Fracture Mechanics of Concrete and Concrete Structures -
Assessment, Durability, Monitoring and Retrofitting of Concrete Structures- B. H. Oh, et al. (eds)

Damage identification of cracked concrete by X-Ray computed tomography method

T. Suzuki & M. Aoki
Nihon University, Kanagawa, Japan

M. Ohtsu
Kumamoto University, Kumamoto, Japan

ABSTRACT: Damage in concrete grows due to the environmental effects. For detailed inspection of concrete damages, unconfined compression tests have been frequently conducted, taking out core samples. However, the mechanical properties are not good enough for practical evaluation of damage degree in concrete materials. The concrete damages are affected by inner crack distribution. In this study, the crack distributions of core samples were inspected with X-ray computed tomography method. The core-samples were collected from a water canal of reinforced concrete, which is strongly influenced by freeze and thawed process. The concrete damage was evaluated by DeCAT in core tests. Thus, the durability index E_0/E^* calculated from DeCAT are clearly correlated with CT characteristics identified by X-ray computed tomography method.

1 INTRODUCTION

The durability of concrete structures decreases easily due to such environmental effects, as carbonation and freeze-thawed process (JCI-C65, 2005). The degree of damage in concrete is, in most cases, evaluated by an unconfined compression test or ultrasonic test. For effective maintenance and management of concrete structures, it is necessary to evaluate not only the strength of physical properties but also the degree of damage. Quantitative damage evaluation of concrete is proposed by applying acoustic emission (AE) method and damage mechanics (Ohtsu 2004). The procedure is named DeCAT (Damage Estimation of Concrete by Acoustic Emission Technique) (Suzuki 2007). The damage is evaluated as a relative value by DeCAT in core tests.

In this study, damage estimation of structural concrete from concrete-core samples is developed, applying AE and X-ray computed tomography methods. Concrete-core samples taken from reinforced concrete of an existing concrete canal wall were tested. These samples were strongly influenced by freeze-thawed process (Suzuki 2009). The crack distribution of concrete was inspected with helical CT scans, which were undertaken at one-millimeter intervals. After helical CT scan, damage of freeze-thawed samples was evaluated, based on fracturing behavior under unconfined compression with AE. The AE generation behavior is associated with crack volume responsible for damage in concrete. The decrease in physical properties could be evaluated by comparing average CT value with AE generation behavior in compression test. These values are affected by the internal actual cracks. Thus, the damaged concrete in service structures could be quantitatively evaluated by AE and X-ray computed tomography method.

2 ANALYTICAL PROCEDURE

2.1 *AE rate-process analysis*

AE behavior of a concrete sample under unconfined compression is associated with the generation of micro-cracks. These micro-cracks gradually are accumulated until final fracture that severely reduces load-bearing capacity. The number of AE events, which correspond to the generation of these cracks, increases accelerated by the accumulation of micro-cracks. It appears that this process is dependent on the number of cracks at a certain stress level and the progress rate of the fracture stage, and thus could be subjected to a stochastic process. Therefore, the rate process theory is introduced to quantify AE behavior under unconfined compression (Suzuki 2002). The following equation of the rate process is formulated to represent AE occurrence dN due to the increment of stress from V to $V+dV$,

$$f(V)dV = \frac{dN}{N} \tag{1}$$

where N is the total number of AE events and $f(V)$ is the probability function of AE at stress level V(%). For $f(V)$ in Eq.1, the following hyperbolic function is assumed,

$$f(V)=\frac{a}{V}+b \qquad (2)$$

where a and b are empirical constants. Here, The value 'a' is named the rate.

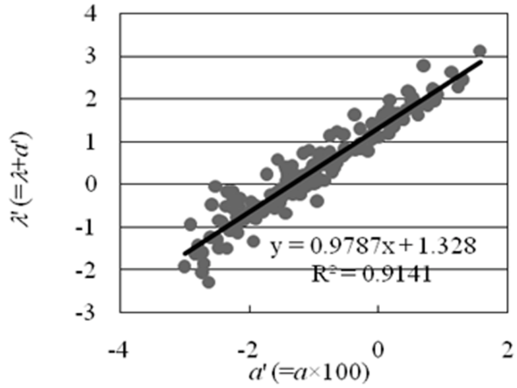

Figure 1. Relation between λ' and a'. (AE database).

In Equation1, the value of 'a' reflects AE activity at a designated stress level, such that at low stress level the probability varies, depending on whether the rate 'a' is positive or negative. In the case that the rate 'a' is positive, the probability of AE activity is high at a low stress level, indicating that the structure is damaged. In the case of the negative rate, the probability is low at a low stress level, revealing that the structure is in stable condition. Therefore, it is possible to quantitatively evaluate the damage in a concrete structure using AE under unconfined compression by the rate process analysis.

Based on Equations1 and 2, the relationship between total number of AE events N and stress level V is represented as the following equation,

$$N = CV^{a}\exp(bV) \qquad (3)$$

where C is the integration constant.

2.2 *Damage mechanics*

A damage parameter Ω in damage mechanics can be defined as a relative change in modulus of elasticity, as follows,

$$\Omega = 1-\frac{E}{E^*} \qquad (4)$$

where E is the modulus of elasticity of concrete and E^* is the modulus of elasticity of concrete which is assumed to be intact and undamaged.

Loland assumed that the relationship between damage parameter Ω and strain ε under unconfined compression is expressed (Loland, 1989),

$$\Omega = \Omega_0 + A_0\varepsilon^{\lambda} \qquad (5)$$

where Ω_0 is the initial damage at the onset of the unconfined compression test, and A_0 and λ are empirical constants of the concrete. The following equation is derived from Equations 4 and 5,

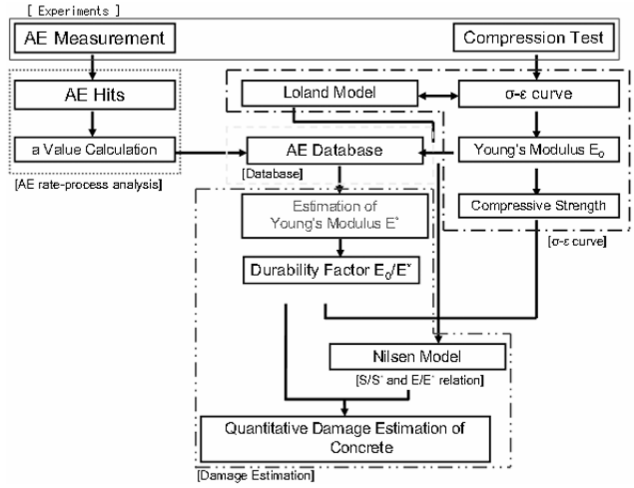

Figure 2. Calculation flow of DeCAT.

$$\sigma = (E_0 - E^* A_0\varepsilon^{\lambda})\varepsilon, \qquad (6)$$

here,

$$E_0 = E^*(1-\Omega_0), \qquad (7)$$

$$E_c = E_0 - E^* A_0 \varepsilon_c^{\ \lambda}. \qquad (8)$$

2.3 *Estimation of intact Young's modulus E* using AE database*

As given in Equation 5, the initial damage Ω_0 in damage mechanics represents an index of damage. In Loland's model (Eq.4), it is fundamental to know Young's modulus of the intact concrete (E^*). However, it is not easy to obtain E^* from an existing structure. Therefore, it is attempted to estimate E^* from AE monitoring in compression test. Two relations between total number of AE events and stress level and between stress and strain are taken into account. Based on a correlation between these two relationships, a procedure is developed to evaluate the intact modulus from AE analysis. A correlation between the damage parameter 'λ' and the rate 'a' derived from AE rate process analysis is shown in Figure 1. Good correlation between the 'λ ' and the rate 'a' 'value is confirmed. Results of all samples damaged due to the freeze-thawed process in model experiments are plotted by blue circles. A linear correlation between 'λ' and the rate 'a' value is reasonably assumed. The equation of λ' is expressed,

$$\lambda' = a'X + Y$$

$$\lambda + (a\times 100) = (a\times 100)X + Y, \qquad (9)$$

here

$$\lambda = \frac{E_c}{E_0 - E_c}. \qquad (10)$$

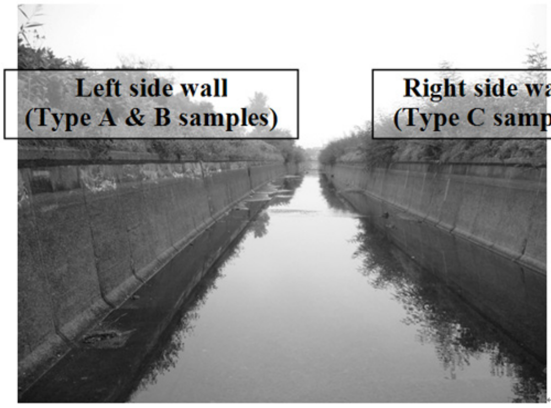

Figure 3. Overview of sampling site.

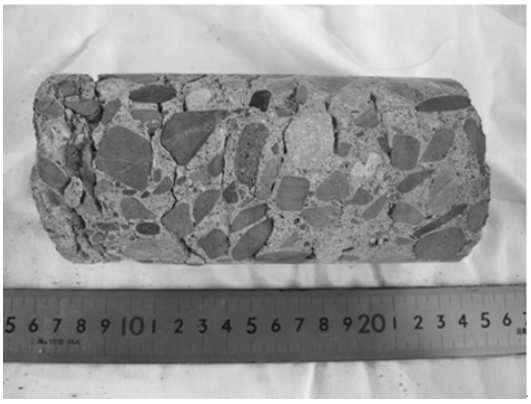
Figure 4. Type A sample (heavy freeze-thawed concrete).

Table 1. Setting used for helical CT scan.

Helical Pitch	15.0
Slice Thickness	0.5mm
Speed	7.5mm/rotation
Exposure	120kW and 300mA
Recon Matrix	512×512
Field of View	100-200mm

Here, it is assumed that $E_0 = E^*$ when a = 0.0. This allows us to estimate Young's modulus of intact concrete E^* from AE rate process analysis as,

$$E^* = E_c + \frac{E_c}{Y} \cdot \qquad (11)$$

In this study, the concrete damage is evaluated by DeCAT. The DeCAT is applicable to evaluate concrete damage based on estimation of an intact modulus of elasticity from AE database (Fig.1). AE database consists of 160 samples tested in the Kumamoto University from 1988 to 2009. Analytical process is shown in Figure 2.

3 EXPERIMENTS

3.1 *Specimens*

Cylindrical samples of 7.5cm in diameter and 15cm in height were taken from a concrete open canal walls affected by freeze and thawed process in Hokkaido prefecture, Japan (Fig.3). The core-samples were drill out from left and right side walls. This

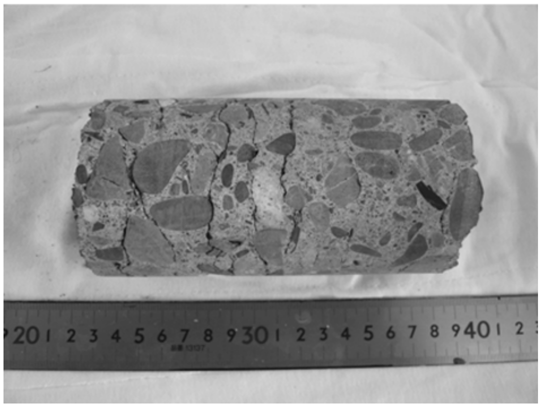
Figure 5. Type B sample (freeze-thawed concrete).


Figure 6. Type C sample (non-cracked concrete).

structure is constructed after about 40 years, which is strongly progress to crack in concrete. These cracked damages are not same degree in left and right side walls (Figs 4, 5 and 6). The left side wall is affected by freeze and thawed damage (Fig.4 (Type A), Figure 5 (Type B)), on the other hand, the right side wall is not appear to damage (Fig.6 (Type C)).

Figure 7. A general view of CT machine during concrete core scanning.

3.2 *X-ray computed tomography method*

The cracked core samples were inspected with helical CT scans at the Animal Medical Center, Nihon University. The helical CT scan was undertaken at one-millimeter intervals before the compression test. The measurement conditions are shown in Table 1. The measuring photos are shown in Figure 7. The output

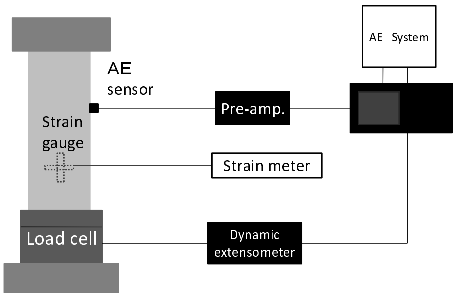

Figure 8. AE monitoring system in compression test.

Table 2. Mechanical properties of core samples.

Sample Name	Sample Number	Compressive * Strength(N/mm^2)	Vp * (m/sec)
Type A	2	4.2- 7.1	1,645-1,654
Type B	2	7.9-14.9	1,873-2,089
Type C	2	27.6-38.2	1,397-1,568

*Minimum-Maximum

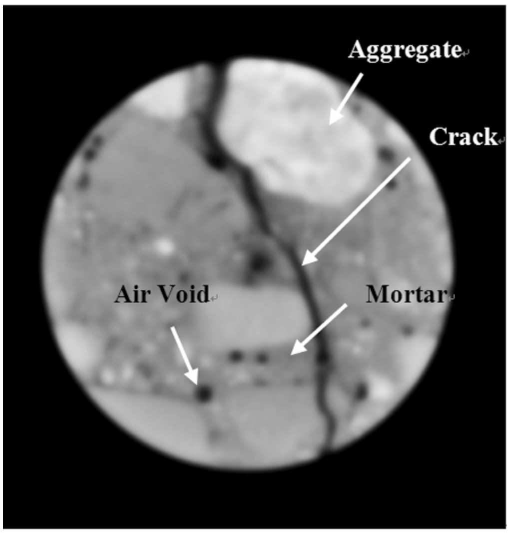

Figure 9. X-ray CT image.

images were visualized in gray scale where air appears as a dark area and the densest parts in the image appear as white. The exact positioning was ensured using a laser positioning device. Samples were scanned constantly at 0.5mm pitch overlapping. A total of 200 to 400 2D-images were obtained from each specimen depending on the specimen length. These 2D images can be assembled to provide 3D representation of core specimens.

3.3 *AE monitoring in compression test*

A uniaxial compression test of the samples was conducted as shown in Figure 8. Silicon grease was pasted on the top and the bottom of the specimen, and a Teflon sheet was inserted to reduce AE events generated by friction. SAMOS-AE system (manufactured by PAC) was employed as a measuring device. AE hits were counted by using an AE sensor UT-1000 (resonance frequency: approx. 1MHz). The frequency range was from 60kHz to 1MHz. To count the number of AE hits, the threshold level was set to 60dB with a 40dB gain in a pre-amplifier and 20dB gain in a main amplifier. For event counting, the dead time was set as 2msec. It should be noted that AE measurement was conducted with two channels as the same as the measurement of axial and lateral strains. Averaged values of the two channels were used for the analysis.

4 RESULTS AND DISCUSSION

4.1 *Mechanical properties of concrete*

Compressive strength and longitudinal wave velocity are summarized in Table 2, with the maximum, and the minimum values of all specimens. 6 samples were collected from concrete walls.

Compressive strengths drill out from the left side wall (Type A and B) are $8.5N/mm^2$ on the average, $14.9N/mm^2$ at the maximum, and $4.2N/mm^2$ at the minimum. On the other hand, the right side wall cores are $32.9N/mm^2$ on the average. The longitudinal wave velocity of concrete are 1,629m/s on the average, which is detected similar values in testing samples.

4.2 *Crack distribution of freeze-thawed concrete*

The crack distribution of the core samples were measured by the helical CT scanner (Figs.4 and 5). The CT scanning system operates on volume elements such that the collection of X-ray absorption values. The values of the absorption coefficients are transformed into CT values using the international Hounsfield scale, where the CT value in Hounsfield Units (HU) represents the mean X-ray absorption associated with each area on the CT image. The CT values vary according to the material properties, generally adjusted to 0.0 for water and to -1,000 for air.

–In this experiment, the CT values were +127 to +1,472 for pores and +2,000 over for aggregates. At cross sections of intact concrete, the average CT values were between +1,625 and +1,993. At the regions where cracks were generated, the average CT values were between -124 and +1,141, which are about 30 percent of those of a non-damaged concrete site (example of X-ray image: Fig.9).

Figure 10 shows chart of CT value in tested concrete cores. In Type A sample, the CT value was decreased in cracked portion. The average CT value was increased from “Type A” to “Type C”. The CT value of Non-damaged sample (Type C) was 1,895 on the average. On the other hand, the damaged samples were decreased average CT value, which is detected 1,743 (Type A) and 1,859 (Type B).

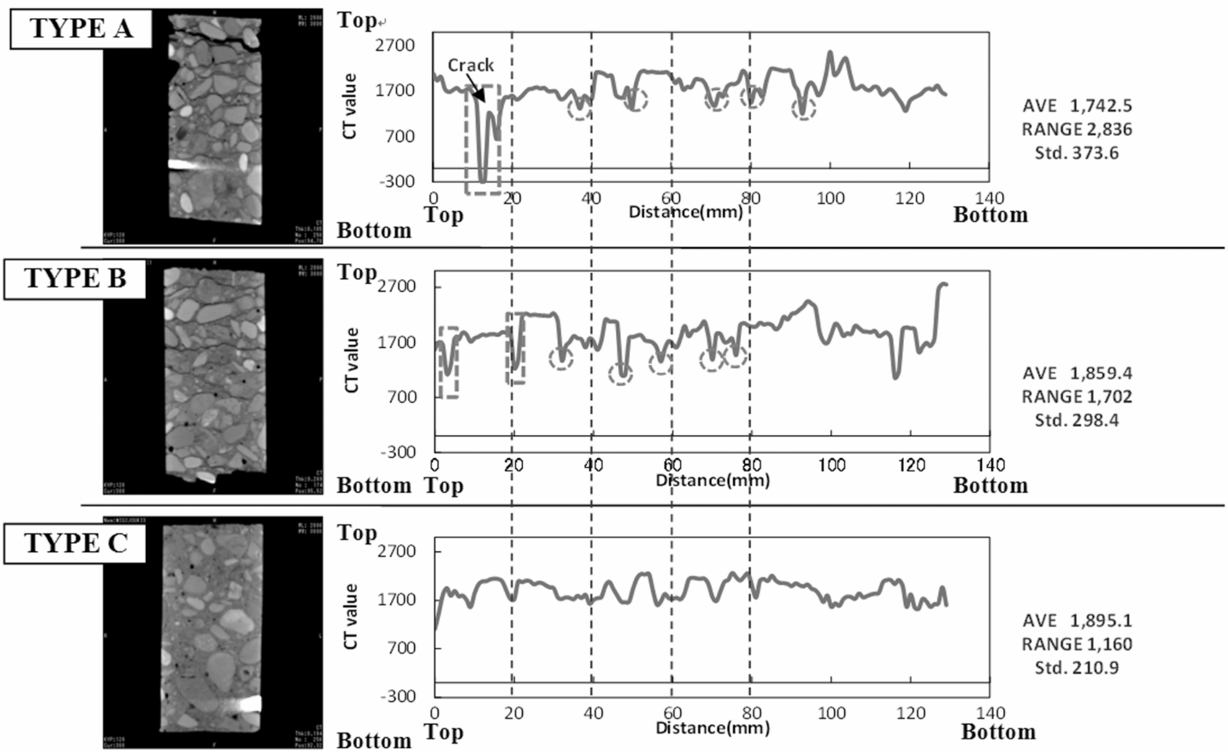

Figure 10. Results of CT values from top to bottom in core-samples.

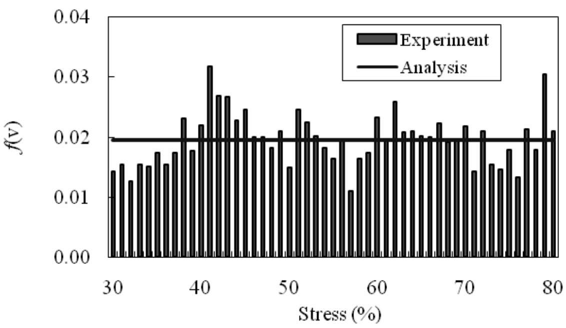

Figure 11. AE generation behaviors. (Type A; drill out from heavy damaged wall)

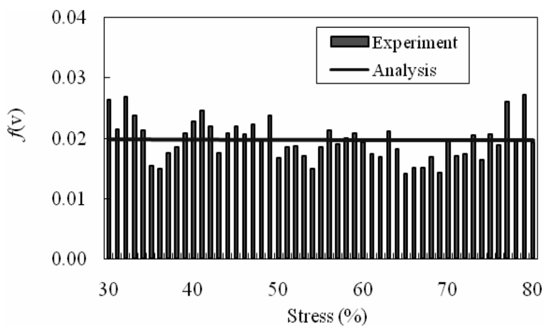

Figure 12. AE generation behaviors. (Type B; little cracked sample)

4.3 *AE generation behavior in compression test*

AE generating behavior of each specimen showed the positive 'a' value in AE rate-process analysis. Results of the probability functions are shown in Figures 11, 12 and 13.

Compared to the 'a' value ($a=-1.2\times10^{-3}$) for normal concrete with 28-day moisture curing (Ohtsu 2004).

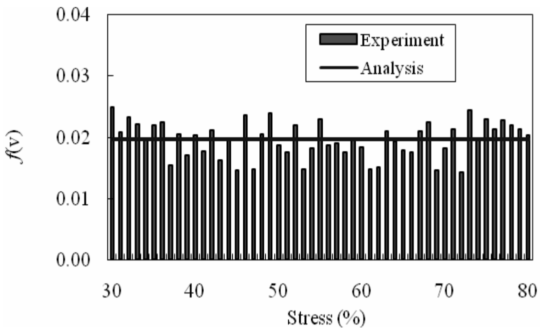

Figure 13. AE generation behaviors. (Type C; non-cracked sample)

In this study, the obtained values are $+1.0\times10^{-5}$ for the specimen with the maximum strength (Fig.13; Type C), and $+5.0\times10^{-5}$ for the specimen with the minimum strength (Fig.11; Type A). The rate '*a*' is positive; the probability of AE activity is high at a low stress level in compression test. It is indicating that the sampling structure is damaged. Therefore, this results of $f(v)$ suggests that an increasing trend of '*a*' value with the increase in damage.

4.4 *Quantitative damage evaluation based on estimation of intact modulus E**

The durability index of specimens was estimated from the ratio's of initial Young's moduli E_0 to intact E^*. The durability indexes (E_0/E^*) are compared with and compressive strengths in Figure 14. This figure also shows previous results of structural concrete-cores in addition to present studies (Suzuki 2007). Those samples were collected from other concrete structures.

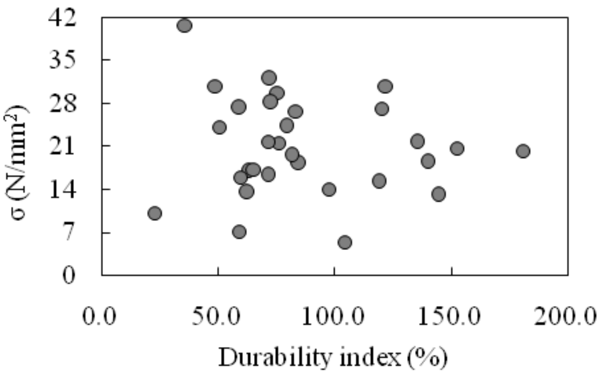

Figure 14. Relation between durability index and compressive strength.

The durability index less than 100% mean accumulation of damages. The damaged conditions are defined as relation between durability index and compressive strength. The baseline compressive strength is a 21N/mm^2, which is defined as standard design strength for concrete water canal of Japan (MAFF 2001).

In Fig.14, it is clearly observed that durability indexes estimated show a similar trend to the compressive strengths. Our recent studies, the relative moduli (E_0/E^*) was positively correlated with the compressive strength (Suzuki 2007).

The results of Type A and Type B are plotted in damaged part (Durability index < 100%, Compressive strength < 21N/mm^2), it is considered that these samples have been fairly damaged.

5 CONCLUSIONS

For quantitative evaluation of concrete damage in a water-canal structure affected by freeze and thawed process. The crack distributions in concrete-core were inspected with X-ray computed tomography method. The damage of concrete due to crack progressive conditions was evaluated by DeCAT in core tests. Thus, AE generation behavior in core test is closely associated with the damage, which can be quantitatively evaluated by DeCAT and X-ray CT images. The durability index $E_0/E^*$is evaluated reasonable agreement with the damage indicator for concrete materials.

REFERENCES

C. U. Gross, M. Ohtsu Edit. 2008. Acoustic Emission Testing, Springer, 3-10.

Japan Concrete Institute (JCI) C65. 2005. Evaluation of concrete performance in natural environmental conditions, 35-140.

Loland, K.E. 1989. Continuous damage model for load – response estimation of concrete, Cement and Concrete Research, Vol.10, 395-402.

Ministry of Agriculture, Forestry and Fisheries of Japan (MAFF) 2001. Japanese standard for design and construction of agricultural water canal structure, 302.

Ohtsu, M. and Suzuki, T. 2004. Quantitative damage evaluation of concrete core based on AE rate-process analysis, Journal of Acoustic Emission, No.22, 30-38.

Suzuki, T., Watanabe, H. and Ohtsu, M. 2002. Quantitative damage evaluation of concrete by acoustic emission, Journal of Applied Mechanics, No. 5, 809-816.

Suzuki, T., Ohtsu, M. and Shigeishi, M. 2007. Relative damage evaluation of concrete in a road bridge by AE rate-process analysis, Materials and Structures, Vol. 40, 221-227.

Suzuki,T., Ogata, H., Takada, R., Aoki M. and Ohtsu, M. 2009. Use of acoustic emission and X-ray computed tomography for damage evaluation of freeze-thawed concrete, The 5rd Kumamoto International Workshop on Fracture, Acoustic Emission and NDE in Concrete.