DOI 10.1007/s11595-011-0264-7

Piezoelectric Actuator/Sensor Wave Propagation Based Nondestructive Active Monitoring Method of Concrete Structures

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Abstract: In order to monitor the basic mechanical properties and interior damage of concrete structures, the piezoelectric actuator/sensor based wave propagation method was investigated experimentally in the laboratory using a specifically designed test setup. The energy attenuation of stress waves was measured by the relative index between the output voltage of sensors and the excitation voltage at the actuator. Based on the experimental results of concrete cube and cylinder specimens, the effect of excitation frequencies, excitation amplitude, wave propagation paths and the curing age on the output signals of sensors are evaluated. The results show that the relative voltage attenuation coefficient *RVAC* is an effective indicator for measuring the attenuation of stress waves through the interior of concrete.

Key words: piezoceramics actuator/sensor; wave propagation method; non-destructive evaluation (NDE); active monitoring; concrete

1 Introduction

Reinforced concrete (RC) structures are widely used in civil infrastructures such as buildings, bridges, highway systems and dams, because of low construction cost and long service life under various conditions. Health monitoring of concrete structures is challenged due to the complexities of damage natures. The integration of the local and global damage identification strategies are considered as the most promising method for identifying the location and extend of damage emerging on the large scale civil infrastructures, while the damage detection at the incipient stage present the largest challenge. These considerations necessitate the deployment of a reliable non-destructive evaluation (NDE) system, capable of detecting local damages at the incipient stage. Recently, the smart material, such as piezoelectric material is emerging to be effective in the health monitoring of civil engineering structures[1,2]. At the beginning, the PZT patches based electro-mechanical impedance (EMI) sensing technique was introduced from other fields to concrete structures. The proof-of-concept experiment of the EMI sensing technique for predicting concrete strength was first investigated by Soh and Bhalla [3]. Their experiment results showed that a strong correlation exists between cube compressive strength of concrete and resonant frequency of the EMI spectrum. The feasibility of the EMI sensing technique was further investigated by Shin *et al* [4,5] using a cylindrical specimen and a different PZT installation technique. It was found that the root mean square deviation (RMSD) index is a suitable and sensitive indicator for the strength gain monitoring of concrete structures. Findings from these studies however also show that this method may not yet be ready for commercialization until its practicality and reliability of measurements are addressed through more investigations. Recently, Tawie and Lee [6] investigated the effects of main parameters in the mix proportion of concrete on the measured EMI resonance spectra *in situ* monitoring of concrete using the low cost PZT patches, and the quantitative relation between the compressive strength of concrete and the indices of RMSD, mean absolute percentage deviation (MAPD) and correlation coefficient deviation (CCD) of EMI spectra were analyzed.

As an effective active monitoring method, the

(Received: Nov. 1,2009; Accepted: Nov. 25,2010)

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Funded by the National Natural Science Foundation of China (No.50708065), the National High-tech R&D Program(863 Program)(No.2007-AA-11-Z-113), and the Key Projects in the Science and Technology Pillar Program of Tianjin (No. 11ZCKFSF00300)

EMI sensing technique has been studied widely and applied for monitoring the damage and early-age strength of concrete, the costly impedance analyzers however are inconvenient in practical application. As an alternative, the PZT based wave propagation method presents another promising way for active monitoring of local damage in civil engineering infrastructures. Gonzalo E Gallo *et al*[7] established the relations between concrete strength, wave velocity and surface wave transmission, and they found the surface wave velocity and normalized surface velocity data correlate well with in-plate strength of concrete. H Gu *et al*[8] proposed a piezoelectric-based strength monitoring method using piezoelectric transducers embedded into the concrete specimen during casting. F Song *et a*l[9] .investigated the surface wave propagation in concrete beam by using surface-bonded PZT elements numerically and experimentally. Mingqing Sun *et al*[10] used piezoelectric ceramic sensors and ultrasonic wave method to monitor the dynamic elastic constants of concrete and cracks as part of the SHM system of concrete structures.

However, the stress waves excited by the actuator are very complex due to reflection, attenuation and transmitting when they propagated inside concrete structures. The mix of concrete, profile and size of concrete structures, micro-cracks in concrete, wave form, amplitude and frequencies of excitation signal will all affect the velocity and attenuation of output signal which will be received by the sensors. Further studies are necessary on PZT-based wave propagation in concrete structures for the widely application.

This paper presents an experimental study to monitor the attenuation of wave propagation along two directions of concrete specimens. The experimental results of two series of specimens are reported herein. The relative voltage attenuation coefficient (RVAC) is defined and used to measure the attenuation of stress waves. The effects of amplitudes, frequencies of excitation signal excited by the piezoelectric actuator on the RVAC of sensors are investigated.

2 PZT-based Wave Propagation in Concrete

2.1 Piezoelectric smart materials

Smart materials are defined as materials capable of altering their physical properties in a specific manner in ‘response’ to a specific ‘stimulus’ input. Among the various commercial smart materials, PZT are alloys of lead zirconate and lead titanate, doped with other materials to obtain specific properties. They are characterized by the development of surface charges (response) on the application of a mechanical stress (stimulus). This effect is called the ‘direct effect’ and is utilized in numerous sensing applications. Piezoceramics also exhibit the ‘converse effect’, that is, they undergo mechanical deformations (response) upon the application of an electric field (stimulus). The converse effect is utilized in actuator applications. Piezoceramics are commercially available as thin patches (typically 5–50 mm wide and 0.1–0.5 mm thick). They demonstrate attractive characteristics such as low-cost, durability, consistency, large operational bandwidth and good dynamic performance, even at high frequencies of the order of 100 kHz. Recently, PZT materials have also been employed as mechatronic impedance transducers and stress wave actuator / sensors for NDE of structures.

Under small field considerations, the general constitutive equations of PZT materials can be written as [11]

$$D_i = \varepsilon^T_{ik} E_k + d^d_{ip} T_q \tag{1a}$$

$$S_p = d^c_{kp} E_k + s^E_{pq} T_q \tag{1b}$$

where D_i is the electric displacement vector; S_p is the strain vector; E_k is the applied electric field vector; and T_q is the stress vector. Piezoelectric constants are the dielectric permittivity, $\varepsilon_{ik}{}^T$, the piezoelectric strain coefficients $d_{ip}{}^c$ and $d_{kp}{}^c$, and the elastic compliance, $s_{pq}{}^E$. The superscripts ‘*d*’ and ‘*c*’ indicate the direct and converse piezoelectric effects respectively, while the superscripts ‘*T*’ and ‘*E*’ indicate that the quantity is measured at constant stress and constant electric field respectively.

In the present application for NDE, the PZT patches are permanently bonded to the concrete specimen to be monitored using high strength epoxy adhesive. One patch in the array is electrically excited by a harmonic sine wave voltage source at high frequencies (from 10 kHz to 50 kHz). Due to the converse piezoelectric effect, the excited patch, acting as an actuator, transmits its vibrations to the monitored structure, generating stress waves that travel away from the patch. The resulting vibrations are then picked up by other PZT patches in the vicinity, which, via the direct piezoelectric effect, consequently develop alternating voltage signals across their terminals. Hence, the other PZT patches act as sensors.

2.2 Wave propagation in concrete

The stress waves generated by PZT actuators carry the information of the host structure, and thus can be used to identify the existence and nature of the damage. The wave propagation of stress waves in concrete structures can be viewed as one dimensional longitudinal wave propagation [12]. The wave equation can be written as

$$\frac{\partial^2 u}{\partial x^2} = \frac{1}{c_b^2}\cdot\frac{\partial^2 u}{\partial t^2} \tag{2}$$

where c_b^2 equals E/ρ, u is the displacement of an element, E is the Young's modulus and ρ is the density of the material.

The average power, p, of the harmonic response over a period can be expressed as

$$p = EA^2\omega^2/2c_b = \sqrt{E\rho}\,A^2\omega^2/2 \tag{3}$$

where A is the harmonic amplitude and ω is the circular, or angular, frequency.

Eq. (3) can be rewritten as

$$A = \left(\frac{1}{\omega}\right)\left(\frac{4p^2}{E\rho}\right)^{1/4} \tag{4}$$

As shown in eq.(4), the harmonic amplitude is affected by the Young's modulus, E , of the medium. During the early-age development of concrete material, the Young's modulus, E, increases as the concrete gains strength during the hydration process. Consequently, the harmonic amplitude will decrease with the increase of the Young's modulus, E. Moreover, the Young's modulus, E, is the major affecting factor in determining concrete strength. Therefore, the harmonic amplitude is correlated with the concrete strength through the Young's modulus. By observing the amplitude change of harmonic stress wave, the strength development of concrete specimens can be monitored and evaluated.

In addition, according to the study conducted by Hu and Yang [11], the material damping reduces (concrete was initially 'soft') during the curing age. As moisture content drops, concrete damping tends to fall down. To take the damping coefficient into account , Song *et al* proposed replacing E by $E(1+\eta)$ in Eq.(4) [12], where η is the damping coefficient. Due to the material and structural damping, waves generated by the PZT actuator attenuate while propagating through the concrete specimens.

3 Experimental Investigation

To verify the applicability and efficacy of the wave propagation technique for monitoring of concrete strength and interior damage, experiments conducted on concrete specimens are presented in this section. First, the experimental program such as specimen preparations, experimental setup and test procedures are introduced, and followed by results and discussions.

3.1 Test specimens

Table 1 Details of the composition of concrete tested

Component	Composition /(kg/m^3)	Description
Cement	424	Type I Portland cement
Sand	581	Well-graded washed sand
Coarse aggregate	1 163	Gravel with the maximum size of 20 mm
Water	195	Tap water

Two series of concrete specimens were casted and cured for the experiments. The concrete cylinder specimens have a total of 25 with a diameter of 150 mm and a height of 300 mm (1 for wave propagation acquisition, 24 for compressive strength and Young' s modulus tests).Another one concrete cube specimen was also prepared for wave propagation acquisition at the same time.

The designed compressive strength of the concrete mixes is 30 MPa, and the constituents of concrete are presented in Table 1. Concrete mixes were casted with steel molds. Immediately after they were made in the laboratory, the specimens were covered with plastic sheets to prevent moisture loss and stored for 24 h in laboratory conditions before the molds were removed. For the remaining period, the specimens were stored in moisture and temperature controlled curing room until testing.

Four PZT patches with the sizes of 10×10×2 mm^3 were instrumented on the cylinder and cube specimens respectively as shown in Fig. 1. The attachment of PZT was done 1 day after casting the concrete specimens. The first test was carried out at the age of 3 days in order to ensure full development of PZT bonding adhesive. Compressive strengths were evaluated at the ages of 3, 7, 14 and 28 days. Days 3, 7, and 28 are the important days in evaluating in-place compressive strength specified in many construction codes. Three specimens were evaluated at each age to obtain average compressive strength and three were used to test for obtaining the Young's modulus.

3.2 Experimental set-up

3.2.1 PZT

The PZT patches selected in the present tests are 10 mm in length, 10 mm in width, 2 mm in thickness,

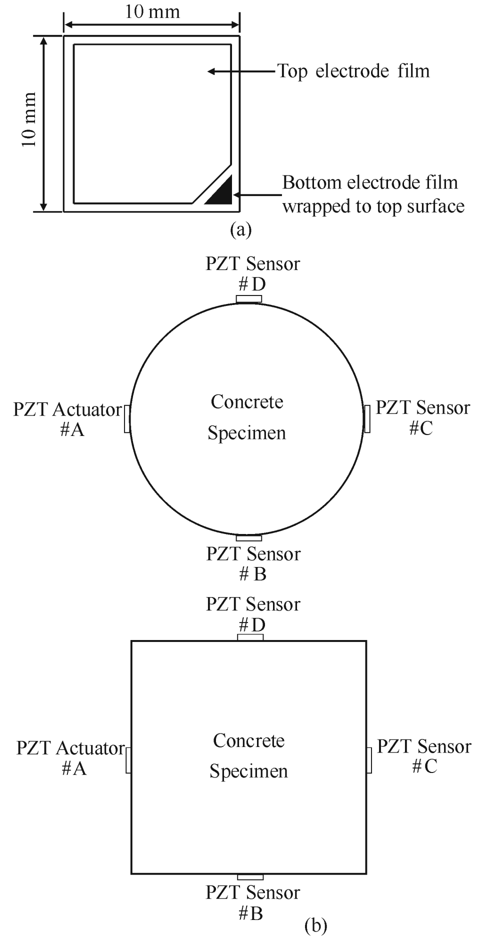


Fig. 1 (a) A typical commercially available PZT patch and (b) Configuration of the PZT patches attached to the concrete specimens

and are polarized in the thickness direction. Fig. 1.(a) shows a typical commercially available PZT patch suitable for using in the present study. The characteristic feature of the patch is that both the electrodes are available on one side of the PZT patch only, and the other side is to be bonded to the concrete specimens. The key parameters for the PZT patch provided by the manufacture are listed in Table 2.

Fig. 1.(b) shows the configuration of the PZT patches bonded on the surfaces of the concrete cylinder and cube specimens, respectively. The piezoelectric actuator and sensors are located on the profiles of the specimen. One is the actuator (#A) and three are sensors (#B, #C and #D), as shown in Fig. 1.(b). Silver epoxy is used to bond PZT to the specimens. The epoxy used in the experiments has the highest stiffness that are available on the market. Energy loss due to material mismatch among the PZT, epoxy, and the concrete is the lowest of all the epoxies.

3.2.2 Experimental system

In this section, specific designed experiment setup was conducted to demonstrate the practical feasibility of generation and reception of the wave using piezoelectric actuators/sensors. The system includes an arbitrary waveform generator (RIGOL DG1022), a digital oscilloscope (RIGOL DS1102E) and a personal computer. Because wave signals decay very quickly

Table 2 Key parameters for the PZT patch

Physical parameters	Values
Density/kg • m^{-2}	7 700
Young's modulus/N • m^{-2}	6.667×10^{-10}
Poisson ratio ν	0.3
Dielectric matrix $[\varepsilon]$ / (C • v^{-1} • m^{-1})	$\begin{bmatrix} 6.45 & 0 & 0 \\ & 6.45 & 0 \\ \text{Symmetry} & & 5.62 \end{bmatrix} \times 10^{-9}$
Piezoelectric matrix [e] / (C • m^{-2})	$\begin{bmatrix} 0 & -6.5 & 0 \\ 0 & 23.3 & 0 \\ 0 & -6.5 & 0 \\ 0 & 0 & 0 \\ 17 & 0 & 0 \\ 0 & 0 & 17 \end{bmatrix}$
Stiffness matrix [c]/Pa	$\begin{bmatrix} 13.9 & 6.78 & 7.43 & 0 & 0 & 0 \\ & 13.9 & 7.43 & 0 & 0 & 0 \\ & & 11.5 & 0 & 0 & 0 \\ & & & 3.56 & 0 & 0 \\ & & & & 2.56 & 0 \\ & \text{Symmetry} & & & & 2.56 \end{bmatrix} \times 10^{10}$

in concrete structures, the signal input on the actuators should be strong enough to generate output readable by the sensors. A wideband power amplifier (HVA-1C0150A0300D) was used to amplify the signals from the function generator. The amplification factor was set equal to 15 for the tests, thereby increasing the wave function generator output of 10 V up to an actuator input of 150 V.

3.3 Test Procedures

In the present study, the sinusoidal waves with the voltage amplitudes of 1, 2, 3, 4 and 5 V were generated by the arbitrary waveform generator and amplified by the power amplifier before exciting the piezoelectric actuator. The resulting voltage amplitude excited on the PZT actuator was from 15 V to 75 V with the increment of 15 V. High frequency sinusoidal excitation signals with frequencies of 1, 2, 5, 10, 20, 30, 50 kHz were utilized for the excitation source for the surface bonded piezoelectric actuators for comparison purposes. It is noteworthy that a frequency range of 1-50 kHz was intentionally chosen for this study, since previous research found that sinusoidal signals with frequency higher than 50 kHz and less than 1 kHz may not be applicable for monitoring applications of concrete structures.

At the curing ages of 3, 7, 14, 28 and 56 days, the compressive strength and Young's modulus of concrete were tested utilizing the cylinder specimens. At the curing ages of 3, 7, 14, 28, 56, 90 and 120 days, wave propagation tests were conducted, where the PZT patch #A was selected as the actuator, and PZT patches #B, #C, #D were sensors. Signals from the sensors (patches #B, #C, #D) were collected by the digital oscilloscope and processed in the computer by the software Ultrascope. In order to minimize incoherent noise components, the signals were sampled with the span of 60 seconds for every case.

3.4 Test results

The cube and the cylinder concrete specimens instrumented with piezoelectric transducers were tested using the proposed method. Experimental results show that the harmonic amplitude dropped with the strength development of the concrete specimens at early ages, which are consistent with the results reported by other researchers. To obtain the normalized sensor output voltage, the relative voltage attenuation coefficient RVAC can be defined as

$$\mathrm{RVAC} = \frac{A_s}{A_a} \tag{5}$$

where A_s is the output voltage amplitude of sensor, A_a is the amplitude of the actuation voltage. According to the analysis conducted by Yuhang Hu *et al*[12], RVAC is a function of the dimensions of the PZT patch and the host structure, the material properties, the frequency of actuation and the distance between the actuator and sensor. In the present study, the later three factors were varied during the wave propagation tests. The experimental results are presented as following.

3.4.1 Time-dependent sensor output voltage

For verifying the wave propagation based concrete strength gain monitoring, the concrete specimens were tested by a universal compression testing machine to obtain the compressive strength value and Young's modulus, as shown in Fig. 2. In order to compare with the existing experiment results of different strength grades and test conditions, the compressive strength and Young's modulus at any curing ages are normalized by the values of 28 days. The curves in Fig. 2 are in agreement with the results reported by other authors [8,14].

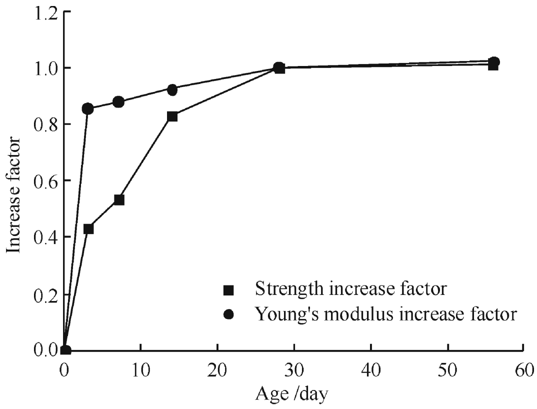
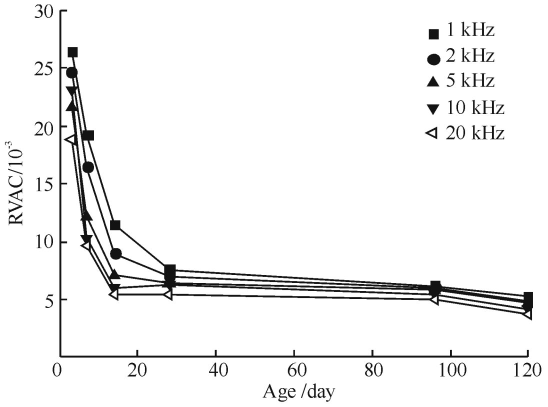


Fig. 2 Increase of compressive strength and Young's modulus *versus* curing age

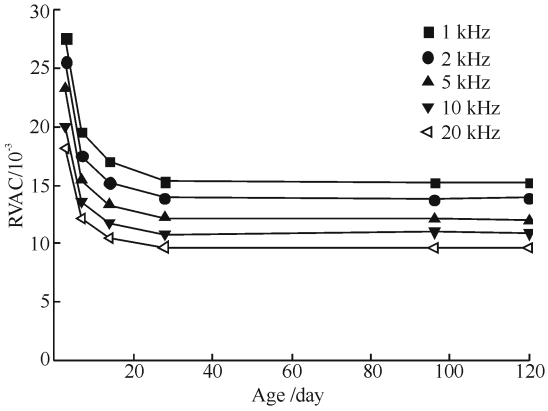
Fig. 3 shows the measured RVAC at six different curing ages for the different wave propagation paths of A-B, A-C, and A-D, respectively. It is apparent from the figures that the RVAC sharply decreases to a relatively stead level after the curing age of 28 days for all of the propagation paths.

3.4.2 Effect of excitation amplitude

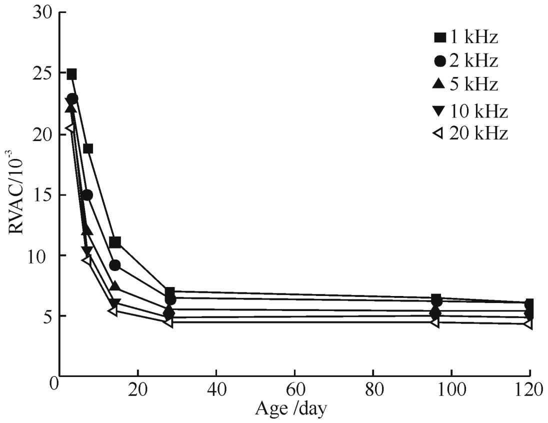
Fig. 4 shows the typical RVAC of received sensor signals observed at the actuator–sensor match of A-C with different excitation frequencies, where the normalized index of RVAC is observed to be independent of the amplitude of excitation signals. The amplitudes of excitation voltage only affect the intensity of sensor signals depending on the distance of actuator-sensor and the thickness of PZT patches.



(a) A-B



(b) A-C



(c) A-D

Fig. 3 Time-dependent RVAC of different propagation paths

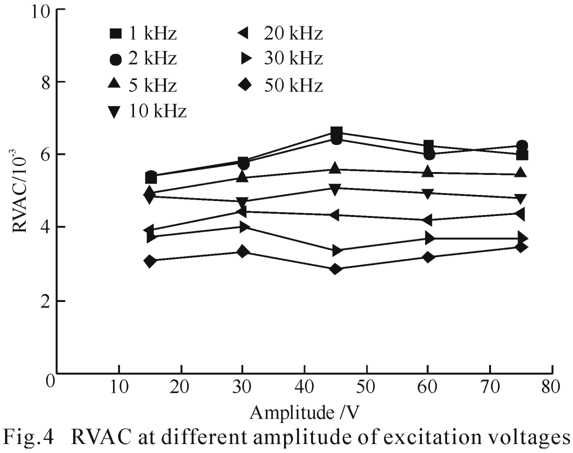
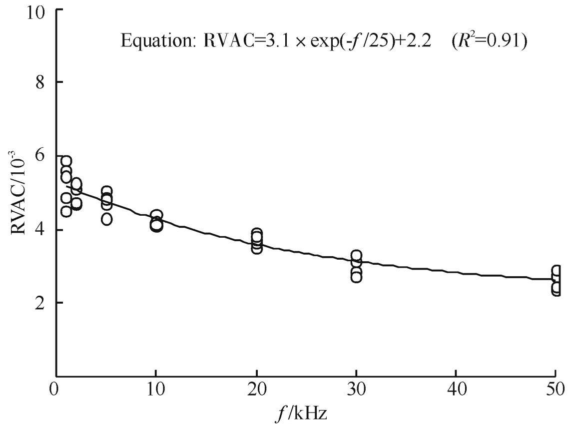
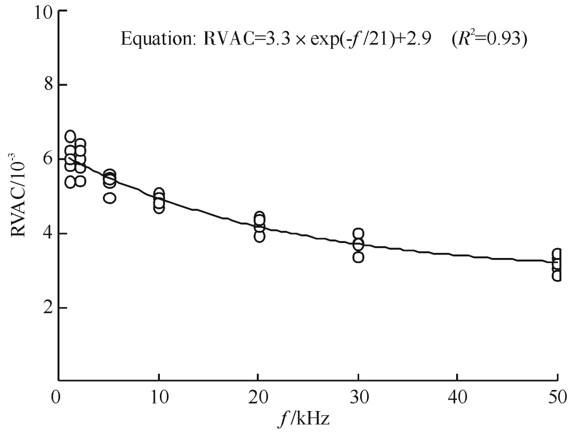


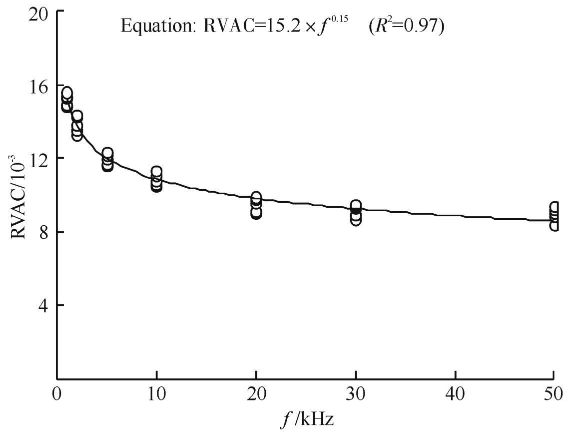
Fig.4 RVAC at different amplitude of excitation voltages



(a) A-B



(b) A-D



(c) A-C

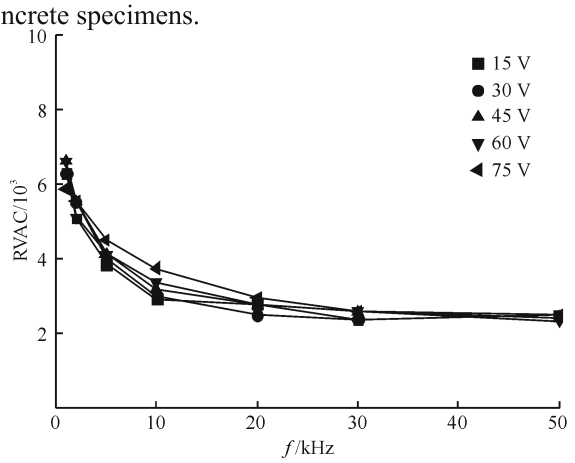
Fig. 5 RVAC of measured output voltages of sensors at different excitation frequencies

3.4.3 Effect of excitation frequencies

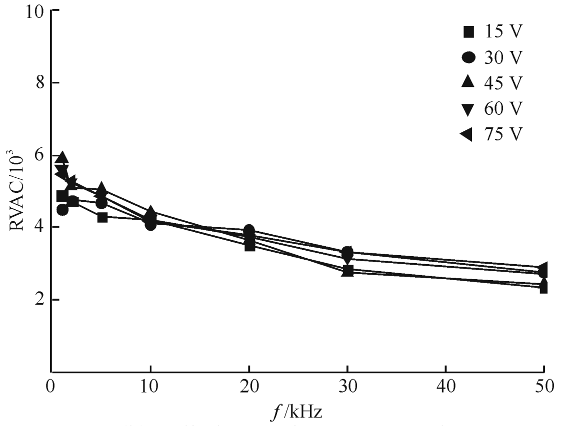
In order to examine the influence of the frequency of the input signal on the RVAC, the input frequency was varied over the range of 1-50 kHz, *i e*, 1, 2, 5, 10, 20, 30 and 50 kHz. The RVACs of measured output voltages of sensors at different excitation frequencies is shown in Fig. 5. It can be observed that as the excitation frequencies increases, the RVAC decreases. The results indicate that the waves generated by actuators attenuate while propagating through the interior of concrete, especially at higher excitation frequencies. For the actuator/sensor match of A-B and A-D, the RVAC curves for different frequency excitations follow a similar trend of exponential attenuation. As to the actuator/sensor match of A-C, the attenuation is faster than the other matches when the frequency is less than 10 kHz.

3.4.4 Effect of specimen type

The difference of RVACs between two types of specimens is illustrated by the experiment results at the curing age of 120 days, as shown in Fig. 6. When the excitation frequencies are lower than 20 kHz, there are little differences between the two profiles of concrete specimens. It is apparent that the wave propagation is affected by different boundary conditions of the two concrete specimens.



(a) Cube specimen A-B 120 days



(b) Cylinder specimen A-B 120 days

Fig. 6 Differences of *RVAC* between two types of specimens

4 Conclusions

In this paper, the PZT-based wave propagation method is introduced to monitor the mechanical properties and interior damage of concrete specimens. A PZT wave propagation monitoring system was established based on the commonly available facilities in the laboratory. Two series of concrete specimens were tested and the following conclusions can be reached:

a) The RVAC of output from the sensor is an effective indicator for measuring the attenuation of stress waves traveling through the interior of concrete.

b) According to the tests on the cylinder specimen, the RVAC sharply decreases to a relativey stead level after the curing age of 28 days for all of the propagation paths.

c) The RVAC of output from the sensor is independent of amplitudes of excitation signals at piezoelectric actuator.

d) The RVAC curves for different frequency excitations follow the trend of exponential attenuation.

This paper is part of on-going study on the application of PZT-based wave propagation method in concrete structures. The results on the present method applied to the cracked concrete beam will be reported in another article, and the numerical simulation will be conducted simultaneously.

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