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Experimental Relationship between Nonlinear Ultrasonic Method and Compressive Strength of Thermally Damaged Concrete

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ABSTRACT

Thermal damage in concrete generates microcracks within and between its constituent materials, which results in the degradation of material properties such as compressive strength of concrete. This study concentrates on the evaluation of the material properties of concrete using nonlinear ultrasonic modulation technique, sensitive for thermal damage in concrete. Nonlinear ultrasonic modulation technique was performed to characterize thermal damage in concrete specimens. Thermal damage of concrete was classified into eight cases; four different target temperatures and two exposure times. To indicate the degradation of material properties, compressive strength test was carried out in the same thermal damaged concrete specimens. Correlation study between two measured data proposes that nonlinear ultrasonic modulation technique can be used as estimating compressive strength of concrete.

INTRODUCTION

The fire of concrete structures causes the structural performance deterioration due to thermal damage in concrete, a fire-resistant material for reinforce steel. When concrete is exposed to high temperature, a matrix of hardened cement paste is collapsed due to dehydration, decomposition, transformation of cement paste, and thermal strain difference between composites (Bazant and Kaplan, 1999). Therefore, the development of microcracks, i.e. early defects, occurs in hardened cement paste, and microcracks coalesce into macro scale as the thermal damage increases (Yim, *et al*., 2012). This phenomenon effects on the degradation of material properties of concrete, so the evaluation of thermally damaged concrete should be able to consider presence of microcracks.

Among various ultrasonic nondestructive testing techniques, nonlinear ultrasonic modulation technique effectively reflects the effects of nonlinearity and heterogeneity caused by microcracks, so it is suitable for characterizing microcracks in fire damaged concrete. Previous studies reported that the technique can be applied to various types of damage in metal and cement-based material in recent years (Van Den Abeele *et al.*, 2000; Donskoy *et al*., 2001; Wanermuende and Wu, 2004; Chen *et al.* 2008). In addition, one of previous studies shows that the nonlinearity parameter, a damage indicator measured by nonlinear ultrasonic modulation technique, to estimate the material properties of concrete, e.g. compressive strength (Yim, *et al*., 2012).

This study focuses on the nonlinear ultrasonic modulation technique and its application to estimate the compressive strength. Two experimental tests are performed on thermally damaged concrete specimens: nonlinear ultrasonic modulation technique, which measures the nonlinearity parameter to characterize thermal damage, and compressive testing, which measures degradation of material properties, such as compressive strength of concrete. Correlation study between the nonlinearity parameter and the compressive strength is conducted for the different thermal damages varied by exposure time and exposed temperature. As a result, the regression equation is presented to estimate the compressive strength of thermally damaged concrete from measuring the nonlinearity parameter.

THERMALLY DAMAGED CONCRETE

Thermal Damage of Concrete

When concrete exposed to high temperature, microcracks are happened in concrete due to physical and chemical reasons (Bazant and Kaplan, 1999). As the exposure temperature rises, thermal strain difference between composites of concrete induces thermal stress. So, the boundary of cement paste-aggregates interface is broken. Also, evaporation of pore water

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(100°C), dehydration of cement gel (180°C), and decomposition of calcium hydroxide ($Ca(OH)_2$) (500°C) induce debonding of hardened cement paste. When the exposure temperature continues to increase, transformation of α-quartz into β-quartz (570°C), decomposition of calcium silicate hydrate (C-S-H) (700°C), decomposition of calcium carbonate ($CaCO_3$), and melting of the cement paste and aggregates (1150-1200°C) are happened. So, the thermal damage can cause serious damage to the material properties of concrete.

Sample Preparation

Concrete specimens were cast and molded into Φ 100 × 200 mm cylindrical molds. The mix proportion for concrete is 0.5:1:1.2:1.8 (water:cement:sand:gravel), and the cement paste was ASTM Type I Portland Cement. All specimens were cured in water during 28 days, after that concrete specimens were stored in a dried machine at 110°C for three days to avoid thermal spalling. Then, concrete specimens were exposed to different high temperature induced by electrical furnace. There were eight different cases of thermal damage that is distinguished by four different target temperatures (300°C, 400°C, 500°C, and 600°C) and two exposure times (1 hour and 2hour). When the electrical furnace reached each target temperature, four specimens were inserted in the furnace during each exposure time. Thereafter, specimens were immediately submerged to water for cooling down.

NONLINEAR ULTRASONIC MODULATION TECHNIQUE

Nonlinear Wave Modulation in Concrete

The elastic behavior of concrete is manifest by load-dependent discrete memory, hysteresis, and strong nonlinearity. When high frequency wave (f_H) and low frequency wave (f_L) propagate simultaneously through concrete, the modulated wave occurs due to the nonlinear elastic behavior of concrete (Van Den Abeele *et al.*, 2000; Donskoy *et al.*, 2001). Frequency characteristics of the modulated wave are related with sum of f_H and f_L. In this study, nonlinear ultrasonic modulation technique, one of nonlinear wave modulation, was performed to measure the nonlinearity parameter as follows (Yim, *et al.*, 2012):

$$D \propto \frac{E_S}{E_L E_H} \tag{1}$$

where D is the nonlinearity parameter, E_L, E_H, and E_S are the equivalent energy of the high frequency wave (ultrasonic wave), the low frequency wave (impact), and the modulated wave, respectively.

Measurements

Fig. 1 represents the schematic diagram of nonlinear ultrasonic modulation technique. A continuous signal, centered at 46.1kHz, is generated by signal generator (National Instruments Corp. PXI 5421), and the signal is amplified through an amplifier (NF BA4825) . An ultrasonic transducer (PANAMERTICS X1021) translates the electrical signal into the ultrasonic wave, which transmits along the longitudinal axis of the specimen. On the other side of the specimen, same transducer detects ultrasonic signal. Low frequency vibration is generated to tap on specimen using impact hammer (PCB 086C03). At the same time as tapping the specimen, data-acquisition (DAQ) system (NI PXI 4472B and NI PXI 5105) is synchronized to save ultrasonic signal and impact signal.

As shown in Fig. 1, DAQ system, which includes NI PXI 4472B (data acquisition digitizer for dynamic signal) and NI PXI 5105 (data acquisition digitizer for ultrasonic signal) is used to record impact signal and ultrasonic signal. Impact is measured by a 3-axis accelerometer (PCB 356A33) which can detect 3-axis vibrations. Frequency analysis is performed using the FFT (fast Fourier transform). In time domain, Hanning window is used to minimize spectral leakage, and zero-padding is used for frequency resolution. The frequency range of E_H is 46.0kHz to 46.2kHz, and the frequency range of E_S is 41.1kHz to 51.1kHz, excluding the range of E_H (46.0kHz to 46.2kHz), and the frequency range of E_L is 0 to 5kHz. In order to ensure the repeatability of the test method, five tests were performed on each thermal damaged specimen changing the impact point and the mounting point of accelerometer.

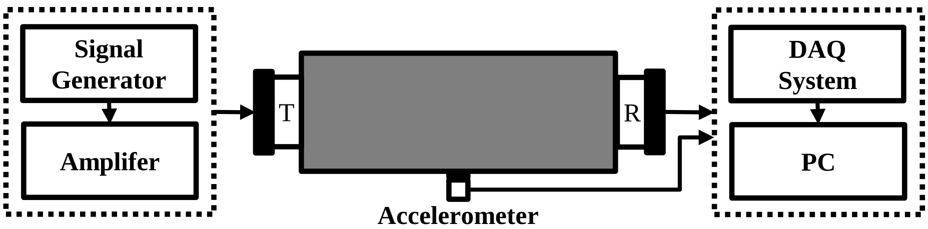

Fig. 1. Schematic of nonlinear ultrasonic modulation technique

Table 1. Experimental results: nonlinearity parameter (*D*) and compressive strength (f_c)

Exposure Time \ Target Temperature	Ref. (20°C)		300°C		400°C		500°C		600°C	
	D	f_c (MPa)	*D*	f_c (MPa)	*D*	f_c (MPa)	*D*	f_c (MPa)	*D*	f_c (MPa)
1 hour	0.0459	51.29	1.246	36.10	2.399	34.91	4.616	29.07	9.730	24.72
2 hours			1.706	34.54	4.644	31.24	10.61	28.96	21.25	22.77

Experimental Results

Results of nonlinear ultrasonic modulation technique are summarized in Table 1, as the average of the nonlinearity parameters. Each measured value includes the results of four specimens. As elevating the target temperature, the measured value increases up to 460 times compared to the reference. Furthermore, the exposure time raises nonlinearity parameter almost doubled compared to the case of 2 hours and the case of 1 hour. This means that the thermal gradient of concrete happens when the concrete is exposed to high temperature. To elevate the temperature of concrete inside, it takes time to be same as the outside temperature, and it also depends on the size and the shape of concrete. The cylindrical concrete specimen is used in this study; the core of the specimen is almost reached at 450°C in an hour and 600°C in two hour by the numerical simulation, when the target temperature sets as 600°C. From the results, the nonlinearity parameter has a high relevance to the target temperature and the exposure time.

CORRELATION STUDY WITH COMPRESSIVE STRENGTH

Measurements of compressive strength

To identify the relationship between the nonlinearity parameter and the compressive strength, compressive strength tests were done on the same specimens, which were measured the nonlinearity parameters before. Tests were followed by ASTM C39, four specimens were measured for each thermal damage case. Tests results are summarized in Table 1. The compressive strength of concrete is decreasing as elevating the target temperature and the exposure time. Test results represent that the thermal damage of concrete causes the degradation of material properties of concrete.

Relationship between nonlinearity parameter and compressive strength

As described above, both two experiments were conducted on each specimen. Therefore, the correlation study between the nonlinearity parameter and the compressive strength can be done by one-to-one matching of the two experimental values measured from each concrete specimen. Fig. 2 represents the regression analysis between the nonlinearity parameter and the compressive strength. As the final result, a regression equation is proposed as the following equation, Eq. (2), that correlates the two measured values.

$$f_c = 35.57D^{-0.11} \tag{2}$$

The proposed equation, Eq. (2), shows the feasibility of estimating the compressive strength from measuring the nonlinearity parameter.

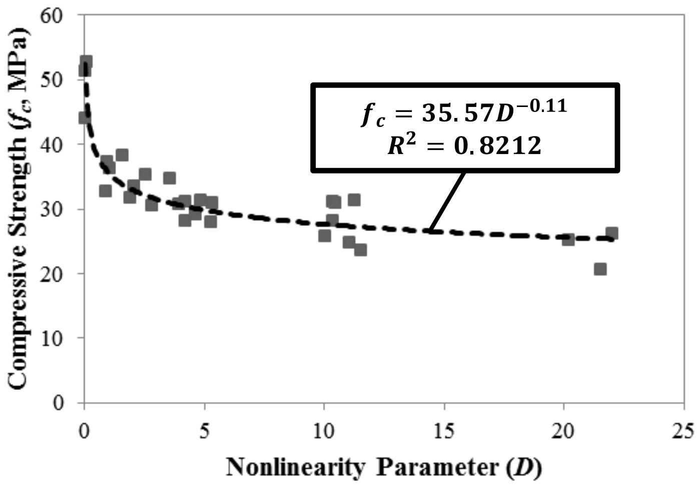

Fig. 2. Correlation study: the nonlinearity parameter (*D*) and the compressive strength (f_c)

CONCLUSION

This study introduces that the material properties of thermally damaged concrete can be estimated by measuring the nonlinearity parameter. On the basis of the test results, thermal damage of concrete induces the degradation of material properties of concrete, and it can be sensitively evaluated by nonlinear ultrasonic modulation technique, a kind of nondestructive testing methods. The proposed regression equation correlates the nonlinearity parameter and the compressive strength based on the experimental values, which did not take into account the effects associated with target temperature and exposed time. From the results, nonlinear ultrasonic modulation technique is feasible to in-situ evaluation of thermally damaged concrete.

ACKNOWLEDGMENTS

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