Characterization of Microcracking in Thermally Damaged Concrete Using Nonlinear Ultrasonic Modulation Technique

Hyo-Gyung Kwak, Sun-Jong Park, and Hong Jae Yim

***Abstract*— This study introduces a reliable method using nonlinear ultrasonic modulation technique for evaluation of thermal damaged concrete. When concrete structure exposed in high temperature, microcracks in all components of material is occurred due to physical and chemical changes. Therefore, the nonlinearity of concrete is increased. While, the conventional ultrasonic nondestructive methods such as measurement of wave velocity have the limitation to evaluate the microcracks, nonlinear ultrasonic modulation technique shows better sensitivity to quantify the microcracks. The modulation of ultrasonic wave and low frequency impact is analyzed to measure the nonlinearity parameter, which can be used as an indicator of thermal damage. Compressive strength of thermal damaged concrete was measured to show the effect of microcracks on performance degradation. As a result, nonlinear ultrasonic modulation technique shows a reliability to evaluate thermally induced microcracks and applicable assessment to estimate compressive strength due to thermal damage.**

***Index Terms*— impact modulation, nonlinear ultrasonic wave, nondestructive evaluation, thermal damaged concrete**

I. Introduction

Concrete consists of mineral aggregates bonded with cement paste, and it is naturally non-flammable and heterogeneous. Also, concrete has low thermal conductivity and thermal diffusivity, so it exhibits fire protection for steel in reinforced concrete. However, when concrete is exposed to high temperature, material properties of concrete are degraded due to cracking, scaling, and spalling, etc. This phenomenon cause to concrete structure be deteriorated.

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Besides, concrete structure exposed in high temperature accompanies the development of microcracks due to the chemo-physical changes [1]. Therefore, the evaluation of thermal damaged concrete needs to have little influence on specimen and to be sensitive to microcracks. To keep the existing structure, various nondestructive evaluation (NDE) techniques have been performed [2].

Conventional tests for the assessment of thermal damaged concrete are Schmidt hammer test, color test, pull-off test, ultrasonic pulse velocity (UPV) test, impact echo, core test, thermogravimetric and dilatometer test, and thermoluminescence test, etc. [2], [3]. Among them, conventional ultrasonic NDE techniques based on linear acoustics are reliable for evaluating severe defects and open cracks, but detectable discontinuities of those techniques are limited [4], [5]. Meanwhile, NDE techniques based on nonlinear acoustics have sufficient sensitivity for microdefects less than micrometer; microstructure change, and crystal lattice defects, etc. [6], [7].Nonlinear acoustic techniques have been used until the 1960’s to characterize microcracks in homogeneous material [8]. Recently, evaluation of microcracks in heterogeneous material (i.e. rocks and concrete) has been performed using nonlinear acoustic techniques [4], [5], [9]-[14].

Nonlinear ultrasonic modulation technique, which is one way of nonlinear acoustic techniques, is appropriate for evaluating microcracks in concrete [13]. This technique measures the nonlinearity parameter, which denotes the degree of microcracks, based on modulated ultrasonic wave [9], [11]. It is applied for various reasons of microcracks, such as stress-induced microcracks [4] and Alkali-silica reaction [5], etc.

This research concentrates on the evaluation of microcracks in thermal damaged concrete on the basis of the nonlinear ultrasonic modulation technique. Nonlinear ultrasonic modulation tests were performed on different thermal damage cases to measure the nonlinearity parameter, which can be used as an indicator of thermal damage, to evaluate thermally induced microcracks. Compressive strength of thermal damaged concrete was measured to represent the performance degradation. Furthermore, correlation study between compressive strength and nonlinearity parameter determines the feasibility of estimating the compressive strength of thermally damaged concrete.

II. Theoretical Background

A. *Thermal damage of concrete*

At high temperature, microcracks are generated in concrete. The reasons of this phenomenon are divided into two categories: physical aspects and chemical aspects. Physically, thermal stress is main factor. Composites of concrete have different coefficient of thermal expansion. So, when the concrete is exposed to high temperature, thermal stress is induced by the difference of coefficient of thermal expansion between cement paste and various aggregates. Bazant summarized several researches on expansion of cement paste and various aggregates: cement paste expands up to 0.2% until 300℃, and its shrinkage starts at 300℃, up to 1.6~2.2% (around 800℃); aggregates expands continuously due to increase in exposed temperature. However, expansion rates of aggregates differ depending on the type of aggregate up to 5 times at 800℃ [1].

There are several chemical reasons to cause microcracking, which are evaporation of water, and chemical transformations of concrete composites: release of evaporable water around 100℃; dehydration of cement gel around 180 ℃; decomposition of calcium hydroxide ($\mathrm{Ca(OH)_2}$) most rapidly around 500℃; transformation of α-quartz transforms to β-quartz around 570 ℃; decomposition of calcium silicate hydrate (C-S-H) around 700℃; and decomposition of calcium carbonate ($\mathrm{CaCO_3}$) around 800℃. So, these physical and chemical changes cause generation of microcracks in concrete exposed to high temperature [1].

B. *Nonlinear wave modulation*

When acoustic wave propagates through a material to represent nonlinear elastic response, different frequencies appear in output signal which are compared with the frequency of input signal. This phenomenon is called as nonlinear acoustic effect, and is caused by the new waves which are generated by modulation of intense acoustic waves at material discontinuities such as voids, cracks, interfaces. It is sensitive enough to characterize micro-discontinuities, compared to conventional ultrasonic NDT techniques. In addition, nonlinear acoustic effect becomes apparent as the increase in microcracks. [6], [7].

Especially, 'Nonlinear Mesoscopic Elastic (NME)' material, e.g. rock and concrete, is inherently large nonlinear due to load-dependent discrete memory [15], and hysteresis, exhibits strong amplitude-dependent (nonlinear) characteristics [16]. When NME material is suffered damage, its nonlinear behavior appears distinctly. Guyer et al. and Abeele et al. proposed a 1-dimensional nonlinear model in their researches [9], [11], [16], which is phenomenological model for NME material. According to the model, the elastic modulus, $E(\varepsilon,\dot{\varepsilon})$, can be expressed by the relationship between stress (σ), strain (ε) and strain rate ($\dot{\varepsilon}$), which is given by

$$\sigma = \int E(\varepsilon,\dot{\varepsilon})d\varepsilon \tag{1}$$

For linear elastic material, its elastic modulus, $E(\varepsilon,\dot{\varepsilon})$ is a constant. However, in the case of material which has nonlinear stress-strain relationship, its elastic modulus $E(\varepsilon,\dot{\varepsilon})$ is determined by the strain rate and the strain amplitude, which is given by

$$E\big(\varepsilon(t),\dot{\varepsilon(t)}\big) = E_0(1-\beta\varepsilon(t) - \alpha\left(\Delta\varepsilon + \varepsilon(t)\times \mathrm{sign}\big(\dot{\varepsilon}(t)\big)\right) + \cdots) \tag{2}$$

where β is the 2nd order classical nonlinearity; α is the non-classical nonlinearity, which is based on the hysteretic nonlinear behavior; ε is the instantaneous strain; and $\Delta\varepsilon$ is the local strain amplitude over the previous period of a propagating wave which evokes the nonlinear behavior to contact defect of grains and friction in microcracks. The coefficient, β, is derived from Taylor's expansion to solve stress-strain relationship in (1). The non-classical nonlinear coefficient, α, is an indicator of hysteresis behavior, which is remarkably high in NME material [15].

Assume the propagation of two different harmonic waves through NME material, whose frequency are different: low frequency (f_L) and high frequency (f_H), and $f_H \gg f_L$. Due to the modulation of two input waves, new waves are measured in the output signal. The generated waves have the frequency characteristics related with f_L and f_H. In this case, the nonlinear coefficients α and β are expressed as a ratio of amplitudes given by [9], [11],

$$\alpha \propto \frac{A(f_H \pm 2f_L)}{A(f_H)A(f_L)} \tag{3.a}$$

$$\beta \propto \frac{A(f_H \pm f_L)}{A(f_H)A(f_L)} \tag{3.b}$$

where $A(f_L)$ is the amplitude of low frequency wave, $A(f_H)$ is the amplitude of high frequency wave, and $A(f_H \pm 2f_L)$ is the amplitude of modulated wave centered at $f_H \pm 2f_L$.

However, it is difficult to measure amplitude terms in (3) due to the complexity of resonant modes and the high frequency modulation [13]. To overcome the difficulties, equivalent energy concept is introduced, which uses impact as low frequency wave and ultrasound as high frequency wave [9]. Each amplitude term in (3) are replaced by the equivalent energy. So the nonlinearity parameter can be formulated by equivalent energies behalf of amplitudes in (3), given by

$$\mathrm{D} \propto \frac{E_S(f_H \pm 2f_L)}{E_H(f_H)E_L(f_L)} \tag{4}$$

where D is a nonlinearity parameter, E_S is equivalent energy of modulation (sideband) energy, E_L is equivalent energy of low frequency impact, and E_H is equivalent energy of high frequency (probing) wave. The equivalent energy is obtained by integrating the power spectrum over the frequency band. Each frequency bands are determined: containing all the impact modes (low frequency band) and including the all sidebands around the high-frequency input (high frequency sideband modulation) [9]. Then, the nonlinearity parameter, D, is integrated factor α and β in (3), and is measured to evaluate thermal damaged concrete in this research.

III. Experiments

A. *Sample Preparation*

Concrete specimens were cast and molded into

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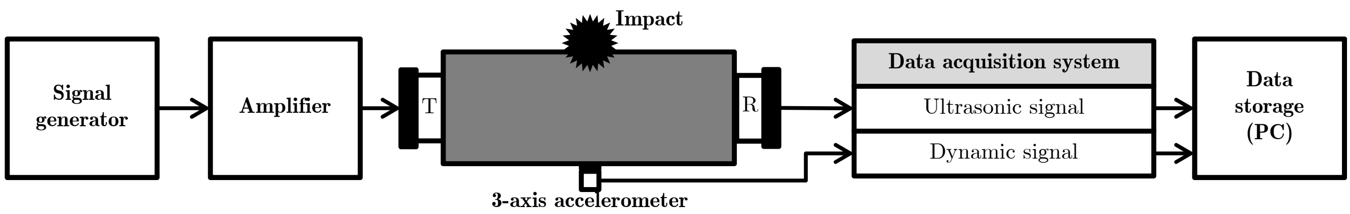

Fig. 1. Schematic diagram of nonlinear ultrasonic modulation technique

Φ100×200mm cylindrical molds. The mix proportion for concrete is 0.5:1:1.2:1.8 (water:cement:sand:gravel) using ASTM Type I Portland Cement. All specimens were cured in water during 28 days, after that concrete specimens were dried in a dried machine at 80°C for a week to avoid thermal spalling of specimens. After 7 days, concrete specimens were exposed to different target temperatures induced by electrical furnace. Four cases of thermal damage are divided by target temperature; 300°C (TD1), 450°C (TD2), 600°C (TD3), and intact case (TD0) for reference. Heating rate of each target temperature was fixed as 10min/°C. When the temperature of electric furnace reaches at the target temperature, temperature is maintained during 2 hours. Immediately thereafter, specimens were submerged to water for cooling down.

B. *Nonlinear Ultrasonic Modulation Technique*

Fig. 1 shows the schematic diagram of nonlinear ultrasonic modulation technique. A continuous signal, centered at 180kHz, is generated by signal generator (National Instruments Corp. PXI 5421), and the signal is amplified through an amplifier (NF BA4825) . An ultrasonic transducer (PANAMERTICS X1019) 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 impact is generated to tap on specimen using impact hammer (PCB 086C03). At the same time as tapping the specimen, data-acquisition systems (NI PXI 4472B and NI PXI 5105) are synchronized to save ultrasonic signal and impact signal. As shown in Fig. 1, NI PXI 4472B (data acquisition digitizer for dynamic signal) and NI PXI 5105 (data acquisition digitizer for ultrasonic signal) are 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 180k±200Hz, and the frequency range of E_S is 160kHz to 200kHz, excluding the range of E_H (180k±200Hz), and the frequency range of E_L is 200 to 10kHz.

In order to ensure the repeatability of the test method, 5 tests were performed on each thermal damaged specimen changing the impact point and the mounting point of accelerometer. Specimens are cut in half for nonlinear acoustic test. For each experiment, 50 impacts were done to determine the nonlinearity parameter as (4). In (4), (E_S/E_H) can be expressed as normalized sideband energy, so the

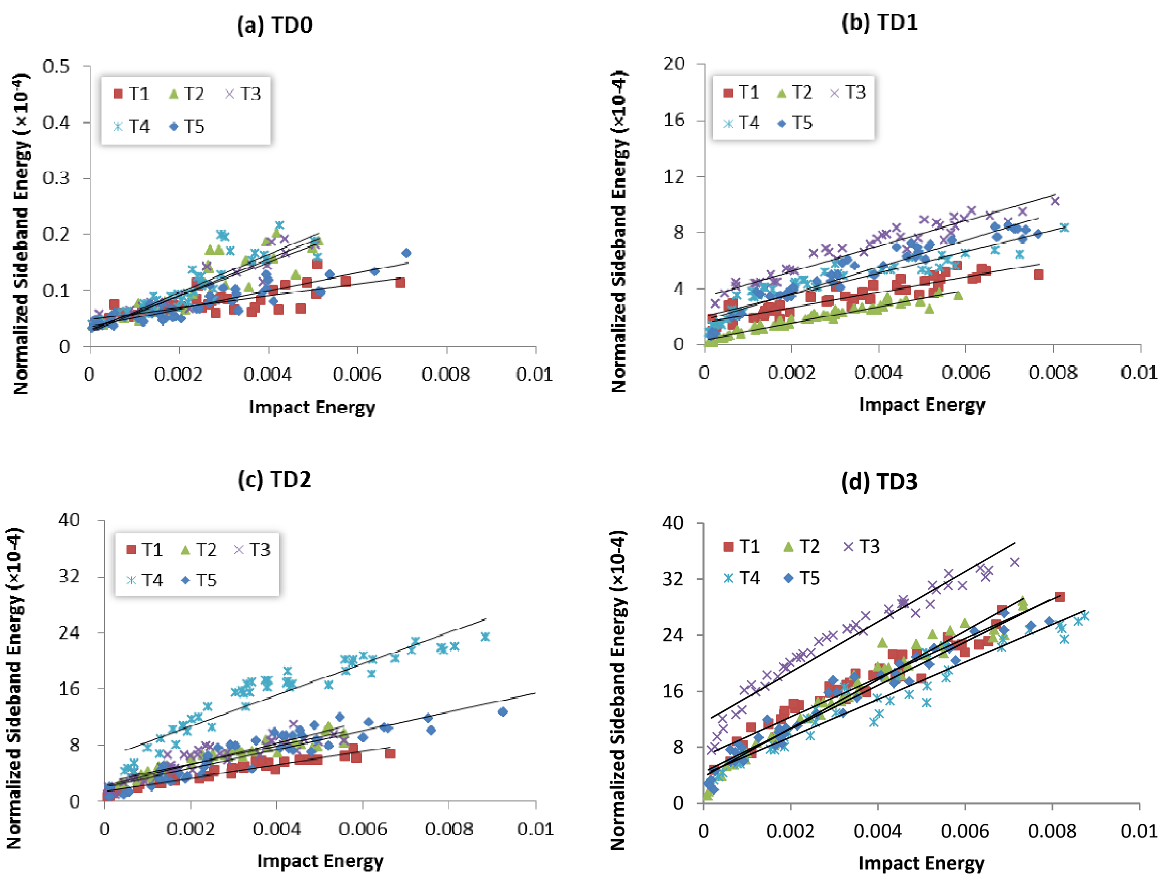

Fig. 2. Nonlinear ultrasonic modulation technique test results: (a) TD0, (b) TD1, (c) TD2, (d) TD3

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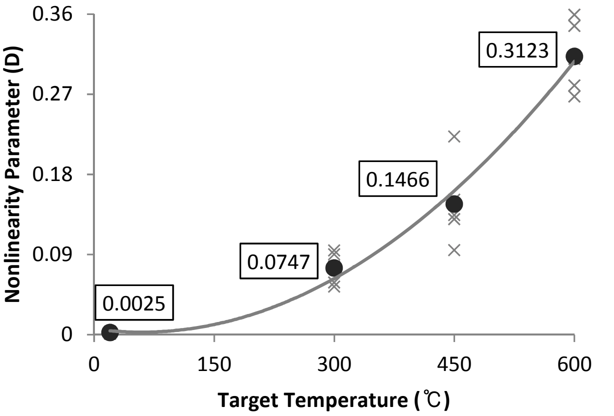

Fig. 3. Comprehensive result of nonlinearity parameter depending on target temperature changes

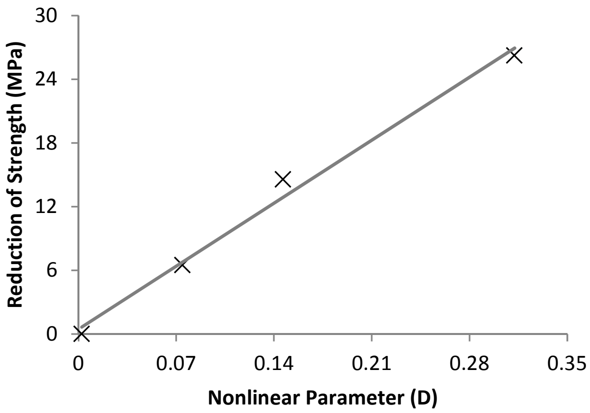

Fig. 4. Correlation between reduction of compressive strength and nonlinearity parameter

TABLE I
RESIDUAL COMPRESSIVE STRENGTH OF THERMAL DAMAGED CONCRETE

Target Temperature	Residual Compressive Strength (MPa)
T0	43.59
T1	37.13
T2	29.05
T3	17.38

nonlinearity parameter D is rewritten as

$$D \propto \frac{E_N}{E_L} \quad (5)$$

where E_N is normalized sideband energy.

C. Test results

Results of nonlinear ultrasonic modulation technique are shown in Fig. 2. Five tests are repeated for each specimen, and are labeled as T1, T2, T3, T4, and T5 for each target temperature. According to (5), the nonlinearity parameter is the slope of each graph. The comprehensive result is shown in Fig. 3, and the labels in Fig. 3 represent the averaged values of nonlinearity parameter of each specimen. As elevating the target temperature, nonlinearity parameter also increases rapidly (Fig. 3). This result shows that nonlinearity parameter can be used as an effective indicator of thermal damage in concrete.

D. Correlation study between compressive strength and nonlinearity parameter

To identify the effect of thermally induced microcracks on the reduction of compressive strength of concrete, compressive strength tests were done following by ASTM C39 [17]. Three specimens were measured for each target temperature. Test results are summarized as the average of compressive strength in Table I: compressive strength decreases as the increase in temperature, and the reduction ratio is up to 60%. Based on the results, correlation study is done by matching nonlinearity parameter to the reduction of compressive strength. Fig. 4 represents the relationship between two measured values, so it is inferred two values are linearly related. Therefore, in thermal damaged concrete, nonlinearity parameter can be used as estimate factor of compressive strength as damage indicator.

IV. CONCLUSION

This research suggests that thermal damage in concrete can be evaluated using nonlinear ultrasonic modulation technique. On the basis of test results, introduced technique is suitable to evaluate thermally induced microcracks in concrete. Correlation study between nonlinearity parameter and reduction of compressive strength shows that nonlinear ultrasonic modulation technique can effectively be used to estimate the compressive strength of thermally damaged concrete.

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REFERENCES

[1] Z.P. Bazant and M.F. Kaplan, *Concrete at High Temperature: Material Properties and Mathematical Models*, Longman Group Limited, 1996, pp. 1-128.

[2] M. Colombo, R. Felicetti, "New NDT techniques for the assessment of fire-damaged concrete structures", Fire Safety Journal 42, 2007, pp. 461-472.

[3] M. Y. L. Chew., "The Assessment of Fire Damaged Concrete", Building and Environment, Vol. 28, No. 1, 1993, pp. 97-102.

[4] K. Warnemuende, H.C Wu, "Actively modulated acoustic nondestructive evaluation of concrete", Cement and Concrete Research 34, 2004, pp. 563-570.

[5] J. Chen, A.R. Jayapalan, J.Y. Kim, K.E. Kurtis, L.J. Jacobs, "Rapid evaluation of alkali-silica reactivity of aggregates using a nonlinear resonance spectroscopy technique", Cemt and Concrete Research 40, 2010, pp. 914-923.

[6] Zheng, Yongping, Maev, Roman Gr., Solodov, Igor Yu, "Nonlinear acoustic applications for material characterization: a review", Canadian Journal of Physics, Vol. 77, 1999, pp.927-967.

[7] Kyung-Young Jhang, "Nonlinear Ultrasonic Techniques for Nondestructive Assessment of Micro Damage in Material: A Review", International Journal of Precision Engineering and Manufacturing, Vol.10, No.1, 2009, pp. 123-135.

[8] A. Hikata, B.B. Chick, and C. Elbaum, "Dislocation Contribution to the Second Harmonic Generation of Ultrasonic Waves", Journal of Applied Physics, vol.36, no.1, 1965, pp. 229-236.

[9] K.E.–A. Van Den Abeele, P. A. Johnson, A. Sutin, "Nonlinear Elastic Wave Spectroscopy (NEWS) techniques to discern material damage, part I: Nonlinear wave modulation spectroscopy (NWMS)", Research in Nondestructive Evaluation, 12:1, 2000, pp. 17-30.

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[10] K.E.-A. Van Den Abeele, J. Carmeliet, J.A. Ten Cate, P.A. Johnson, “Nonlinear Elastic Wave Spectroscopy (NEWS) Techniques to Discern Material Damage, Part II: Single-Mode Nonlinear Resonance Acoustic Spectroscopy”, Research in Nondestructive Evaluation, 12:1, 2000, pp. 31-42.

[11] K.E. –A. Van Den Abeele, A. Sutin, J. Carmeliet, P. A. Johnson, “Micro-damage diagnostics using nonlinear elastic wave spectroscopy”, NDT&E International 34, 2001, pp. 239-248.

[12] A.A. Shah, Y. Ribakov, “Non-linear ultrasonic evaluation of damaged concrete based on higher order harmonic generation”, Materials and Design 30, 2009, pp. 4095-4102.

[13] C. Payan, V. Garnier, J. Moysan, “Effect of water saturation and porosity on the nonlinear elastic response of concrete”, Cement and Concrete Research, 2010, pp. 473-476.

[14] K.J. Les´nicki, J.Y. Kim, K.E. Kurtis, L.J. Jacobs, “Characterization of ASR damage in concrete using nonlinear impact resonance acoustic spectroscopy technique”, NDT&E International, NDT&E International, Vol. 44, 2011, pp. 721-727.

[15] D.J. Holcomb, “Discrete memory in rock: A review”, Journal of Rheology Vol. 28, 1984, pp. 725-728.

[16] R.A. Guyer, P. A. Johnson, “Nonlinear Mesoscopic Elasticity: Evidence for a New Class of Materials”, Physics Today, 1999, pp. 30-36.

[17] ASTM International, *Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens,* ASTM C39, American Society for Testing and Materials

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