Cement and Concrete Research 42 (2012) 1438–1446

Contents lists available at SciVerse ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Characterization of thermally damaged concrete using a nonlinear ultrasonic method

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ARTICLE INFO

Article history:
Received 8 March 2012
Accepted 9 August 2012

Keywords:
Concrete (E)
Temperature (A)
Microstructure (B)
Degradation (C)
SEM (B)

ABSTRACT

Thermal damage in concrete usually induces contact-type defects, which result in degradation of the concrete's performance. This paper attempts to visualize the thermal damage in a multiscale, and characterizes the thermally damaged concrete using a nonlinear ultrasonic method. An impact-modulation method is used to obtain nonlinearity parameters, as a quantitative measure of contact-type defects, and shows better sensitivity than phase velocity variation as a linear ultrasonic method for thermally damaged concrete. The measured nonlinearity parameter is compared with the permeable pores, which reflect the occurrence of opening and pores in thermally damaged concrete. Degradation of concrete strength due to thermal damage is also assessed via the measurement.

1. Introduction

Nondestructive evaluation based on ultrasonic waves is a reliable method to assess the degradation of cement-based materials. Various linear ultrasonic methods, such as using the propagating velocity or attenuation of waves, have been developed to provide nondestructive tests for detecting and evaluating defects in cement-based materials [1–6]. When a wave propagates through the medium, the phase and amplitude of a propagating wave is changed depending on the material properties. The characteristics of variation can be used to estimate the progressive damage of cement-based materials. However, it has been reported that the linear ultrasonic methods are less sensitive than nonlinear ultrasonic methods, especially when a sample having distributed damage is tested [7]. Research has indicated that nonlinear ultrasonic waves sensitively interact with contact-type defects, which involves opening and closing of the crack interface at the multiscale. Accordingly, nondestructive techniques using nonlinear ultrasonics have been applied for early crack detection of metal materials [8,9].

Heterogeneous materials such as concrete inherently have contact-type defects, which cause ultrasonic waves to show significant nonlinear behavior. The nonlinear effect increases when defects are accumulated in the material. The accumulated defects are referred by damage, which decreases the strength, stiffness, and durability of concrete. A previous study reported the ability of the nonlinear ultrasonic method to estimate the micro-cracks [10] and to evaluate the strength of concrete [11,12], and its application to various damages such as alkali-silica reaction and the effect of water saturation and porosity in cement-based materials that can also be found in the literature [13,14].

Thermal damage of concrete exposed to high temperature due to fire is thought to be one of the contact-type defects, because cement paste debonds with aggregates having different thermal expansion and the paste matrix itself becomes disjunctive. The thermally damaged concrete undergoes permanent residual expansion and loss of its strength even after cooling [15]. Degradation is accelerated if the degree of thermal damage in concrete is severe [16,17].

The objective of this research is to characterize the thermally damaged concrete using a nonlinear ultrasonic method. This study attempts to visually identify in a multiscale whether the thermal damage in concrete is classified as a contact-type defect, and furthermore a nondestructive test method using nonlinear ultrasonics is applied to support the identification. For this purpose, Scanning Electron Microscopy (SEM) visualizes the microstructure of the thermal damage and its sensitivity to nonlinear wave modulation spectroscopy, a promising nonlinear ultrasonic technique [18,19], is reported. The sensitivity to the nonlinear ultrasonic method is compared with that of the dynamic modulus and phase velocity measurement based on the principle of a linear ultrasonic wave. As a result, the thermal damage is more sensitively characterized with the nonlinear ultrasonic method. Permeable pore increase and strength degradation by thermal damage are also comparable with the measured nonlinearity parameter quantifying the degree of thermal damage. In other words, the nonlinear ultrasonic method provides scientific criteria which decide on continuous use of thermally damaged concrete.

2. Sample preparation

A total of 5 groups were prepared, on which different amounts of thermal damage were imposed. All of the samples were produced with type I Portland cement and crushed gravel. The maximum size

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0008-8846/$ – see front matter.
http://dx.doi.org/10.1016/j.cemconres.2012.08.006

Table 1
Material property of concrete samples.

Label[a]	Exposed temperature [°C]	Compressive strength [MPa][b]
C020	20	43.0
C150	150	39.6
C300	300	34.8
C450	450	28.9
C600	600	16.9

[a] The mixture proportions of all samples are 0.5:1:2.34:2.69, which is expressed as the weight ratio of water, cement, sand, and gravel, in sequence.
[b] The compressive strengths of concrete are determined as the averaged value of 5 cylindrical samples.

Table 2
Expansion and permeable pore measurement of concrete samples.

Label	Density [kg/m^3]	Apparent expansion [%]	Permeable pore (before heating) [%]	Permeable pore (after heating) [%]	Permeable pore increase [%]
C020	2294	0	–	–	–
C150	2292	0.038	12.13	12.29	1.3
C300	2232	0.006	12.66	15.01	19
C450	2285	0.099	12.91	17.13	33
C600	2262	0.63	13.22	19.38	47

of the gravel was 19 mm, and admixtures were not used in any of the mixes. All of the samples were cured in water for 3 months. Each group labeled C020 to C600 experienced peak temperature of 20 °C, 150 °C, 300 °C, 450 °C, and 600 °C, respectively. In each group, two cylindrical samples, suffixed A and B, were prepared and all of them have a height of 10 cm and a diameter of 10 cm. An electric muffle furnace was used for heating the concrete samples up to the maximum exposed temperature. The heating rate was 15 °C per minute, and the exposure time at the peak temperature was 2 h. To avoid risk of spalling and explosion during heating in the furnace, the constant relative humidity of the samples was maintained below 5%. The subsequent cooling of the thermally damaged samples was accomplished with water cooling to room temperature, 20 °C.

As a reference, the compressive strengths (Table 1) and dynamic moduli (Table 3) of the samples were measured in accordance with the ASTM C 39 [20] and ASTM C 215 [21], respectively. Both results are the average values measured with 5 cylinders having 10 cm-diameter and 20 cm-height. The densities of samples (Table 2) are also measured at room temperature.

3. Visual identification of thermal damage

Optical microscopy and SEM visualize the thermal damage in concrete at the micro-scale. Fig. 1 shows cross-sectional images obtained by optical microscopy, where their surfaces were polished in advance. Fig. 1 (B) and (D) taken from thermally damaged concrete, experienced peak temperature of 450 °C, shows pink discoloration due to the state conversion of iron oxides by dehydration and visible opening at the interface between mortar and gravel.

The back-scattered electron image of SEM used in the study is one of the most effective tools for morphology analysis at the micro-scale [22]. The samples were polished for surface preparation of concrete using finer silicon carbide abrasive paper in the order of #220, #400, #800,

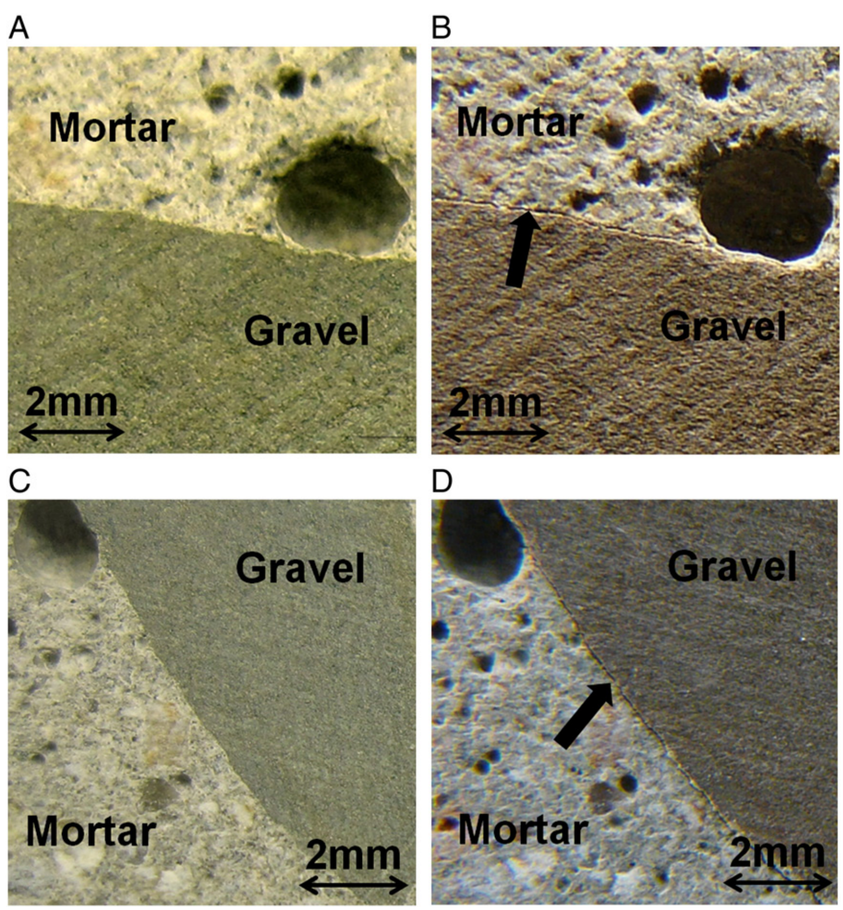

Fig 1. Cross-sectional images of sample C450: (A) a location before heating and (B) the same location after heating; (C) another location before heating and (D) after heating.