Fracture Mechanics of Concrete and Concrete Structures -
Assessment, Durability, Monitoring and Retrofitting of Concrete Structures- B. H. Oh, et al. (eds)
ⓒ 2010 Korea Concrete Institute, Seoul, ISBN 978-89-5708-181-5

Detection of cracks in concrete and evaluation of freeze-thaw resistance using contrast X-ray

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ABSTRACT: With the aim of developing a technique of evaluating the freezing and thawing resistance of existing concrete structures by contrast X-ray radiography, a method of quantifying cracks and voids in concrete is proposed, and the relationship between the quantified values (transmission dose difference) and the degree of deterioration by freezing and thawing is determined. The relationship between the transmission dose difference and scaling of concretes with different strengths is also determined to examine if the transmission dose difference can serve as an index to freezing and thawing resistance. Experiment results show relative dynamic modulus and scaling are closely related to transmission dose difference, suggesting the possibility of evaluating the freezing and thawing resistance of concrete by this technique.

1 INTRODUCTION

In the Tohoku district in Japan, concrete structures are prone to deterioration under freezing and thawing action in winter. Concrete with an entrained air content of 4% or more is generally regarded as being resistant to freezing and thawing. However, a 4% air content and its dispersion while fresh can greatly change after hardening depending on the placing and curing methods. Also, the freeze-thaw resistance of a completed concrete structure has been judged by whether or not the air content at the time of placing and subsequent compressive strength of the concrete exceed the specified values. If the freeze-thaw resistance of a concrete structure after being put into service can be evaluated by examining the properties of drilled cores including early defects and cracks, such evaluation will greatly enhance the reliability of its durability evaluation. With the aim of developing a technique of evaluating the freezing and thawing resistance of existing concrete structures by contrast X-ray radiography, a method of quantifying cracks and voids in concrete is proposed, and the relationship between the quantified values (transmission dose difference) and the degree of deterioration by freezing and thawing is determined. The relationship between the transmission dose difference and scaling of concretes with different strengths is also determined to examine if the transmission dose difference can serve as an index to freezing and thawing resistance. Experiment results show relative dynamic modulus and scaling are closely related to transmission dose difference, suggesting the possibility of evaluating the freezing and thawing resistance of concrete by this technique The authors have conducted studies using a contrast X-ray technique to detect micro-cracks in concrete[1), 2), 3),4)]. In these studies, cores were drilled from deteriorated concrete structures and cut into slice specimens 10 mm in thickness. After impregnating these specimens for a certain period with a liquid originally developed by our laboratories to serve as a contrast medium, their X-ray images were taken to compare the transmission dose with the dose before immersion. Based on the transmission dose differences, the amounts of voids and micro-cracks in specimens were quantified, thereby quantifying their deterioration. This method is characterized by the following points: The state of voids and micro-cracks can be visually confirmed; the progress of deterioration along the depth can be recognized together with quantitative changes at different depths; and the permeability, which is closely related to durability, is reflected on the test results. The authors considered that, if the state of voids and micro-cracks in concrete is quantified by this method, then the properties of surface and inner concretes can be compared, and that the quantified values may be closely related to the resistance of concrete to freezing and thawing action. With this as a background, tests were conducted in the present study with the aim of developing a technique of determining the freezing and thawing resistance of existing concrete structures using contrast X-ray radiography as follows: Take contrast X-ray images of seven types of air-entrained concrete specimens, which were deteriorated to different relative dynamic moduli, to visualize micro-cracks and voids resulting from freezing and thawing action. Quantify their amounts to determine their relationship with the relative dynamic moduli. Concretes having different water-cement ratios (W/Cs) with or without entrained air were also subjected to contrast X-ray radiography to quantify voids and micro-cracks. These and the above-mentioned specimens were then subjected to freezing and thawing cycles in saline water to determine the number of cycles to a mass loss of 10%. Based on the obtained relationships, a method of judging the freezing and thawing resistance is proposed.

2 METHOD OF QUANTIFYING CRACKS AND VOIDS IN CONCRETE

2.1 *Outline of specimens*

Concrete proportioned as given in Table 1 (compressive strength: 48 N/mm^2, air content: 3%) were made into beam specimens 100 by 100 by 400 mm in size. These specimens were subjected to freezing in water and thawing in water by the method specified in ASTM C 666. Seven specimens were thus prepared with relative dynamic moduli reduced to different levels ranging from 100% to 40% at 10% intervals. When the target relative dynamic modulus was attained, three slices (100 by 100 by 10 mm) were cut out from the mid-length of each specimen and left to stand for 24 hours in a thermohygrostatic room at 20°C and 60% R.H. before taking contrast X-ray images.

Table 1. Composition of the concrete.

G_{max} (mm)	Slump (cm)	W/C (%)	Air (%)	s/a (%)	Concrete composition (Kg/m^3)				
					W	C	S	G	Ad.
20	8	50	3	47	198	396	815	905	0.66

Table 2. Photography conditions.

X-ray source (WS-125S)	Tube voltage	100kV
	Tube current	2mA
	Focal distance	900mm
	Exposure time	70sec
	Focus dimension	0.8×0.8mm
Film	Industrial X-ray	IX #50
Intensify screen	Lead foil screen (0.03mm)	

2.2 *Contrast X-ray radiography*

Contrast X-ray images were taken under the conditions given in Table 2 before and after impregnation with a contrast medium for 60 min. The contrast medium was a material developed at the authors' laboratories with a mass absorption coefficient of around 0.18 cm^2/g for 100 keV. Sliced specimens were immersed in containers filled with the contrast medium as shown in Figure 1 to allow the medium to permeate into them without pressure. These were removed from the containers after impregnation for 60 hours and wiped with a rubber wiper to remove excessive liquid from the surfaces for X-ray radiography.

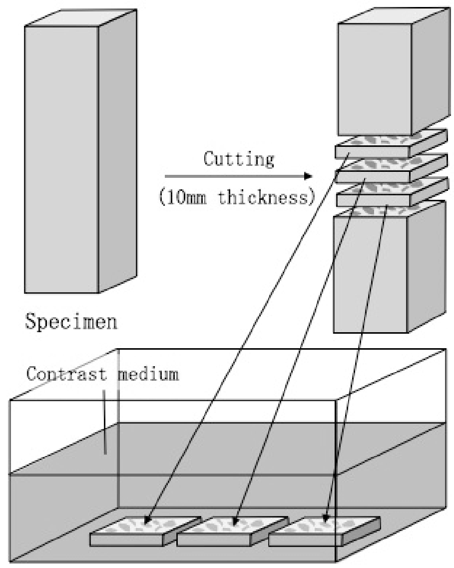

Figure 1. Impregnation method of contrast medium.

Figure 2 shows the state of taking X-ray images. Specimens set as given in Table 2 were X-irradiated from above for radiography. A reference mortar specimen was also placed together with the specimens under test to monitor the optical density of films after development, which can vary depending on the conditions of the developer and/or fixer. An automatic processor was used for developing the X-ray film after shooting.

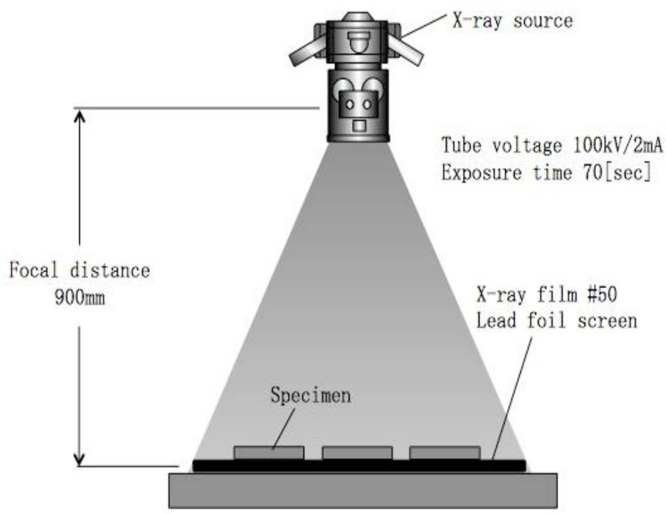

Figure 2. State of taking X-ray images.

2.3 *Method of quantifying voids and micro-cracks*

Radiographic films of a type photosensitive to X-rays (non-screen type), such as IX #50 manufactured by Fuji Photo Film Co., are characterized by their optical density changing in proportion to the level of X-ray irradiance. The optical density of X-ray films was therefore determined to quantify the amount of voids and micro-cracks. A densitometer is normally used for measuring the optical density of X-ray films. It determines the density from the amounts of incident light and light received through the X-ray film using Equation (1).

$$D = \log(I_o / I_t) \qquad (1)$$

where D is the X-ray film density, I_0 is the incident light amount at the measuring area, and I_t is the amount of light passing through the film. Due to the small area measurable at a time, however, it is difficult to measure initial defects and voids including micro-cracks of the entire specimen in an averaged and quantitative manner using a densitometer. This method can thus lead to serious errors.

For this reason, it was decided to employ an illuminometer for the measurement of the optical density of X-ray films in this study. Illuminance refers to the amount of light flux per unit area of a surface exposed to light. The authors considered that the average density of X-ray films of an entire specimen is measurable by using an illuminometer as follows: First, measure the illuminance through a dark box placed on a 'schaukasten' (X-ray film viewing device) to determine the incident illuminance, I_0. Then insert an X-ray film between the schaukasten and the dark box to measure the transmitted illuminance, I_t, and determine the optical density of the X-ray film, D, using these illuminance values by Equation (1). The density of an X-ray film before impregnation with the contrast medium (hereafter referred to as 'before impregnation'), D_B, and the value after impregnation with the contrast medium ('after impregnation'), D_A, were then determined to calculate the difference between the transmission doses before and after impregnation, T, as given in Equation (2), as an index to the amount of voids and micro-cracks.

$$T = D_B - D_A \qquad (2)$$

Note that the sensor of the illuminometer used in the measurement comprises a silicon photodiode (electrical performance: 200 to 2.0 × 105 Lux, resolution: 0.1 to 100). The measurement setup is shown in Figure 3.

2.4 *Test results*

Photo 1 shows typical X-ray images of specimens with relative dynamic moduli reduced to 90%, 60%, and 40% taken before and after impregnation with

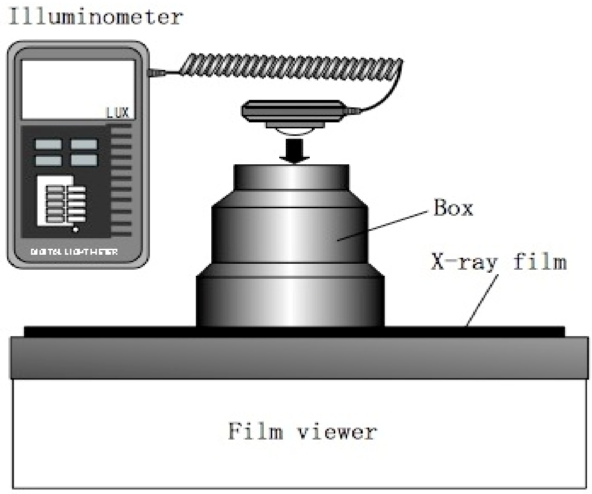

Figure 3. Measurement setup of illuminometer.

the contrast medium for 60 min. All images before impregnation show aggregate particles lighter than the mortar matrix, with black spots that appear to be air voids. No fine defects or micro-cracks are recognized on these images.

On the other hand, all images after impregnation show micro-cracks occurring at the edges, which are found to develop inward as the relative dynamic modulus decreases, increasing to a significant extent. Micro-cracks that cannot be recognized by the naked eye or general X-ray radiography are thus detected by this contrast X-ray technique.

Figure 4 shows the relationship between the relative dynamic modulus and the transmission dose difference after impregnation for 60 min, which turned out to be a linear relationship with a correlation coefficient of 0.98. Accordingly, the amount of freezing and thawing-induced micro-cracks quantified in terms of transmission dose difference determined by

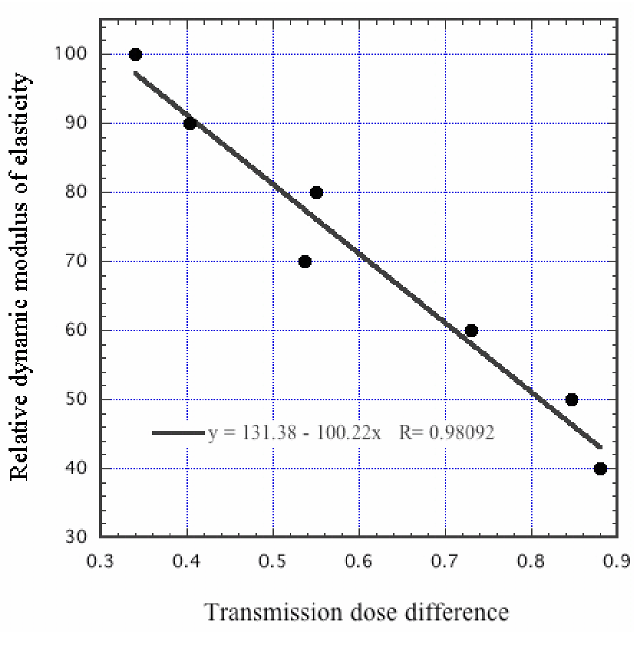

Figure 4. Relationship between the relative dynamic modulus and the transmission dose difference.

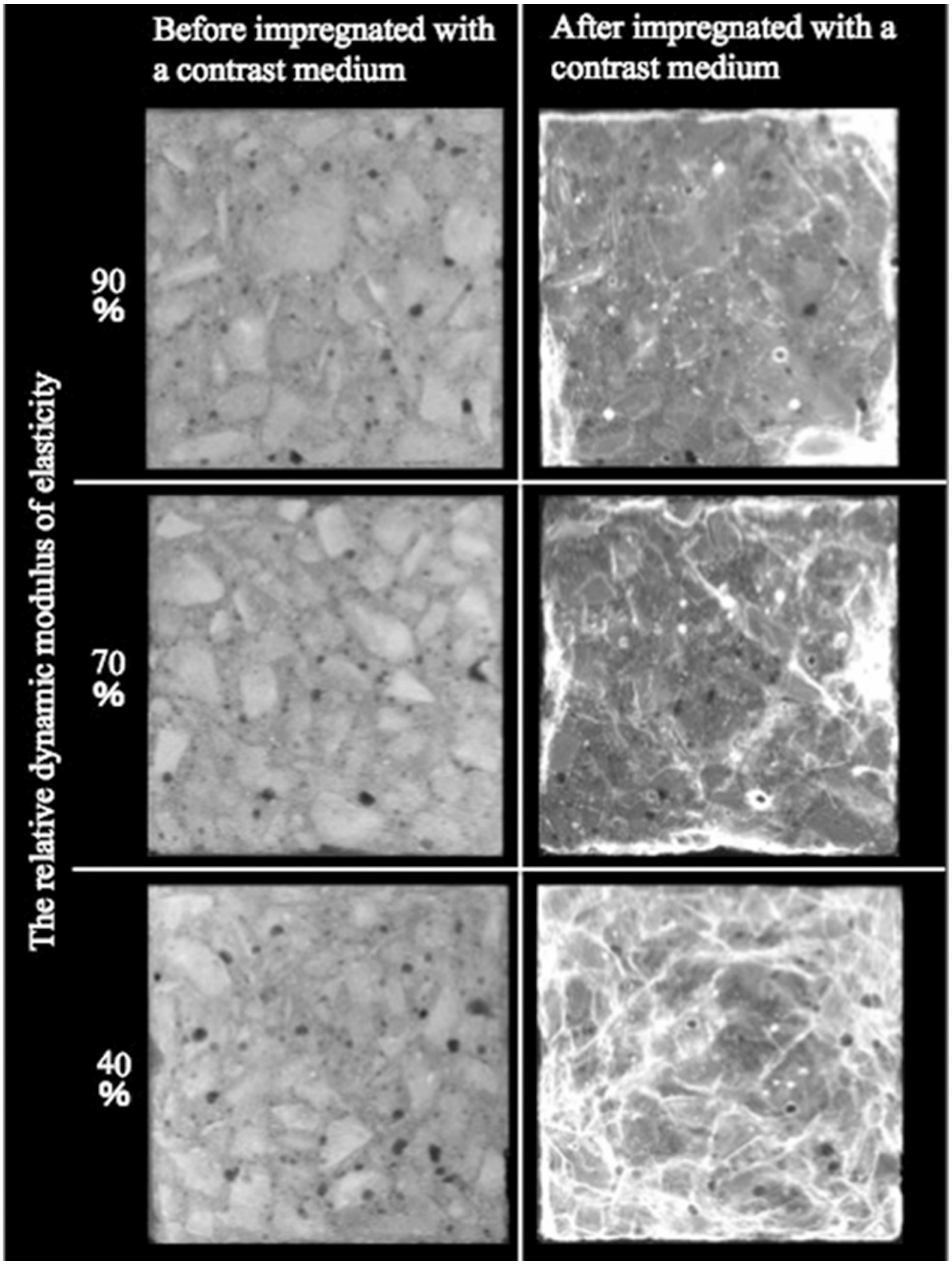

Figure 5. Typical X-ray images of specimens with relative dynamic moduli reduced to 90%, 60%, and 40% taken before and after impregnation with the contrast medium for 60 min.

radiography with a contrast medium is found to be closely related to the relative dynamic modulus of elasticity. This method is therefore proven valid as a means to quantify air voids and micro-cracks in concrete.

3 RELATIONSHIP BETWEEN TRANSMISSION DOSE DIFFERENCE AND RESISTANCE TO SCALING UNDER FREEZING AND THAWING ACTION

Concretes having different W/Cs with or without entrained air were subjected to contrast X-ray radiography to calculate the transmission dose differences, as well as to freezing and thawing cycles in a saline environment. Based on the results, the relationship between the transmission dose difference and the number of freezing and thawing cycles to a mass loss of 10% was determined with the aim of proposing a method of judging the resistance of concrete to combined deteriorative action involving chlorides and freezing and thawing. This experiment included the determination of the transmission dose of sound specimens, which implies the amount of initial defects and voids in specimens, providing information on its relationship with their resistance to combined deterioration due to freezing and thawing with chlorides. Similar tests were also conducted on seven types of air-entrained concrete specimens with reduced dynamic moduli used in section 2 above for quantifying concrete deterioration. This was done to determine the relationship between the transmission dose difference, which quantifies micro-cracks due to initial cracks and voids as well as those resulting from repeated freezing and thawing, and the resistance to combined deterioration involving freezing and thawing and chlorides.

3.1 *Outline of specimens*

Test specimens included the following: Six types of non-air-entrained concrete specimens with W/Cs varying from 45% to 75% and compressive strength varying from 60 to 13 N/mm^2; seven types of air-entrained concrete having W/Cs ranging from 40% to 70% and compressive strength ranging from 60 to 20 N/mm^2; and seven types of specimens used for quantifying concrete deterioration in section 2 above. Note that the compressive strength was determined by uniaxial compression tests conducted immediately before the experiment.

Tables 3 and 4 give the mixture proportions of non-air-entrained and air-entrained concretes, respectively. Cement was high-early-strength portland cement. Crushed stone and river sand were used as coarse and fine aggregates, respectively. These concretes were fabricated into cylindrical specimens 100 mm in diameter, and three each cylinders were used for each strength, totaling 39. After placing, specimens were water-cured at 20°C for two weeks and then cut into disks 10 mm in thickness. These were left to stand for 24 hours in a thermohygrostatic room at 20°C and 60% R.H. before being subjected to testing. The disks were taken from the mid-height portion of each specimen to eliminate the effect of bleeding after placing. As to beam specimen used for quantifying concrete deterioration in section 2 above, slices were taken from the remaining portions.

3.2 *Methods of contrast X-ray radiography and calculating transmission dose difference*

Contrast X-ray images of all specimens were taken under the conditions given in Figure 1, 2 and Table 2 before and after impregnation with the contrast medium. The transmission difference was calculated by Equation (2) from the optical densities of X-ray films before and after impregnation measured under the conditions shown in Figure 3.

3.3 *Method of measuring scaling due to freezing and thawing*

Ten millimeter-thick specimens used for X-ray radiography were subjected to repeated freezing and thawing both in water containing 3% NaCl to determine the number of cycles to a mass loss of 10%. Since the specimens were impregnated with the contrast medium, these were rinsed with running water for seven days. These were then immersed in a 3% NaCl solution in a container to be subjected to cycles of freezing in water and thawing in water with temperatures ranging between 5°C and 17.8°C in accordance with ASTM C 666 to a target mass loss of 10% (scaling amount: 2.5 kg/m^2). A mass loss of 10% roughly corresponds to levels 3 to 4 by visual rating[5)].

Table 3. Composition of the concrete (Non-AE Concrete).

G_{max} (mm)	Slump (cm)	W/C (%)	Air (%)	s/a (%)	Concrete composition (Kg/m^3) W	C	S	G
20	8	45	2	47	198	440	798	887
		50				396	816	906
		55				360	830	922
		60				330	842	935
		65				305	852	947
		70				283	861	956

Table 4. Composition of the concrete (AE Concrete).

G_{max} (mm)	Slump (cm)	W/C (%)	Air (%)	s/a (%)	Concrete composition (Kg/m^3) W	C	S	G	Ad.
20	8	40	4.5	41	179	448	675	955	0.13
		45				398	692	979	0.12
		50				358	706	999	0.11
		55				325	718	1015	0.10
		60				298	727	1028	0.09
		65				275	735	1040	0.08
		70				256	742	1031	0.08

3.4 *Relationship between transmission dose difference and mass loss*

Figure 5 shows the relationship between the transmission dose difference with an impregnation time of 60 min and the number of cycles to a mass loss of 10% of non-air-entrained concretes with a compressive strength of 13 to 60 N/mm^2. Specimens with a larger transmission dose difference (low strength specimens) tend to reach a mass loss of 10% with a smaller number of cycles. Assuming this relationship to be logarithmic, the coefficient of correlation is 0.99, suggesting strong correlation.

Figure 6 shows the similar relationship of air-entrained concretes with a compressive strength of 20 to 60 N/mm^2 and air-entrained concretes with relative dynamic moduli ranging from 100% to 40% at 10% intervals. Similarly to Figure 5, specimens with a larger transmission dose difference (low strength specimens) tend to reach a mass loss of 10% with a smaller number of cycles. Due to being air-entrained with an air-entraining admixture, the freezing and thawing resistance of these specimens is significantly higher than that of non-air-entrained

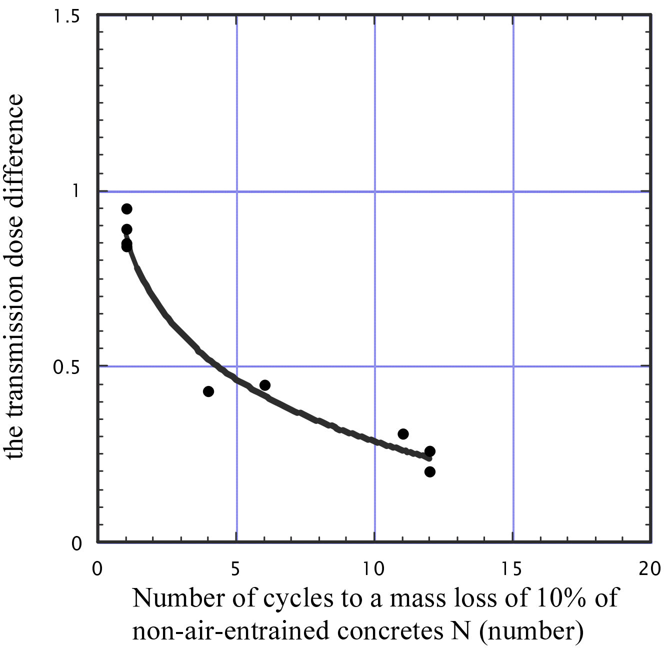

Figure 5. Relationship between the transmission dose difference with an impregnation time of 60 min and the number of cycles to a mass loss of 10% of non-air-entrained concretes.

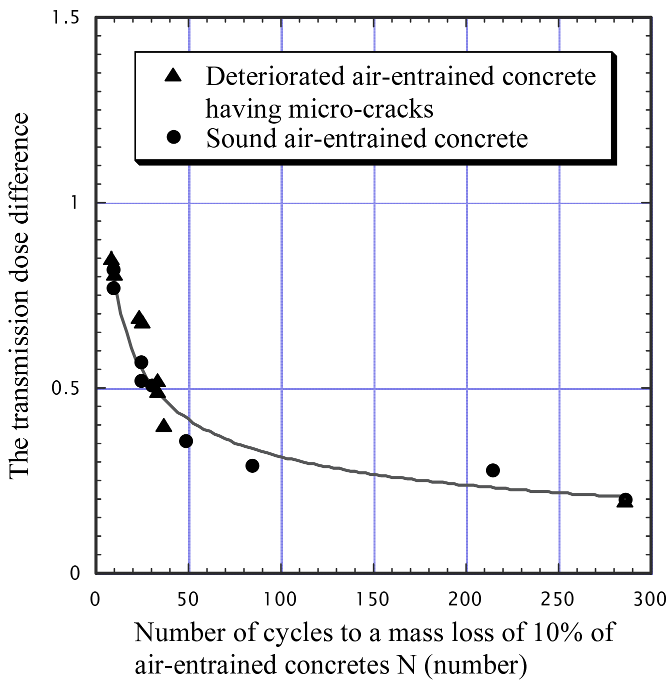

Figure 6. Relationship between the transmission dose difference with an impregnation time of 60 min and the number of cycles to a mass loss of 10% of air-entrained concretes.

concrete specimens, with the numbers of freezing and thawing cycles to a 10% mass loss being significantly larger than those of non-air-entrained concrete specimens. Air-entrained concrete with a transmission dose difference of 0.2 or less shows particularly high resistance to freezing and thawing even under composite deteriorative conditions, with the number of cycles to a mass loss of 10% being nearly 300. Whereas the relationship shown in Figure 5 demonstrates strong correlation by assuming a logarithmic relationship, the relationship of air-entrained concrete shown in Figure 6 should rather be approximated to an exponential relationship with a correlation coefficient of 0.97, since the number of cycles to a 10% mass loss is greater than non-air-entrained concrete because of the high freezing and thawing resistance of air-entrained concrete. Similarly close relationships are observed between the transmission dose difference and the number of cycles to a mass loss of 10% for both sound air-entrained concrete and deteriorated air-entrained concrete having micro-cracks. Because close correlation is thus observed between the transmission dose difference and the number of cycles to a 10% mass loss in various types of concretes, it is inferred effective to determine the transmission dose difference as a method of judging the resistance of concrete to combined deteriorative action involving freezing and thawing and chlorides. However, these results were obtained in laboratories from forced freezing and thawing in water containing 3% NaCl. It is considered necessary to investigate these relationships under deteriorative action in actual environments.

4 CONCLUSION

A technique of evaluating the resistance of concrete to freezing and thawing was developed using contrast X-ray radiography. Within the range of the experiments, the following results were obtained:

(1) Micro-cracks in concrete under the microscopic destructive action of repeated freezing and thawing can be visualized by using contrast X-ray radiography.

(2) Contrast X-ray images of air-entrained concrete specimens deteriorated by freezing and thawing testing were taken before and after impregnation with a contrast medium to determine the transmission dose differences from the obtained X-ray films. The transmission dose difference tended to increase as the degree of deterioration increased (as the relative dynamic modulus decreased). A clear linear relationship was observed between transmission dose difference and relative dynamic modulus. It can therefore be said that the deterioration of air-entrained concrete is quantifiable by transmission dose differences.

(3) Freezing and thawing tests were conducted on specimens of sound concrete with or without entrained air and deteriorated concrete with entrained air, to determine the number of freezing and thawing cycles to a mass loss of 10% and the transmission dose difference. These were found to be closely related to each other. The number of cycles to a 10% mass loss tended to decrease as the transmission dose difference in-

creased, and vice versa. The high resistance to freezing and thawing of air-entrained concrete was also expressed by the transmission dose difference. It is thus considered that the freezing and thawing resistance of concrete can be judged by determining its transmission dose difference.

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