

# Depth-dependent Evaluation of Residual Material Properties of Fire-damaged Concrete

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(Received November 24, 2016, Revised February 9, 2017, Accepted April 3, 2017)

**Abstract.** In this study, fire-damaged concrete was investigated by a nonlinear resonance vibration (NRV) technique, in order to evaluate its residual material properties. For the experiments, five cubic concrete specimens were prepared and four of them were damaged at different temperatures using a furnace. With a thermal insulator wrapped at the sides of specimen, thermal gradation was applied to the samples. According to the peak temperatures and depths of the samples, nonlinearity parameters were calculated with the NRV technique before the tendency of the parameters was evaluated. In addition, compressive strength and dynamic elastic modulus were measured for each sample and a comparison with the nonlinearity parameter was carried out. Through the experimental results, the possibility of the NRV technique as a method for evaluating residual material properties was evaluated.

**Keywords:** fire-damaged concrete, nonlinear resonance vibration (NRV), thermal gradation, residual material property, compressive strength, dynamic elastic modulus

## 1. Introduction

Concrete is a widely used material because of its high compressive strength and excellent thermal resistance. However, if the concrete is exposed to high temperature for a long time, the material suffers severe damage such as internal and external cracks, delamination, and spalling (Bazant and Kaplan, 1996; Choi *et al.*, 2017; Zhang *et al.*, 2017). As a result of this damage, the physical properties of the material also deteriorate, specifically compressive, tensile strength and elastic modulus (Yu and Lu, 2015). This damage is due to the microphysical and microchemical effects of the internal cement and aggregate matrix due to the continuous high temperature exposure. According to previous research, concrete exposed to high temperature above 100°C starts to release moisture, and dehydration in cement gel occurs above 180°C. At temperatures above 500°C, decay of Ca (OH)<sub>2</sub> and transformation of alpha-quartz to beta-quartz proceed, as well as the collapse of ettringite structures (Alonso and Fernandez, 2004; Handoo *et al.*, 2002). In order to overcome these drawbacks, various experimental studies on deterioration damage of fire-damaged concrete have been carried out, and related codes have been newly improved due to improvement of the mix proportion and the incorporation of new materials (ACI, 1989; ACI, 1997; Tang, 2017).

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1 A variety of studies have been conducted to measure the durability and strength of fire-  
2 damaged concrete. According to the ACI report, various nondestructive testing methods have been  
3 suggested as visual inspection and stress-wave techniques. In 2008, Kim and Kwak evaluated the  
4 elastic properties of concrete by using a surface wave (ACI, 1998; Kim and Kwak, 2008). Recently,  
5 nondestructive testing methods based on elastic waves have been widely applied for evaluating  
6 damaged concrete. Among these, ultrasonic pulse velocity and dynamic elastic modulus  
7 techniques use linear elastic waves to estimate the residual properties of structures. Cloni (2007)  
8 investigated a fire-damaged column with ultrasonic velocity, and Yang (2009) conducted a study  
9 on the residual compressive strength of fire-damaged concrete (Cloni *et al.*, 2007; Yang *et al.*,  
10 2009). However, it has been reported that this method suffers from limited sensitivity when  
11 measuring microstructural change under a micrometer scale (Jhang, 2009; Van Den Abeele *et al.*,  
12 2000a). Examples of techniques based on nonlinear ultrasonic waves, meanwhile, include higher  
13 harmonics, nonlinear resonant ultrasonic spectroscopy, and nonlinear resonance vibration. These  
14 techniques reflect the changes of the microstructure such as voids, phases, etc., and show more  
15 accurate measurement results (Park *et al.*, 2017; Gomez *et al.*, 2017). In previous studies, cement-  
16 based materials exposed to high temperatures were investigated with nonlinear techniques, (Payan  
17 *et al.*, 2007).

18 In the present study, the properties of concrete exposed to high temperature were measured by  
19 temperature and depth by adopting a nonlinear resonance vibration technique. For this purpose,  
20 five concrete specimens of 300 mm × 300 mm in section and 200 mm in depth were prepared, and  
21 four specimens were damaged by 200°C, 400°C, 600°C, and 800°C, respectively. The values of  
22 the nonlinearity parameter were calculated by measuring the resonant frequency of each specimen,  
23 and the changes of these values were compared and analyzed. The compressive strength was then  
24 estimated by measuring the splitting tensile strength of each specimen, with a comparison of the  
25 nonlinearity parameters and the compressive strength. In addition, the dynamic elastic modulus  
26 was estimated from the resonance frequency measurement, and the change of the dynamic  
27 modulus and the value of the nonlinearity parameter were compared. Finally, the possibility of  
28 estimating the depth-dependent material properties of fire-damaged concrete through a nonlinear  
29 resonance vibration technique was confirmed.

## 30 31 **2. Experimental details**

### 32 33 *2.1 Nonlinear resonance vibration*

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35 In this experiment, a nonlinear resonance vibration technique was introduced to measure the  
36 changing resonance characteristics of a concrete specimen when a gradually increasing impact was  
37 applied. This technique can sufficiently reflect the nonlinear behavior of concrete and is therefore  
38 suitable for measuring the degree of damage to a specimen subjected to fire damage. In the case of  
39 a heterogeneous medium such as concrete, the relationship of stress strain exhibiting nonlinear  
40 hysteretic behavior can be expressed as the following equation.

$$41$$
$$42 \quad E(\varepsilon(t), \dot{\varepsilon}(t)) = E_0 [1 - \beta \varepsilon(t) - \alpha \{ \Delta \varepsilon + \varepsilon(t) \cdot \text{sign}(\dot{\varepsilon}(t)) \} + K] \quad (1)$$
$$43$$

44 where  $E$  is the elastic modulus,  $E_0$  is the linear elastic modulus,  $\varepsilon$  the strain, and  $\dot{\varepsilon}$  the strain  
45 rate. Also,  $\beta$  is the second order nonlinearity parameter of the material and  $\alpha$  is the