# The Estimate for Deterioration Due to Alkali-Aggregate Reaction by Ultrasonic Methods

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**ABSTRACT**

In this study, the deterioration of a reinforced concrete structure due to alkali-aggregate reaction was estimated by using ultrasonic methods.

Tests were carried out for concrete with reactive bronzite andesite crushed stone and total equivalent $Na_2O$ of 6 $kg/m^3$. The specimens were cured in the chamber with 40°C and 100% relative humidity for two months after the age of 14 days.

The pulse velocity was measured during the accelerating curing period, and after the age of 10 months, the spectral analysis of ultrasonic pulse waves transmitted through concrete was applied to estimate the deterioration.

The pulse velocity of test specimens decreased abruptly with compressive strength and modulus of elasticity because of deterioration due to the reaction. On the other hand, the velocity of concrete core slightly decreased due to the residual expansion after sampling the core, and then it increased to more than the velocity of the test specimen because the silicate gel formed by the reaction may be filled in the cracks.

It is easy to estimate the deterioration due to the reaction by the ultrasonic pulse velocity method and the spectral analysis of ultrasonic pulse waves transmitted through concrete proposed in this study.

## 1. INTRODUCTION

Recently, extensive map cracking and expansion in existing concrete structures caused by alkali-silica reaction (ASR) have been found in Japan. It may be very important to estimate the degree of deterioration of concrete due to ASR by nondestructive testing of concrete in order to maintain the structures.

In this study, ultrasonic pulse velocity method and ultrasonic spectroscopy were used to estimate the internal texture changes of concrete due to ASR. The term of "ultrasonic spectroscopy" was first used by O. R. Gericke who devised and patented, a device which ultrasonic echo pulses from internal discontinuities in a test specimen could be displayed on an oscilloscope along with their frequency spectra. He demonstrated the diagnostic possibilities of his technique in materials evaluation (Brown 1982). It is necessary to measure the pulse-echo and to use the broad band transducers in his technique. Although the ultrasonic pulse attenuation coefficient of concrete is very large and hence the pulse-echo through concrete is very difficult to measure, the degree of deterioration due to ASR can be estimated by the response function of concrete specimen which was calculated by the application of the linear system theory to the ultrasonic spectral analysis.

## 2. RESPONSE FUNCTION OF CONCRETE BY LINEAR SYSTEM THEORY

The response function h(t) of material in a linear system may be obtained by the inverse Fourier transform of the ultrasonic frequency response $H(\omega)$. When the input signal to the transmitter is constant, $H(\omega)$ of concrete specimen can be obtained from the Fourier transform of two outputs from the transducer and the transducer-specimen systems **Figure 1** :

$$H(\omega)=Y(\omega)/Y^{o}(\omega) \quad (1)$$

where $Y(\omega)$ is a Fourier transform of the output signal from a system, the overscript $^{o}$ means the transducer system and $\omega$ is angular frequency.

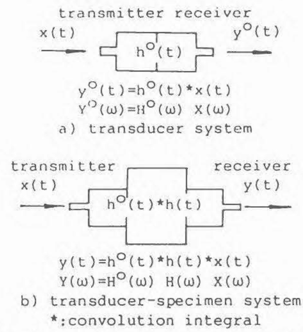
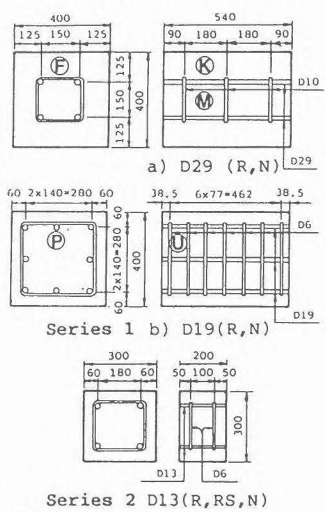



**Figure 1** Relation between Input and Output in Linear System

## 3. TEST PROGRAMS

### 3.1 Test Specimens

Two series of tests were made, in Series 1, the effect of a thickness of concrete cover upon the changes of concrete properties due to ASR was examined. In Series 2, the effectiveness of the silica fume in reducing the expansion due to ASR was examined by the spectral analysis of the transmitted ultrasonic pulse wave. The details of the test specimens are shown in **Figure 2.**




Note ○ is sampling position

**Figure 2** Specimens and Arrangements of Reinforcing Bars

All the concrete was made from a mix with W/C=0.50, S/a=0.44 and W=176 kg/$m^3$ and, in Series 2, 25% silica fume, by weight of cement was used. (Mix:**RS**)

The following materials were used:

- Ibi river sand as normal fine aggregate;
- Bronzite andesite crushed stone as reactive coarse aggregate (Mix:**R**) and Takatsuki crushed stone as normal aggregate(Mix:**N**), maximum size=20 mm;
- Ordinary portland cement containing 0.95% equivalent $Na_2O$;
- silica fume containing 1.97% equivalent $Na_2O$ and 85.4% $SiO_2$.

In order to accelerate the reaction, the total equivalent $Na_2O$ of reactive concrete was 6 kg/$m^3$ which was adjusted by the addition of NaOH.

The specimens of Series 1 were cured under the accelerated condition of

40°C and 100% RH for two months after curing for two weeks under the wet blanket, and then they were left in the laboratory room until sampling by coring. In Series 2, they were cured under the accelerated condition after curing in water (20±1 °C) for two weeks.

3.2 Test Procedures

In Series 1, the pulse velocity was measured in accordance with ASTM C 597-83 while the reaction was accelerated. After 10 months, concrete cores with the diameter of 68 mm were taken from the test specimens. Compressive strength and modulus of elasticity of the cores were measured after the measurement of the residual expansion by Lenzner's method (1978) and pulse velocity.

In Series 2, the response function h(t) of concrete specimens at the age of 72 days was calculated by the fast Fourier transform method as follows: the rectangular impulse having 1 μs in width and 22 volt in amplitude produced by a function generator was impressed on the transmitter, and the measurement was carried out to obtain the mean of 50 times the Fourier transform Y(ω) of the output signal with a sampling interval of 2.44 μs and a data length of 10 ms. The signals were analyzed up to the frequency of 102.3 KHz. The transducers of PZT-7 with resonance frequency of 100 KHz set in stainless steel cases were used.

## 4. TEST RESULTS AND DISCUSSIONS

4.1 Series 1

**Figure 3** shows the changes of pulse velocity of concrete encaged by longitudinal bars and stirrups while the reaction was accelerated. The pulse velocity of deteriorated test specimen **R** decreased abruptly to about 90% of the normal **N**. After about two months from the beginning of the accelerating curing, the pulse velocity of deteriorated concrete remained constant. Extensive map cracking due to ASR was observed as shown in **Figure 4**.

**Figure 4** illustrates the ratios of pulse velocities measured by the direct and the semi-direct ultrasonic pulse methods. As these ratios are nearly equal 1, it may be concluded that concrete within and outside longitudinal bars and stirrups has been identically deteriorated by ASR. The pulse velocity by semi-direct method should be greater than by direct method if there are few cracks within the reinforcement cage due to the restraint by these bars.

**Table 1** and **Figure 5** illustrate, respectively, the properties and the

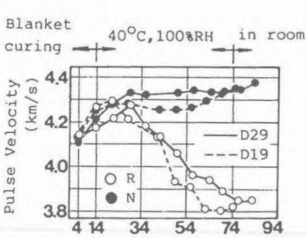
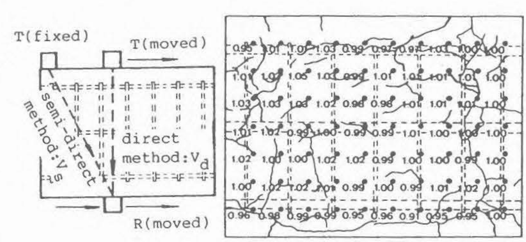



**Figure 3** Change of Pulse Velocity by ASR in Series 1




$V_d$:Pulse velocity by direct method
$V_s$:Pulse velocity by semi-direct

**Figure 4** Ratio ($V_s/V_d$) of Pulse Velocity and Pattern of Map Cracking by ASR stress-strain curves of the core sampled after the age of 10 months. Although the strength and the modulus of elasticity of normal concrete was higher at 10 months than that 28 days, the strength of deteriorated concrete was about 70% of that at the age of 28 days and the modulus of elasticity was also only about 45%. In addition, the relative value of critical stress of deteriorated concrete core also decreased to about 50%, compared to about 90% for normal concrete. The relative values of critical stress of concrete near the center of deteriorated specimen was smaller than near the surface.

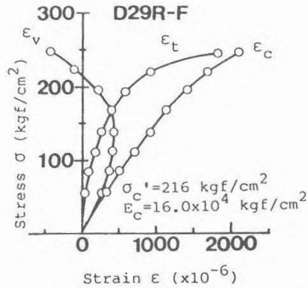



**Figure 5** Stress-Strain Curve of Deteriorated Concrete Core

**Figures 6** and **7** show the changes of the pulse velocity and the residual expansion of concrete cores sampled after the age of 10 months respectively. Although the pulse velocity of the normal concrete core was slightly decreased by drying, that of the deteriorated concrete core decreased until a minimum velocity was reached when it held almost constant and then recovered to near or more than that of test specimen. It may be concluded that this recovery of pulse velocity is caused by the silicate gel filling the cracks. The pulse velocity of deteriorated concrete cores (D19R-P, D29R-M) within reinforcement cages changed much more than that of the cover concrete core D29R-K.

**Table 1** Properties of concrete core in Series 1

| concrete | compressive strength (kgf/cm²) | modulus of elasticity (x10⁴ kgf/cm²) | critical stress level: specimen | coring position | near surface | near center |
|---|---|---|---|---|---|---|
| normal | 388(1.22) | 32.2(1.15) | D29 | K | 0.90 | 0.93 |
| ASR | 266(0.69) | 12.8(0.44) | D29 | E | 0.55 | 0.37 |
| | | | D29 | F | 0.57 | 0.50 |
| | | | D19 | u' | 0.55, 0.6 | |

( ):ratio of concrete core to 28 days

The residual expansion of concrete cores became larger with the restriction of expansion by reinforcing steel; a corresponding change of pulse velocity was also noted. As the pulse velocity method is more easily applicable than the measurement of residual expansion by Lenzner's method in both field and laboratory testing, the former method may be advantageous for assessing the degree of deterioration due to ASR.

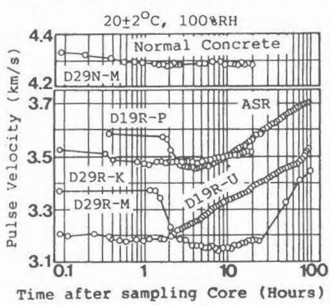



**Figure 6** Changes of Pulse Velocity of Concrete Cores

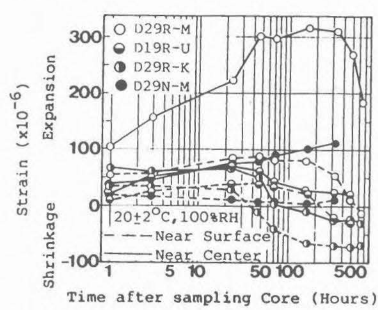



**Figure 7** Changes of Residual Expansion of Deteriorated Concrete

4.2 Series 2

**Figure 8** shows the change of pulse velocity of the concrete specimens in

Series 2. The pulse velocity of deteriorated test specimen **R** had decreased to about 90% of normal specimen **N** similar to what was found in Series 1. On the other hand, the velocity of specimen **RS** containing silica fume was larger than the normal specimen **N**, and extensive map cracking and expansion due to ASR were not found in this specimen until the age of 2 years. The use of 25% silica fume by weight of cement is effective in preventing deterioration due to ASR.

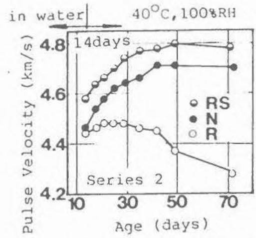



**Figure 8** Change of Pulse Velocity

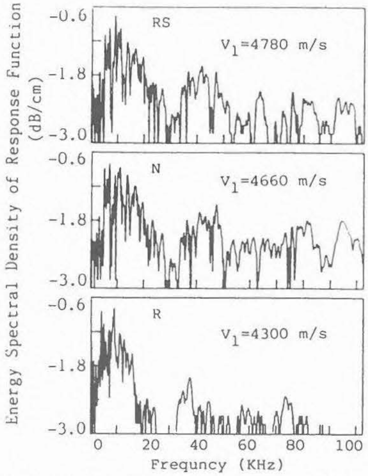



**Figure 9** Energy Spectral Density of Response Function

The energy spectral density of response function of concrete specimen are shown in **Figure 9.** The response functions of specimen **RS** and **N** were roughly similar; the waves with frequencies up to 100 KHz were transmitted readily. But in specimen **R** with cracks and low pulse velocity due to ASR, the attenuation of waves with frequency higher than 20 KHz was greater and these waves practically did not transmit.

The degree of deterioration of concrete due to ASR can be estimated by the spectral analysis of ultrasonic pulse waves passing through concrete by the application of the linear system theory.

## 5. CONCLUSIONS

1) Alkali silica reaction damaged the interior concrete of the reinforcement cage as well as cover concrete. Pulse velocity of concrete damaged was decreased to about 90% compared with normal concrete. Compressive strength of cores was decreased to 70% and modulus of elasticity to 45%. In addition, the relative value of critical stress also decreased to about 50%.
2) The pulse velocity of deteriorated concrete cores decreased slightly immediately after sampling, and then recovered up to or greater than the velocity of the test specimen. The residual expansion due to ASR can be estimated by the pulse velocity method more easily than Lenzner's method.
3) The more severe the deterioration of concrete due to ASR, the more the ultrasonic pulse through the concrete was attenuated. Spectral analysis of ultrasonic pulse waves passing through concrete can be used for evaluating internal texture changes due to ASR by the application of linear system theory.
4) It is easy to estimate the deterioration of concrete due to ASR by the ultrasonic methods proposed in this study.

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