Evaluation of Condition and Damage in Reinforced Concrete by Elastic Wave Method

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Abstract In this study acoustic emission and ultrasonic testing were applied to evaluate cracking induced rebar corrosion. It is clarified that AE activity becomes high and wave velocity detected by ultrasonic testing decreases due to cracking-induced rebar corrosion. In addition, impact echo and ultrasonic testing are applied in order to develop an evaluation formula and estimate the concrete strength for several W/C concrete specimens. As a result, it was observed that there is a good correlation between compressive strength and estimated strength in both testing methods.

1 Introduction

The evaluation of concrete condition and damage is very important to estimate the performance of reinforced concrete (RC) structures for maintenance and asset management. When these cracks reach the concrete surface, damage of rebar cor-

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rosion is readily recognized by visual inspection. In this case, however the damage is referred to as the accelerated stage. In order to evaluate the performance of concrete structures, it is important to ascertain the corrosion of rebar as early as possible. In addition, compressive strength of concrete is required as fundamental data. In order to evaluate compressive strength, core samples are collected from the concrete structure. In this case, the coring holes become defects of the structure, and the holes must be repaired carefully to ensure durability of the structure. Non-destructive tests can obtain many points of data and understand distributions on a greater scale without compromising the structure.

Therefore, Acoustic Emission (AE) and Ultrasonic Testing (UT) are applied to evaluate rebar corrosion in concrete specimens. The impact echo (IE) method and UT are conducted to estimate compressive strength.

2 Evaluation of Damage-Induced Rebar Corrosion and Concrete Strength by NDT Based on Elastic Waves

Recently, several NDE methods using elastic-waves have been studied to evaluate corrosion damage of reinforced concrete. The AE method was introduced to detect corrosion-induced cracking in concrete [1, 2]. UT is applied to evaluate corrosion induced cracks and rebar corrosion [3, 4]. In this study, both AE and UT are conducted for RC specimens to detect internal cracks induced rebar corrosion.

In Japan, JSNDI (The Japanese Society for Non-destructive Inspection) standardizes NDT for concrete. UT, Impact elastic wave method and Impact Acoustics Method were standardized as NDIS 2426 Part1, Part 2 and Part 3: Method of elastic wave test for concrete structures in 2009. NDIS 2426 Part 2: Impact elastic wave method was revised in 2014. In this standard, a method which evaluates compressive strength of concrete in new concrete structures is shown as Annex D. Relationship of Ultrasonic pulse velocity and concrete properties have been studied by many researchers. Ultrasonic pulse velocity was used to estimate concrete strength and quality [5, 6]. In this study, in order to clarify the applicability of the method which is shown by the Annex D in NDIS2424, was applied to estimate concrete strength of cylindrical specimens which cast several W/C by IE and UT.

3 Experiment

3.1 Test to Evaluation Rebar Corrosion

Three RC specimens are prepared. These are concrete prisms with dimensions of 100 × 100 × 400 mm. A deformed steel-bar of nominal 13 mm diameter is embedded at 30 mm depth. The water-to-cement ratio is 55%. High early strength

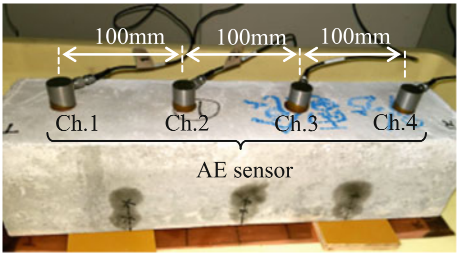


Fig. 1 AE sensor arrangements

Portland cement, crushed sand and coarse aggregate are used. Specimens were moisture-cured for 14 days. An electrolytic corrosion test was applied after curing. Specimens were soaked in water solution with 5% sodium chloride solution and electric current density charge was controlled at $2A/m^2$. A visible crack appeared on the surface 25 days after onset of the test.

The AE method was applied to one specimen to detect micro-cracks induced by rebar corrosion during the electrolytic corrosion test. Because the micro cracks penetrate from inside the surface of the specimen, AE methods were expect to be able to recognize when the cracking starts in a specimen. Four sensors were set on the side of the specimen as presented in Fig. 1. The sensors were 150 kHz resonance type. The threshold level was 40 dB.

UT was conducted once every week by using an ultrasonic measurement system. Two sensors were attached on the surface of the specimen with contact medium as shown in Fig. 2. In this case, the receiver mainly detects reflected waves from rebar as well as the boundary of the specimen. The driving frequency was set as 200 kHz and pulse voltage at 400 V.

3.2 Test of Concrete Strength

Table 1 shows the mixture proportions of cylindrical specimens. In order to observe the relationship between compressive strength and wave velocity, water cement ratios were set at 45, 50, 55 and 60%.

Uniaxial compressive tests were conducted for these specimens. In the tests, the age of the concrete specimens were 3 days, 7 days, 8 days and 56 days, respectively.

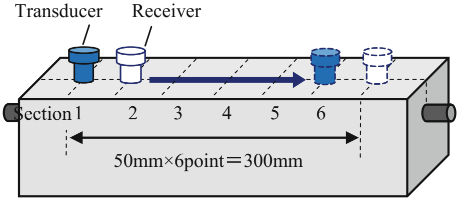


Fig. 2 Sketch of sensor arrangement of UT

Table 1 Mixture proportion of concrete specimens

W/C (%)	s/a (%)	Unit weight (kg/m³)						SL (cm)	Air (%)
		W	C	S	G	AEA	SP		
45	45	157	349	790	965	0.007	4.2	10.0	5.2
50		164	327			0.008	3.3	12.5	5.0
55		170	308			0.009	3.1	7.5	4.5
60		175	292			0.010	2.6	10.0	3.0

Before the compressive tests, IE and UT methods were performed in order to detect wave velocity. In the impact echo test, the impactor and accelerometer were set on the surface as given in Fig. 3. The diameter of the steel ball was 10 mm and sampling time was 10 µs. The measured time-domain waveform was transformed to frequency domain by an FFT to determine the peak frequency. The peak frequency was used to detect the wave velocity using Eq. 1.

$$V_p = 2 \cdot f_0 \cdot L \tag{1}$$

V_p: wave velocity, f_o: peak frequency, L: Length of specimen.

Ultrasonic tests were conducted using ultrasonic measurement equipment as shown in Fig. 3. The equipment measured propagation time. Wave velocity was calculated by Eq. 2.

$$V_p = L/t \tag{2}$$

V_p: wave velocity, L: Length of specimen, t: propagation time.

In NDIS 2426 part 2, an evaluation formula, which shows relation between wave velocity and compressive strength, is proposed as in Eq. 3.

$$F_C = \beta \times V_p^{\alpha} \tag{3}$$

F_c: compressive strength, V_p: wave velocity, $\alpha\,\beta$: coefficient of regression.

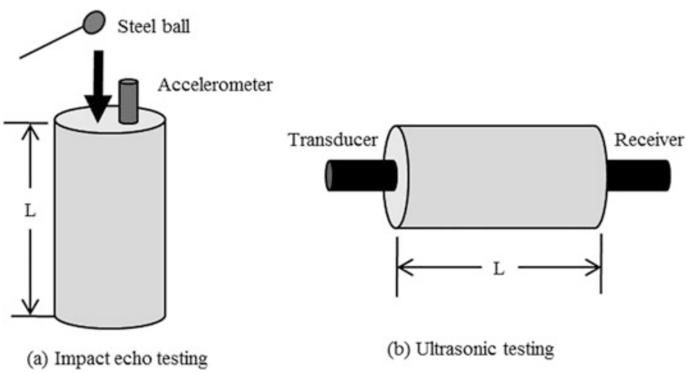


Fig. 3 Sketch of measurement by IE and UT

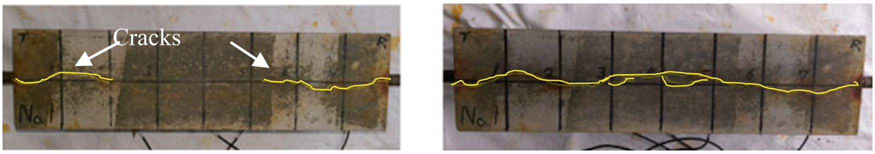


Fig. 4 Views of cracks on RC specimen (left: 25 days after, right: 30 days after)

4 Results and Discussion

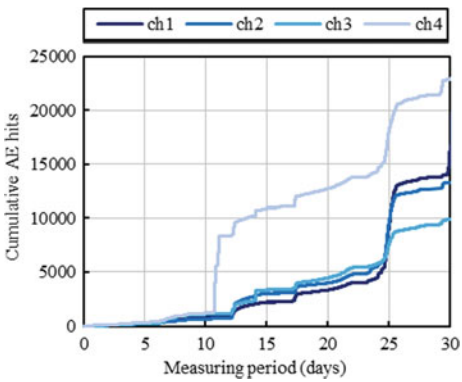
4.1 Results of Evaluation Rebar Corrosion

Figure 4 shows visible cracks on the surface of an RC specimen. When the period of electrolytic corrosion test reached 25 days, visible cracks were observed on all specimens.

The relationship between AE hits and test period are shown in Fig. 5. It is observed that the cumulative number of AE hits was constant from 0 to about 11 days, and AE hits increased from 12 days rapidly. When the test period was 25 days, the increase of AE hits accelerated. Therefore it may be inferred that corrosion started after several days and cracking induced rebar corrosion in cover concrete occurred from 12 days to 25 days and, finally, cracks reached the surface.

Figure 6 shows the relationship between ratio of wave velocity detected by UT and test period. The ratio of wave velocity was calculated as velocity of test periods divided by initial velocity before electrolytic corrosion. Decrease of the ratio is recognized about 15 days after initiating the experiment. This decrease started as the number of AE hits increased as can be seen in Fig. 5. It is clear that wave velocity decreases due to corrosion induced cracks. These results suggest that AE and UT methods are able to detect cracks prior to the acceleration stage.

Fig. 5 Relation between cumulative AE hits and measuring period



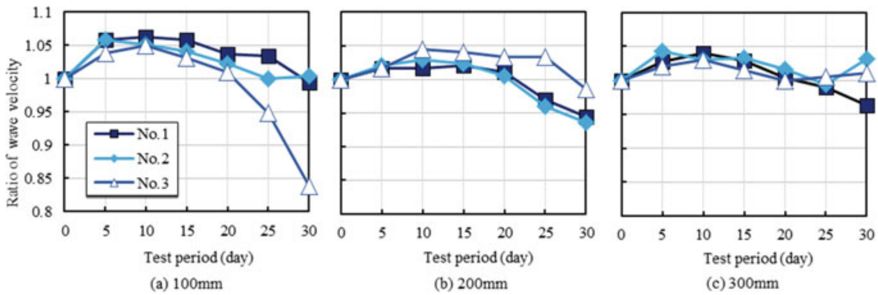


Fig. 6 Ratio of wave velocity

4.2 Results to Estimate Concrete Strength

The relationship between compressive strength and wave velocity measured by IE and UT are shown in Fig. 7. The curves represent the evaluation formulas of each W/C given by Eq. 3. It is observed that wave velocities have a high correlation with compressive strength in the case of the same W/C. In NDIS 2426, it is recommended that evaluation formula should take into account each mixture's proportion. Table 2 shows coefficients of evaluation formula of IE and UT. It is understood that the coefficients of IE and UT are not matched.

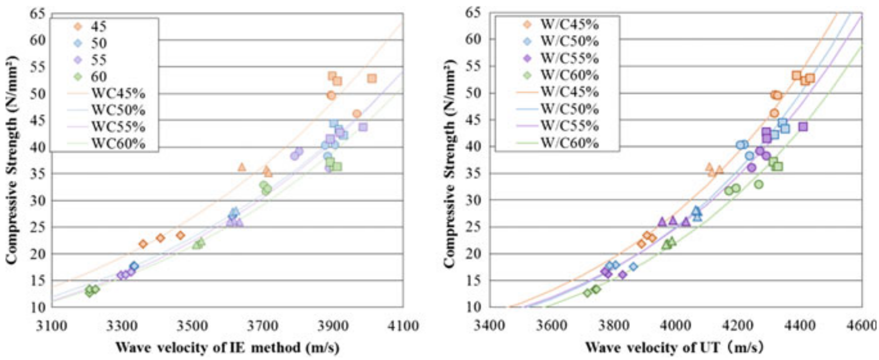


Fig. 7 Relation between compressive strength and wave velocity measured by IE and UT (left: IE, right: UT)

Table 2 Coefficients of evaluation formula of IE and UT

	Curing period (days)							
	3		7		28		56	
	α	β	α	β	α	β	α	β
IE	5.479	1.00×10^{-18}	5.416	1.50×10^{-18}	5.629	0.25×10^{-18}	5.519	0.59×10^{-18}
UT	6.995	1.80×10^{-24}	7.258	0.18×10^{-24}	6.885	3.90×10^{-24}	7.057	0.84×10^{-24}

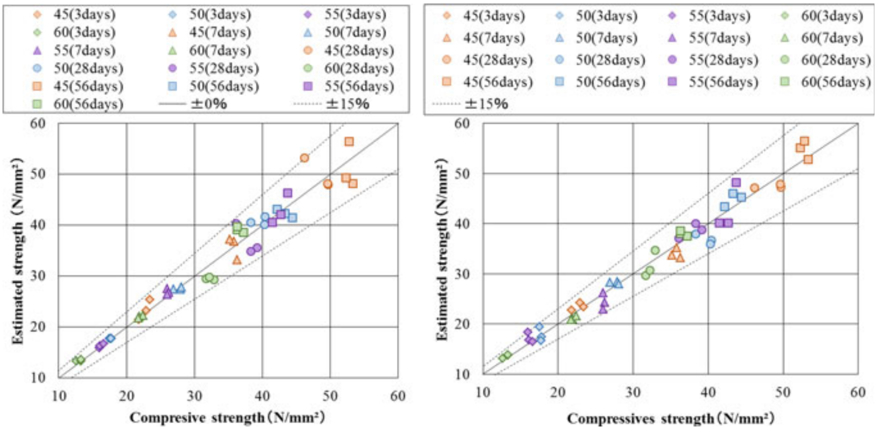


Fig. 8 Relationship between estimated strength and compressive strength (left: IE, right: UT)

Relationship between estimated strength and compressive strength is shown in Fig. 8. It is observed that the estimated strength corresponds to the actual compressive strength. Variations of IE and UT are almost of the same magnitude.

5 Conclusions

In this study, corrosion-induced cracks were experimentally evaluated. It was clarified that AE activity became high and wave parameter of ultrasonic testing decreased due to cracking induced rebar corrosion. In addition, IE and UT were applied to estimate the compressive strength of concrete. As a result, it was observed that wave velocities have a high correlation with compressive strength and the evaluation formula can estimate compressive strength with high fidelity.

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