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Damage Detection of Concrete under Static Loading Based on Ultrasonic Sensor

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ABSTRACT

In this paper, an ultrasonic sensor for concrete damage detection was designed and prepared. The ultrasonic sensor was used to detect concrete under static load. The results show that the piezoelectric sensor has high sensitivity when the resonant frequency of piezoelectric ceramic is 112kHz and the thickness of alumina matching layer is 1.5mm. As the concrete load increases gradually, the waveform moves backward, and the time for the sensor to receive the waveform becomes longer and the propagation speed becomes slower. When the load force on the concrete test block is small, peak-to-peak value and first wave amplitude decrease rapidly, while the loading force increases, and the decreasing amplitude gradually decreases. The peak-to-peak value decreases from 8.432V before loading to 1.289V when the loading force is 110kN, and the first wave amplitude decreases from 0.045V to 0.01V, proving that at this time, large damage has occurred in the concrete.

1. INTRODUCTION

Concrete is sometimes affected by environmental factors, or because of poor construction management, its internal may appear cracks or holes, etc., external may appear honeycomb pitting surface defects, such as the existence of these defects will affect the durability and bearing capacity of concrete[1,2,3] therefore, adopting effective methods to monitor concrete damage is of great significance to improve concrete durability.

The ultrasonic wave has the characteristics of strong penetrating power and ultrasonic testing equipment operation more convenient, therefore, the ultrasonic testing technique is widely used in concrete non-destructive testing in the process[4], the propagation speed of ultrasonic pulse wave is directly related to the compactness of concrete[5], concrete of proportion of raw materials, age, certain circumstances, the velocity of ultrasonic wave can directly reflect the density of the material. Therefore, the acoustic parameters such as peak-to-peak value, first wave amplitude, and propagation time can reflect the damage of concrete.

In the 1990s, China promulgated the Technical Specification for Ultrasonic Detection of Concrete Defects[8]. In recent years, more and more scholars combine concrete with piezoelectric materials to detect concrete damage[6-18]. Zhang[15] used ultrasonic detection technology to detect cracks in concrete specimens, analyzed and compared monitoring data with theoretical data, and put forward suggestions on crack detection methods. Chen[16]conducted ultrasonic tests on soil-cement to judge the strength and quality of soil-cement. Xu[17] studied the influence of temperature and load on embedded piezoelectric sensors in structural health monitoring. Ultrasonic sensors were used instead of sensors common in the market[18]. The acoustic impedance of the composite material is very close to that of hardened concrete, ensuring minimum signal distortion and maximum signal energy transmission efficiency between the two materials. Because of this, this paper designed and produced a targeted ultrasonic sensor to carry out the detection and identification of concrete damage, providing a new method for concrete damage detection.

2 EXPERIMENTAL PROGRAMS

2.1 RAW MATERIALS

The piezoelectric ceramic used in this paper is PZT-5H produced by Zibo Yuhai Electronic Ceramics Factory, the epoxy resin is grouting resin of Beijing Jinhong Century Technology Co., LTD., the tungsten powder comes from Sinophem Chemical Reagent Co., LTD., and the alumina ceramic is provided by Huiwen New Material Technology Co., LTD.

2.2 PRINCIPLE OF ULTRASONIC

When an ultrasonic wave propagates in concrete, it will produce strong scattering, reflection, absorption, and other phenomena, leading to strong attenuation of the acoustic wave. The attenuation phenomenon of the ultrasonic wave varies with the damage of concrete, and the propagation speed is also constantly changing. Therefore, ultrasonic sensors were prepared in this paper to monitor concrete damage through the ultrasonic method, collect ultrasonic information transmitted through concrete, analyze waveform and parameter changes, and then detect concrete damage. The monitoring system and its working principle are shown in Figure 1.

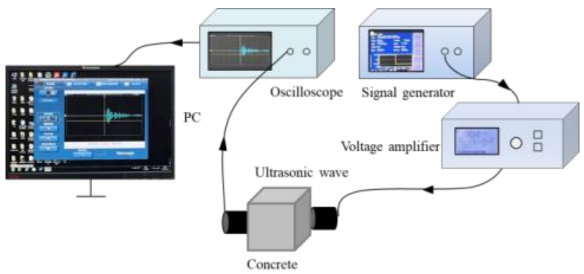

Figure 1. Principle of ultrasonic monitoring

3. RESULTS AND ANALYSES

3.1 PREPARATION OF ULTRASONIC SENSORS

As an important part of the ultrasonic nondestructive test, the piezoelectric sensor has the characteristics of self-sensing, good stability, and high sensitivity, which can realize the mutual conversion of mechanical energy and electric energy. The ultrasonic sensor was encapsulated by a metal shell, which can receive more signals. In this paper, the sensor was designed from the three aspects of a piezoelectric component, matching layer, and backing layer respectively. The specific production flow chart is shown in Figure 2.

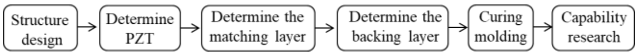

Figure 2. Flow chart of making ultrasonic sensor

3.1.1 PIEZOELECTRIC COMPONENTS

There are many kinds of piezoelectric ceramics, so the selection of appropriate piezoelectric ceramic components is the key to preparing piezoelectric ultrasonic sensors.PZT-5H is a kind of high sensitivity receiving piezoelectric ceramic with a large piezoelectric strain constant, therefore, PZT-5H piezoelectric ceramics were selected as the core components of the ultrasonic sensors in this paper. A fine cutting machine was used to cut PZT ceramics into cubes with sizes of 10×10×10 mm, 8×10×10 mm, and 5×10×10 mm respectively. The main performance parameters are shown in Table 1.

Table 1. Main performance parameters of piezoelectric ceramics

Piezoelectric ceramics	Density / (10^3 kg·m^{-3})	Piezoelectric strain constant/ (pC·N^{-1})	Resonance frequency/kHz
PZT-5H	7.5	430	112

The performance of the PZT-5H piezoelectric component of three different sizes was tested. The test results are shown in Figure 3. It can be seen that the resonant frequency gradually decreases with the increasing thickness of piezoelectric ceramics. As concrete is a heterogeneous material, the transmission of ultrasonic waves in concrete will attenuate, and the greater the resonant frequency of the piezoelectric components, the more serious the attenuation will be. Therefore, a smaller resonant frequency should be adopted to detect the damage of concrete, within the range of 30 kHz-300 kHz. PZT-5H ceramics with a size of 10*10*10 mm were selected in this paper, and their resonant frequency is 112 kHz.

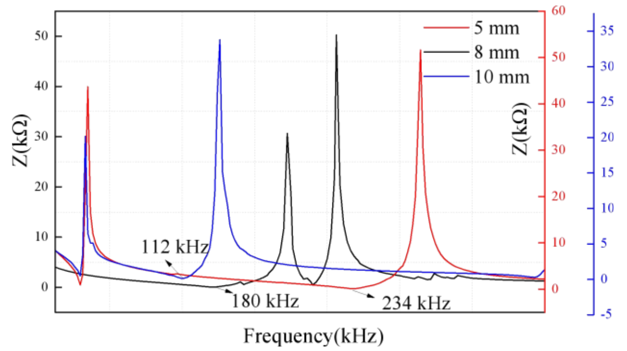

Figure 3. Impedance spectra of piezoelectric components with different thickness

3.1.2 THE MATCHING LAYER

The matching layer of ultrasonic sensor was used for concrete damage detection needs to be able to match the acoustic impedance of damage, to improve the transmission coefficient of acoustic wave between the sensor and concrete structure, and to protect piezoelectric components. According to the theory of sound matching, alumina sheets, aluminum sheets and epoxy tungsten powder sheets were selected as the matching layer. The resonant frequency of piezoelectric ceramics was used in the test is about 112 kHz. According to the quarter wavelength theory, the matching layer thickness of the ultrasonic sensor is 15 mm. In consideration of economic benefits and acoustic performance of the piezoelectric ultrasonic sensor, 1mm alumina, 1.5 mm alumina, 1.5 mm aluminum and 1.5 mm epoxy tungsten powder were selected as matching layers for experiments. Piezoelectric sensors made of matching layers of different materials are shown in Figure 4.

Figure 4. Pictures of sensors at different matching layers

Four ultrasonic sensors with different matching layers were prepared and tested on the ultrasonic nondestructive thickness test block. The peak-to-peak values of test waveforms were obtained as shown in Figure 5. With the increase of the thickness of the steel block, the peak-to-peak values of waveform received by sensors prepared by each matching layer show a trend of gradual decline. The sensor with 1.5 mm alumina as the matching layer received the maximum peak-to-peak value, so a 1.5 mm alumina sheet was selected as the matching layer.

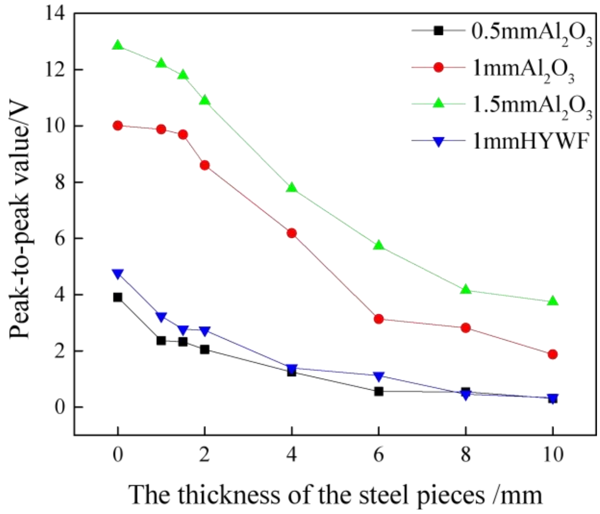

Figure 5. Peak-to-peak values of different matching layers

3.1.3 THE BACKING LAYER

In order to curb the spread of the thickness of the piezoelectric component vibration mode, reduce the piezoelectric ceramic back to the launch of the acoustic effect the performance of the sensor, the sensor internal design proper backing materials, however, the acoustic properties and attenuation properties of the existing single material cannot meet the requirements of the material used as the sensor backing layer, special composite materials were used as the backing layer of the ultrasonic sensor. Four kinds of backing layers with different ratios of epoxy and tungsten powder were prepared, and their specific performance parameters are shown in Table 2. It can be seen that, with the increase of the proportion of tungsten powder, the compressive strength gradually decreases and the degree of acoustic impedance decreases gradually. When epoxy and tungsten powder are 1:1, the compressive strength and acoustic impedance are the highest. The ratio of epoxy and tungsten powder is 1:1 was selected as the backing layer of the external ultrasonic sensor.

Table 2. Performance parameters of backing layers in different proportions

Epoxy/tungsten powder ratio	Density (10^3kg/m^3)	Velocity(m/s)	Acoustric impedance (MRayl)	Compressive strength (Mpa)
1:1	1.555	2103	11.2	65.5
1:2	1.354	2051	10.1	51.4
1:3	2.234	1875	5.6	35.9
1:4	3.884	1593	3.2	34.1

Performance tests were carried out for sensors with backing layers of different ratios, and the test results are shown in Figure 6, the amplitude received by the sensor gradually decreases with the gradual increase of the ratio of the backing layer, indicating that the presence of the backing layer will affect the receiving performance and sensitivity of the sensor. Comprehensively considering, epoxy tungsten powder ratio of 1:1 can not only meet the strength and requirements but also save the cost.

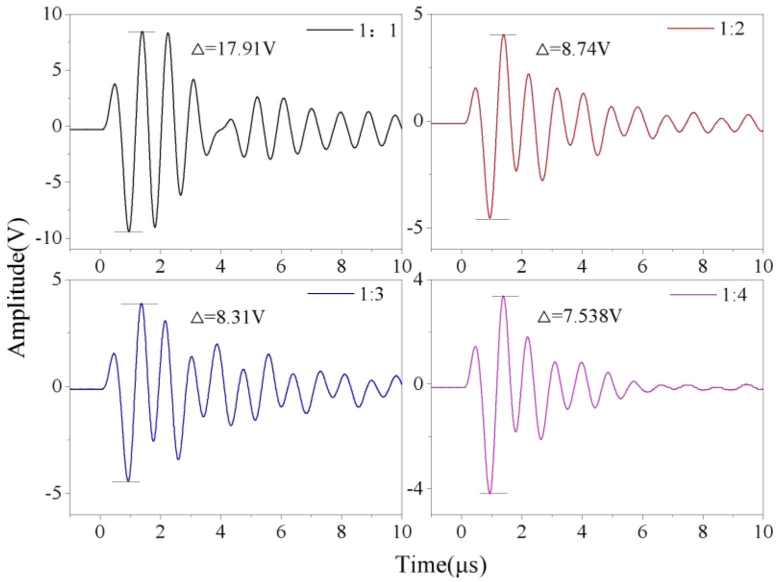

Figure 6. Time-domain waveform of different backing ratio

3.2 STATIC DAMAGE DETECTION OF CONCRETE

In this paper, the ratio of cement to mortar was 0.4 and the cube specimen with a size of 100□100□100 mm was prepared for compression test. A universal testing machine was used to carry out a static loading test on the concrete and an ultrasonic sensor was used to detect its damage.

3.2.1 LOADING MODE

The average value of the three groups of specimens was taken to obtain the maximum bearing capacity of the concrete specimen of 320 kN, 320 kN was set as the maximum load, and the loading was carried out within the linear variation range of the loading curve (20 kN-150 kN).The concrete specimens cured for 28 days were subjected to failure loading, and the loading system was modulated to load at a rate of 1 mm/min, and the pressure was stabilized for 2 min in each stage.

3.2.2 TIME DOMAIN WAVEFORM ANALYSIS

The received time-domain waveform under randomly selected different loads was shown in Figure 7. Under different loads, the overall trend of the waveform changes less than that of the waveform collected without loading. At the same time, it can be seen from Figure 7. that under the loading of different forces, the waveform was more chaotic and several continuous wave packets appear. This was mainly due to the fact that the concrete is composed of different materials, resulting in a lot of interface in the material, ultrasonic through a different interface, will occur reflection, refraction phenomenon, these waves superimpose each other, so that the waveform of multiple wave packets, the transmission path was more complex. When not loaded, the peak-to-peak value of the ultrasonic waveform was 8.432 V. With the increasing loading force, the amplitude of the ultrasonic waveform decreased gradually. When the loading force reached 110 kN, the peak-to-peak value dropped to 1.289 V.

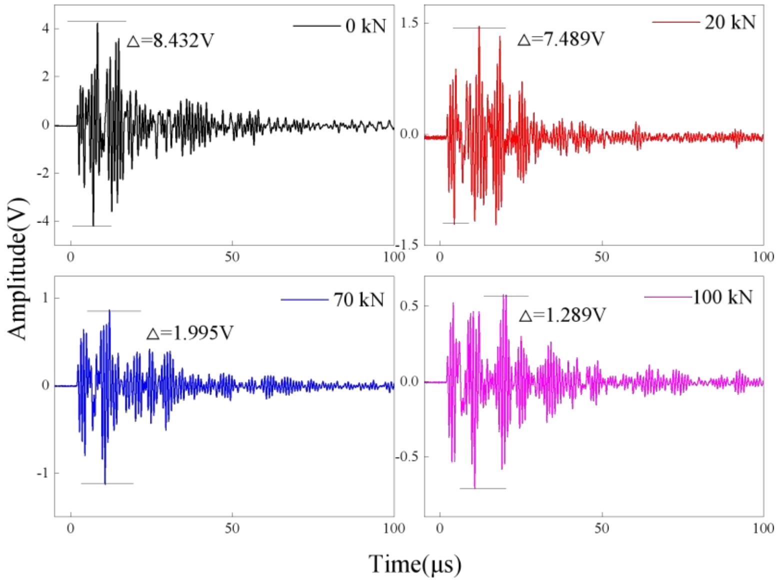

Figure 7. Time-domain waveform at different loading stages

3.2.3 PROGATION SPEED AND PROGATION TIME

The time domain diagram of different loading stages was shown in Figure 8. It can be seen that, when the loading force was 20 kN, 70 kN and 110 kN, the waveform moved backward, that is, it took longer for the sensor to receive the ultrasonic signal, and the ultrasonic wave propagated slower through concrete. This is because with the increasing of the load, crack of concrete structure gradually, which makes the ultrasonic in the crack propagation process, complicating propagation path, cause the ultrasonic wave energy attenuation. As a result, the ultrasonic wave takes longer to reach the receiving sensor and travels at a slower speed. Therefore, the damage inside concrete can be judged by the change of sound time.

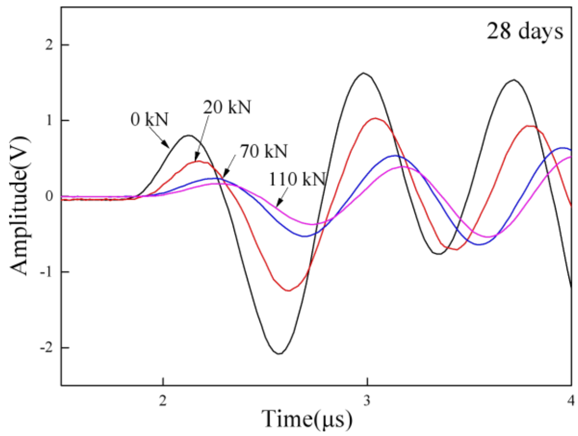

Figure 8. Time domain waveform of different loading stages

3.2.4 PEAK-PEAK ANALYSIS

The peak-to-peak value and first wave amplitude of ultrasonic wave received at different loading stages was shown in Figure 9. It can be seen from the Figure 9. that, with the increasing loading force, peak-to-peak value and first wave amplitude both showed a trend of gradual decrease, and the changing trend is the same. The main reason for this is that cracks in concrete structures are always wide on the surface, and the deeper they go, the narrower they get until they close. And the concrete at both ends of the cracks cannot be completely separated by air. The larger the load is, the wider the crack is and the fewer connected places are. On the contrary, the narrower the crack is, the more connected places are. Therefore, when the ultrasonic passes through the crack, part of it is reflected by the air layer, and part of it is transmitted to the receiving sensor through the connecting point, leading to the gradual decrease of the peak-to-peak value of the received waveform and the amplitude of the first the amplitude.

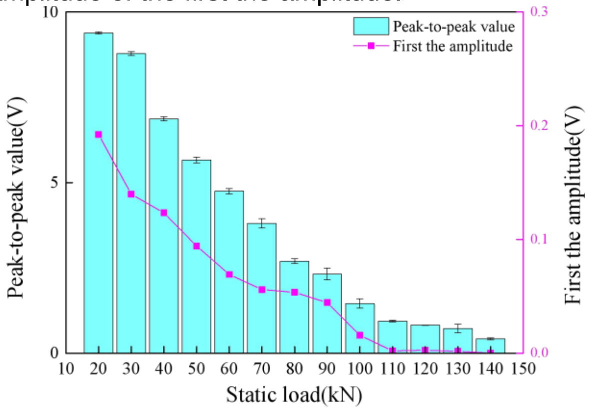

Figure 9. Peak-to-peak value and amplitude of first the amplitude in different loading stages

4 CONCLUSION

In this paper, piezoelectric ultrasonic sensor was prepared and ultrasonic detection was carried out on concrete damage under static load, and the main conclusions were as follows: The resonant frequency of the piezoelectric ultrasonic sensor developed is 112 kHz. The matching layer is made of 1.5 mm alumina, and the backing layer is made of epoxy resin and tungsten powder. Under different loads, the time-domain waveform is more chaotic and several continuous wave packets appear. With the increase of load, the number of wave packets increases gradually. Before loading, the peak-to-peak value of ultrasonic waveform is 8.432

V. With the increasing of loading force, the ultrasonic wave amplitude gradually decreases. When the loading force was 110 kHz, the

peak-to-peak value decreased to 1.289 V, and the first wave amplitude decreased from 0.045 V to 0.01

V. At this time, large damage had occurred inside the concrete. As the loading force gradually increases, the waveform moves backward, and the time for the sensor to receive ultrasonic wave becomes longer. This is because the internal structure of concrete cracks, ultrasonic waves encounter cracks, and the propagation path becomes complicated, resulting in the attenuation of propagation energy.

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