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Evaluation of concrete degradation depending on heating conditions by ultrasonic pulse velocity

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HIGHLIGHTS

- Concrete of similar compressive strengths has different UPV depending on elastic modulus.
- UPV can measure expansion of crack width in concrete by cooling.
- UPV can decreases sharply during heating when thermal strain exceeds static fracture strain.
- Proposed method is anticipated to allow integrity evaluation of concrete during heating.

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ABSTRACT

As the mechanical properties of concrete subjected to high-temperature heating decrease due to continuous degradation, it is necessary to evaluate the integrity of concrete in real time. Hence, the degradation monitoring (continuous integrity evaluation) of concrete subjected to high-temperature heating was examined by employing ultrasonic pulse velocity. In this study, the mechanical properties and the ultrasonic pulse velocity in concrete subjected to high-temperature heating were evaluated for ordinary-strength to ultra-high-strength concrete. To measure the ultrasonic pulse velocity in concrete during high-temperature heating, transducers were contacted to the top and bottom surfaces of the concrete specimens using SUS bars. This enabled monitoring of concrete degradation due to heating. In a range of 200–300 °C, it was confirmed that the thermal strain coincides with the static fracture strain at room temperature. The cracks generated during heating and the expansion of the cracks after cooling were clearly confirmed by continuous measurement of the ultrasonic pulse velocity. The cracks generated at temperatures up to 300 °C had little effect on the decrease in compressive strength. However, it was confirmed that the elastic modulus continuously decreased, because the cracks generated during heating and expanded after cooling led to strain increase at the peak stresses. Therefore, the evaluation method proposed in this study is anticipated to allow the integrity evaluation of concrete at high temperature heating.

1. Introduction

The mechanical properties of concrete degrade when it is exposed to high temperature due to the physical and chemical changes in the constituent materials. In addition, since the internal structure of high-strength concrete is dense due to a considerable amount of binder content, it is likely to undergo spalling [1], and its mechanical properties will significantly degrade when exposed to high temperatures [2–4]. Therefore, the integrity of concrete degraded due to exposure to high temperatures needs to be evaluated.

The ultrasonic pulse velocity method was employed to evaluate the integrity of concrete subjected to high-temperature heating. The method has a number of advantages, such as low influence on the structure tested, a simple evaluation procedure, and the ability to evaluate the changes in the internal structure of concrete.

Previous studies on the integrity evaluation of concrete have proposed equations to estimate the compressive strength of concrete and criteria for evaluating the integrity by measuring the ultrasonic pulse velocity in concrete [5–7]. In addition, Yang et al. [8] proposed an equation for estimating the compressive strength of concrete exposed to high temperatures, considering

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various design compressive strengths of concrete. Similarly, Benedetti [9] and Lie et al. [10] evaluated the residual mechanical properties and the integrity of concrete exposed to fire condition. In recent years, ultrasonic pulse characteristics such as propagation time and amplitude have been used to evaluate the degradation of concrete. Shah [11,12] studied the harmonic wave generation on loading in concrete specimens of standard size and of 150 mm cubic size. Moreover, [13] investigated cracks in concrete structures using the interaction of ultrasonic pulse. In these studies, the ultrasonic pulse velocity and the mechanical properties of concrete were evaluated after concrete degradation has already progressed. However, since concrete is being continuously degraded during high-temperature heating, it is necessary to evaluate the integrity of concrete during the heating. Also, in order to clarify the correlation between the ultrasonic pulse velocity and mechanical properties of concrete, it is necessary to evaluate it both during and after the degradation has progressed.

In this study, the ultrasonic pulse velocity in concrete was measured before, during, and after the heating process by a portable ultrasonic non-destructive digital indication tester (PUNDIT) for 30, 70 and 110 MPa concrete specimens as shown in Fig. 1. In addition, the relationship between the ultrasonic pulse velocity and the mechanical properties of concrete exposed to high-temperature was investigated.

2. Experiment

2.1. Experimental plan

Table 1 presents the experimental plan of this study. The concrete specimens with design compressive strengths of 30, 70, and 110 MPa were heated to target temperatures of 100, 200, 300, 400, 500, 600, and 700 °C at a heating rate of 1 °C/min. The stress–strain relationship, residual compressive strength, residual elastic modulus, thermal strain, water vapor pressure, permeability of the concrete specimens, and the ultrasonic pulse velocity in the concrete specimens before, during, and after heating were determined.

Table 1
Experimental plan.

f_{ck}	Heating method	Heating temp. (°C)	Test item
30 70 110	Heating to target temp. at 1 °C/min	100 200 300 400 500 600 700	• Stress–strain • Residual compressive strength • Residual elastic modulus • Thermal strain • Water vapor pressure • Permeability • Ultrasonic pulse velocity (before, during, after heating)
	Temp. maintaining after heating to target temp. at 1 °C/min	100 200 300	• Ultrasonic pulse velocity during heating

2.2. Mix proportion and material

Table 2 presents the mix proportions of the concrete. Water-to-binder ratios of 0.55, 0.33, and 0.19 were used, and cylindrical specimens of $\varnothing 100 \times 200$ mm dimensions were employed. And Table 3 presents the physical properties of the materials used in concrete fabrication.

2.3. Preparation of specimens

Concrete cylindrical specimens of a 100-mm diameter and 200 mm height were fabricated for high-temperature heating in accordance with ASTM C192-Making and Curing Concrete Test Specimens in the Laboratory. The specimens were cured in water for seven days after demolding, and subsequently, cured in a

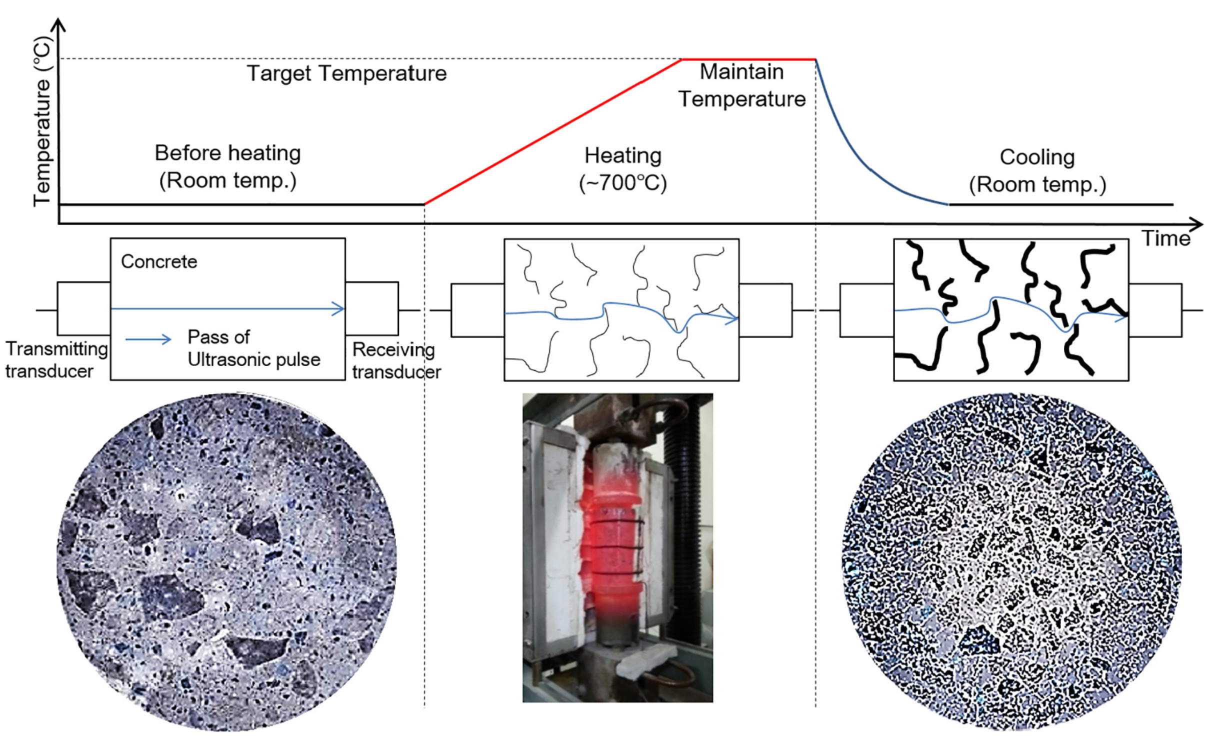

Fig. 1. Outline of this study.