PREDICTION METHOD FOR PROPERTIES OF CONCRETE ON ULTRASONIC NON-DESTRUCTIVE TESTING

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Abstract

In this study, a prediction method to evaluate existing expansion of concrete having deteriorated due to alkali-aggregate reaction was investigated by using concrete cores and ultrasonic non-destructive testing. The purpose of this study is to show that a diagnosis of concrete structures may be made possible by non-destructive testing in the future.

First, using cylindrical specimens containing alkali-silica reactive aggregates, each correlation between expansion and ultrasonic propagation characteristics consisting of several indices were compared experimentally in an accelerated curing condition. Second, the correlations were analyzed by an artificial neural network. The input data consisted of the ultrasonic propagation characteristics; the output data entailed the expansion. Third, several cores drilled from an actual concrete structure were measured ultrasonically in another accelerated curing condition; thereafter, their expansion was evaluated by the neural network structure after obtaining the correlations obtained from the cylindrical specimens. The increment of the estimated expansion was compared to the increment of the measured expansion after the beginning of the accelerated curing.

As a result, it was clarified that the prediction method was effective for the evaluation of the expansion of concrete.

Keywords: ultrasonic non-destructive testing, expansion, propagation characteristics, neural network

1 INTRODUCTION

In Japan, concrete damage due to alkali-silica reaction (ASR) has been found since the 1980s in some concrete structures with crushed andesite stones. Various remedial measures have been carried out since the 1990s. In particular, non-destructive testing methods are becoming more and more important to maintain the long-term safety of concrete structures.

The ultrasonic method, one of the various non-destructive testing methods, has been used to estimate compressive strength with ultrasonic velocity since early times. However, the result of its effectiveness is not conclusive yet because concrete is a complex material consisting of cement, aggregate, water, and air void content; particularly, the quantity and quality of aggregates are not uniform. Moreover, ultrasonic waves usually have only a small propagation energy and a high frequency band in the measurement of concrete. Therefore, many ultrasonic waves transmitted into concrete mostly diffuse and attenuate.

In this paper, an evaluation method of expansion of concrete due to ASR was investigated by a ultrasonic method as hereinafter defined. Expansion and six indices as ultrasonic propagation characteristics, which were investigated by amplitude and frequency of the received wave including ultrasonic velocity, were measured with cylindrical specimens. Next, the individual relationship between expansion and the six indices were analyzed by an artificial neural network (NN). Finally, the values of expansion capacity, which was drilled from an actual structure, were evaluated by using the outcome of NN learning; thereafter, the evaluation method was considered.

2 MATERIALS AND METHODS

2.1 Experiment with Specimens

Specimens

Expansion and ultrasonic propagation characteristics were experimentally compared with cylindrical specimens.

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Materials used in the specimens included Normal Portland Cement; non-reactive crushed sand from diorite, and a blend of reactive coarse aggregate from andesite and rhyolite (Table 1). Firstly, rectangular solid specimens, which were 500 mm wide, 900 mm long, and 600 mm high, was made. Nine cores, which were 100 mm in diameter, were drilled from the specimen after eight months. Each core was cut into lengths of 250 mm (hereinafter called the core specimen).

Accelerated expansion and the measurements

The core specimens were measured in an accelerated curing condition based on the Danish method [1]. They were immersed in a saturated sodium chloride solution at a temperature of 50°C as shown in Figure 1.

During the accelerated curing condition, the length alteration of cores was regularly measured by a contact-type strain gauge according to specification by JIS A 1129-2-2001. Therefore, the coefficients of expansion (hereinafter called expansion) were calculated by length alteration from the point at which the core specimens were drilled. At the same time, the ultrasonic testing was measured. Both ends of each core were immediately cut one by one at lengths of 200 mm when the expansion of each core reached the expected size. Thereafter, compressive strength and elasticity modulus were tested according to specification by JIS A 1108-1999 and JIS A 1149-2001. The ultrasonic testing was also measured once again.

Ultrasonic testing

The ultrasonic testing was measured by a transmission method. The ultrasonic wave was transmitted lengthwise through the core specimens. Piezoelectric elements with a diameter of 40mm were used for both the oscillator and the receiver. The resonance frequency was 0.5MHz. The sampling time is 819×10^{-6} seconds. The resolution of the frequency is 1.22 kHz.

Six indices as ultrasonic propagation characteristics were considered as discussed below. The ultrasonic velocity, the maximum amplitude and the amplitude of the first wave were adopted for the indices from a receiving wave (Figure 2). The maximum spectral intensity, the total energy of spectral intensity from 0 kHz to 2500kHz (hereinafter called received total energy), and the frequency with respect to the half value of received total energy (hereinafter called received average frequency) were adopted for the indices from the frequency distribution (Figure 3).

Results

Figure 4 shows the correlations between the expansion and the ultrasonic propagation characteristics, which were obtained by the ultrasonic measurements of core specimens cut into 200 mm before the compressive strength testing. The maximum amplitude, the amplitude of the first wave, the maximum spectral intensity, and the received total energy were converted to each dimensionless value which was divided by the largest one. Several exposed length in the saturated sodium chloride solution were 147days(0.079%), 168days(0.154%), 224days(0.535%).

The ultrasonic velocity constantly decreased in proportion to the increase of the expansion. Other indices sharply dropped in an expansion range of 0.1% or less. On the other hand, they were slow to respond above 0.1%.

Figure 5 shows the relation between the expansion and the compressive strength, and the elasticity modulus. It is often observed in ASR affected concrete that the reduction in the modulus of elasticity is more remarkable than that of the compressive strength [2,3].

2.2 NN Learning

Learning procedure

The relations between the expansion and the ultrasonic propagation characteristics, which were obtained by measurements of core specimens cut into 250 mm, were analyzed by the NN. The NN structure was composed of 3 layers consisting of input, hidden, and output layers (Figure 6). The input factors were taken as the ultrasonic propagation characteristics; the output factor was taken as the expansion. The backpropagation method was used for analyzing and structuring in the NN.

The total number of data was 76; an activation function was the sigmoid function; the learning rate was 0.05; the total number of times of learning was 2000 times.

Learning result

Figure 7 shows a comparison of desired outputs, which are data from the core specimens, and actual outputs, which are data calculated by the NN, within the expansion of 0.1%. Figure 8 shows error distributions in all data. The error was described by Equation 1:

$$Er = (Pc-Pe)/Pe \times 100 \quad (1)$$

where Er = error (%), Pc = expansion of learning result (%), and Pe = expansion of desired output (%). Therefore, the average absolute value of the error was 28%.

2.3 Estimation of Expansion

In this study, expansion for several cores drilled from one actual concrete structure (hereinafter called the sampling core) was estimated by using the ultrasonic method.

The structure was a gravity-type retaining wall of unreinforced concrete. The aggregates in the structure were crushed andesite stones. A large number of cracks due to ASR were observed on the surface. It was unclear how much expansion the wall had already undergone. Therefore, a diagnosis of the wall was run to measure potential expansion according to specifications by JCI-DD2. The sampling cores were 100 mm in diameter. The total number of them was 12 pieces, 4 pieces each from 3 sampling places. From the 12 pieces, 1 piece each from sampling points A and B and 2 pieces from sampling point C were chosen in order to measure the expansion. The sampling points were named A~C and the cores were numbered 1~4. The cores were cured in moist chambers at 40°C and not less than 95% relative humidity(JCI-DD2). Expansion was measured by the length change at regular intervals (hereinafter called the measured expansion) [4].

While the expansion test had been running, the ultrasonic measurements were carried out. Ultrasonic propagation characteristics, which were obtained from the results of the ultrasonic measurements, were inputted into the NN structure, in which the previous NN learning results were used. The output values were taken as estimated expansion (hereinafter called the calculated expansion).

3 RESULTS

Figures 9,10 and 11 show ultrasonic velocities, ratios of the maximum amplitude, and receiving average frequencies, which were plotted against the measured expansion. The maximum amplitudes were converted to each dimensionless value which was divided by the largest value of A-1.

Figure 12 shows the results of comparisons between the calculated expansion and the measured expansion. The measured expansion was considered as the potential expansion. Therefore, all of the initial-values were set at 0.0%. On the other hand, the calculated expansion was indicated with the output-value from the NN structure.

Figure 13 shows the relations between the ratio of elasticity modulus to compressive strength and the compressive strength which were measured by the sampling cores. The plots in Figure 13 tend to come down at the lower left in the case of concrete due to ASR [2,3]

For A-1 and B-3, the alteration of expansion were appropriately measured by the maximum amplitude and the received average frequency(Figure 9,10). However, the ultrasonic velocity was not(Figure 11). The increment of the measured expansion of B-3 was 0.031% for 180 days, while the calculated one was 0.057% ranging from 0.018% to 0.075% (Figure 12b). On the other hand, the increment of the measured expansion of A-1 was 0.024% for 180 days, while the calculated one was 0.045% ranging from 0.050% to 0.095%. Several estimated errors of A-1 between the calculated expansion and the measured expansion were large(Figure 12a). From Figure 13, the data at point B were close to the line of sound cores. However, the data at point A were not on the line.

For C-1 and C-3, the ultrasonic propagation characteristics were relatively low degrees (Figures 9,10 and 11). Both increments of the calculated expansion of C-1 and C-3 could not estimate the measured one. Additionally, the calculated expansions were above 0.1% (Figure 12c,d). From Figure 13, the data at point C were not close to the line of sound cores.

4 DISCUSSION

For B-3, the increment of the calculated expansion was successfully evaluated. From previous experimental results of the core specimens, the ultrasonic propagation characteristics are sensitive to the expansion in the range of 0.1% (Figure 4). It appears that the existing expansion at point B, when the sampling cores were drilled, was 0.1% or less from Figure 13. Therefore, the calculated expansion was mostly accurate.

For A-1, the several large estimated errors between the calculated expansion and the measured expansion(Figure 12a) corresponded to gap points of the maximum amplitude measurement result (Figure 10). One of the reasons seems to be due to the condition of contact between a concrete surface and an ultrasonic transducer. Received amplitude, which is the basis of ultrasonic propagation characteristics, is largely affected by adhesion of a contact medium between the transducer and the concrete surface.

For C-1 and C-3, considering the relative low degrees of the ultrasonic propagation characteristics (Figures 9, 10 and11) and test results at point C (Figure 13), the measured concrete structure seemed to be damaged by ASR. Therefore, the existing expansion was probably above the range of 0.1%. As a result, the sensitivity of ultrasonic measurements was low as shown in Figure 4.

Additionally, each relative difference between the calculated expansion and the measured expansion at the starting point of accelerated curing as shown in Figure 12 was about 0.05% (A-1), 0.018% (B-3), 0.111% (C-1) and 0.187% (C-3). These estimated values had a similar inclination relative to the condition of concrete at the sampling points considering from the result of Figure 13. For this reason, there is a possibility that the calculated expansion with ultrasonic method represents the existing expansion. Only the data at point A was different from other places. However, both the ratio of the maximum amplitude and the received average frequency with A-1 were as high as the data for B-3 (Figure 10,11). It therefore seems that the expansion of the used sampling core (A-1) was in an early stage deterioration due to ASR.

From the results of the calculated expansion, for the existing expansion in the range of 0.1% or less, it appears that the ultrasonic method successfully estimates the expansion due to ASR. However, it is difficult to estimate it for expansion over 0.1%. As for the range of the expansion over 0.1%, A confirmation that the measured concrete may be over 0.1% seems to be possible by the comparison between the measurement for a damaged place and the one of a sound place.

The received amplitude, which is an indicator concerning the amount of propagated energy, was largely affected by the adhesion of the contact medium. The examination on the measurement errors is necessary to improve the prediction method for the expansion of concrete.

5 CONCLUSIONS

The prediction method using ultrasonic sound to evaluate the expansion of concrete due to ASR was investigated by using concrete cores.

To compare ultrasonic propagation characteristics with expansion was investigated by measuring with cylindrical specimens in accelerated curing condition. As a result, it was discovered that there was a significant correlation between the expansion and the ultrasonic propagation characteristics.

From another investigation using the cores drilled from the retaining wall structure using an ultrasonic method, for the existing expansion in the range of 0.1% or less, there is the possibility that the ultrasonic method can estimate the expansion of concrete due to ASR by using ultrasonic propagation characteristics.

6 REFERENCES

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TABLE 1: Mixture proportions of concrete specimens

G.max (mm)	W/C (wt%)	Slump (cm)	Air content (vol%)	s/a (wt%)	Unit weight (kg/m^3)			
					Cement	Water	Coarse aggregate	Fine aggregate
20	50	12±2	4.5±1	44.4	330	165	981	784

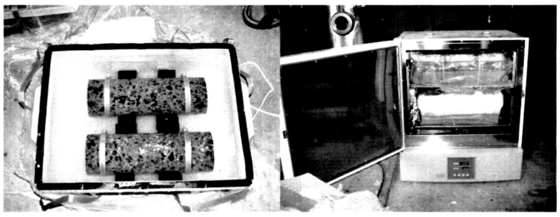

Figure 1: A test situation of the accelerated curing

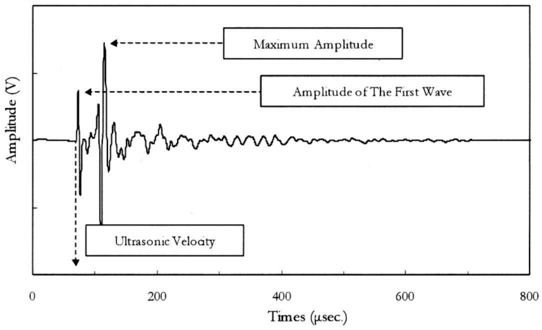

Figure 2: ultrasonic propagation characteristics estimated from a receiving wave

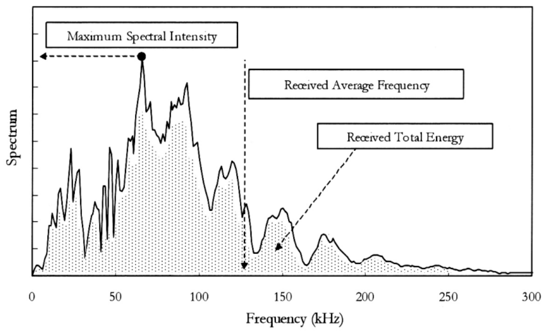

Figure 3: ultrasonic propagation characteristics estimated from a frequency distribution

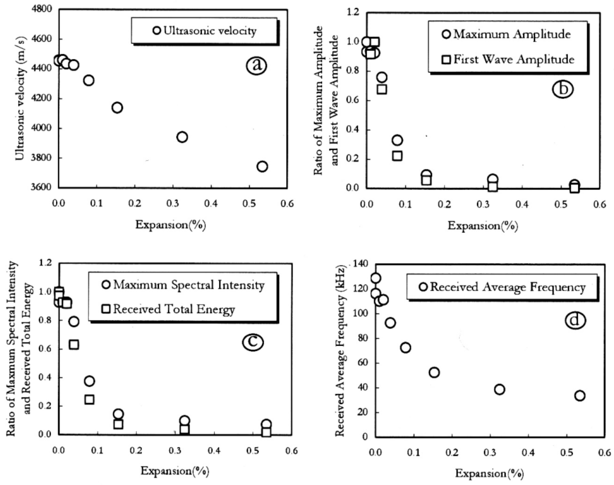

Figure 4: Correlations between the expansion and the ultrasonic propagation characteristics (the core specimens cut into 200 mm)

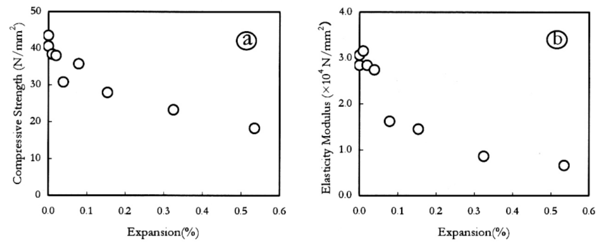

Figure 5: Correlations between the expansion and the compressive strength, the elasticity modulus

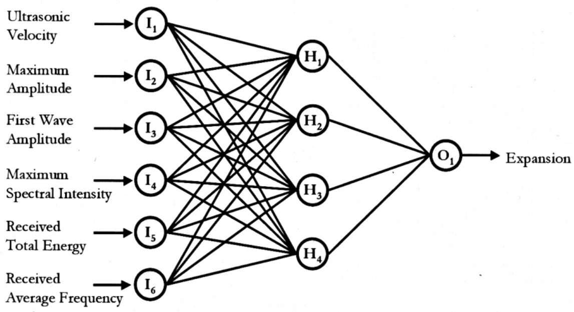

Figure 6: NN structure

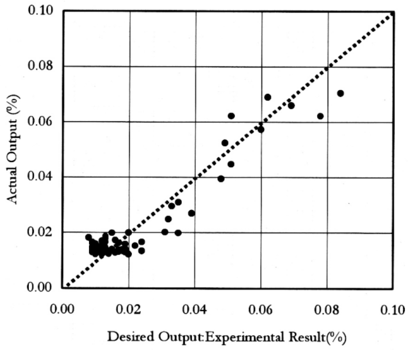

Figure 7: An appearance of the NN learning results within the expansion of 0.1%

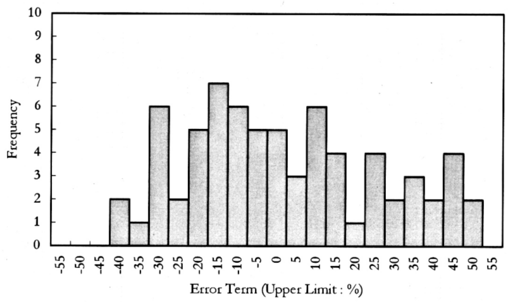

Figure 8: Error distributions in all date by the NN learning

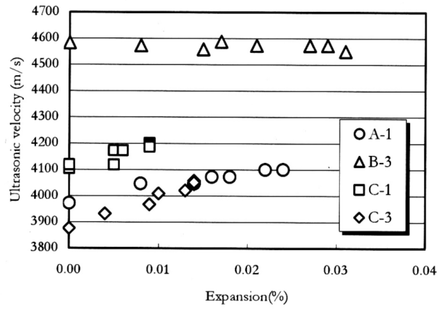

Figure 9: Correlations between the expansion and the ultrasonic velocities of the sampling cores

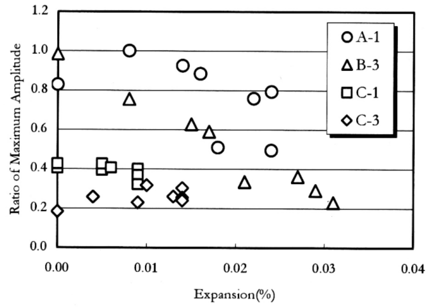

Figure 10: Correlations between the expansion and the ratios of maximum amplitude of the sampling cores

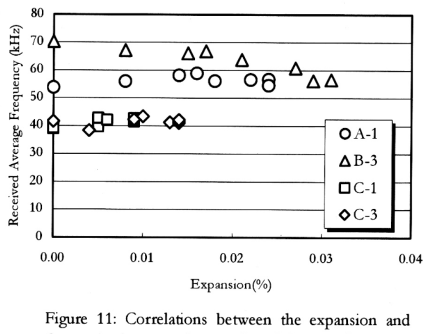

Figure 11: Correlations between the expansion and the received average frequencies of the sampling cores

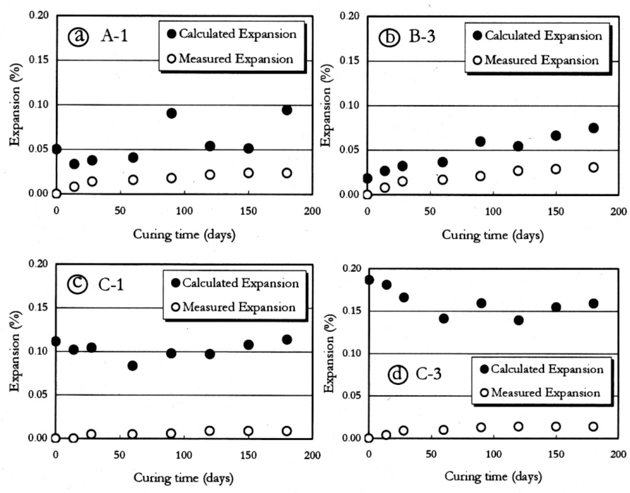

Figure 12: Comparisons between the calculated expansion and the measured expansion

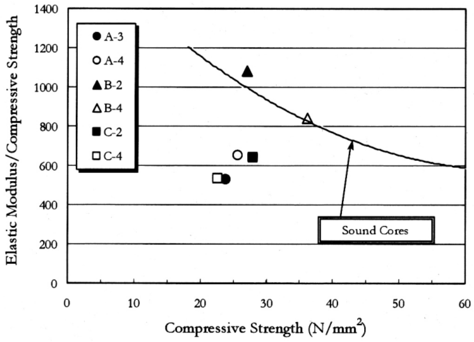

Figure 13: Relations between the ratio of elasticity modulus to compressive strength and compressive strength of the sampling cores