An investigation of ultrasonic method to monitor expansion of concrete due to ASR

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Abstract

This paper discusses an investigation of an ultrasonic testing method to monitor an expansion progress due to alkali-silica-reaction (ASR). A concrete specimen including aggregates with an ASR potential was made for the experiment. Measuring ASR expansion with strain gauges, ultrasonic testing was periodically carried out for 568 days between a maximum concrete temperature of 35°C in summer and a minimum concrete temperature of 5°C in winter. Direct and Semi-direct transmission modes were used to investigate three characteristics: an ultrasonic pulse velocity (UPV), a received total energy (RTE) calculated by a received wave amplitude, and an average frequency (AF) calculated by a frequency distribution. The three indices decreased with the expansion change in the direct transmission method. The RTE and the AF were more sensitive than the UPV to detect for the ASR expansion changes. The AF held a stable change in spite of the irregular result of the RTE. The UPV and the RTE grasped the expansion change by the decrease of the indices in the semi-direct transmission method. However, the AF did not have the same measurement accuracy as the direct transmission method. The results from the experiment revealed that the ultrasonic testing method has a potential to identify the expansion due to ASR. Additionally, it was found that the two transmission methods and three indices obtained by the measurement improve the measurement accuracy by using them at the same time.

***Keywords**: alkali-silica-reaction; non-destructive method; monitoring; ultrasonic testing*

1. INTRODUCTION

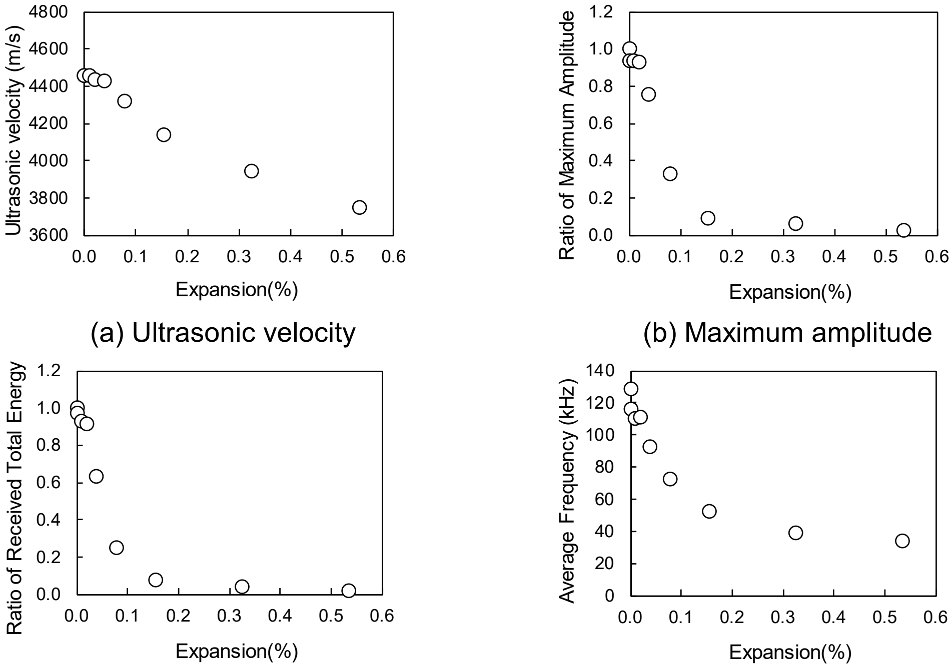
In Japan, many concrete structures were constructed in the 1970s. During that time, a relatively large number of structures were damaged by alkali-silica-reaction (ASR). More than 40 years later, despite the beginning of pre-ASR measures in the 1980s, ASR has not completely disappeared and a maintenance of these structures is becoming increasingly important. Non-destructive measurements enable the maintenance to carry out a periodic diagnosis without damaging the structures. It is an useful method for observing the progress of the generated ASR.

There are mainly two applications for the use of an 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 [1]. ASTM C597-16 (2002) describes the standard test method for measuring ultrasonic pulse velocity (UPV) of a specimen or structure [2]. UPV is one of the effective methods to check concrete quality. However, the amount and type of aggregate have a strong influence on UPV versus strength relationship [3].

The ultrasonic device is composed of two transducers. The ultrasonic pulse transmitted from one transducer to another is stable and propagates inside the concrete. The ultrasonic method is considered to be a useful technique for maintaining and managing ASR where the inside of concrete is to be observed regularly.

UPV decreases with changes in ASR expansion [4]. Besides, the indices such the amplitude or the frequency obtained from the received waveform also decrease with the ASR expansion. Correlations between the ASR expansion coefficients and ultrasonic propagation characteristics are shown in Figure 1.1 [5]. The characteristics are indices obtained from ultrasonic measurements such as the amplitude of received waves and the frequency spectrum. These indices are discussed in the chapter 2.5. The ultrasonic velocity almost decreased in proportion to the expansion as shown in Figure 1.1(a). The maximum amplitude, the received total energy and the average frequency greatly decreased until 0.1%, and after that it was a slow change as shown in Figure 1.1(b),(c) and (d). These results show the possibility that be able to monitor the ASR expansion change by using some indices to be provided by the ultrasonic measurement. However, this experiment is a result under the environment of 20 °C and 60%. There is a past study that the attenuation and energy loss of the received waves are greatly affected by the coupling of the transducers and are not suitable for field monitoring [6].

In this study, cylindrical concrete specimens using aggregates that generate ASR were manufactured. To investigate a monitoring method using the ultrasonic testing for ASR concrete, ultrasonic measurements were conducted for 562 days in an environment affected by outside air temperature.



(a) Ultrasonic velocity (b) Maximum amplitude

(c) Received total energy (d) Average frequency

Figure 1.1: Correlation between ASR expansion and ultrasonic propagation characteristics [5]

2. EXPERIMENT

2.1 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 2.1. The mixture proportion of the concrete used is summarized in Table 2.1. 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) [7]. 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 as shown in Figure 2.2. The minimum cover thickness was 50mm and an elastic adhesion bond was used at each attachment between the bars to avoid a restraint for the 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.

2.2 Curing of specimen

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

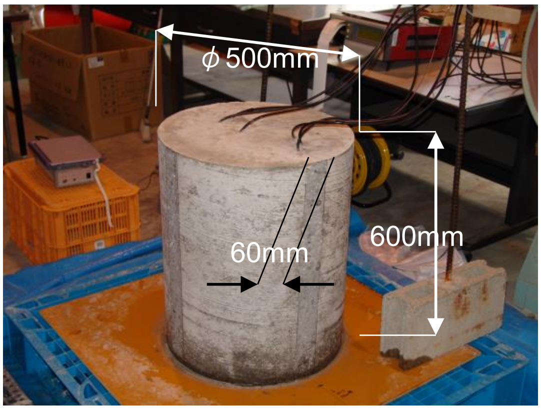
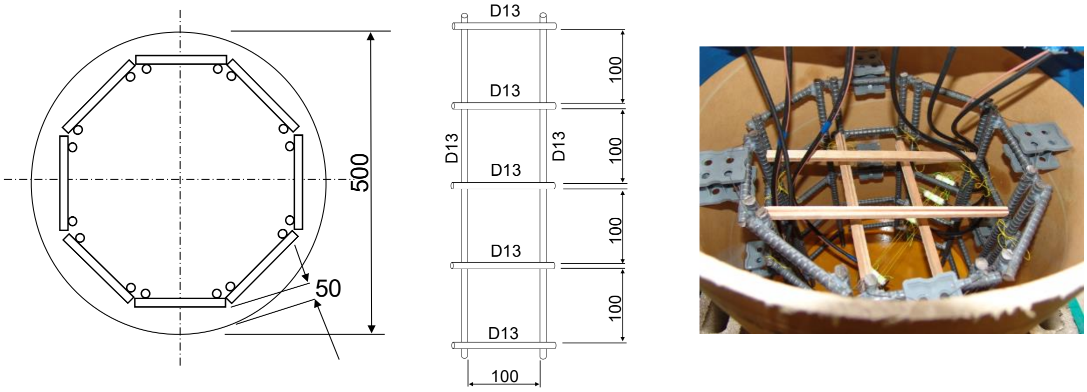


Figure 2.1: Concrete specimen

Table 2.1: 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

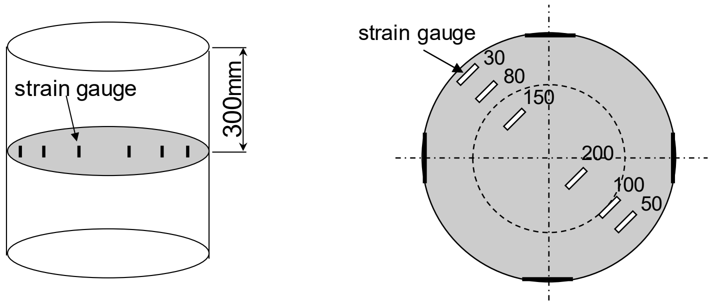


(a) Rebar appearance (b) Rebar appearance (1 unit) (c) Rebar and Strain gauges

Figure 2.2: Rebar layout of the specimen

2.3 Expansion measurement of specimen

Six strain gauges were set to measure ASR expansion as shown in Figure 2.3. They were embedded 30, 50, 80, 100, 150, and 200 mm from the lateral surface of the cylinder and 300 mm from the top surface of the cylinder. 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 and a measurement was recorded automatically every hour.



(a) Installation height (b) Plane arrangement

Figure 2.3: Installation position of embedded strain gauges

2.4 Ultrasonic measurement

For the direct transmission, the two transducers were set at 500 mm intervals, two directions (M1-M3 and M2-M4) with upper and lower level positions, as shown in Figure 2.4(a). For the semi-direct transmission, the two transducers were set four pairs (M1-M2, M2-M3, M3-M4 and M4-M1) with upper and lower level positions, as shown in Figure 2.4(b). The transducers had a diameter of 40 mm, a resonant frequency of 500 kHz, and an applied voltage of 500 V. The setup is shown in figure 2.5.

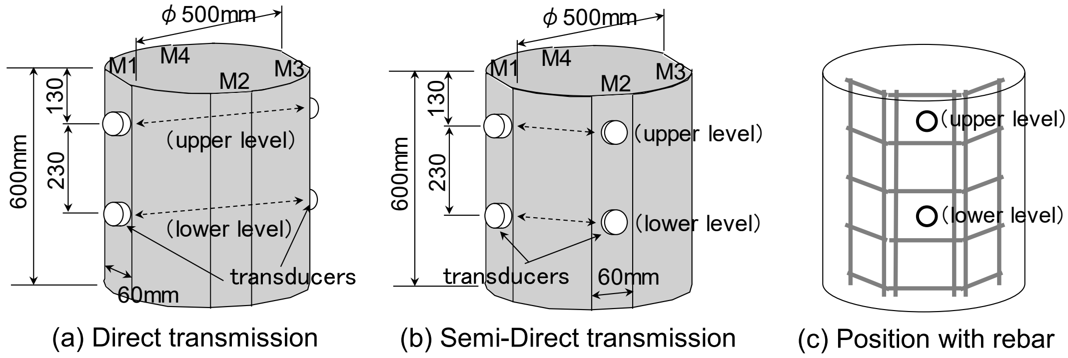


Figure 2.4: Measurement method and height position

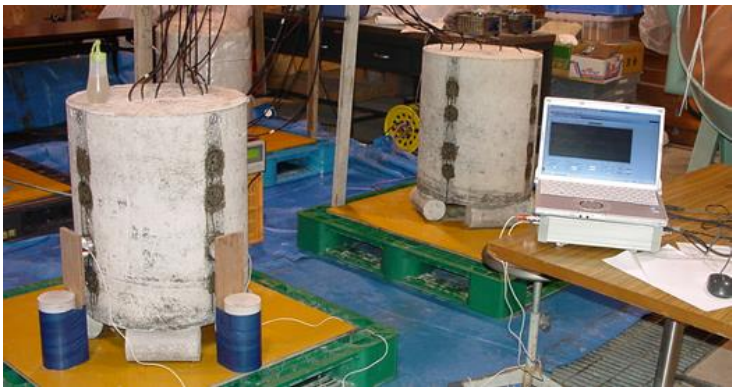


Figure 2.5: Measurement by ultrasonic method and installation of the transducers

2.5 Ultrasonic propagation characteristics

Three characteristics were used to investigate ASR expansion variation: ultrasonic pulse velocity (UPV), received total energy (RTE), calculated by a received wave amplitude, and average frequency (AF), calculated by a frequency distribution as shown in Figures 2.6 and 2.7. The propagated energy (hereinafter referred to as received total energy) is the integrated area bounded by the received wave line and the zero line of amplitude as shown in Figure 2.6 and added values multiplying the received amplitude by the sampling time. The average frequency is frequency indices corresponding to half values of the area bounded by the frequency spectrum as shown in Figure 2.7.

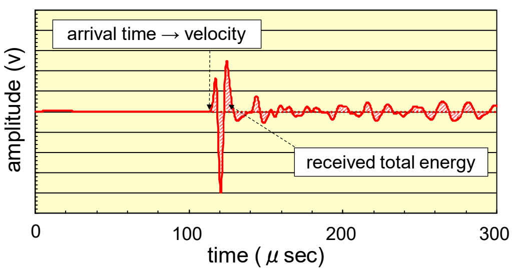


Figure 2.6: Received wave

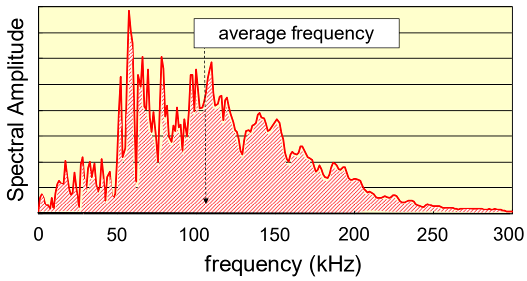
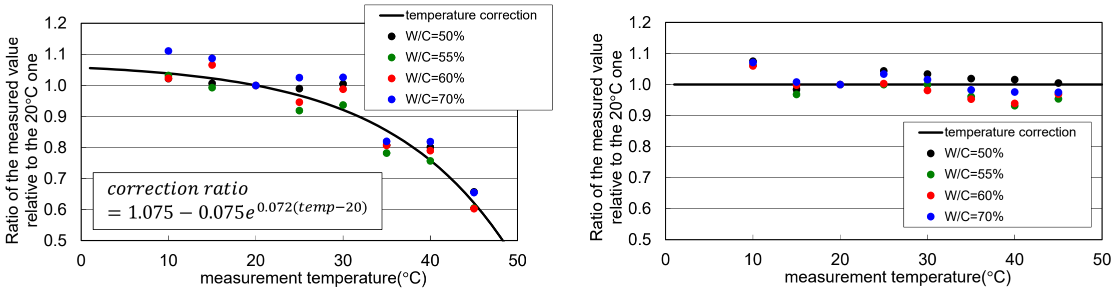


Figure 2.7: Frequency spectrum

2.6 Correction of couplant influence

A water-soluble grease was used as a coupling agent not to leave it after the measurement. The result of a measurement by the use of the couplant changes under the influence of temperature and humidity. Figure 2.8 shows relationships between outside temperature and RTE [8], AF. All measured RTE and AF values were rated into the ratio with the value in 20°C. In this experiment, RTE was converted by the influence of temperature, AF did not consider it. The viscosity of the couplant decreases by absorbing moisture in the air. However, controlling an exposure time is difficult. Using a container that is not easily exposed to air, it was applied just before the measurement.



(a) RTE [8] (b) AF

Figure 2.8: The effects of temperature to RTE and AF

3. EXPERIMENTAL RESULT

3.1 Expansion of specimen

Figure 3.1 shows the strain variation inside the specimen for each depth. A downward change in the figure indicates circumferential expansion of the specimen. On day 120, the occurrence of cracks were

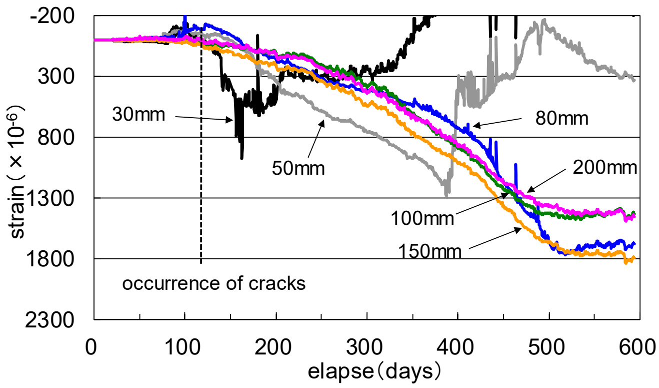


Figure 3.1: Measured result of strain gauges

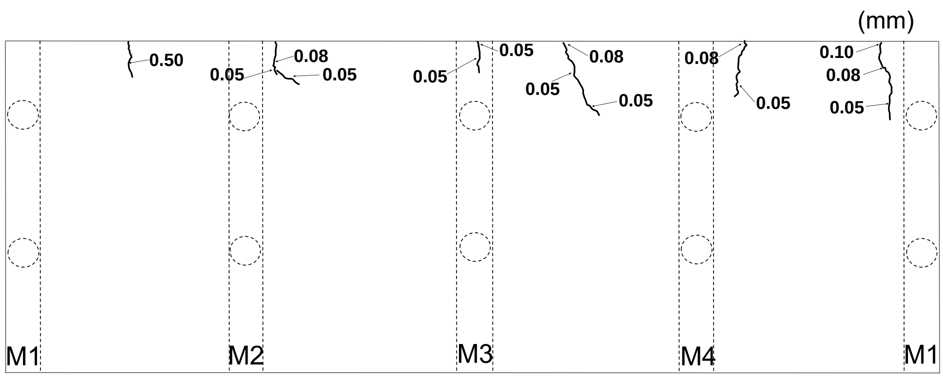


Figure 3.2: Crack distribution on days 120 (lateral side of the specimen)

found around the upper part of the specimen as shown in Figure 3.2. Depths 30 and 50 mm changed rapidly around the 160th and 390th days. At depths 80, 100, 150, and 200 mm, the expansions of the specimen continued until the 500th day, and no change in expansions were observed after the 500th day.

3.2 Temperature of specimen

Figure 3.3 shows the concrete temperature change inside the specimen for each depth. There was no temperature difference for each depth. Since the temperature was not controlled, the difference in concrete temperature was 30°C, from the maximum temperature of 35°C in summer to the minimum temperature of 5°C in winter.

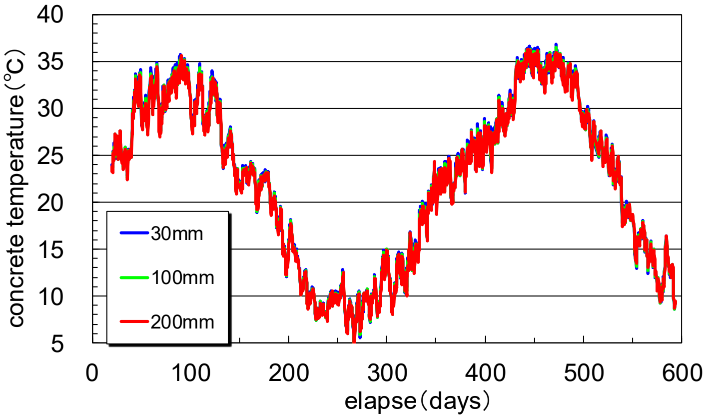


Figure 3.3: Concrere temperatuire in the specimen

3.3 Ultrasonic propagation characteristics

3.3.1 Direct transmission

The measurement locations M1-M3 and M2-M4 indicate two directions, as shown in Figure 2.4(a). The measurement results are shown in Figure 3.4 and Figure 3.5. The values of the vertical axis are the ratio for the maximum during the measurement period. The results of the UPVs were enlarged as shown in Figure 3.6 and 3.7.

All indices decreased according to strain changes. The three indices of the upper level and the AF indices of the lower level had a period not to change on the way from day 200 to day 350. The degree of the change of each index had a bigger at the upper level than that of the lower level. The RTEs were scattered for up to 300 days. The AFs, however, decreased accurately in spite of the varied RTE.

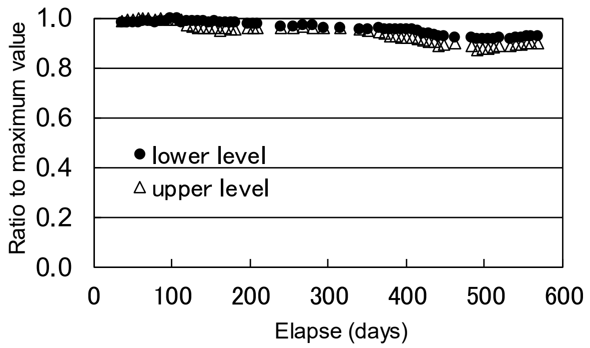
The UPVs were about 10 % lower than the maximum value within the whole measurement period. The RTEs decreased by 70 ~ 80 %, and the AFs decreased by 50 ~ 60 %. The changes of both the RTEs and the AFs with respect to the strain change in concrete was bigger than the UPVs.

3.3.2 Semi-direct transmission

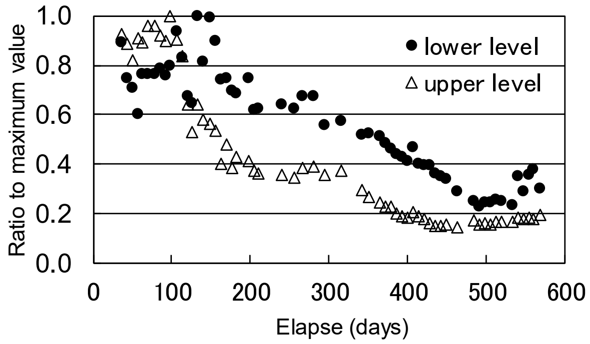
The measurement locations M1-M2, M2-M3, M3-M4, and M4-M1 indicate four directions, as shown in Figure 2.4(b). The measurement results M1-M2 are shown in Figure 3.8. The values of the vertical axis are the ratio for the maximum during the measurement period. The result of UPVs were enlarged as shown in Figure 3.9. The three following directions (M2-M3, M3-M4 and M4-M1) are shown in Figure 3.10 to Figure 3.15.

The two indices of the UPVs and the RTEs showed the variations that were similar to the strain change until day 500. Both indices showed a slight increasing tendency after the 500th day. The AFs, unlike the direct transmission method, showed a regular change partially. The change in all measurement periods was a lack coherence.

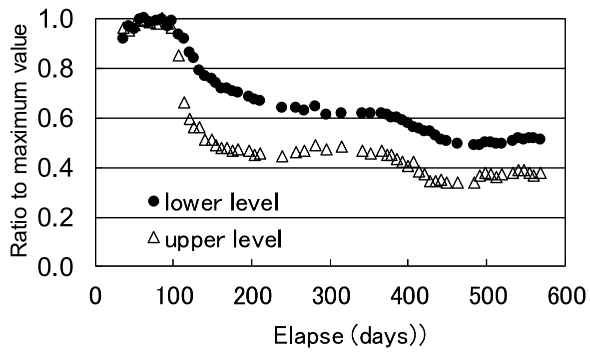
The UPVs were about 10 % lower than the maximum value within the whole measurement period and the RTEs decreased by 80 %. The changes of the RTEs with respect to the strain change in concrete were bigger than the UPVs.



(a) UPV

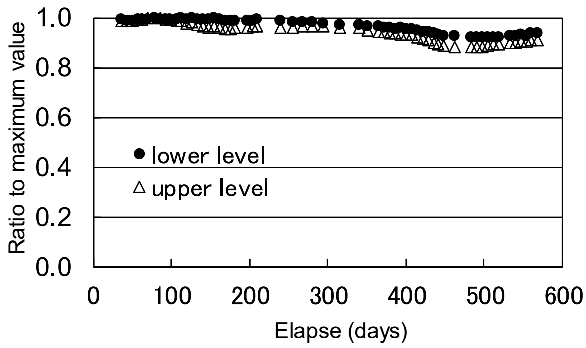


(b) RTE

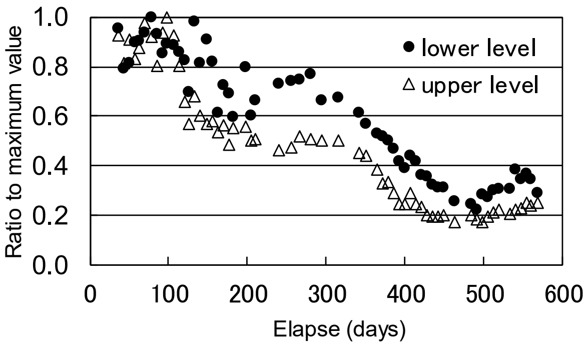


(c) AF

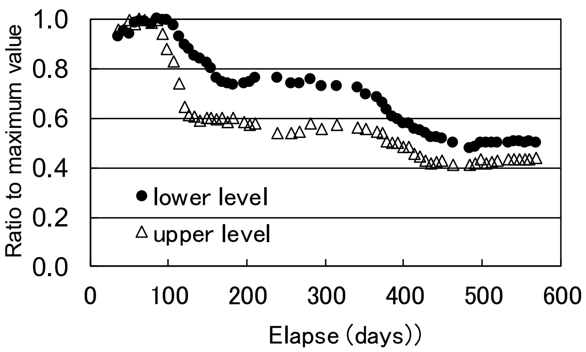
Figure 3.4: Direct transmission (M1-M3)



(a) UPV



(b) RTE



(c) AF

Figure 3.5: Direct transmission (M2-M4)

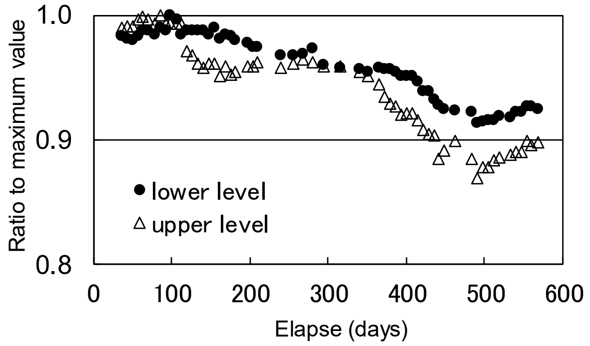


Figure 3.6: Direct transmission (M1-M3)
(Expand the vertical axis of UPV)

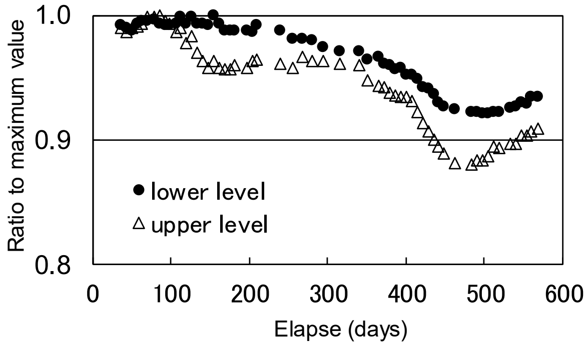
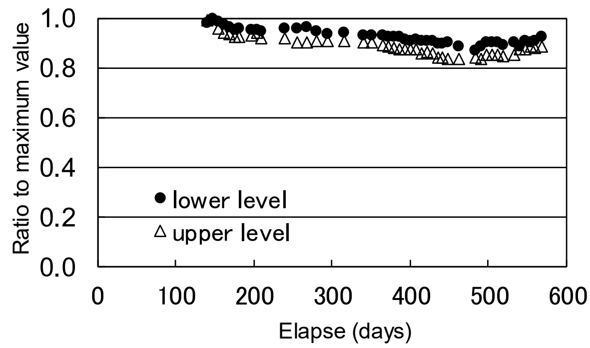
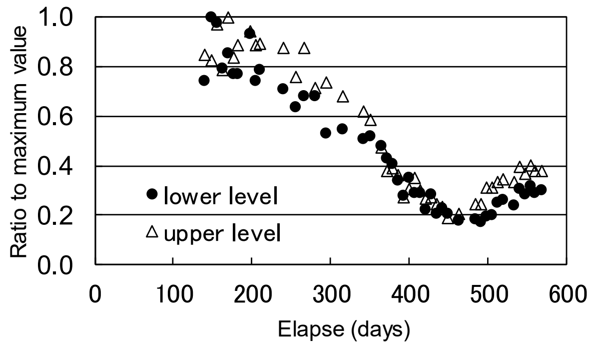


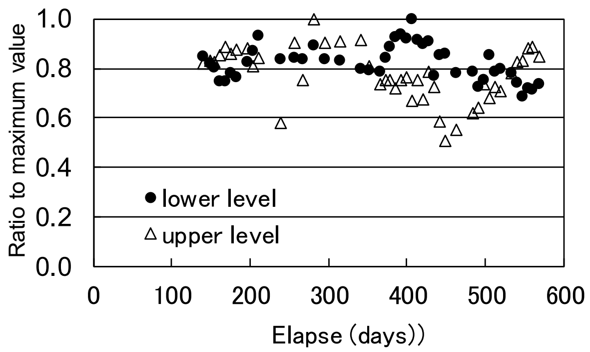
Figure 3.7: Direct transmission (M2-M4)
(Expand the vertical axis of UPV)



(a) UPV

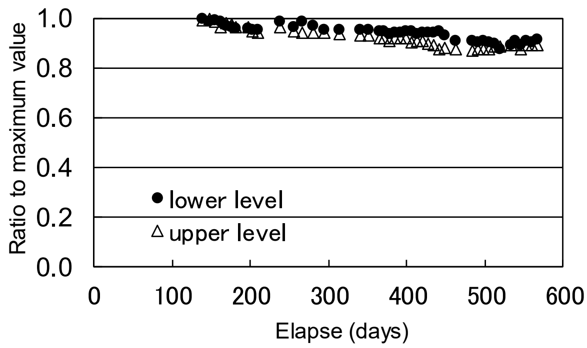


(b) RTE

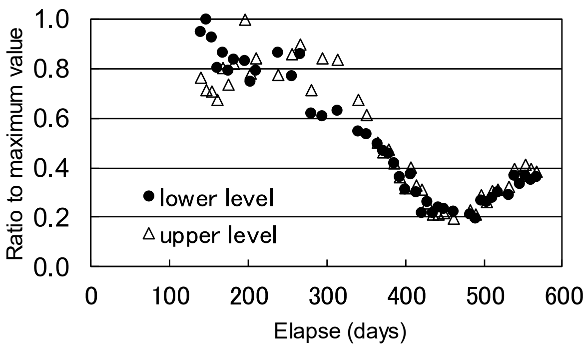


(c) AF

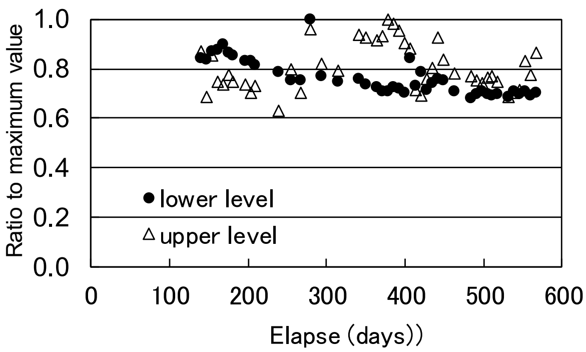
Figure 3.8: Semi-direct transmission (M1-M2)



(a) UPV



(b) RTE



(c) AF

Figure 3.10: Semi-direct transmission (M2-M3)

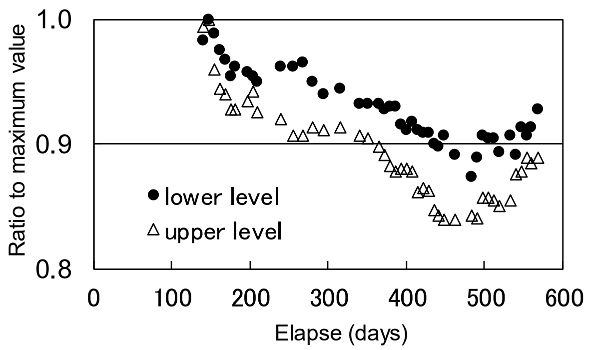


Figure 3.9: Semi-direct transmission (M1-M2)
(Expand the vertical axis of UPV)

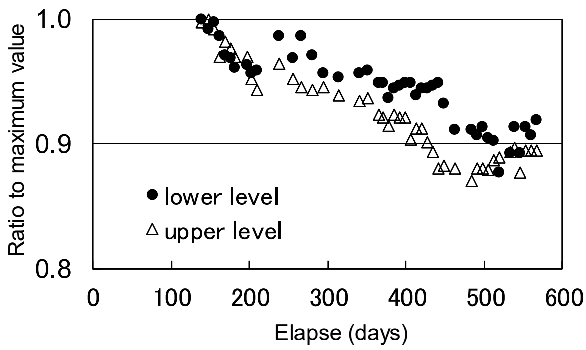
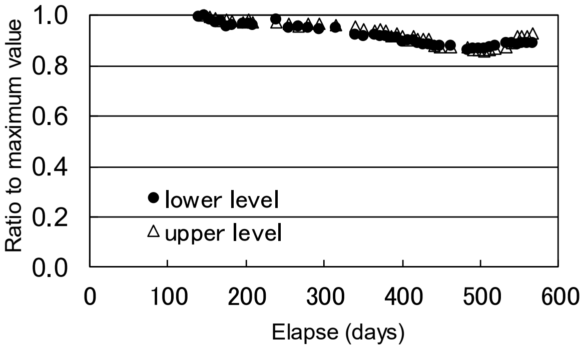
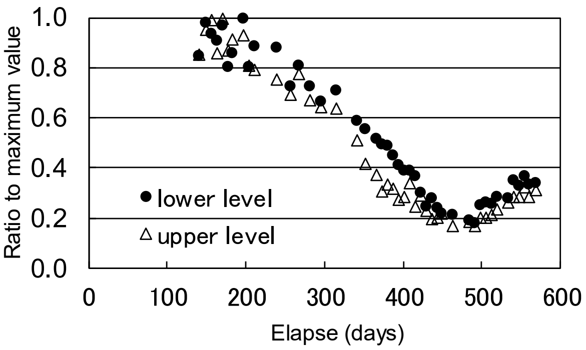


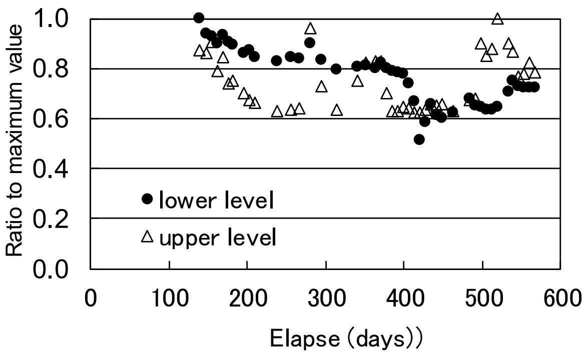
Figure 3.11: Semi-direct transmission (M2-M3)
(Expand the vertical axis of UPV)



(a) UPV

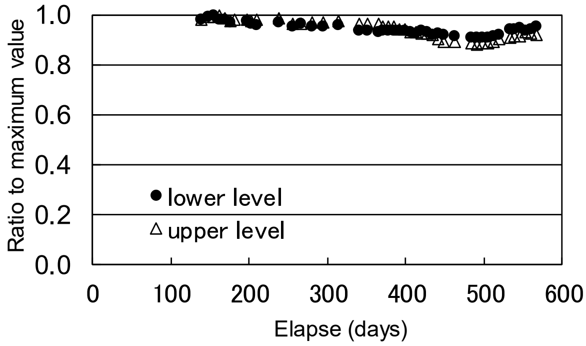


(b) RTE

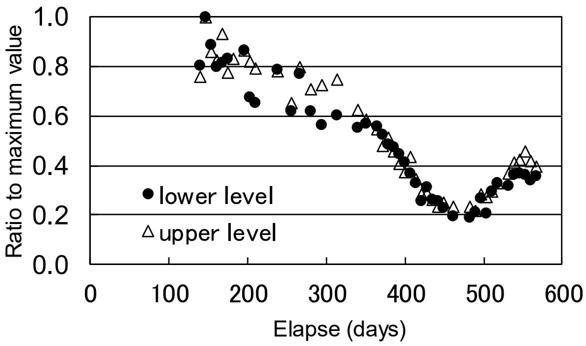


(c) AF

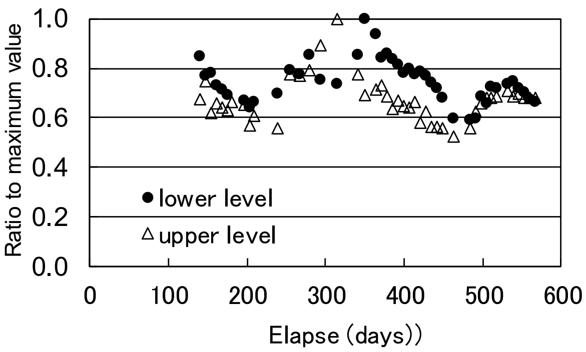
Figure 3.12: Semi-direct transmission (M3-M4)



(a) UPV



(b) RTE



(c) AF

Figure 3.14: Semi-direct transmission (M4-M1)

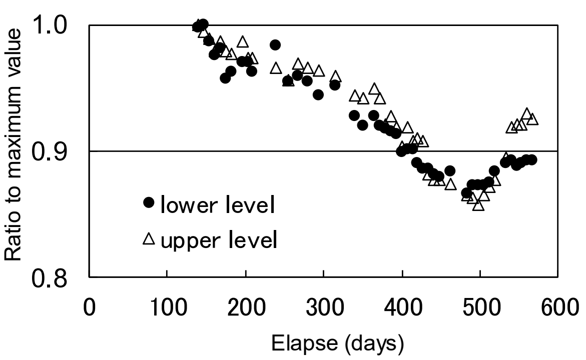


Figure 3.13: Semi-direct transmission (M3-M4)
(Expand the vertical axis of UPV)

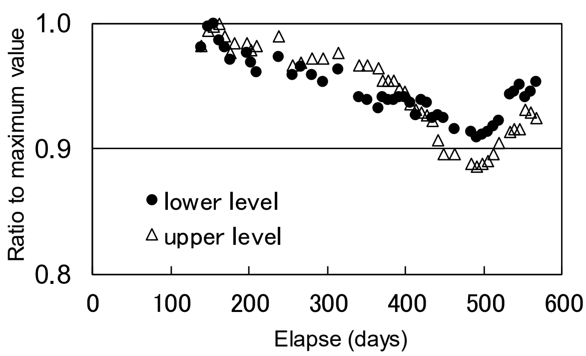


Figure 3.15: Semi-direct transmission (M4-M1)
(Expand the vertical axis of UPV)

4. DISCUSSION

4.1 Expansion due to ASR

The specimen concrete continued to expand even during the winter when the temperature fell from day 150 to day 250 as shown in Figure 3.1 and Figure 3.3. This strain change probably demonstrates that the expansion of the specimen was due to ASR. As the temperature increased from day 250 to day 450, ASR was accelerated, and the deterioration influenced the strain change rate. Stopping the water supply, which was to keep a wet state on the surface of the specimen, slowed the expansion after 500 days. Disordered strain changes at 30 and 50 cm depth seems to be due to occurrences of cracks at the gauge position in the specimen.

Figure 4.1 shows the condition of cracks with a width of 0.2 mm or more at the end of measurement. The fact that many cracks were observed in the upper part of the specimen (Figure 3.2 and 4.1) suggests that the ASR expansion was relatively advanced in the upper part.

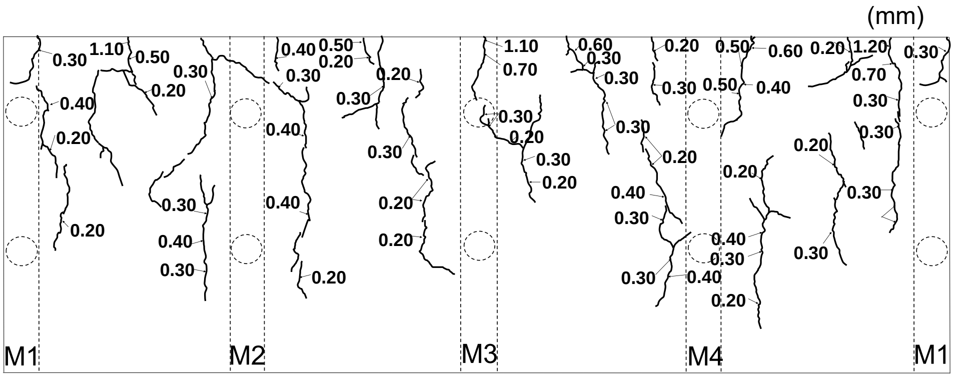


Figure 4.1: Crack distribution on the end (lateral side of the specimen)

4.2 ASR monitoring capability

4.2.1 Direct transmission

The three indices, which were UPV, RTE and AF (Figure 3.4 ~ 3.7), decreased with the expansion of the concrete specimen. The decreases in the UPV with respect to the concrete expansion were similar to previous research results [6, 9]. The rate of the total changes during the measurement period that the RTEs and the AFs were greater than the UPVs. The RTEs and the AFs are more sensitive than the UPVs to detect for the ASR expansion changes.

The degree of the change of each index had a bigger at the upper level than that of the lower level. The occurrence of cracks at the top of the specimen (Figure 3.2 and 4.1) indicate an early concrete expansion of the upper part. The three indices were able to measure the difference of the expansion.

The irregular result of the values in the early stage of the RTEs, which were similar for all results in this study, was due to the method of setting the transducers on the specimen in which the degree of adhesion between the transducers and the specimen, was not stable. After the 300th day, the measurement was stable.

From the 200th day to the 300th day, there are two possible influencing factors during the unchanged period. The expansion changes shown in Figure 3.1 are the strain changes in the circumferential direction. On the other hand, the wave propagation direction is the diameter direction of the cylindrical specimen. The amount of the expansion change was probably not large in the diameter direction. The second factor is a hardening of viscosity of the couplant in winter. The concrete temperature was below 10°C. It is necessary to investigate further on the effects of viscosity in the environment below 10°C (Figure 2.8). The UPVs and the RTEs increased even though the specimen did not expand after the 500th day. The uptrend seems to be due to the ASR gel filling, which was confirmed as a white precipitate on the specimen.

AF is the value calculated from the received wave as shown in Figure 2.7. The AFs were not affected by the irregular result of the RTEs in the early stage.

4.2.2 Semi-direct transmission

The UPVs and the RTEs grasped the expansion change by the decrease of the indices (Figure 3.8 ~ 3.15). The increase of the two indices, after the 500th day, seems to be due to the ASR gel filling. Matching the expansion direction with the measurement direction led to improvement in the RTE measurement accuracy.

On the other hand, the AFs did not have the same measurement accuracy as the direct transmission method. The AF values were 40 ~ 50 kHz (M1-M2 and M2-M3), 40 ~ 80 kHz (M3-M4 and M4-M1). The AF values by the direct transmission method were 40 ~ 90 kHz. The frequency band, which is 40 ~ 50 kHz, is probably the lack of capacity to grasp the expansion change due to ASR.

5. CONCLUSION

The ultrasonic measurement was carried out to investigate the potential to monitor the expansion change due to ASR. Three characteristics were examined: an ultrasonic pulse velocity (UPV), a received total energy (RTE), calculated by a received wave amplitude, and an average frequency (AF), calculated by a frequency distribution.

1. The three indices decreased with the expansion change in the direct transmission method. The RTE and the AF were more sensitive than the UPV to detect for the ASR expansion changes. The AF held a stable change in spite of the irregular result of the RTE in the early measurement time.

2. The UPV and the RTE grasped the expansion change with the decrease of the indices in the semi-direct transmission method. The AF did not have the same measurement accuracy as the direct transmission method.

The accuracy of the ASR monitoring is affected with the relationship between the expansion direction and the measurement direction, and the frequency band obtained from the received wave.

The direct transmission method and the semi-direct transmission method have a potential to monitor the expansion change due to ASR. However, the precision of the three indices, which are UPV, RTE and AF, were different between the two methods. On the other hand, an use of the two ways at the same time permits the monitoring to improve its accuracy.

The measurement result for 568 days indicates that this ultrasonic method has a possibility of the monitoring outside in environmental changes. However, the influence of humidity was not considered in this study. It is necessary to investigate further on the effects of the humidity.

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