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Elastic Wave Property of Concrete Decomposed by Steam Pressure Cracking Agent

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Abstract: A steam pressure cracking (SPC) agent is a method that can dismantle concrete safely and quickly. In previous studies, the authors showed that the direction of the crack could be controlled by the tensile stress at the induction holes and not by the compressive stress at the SPC hole. We demonstrate that the compression elastic wave changes to a tensile wave when the wave is reflected at the free surface of the induction hole. We also examined the properties of the concrete by developing an elastic wave measuring system that is difficult to break down even in high-temperature, wet, and radiation environment. The elastic wave velocity change in the four concrete types was less than 4%. It was found that the standard deviation value, σ, changed four times. Therefore, it is possible to determine the deterioration of the internal structure of concrete using the standard deviation value σ, which indicates the dispersion of the elastic wave velocity.
Keywords: Concrete demolition; Steam pressure cracking; Elastic wave velocity; Elastic wave reflection.

1. Introduction

The demolition of concrete by a steam pressure cracking (SPC) [1] agent can enable the dismantling of concrete safely and quickly [2–4] because there is less vibration than in the blasting method using explosives [5]. An SPC agent was developed by Nippon Koki Co. Japan and contributes to recycling technology [6–8] from the EDG's [9] viewpoint. In previous studies, the authors showed that the direction of cracks can be controlled by inducing holes in concrete specimens [2]. It was clarified that the principle of control is that the elastic wave of compression generated from the SPC changes to tensile elastic waves owing to the free surface of the induction hole. It was shown that it could be controlled and crushed by induction holes in a large concrete. In this study, we measured the elastic wave in concrete and examined the change in elastic wave propagation behaviour. According to previous studies, when the direction of the crack can be controlled, the compressive force generated at the moment of ignition does not cause the cracking of concrete. When this compressive elastic wave propagates and is reflected on the surface of the inductive hole, the direction of the crack can be controlled by generating tensile stress. The Hopkinson effect [10] was applied to concrete that was strongly resistant to compressive stress and weak to tensile stress.

In the controlled cracking of concrete, it can be observed that the behaviour of the elastic wave and the strength of the concrete are key points. Murasaka et al. used the shock elastic wave method for concrete to show that the speed of elastic waves decreases when the compressive strength decreases [11]. Iwanami et al. showed that the velocity of the elastic wave hardly changes as the microcracks increase in concrete, but a scattering of the elastic wave occurs [12]. However, there are no examples of applying the scattering phenomenon of elastic waves to the evaluation of concrete.

In this study, we examined a method to evaluate the deterioration of concrete based on the dispersion state of the elastic wave velocity measurement value of concrete pieces crushed by SPC.

2. Experimental method

2.1 Dismantling concrete samples

To measure the elastic wave, a large concrete is cut with an SPC. The SPC agent can be ignited using a special igniter, and gas can be generated instantaneously. Compared to explosives, because the reaction rate is less than 300 m/s, no shock waves occur, and the vibration can be reduced from 1/2 to 1/5.

Using 240 g of this SPC agent, the size was 1.0×1.0×0.5 m^3. Concrete was crushed [3], and the obtained sample is shown in Figure 1.

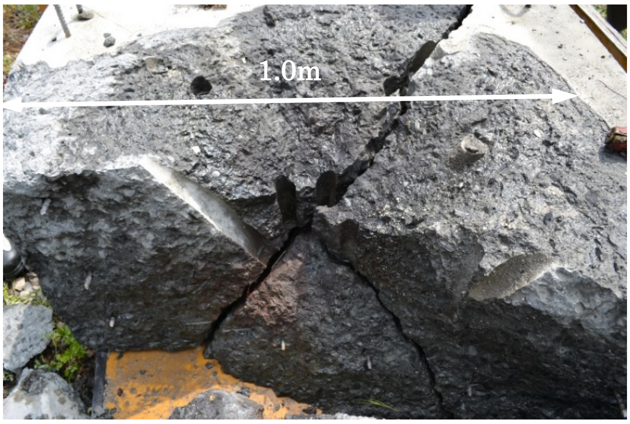

Figure 1. Reinforced concrete cut with SPC

To establish a crush control method using an SPC agent, it is necessary to determine the velocity of the generated elastic wave. In addition, by analysing the elastic wave propagating in the material, it is possible to determine the strength and damage degree of the material. In particular, it is necessary to promptly analyse the characteristics of the materials in a field where landslides and industrial waste are treated; therefore, the speed measurement of elastic waves is an extremely important task.

In this study, we established a method for measuring the velocity of the elastic waves and examined whether the results were appropriate when tested.

2.2 Elastic wave measurement

In this study, a sensor was attached to the specimen at two places at its either end; one side was struck with a metal hammer, and the elastic wave at both ends was observed with a data logger. The rise of the input and reflected waves measured by the sensor was observed with a data logger, and the velocity of the elastic wave was calculated from the phase difference at that time and the length of the specimen. An outline of the test equipment is shown in Figure 2.

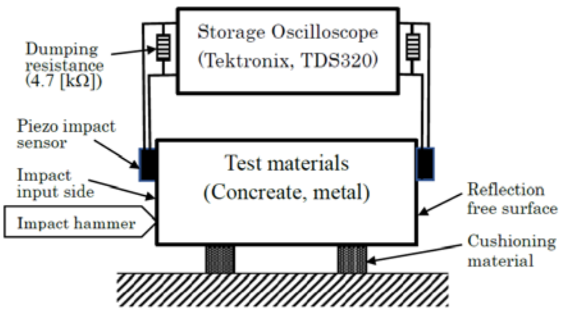

Figure 2. Measurement system for elastic wave velocity of concrete

Because the test to be conducted this time assumes on-site measurements, the sensor should not have an amplifier. A normal sensor in the combination of “strain gauge + DC bridge amplifier” is not suitable for on-site measurements, because it is vulnerable to water wetting and disturbances. Conversely, if it is a measurement by a high sensitivity “piezo type impact sensor + damping resistance”, the measurement accuracy may be slightly reduced, but it is suitable for on-site measurement.

Therefore, in this study, we used the impact sensor PKS-4A1 (40mV/G, 10Hz～higher 3kHz) manufactured by Murata Manufacturing Co., Ltd. In addition, the installation of the sensor was performed by attaching to the specimen using an epoxy resin and impact tests.

For the hammer impact method to achieve small variations in the force to be struck with, the hammer is fixed to a support such as a pendulum which is shown in Figure 3. In the preliminary test, the hammer was impacted at a slope of 10° with a sharp increase in the elastic waves and the smallest variation.

The test procedure is as follows.

1) Bond the sensor to both ends of the specimen with epoxy resin.
2) Connect the sensor to the data logger via a damping resistance.
3) Wait for the data logger to trigger and wait.
4) Strike one end face of the specimen with a hammer.
5) Read the phase difference between the input and reflected waves displayed in the data logger.
6) Calculate the velocity of the elastic wave from the length between the read phase difference and the end face of the specimen.

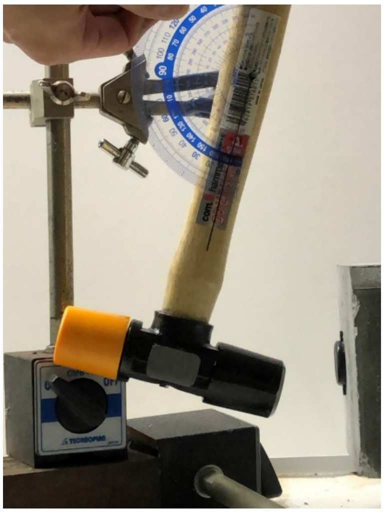

Figure 3. Alignment of the hammer impact method

3. Results and discussion

3.1 Input and reflection of elastic waves produced by hammer strikes

Figure 4 shows the initiation and reflection of the elastic waves produced by hammer strikes in concrete materials, as shown in Figure 1. These data correspond to the surface strain measured by sensors attached to both the input and reflection sides. The input wave is compressive strain, and the reflected wave is changed to tensile strain. This phenomenon demonstrates the hypothesis that tensile strains generate cracks in the concrete.

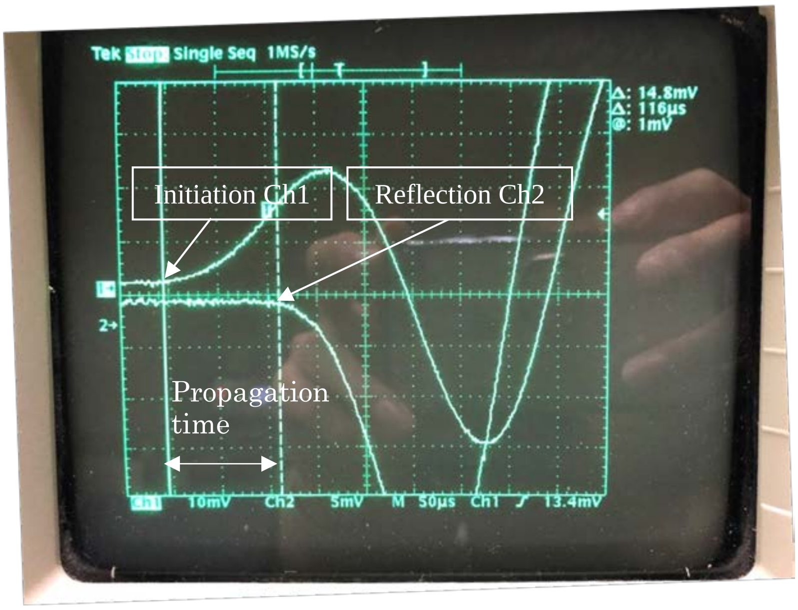

Figure 4. Example of elastic wave measurement in concrete pile Time 50μs/div. Ch1 10mV/div. Ch2 5mV/div.

3.2 Measurement verification with reference materials

The validity of the measurement method used in this study was verified. Al, Cu, and stainless steel as shown in Figure 5, which have known elastic wave velocities, were used as standard specimens, and the validity of this test method was confirmed by examining the error between the conventional value and the data obtained using this method. The number of tests in this test was 10, and the average propagation time was t μs.

The results of elastic wave velocities measured are shown in Table 1.

The accuracy of the elastic wave velocity (EWV) measurement system was high because the fluctuation of the data was lower than ±3% and close to the reference data [13], as shown in Table 1.

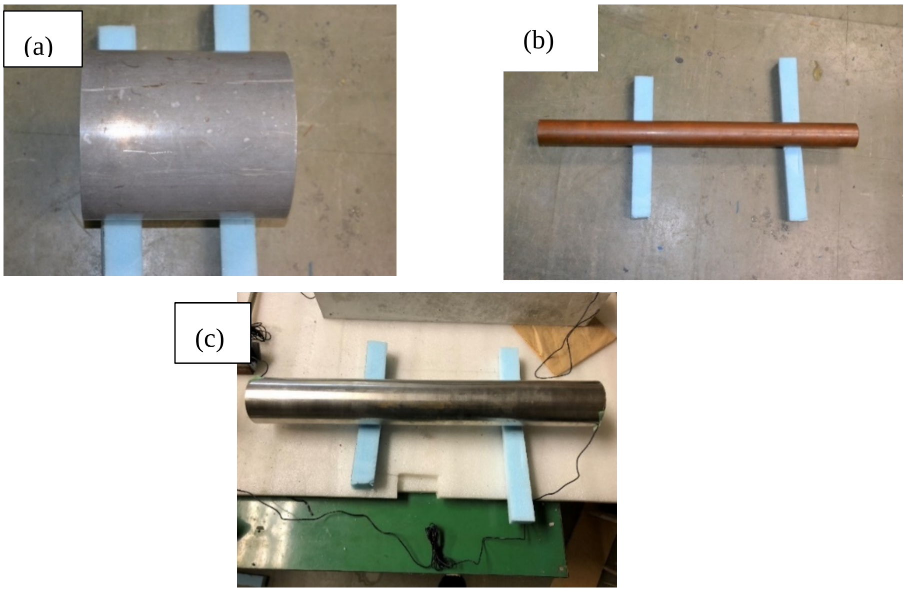

Figure 5. Setting of standard materials for EWV measurement, (a) Al, (b) Cu and (c) austenitic stainless steel (SUS304).

Table 1. Measurement of Elastic wave velocity (EWV) of standard materials.

	Al	Cu	SUS304
Length L[m]	0.195	0.655	0.611
Propagation time t [μs]	29.3±0.8	149±1.0	105±1.0
Mean EWV measured v=L/t [m/s]	6658	4393	5825
Standard deviation of EWV[σ]	127	21	39
Reference data of EWV [m/s] [13]	6420	4760	5790

3.3 Results of concrete EWV and discussion

Because the physical properties of concrete differ depending on the preparation method and hardness, the velocities of the propagating elastic waves vary depending on the specimen.

First, in this test, we measured the velocity of the propagating elastic waves using two types of commercial concrete specimens (pile and cubic) with different end-face distances, as shown in Figure 6(a) and 6(b). Next, the elastic waves propagating through the crushed concrete pieces in the steam crushing test were measured, as shown in Figure 6(c) and 6(d). Thereafter, we verified the measurement results based on the presence or absence of concrete internal cracks, as shown in Figure 7(b). Figures 7(a) and 7(b) show the back sides of the specimens shown in Figures 6(c) and 6(d), respectively. Some cracks did not lead to destruction in the concrete block, as indicated by Figure 7(b).

The elastic wave signals can be observed by the oscilloscope, as shown in Figure 8(a)–(d), corresponding to Figure 6(a)–(d), respectively. In Figure 8(a), the left edge of the oscilloscope screen is the moment of impact of the hammer (t= 0 s), indicating that the strain due to the elastic wave after the right end was struck was 500 μs. The compression strain above the centre of the screen and the lower side shows the tensile strain. In this case, it can be observed that the elastic wave propagated by compression is converted to tensile strain by reflection after 116 μs. These tensile strains generated lead to crack initiation at the free surface and controlled crack propagation because the tensile strength of concrete is lower than its compressive strength [14]. The output data are presented in Table 2.

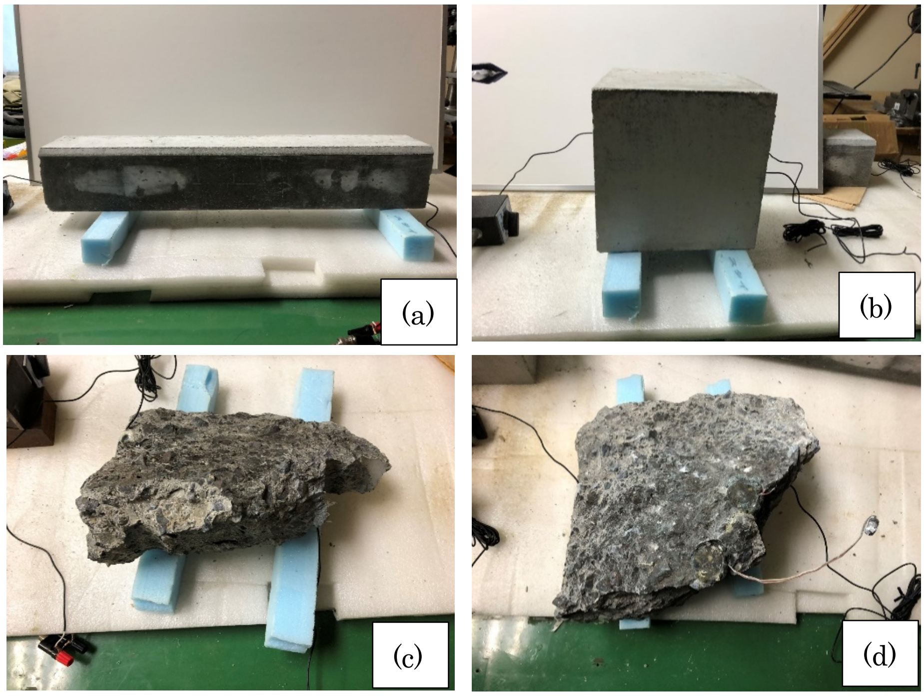

Figure 6. Concrete test pieces for EWV measurement, (a) pile of 100×100×600 mm^3, (b) cube of 200×200×200 mm^3, (c) crushed piece having approximately 400 mm length without cracks, (d) crushed piece having approximately 300 mm length with cracks.

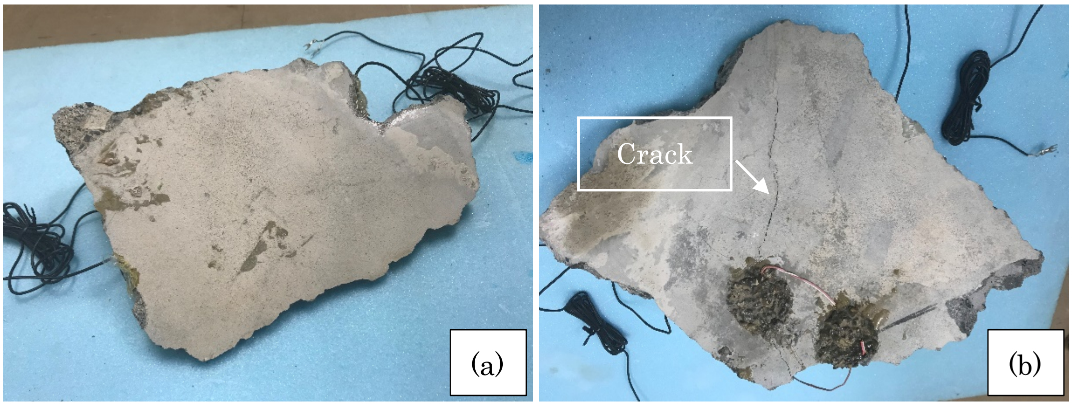

Figure 7. Concrete test pieces crashed by the steam pressure cracking agent, (a) piece having approximately 300 mm length without cracks, (b) piece having approximately 400 mm length with cracks.

3.4 Normal distribution of elastic wave velocity measurements

The data was analysed from a statistical perspective. It was assumed that the EWA data followed a normal distribution (Gaussian distribution). Figure 9 and 10 show the cumulative distribution of the EWA when the vertical axis is the standard normal deviation, Z. The equation for Z is as follows:

$$Z = \frac{(X-\mu)}{\sigma} \tag{1}$$

where X is the measured EWV data, μ is the mean value of the EWV, and σ is the standard deviation of the

EWV. The values were analysed from the data in Figure 9 and 10 and summarised numerically in Tables 1 and 2.

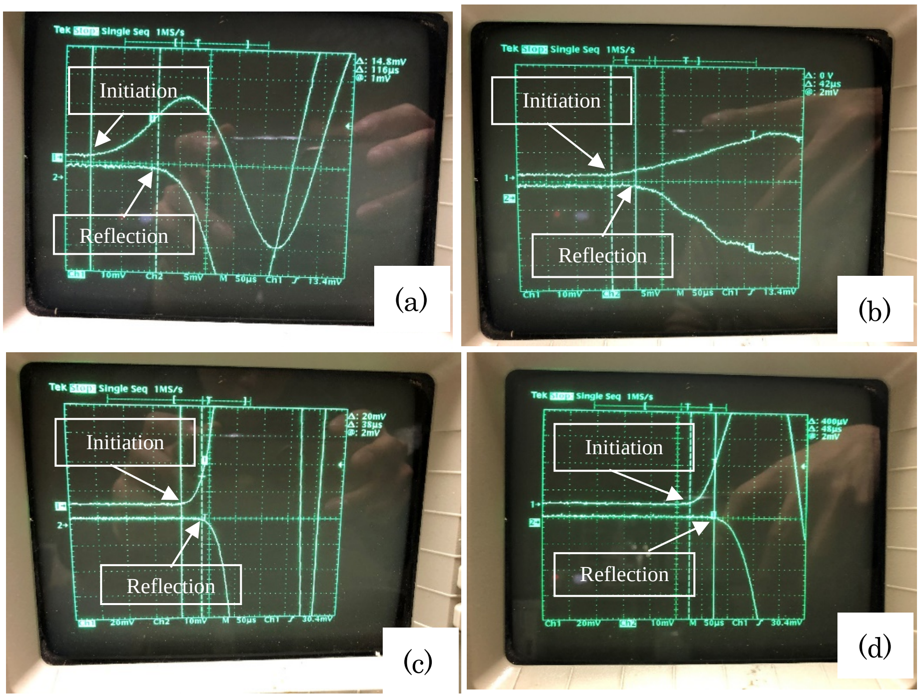

Figure 8 Elastic wave propagations of concrete on oscilloscope, (a) concrete pile having dimensions of 100×100×600 mm^3, (b) concrete cube having dimensions of 200×200×200 mm^3, (c) crashed concrete having no cracks, (d) crashed concrete with cracks. Time (a)～(d) 50μs/div.
Ch1 (a), (b) 10mV/div. (c), (d) 20mV/div. Ch2 (a), (b) 5mV/div. (c), (d) 10mV/div.

Table 2. Measurement of Elastic wave velocity (EWV) of concretes.

	Pile type	Cube type	Fragment without crack	Fragment with crack
Length L[m]	0.60	0.20	0.19	0.22
Traveling time t [μs]	126.0	41.6	40.0	44.7
Average EWV v=L/t [m/s]	4763	4808	4757	4937
Standard deviation of EWV σ	52.3	149.3	138.4	227.2

The error of the measurement system in this study was lower than 8% when compared with the reference data in Table 1. The standard deviation, σ, was lower than 127 m/s, as shown in Figure 9. These data indicate the accuracy of the system.

Regarding the concrete data, the test results in Table 2 show that the velocity of the elastic waves propagating in any specimen ranged from 4763 to 4937 m/s, and there was no significant change within 3.7%. The mean values of the EWV measurements cannot be used to evaluate changes in concrete properties, such as the existence of cracks, because the error of this system is 8%. Conversely, the difference in deviation (D_σ [%]) between the concrete fragments without cracks (σ_0) and with cracks (σ_c) will be considered.

$$D_\sigma = \frac{(\sigma_c - \sigma_0)}{\sigma_0} \times 100\% \quad (2)$$

In this study, D_σ was calculated to be 65%, which is a significant difference, and this value can be used for the inspection of concrete integrity.

The EWV value can be theoretically calculated using Equation (3) [12].

$$EWV = \sqrt{\frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)}} \quad (3)$$

where E is the elastic modulus, ρ is the specific gravity, and ν is the Poisson's ratio. When the volume ratio of the concrete aggregate increased, the elastic wave velocity increased because the elastic modulus E increased [12]. When the internal defects of concrete are repaired with different materials, the elastic wave velocity can be observed [15]. In addition, rock has been investigated based on the change in the elastic wave velocity [16]. When the elastic modulus and specific gravity change, the deterioration of the concrete can be determined by changing the elastic velocity. When a large crack is present, the propagation distance may increase owing to elastic wave turning, and the apparent elastic speed may be reduced [16]. In general, the elastic wave velocity does not change because of the presence of cracks [11, 12]. When the crack or delamination defect is close to the sensor, it can be detected by observing the reflected wave from the defected surface [17, 18]. However, because the position of defects at a construction site would be unknown, it would be difficult to expect a reflected wave from such defects.

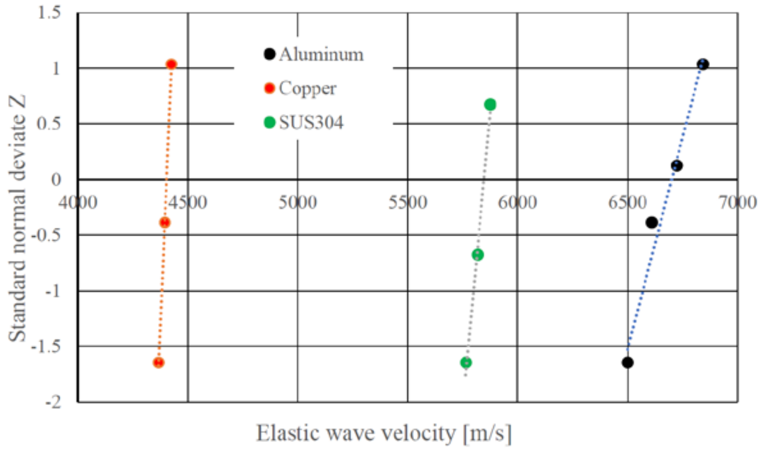

Figure 9. Cumulative distribution of EWV data of metals

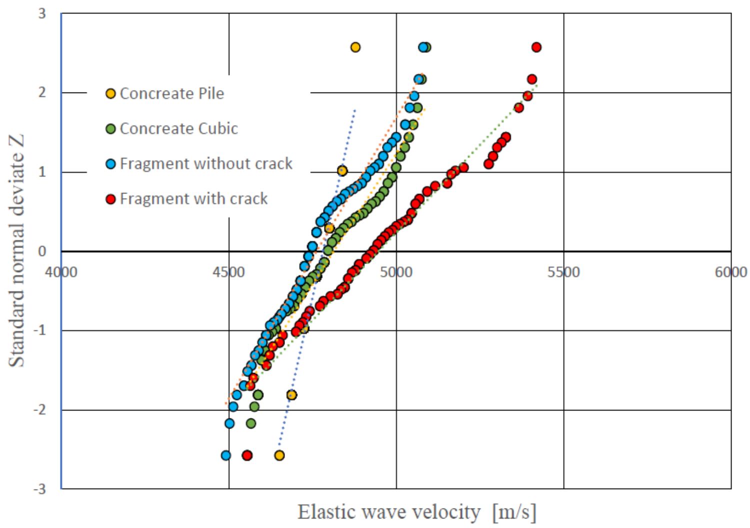

Figure 10. Cumulative distribution of EWV data of concreate

However, it has been reported that the frequency characteristics change because of the scattering and absorption of elastic waves owing to the presence of microcracks [6]. The scattering and absorption of elastic waves owing to cracks inherent in concrete are thought to be based on the frequency, energy levels, and crack density. In this experiment, it was considered that the standard deviation of the measured elastic velocity changed because the elastic wave was scattered by the presence of a crack. It was concluded that the degree of internal damage of concrete can be analysed by the dispersion of the elastic wave velocity due to repeated impacts.

4. Conclusions

We previously developed a quick and safe decommissioning method for reinforced concrete using an SPC agent. In this study, we examined the changes in concrete properties using an elastic wave measuring system that is difficult to break down even in a high-temperature, wet, and radiation environment. From this study, the following conclusions are drawn.

1) We demonstrated that the compression elastic wave changed to a tensile wave when the wave was reflected at the free surface of the concrete. The presence of elastic waves at this tensile strain is essential for crack control.

2) Using the proposed simple test method, we accurately measured the velocity of elastic waves propagating in the concrete.

3) The elastic wave velocity change in the four concrete types was less than 4%. It can be presumed that it is difficult to determine the degree of composition change and deterioration of concrete by the propagation velocity.

4) Assuming that the elastic wave velocity is measured under normal distribution, it is found that the standard deviation value σ changes four times. Therefore, it is possible to determine the deterioration of the internal structure of concrete using the standard deviation value σ, which indicates the dispersion of the elastic wave velocity.

5) In SPC-crushed concrete, it was revealed that the standard deviation of the elastic wave velocity measurements of cracked debris increased by 65% when compared with concrete those without cracks.

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