The 2023 World Congress on
Advances in Structural Engineering and Mechanics (ASEM23)
GECE, Seoul, Korea, August 16-18, 2023

Interaction of highly nonlinear solitary waves in a granular crystal sensor with cement

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ABSTRACT

This study investigates the interaction of highly nonlinear solitary waves (HNSWs) with cement paste towards a goal to develop a novel HNSW-based non-destructive evaluation technique for cementitious materials. Of particular interest is an experimental study of the sensitivity of HNSWs in a granular crystal sensor on the variation of a water-to-cement (w/c) ratio at different curing ages of cement paste. The granular crystal sensor, made of vertically aligned spherical steel beads in a one-dimensional chain, generates HNSW propagating into cement. The sensitivity of HNSWs on cement cube samples is examined by analyzing the HNSWs reflected from cement cube samples with various w/c ratios and curing ages. High sensitivity of the time of flight of the reflected HNSWs was observed for the w/c ratio ranging from 0.3 to 0.6 and curing age ranging from 1 to 28 days. These results verify the possible application of the HNSW-based technique for non-destructive evaluation of cementitious materials.

1. INTRODUCTION

Non-destructive evaluation (NDE) using HNSWs has been recently introduced as an alternative technique to existing techniques, such as ultrasound and X-ray, due to their simplicity, portability, and energy efficiency. The HNSW-based NDE method for applications in cementitious materials has advantages over traditional NDE methods such as ultrasonic pulse velocity method, the Schmidt hammer, and the resonant frequency method (Deng 2016 and Rizzo 2016). In contrast to the ultrasonic pulse velocity method, it does not require the access to the back-wall of concrete or any information of the distance between a transmitter and a receiver. Compared with the Schmidt hammer, which may unintentionally cause plastic deformation or microcracks, the HNSW-based method can be completely nondestructive. Moreover, unlike the

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resonant frequency method, the local mechanical properties of cementitious materials can be determined without the influence of the sample's size.

HNSWs are generated in a granular crystal sensor which is typically made of a one-dimensional chain of vertically aligned spherical steel particles (Yoon 2021 and Schiffer 2020). HNSWs have unique features such as a compact wave form, a tailorable wave speed, and high energy intensity (Nesterenko 2001). Moreover, HNSWs reflected from the interaction of an inspection medium retains a compact waveform without significant dispersion/attenuation. More importantly for NDE applications, recent studies verified high sensitivity of HNSWs on the mechanical and geometrical properties of an inspection medium (Daraio 2005, Sen 2008, Yang 2011). Motivated by such advantages of HNSWs, the goal of this study is to develop the HNSW-based NDE method for cementitious materials.

To achieve this goal, as the first step, this study focuses on an experimental study of the sensitivity of HNSWs to the variation of the w/c ratio and curing age of hardened cement. In doing so, cement cube samples were produced at varying w/c ratios at various stages of curing ages. An experimental setup of the granular crystal sensor was established for NDE of cementitious materials. Experiments were then performed using cement cube samples and the experimental setup. The sensitivity of the reflected HNSWs from cement cube samples was investigated by analyzing the time of flight of HNSWs for various w/c ratios of 0.3 to 0.6 at different curing ages ranging from 1 day to 28 days.

2. Experiment

To study the sensitivity of HNSWs on the w/c ratio and curing age, a total of 48 50 mm cement cube samples were produced at four different w/c ratios of 0.3, 0.4, 0.5, and 0.6 in accordance with the ASTM C109 using Type I cement. They were cured in distilled water at four different curing ages, i.e., 1 day, 7 days, 14 days, and 28 days. Each sample mix consists of 12 samples per w/c ratio with 3 samples per curing day. The cement samples were tested using the granular crystal sensor after each curing duration.

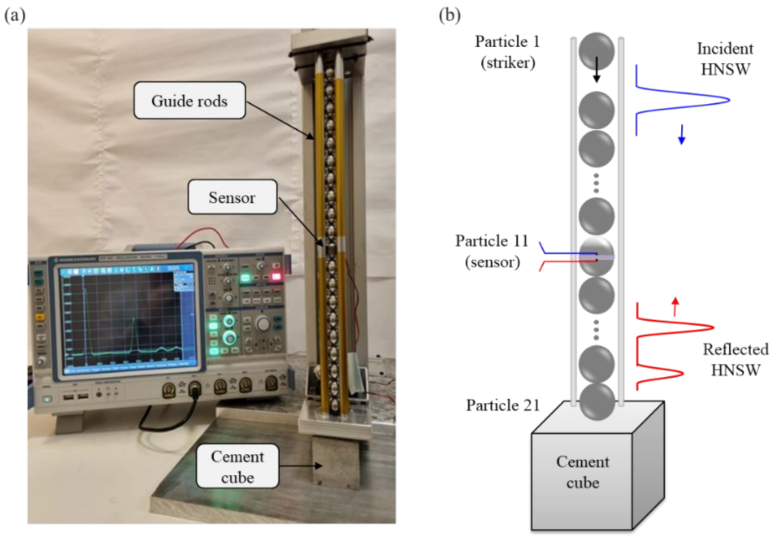

Fig. 1 (a) An experimental setup and (b) a schematic of a granular crystal sensor

Fig. 1 shows an experimental setup of the granular crystal sensor used in our experiments. The sensor is made of a granular chain of 21 vertically aligned spherical steel beads or particles, with a radius of $R = 9.5\ \mathrm{mm}$ and a mass of $m = 28\ \mathrm{g}$, made of AISI 52100 steel with density $\rho = 7860\ \mathrm{kg/m^3}$, Young's modulus $E = 208\ \mathrm{GPa}$, Poisson's ratio $\nu = 0.3$ and yield strength $\sigma_y = 1600\ \mathrm{MPa}$. The cement cube samples are in contacting directly with the last bead of the chain at the bottom. The first spherical particle in the chain, called a striker particle, generates the incident HNSW by dropping or impacting the rest of the chain from a certain height. The incident HNSW propagates downwards along the granular chain and interacts with the adjacent cement cube sample, giving rise to the formation of multiple reflected HNSWs. The incident and reflected HNSWs are monitored and recorded with the piezoelectric sensor embedded in the sensor particle located at the 11th particle from the top of the chain as shown in Fig. 1. The oscilloscope records the time history of HNSWs which can be used to determine wave parameters, related to the mechanical and geometrical properties of the cement sample, such as travel time, i.e., the time difference between the incident and reflected HNSWs.

3. Results and Discussion

The sensitivity of HNSWs on the variation of the w/c ratio and curing age is examined by analyzing the characteristic features of the reflected HNSWs measured from the experiment.

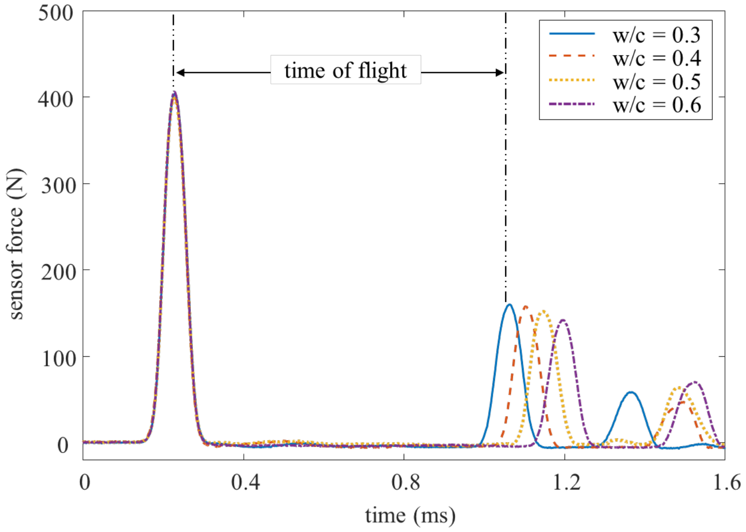

Fig. 2 Time histories of the sensor forces for cement samples at various w/c ratios

In Fig. 2, we show the time histories of the sensor forces for cement cube samples with the w/c ratios of 0.3, 0.4, 0.5 and 0.6 at curing age of 1 day. The sensor forces are recorded from the 11th sensor particle as illustrated in Fig. 1. In the figure, the first impulses are the incident HNSWs generated by the impact of the striker particle. These waves are recorded at the sensor particle without interacting with cement samples and, thus, they are identically recorded at 0.23 sec. The subsequent waves are the two reflected HNSWs arriving back to the sensor particle after interacting with the cement cube samples. In this study, the first reflected HNSWs are considered as the marker for the sensitivity analysis. For quantitative analysis, the difference in arrival time between the incident and first reflected HNSWs is defined as the time of flight as illustrated in Fig. 2. The results in Fig. 2 show the increase of the time of flight of the first reflected HNSWs with increasing w/c ratio. In addition, the amplitudes of the first reflected HNSWs are slightly reduced as w/c ratio increases. Notice that this trend is the same for other curing ages.

In Fig. 3, we display the time of flight of the first reflected HNSWs for cement cube samples for varying the w/c ratio and curing age. The results clearly show that the time of flight of the first reflected HNSWs becomes longer with increasing the w/c ratio and shorter with increasing curing age. The increase of the time of flight with higher w/c ratio and lower curing age is because of the reduction of the hardness/stiffness of cement with increasing the w/c ratio and decreasing curing age. These findings are consistent with those found by Yang (2011) and Ni (2012).

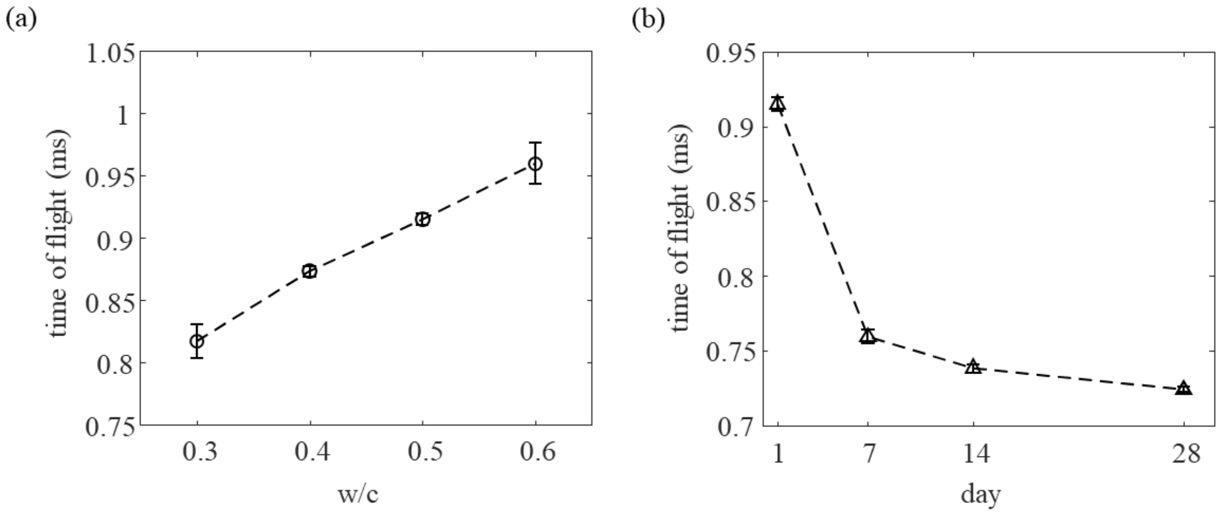

Fig. 3 Sensitivity of HNSWs on w/c ratio and curing age: (a) time of flight vs. w/c ratio and (b) time of flight vs. curing age at w/c=0.5

4. CONCLUSIONS

In this study, we experimentally demonstrated the sensitivity of HNSWs to changes in the w/c ratio and hydration, i.e., curing age, of cement paste. HNSWs reflected from cement cube samples showed a clear differentiation in travel time, i.e., time of flight, to the variation on the w/c ratio and curing age. As the cement samples aged, the reflected HNSW was less sensitive to the change in the strength of the samples. This can be attributed to the change in the hardness of the surface of the samples, as the sample ages it becomes harder and less plastic. Our studies revealed that the reflected HNSWs have been shown to be greatly influenced by surface conditions, although it has good repeatability and reliability. Future research in surface treatment techniques for the application of HNSWs can give more insight into solving this.

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