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Thermal modulation of nonlinear coda wave for evaluation of alkali-silica reaction damage in concrete

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ABSTRACT

Nonlinear ultrasonic methods such as nonlinear resonance acoustic spectroscopy (NRAS) and nonlinear wave modulation spectroscopy (NWMS) show higher sensitivity to microcracking damage in concrete than the conventional linear ultrasonic testing methods. However, the NRAS method are only applicable to small specimens, and the NWMS method needs complicate and expensive equipment. In this work a modified NWMS method is proposed using thermal modulation of nonlinear ultrasonic waves. Ambient temperature change excites and modulates nonlinear behaviour of ultrasonic waves in concrete with microcracks. Coda wave interferometry is used to analyze the relative velocity change with temperature, which is defined as the thermal-modulation coefficient. Experiments were performed on concrete specimens with alkali-silica reaction (ASR) damage. Results indicate that the concrete samples with higher damage level demonstrated higher relative velocity change to temperature variation. Therefore, the thermal-modulation coefficient can be used as a nonlinear parameter for concrete damage characterization. The proposed method has potential applications to in-situ evaluation and health monitoring of concrete structure.

INTRODUCTION

Concrete shield building wall is a critical structure in a nuclear power plant and the degradation of the concrete wall will cause the safety issues and affect the normal operation of nuclear power plant. In 2010, Alkali-silica Reaction (ASR) damage was found in the shielding wall of Seabrook nuclear power plant in New Hampshire. ASR is a reaction between the reactive non-crystalline silica in the aggregate and the alkali hydroxide in cement paste to form a swelling gel as the reaction product. The ASR gel may absorb water and swell causing microcracks and cracks in concrete, which further leads to concrete degradation and reinforcement corrosion. Currently most ASR assessment programs mainly rely on visual inspection or petrographic examination. Visual inspection may not provide reliable information for the internal damages in concrete, while the petrographic analysis needs coring and is time consuming. Nondestructive testing (NDT) methods, such as ultrasonic methods, which can be used for continuous and long-term monitoring of concrete, may provide a promising solution for ASR damage evaluation. Conventional linear ultrasonic methods mainly use ultrasonic wave velocity and amplitude to characterize concrete damage. However, in the early stage of ASR with only microcracks, the linear ultrasonic methods are not sensitive to these microcracks since the crack sizes are smaller than the wavelength. Comparing to linear ultrasonic methods, nonlinear ultrasonic methods are more sensitive to early stage damage since even a small amount of microcracks will significantly increase the concrete nonlinearity.

Nonlinear resonance acoustic spectroscopy (NRAS) and nonlinear wave modulation spectroscopy (NWMS) are two common nonlinear ultrasonic methods. The NRAS method (K. E.-A. Van Den Abeele et al. 2000a) measures the resonance frequency shift when a concrete sample is excited at different strain levels. Frequency shift is caused by material softening at high strain levels. This method is only applied on small samples. The NWMS method mixes a low frequency (f_1) wave and a high frequency ((f_2) probing wave and measures the sideband energy at frequencies ($f_2 \pm f_1$) (K. E.-A. Van Den Abeele et al. 2000b). The relationship between the sideband energy and the low frequency energy level represents the material nonlinearity. High amplitude vibration or impact modulation are used to drive nonlinear movement of microcracks in the concrete. Dynamic acousto-elastic testing (DAET) is a recently developed nonlinear ultrasonic method, which uses coda wave interferometry (CWI) to detect the small velocity change of the probing wave caused by the low frequency pump wave and builds the relationship between relative velocity change and dynamic strain levels (Renaud, Callí, and Defontaine 2009; Rivière et al. 2013; Shokouhi et al. 2017). This method has the same limitations with NWMS method. For large structures, high energy input is needed for the low frequency pump wave to excite the nonlinear behaviour of concrete structures.

In this work, a thermal modulation of nonlinear coda wave method is proposed for evaluation of ASR damage in concrete. Ambient temperature change is used to modulate the nonlinear behaviour of ASR damage in concrete, instead of using low frequency pump, since most concrete structures are exposed to ambient temperature change. CWI is used to detect the small relative velocity changes caused by temperature change. Temperature change is usually treated as a pollution to CWI results (Planès and Larose 2013) due to CWI's high sensitivity to temperature. However, in this work, temperature change is used as the driving force of nonlinear behavior, and the relative velocity change from CWI will be correlated to the temperature changes and the relationship will be used to evaluate the damage level of the concrete samples affected by ASR.

THERMAL MODULATION OF NONLINEAR CODA WAVE

Concrete samples

Three concrete samples were cast and studied in this work (see Figure 1a). The first specimen, ASR (unconfined) specimen was cast with reactive coarse aggregate and sodium hydroxide was added to promote the development of ASR. The second specimen, ASR 2D-confined specimen, was constructed using the same mix design with the ASR specimen, but headed rebars were used in the longitudinal and vertical directions (see Figure 1b) to constrain the expansions in these two directions. The control specimen has no reinforcement or added sodium hydroxide, and nonreactive aggregate were used in the mix design. These specimens were initially conditioned in an environmental chamber at 38°C and 95% of relative humidity, and then were moved outdoor.

The expansions in the transverse direction (the ultrasonic test direction, see Figure 1a) at the NDT test date were 0.018%, 0.123% and 0.167% for the control, ASR unconfined and ASR 2D-confined samples. Since the ASR 2D-confined sample is confined in the other two directions except for the transverse direction, it has the highest expansion in the transverse direction. This indicates that the ASR 2D-confined sample has the highest damage level in the transverse direction. The three concrete specimens were placed outdoor subject to ambient temperature changes. An additional control sample (sample #4) with an embedded temperature sensor was used to monitor the internal temperature of these samples.

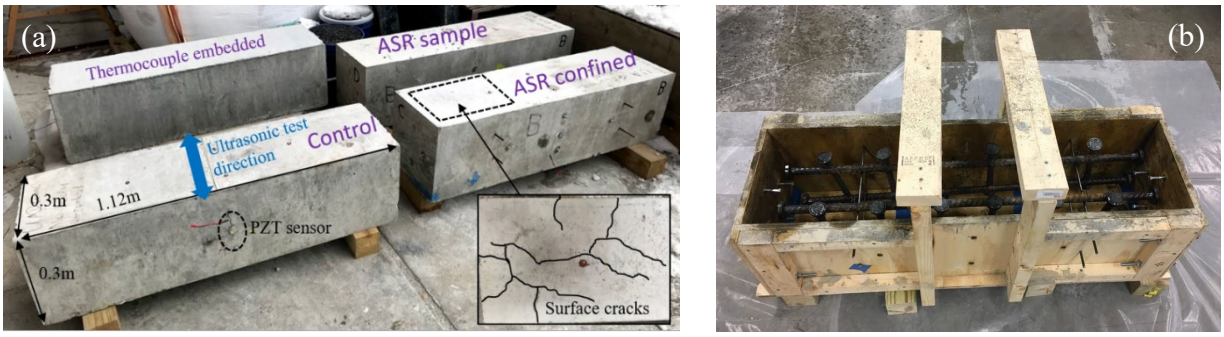

Figure 1. (a) Concrete samples for ultrasonic testing, (b) Headed reinforced bars in vertical and horizontal directions for the ASR 2D-confined sample

Experimental setup

Concrete samples were monitored using ultrasonic wave during the temperature change process. Two piezoceramic disks were installed on the opposite surfaces on each sample as the transmitter and receiver (see Figure 2). An ultrasonic pulser/receiver (Olympus 5077PR) emitted square wave pulses to drive the transmitter at the frequency of 100 kHz. The received signals were amplified by 20 dB and digitized by an oscilloscope (PICO4224) with a sampling rate of 20 MHz. A switch (Agilent 34970a/34903a) was used to switch the transmitter and receiver among the three samples. Meanwhile, the internal and surface temperature of these samples were monitored using a thermocouple sensor embedded in the additional sample and a thermocouple on surface. The sample #4 was placed next to other three samples; therefore, all these four samples are assumed to have the same surface and internal temperature during the test. The test samples were covered with towels in order to reduce the temperature gradient on these samples.

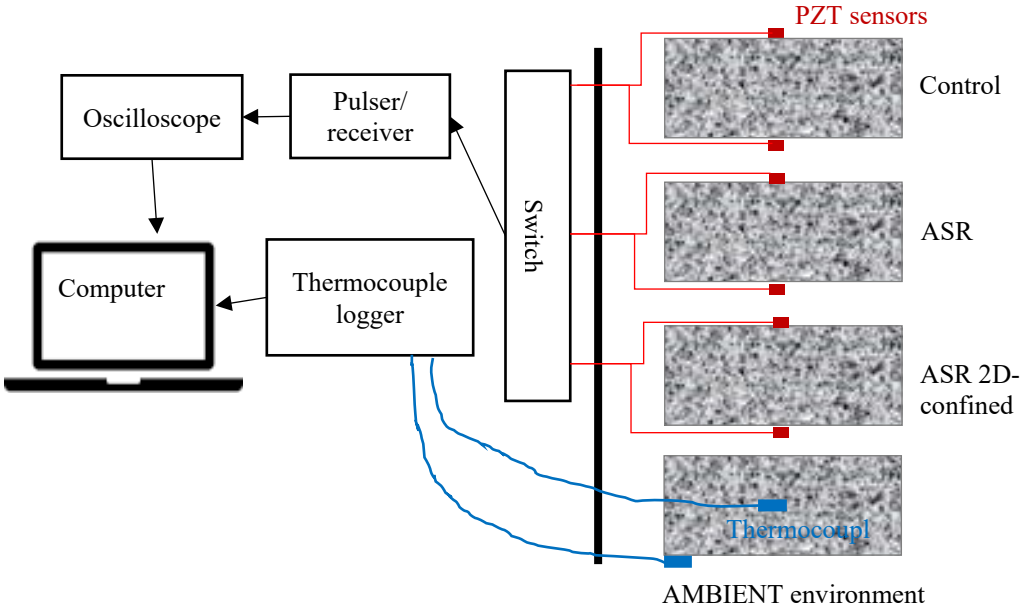

Figure 2. Experimental setup for ultrasonic and temperature monitoring

Coda Wave Interferometry

For temperature induced uniform velocity change in the test object, the stretching technique (Lobkis and Weaver, 2003) is typically used, which allows processing the full coda part as a whole. Using the stretching technique, the cross-correlation coefficient is evaluated as:

$$CC(\varepsilon) = \frac{\int_{t_1}^{t_2} \varphi'[t(1-\varepsilon)]\varphi[t]dt}{\sqrt{\int_{t_1}^{t_2} \varphi'^2[t(1-\varepsilon)]dt \int_{t_1}^{t_2} \varphi^2[t]dt}} \quad (1)$$

where ε is the stretching factor. The stretching factor ε_{max} which maximizes the cross-correlation coefficient represents the relative velocity change dv/v. Figure 3 shows two signals from the ASR unconfined sample at different temperatures. Since temperature drop will increase the ultrasonic velocity, the wave velocity at -5 °C was higher than the velocity at 0 °C. However, the velocity change is not very clear in the early part of the signal (inset (a)). In the coda wave part (inset (b)), there is an obvious time shift between the two signals.

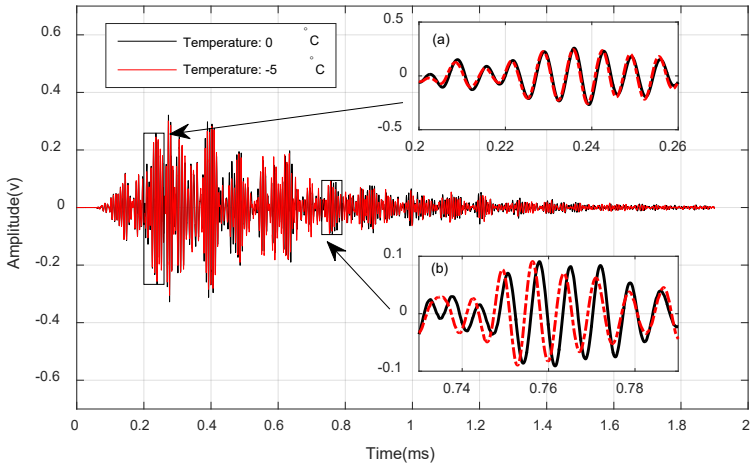

Figure 3. Ultrasonic signals of the ASR sample at the temperatures of 0 °C and −5 °C

RESULTS AND DISCUSSIONS

Figure 4a shows the temperature history of the concrete samples. The air temperature dropped from -2 °C to about -10 °C from 01/18/2019 to 01/19/2019. The internal and surface temperatures were higher than the air temperature but show similar trends. The maximum temperature difference was about -1.8 °C between the internal and surface temperature. Therefor the average of the internal and surface temperatures was used to represent the temperature change of the concrete samples (0 °C to -5.2 °C). The relative velocity change histories are shown in Figure 4b for the three samples. For each sample, the first signal at the beginning of monitoring was used as the reference in the CWI analysis, so that the relative velocity change started from zero. Test results indicate that the ASR 2D-confined sample shows the highest relative velocity change while the control sample has the lowest when experiencing the same temperature changes.

The correlation curves between the relative velocity change and temperature are shown in Figure 4c for the three samples. The three curves are fitted with linear relationships and the goodness of fit coefficients R^2 are all above 0.99, which indicates that the relative velocity change has a strong linear

relationship with the temperature change. The slope of the linear relationship, which represents the sensitivity of the relative velocity change to the temperature variation, is denoted as the thermal-modulation coefficient. The absolute values of thermal-modulation coefficients k are 2.4×10^{-4}/°C, 5.5×10^{-4}/°C and 7.7×10^{-4}/°C for the control, ASR unconfined and ASR 2D-confined, respectively. The trend of the thermal-modulation coefficients agree with the damage levels (expansions in the transverse direction) of the three samples. The different thermal-modulation coefficients can be explained by nonlinear behaviours of the microcracks and cracks when temperature changes. The microcracks in concrete will open (close) when subject to heating (cooling) and the opening (closing) of microcracks will decrease (increase) the ultrasonic velocity. Therefore, for a sample with a higher level of microcracking damage, the relative velocity change will be more sensitive to temperature changes than a sample with less microcracking damage.

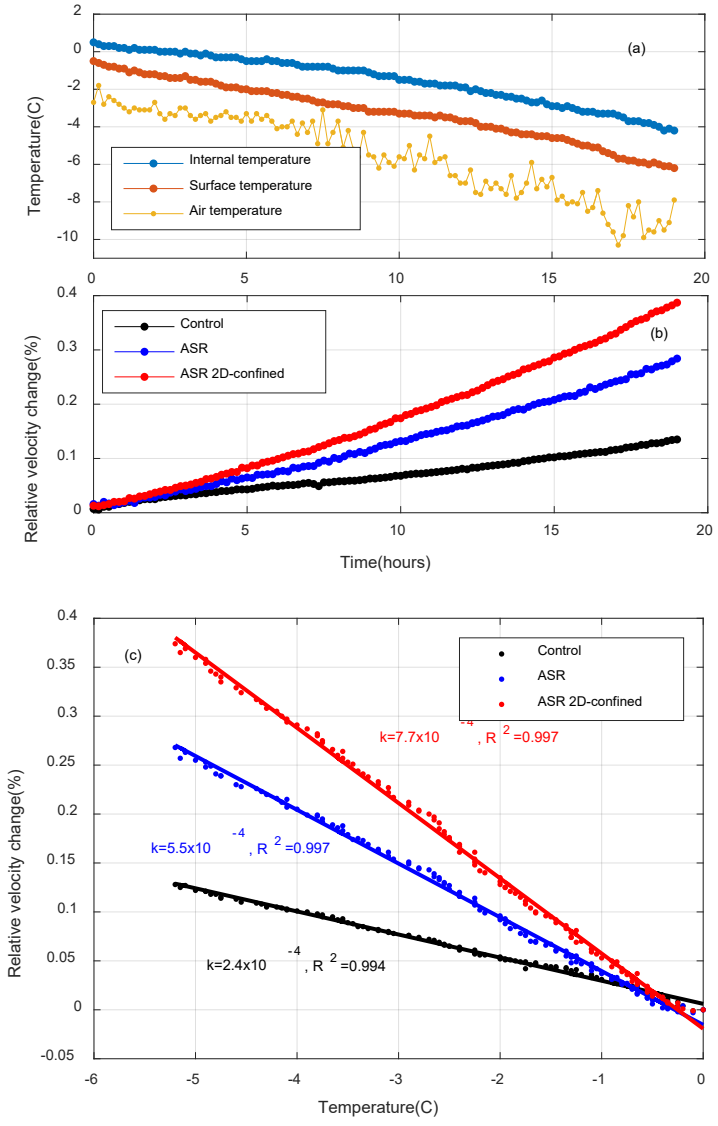

Figure 4 (a) Temperature history, (b) relative velocity change history, (c) correlations of temperature and relative velocity change for the three samples

CONCLUSION

The thermal dependence of relative velocity change has been investigated on ASR samples with two damage levels and a control sample without damage. The relative velocity change on the sample with more microcracking damage is more sensitive to temperature changes than the sample with less microcracking damage. This is caused by the nonlinear behaviour of the microcracking in the ASR samples. To validate the repeatability of the method proposed, the experiment was repeated on another day with a different temperature range (-2 °C to 8 °C). The thermal-modulation coefficients obtained in this temperature range are very close to the results in Figure 4. Therefore, the proposed thermal modulation method can be used as a nonlinear ultrasonic method to characterize ASR damage in concrete.

This method has been validated on different concrete samples with different damage types. The thermal-modulation coefficient can be used to characterize damage level without baseline measurements. Since the ambient temperature change is used as the modulation, this method has high potential application for in-situ monitoring of large scale concrete structures. In the future, the effects of temperature range and temperature changing rate may will be further investigated.

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