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DEVELOPMENT OF DAMAGE PARAMETER FOR CONCRETE BY USING ACOUSTIC EMISSION AND X RAY COMPUTED TOMOGRAPHY

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Abstract: As a detailed inspection of a concrete structure in service, core samples are usually drilled out and then physical properties are measured. In this study, damage estimation of structural concrete from concrete-core samples is developed, applying acoustic emission (AE) and X-ray CT methods. By the authors, the quantitative damage evaluation of concrete has been proposed in RILEM TC-212ACD, by applying AE energy parameter and damage mechanics in the compression test. In this study, detection of cracking damage in concrete by detected AE energy in core test. Prior to the compression test, distribution of micro-cracks in a concrete-core sample is inspected by helical X-ray computer tomography (CT). Then, freeze-thawed samples are tested by the compression test with AE measurement. Concrete-core samples were taken out of a head works in Hokkaido, Japan which is extremely developed inner damage. Thus, it is demonstrated that the concentration of material damage could be evaluated by comparing geometrical characteristics of cracks with the “energy rate” of AE generation, which is analyzed by AE parameter analysis. A relation between AE energy rate and damage parameters is correlated, and thus the damage of concrete is qualitatively estimated.

1 INTRODUCTION

The durability of concrete structures decreases easily due to environmental effects that include the freeze-thaw process [1]. 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 mechanical propertiesbut also the degree of damage. Quantitative damage evaluation of concrete is proposed by applying the acoustic emission (AE) method and damage mechanics [2], [3]. The procedure is named DeCAT (**D**amage **E**stimation of **C**oncrete by **A**coustic Emission **T**echnique) and is based on estimating an intact modulus of elasticity in concrete [4], [5]. By the author, the concrete damage was detected using X-ray CT images, which was visualized and quantify for cracking damage. The X-ray CT index reveals that it is closely related to AE generated in the compression loading process [6], [7], [8].

In this study, a method for damage estimation of structural concrete from concrete-core samples is developed by applying AE energy parameters in core tests. Concrete-core samples were taken from reinforced concrete of a canal's head works. These samples were strongly influenced by freeze-thaw process [5]. The crack distribution in the concrete was inspected with helical CT scans. After helical CT scanning, the damage of freeze-thawed samples was evaluated based on fracturing behavior under unconfined compression with AE. The AE energy intensity is associated with the crack volume responsible for damage in concrete. The decrease in physical properties could be evaluated by comparing the geometrical characteristics of cracks with AE generation behaviour in compression tests.

2 ANALOTOCAL PROCEDURE

2.1 Quantification of crack effects in concrete using damage mechanics

Concrete damage is defined as a decrease of the effective area in a cross-section that can be detected by an X-ray CT test [9], [10]. Quantification of concrete damage is performed using X-ray CT images, which are analyzed by spatial statistics parameters with damage mechanics [7]. In this study, estimation of concrete damage is defined as high AE energy strength at a low-strain level that is affected by the development of crack systems in a concrete-core sample. Using the results of AE analytical data, concrete damage estimation is conducted by comparing the X-ray CT and AE energy parameters.

In damage mechanics, the damage parameter Ω in continuum damage mechanics is defined as a relative change in the modulus of elasticity, as follows,

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

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

Loland assumed that the relationship between damage parameter Ω and strain ε under uniaxial compression is expressed [10],

$$\Omega = \Omega_0 + A_0 \varepsilon^{\lambda} \tag{2}$$

where Ω_0 is the initial damage at the onset of the uniaxial compression test, and A_0 and λ are empirical constants of the concrete.

The following equation is derived from Eqs.1 and 2,

$$\sigma = (E_0 - E^* A_0 \varepsilon^{\lambda})\varepsilon \tag{3}$$

The damage of concrete is evaluated by damage parameter "λ". The equation for λ is

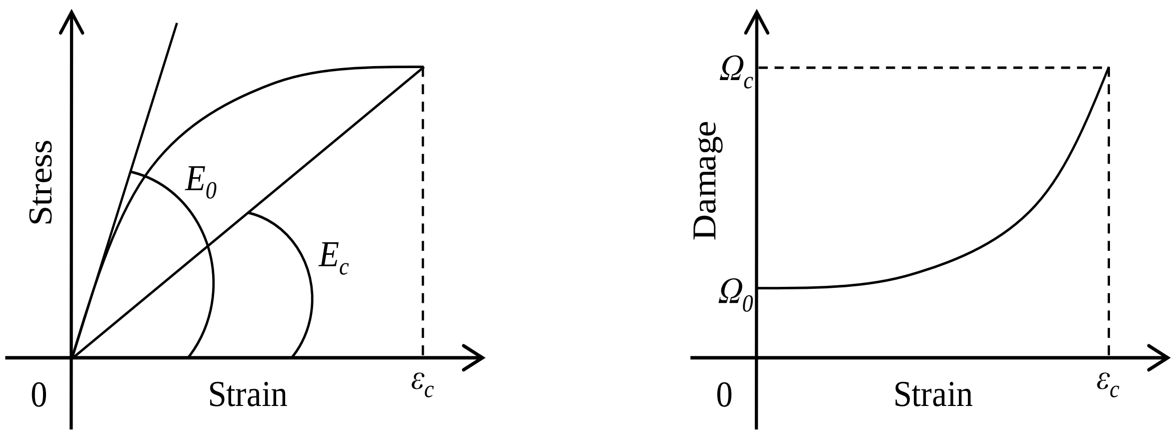


Figure 1: (a) Stress-strain relation and (b) Evolution of damage.

expressed (**Figure 1**),

$$\lambda = \frac{E_c}{E_0 - E_c} \qquad (4)$$

In this study, accumulation of mechanical concrete damage is evaluated by damage parameter 'λ', detected AE and X-ray CT image. The X-ray CT parameters are based on quantification of detected CT numbers, which are obtained in Hounsfield Units (HU) representing the mean X-ray absorption associated with each area on the CT image. The CT numbers vary according to the material properties (i.e. crack concentration) and are generally adjusted to 0.0 for water and to -1,000 for air. After X-ray CT test, the air voids and cracks in concrete are detected by binary treatment of the X-ray CT image. The detected void structure is analyzed by the void outer length (include of air void and crack damage). The crack detection accuracy is approximately 200 μm in each X-ray CT image.

2.2 Evaluation of AE energy properties in core test

The AE activity of a concrete core under compression is associated with the introduced rate process theory [11], [12]. The AE behavior of a concrete sample under compression is associated with the generation of micro-cracks. These cracks tend to gradually accumulate until final failure. Since this process could be referred to as stochastic, the following equation of the rate process is introduced to formulate the number of AE events, *dN*, due to the increment of strain from ε to $\varepsilon+d\varepsilon$,

$$f_h(\varepsilon)d\varepsilon = \frac{dN}{N} \qquad (5)$$

where *N* is the total number of AE events and $f_h(\varepsilon)$ is the probability function of AE at strain level ε %. For $f_h(\varepsilon)$ in Eq. 6, the following exponential function is assumed,

$$f_h(\varepsilon) = \alpha \cdot \exp(\beta\varepsilon) \qquad (6)$$

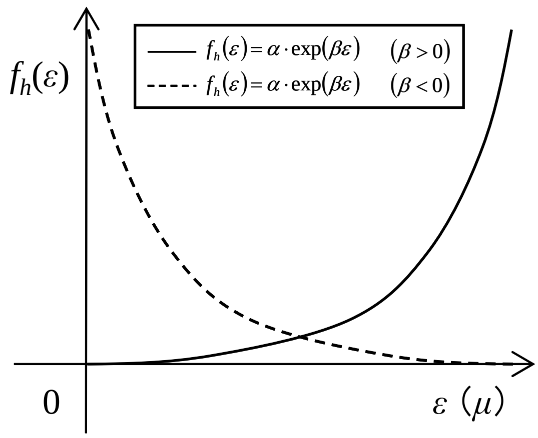


Figure 2: Two possible relations of probability function $f_h(\varepsilon)$.

where α and β are empirical constants. Here, the value β is named the rate (**Figure 2**). The probability varies in particular at a low strain level, depending on whether rate β is positive or negative (**Figure 2**) [13]. If rate β is negative, the probability of AE events is high at a low strain level. This indicates that the tested concrete may be damaged. If the rate is positive, the probability is low at a low strain level and the concrete is in stable condition. Therefore, it is possible to quantitatively evaluate the damage in concrete using AE under uniaxial compression using AE generation behavior. In this study, quantitative damage evaluation of freeze-thawed concrete are analyzed by comparison of the AE and X-ray CT parameters.

These results are compared to the concrete's physical properties (e.g. Dynamic Young's Modulus, E_d) and AE energy parameters (Eq. 8).

$$E_{AE} = a^2 \qquad (7)$$

where E_{AE} is detected AE energy (V^2) and '*a*' is maximum amplitude of detected AE wave (V). In evaluation of detected AE energy in core tests using the rate process theory, the following equation is introduced to formulate the AE energy, dE_{AE}, due to the increment of strain from ε to $\varepsilon+d\varepsilon$,

$$f_e(\varepsilon)d\varepsilon = \frac{dE_{AE}}{E_{AE}} \qquad (8)$$

where E_{AE} is the total number of AE energy and $f_e(\varepsilon)$ is the probability function of AE energy at strain level ε %.

3 EXPERIMENTAL PROCEDURE

3.1 Specimens

Two kinds of concrete samples were set, (a) Non-damaged concrete and (b) Freeze-thawed Concrete. Non-damaged concrete was casting in laboratory. The compressive strength was determined as the average value of three cylindrical samples of 100 mm diameter and 200 mm height after 28-day saturated curing.

In Freeze-thawed concrete, cylindrical samples of 10 cm in diameter and about 20 cm in height were taken from the damaged canal structures (head work) which is constructed after about 56 years (Construction: 1963, **Figure 3**) in Hokkaido, Japan. The experiments were set to 13 samples, which was compared in terms of their mechanical properties, X-ray CT parameter and AE.

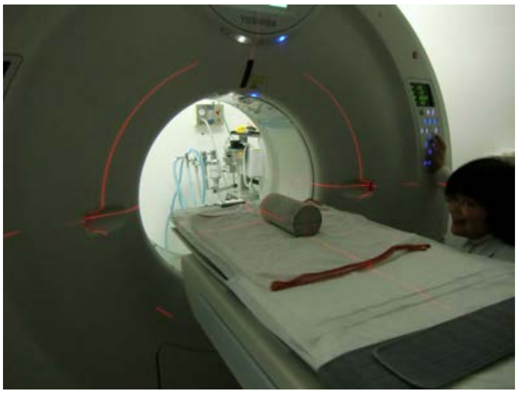
3.2 X-ray CT monitoring

The core samples were inspected with helical CT scans Aquilion ONE (TSX-301C/6A) (manufactured by TOSHIBA) at the Animal Medical Center, Nihon University. The helical CT scan was undertaken at one-millimeter intervals before the AE monitoring in compression test. 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 (**Figure 4(a)**). Detected X-ray CT images were scanned constantly at 0.5 mm pitch overlapping. A total of 200 to 400 2D-images were obtained from each specimen depending on the specimen length (**Figure 4(b)**). These 2D images can be assembled to provide a 3D representation of core specimens.

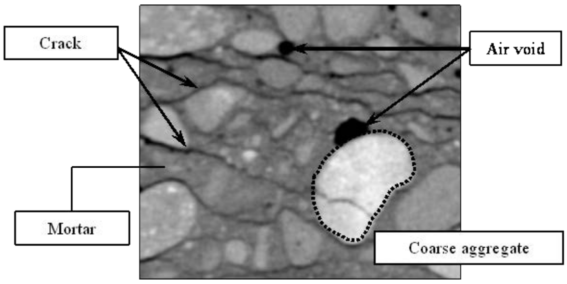
3.3 Ultrasonic test

After X-ray CT measurement, an ultrasonic test and a compression test were performed, measuring the primary wave (P-wave) velocity, AE energy activities and stress-strain relation. The P-wave velocity was

Figure 3: Overview of sampling structure (Location: Hokkaido, Japan, Head works in Ishikari river).



(a) A general view of CT machine.



(b) X-ray CT characteristics

Figure 4: (a) X-ray CT characteristics and (b) A general view of CT machine.

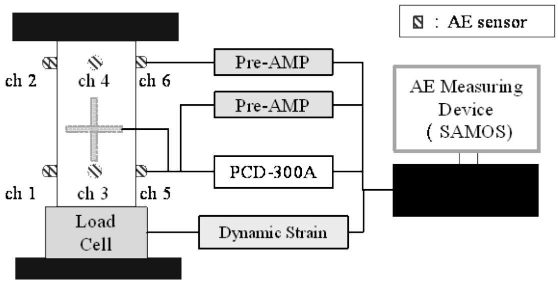


Figure 5: Test set up for AE monitoring in core test.

measured by using a UT device (Pundit Lab system manufactured by PROCEQ). A through-transmission technique was applied to measure the transit time (time-of- flight). The input wave frequency was set to 54 kHz. Elastic waves are generated and propagate in concrete due to either a dynamic force (UT) or generation of cracking (AE). In an isotropic elastic body, P-wave propagation with the velocity V_p,

$$V_p = \sqrt{\frac{E_d(1-\nu)}{\rho(1-2\nu)(1+\nu)}} \tag{9}$$

where E_d is the dynamic modulus of elasticity, ν is Poisson's ratio and ρ is the density of concrete. If the dynamic modulus of elasticity, E_d, is determined from Eq. 9,

$$E_d = \rho V_p^2 \left(\frac{(1-2\nu)(1+\nu)}{1-\nu} \right) \tag{10}$$

In our recent studies, the decrease trend of calculated E_d was correlated with inner damage [13], [14], [15]. The dynamic Young's modulus is most useful parameter for damage evaluation of concrete.

3.4 Compression test with AE

After the ultrasonic test and X-ray CT measurement, a compression test was performed, measuring AE activities and the stress-strain relation. AE monitoring was conducted by employing AE sensors of 150 kHz resonance (R15α, PAC) attached to 6 parts of the specimen (**Figure 5**). Amplification was 60 dB gains in total. The frequency range was set from 60 kHz to 1 MHz. AE hits were detected at threshold level 42 dB by an AE system (SAMOS-AE, PAC). Strain monitoring was conducted by DICM in the core tests.

4 RESULTS AND DISCUSSION

4.1 Mechanical properties of core concrete

The mechanical properties of the tested samples are shown in **Table 1**, with the detected and calculated values provided for all specimens. As seen in the table, the

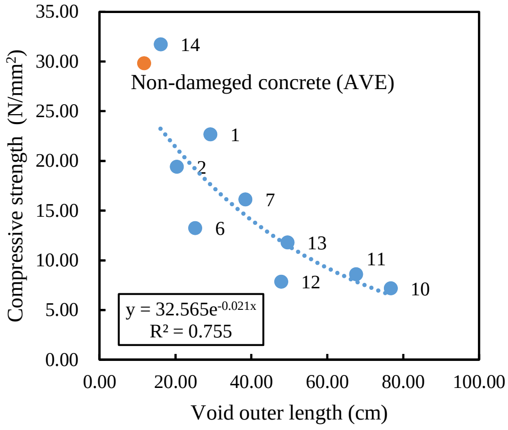


Figure 6: Comparison of compressive strength and void outer length.

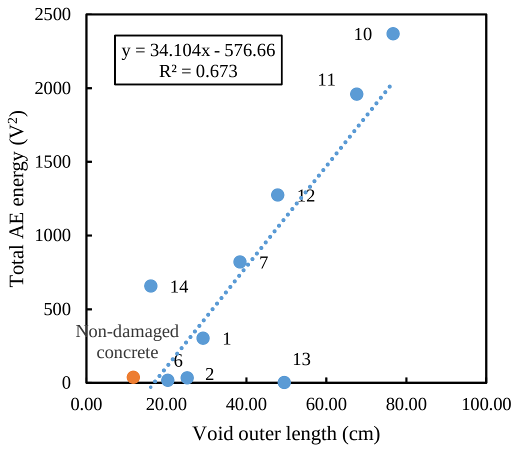


Figure 7: Comparison of total AE energy in core test under 100 μ strain and void outer length.

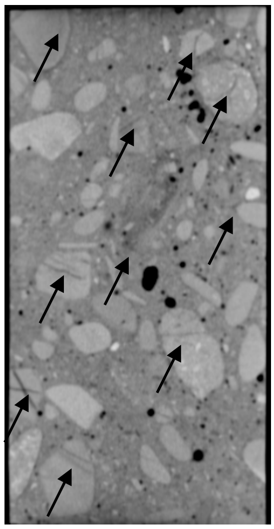


Figure 8: X-ray CT image of Freeze-thawed Concrete (No. 14, Max strength sample, →: Damage) .

Table 1: Mechanical properties of testing concrete.

Sample	No.	Compressive strength (MPa)	Max strain (μ)	V_p (m/s)	E_d (GPa)
Freeze-thawed Concrete	01	22.66	1,160	3,892	31.74
	02	19.42	790	4,051	34.63
	03	6.53	235	3,770	29.89
	04	12.91	177	3,783	30.03
	05	14.16	-	3,892	31.26
	06	13.24	315	4,311	39.21
	07	16.12	485	3,938	31.35
	08	15.44	60	4,008	34.38
	09	23.14	645	4,011	32.69
	10	7.18	435	3,884	31.00
	11	8.61	415	3,972	32.78
	12	7.86	440	4,142	35.22
	13	11.80	865	4,118	35.58
	14	31.74	1,530	3,926	31.75
Non-damaged concrete	3-1	-	-	4,056	35.46
	3-2	34.39	1750	4,115	36.48
	3-3	29.83	1,430	4,098	36.58
	3-4	38.01	1860	4,123	36.79
	3-5	21.00	795	4,166	36.94

Table 2: Air void and crack properties of testing concrete using X-ray CT images.

Sample	No.	Porosity (%)	Void outer length (cm)	Aspect ratio
Freeze-thawed Concrete	01	0.93	29.17	2.31
	02	0.88	20.34	1.44
	03	1.05	28.43	1.68
	04	1.37	25.49	3.13
	06	0.80	25.18	2.26
	07	1.86	38.39	1.78
	08	1.14	31.39	1.56
	09	2.89	92.91	1.60
	10	2.03	76.67	1.54
	11	2.25	67.60	1.51
	12	1.30	47.82	1.69
	13	1.31	49.47	1.64
	14	0.95	16.07	1.45
Non-damaged concrete	3-1	0.26	10.63	0.96
	3-2	0.40	13.75	0.97
	3-3	0.42	11.71	0.94
	3-4	0.72	22.40	0.58
	3-5	0.44	16.06	0.53

compressive strength of the freeze-thawed concrete varies from 6.53 to 31.74 MPa, while in the non-damaged concrete, it varies from 21.00 to 38.01 MPa (average: 30.81 MPa). The freeze-thawed concrete samples are strongly influenced by cracking effects. The damage parameter E_d average to 36.45 GPa in non-damaged concrete. In the freeze-thawed concrete, a little decrease trend of average E_d is detected (average: 32.97 GPa, max: 39.21 GPa, min: 29.89 GPa). Thus, decrease in the mechanical properties is observed in the testing of freeze-thawed concrete samples.

4.2 Visualization and Evaluation of damage using X-ray CT parameter

The air void and crack properties of the tested concrete are estimated from the X-ray CT data given in **Table 2**. In non-damaged concrete, porosity is 0.45 % as an average. On the other hand, in the freeze-thawed concrete, porosity is detected to have an increasing trend that varies from 0.80 to 2.89 %. This detected data indicates that the tested freeze-thawed concrete may be damaged. This parameter is one of the evaluation indices of void total amount, which is calculated from X-ray CT images with binary treatment. A similar trend is confirmed in other void parameter values in **Table 2**.

4.3 AE energy characteristics in core test

The relations between compressive strength and void parameter are shown in **Figure 6**. The mechanical properties can be clearly correlated with void outer length (R^2=0.755). Our recent studies, the concentration of crack damage in concrete was positively correlated with decrease trend of CT value [6]. Thus, the results of the freeze and thawed samples are plotted in high void parameter value, it is considered that testing samples have been fairly damaged. In **Figure 7**, the accumulation of crack damage in testing samples is positively correlated with increase trend of void outer length and AE energy index. The total AE energy parameter and void parameter are compared, which is positively correlated (R^2=0.673).

Therefore, in a damaged condition, the AE energy is highly released at a low strain level, which is evidence of damage accumulation of in-service structure. The maximum strength No. 14 sample was detected cracking damage using X-ray CT image (see **Figure 8**).

5 CNCLUSION

For quantitative estimation of damage in concrete using AE energy parameter, AE monitoring is applied to uniaxial compression testing of concrete samples. In this study, AE energy analysis is applied to damage estimation of concrete-core samples taken from a concrete head works in canal structure, which is affected by the freeze-thaw process. It is quantitatively demonstrated that tested concrete is damaged. In addition, the spatial distribution of cracking damage in core samples is readily determined by applying the X-ray CT test. Reasonable agreement with the spatial distribution of cracks in concrete is confirmed by the results of AE energy generation behavior in core tests.

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