Quantitative Damage Estimation of Concrete Core based on AE Rate Process Analysis

Masayasu Ohtsu, Kumamoto University, Kumamoto 860-8555, Japan
Tetsuya Suzuki, Nippon Suiko Consultants Co., Kumamoto 862-0936, Japan

ABSTRACT

Damage of concrete is quantitatively estimated by applying acoustic emission (AE) measurement and damage mechanics. Concrete samples of controlled damage due to accelerated carbonation are examined to confirm an applicability of damage estimation in the uniaxial compression test. AE activities under compression is analyzed, on the basis of the rate process theory. Using Loland's model in damage mechanics, a relationship between stress and strain is modeled. The database on a correlation between AE rate and the damage parameter is updated, and relative damages of concrete samples are quantified. Results are in remarkable agreement with actual damages of controlled samples. Applying the database, relative damages of core samples taken from a buried pipeline are estimated.

1. INTRODUCTION

As widely recognized, concrete structures are no longer maintenance-free. Diagnostic inspections of the structures in service are in great demand. For detailed inspections, core samples are often drilled out and then both chemical and physical properties are examined. Concerning mechanical properties, the compressive strength and the modulus of elasticity (Young's modulus) are normally determined by conducting a uniaxial compression test. The strengths are compared, if possible, with those of the specification. Otherwise, there is no qualified procedure to estimate the deterioration of concrete. Consequently, it is desirable to estimate the damage of concrete quantitatively, not relying only on the strength.

To inspect existing concrete structures, acoustic emission (AE) techniques deserve to draw an attention. This is because crack nucleation and extension are readily detected and monitored. AE techniques have been investigated in concrete engineering for more than four decades[1)]. Achievements of AE research are going to be applied to practical use[2),3)] and are standardized as a code[4)]. A feasibility of this standard has been experimentally confirmed by testing reinforced concrete beams damaged under cyclic loading[5)].

As another application, measurement of AE activity in a uniaxial compression test was proposed[6)]. To model AE generating behavior under compression, the rate process theory was introduced. It is demonstrated that AE rate estimated is closely associated with the presence of microcracks in concrete[7)].

In the present study, AE measurement is conducted in the uniaxial compression test. Concrete samples chemically damaged were prepared by an accelerated carbonation test. AE activity under compression is analyzed as the rate process, and the damage parameter is evaluated by using Loland's model in damage mechanics. Correlating AE rate with the damage parameter, a database is updated, which has been constructed as applicable to a limited number of core samples taken from existing structures[8)]. Relative damages of cores taken from an existing aqueduct of concrete are estimated.

2. AE ANALYSIS AND DAMAGE MECHANICS

2.1 AE Rate Process Analysis

AE behavior of a concrete sample under uniaxial compression is associated with the generation of microcracks. These cracks tend to be gradually accumulated until final failure.

The number of AE events, which correspond to nucleation of these cracks, increases acceleratedly in accordance with the accumulation of microcracks. Since this process could be referred to as stochastic, the rate process theory was introduced[7)].

The following equation of the rate process is derived to formulate the number of AE events, dN, due to the increment of stress from V to V+ d V,

$$dN/N = f(V)\,dV, \qquad (1)$$

where N is the total number of AE events and $f(V)$ is the probability function of AE at stress level V(%). Then, a hyperbolic function $f(V)$ is introduced,

$$f(V) = a/V + b, \qquad (2)$$

where a and b are empirical constants. Here-in-after, the value 'a' is called the rate, and reflects AE activity at a designated stress level. The probability varies, in particular, at low stress level, 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. This implies that concrete could be damaged. If the rate is negative, the probability is low at a low stress level, and then concrete is referred to as sound.

Substituting Eq. 2 into Eq.1, a relationship between total number of AE events N and stress level V is obtained as,

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

Where C is the integration constant.

2.2 Loland's model

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

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

where E is the modulus of elasticity and E^{*} is the modulus of the concrete which is assumed to be intact and undamaged. Loland[9)] assumed that a relationship between damage parameter Ω and strain ε under compression is represented,

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

where Ω_0 is the initial damage at the onset of compression test, and A_0 and λ are empirical constants. From Eqs. 4 and 5, the following equation is derived,

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

and

$$E_0 = E^{*}(1-\Omega_0). \qquad (7)$$

2.3 Damage Estimation

To estimate the initial damage Ω_0 in Eq. 7, it is essential to obtain Young's modulus of intact concrete E^{*}. Yet, it is not feasible to determine E^{*} of concrete in an existing structure. To estimate E^{*} from AE measurement, the relation between total number of AE events and stress level in Eq. 3 is correlated with Loland's model.

In the uniaxial compression test, a relation between stress and strain is obtained as shown in Fig. 1(a). Young's modulus varies from initial E_0 to final Ec. The former is a tangential modulus and the latter is a secant modulus. Corresponding to the stress-strain relation, the damage Ω increases from Ω_0 to Ωc as shown in Fig. 1(b).

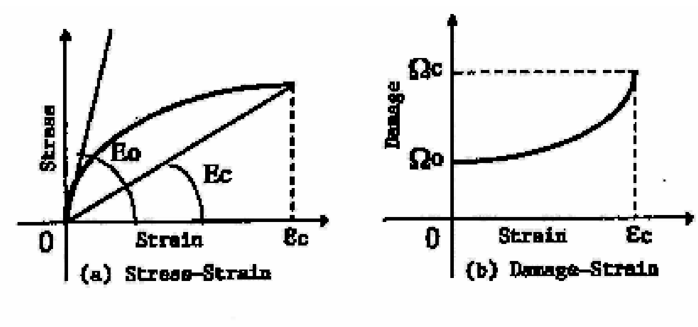

Fig. 1 (a) Young's moduli E_0 and Ec and (b) damage evolution.

In the previous study[10)], it is found that a correlation between the increase in the damage (Ωc-Ω_0) and the rate '*a*' is the highest. According to Loland's model, the increase in the damage corresponds to the decrease in Young's modulus (E_0-Ec), as follows;

$$E_0 - E_c = E^*(1-\Omega_0) - E^*(1-\Omega_c) = E^*(\Omega_c - \Omega_0). \qquad (8)$$

Thus, a linear correlation between $\log_e(E_0-E\mathrm{c})$ and the rate '*a* ' value is proposed as,

$$\log_e(E_0 - E_c) = \log_e[E^*(\Omega_c - \Omega_0)] = \mathrm{D}a + c. \qquad (9)$$

Then, it is assumed that $E_0 = E^*$ when $a = 0$. This allows us to estimate Young's modulus of intact concrete E^* from,

$$E^* = E\mathrm{c} + \exp(c). \qquad (10)$$

3. EXPERIMET

3.1 Accelerated Carbonation Test

Cylindrical samples of 10 cm in diameter and 20cm in height were made. Concerning mixture proportion, 1 m^3 concrete consist of 182 kg water, 331 kg cement, 746 kg sand and 1204 kg gravel, as the water-to-cement ratio = 55%. The maximum size of gravel is 20 mm. At the state of fresh concrete, the slum value was 7.9 cm and air content adjusted by admixture was 6.3 %. The compressive strength of concrete was 39.4 MPa after 28-day moisture cure.

After cured in the standard condition, cylindrical samples were stored in a reservoir and acceleratedly deteriorated by supplying 10% CO_2 gas continuously. Three samples of controlled damage were prepared after 2 weeks, 4 weeks and 6 weeks.

3.2 Core Samples

Cylindrical samples of 5cm in diameter and 10cm in height were taken from a thrust block of an agricultural aqueduct (buried pipeline) in Kasanohara district, Kagoshima prefecture, Japan. This pipeline was constructed in 1967 and repaired in 1979. The degree of carbonation was measured by spraying 1% phenolphthalein solution to the samples from concrete constructed in 1967. Heavy carbonation was observed in these cores. The concrete pipeline had been buried at the depth of 3 meters in Ando soil originated from Sakurajima Island. Table 1 shows soil properties. They imply that sulfate was detected and acid environment was minor as pH = 6.7.

Table 1 Soil properties

Soil	Texture	Particle Density (g/cm^3)	pH (H_2O_2)	Sulfate	Water Content (%)
Ando soil	LiC	2.424	6.7	Detected	84

3.3 Uniaxial Compression Test

All cylindrical samples were tested. A set-up for the uniaxial compression test is shown in Fig.2. Silicon grease was pasted on the top and the bottom of the sample, and a teflon sheet was inserted to reduce AE events generated by friction. MISTRAS-AE system (PAC) was employed as AE measuring device. AE sensor was of wide-band type (UT-1000; resonance frequency: approx. 1 MHz). The frequency range was from 60 kHz to 1 MHz. To count the number of AE hits, the threshold level was set to 45 dB with a 40 dB gain in a pre-amplifier and 20 dB gain in a main amplifier. For event counting, the dead time was set at 2 msec. It should be noted that AE measurement was conducted with two channels as well as the measurement of axial and lateral strains. Then, averaged values of two-channel measurement were analyzed.

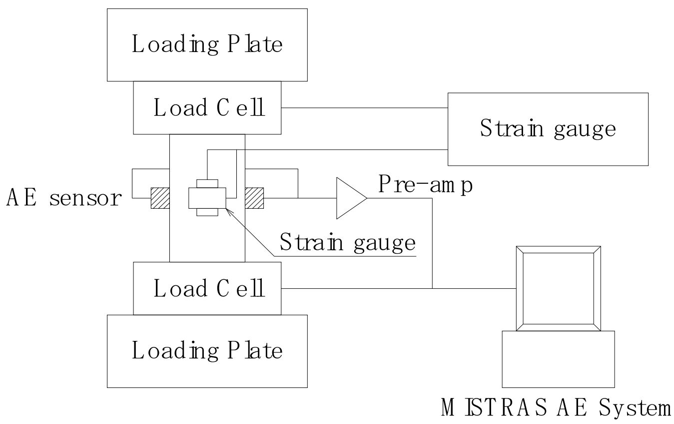

Fig. 2 Test set-up for the uniaxial compression test.

4. RESULTS AND DISCUSSION

4.1 Young's Modulus

A stress-strain curve measured was first analyzed by Loland's model. To determine the initial damages Ω_0 in Eq. 7, averaged Young's moduli E_0 of three sample right after 28-day moisture cure was referred to as E^* in the compression test. Here, Young's modulus E_0 was quantitatively determined as a tangential gradient of the stress-strain curve, which is approximated as a hyperbolic function as,

$$\sigma = a_1\varepsilon + a_2\varepsilon^2 . \qquad (11)$$

Here, a_1 and a_2 are empirical constants. From the stress-strain relation in Eq.11, Young's modulus E_0 is derived as a tangential modulus : $d\sigma/d\varepsilon$ at $\varepsilon = 0$,

$$a_1 = E_0$$

As indicated in Fig. 1(a), two moduli of elasticity, E_0 and Ec, were determined from the test. The rate process analysis was conducted at stress level in the range from 30% to 80%. This is because AE events occurring at initial loading below 30% strength due to contact with the loading plate and at an accelerated stage above 80% have little to do with the damage.

Concerning core samples, Young's moduli E_0 and E_c were also determined. Table 2 shows mechanical properties of all the samples. Carbonation ratio was estimated as the ratio of carbonation depth to total depth. $f'c$ is the compressive strength, and E_D is dynamic Young's modulus. As seen in the table, initial Young's modulus E_0 varies from 8.7 to 34.0 GPa, while the unconfined compression strength varies from 8.0 to 20.4 MPa.

Table 2 Mechanical properties

No.	Construction	Carbonation ratio (%)	$f'c$ (MPa)	E_0 (GPa)	E_c (GPa)	E_D (GPa)
1	1979	13.4	20.4	26.2	18.2	29.8
2	1979	4.7	19.0	34.0	13.1	36.7
3	1979	6.8	9.9	22.9	11.9	34.0
4	1979	62.9	8.0	10.4	4.4	21.7
5	1967	100.0	18.0	19.9	10.0	24.7
6	1967	100.0	13.8	18.4	7.8	26.7
7	1967	16.3	15.7	18.6	8.2	25.6
8	1967	100.0	9.7	18.4	12.2	16.6
9	1967	100.0	8.7	8.7	4.2	15.0
10	1967	100.0	9.6	16.1	6.8	22.1

$f'c$: Compressive strength, E_D: Dynamic Young's modulus

4.2 Estimation of Relative Damage

In data analysis, Young's modulus of intact concrete E^* was estimated by Eq. 10. Then, relative damage of concrete was determined as the ratios E_0/E^*, which is the ratio of the tangential Young's modulus to intact Young's modulus estimated.

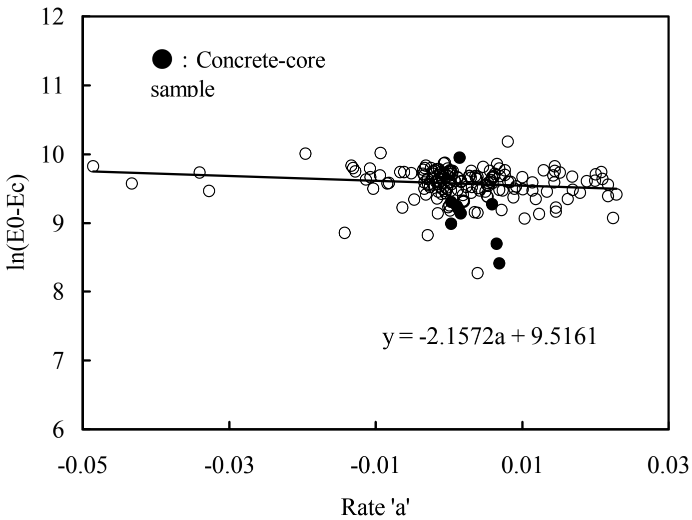

Fig. 3 Relations between $\log_e(E_0\text{-}Ec)$ and the ratio '*a*'

To determine E^* from the relationship in Eq. 9, a large number of data are desirable. However, the number of concrete cores available is limited in existing structures. Therefore a database, which could allow even a single concrete core to be evaluated, is constructed as shown in Fig. 3. The samples enrolled in a database in the figure are all tested in the previous research, in which the data of the present tests are included. In total, 343 points are plotted. By using this database, Young's modulus of the normal concrete E^* and then the relative damage of specimens, E_0/E^* were calculated.

Damages due to carbonation were estimated as the ratio of tangential Young's modulus after carbonation periods, *En weeks*, to that of 28-day cure, E_0. Then, these were compared with E_0/E^*. Results are given in Fig 4. A remarkable agreement is observed. These results confirm that the relative damage could be estimated quantitatively by AE rate process analysis.

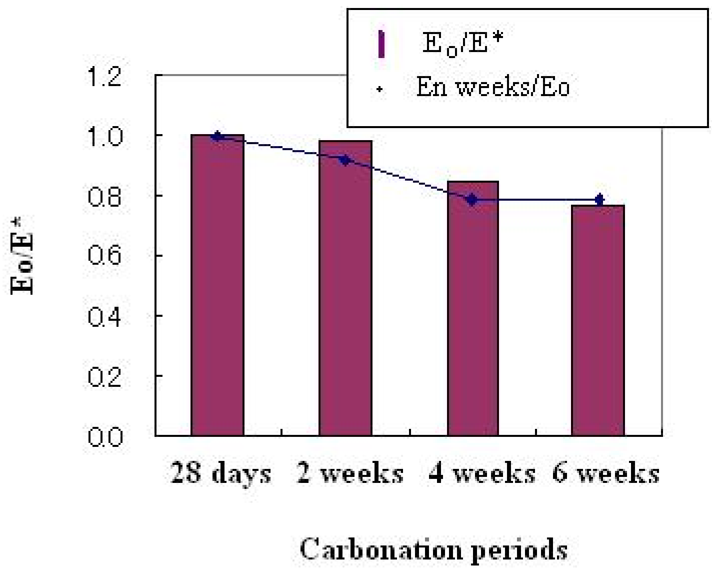

Fig. 4 Relative damages estimaded Eo/E* and actual damages.

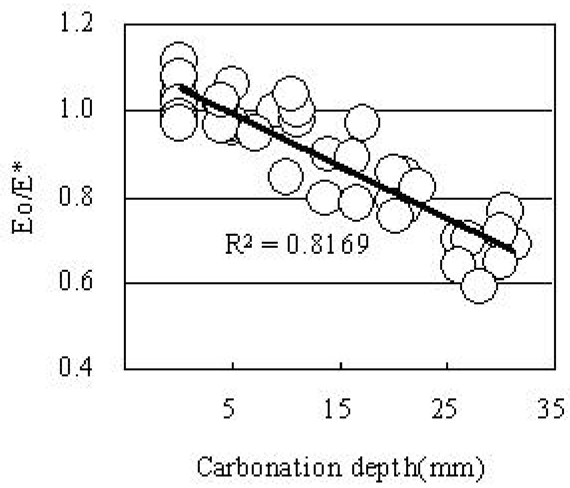

Fig. 5 Relations between relative damages and carbonation depths.

In order to investigate an applicability of the relative damage as a damage index, data E_0/E^* of the carbonation tests are compared with the depths of carbonation. As seen in Fig. 5, a strong correlation between the relative damages and the depths of carbonation is observed. This implies that AE rate process analysis could give us quantitative information on the damage even due to a chemical effect.

It is also demonstrated that the relative damage based on Young's modulus of intact concrete E* is practically determined by using the database. The database is applicable to evaluate the relative damage even in the case that there are not enough the number of specimens available from existing structures.

Relative damages of ten core samples in Table 2 were then determined and are shown in Fig. 6. Relative damages E_0/E^* vary from 0.48 to 1.25. Damages estimated in nine samples are below 1.0. In the figure, lines with open circles denotes the compressive strengths determined. Though the degrees of damage in the concrete samples are not quantitatively evaluated only from the strengths, they are quite comparable to the relative damages. From them, it is concluded that core are fairly damaged except core No.2. Thus, the degree of damage is clearly identified as the relative damage by AE measurement.

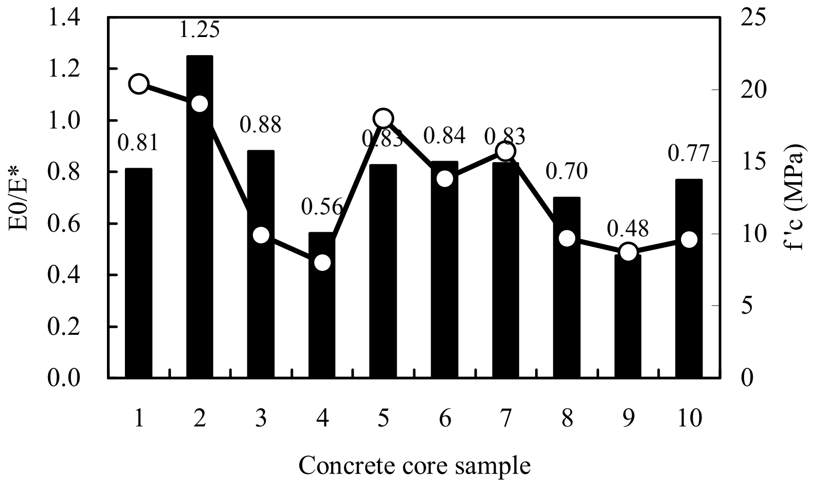

Fig.6 Relative moduli E_0/E^* in an actual structure.

5. CONCLUSION

In the uniaxial compression test, the relation between the AE activity and the damage of concrete is analyzed, based on the rate process theory and damage mechanics. Thus, the degrees of damage in concrete samples are quantitatively estimated, even when the initial physical properties of concrete structure at construction are unknown. Conclusions are summarized below.

1) AE behavior in concrete is dependent on the damage, and could be approximated by applying the rate process analysis. Loland's model could approximate the relation between stress and strain, and the applicability of the damage parameter in the model is confirmed.
2) Based on the correlation between the decrease of Young's modulus and the rate' a', Young's modulus of intact concrete is successfully evaluated. As the ratio to the initial tangential Young's modulus, the relative damage of concrete can be estimated.
3) Using the database, it is demonstrated that Young's modulus of intact concrete is calculated

from a small number of core samples taken from existing structures. Though the degrees of damage in the concrete samples are not quantitatively identified only from the strengths, they were quite comparable to the relative damages. The degree of damage is clearly identified as the relative damage by AE measurement.

RFERENCES

1) Ohtsu, M.(1989). A Review of AE in Civil Engineering with Emphasis on Concrete, *Journal of AE*, Vol. 8, No. 4, 93-98.
2) Ohtsu, M.(2000). Diagnosis of Reinforced Concrete Structures by AE, *Concrete Journal,* Vol. 38, No. 7, 10-16.
3) Colombo, S., Forde, M., Das, O. and Halliday, J.(2001). AE Experiments on Concrete Beams : General Overview and Research in Progress on Bridges, P*roc. 9th Int. Conf. onStructural Faults & Repair*, CD-ROM(Day 2).
4) *NDIS 2421,* Recommended Practice for Ins-Situ Monitoring of Concrete Structures by AE, Japanese Society for Nondestructive Inspection, 2000.
5) Ohtsu, M., Uchida, M., Okamoto, T. and Yuyama, S.(2002). Damage Assessment of Reinforced Concrete Beams qualified by AE, *ACI Structural Journal*, Vol. 99, No. 4, 411-417.
6) Ohtsu, M.(1987). Acoustic Emission Characteristics in Concrete and Diagnostic Applications, *Journal of AE*, Vol. 6, No. 2, 99-108.
7) Ishibashi, A, Hidaka, E., Farahat, A. M. and Ohtsu, M.(1995). Deterioration Evaluation by AE in Concrete Samples, *Proc. 6th Int. Conf. Structural Faults and Repair*, Vol. 2, 69-74.
8) Suzuki T., Watanabe, H. and Ohtsu, M (2002). Damage Evaluation in concrete Using Acoustic Emission Method, *6th Far-East Conference on Non-Destructive Testing,* 111-116.
9) Loland, K.E.(1989). Continuous Damage Model for Load-Response Estimation of Concrete, *Cement and Concrete Research*, Vol.10, 395-402.
10) Ohtsu, M. and Watanabe, H.(2001). Quantitative Damage Estimation of Concrete by Acoustic Emission, *Construction and Building materials*, Vol. 15, Nos. 5-6, 217-224.