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Monitoring of Deterioration due to ASR Using Ultrasonic Frequency Spectrum

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ABSTRACT

This paper discusses an ultrasonic testing method to detect an expansion change due to alkali-silica-reaction (ASR). A concrete specimen including aggregates with an ASR potential was made for the experiment. The measurement of the ultrasonic testing was carried out during the progress of the specimen's expansion. Three characteristics obtained from the measurement were investigated: ultrasonic propagation velocity, received amplitude and frequency spectrum. The three ultrasonic characteristics were compared with strain values obtained from embedded strain gauges. As results from this study show, 1) the testing method of frequency spectrum has a higher sensitivity to detect expansion variation than the other two testing methods. 2) The most sensitive frequency band before ASR crack generation is from 100kHz to 150kHz. 3) The frequency indicator reduces the unevenness of errors influenced by environmental conditions for the measurement.

Keywords. Non-destructive, alkali-silica-reaction, ultrasonic testing, expansion, frequency spectrum

INTRODUCTION

Ultrasonic method for concrete field. There are mainly two applications for the use of the ultrasonic method in concrete structure measurement. One of the uses is to probe internal defects such as cracks and voids. Another use is to estimate the performance of compressive strength or density distribution on concrete masses (Concrete Engineering Series, 2004). However, when using the ultrasonic method, the measurement accuracy of concrete does not improve due to high-frequency scattering through inhomogeneous material (Chi Won In et al., 2012). In addition, the propagating characteristic is affected by the difference in the kind of aggregates in a variety of concretes (ACI Committee Report, 2003). These issues have prevented the establishment of measurement reliability and the reproducibility on ultrasonic testing for concrete. The development of this non-destructive testing method, which can be used repeatedly on the same piece of concrete, will make it possible to maintain a large number of concrete structures in the future.

Ultrasonic method for the deterioration due to ASR. ASR is a type of distress which causes premature deterioration; it affects numerous concrete structures around the world. Structures affected by ASR will begin to exhibit cracking and movement due to excessive expansion. We have been researching into the progress of ASR deterioration by using the ultrasonic method. Correlations between the ASR expansion coefficient and ultrasonic propagation characteristics are shown in Figure 1 (Nakagawa et al., 2008). The characteristics are indices obtained from ultrasonic measurement such as the amplitude of received wave and the frequency spectrum (as will hereafter be described in detail). The indices of Figure 1 indicate a significant change relative to the expansion. The amplitude index or the frequency index were remarkably sensitive with respect to the expansion change before 0.1%.

The objective of this paper is to make a comparative review of ultrasonic propagation characteristics to improve the detecting ability of ASR expansion variation. A concrete cylindrical block was made for this investigation. It was created in such a way as to display the typical structural weakness caused by ASR. The ultrasonic measurement was carried out on the specimen during ASR expansion.

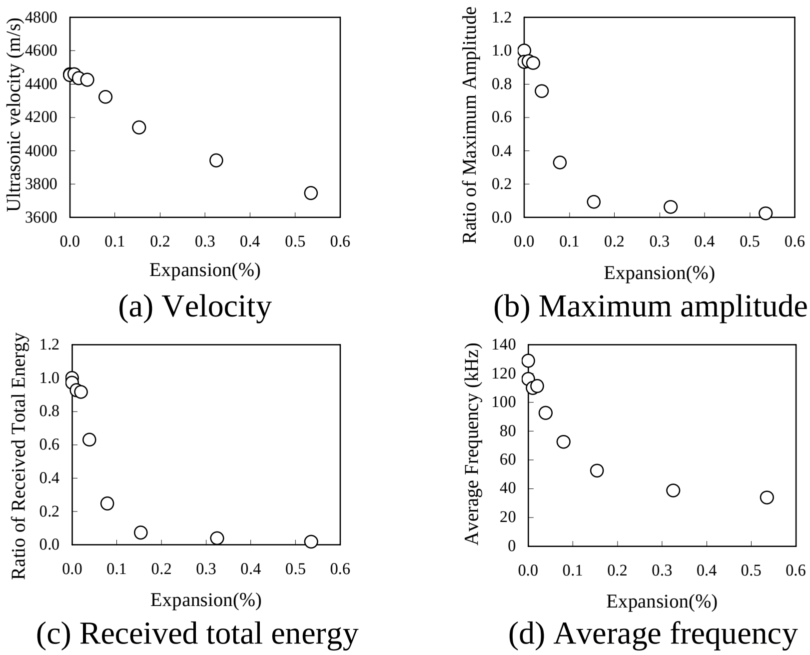


Figure 1. Correlations between the ASR expansion coefficient and ultrasonic propagation characteristics

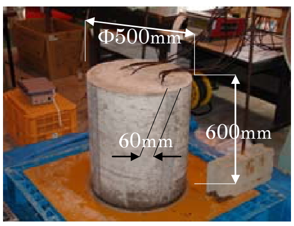


Figure 2. Specimen

Table 1. Mixture proportion

G.max	W/C	Slump	Air content	s/a	Unit weight (kg/m^3)					AE-Water Reducing Agent	NaCl (Na_2Oeq)
					Cement	Water	Fine Aggregate	ASR Aggregate	Sound Aggregate		
(mm)	(wt%)	(cm)	(vol%)	(wt%)						C×(%)	(kg/m^3)
20	60	12±2	5.0±1	44.0	300	180	829	611	419	0.18	10

EXPERIMENT

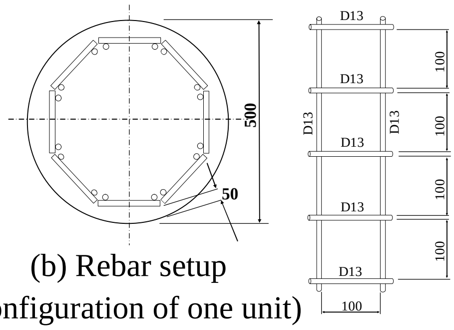
Concrete specimen. A concrete cylindrical block was casted for the ultrasonic testing method. The size of the specimen was 500mm in diameter and 600mm high as shown in Figure 2. The mixture proportion of the concrete used is summarized in Table 1. Andesite which typically has the potential of causing ASR was used as coarse aggregate. Sandstone which has no possibility of exhibiting ASR was also blended with andesite. The pessimum content ratio, which was used for the blending of aggregates in this experiment, was 6 (andesite) to 4 (sandstone) (Nakagawa et al., 2010). NaCl was added in the amount of 10kg/m^3 (Na_2O equivalent). The compressive strength of the concrete at 28 days was 30.8 N/mm^2. Rebar fabricated in the specimen were 13mm in diameter all as shown in Figure 3. The minimum cover thickness was 50mm. An elastic adhesion bond was used at each attachment between the bars to prevent a restraint of ASR expansion.

The specimen was removed from the mold after 8 days, polished in 4 places at a width of 60mm on the lateral side to mount the ultrasonic sensors.

Curing of the specimen. The specimen was set indoors during the experiment, covered with a water-absorbing sheet − except during the measurement − to prevent drying on the surface. The inside temperature and humidity were not controlled for.

Expansion of the specimen. Six strain gauges were set to measure ASR expansion as shown in Figure 4, embedded 30, 50, 80, 100, 150, 200mm from the surface and 300mm from the top. The angle of each of the six strain gauges was fixed in a circumferential direction to measure the expansion of the circular arch length at each position. The

(a) Rebar appearance



(b) Rebar setup
(Configuration of one unit)

Figure 3. Rebar layout of the specimen

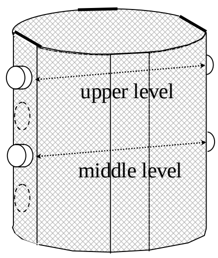
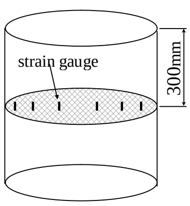
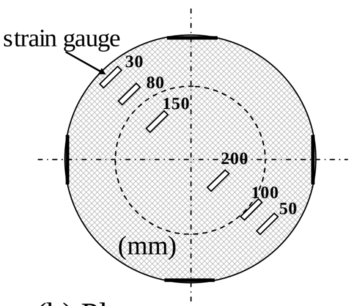


Figure 5. Measuring method



(a) Installation height



(b) Plane arrangement

Figure 4. Installation position of embedded strain gauges

Figure 6. Ultrasonic equipment

measurement was recorded automatically every one hour.

Ultrasonic measurement. The measurement was conducted by performing the transmission method on the specimen as shown in Figure 5, implemented every one or two weeks. The length between the sensors was 500mm. The height of setting the transducers were at two levels on the surface of the specimen as shown in Figure 5. The transmitted direction was in two directions at right angles to each other. The used ultrasonic measuring equipment is a commercially available product as shown in Figure 6. The broadband transducers were 40mm in diameter at central frequency of 500kHz with an applied voltage of 500V.

Ultrasonic propagation characteristics. Three characteristics were used to investigate ASR expansion variation: P-wave velocity, propagated energy, and average frequency as shown in Figures 7 and 8. The propagated energy (hereafter called received total energy) is the integrated area bounded by the received wave line and zero line of amplitude as shown in Figure 7 and added values multiplying the received amplitude by the sampling time. The

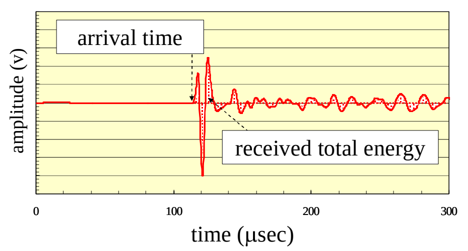


Figure 7. Received wave

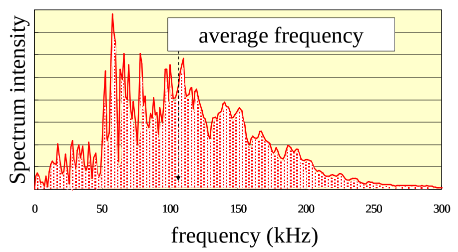


Figure 8. Frequency spectrum

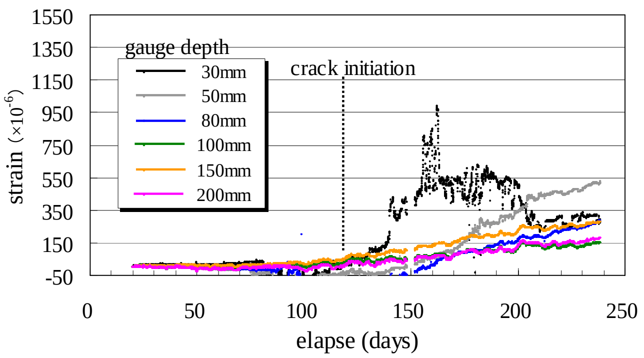


Figure 9. Measured result of strain gauges

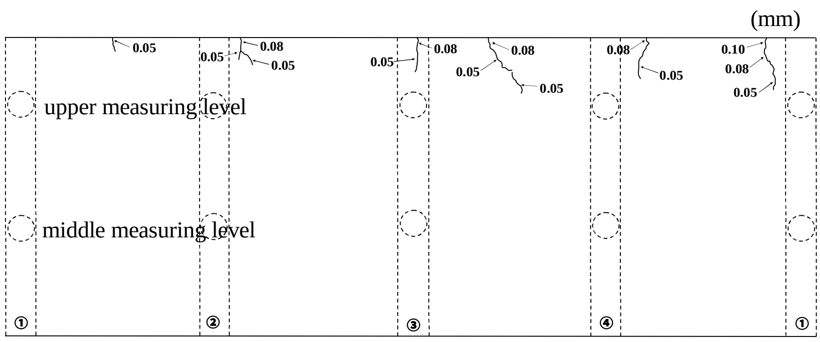


Figure 10. Crack distribution (the lateral side of the specimen)

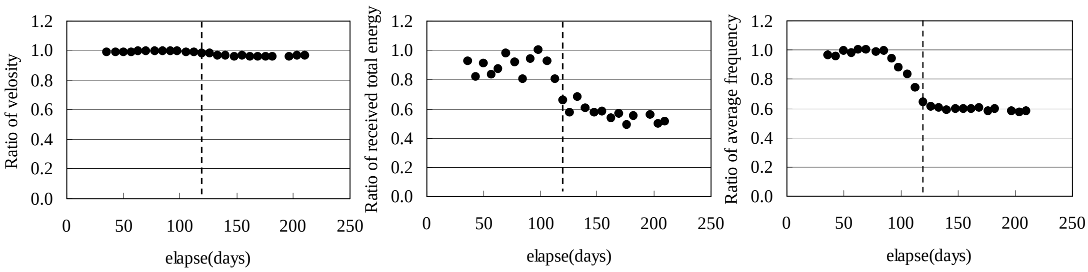
average frequency is frequency indices corresponding to half values of the area bounded by the frequency spectrum as shown in Figure 8.

EXPERIMENTAL RESULT

Specimen Expansion. Measurement results of strain gauges in the specimen are shown in Figure 9. The rising curve of the strain variation represents a longitudinal extension of the gauge, indicating an expansion of the specimen due to ASR. The dot-line shown in Figure 9 represents the stage of crack initiation that was found on the surface of the specimen. The generated crack status, which is represented on the developed lateral side of the specimen, is shown in Figure 10. The numbers in Figure 10 represent the crack width. It was observed that the crack distribution was concentrated at the upper side of the specimen.

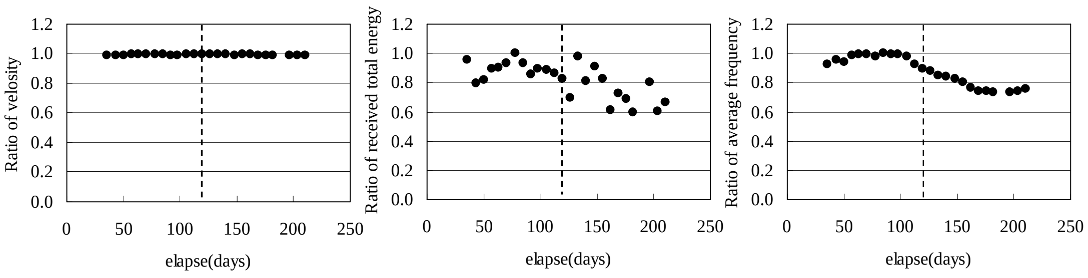
As found in Figure 9, the increasing level of the strain gauges was approximately 150~550μ in a circumferential direction on the specimen. A strain variation at a depth of 30mm, where there is a cover-concrete zone outside the reinforcement, showed an expanding change immediately after the crack initiation; then it relented.

Ultrasonic propagation characteristics. Three characteristics obtained from the ultrasonic measurement, which is one of the two transmission directions, are shown in Figures 11 and 12. Two figures show upper-level measuring (Figure 11) and mid-level measuring (Figure 12). The dot-line in the two figures represents the days when cracks were found on the surface, as in Figure 10. The three characteristics on the vertical axis were



(a) Velocity (b) Received total energy (c) Average frequency

Figure 11. Three characteristics variation (the upper level)



(a) Velocity (b) Received total energy (c) Average frequency

Figure 12. Three characteristics variation (the middle level)

converted to dimensionless values corresponding to the ratio of the measured data to the maximum value respectively.

The used couplant transmutes viscosity depending on the ambient temperature, which affects the received total energy. Figure 13 shows a correlation between the measurement temperature and the received total energy (Nakagawa et al., 2011). In this paper, the received total energy was converted to a 20°C condition by using the correlation as shown in Figure 13.

Three characteristic values descended with time as shown in Figures 11 and 12. The amount of decrease in the dimensionless value on the upper-level (Figure 11) occurred relatively earlier than at the mid-level (Figure 12). As for comparisons between the characteristic values, the average frequency showed a predominant variation, the velocity was little.

The average frequency was not as widely distributed over the time-sequence diagram as the received total energy, clarifying a degressive variation due to ASR.

DISCUSSION

Detection ability. Expansion due to ASR degrades the value of ultrasonic propagation characteristics as evinced in our study results (Figure 1). Expansion due to ASR inducts a fall in dynamic modulus. Since both the dynamic modulus and ultrasonic velocity are theoretically interrelated, the velocity falls with expansion (R. N. Swamy et al., 1988). In the case of concrete affected by ASR, a network of microcracks develops in the inner part of the concrete. The microcracks increase with connecting the aggregate particles(Benoit Fournier et al., 2010). The continuity lack generated by the microcracks interfere with a propagation of ultrasonic wave, and scatter a high frequency range of the wave. As a result, both the received total energy and the average frequency are assumed to be the falls with expansion due to ASR. An equivalent relation was also found in this study between ASR expansion and the decrease of the three ultrasonic characteristics. In addition, crack distribution on the specimen indicates that the upper side degraded more than the mid level. The degradation is assumed to be due to ASR expansion. The difference of the crack distribution corresponded to the difference of the reduction of the three ultrasonic characteristics between two-tier measurements on the specimen as shown in Figures 11 and 12. As a consequence, ultrasonic propagation characteristics were considered to detect degressive variation due to ASR.

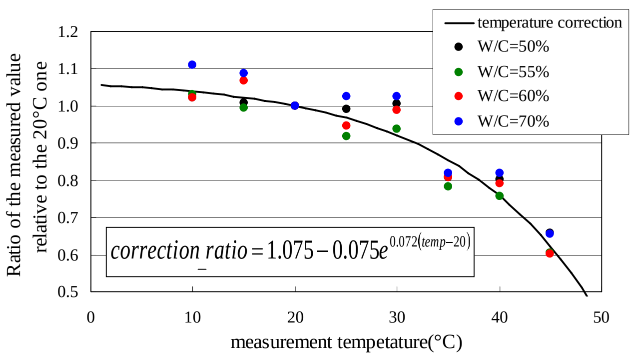


Figure 13. Correlation between the received total energy and temperature

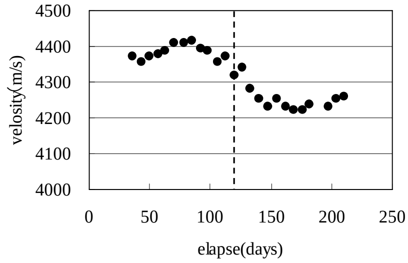


Figure 14. Broadened velocity variation from Fig. 11(a)

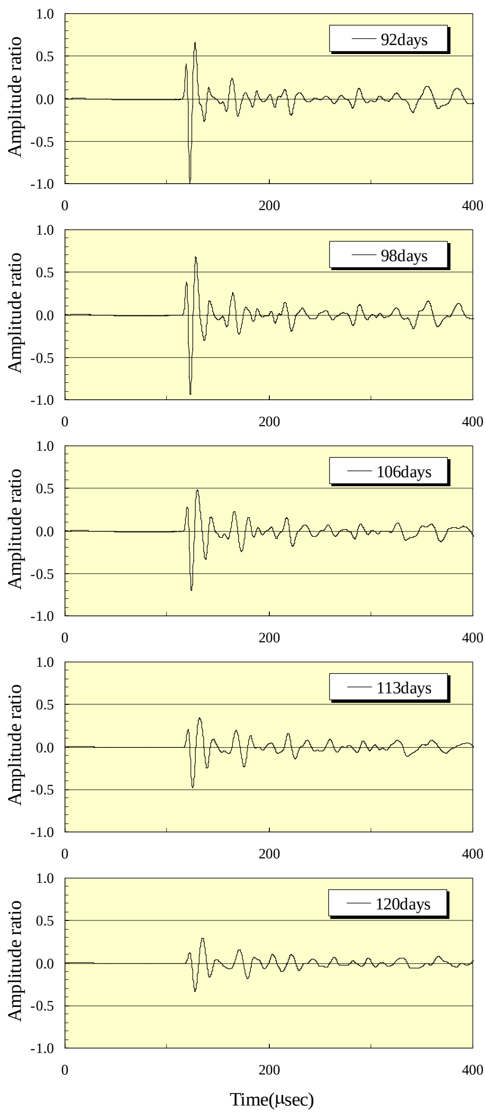


Figure 15. Received wave

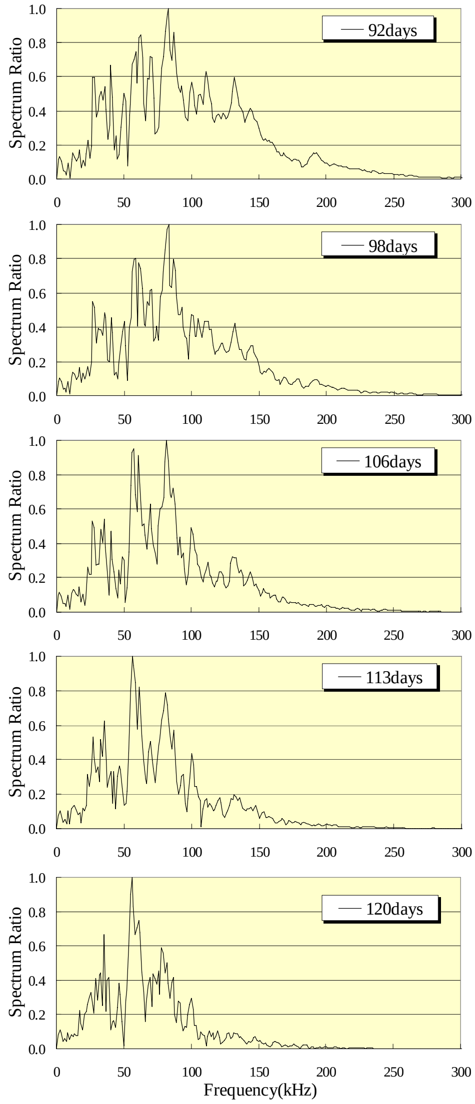


Figure 16. Frequency spectrum

Sensitivity to ASR expansion. The result of this experiment showed that average frequency and received total energy had sensitivity to ASR expansion variation whereas propagation velocity did not display such sensitivity.

In order to investigate sensitivity of velocity on expansion in this experiment, velocity variation (Figure 11(a)) was broadened as shown in Figure 14. It was observed that both the amount and the gradient of velocity variation had similar rates before and after crack initiation time as shown in Figure 14. In contrast, the other two characteristics dropped immediately before crack initiation and lacked sensitivity to ASR expansion after crack initiation as shown in Figures 11(b) and 11(c). These several experimental results are consistent with the correlation curves as shown in Figure 1. From this investigation, the three characteristics are considered to have different sensitivities to ASR expansion.

Figures 15 and 16 show the measurement results for 5 times just prior to crack initiation comprising the received wave (Figure 15) and the frequency spectrum (Figure 16). The received amplitude was calculated as an amplitude ratio to the maximum amplitude at day 92. The maximum intensity values of the frequency spectrum were converted to one. Crack initiation was found at day 120. Peak frequency values remained constant at 57kHz or 83kHz before crack initiation and shifted to 57kHz after cracking occurred. Peak frequency showed no significant change for ASR expansion. On the other hand, spectrum ratios decreased clearly within a frequency band of 100kHz to 150kHz. The frequency band of 100kHz to 150kHz is relatively sensitive to ASR expansion before crack initiation.

Accuracy for ASR measurement. The data dispersion of velocity was relatively small. However, the velocity sensitivity to ASR expansion was less compared to the other two indices. It is not enough to catch a subtle change of ASR expansion.

The scatter of the data points of received total energy was not small. The used couplant is an unstable material when applied constantly to a measuring place in the same layer. Typical concrete surfaces are not flat completely, and this flaw causes instability for conditions of transducers mounted on the surface of concrete. Consequently, incident energies from transducers are affected by the conditions of the couplant.

The average frequency showed good accuracy in terms of the stability on the periodical measurement. Spectrum distributions over the whole band of frequency spectrum were not affected by the difference in propagation energy. The average frequency remains constant regardless of the varying propagated energy, which produces a precise evaluation of ASR expansion.

CONCLUSION

Ultrasonic measurement and investigations of ultrasonic propagation characteristics were carried out to observe the expansion change due to ASR. The three characteristics are propagation velocity, received total energy and average frequency.

1. The three characteristics detect ASR expansion change through decreases of the values.

2. The average frequency has a higher sensitivity to ASR expansion than velocity; the characteristic provides a stable measuring to detect ASR expansion change.

3. The frequency range from 100kHz to 150kHz makes possible the accurate measurement of ASR expansion variation.

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