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Characterization of stress-dependent ultrasonic nonlinearity variation in concrete under cyclic loading using nonlinear resonant ultrasonic method

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HIGHLIGHTS

- Compressive loading effects on decreasing the ultrasonic nonlinearity.
- Cyclic compressive loading effects on increasing the ultrasonic nonlinearity.
- Thermal damage of concrete effects on increasing the ultrasonic nonlinearity.

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ABSTRACT

In this work, an experimental study was carried out to investigate the stress-dependent characteristics of concrete under cyclic loading, based on a nonlinear resonant ultrasonic method. Since concrete subjected to cyclic loading accompanies variations in the elastic and plastic characteristics of concrete in relation to microstructural changes, the adoption of a nonlinear ultrasonic approach is required, which has advantages for the evaluation of micro-cracks in concrete. In this experimental study, two types of loading were considered, namely, continuously increased and cyclic repeated, to identify their effects on the ultrasonic nonlinearity of concrete and the load-induced damage. An additional experiment on the exposure of concrete samples to high temperature was conducted to further investigate the effects of cyclic loading accompanied by an increased occurrence of micro-cracking. A comparison analysis was also performed on the experimental results, and the potential to monitor the stress history of concrete by using the nonlinear resonant ultrasonic method was evaluated.

1. Introduction

Concrete is a popular material in the construction industry due to its advantages of cost-effectiveness, water-resistance, thermal characteristics (similar to the steel), and low thermal conductivity. Generally, the compressive strength of concrete is 10 times higher than its tensile strength. Therefore, for most concrete structures, concrete plays a major role in sustaining compressive forces according to the self-weight of structural members and external loadings. It is also intended to resist compressive stress on concrete structures. However, concrete structures can suffer reduced durability if they are exposed to excessive loading or other damaging conditions, which can cause deterioration in the concrete microstructure and its corresponding mechanical properties [1]. There are several causes of increased micro-cracks in concrete. Most of them are based on chemical mechanisms, such as alkali-silica reaction, sulfate attack, carbonization, and fire-induced damage, while others are based on physical mechanisms, such as freeze-thaw damage and load-induced damage. Generated micro-cracks weaken the binding forces of the cement matrix, and the bonding forces of the interfacial zone between the cement matrix and aggregates [2]. Among them, the stress-dependent characteristics of concrete have been investigated to evaluate the load-induced damage state or to monitor the load level of concrete structures. Several studies have concentrated on monitoring the compressive or tensile load history by determining the acoustoelasticity of concrete, which represents the load-dependent characteristics of concrete. It is mainly evaluated by measuring ultrasonic velocity based on coda wave interferometry, which sensitively reflects changes in ultrasonic velocity compared to the conventional method of measuring ultrasonic velocity [3–6].

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On the other hand, other studies have monitored the stress-dependent characteristics of concrete by using nonlinear ultrasonic methods, such as the higher harmonics method, the time-shift method, and the nonlinear resonant ultrasonic method, for measuring ultrasonic nonlinearity, which is based on the nonlinear acoustic behavior of concrete caused by its stress-strain nonlinearity [7–10]. These nonlinear ultrasonic methods have also been reported to sensitively evaluate the conditions that may lead to micro-cracks in concrete, such as alkali-silica reaction, fire-damage, carbonation, and load-induced damage [11–18]. Shah reported that the higher harmonics characteristics of concrete are dependent on the continuous increase of compressive loading, at 20%, 40%, 60%, and 80% compressive strength [7]. Antonaci et al. reported that the compressive stress level of concrete can be effectively monitored by measuring the nonlinear ultrasonic characteristics of concrete by using the time-shift method [8,9]. Kim et al. reported in their preliminary study the possibility of using the nonlinear resonant ultrasonic method to monitor the compressive stress state of concrete, and the ultrasonic nonlinearity results were compared to experimental results obtained by measuring ultrasonic pulse velocity [10]. Previous studies have identified the stress-dependent characteristics of the nonlinear ultrasonic behavior of concrete, and they have suggested the possibility of its application in monitoring the stress state of concrete. Additionally, it seems that increases in stress-induced damage are related to increased measured ultrasonic nonlinearity.

In this study, an experimental research was performed to characterize the stress-dependent characteristics of concrete based on the measurement of the nonlinearity parameter, the purpose of which was to identify the effects of cyclic loading on ultrasonic nonlinearity and to evaluate the load-induced damage of concrete using the nonlinear resonant ultrasonic method. For this purpose, two types of loading were considered, and the nonlinearity parameter was measured for concrete samples under various levels of compressive loading. Additionally, experimental procedures were performed on the concrete samples after exposure to high temperature to identify the effects of an increasing number of micro-cracks distributed throughout the concrete on the stress-dependent ultrasonic nonlinearity of the concrete. Based on the test results, the effects of continuous and cyclic loading histories as well as an increasing number of micro-cracks in the concrete on ultrasonic nonlinearity and load-induced damage were investigated. Finally, a comparison analysis was performed based on the experimental results.

2. Experimental details

2.1. Sample preparation

The concrete samples for the experiments were made with the mixture proportions shown in Table 1, with Type I Portland cement, coarse aggregate particles smaller than 19 mm, and fine aggregate particles smaller than 4 mm. Admixtures were not used in any of the concrete mixtures. The samples were cast and molded into two shapes and were cured in water. A cylindrical shape 100 mm in diameter and 200 mm in height was intended for measuring the compressive strength of concrete, and a slender rectangular prism shape with a 100 mm × 100 mm square cross-section and 300 mm in height was intended for measuring the stress-dependent nonlinear characteristics of concrete. The dimensions of the prism shaped concrete samples could effectively minimize the stress distribution on the center of each sample, which is caused by the confining effects at the surface between the sample and the bearing plates of the universal testing machine. After the concrete samples had cured for 28 days, they were stored under ambient conditions at 20 °C and 50% relative humidity for 2 months. After that, the compressive strength of the concrete was evaluated by testing of five cylindrical concrete samples, which was followed by ASTM C39 [19]. The averaged measured compressive strength and the standard deviation of the five concrete samples were 50.0 MPa and 3.2 MPa, at respectively. To measure the stress-dependent nonlinear ultrasonic characteristics, three prism-shaped samples were prepared. Two of them were stored under the same ambient conditions, and the other one was exposed to 200 °C temperature in a drying oven to increase the amount of micro-cracking in the concrete sample. It has been reported that the strength of concrete exposed to 200 °C is decreased slightly or remains almost same, but it suffers from a rapid increase of micro-cracks, which has been observed by scanning electron microscopy, measurement of volume change in the concrete, and measurement of its nonlinear ultrasonic characteristics [14,20]. Total exposure time was 5 h, including 20 min to raise the temperature of the drying oven enough to increase the temperature of the core of the sample to the same temperature as the outer part. Then, the sample exposed to high temperature was cooled down at the ambient conditions. After that, the compressive strength of the fire-damaged concrete samples was evaluated by testing of five cylindrical concrete samples, which was followed same as undamaged concrete samples, and the averaged compressive strength and its variation were 42.3 MPa and 2.8 MPa, at respectively. The experiments for measuring nonlinear ultrasonic characteristics under compressive loading were performed following the experimental procedures described in the next section.

Table 1
Mixture proportion of concrete samples (kg/m^3).

Water	Cement	Fine aggregate	Coarse aggregate
180	360	837	970

2.2. Nonlinear resonant ultrasonic method

The nonlinear resonant ultrasonic method is based on the comparison of frequency spectra, which are measured from different impulse responses by varying the input amplitude [10,12,13,22].

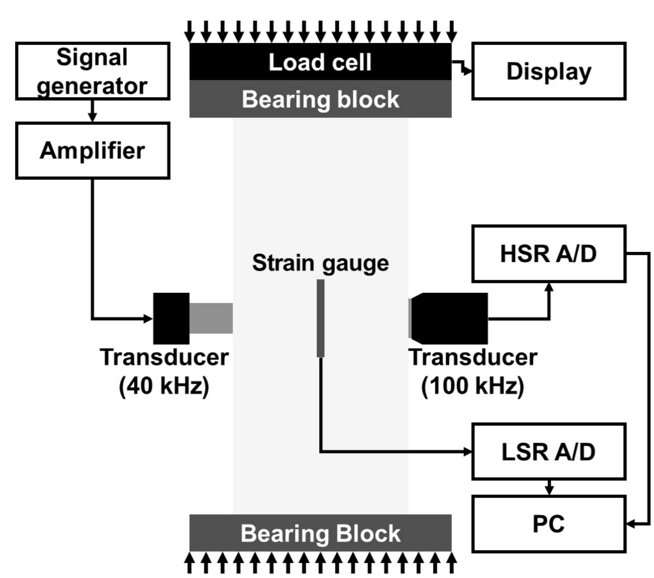

Fig. 1. Schematic diagram of nonlinear resonance vibration method on a concrete sample under cyclic loading.