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Evaluation of residual mechanical properties of concrete after exposure to high temperatures using impact resonance method

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HIGHLIGHTS

- Measurement of dynamic elastic modulus is proposed to increase accuracy of measurement on concrete sample.
- Degraded dynamic elastic modulus is not recovered in air re-curing condition.
- Estimating equations for tensile and compressive strengths are proposed based on measurement of dynamic modulus.

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ABSTRACT

After exposure to high temperature, concrete suffers degradation of its mechanical properties, such as its mechanical strength and elastic modulus, and these residual properties must be evaluated using various destructive and nondestructive methods in order to determine the durability of concrete structures. This study aims to investigate the change in the dynamic elastic modulus of concrete after exposure to high temperature depending on various experimental conditions including mixture proportions, exposure temperatures, post-fire storing period, and post-fire curing regimes. For this purpose, an improved impact resonance method is proposed for measuring the identical resonance frequency of the sample and for evaluating the dynamic elastic modulus, and an experimental study is performed on a total of 350 concrete samples. Accordingly, the estimating equations were obtained in order to evaluate the tensile and compressive strengths of the concrete samples based on a correlation analysis with the measured dynamic elastic modulus.

1. Introduction

When exposed to high temperatures, e.g., in fire accidents, concrete structures encounter various endothermic phenomena, such as loss of evaporable water, dehydration of constituent materials, and changes in chemical compositions, which accordingly induce contact-type defects in the concrete [1–3]. This results in degradation of the concrete's mechanical properties, such as its compressive and tensile strength and elastic modulus. In previous research, experimental investigations have been carried out to identify the effects of fire on the mechanical properties of concrete made up of various mixture proportions, based on various parameters such as exposure temperature, exposure time, and heating and cooling rates [4–10]. Investigating the degradation of the elastic moduli of concrete at high temperatures is significant for determining the durability of concrete structures, and therefore, many researchers have attempted to evaluate the residual property [11–14], and it has been reported that the exposure temperature and heating ratio have a significant effect on the decrease in elastic moduli up to temperatures of about 800 °C [1].

The dynamic elastic modulus is larger than the static elastic modulus measured in the same fire-damaged concrete samples [14]. The two types of elastic moduli of concrete differ in terms of the measurement method. The static elastic modulus is generally obtained from the slopes of the stress–strain relationship by using quasi-static loading tests of concrete samples [15,16]. Depending on set a reference points of the slopes of the stress–strain relationship, three types of elastic moduli are defined, namely, the tangent elastic modulus (slope of a tangent line at any location of the curve), the secant elastic modulus (slope of a line passing through the origin and 40% stress of failure load), and the chord modulus (slope of a line passing through two points, strain of 50 μm/m, and 40% stress of failure load). The dynamic elastic modulus is typically measured by an impact resonance

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method, which assumes generation of an infinitesimal instantaneous strain on concrete [17]. Therefore, the measured dynamic elastic modulus can represent the initial tangent modulus of a sample, and it is normally greater than the secant elastic modulus and the chord modulus [15]. Among the methods for measuring the static and dynamic elastic moduli, measurement of the dynamic elastic modulus is considered a nondestructive evaluation technique, and so it presents an advantage of no additional damage to the sample.

Among the several experimental methods to determine the dynamic elastic modulus of fire-damaged concrete, the impact resonance method is the most typically used method that measures the resonance frequency of cylindrical or prismatic shaped concrete samples in accordance with ASTM C 215 [17], and the resonance frequency could also be determined by the impact-echo method [12]. For application in a field test, Dilek et al. introduced circular, thin disk-shaped concrete samples to evaluate fire damage using the impact resonance method [18]. The experimental results show the advantages of reducing the size of the samples and improving availability for *in situ* testing, and clearly reflect the damage of thermal gradient in concrete structures at high temperatures. The abovementioned methods are types of linear acoustic methods, which assume that the resonance frequency is independent of the input amplitude [19]. However, the measured resonance frequency of concrete structures damaged due to fire or other reasons is clearly shifted depending on the input amplitude [20–23]. This phenomenon can be explained by the nonlinear hysteretic behavior of damaged concrete [24–26]. Therefore, an improved method is required for accurately evaluating the resonance frequency and dynamic elastic modulus of damaged concrete. In addition, the effects of post-fire behaviors, such as periods after fire or specific post-fire curing regimes, on elastic moduli have not yet been sufficiently clarified.

To investigate the aforementioned issues, an experimental study was performed on fire-damaged concrete for developing an improved impact resonance method to evaluate residual dynamic elastic modulus, and for identifying the effects of post-fire behaviors of concrete on the elastic modulus of fire-damaged concrete. For this purpose, concrete samples were prepared with four different mixture proportions, and various conditions after exposure to high temperatures were considered, including four exposure temperatures and four storing periods after fire. The dynamic elastic modulus of all prepared samples was measured by the improved impact resonance method to avoid the effects of resonance frequency shift due to the nonlinear hysteretic behavior of concrete. Based on the measured dynamic elastic modulus, a correlation analysis was performed with the splitting tensile strength and the estimated compressive strength. The proposed relationship indicates the possibility of estimating the residual strengths of fire-damaged concrete without consideration of exposure temperature, mixture proportion, and storing period after fire by using the measurement of the dynamic elastic modulus.

2. Experimental details

2.1. Sample preparation

Concrete samples for the experiments were made for representing normal strength with four mixture proportions of differing water content ratios (0.5 and 0.6) and fine-to-coarse aggregate ratios (0.68 and 1.00), as described in detail in Table 1. The constituent materials of concrete used are as follows: Portland cement type I, river sand for fine aggregates with a maximum size of 4 mm, and crushed gravel for coarse aggregates with a maximum size of 19 mm. The concrete was casted with cylindrical molds that were 100 mm in diameter and 200 mm high. All cylindrical concrete samples were cured in water for 28 days, and cut into thin, disk-shaped, 25-mm-thick samples by using a diamond saw. To avoid explosive spalling, the thin disk-shaped samples were kept in a drying oven set to 80 °C for 24 h. The samples were then exposed for an hour to four different high temperatures, 200 °C, 400 °C, 600 °C, and 800 °C, which included temperature ranges that induce physical and chemical changes in the constituent materials, such as loss of pore water evaporation (around 100 °C), decomposition of ettringite (lower than 100 °C), $CaOH_2$ (around 500 °C), $CaCO_3$ (around 700 °C) and C–S–H (around 600 °C), and transformation of quartz (around 570 °C) [1]. At the end of the high temperature exposure, the samples were directly cooled down by immersion in water at 20 °C. After 30 min, the samples were kept out and stored under laboratory conditions (average storing temperature of 20 °C and average relative humidity of 50%). To investigate the effects of post-fire storing period on the residual elastic modulus of damaged concrete, the samples were divided into four groups of storing periods, namely 7 days, 30 days, 180 days, and 360 days, and stored under laboratory conditions during the given periods. For each condition of the exposure temperature and the storing period, five samples were prepared for reducing the experimental errors, and validating the reproducibility of experiments.

Table 1
Mixture proportion of concrete samples (kg/m^3).

Sample label	Water	Cement	Fine aggregate	Coarse aggregate	Density
WC50-0.68	160	320	744	1100	2274
WC60-0.68	171	285	744	1100	2241
WC50-1.00	160	320	922	922	2235
WC60-1.00	171	285	922	922	2202

2.2. Impact resonance method

The impact resonance method was used to determine the dynamic elastic modulus of the fire-damaged concrete samples, and the fundamental flexural resonance frequency of the disk-shaped samples was measured. The experimental details are presented in Fig. 1a. The concrete sample was placed on a support mat, which is made of polyurethane foam, to maintain the free vibration of the sample and minimize the effects of noise. A piezoelectric shear accelerometer was attached to the center of the sample for measuring the resonance vibration response, and a steel bead (13.8 g in mass and 15 mm in diameter) was dropped on the opposite point of the sample. The measured results were converted and recorded by using an analog-to-digital digitizer. For each experiment, the sampling rate and the duration of the measurement were maintained at 100 kS/s and 50 ms, respectively. Accordingly, the resonance frequency was measured from the frequency domain result, which was converted by fast-Fourier transform (FFT). Before performing FFT, the length of data was extended

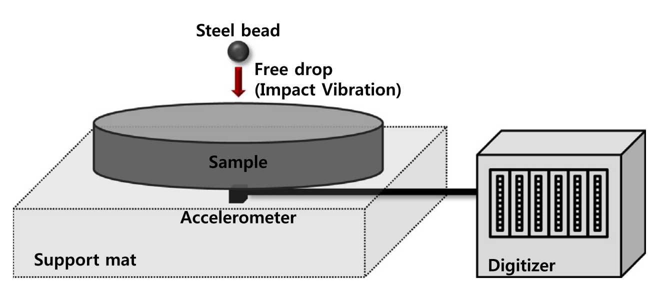

Fig. 1. Schematic diagram of experimental setup: impact resonance method.

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