
Damage Evaluation of Core Concrete by AE

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Abstract

For a detailed inspection of a concrete structure, core samples are usually drilled out and then their physical properties are measured. In this study, damage evaluation method for concrete materials is studied, applying acoustic emission (AE) method and computerized tomography (CT) scanning procedure. We have proposed a quantitative damage evaluation of concrete, based on AE measurement and damage mechanics in the compression test. The procedure is named DeCAT (Damage Estimation of Concrete by Acoustic Emission Technique), which is based on estimating an intact modulus of elasticity in concrete. Concrete-core samples were taken from reinforced concrete walls in a canal. These samples are strongly damaged by a freezing and thawing process. Crack distributions in the samples were inspected with helical CT scans, which were undertaken at one-millimetre interval. After the helical CT scan, damage of freeze-thawed samples was evaluated by applying the DeCAT analysis. These results demonstrate that the decrease in physical properties could be evaluated by comparing the averaged CT number with the durability index by AE. The both values clearly reflect amount of internal cracks in core samples.

Keywords: Acoustic emission; Rate-process analysis; Damage mechanics; DeCAT; CT number.

1. Introduction

The durability of concrete structures decreases easily due to such environmental effects, as carbonation and freeze-thawed process [1]. The degree of damage in concrete is, in most cases, evaluated by an unconfined compression test or a 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 method for concrete is proposed by applying acoustic emission (AE) method and damage mechanics [2]. The procedure is named DeCAT (Damage Estimation of Concrete by Acoustic Emission Technique) [3]. The damage is evaluated as a durability index.

In this study, damage estimation method for concrete is studied, applying DeCAT analysis and CT scans to core-concrete samples. These samples were taken from reinforced concrete walls

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in a canal, which were strongly damaged by a freeze-thawed process. Crack distribution is inspected with helical CT scans, which were undertaken at one-millimetre intervals. After helical CT scan, damages of freeze-thawed samples are evaluated, based on the CT value and the durability index by AE.

2. Analytical Procedure

2.1. AE rate-process analysis

AE behaviour of a concrete sample under unconfined compression is associated with the generation of micro-cracks. This process is dependent on the number of cracks at a certain stress level and the progress rate of the fracture stage, and could be referred to as a stochastic process. Thus, the rate process theory is introduced to quantify AE behaviour under unconfined compression [3]. The following equation of the rate process is formulated to represent AE occurrence dN due to the increment of stress from V to $V+dV$,

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

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,

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

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

2.2. Damage Estimation by scholar damage parameter

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

$$\Omega = 1 - \frac{E}{E^*}, \quad (3)$$

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 as [4],

$$\Omega = \Omega_0 + A_0 e^{\lambda \varepsilon}, \quad (4)$$

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. 3 and 4,

$$s = (E_0 - E^* A_0 e^{\lambda \varepsilon}) e, \quad (5)$$

As given in Eq. 4, the initial damage Ω_0 in damage mechanics represents an index of damage, and in Loland's model (Eq. 5) 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 the 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 coefficient ' λ ' and the rate ' a ' is shown, as results of samples damaged due to the freeze-thaw process in experiments are plotted by gray circles. A linear correlation between ' λ ' and the rate ' a ' is reasonably assumed, as follows:

$$I' = a'X + Y$$

$$I + (a \times 100) = (a \times 100)X + Y, \quad (6)$$

here

$$I = \frac{E_c}{E_0 - E_c}. \quad (7)$$

Then, 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,

$$E^* = E_c + \frac{E_c}{Y}. \quad (8)$$

This damage evaluation process is named 'DeCAT'. The DeCAT is applicable to evaluate concrete damage based on estimation of an intact modulus of elasticity from AE database shown in Fig. 1. AE database consists of 200 samples tested in the Kumamoto University and Niigata University from 1988 to 2011.

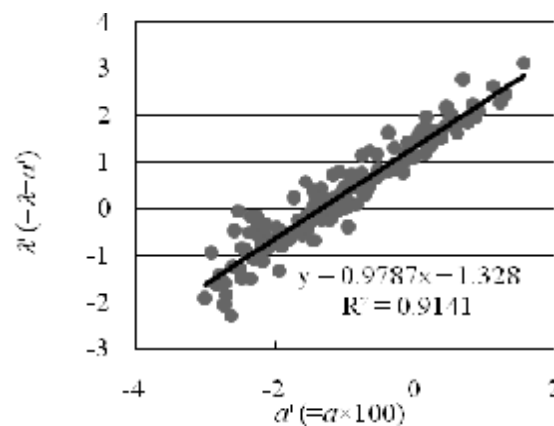


Figure 1. AE database of DeCAT system.

3. Experimental Procedure

Cylindrical concrete samples of 5cm in diameter and about 10cm in height were taken from concrete walls in an open canal wall in Hokkaido prefecture, Japan. The walls were constructed about 40 years ago, and heavily damaged by freezing and thawing cycles. Here-in-after, core samples severely cracked are named Type A. The samples with a few cracks are named Type B, and sound samples are named Type C.

These core samples were inspected with helical CT scans at the Animal Medical Center, Nihon University. The helical CT scan was undertaken with one-millimeter intervals before the compression test. After CT scan, a uniaxial compression test of the sample was conducted. SAMOS-AE system (manufactured by PAC) was employed. AE hits were detected by using an AE sensor R15 (resonance frequency: approx. 150 kHz).

4. Results and discussion

4.1. Physical properties of concrete samples

Physical properties are evaluated by mechanical parameters, X-ray CT value and the rate 'a' in AE analysis. Mechanical parameters obtained are summarized in Table 1, with the maximum, and the minimum values of all specimens.

Since these mechanical properties are affected by crack distributions, CT values were obtained by the helical CT scanner. Figure 2 shows charts of CT values in concrete cores. In Type A sample, the CT values clearly decrease at cracked portions. The averaged CT values increase from Type A to Type C. The CT value of a non-cracked sample (Type C) is 1.895 as the average, while the averaged CT values are 1.743 in Type A and 1.859 in Type B.

TABLE I. MECHANICAL PROPERTY 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

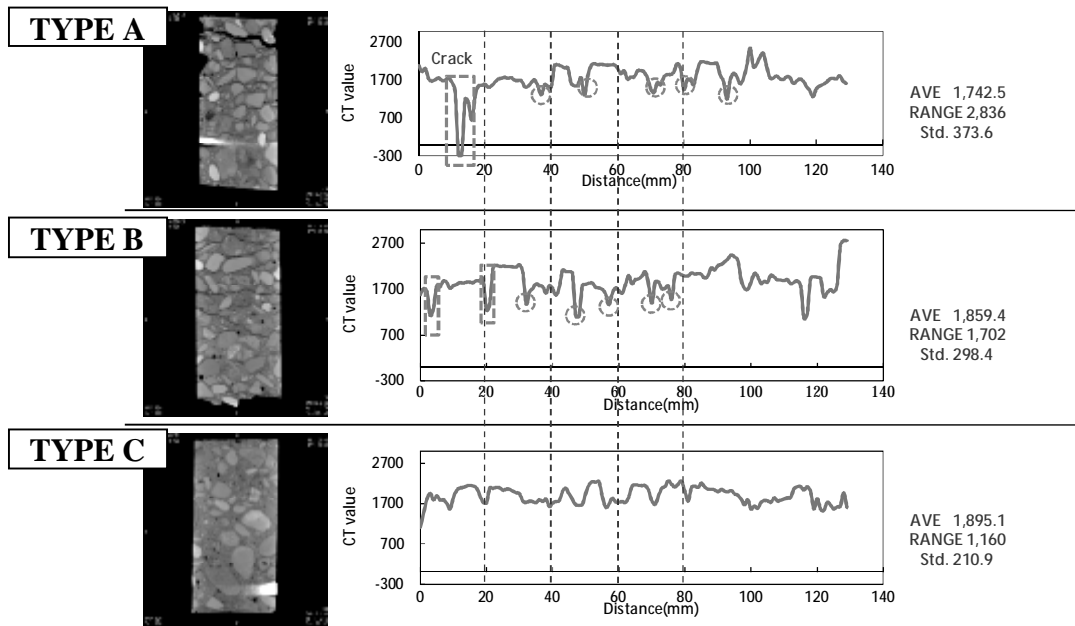


Figure 2. Results of X-ray density analysis from top to bottom in core-sample.

4.2. AE rates in compression tests

The rate process analysis of AE generating behavior shows the positive ‘a’ values in all samples, whereas the rate ‘a’ denoted ($a = -1.2 \times 10^{-3}$) for normal concrete with 28-day moisture curing [2]. The rate obtained were $+1.0 \times 10^{-5}$ for the specimen with the maximum strength (Type C), and $+5.0 \times 10^{-5}$ for the specimen with the minimum strength (Type A). The rate ‘a’ is so positive that the probability of AE activity is high at a low stress level in the compression test. This implies that the concrete walls are damaged, and that an increasing trend of the rate ‘a’ is demonstrated with the increase in damage.

4.3. Quantitative damage evaluation based on estimation of intact modulus E^*

A durability index is defined as the ratio (E_0/E^*) of the initial Young’s moduli E_0 to the intact E^* estimated by the DeCAT analysis. Results are compared with the compressive strengths in Fig. 3. Here, all previous results are plotted along with those of the present study. As seen, the durability index less than 100% means the state of heavily damage. The baseline of the strength is

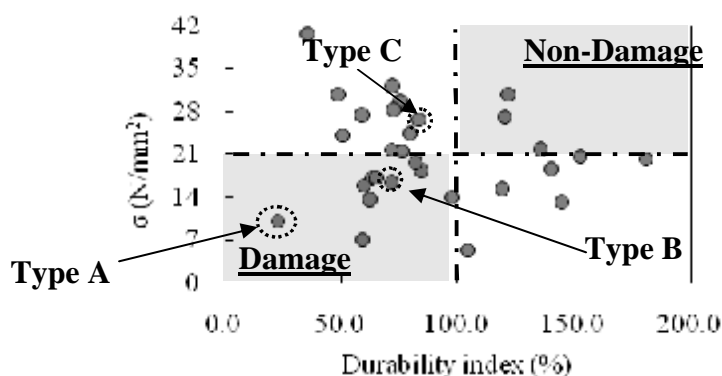


Figure 3. Comparison of durability index and compressive strength

set to 21 N/mm^2 , which is defined as the standard design-strength for concrete in water canals in Japan [5]. It is clearly observed that durability indices estimated show a reasonable relationship with the compressive strengths, as the relative moduli (E_0/E^*) are positively correlated with the compressive strengths [3]. Results of Type A and Type B are plotted in the damaged zone (Durability index $< 100\%$, Compressive strength $< 21 \text{ N/mm}^2$), and that of Type C is denoted in the non-damage zone.

5. Conclusion

For quantitative evaluation of concrete cores in a water-canal structure damaged by freezing and thawing actions, crack distributions in the core samples were inspected with X-ray CT method. The damage of concrete was evaluated by the DeCAT analysis in the compression tests. It is demonstrated that the damage can be quantitatively evaluated by the DeCAT analysis and X-ray CT values. The durability index (E_0/E^*) is evaluated in reasonable agreement with the strengths of damaged concrete.

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