	B	C	D
G_{max} (mm)		**150**	**150**[1)]			
Unit Weight (kg/m^3)	C+F	**210**	**211**			
	W	**99**	**93**	**105**		**93**
F/C+F (%)		**30**	**25**			**0**
W/C+F (%)		**47**	**44**	**50**		**44**
s/a (%)		**23**	**23**	**26**	**24**	**23**
Slump (cm) [2)]		**2.5**	**4.7**	**7.2**	**15**	**1.5**
Air Content (%) [2)]		**3.5**	**3.3～3.4**		**0.5**	**2.9**
σ_{91} (N/mm^2)		**28.7**	**33.1**	**29**	**33.5**	**38.8**
Durability Factor(%)[3)]		**83**	**76**	**87**	**4**	**86**
Remarks		External Concrete	Standard Mix Proportion	W/C increased	W/C increased Non-AE	Non-FA

C: Moderate Heat Portland Cement, F: Fly Ash, Aggregate: Crushed Stone and Sand
1) 40 mm In case of small specimens (wet screening)
2) Tested after wet screening
3) Laboratory test (ASTM C292-52T) 300 cycles, after 91-day standard curing

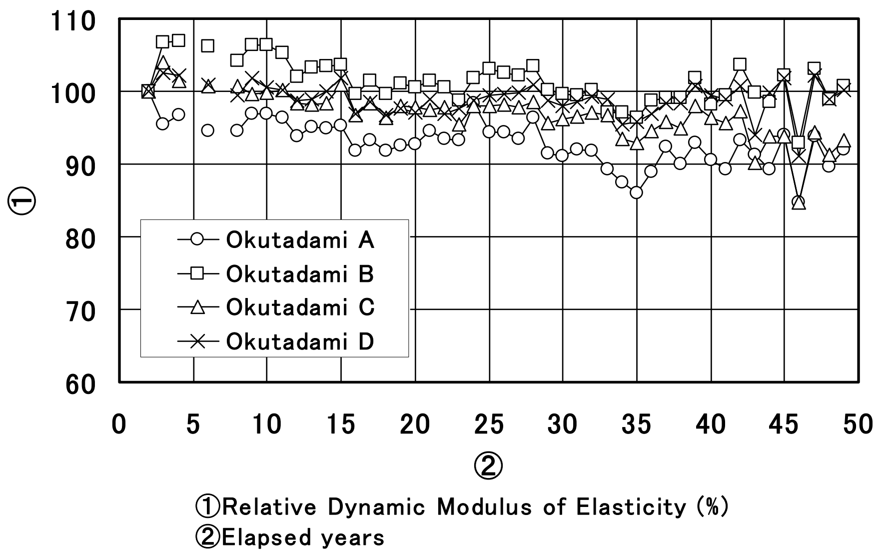


Figure 3. Changes over Time in the Relative Dynamic Modulus of Elasticity (Block Specimens)

The long-term change in the dynamic modulus of elasticity percentage of exposure test is shown in Figure 3. After 49 years, the dynamic moduli of elasticity percentage of the large blocks are from around 90% to 100%, and there is no significant difference between mix proportions. Although the result of the accelerated freeze-thaw test (ASTM C292-52T) implemented before making the blocks showed the significant impact of an AE agent (Table 1), there was no major impact of the AE agent in the exposure test.

EVALUATION OF CONCRETE CORE SPECIMENS

Core specimens

In order to evaluate the detailed deterioration status caused by frost damage, concrete cores (diameter 100mm, length about 200mm, 3 pieces from each of the large blocks) were obtained from the upper section of the large blocks. The time of coring was October 2000, namely 37 years since pouring the concrete.

In addition, to evaluate the difference between the large blocks and the actual-size structure, a concrete core (diameter 300mm, length about 3000mm) was obtained from the right bank of Okutadami Dam (in the vicinity of No.24 Block, Elevation: 715 m). The coring location is shown in Figure 4, while the concrete mix proportion of Okutadami Dam is shown in Table 1. The time of coring was October 2000, 39 years since placing the concrete (May 1961).

Measurement method

To evaluate the carbonation depth, the deterioration depth caused by frost damage and the freeze-thaw resistance, the following measurements were implemented. To evaluate the deterioration depth caused by frost damage, the change in physical properties of a hardening body in the depth direction was evaluated by the pore volume distribution and Electron Probe Micro-Analyzer (EPMA).

(1) Dynamic modulus of elasticity. The dynamic moduli of elasticity of core specimens taken from blocks were determined by measuring the ultrasonic propagation velocity.

(2) Carbonation depth. To evaluate the carbonation depth, a phenolphthalein solution of one percent concentration was sprayed on the cutting surface of the concrete core, and the boundary depth of the color change part was measured.

(3) Area analysis by EPMA. To evaluate the distribution of Ca, Si, Al and C, the EPMA area analysis was implemented about a cube specimen measuring around 40 mm per side including the outermost surface.

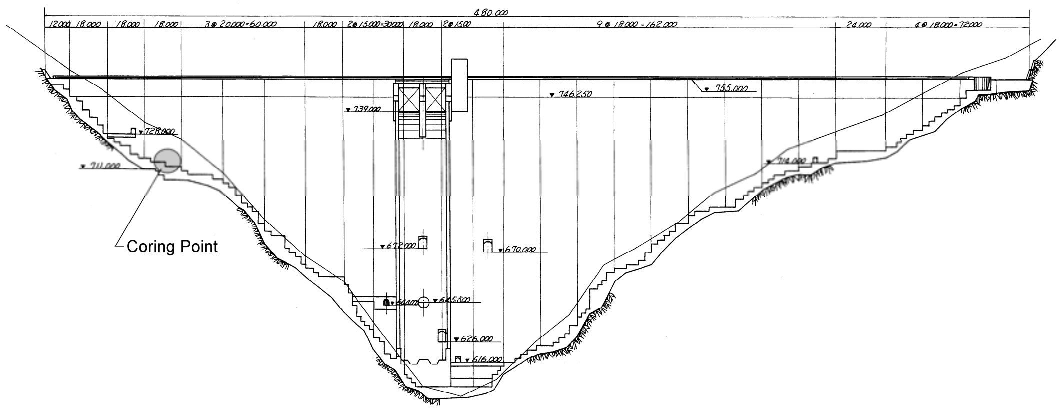


Figure 4. Coring point of Okutadami Dam.

(4) Pore volume distribution. The pore volume distribution was measured by a mercury intrusion porosimeter. The specimens were cut into cubes measuring around 9 mm per side, extracted from depths of 0 to 10, 10 to 20 and 20 to 30 mm from the surface respectively, and treated by immersion into acetone for one hour, air drying in a room for 24 hours, and then drying by a vacuum freeze dryer for a week.

(5) Freeze-thaw resistance. In addition, to ascertain the effect of long-term exposure to freeze-thaw cycles, a freeze-thaw test using the core specimen according to the JIS A1148A test (freezing and thawing in water test) was performed.

Measurement results

(1) Evaluation of the hardening body by strength properties. Figure 5 shows a comparison of the percentage of ultrasonic propagation velocity between concrete cores and the large blocks (Okutadami A, B, C, D). It shows how the measured value of concrete core slightly exceeds the results of the large blocks measured on-site. Naruoka et al. (2007, in Japanese) suggested that the ultrasonic propagation velocity tended to be increased by

cutting away several millimeters of the surface layer of a large block. Consequently, it is presumed that the deterioration of the large blocks occurs within a range of several millimeters of the surface layer. Figure 6 shows the compressive strength of Okutadami Dam's concrete. These specimens of different depth were cut from the dam concrete core. Compressive strengths of dam cores exceed that of construction period. Based on these results, the dam concrete is considered to be in sound condition.

(2) Carbonation depth. The carbonation depth of the core specimens obtained from four large blocks and dam body is shown in Table 2. Although the individual specimens vary slightly, the carbonation is only several millimeters.

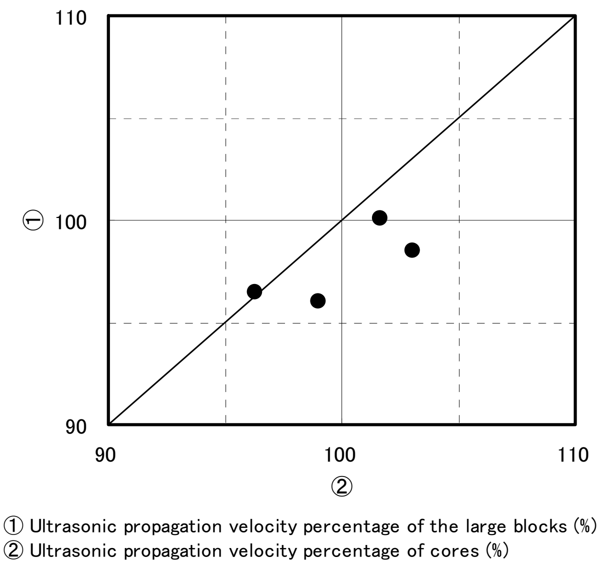


Figure 5. Comparison of the ultrasonic propagation velocity of large blocks and cores.

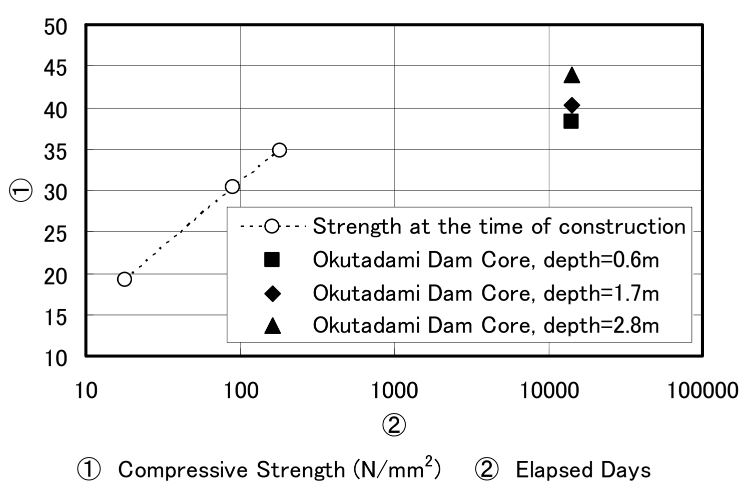


Figure 6. Compressive strength of the core from the bank of Okutadami Dam.

Table 2. Carbonation depths.

Name of specimen		Okutadami Dam	Okutadami A	Okutadami B	Okutadami C	Okutadami D
Carbonation depth(mm)	Minimum	0.0	1.9	0.0	0.0	0.0
	Maximum	0.0	5.5	0.0	3.1	0.0
	Average	0.0	4.1	0.0	1.4	0.0

<u>(3) Evaluation of the frost deterioration depth of concrete cores.</u> Figure 7 shows the result of the EPMA area analysis of carbon implemented for an area of 4 cm square. Carbonation is found to occur within the range of around 5 mm in the vicinity of the surface, which resembles the result obtained with the phenolphthalein method. Also, Figure 7 shows the crack propagating along the surface of the aggregate, and the advance

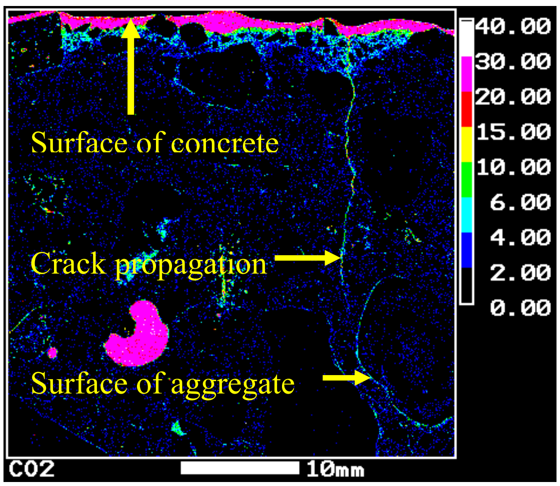


Figure 7. EPMA area analysis (Okutadami C, Carbon, Field of view: 4 cm)
The color legend shows the carbon concentration (mass %)

of carbonation near the crack. Those cracks were observed on almost all specimens, showing that the carbonation progressed along with the cracks, following the occurrence of fine cracks caused by the frost damage. To ascertain the change in structure from the surface, the change in the pore volume distribution from the surface to a depth of 3 cm was evaluated, with the result shown in Figure 8. The result of a mortar test by Okamoto et al. (1996, in Japanese) shows that the number of pores of around 0.1 to 1.0 µm increases due to microscopic fractures caused by frost damage. Uomoto et al. (2007, in Japanese) reported that the influenced minimum pore diameter is 0.1µm when the freezing temperature is -10°C. Because the minimum temperature of the Okutadami Dam is -10°C, the pore volume of diameters of 0.1 to 1.0 µm and total pore volume were compared. All specimens showed that the pore volume of 0.1 to 1.0 µm tended to decline with depth, which indicates that the greater the depth, the less the impact of frost damage. For Okutadami Dam, Okutadami C and D in particular, the change in pore volume continued to a depth of 20 to 30 mm, due to the effect of frost damage.

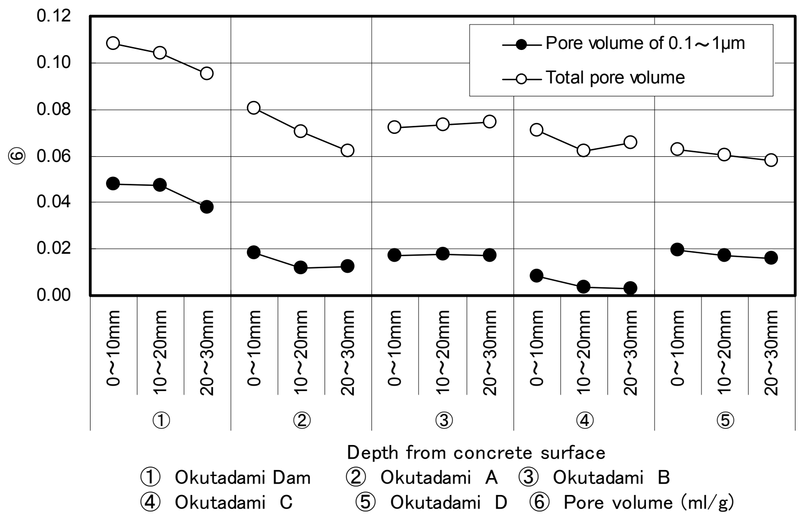


Figure 8. Change in Pore volume distribution.

<u>(4) Effect of the mix condition on freeze-thaw resistance.</u> The air-void spacing factor measured by the linear traversing method based on ASTM C457 and durability factors of pre- and post-exposure are shown in Table 3.

When Okutadami A and C are compared to evaluate the effect of an AE agent, it is found that the air-void spacing factor of Okutadami A mixed with an AE agent is smaller than that of Okutadami C. This result indicates that an AE agent improves freeze-thaw resistance. When comparing Okutadami A and B, they were found to have differing water content and water binder ratios, while Okutadami B, with large water content and water binder ratio, had a greater freeze-thaw resistance. Considering the fact that the air-void spacing factors are approximately equal, it seems that Okutadami B, with a significant slump and workable mix proportion, was more durable concrete. The durability of the Okutadami Dam was also confirmed as sufficient, since the durability factor was 84 and the air-void spacing factor was small.

In addition, comparison of the pre- and post-exposure durability factors shows values reduced to approximately 80% in some cases. This decrease requires care, because the durability factors concerned may be affected not only by frost damage but also disturbance by coring. Okutadami D, which does not use fly ash, and Okutadami A, which does, have approximately equivalent values for durability and air-void spacing factors, showing no difference in durability. The ratios of CaO/SiO_2 and CaO/Al_2O_3 in the paste part determined from EPMA are shown in Figure 9. Both ratios of CaO/SiO_2 and CaO/Al_2O_3 tend to decrease with the mixing of fly ash. Consequently, it is clear that the reaction of fly ash affects the physical properties of the paste. Figure 10 shows a comparison of the change in pore volume distribution, accompanied by the mixing of fly ash. The latter results in a decline of voids of 0.03μm or more and an increase of those of 0.03μm or less. Previous studies described that the similar tendency of voids was observed in the fly ash concrete (e.g., Satou et al. 1999, in Japanese). The result of the acceleration test showed no difference in freeze-thaw resistance when using fly ash. However, considering the link between water-tightness and the small diameter of air-void, the mixing-in of fly ash has the potential to enhance durability against frost damage. This will be verified using a long-term durability test in future.

(5) Prediction of deterioration caused by frost damage. Focusing on the crack propagation or the loosening of a boundary aggregate, the frost deterioration depth is deemed to be around 3 to 4 cm.

Predicting the precise deterioration for actual structures is difficult, because frost damage is affected by temperature conditions during freeze-thaw and water provision from outside. If it is assumed that, however, the yearly ambient temperature remains almost constant, it is conceivable that the yearly number of freeze-thaw cycles will also be constant. Accordingly, when the frost deterioration depth was assumed to be related to the exposed years, the frost deterioration depth could be estimated by applying the means of predicting the carbonation depth.

$$y = b \times \sqrt{t} \tag{1}$$

Where, ***y***: Frost deterioration depth(mm), ***b***: Frost damage velocity coefficient, ***t***: Elapsed years

Figure 11 shows the relation between the elapsed years and frost deterioration depth in freeze-thaw environmental area of Japan. The prediction accuracy of the frost deterioration depth will be improved by accumulating such data.

Table 3. Air-void spacing factor and Durability factors.

	Air-void spacing factor (μm)	Durability factor	
		Pre-exposure	Post-exposure
Okutadami Dam	86	83	84
Okutadami A	173	76	66
Okutadami B	179	87	84
Okutadami C	786	4	8
Okutadami D	202	86	64

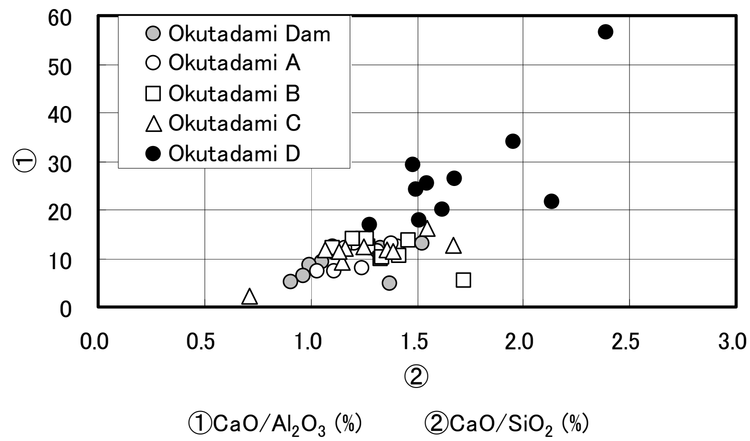


Figure 9. Relation of the Ratio of CaO/SiO_2 and CaO/Al_2O_3

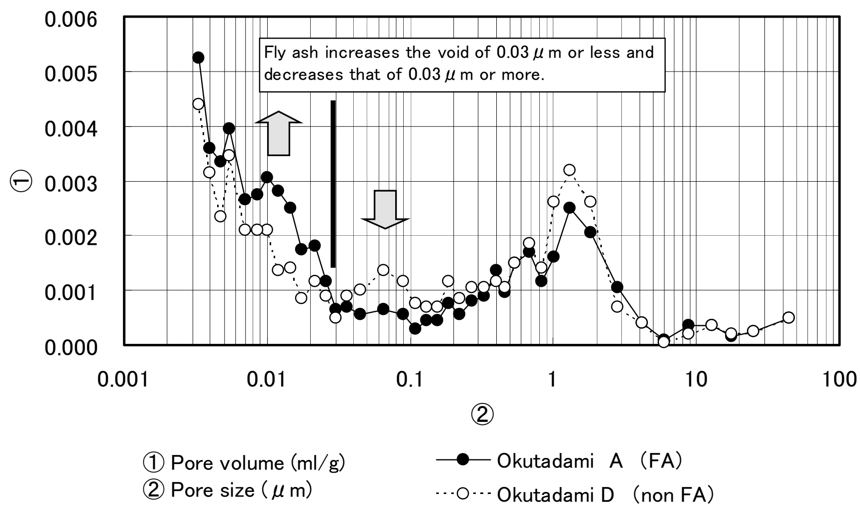


Figure 10. Change in pore volume distribution resulting from the mixing-in of fly ash.

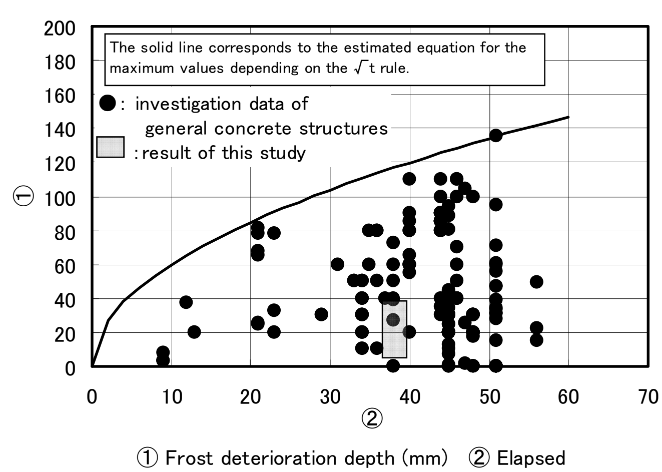


Figure 11. Relation between the frost deterioration depth and elapsed years.

CONCLUSION

Evaluation of the deterioration depth caused by frost damage of the concrete cores obtained from the large blocks, the dynamic modulus of elasticity of which had been measured for 40 years by nondestructive inspection, was implemented. The results were as follows:

1) The region around 5 mm from the surface layer had a carbonized porous structure, which could conceivably affect the ultrasonic propagation velocity measurement, also for the large blocks.

2) Deterioration at a depth of 3 to 4 cm, due to crack propagation, was observed by EPMA analysis. The result of pore volume distribution showed that the impact of frost damage extended to several centimeters.

3) A freeze-thaw test was implemented for cores. The result showed that the pre-exposure freeze-thaw resistance was approximately equivalent to the post-exposure freeze-thaw resistance.

4) Although the durability effect of an AE agent was unclear from the measurement result of the dynamic modulus of elasticity, the result of the freeze-thaw tests implemented pre- and post-exposure showed the AE agent improves the freeze-thaw resistance.

5) The mixing of fly ash results in a decline of voids of 0.03 μm or more and an increase of those of 0.03μm or less.

6) The method used to predict the advance of frost damage involved the $\sqrt{t}$ formula based on the relation between elapsed years and the frost deterioration depth.

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