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Investigation of Fire Damaged Concrete Using Nonlinear Resonance Vibration Method

Kang-Gyu Park, Sun-Jong Park, Hong Jae Yim, Hyo-Gyung Kwak

Abstract**—**This paper attempts to evaluate the effect of fire damage on concrete by using nonlinear resonance vibration method, one of the nonlinear nondestructive method. Concrete exhibits not only nonlinear stress-strain relation but also hysteresis and discrete memory effect which are contained in consolidated materials. Hysteretic materials typically show the linear resonance frequency shift. Also, the shift of resonance frequency is changed according to the degree of micro damage. The degree of the shift can be obtained through nonlinear resonance vibration method. Five exposure scenarios were considered in order to make different internal micro damage. Also, the effect of post-fire-curing on fire-damaged concrete was taken into account to conform the change in internal damage. Hysteretic nonlinearity parameter was obtained by amplitude-dependent resonance frequency shift after specific curing periods. In addition, splitting tensile strength was measured on each sample to characterize the variation of residual strength. Then, a correlation between the hysteretic nonlinearity parameter and residual strength was proposed from each test result.

Keywords**—**Fire damaged concrete, nonlinear resonance vibration method, nonlinearity parameter, post-fire-curing, splitting tensile strength.

I. INTRODUCTION

AFTER exposing to fire, concrete undergoes decrease of reliability and safety due to thermophysical and thermochemical effects of concrete [1]. Degradation of material properties due to fire exposure is accompanied by the development of contact-type defect which are mainly caused by hygrothermal effect and chemical dehydration [2]-[4]. Experimental investigations have been carried out to ascertain the effects of high temperature on the material properties of concrete with various mixtures and different fire scenarios [1], [2], [5], [6]. Meanwhile, many researches have been performed to investigate the effect of fire damage on concrete using nondestructive test. In addition, it has been reported that nonlinear nondestructive methods can more sensitively evaluate distributed defects and contact-type defects than linear nondestructive methods [7], [8].

In this study, as a part of efforts to evaluate the degradation of concrete specimens according to post-fire-curing periods and target temperature, nonlinear resonance vibration method was performed on thin concrete disks to obtain hysteretic nonlinearity parameter (HNP), one of the damage indicator, and residual splitting tensile strength. Then, a correlation between the hysteretic nonlinearity parameter and residual strength was proposed from the test results.

II. SAMPLE PREPARATION

Concrete samples were made with two different mixing ratios as given at Table I. The maximum size of aggregate was 19mm and the maximum size of same was 4mm. The admixture and additional materials were not used. Samples were casted and molded into cylindrical shape with 100mm in diameter and 200mm in height. After 28 days of water curing, specimens were cut into thin disk (about 25mm in thickness). In this study, concrete disks were stored in drying oven at 80°C during 24hours to avoid hygrothermal spalling before applying fire damage. After drying, all the concrete disks were immediately moved and stored in electrical furnace for 1hour with specified target temperatures; 200°C, 400°C and 600°C, 800°C. Then, the samples were taken out of the furnace and soaked into 20°C water for cooling during 3 hours. Then, concrete samples were taken out from water and kept in laboratory condition (ambient temperature) with different post-fire-curing; 7days, 1month, 6months. For each mixing ratio and fire scenarios (including target temperature and post-fire-curing), 5samples were prepared to reduce the experimental error and to validate the reproducibility of tensile strength test and nonlinear resonance vibration method.

TABLE I
MIX PROPORTIONS OF CONCRETE SAMPLE

Label	Water-cement ratio	Fine-coarse aggregate ratio
A	0.5	0.68
B	0.6	0.68

III. NONLINEAR RESONANCE VIBRATION

There have been reported that amplitude-dependent resonance characteristics, such as nonlinear attenuation, harmonic generation, and amplitude-dependent resonance frequency shift, can be used as damage indicators highly sensitive to distributed contact-type defects for different materials [9]. Among them, the shift of resonance frequency was measured to obtain HNP of fire-damaged concrete disks depending on the change in input amplitude. The relationship between change in input amplitude and the shift of resonance frequency can be expressed as follows [9], [10]:

$$\frac{f_0 - f}{f_0} = \alpha_h \Delta\varepsilon \tag{1}$$

Kang-Gyu Park, Sun-Jong Park, and Hyo-Gyung Kwak is with the Civil and Environmental Engineering Department, Korea Advanced Institute of Science and Technology, South Korea (e-mail: naksa@kaist.ac.kr, tomems@kaist.ac.kr, kwakhg@kaist.ac.kr, respectively).

Hong Jae Yim is with the Department of Construction and Disaster Prevention Engineering, Kyung Pook National University, South Korea (e-mail: yimhj@knu.ac.kr).

where f_0 is the measured linear resonance frequency, and f is the measured resonance frequency at increased input amplitudes.

A. Experimental Setup

Nonlinear resonance vibration was performed on the basis of impact induced by dropping steel beads. The schematic diagram is shown in Fig. 1. The steel bead was dropped on the center of a concrete disk that induces the fundamental flexural resonance vibration. The vibration signal of a concrete disk was measured by a shear piezo-electric accelerometer (PCB 353B15; PCB Piezotronics Inc.) which was attached at the opposite side of concrete disk. The excitation amplitude was measured by peak amplitude of acceleration signal. In order to avoid the noise from external experimental conditions, a soft mat (2 inch) was used to support a concrete disk. The measured signal was converted into digital through an analogue-to-digital converter converter (NI PXI 4472-B; National Instruments Corp.), and then the signal were stored in PC.

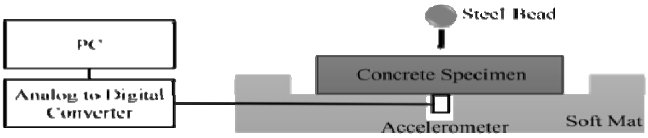
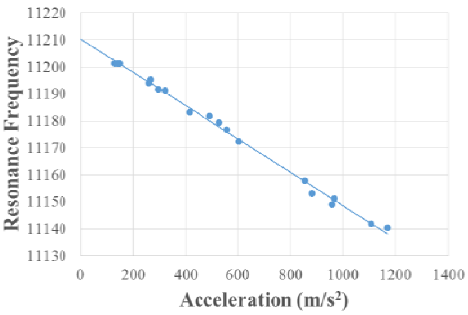


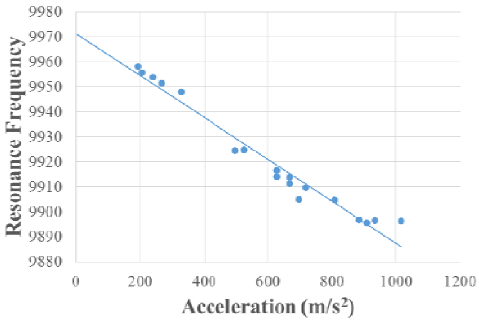
Fig. 1 The schematic diagram of nonlinear resonance vibration method

B. Results

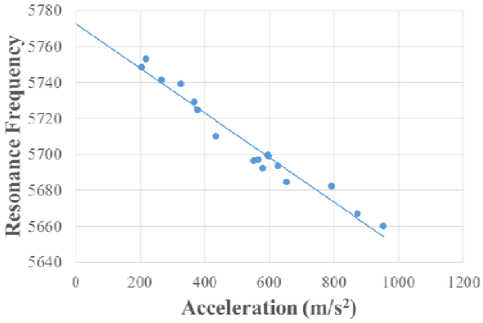
To measure shift of resonance frequency with excitations, steel bead was dropped on each concrete disk 20 times differed with drop-height. As representative results, Fig. 2 shows the amplitude-dependent resonance frequencies at 7days after curing. Resonance frequency decreased as excitation amplitude increased. The linear resonance frequency in (1) is defined as resonance frequency at smallest excitation; so, the linear regression analysis was adopted to calculate the linear resonance frequency at zero excitation. Also, Fig. 3 shows relative resonance frequency shifts of each target temperature and each mixing ratio, at 7 days after curing.



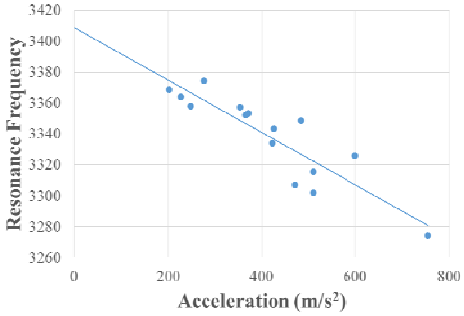
(a) 200°C



(b) 400°C

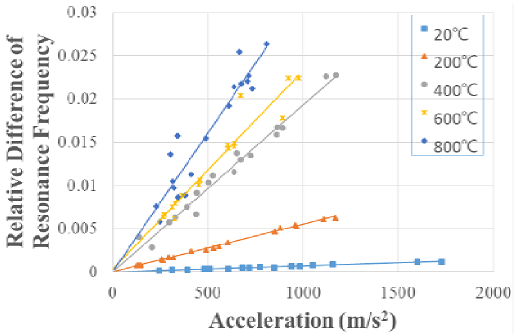


(c) 600°C

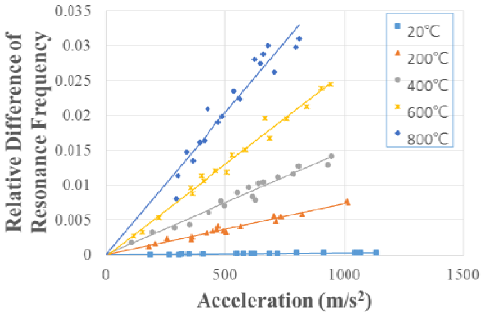


(d) 800°C

Fig. 2 Amplitude-dependent resonance frequencies

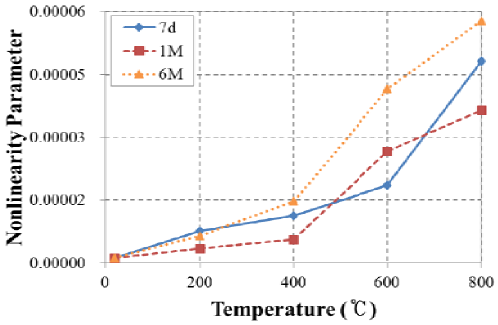


(a) Mix proportion A

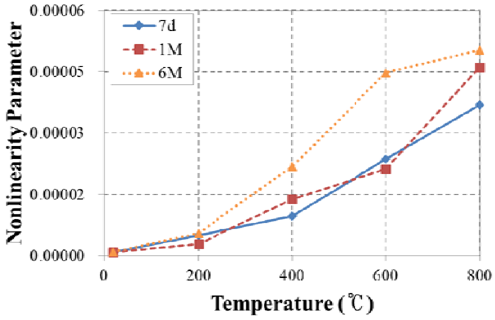


(b) Mix proportion B

Fig. 3 The relative resonance frequency shifts versus excitation magnitude



(a) Mix proportion A



(b) Mix proportion B

Fig. 4 Correlation between hysteretic nonlinearity parameter and target temperature according to post-fire-curing periods

The HNP was calculated from (1), as the slope between measured acceleration and relative shift of resonance frequency. Fig. 3 shows the linear regression analysis to determine HNP from the results. Each slope of the lines denotes the calculated HNP, and it became steeper as rising the target temperature.

Fig. 4 shows the relation between Hysteretic nonlinearity parameter and target temperature according to post-fire-curing periods. The variation of HNP from 400°C to 600°C can be seemed that enhanced contact-type defects results a rapid increase in hysteretic nonlinear behavior. However, it is difficult to find a clear correlation between HNP and the post-fire-curing periods.

IV. SPLITTING TENSILE STRENGTH TEST

A. Experimental Setup

In order to validate the degradation of material properties in fire-damaged concrete, splitting tensile strength test was performed on each concrete disk. The overall test procedure was followed by ASTM C 496[11]. The experimental setup was consisted with universal testing machine, data logger for load cell. Fig. 5 shows a picture of experimental apparatus.

Fig. 5 Experimental apparatus

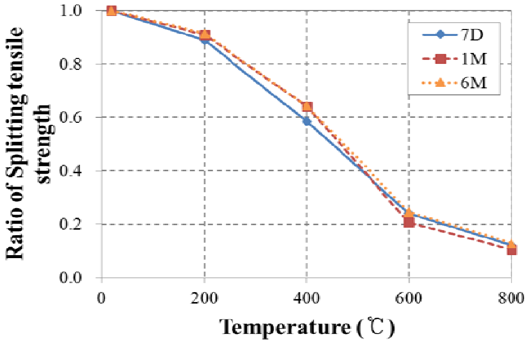
During the test, samples were loaded continuously without shock, and the maximum applied loads were recorded at failure.

The splitting tensile strength was calculated from the following equation [11],

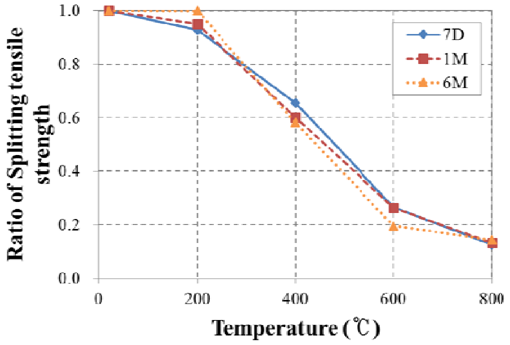
$$T_s = \frac{2F}{\pi l d} \tag{2}$$

where T_s is splitting tensile strength, F is the maximum applied load recorded at failure, l is the length of sample, and d is the diameter of sample. The decreased ratio of tensile strength is shown in Fig. 6 as averaged values.

The tendencies of splitting tensile strength decreased as rising the target temperature, and were almost same for all the cases regardless of mixing ratios and post-fire curing durations. In addition, the signs of recovery of tensile strength were not observed for fire-damaged concrete stored at the ambient condition during specific periods. Therefore, it can be concluded that the appropriate conditions (high humidity or saturated in water at specific temperature), should be needed to expect the recovery of material properties, which was already reported by previous researches [12]-[14].



(a) Mix proportion A

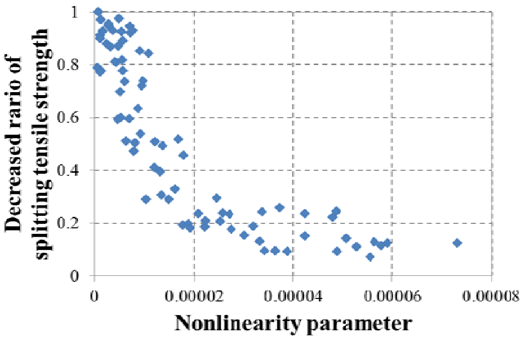


(b) Mix proportion B

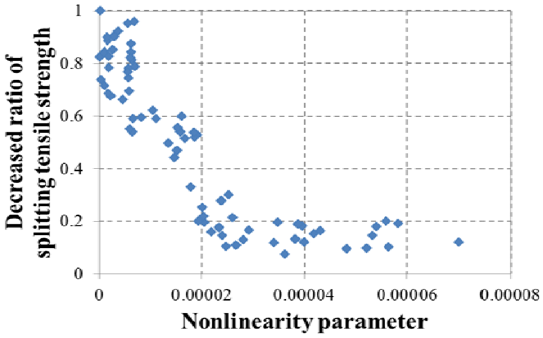
Fig. 6 Correlation between decreased ratio of residual splitting tensile strength and temperature according to post-fire-curing periods

B. Correlation with Nonlinearity Parameter

According to preceding experimental results [15], hysteretic nonlinearity parameter can be sensitively interacting with micro damage in concrete induced by fire. Accumulated micro damage inside concrete reduces the material properties, which can be possible to correlate HNP with measured splitting tensile strength. The correlation between the two values is shown in Fig. 7 depending on mix proportions without consideration of curing periods and peak temperatures. From test results, splitting tensile strength ratio linearly decreased with an increased value of HNP. Also, after the value of HNP of 0.00002, the slope between the two parameters was almost not changed.



(a) Mix proportion A



(b) Mix proportion B

Fig. 7 Relation between ratio of splitting tensile strength and hysteretic nonlinearity parameter

V. CONCLUSION

In this research, a series of tests were performed to evaluate degraded material property of concrete subjected to high temperatures according to post-fire-curing periods using nonlinear resonance vibration, a mean of nondestructive tests. One of nonlinear resonance characteristics, amplitude-dependent resonance frequency shift, was adopted to measure hysteretic nonlinearity parameter of fire-damage concrete disks. Also, the material property of the concrete disks was measured by the splitting tensile strength test. Based on the test results, with increasing the target temperature, residual tensile strength was decreased, and hysteretic nonlinearity parameter was increased regardless of different mixing ratio. In addition, port-fire-curing duration at ambient condition did not effect on the recovery of degraded tensile strength and hysteretic nonlinearity parameter. Based on the previous research, a correlation between ratio of splitting tensile strength and hysteretic nonlinearity parameter was proposed. By using this relation, it is thought that the severity of damage of concrete can be evaluated according to measured HNP.

ACKNOWLEDGMENT

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