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Damage Estimation of Freeze - Thawed Concrete by AE Analysis in Core Test

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ABSTRACT

As a detailed inspection of concrete structures in service, core samples are usually drilled out and then mechanical properties are measured. In this study, damage estimation of concrete structures from core samples is developed, applying acoustic emission and X-ray computed tomography method. Concrete-core samples were taken from reinforced concrete of an existing canal. These samples are strongly influenced by freezing and thawing process. The crack distributions of concrete-core samples were inspected with helical CT scans. After helical CT scan, damage of testing samples was evaluated, based on fracturing behavior under unconfined compression with acoustic emission. The AE generation behavior is associated with crack volume responsible for damage in concrete. The damage is quantitatively defined by a scalar damage parameter in damage mechanics. The decrease in mechanical properties could be evaluated by comparing average CT number with AE parameters. These values are affected by the internal actual cracks.

Keywords. Freezing - Thawing Effect, X-Ray CT Method, AE, Concrete Damage

INTRODUCTION

The durability of concrete structures decreases easily due to environmental effects, such as freeze-thawed process (JCI-C65, 2005). The degree of damage in concrete is, in most cases, evaluated by mechanical tests. For effective maintenance and management of concrete structures, it is necessary to evaluate not only mechanical properties but also the degree of damage. To inspection concrete structures for maintenance, acoustic emission (AE) technique is known to be useful (C. U. Gross *et al.*, 2008). This is because crack extension in concrete is readily detected by AE. In this respect, monitoring of AE activity in the uniaxal compression test of core samples was proposed (Ohtsu, M. *et al.*, 2004). AE behavior under compression is formulated by the rate-process theory. Quantitative evaluation of damage has been performed by AE rate-process analysis and damage mechanics. The damage of concrete samples drilled out from structures were attempted to be estimated. By calculating Young's modulus of intact concrete E^* from the AE database, the degree of damage in a road bridge was successfully estimated (Suzuki, T. *et al.*, 2007a). Thus, a procedure to estimate the relative damage E_0/E^* of concrete is implemented as

DeCAT (**D**amage **E**stimation of **C**oncrete by **A**coustic Emission **T**echnique) (Suzuki, T. *et al.*, 2009; Suzuki, T. *et al.*, 2010).

In this study, damage estimation of concrete-core samples is investigated, applying AE and X-ray computed tomography methods. Testing samples were taken from reinforced concrete of an existing canal wall. These samples were strongly influenced by freeze-thawed process. The inner-crack of concrete-core 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 behavior is associated with crack volume responsible for damage in concrete. The damage accumulation of concrete could be evaluated by comparing average CT number with damage parameters. These values are affected by the actual cracks. Thus, the damage of concrete could be quantitatively evaluated by AE and X-ray computed tomography method.

ANALYTICAL PROCEDURE

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 (Yokobori, T., 1955; Suzuki, T., 2002). The following equation of the rate process is formulated to represent AE occurrence dN due to the increment of stress from V to $V+dV$,

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

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.

In **Eq.1**, 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 AE rate process analysis.

Based on **Eqs.1** 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.

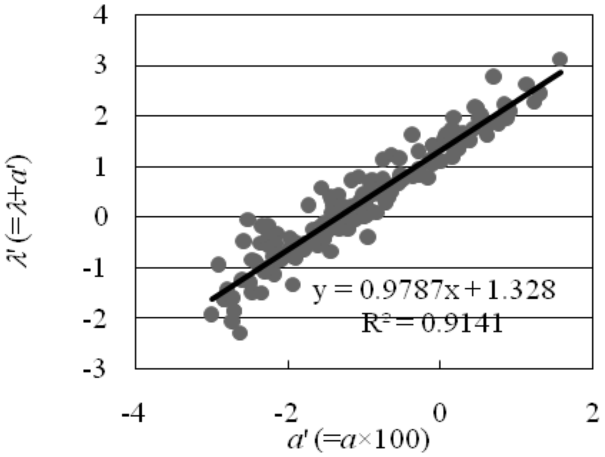


Figure 1. AE database of DeCAT system.

Scalar Damage Parameter. A scalar damage parameter Ω in damage mechanics can be defined as a relative change in modulus of elasticity, as follows,

$$\Omega = 1 - \frac{E}{E^*}, \tag{4}$$

where E is the modulus of elasticity and E^* is the modulus 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 as (Loland, K.E, 1989),

$$\Omega = \Omega_0 + A_0 \varepsilon^{\lambda}, \tag{5}$$

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 **Eqs. 4** and **5**,

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

here,

$$E_0 = E^*(1 - \Omega_0), \tag{7}$$

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

Estimation of Young's Modulus *E for Intact Concrete.** As given in **Eq.5**, the initial damage Ω_0 in damage mechanics represents an index of damage. In Loland's model (**Eq.6**), 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 **Fig.1**. Good correlation between the 'λ' ' and the rate 'a' 'value is confirmed. Results of all samples damaged due to the freeze-thawed

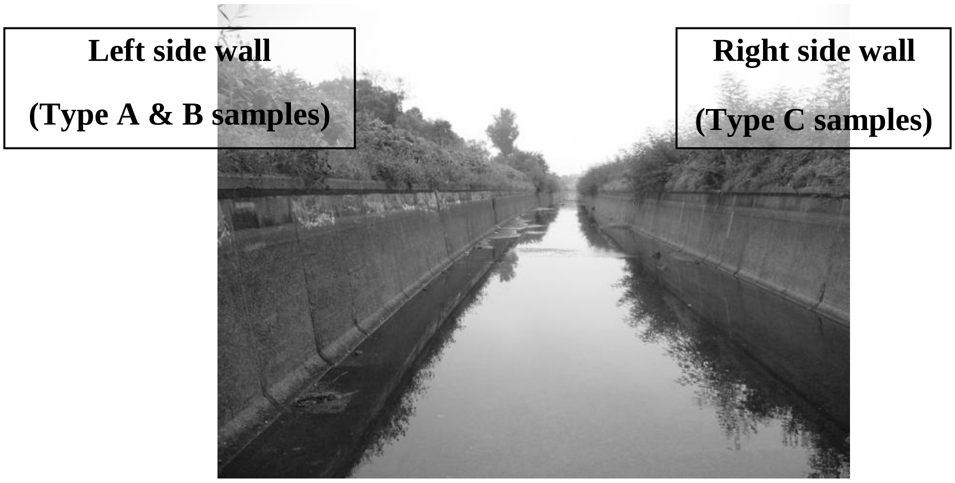


Figure 2. Overview of sampling site.

process in model experiments are plotted by gray circles. A linear correlation between 'λ'' and the rate 'a'' value is reasonably assumed. The equation of λ' is expressed,

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

$$\lambda + (a \times 100) = (a \times 100)X + Y. \tag{9}$$

here

$$\lambda = \frac{E_c}{E_0 - E_c}. \tag{10}$$

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 database as,

$$E^* = E_c + \frac{E_c}{Y}. \tag{11}$$

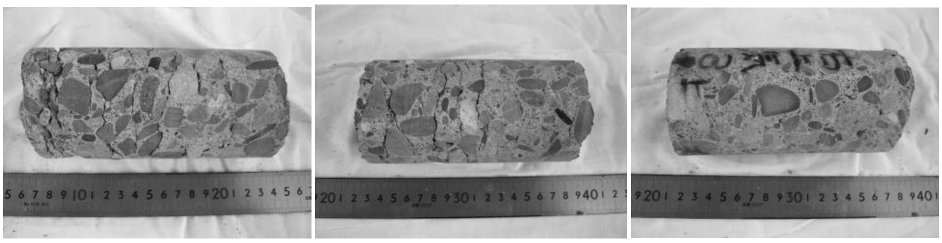
In this study, the concrete damage is evaluated by relative moduli E'. The equation of E' is expressed,

$$E' = \frac{E^*}{E_0} \times 100. \tag{12}$$

Here E_0 is the tangent modulus of elasticity in the compression test. The DeCAT is applicable to evaluate concrete damage based on estimation of an intact modulus of elasticity E^* from AE database (**Fig.1**). The AE database consists of 200 samples tested in the Kumamoto University and Niigata University from 1988 to 2012.

EXPERIMENTS

Specimens. The cylindrical samples of 5cm in diameter and about 10cm in height were taken from a concrete open canal walls affected by freeze and thawed process in Hokkaido prefecture, Japan (**Fig.2**). The core-samples were drill out from left and right side walls.



(a) Type A (b) Type B (C) Type C

Figure 3. Testing core samples.

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

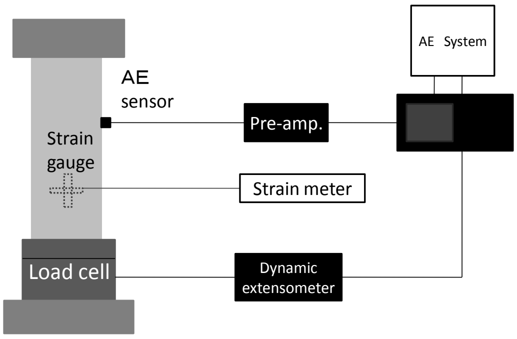


Figure 4. Test setup for AE in core test.

This structure is constructed after about 40 years, which is strongly progress to crack in concrete. This crack distribution is not same degree in left and right side walls (**Figs. 3 (a), 3 (b)** and 3 **(c)**). The left side wall is appeared to freeze and thawed damage (**Fig.3 (a)** (Type A), **Fig.3 (b)** (Type B)), on the other hand, the right side wall is not appear to inner concrete-crack (**Fig.3(c)** (Type C)).

Visualization of Concrete Crack using X-Ray CT 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 output 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.

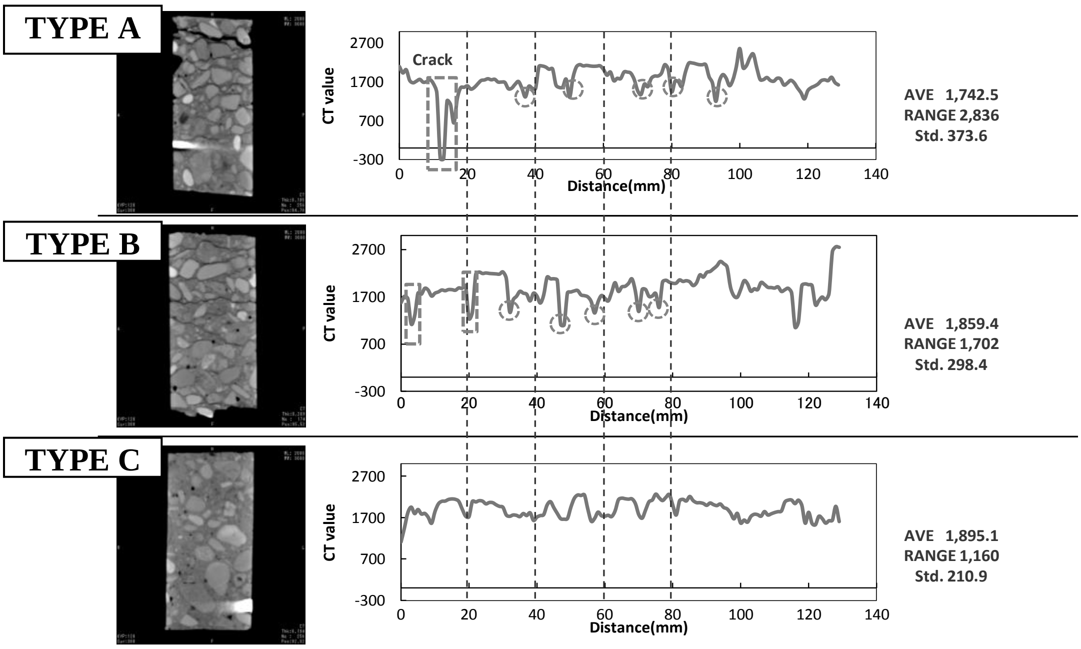


Figure 5. Results of X-ray density analysis from top to bottom in core-sample.

Table 2. Mechanical properties of core samples.

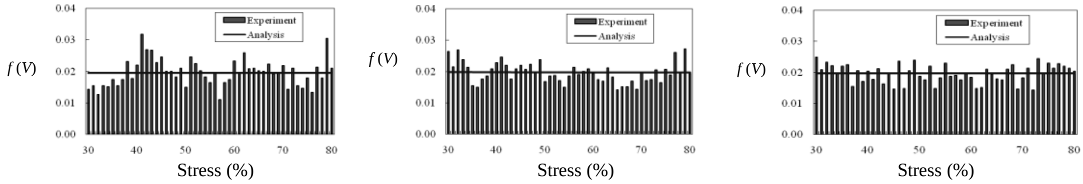
Sample Name	Sample Condition	Sample Number	Compressive * Strength(N/mm^2)	Vp * (m/sec)
Type A	Heavy cracked core	2	4.2- 7.1	1,645-1,654
Type B	Little cracked core	2	7.9-14.9	1,873-2,089
Type C	Non-cracked core	2	27.6-38.2	1,397-1,568

*Minimum-Maximum

Compression test with AE monitoring. A uniaxial compression test of the samples was conducted as shown in **Fig.4**. 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. The 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 60 kHz 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 2ms. AE measurement was conducted with two channel as the same as the measurement of axial and lateral strains.

RESULTS AND DISCUSSION

Mechanical Properties of Concrete. The concrete mechanical properties are summarized in **Table 2**, with the maximum and the minimum values of all specimens. 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, which is 3.87 times higher than the left side wall cores (Type A and B). The longitudinal wave velocity of concrete are 1,629m/s on the average, which is detected similar values in testing samples.



(a) Type A (b) Type B (C) Type C

Figure 6. AE generation behavior in compression test.

Quantification of Crack Properties by X-ray CT Data. The crack distribution of the core samples were measured by the helical CT scanner. 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 numbers using the international Hounsfield scale, where the CT number in Hounsfield Units (HU) represents the mean X-ray absorption associated with each area on the CT image. The CT numbers vary according to the material properties, generally adjusted to 0.0 for water and to -1,000 for air.

In this experiment, the CT numbers are detected +127 to +1,472 for pores and +2,000 over for aggregates. At cross sections of intact concrete, the average CT numbers are between +1,625 and +1,993. At the regions where cracks were generated, the average CT numbers are between -124 and +1,141, which are about 30 percent of a non-damaged concrete. **Fig.5** shows chart of CT number in tested concrete cores. In Type A sample, the CT number is decreased in cracked portion. The average CT number is increased from "Type A" to "Type C". The CT number of non-cracked core (Type C) is 1,895 on the average. On the other hand, the damaged cores are decreased average CT number, which is detected 1,743 (Type A) and 1,859 (Type B). These results suggest that a decreasing trend of CT number is affected by accumulation of damage. So, we try to be evaluation of concrete damage using comparison of AE activity in compression test and CT data.

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 **Figs. 6 (a)**, **6 (b)** and **6 (c)**. Compared to the value ($a = -1.2\times10^{-3}$) for normal concrete with 28-day moisture curing (Ohtsu, M. *et al.*, 2004). In this study, the obtained values are $+1.0\times10^{-5}$ for the specimen with the maximum strength (**Fig. 6 (c)**; Type C), and $+5.0\times10^{-5}$ for the specimen with the minimum strength (**Fig. 6 (a)**; 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, these results of $f(v)$ suggest that an increasing trend of 'a' value with the increase in damage.

Damage Evaluation of Concrete-Core. The relative damage of specimens was calculated from the ratio of initial Young's moduli E_0 to intact E^* (**Eq.12**). The relative damage (E_0/E^*) are compared with and compressive strengths in **Fig.7**. This figure shows previous results of structural concrete-cores in addition to present studies (Suzuki, T. *et al.*. 2007b). Those samples were collected from other concrete canal structures in service.

The relative damage index less than 100% mean accumulation of damages. The damaged conditions are defined as relation between relative damage and compressive strength. The baseline of compressive strength is a 21N/mm^2, which is defined as standard design strength for concrete water canal of Japan (MAFF, 2001). The damaged samples (Type A and B) are plotted in "Damage" portion. These samples are fall below a threshold (relative damage <

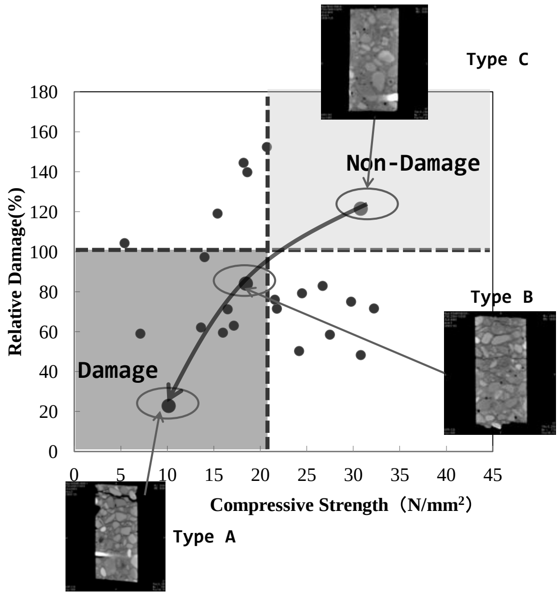


Figure 7. Comparison of relative damage and compressive strength.

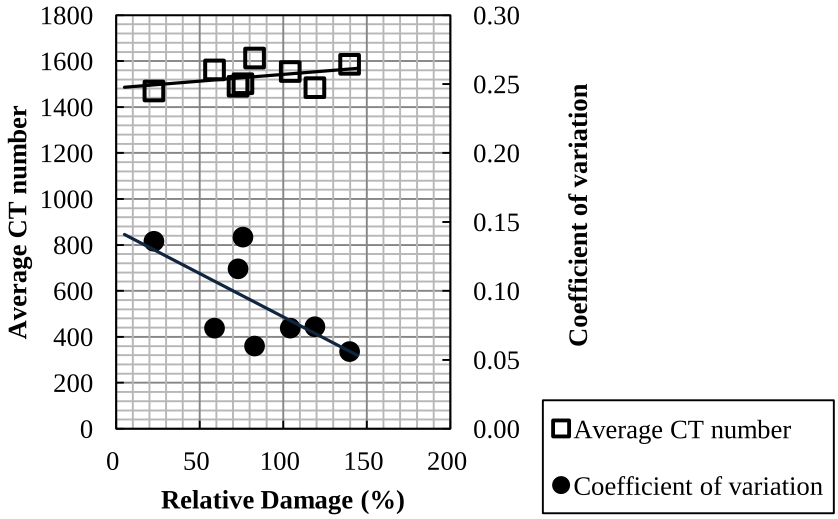


Figure 8. Comparison of relative damage and statistical properties of CT data.

100%, compressive strength < 21 N/mm^2). Our recent studies, the relative moduli (E_0/E^*) was positively correlated with the compressive strength (Suzuki, T. *et al.*, 2007a). Thus, the results of Type A and Type B are plotted in damaged portion; it is considered that these samples have been fairly damaged.

The relative damage is compared with statistical properties of CT data in **Fig. 8**. The coefficient of variations is negatively correlated with durability indexes. The coefficient of variation is calculated from the ratio of variance to average. The damaged concrete samples are appeared to be increasing trend of variance of CT numbers. Therefore, relative damage is correlated with crack distribution in core samples. A similar trend was confirmed in a current research (Suzuki, T. *et al.*, 2006).

CONCLUSIONS

For quantitative damage evaluation of concrete, AE and X-ray CT methods were applied to the experiments of core samples. The crack distributions of concrete-core were inspected with X-ray CT method. The damage of concrete due to crack progressive conditions was evaluated by DeCAT in compression tests. AE generation behavior in core test is closely associated with the damage, which can be quantitatively evaluated by relative damage calculated from DeCAT. The durability index is associated with statistical properties of CT data. Thus, the damage of concrete is quantitatively estimated as damage parameters by DeCAT.

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