Research Article

Early Age Concrete Strength Monitoring Using Power Spectral Density and Wavelet Packet Analysis

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Concrete is a complex building material. Under normal curing conditions, concrete strength shows a nonlinear development process at an early age (1~28 d). In the first few days after the completion of pouring, the strength of concrete increases slowly. Subsequently, the strength of concrete increases rapidly, reaching about 90% of its age strength. Finally, its strength gradually stabilizes. This paper introduces the experiment of 28-day concrete age strength monitoring based on embedded piezoelectric smart aggregate (SA). Two piezoelectric SAs were embedded in a concrete-filled GFRP (glass fiber reinforced polymer) tube column, one of which emitted a sinusoidal sweep signal and the other SA received the signal. With the hydration reaction of concrete, the stress wave would be significantly different when passing through concrete, and the received signal is changing constantly. Through power spectral density and wavelet packet energy analysis, the monitoring signal of concrete age within 28 days was analyzed. The experimental results show that the wavelet packet energy and power spectral density of the sensor monitoring signal show a nonlinear growth trend with time during the concrete target age. It can be divided into three stages, and the fifth day and the fourteenth day are the demarcation point of energy growth. And the trend of energy change corresponds well with the change of actual concrete strength and age. Comparing and analyzing the received signal energy of the sensor and the power spectral density function of the stress wave signal of the concrete specimen, the trend of the amplitude in the natural frequency domain is found to be the same in the three stages.

1. Introduction

Concrete is one of the most widely used building materials in modern buildings due to its relatively low material cost, high durability, and versatility, and its material strength is directly related to the safety of buildings. Concrete is a heterogeneous material with a complex microstructure, mainly composed of water, cement, sand, stones, and other additives. It is often mixed on site. In terms of strength and durability, the quality of the final product highly depends on the process of mixing, handling, installation, vibrating, and curing. And the final performance of concrete also depends on its treatment after reaching the construction site [1]. Therefore, strengthening the early strength monitoring of

concrete to ensure the efficiency and effectiveness of consolidation and curing procedures are critical for attaining the full potential of a concrete mixture.

At present, the conventionally used methods for detecting the strength of concrete mainly include the rebound method, ultrasonic-rebound method, core drilling method, pulling-out method, postanchoring method, and decompression method [2–4]. Although these methods are simple and reliable, they often cause some damage to the structure.

In recent years, the emergence of smart materials provides an effective way for structural health monitoring. Structural health monitoring technology based on piezoelectric materials has developed rapidly and attracted

extensive attention of many scholars. In particular, the use of piezoelectric materials to study the age strength of concrete has proved to be an effective way [5–7]. Electromechanical impedance (EMI) is a method for detecting structural characteristics and state changes of piezoelectric materials based on smart impedance analysis [8–11]. Professor Soh's research group [12–14] analyzed and proposed an empirical method for determining the strength of concrete on site based on the change of admittance signal of surface-bonded PZT (lead zirconate titanate) sensor. Subsequently, research on the prediction of concrete strength development based on EMI method has attracted many scholars' interest. The results show that the EMI method is very sensitive to the early development of concrete strength, so it is considered suitable for the monitoring of concrete strength development. The research from professor Inman [15–17] focuses on the monitoring of structural mechanical properties of PZT sensors. The research team of Zhu [11, 18–20] used PZT sensors to conduct a series of experimental studies on bolt loosening of steel frame structures, solidification process of concrete cubes, and temperature compensation of piezoelectric impedance technology, which promoted the application of EMI method in civil engineering.

In addition, active sensing based on wave propagation theory is also widely used in structural health monitoring to detect cracks and other damage in the structure [21–30]. Song et al. [31, 32] first proposed the concept of piezoelectric smart aggregate (SA), which is to pack the piezoelectric ceramic piece with marble to achieve its protection. Two SAs are embedded in concrete. One SA transmits signals and the other SA receives signals. Zhu et al. [33] utilized piezoceramic bender elements and successfully measured the velocities of the P-wave and S-wave during the first 6 h of very early age concrete paste hydration. Kong et al. [34] used the swept sine wave and the constant frequency sine wave excitation methods to monitor the signals received by the sensors during the hydration of the early age (0–20 h) of the concrete. Through the amplitude level and frequency domain analysis, three states during the concrete hydration were found: (1) the liquid state, (2) the transition state, and (3) the hardened state. Chung et al. [35] tested the strength of early age concrete and mortar slab specimens based on the piezoelectric active sensing method. Chen et al. [36] designed a wireless sensor network based on piezoelectric SA, which can realize early concrete strength monitoring. Based on piezoelectric impedance technology, Cai et al. [37] carried out the monitoring test of concrete strength development and established the quantitative relationship between the conductivity spectrum and the compressive strength of the standard test block.

However, the concrete hydration performance at an early age (1–28 days) has not received enough attention in most of the research. It is well known that the strength at the age of 28 days of concrete is a very significant parameter in engineering practice, and it is called standard strength. The early age concrete hydration is a very important part of the entire concrete hydration and the concrete experiences a complicated chemical reaction from the liquid stage to the hardened stage during the first 28 days after concrete casting.

Gu et al. [38] employed an SAs-based active sensing method to monitor strength development during concrete hydration from day 1 to day 28 by sending single frequency harmonics and proposed a fuzzy logic system based on the received signal amplitude to evaluate it, but there are still several problems in their experiment: (1) they used the first generation SAs with cement mortar as the protective shell, in which the performance of the embedded PZT sheet will be seriously affected by cement hydration, and it would make a difference in the experimental results; (2) they used single frequency harmonics to monitor, which are easily distorted by external interference; (3) they only chose the signal amplitude that is easily influenced by the external environment to judge the concrete age strength, which lacks persuasion; (4) their work was published 15 years ago when the technology for monitoring piezoelectric signals was not yet fully developed. Based on the above considerations, the experimental research of early age concrete strength monitoring using power spectral density and wavelet packet analysis begins.

Glass fiber reinforced polymer (GFRP) is a kind of composite material which is made of resin and glass fiber, with resin as a matrix and glass fiber as a reinforcing material [39, 40]. It has the advantages of high tensile strength, good corrosion resistance, lightweight, good elastic deformation, thermal expansion coefficient close to concrete. In recent years, as a new kind of composite structures, the use of GFRP tube confined concrete columns have received increasing interest in engineering [41, 42].

In this paper, two SAs are embedded in concrete-filled GFRP tube column by the active sensing method. One SA emits a swept sine signal and the other SA receives a signal. During the early age of concrete, the hydration reaction will change the internal properties of concrete structure, which causes the stress waves to change as they pass through the concrete and the acquired signals behave differently. From the perspective of energy and power analysis, this paper describes the combination of wavelet packet energy and power spectral density analysis in concrete age strength monitoring. Through the comparative analysis of the strength development of the whole hydration process of concrete, the early strength growth period of the three stages of concrete was found. This shows that the analysis method combining wavelet packet energy and power spectral density analysis is accurate and efficient. The result shows that it is a signal analysis method with high application value and can provide a basis for determining the strength of concrete age in engineering practice.

2. Test Method and Theory

2.1. Test Method. Lead zirconate titanate (PZT), as one of the most widely used intelligent materials at present, can generate an electric charge when subjected to a stress or strain and can likewise generate a stress or a strain when subjected to an electric field. Due to its fast response, wide frequency response range, easy tailoring, and low price, it has great application potential in structural health monitoring [43–46]. In order to protect a fragile PZT patch, the first

generation of SAs is made of a concrete block surrounding a waterproofed PZT patch and is successfully applied for several concrete structure health monitoring tests [34]. In this experiment, the second generation of SAs with the embedded piezoelectric patch was used, which was proposed by Kong and Song, and it consisted of a BNC wire, a piezoelectric patch, an epoxy resin protective layer, and a marble protective layer; it is illustrated in Figure 1. PZT patch is placed in the middle of the marble and bonded and encapsulated with epoxy resin for protection purposes. The size of the PZT patch is $15 \text{ mm} \times 15 \text{ mm}$, and the thickness is 0.3 mm . The diameter of the SA is 25 mm and the height is 20 mm , as shown in Figure 2. Parameters of the PZT patch used in the test are shown in Table 1.

The active sensing method was used in the experiment. The principle is that two piezoelectric sensors are embedded in the upper and lower ends of the concrete-filled GFRP tube column, as shown in Figure 3. One of the SA (actuator) is used as a driver to emit a fixed frequency band sweep sine signal under external electric field excitation. The stress wave signal propagates in the concrete medium, and finally another SA (sensor) converts the received stress wave signal into an electrical signal and outputs it. Because, in the course of curing, the change of concrete age strength largely depends on the process of concrete hydration, and the strength of concrete will gradually increase with the development of the hydration process, which is more conducive to the propagation of stress waves in concrete specimens. Under the same excitation signal, the energy of the received signal will increase accordingly. Therefore, the stress wave signals received can be theoretically analyzed in the time domain and frequency domain, and the change of the characteristic parameters of the received signals can be used to evaluate the growth process of concrete strength.

2.2. Signal Analysis Theory. There are many signal processing methods of structural health monitoring, among which wavelet packet and power spectral density analysis are commonly used processing methods [47]. Power spectral density analysis is an analysis method for obtaining pulsation information in time series [48–50]. It divides a finite sequence $x(n)$ ($0 \leq n \leq N_s - 1$) into segments, each of which is M , and the overlap between segments is $M-K$. After adding the window function, the i^{th} data segment can be represented as $xi = G(n) x(n + iK)$ ($0 \leq i \leq L - 1$, $0 \leq n \leq M - 1$), K is an integer, and L is the number of segments. The relationship between them is satisfied $(L - 1)K + M \leq N_s$, and $G(n)$ is a window function. The power spectral density of this data segment is estimated as

$$P^i(\omega) = \frac{1}{MU} \left| \sum_{n=0}^{M-1} X^i(n) e^{-j\omega n} \right|^2, \quad (1)$$

where A is the normalization factor as

$$U = (2\pi M)^{-1} \int_{-\pi}^{\pi} |G(\omega)|^2 d\omega. \quad (2)$$

FIGURE 1: Structure of the SA.

FIGURE 2: SA.

TABLE 1: Parameters of the selected PZT patch.

Parameters	Value
Young's modulus (GPa)	50
Poisson ratio	0.35
Density (kg/m^3)	7.6
Curie temperature ($^{\circ}\text{C}$)	310
Piezoelectric strain constant (pC/N)	450
Dielectric constant	1800

FIGURE 3: Experimental diagram.

The purpose of using normalization factor U is to ensure that the obtained spectrum is an asymptotically unbiased estimation of the true power spectrum. The average power spectrum value obtained from this method is

$$\bar{P}(\omega) = \frac{1}{L} \sum_{i=0}^{L-1} P^i(\omega) = \frac{1}{\text{LMU}} \sum_{i=0}^{L-1} \left| \sum_{n=0}^{M-1} X^i(n) e^{-j\omega n} \right|^2. \quad (3)$$

Power spectral density analysis has good results in processing stationary and time-invariant signals.

Wavelet packet analysis is a more precise signal analysis method, and it is widely used in the signal postprocessing process of structural health monitoring based on piezoelectric transducer [51–55]. Assuming that the monitoring signal S is analyzed by wavelet packet, S can be decomposed into multiple signals with equal bandwidth. The monitoring signal of the sensor during concrete curing is decomposed by wavelet packet analysis. Wavelet packet analysis is used to decompose the monitoring signal of the sensor during concrete curing. S is the original monitoring signal with n sampling points. After N -layer wavelet packet decomposition and reconstruction, $2N$ subsignals S_i ($i = 1, 2, \dots, 2^N$) can be obtained as

$$S_i = [S_{i,1}, S_{i,2}, \dots, S_{i,j}, \dots, S_{i,M-1}, S_{i,M}], \quad (4)$$

where $i = 1, 2, \dots, M$, where M is the number of samples of the signal in the i -th band. After the signal is decomposed by the wavelet packet, the subband energy of each band in the last layer is $e_i = \sum_{j=1}^M |S_{i,j}|^2$. Then, the total energy of signal S reconstructed by wavelet packet decomposition is as follows:

$$E = \sum_{i=1}^{2N} e_i. \quad (5)$$

3. Experimental Setup

As shown in Figure 4, the active detection system based on PZT transducers consists of the PC (Personal Computer) equipped with SCHYPZTV3 software, the multifunction piezoelectric signal detection and analysis system, two piezoelectric SAs, and a concrete-filled GFRP tube column with SAs embedded. The multifunction piezoelectric signal detection and analysis system is produced by Sanchuan Intelligent Technology Co., Ltd., from Jiangsu, China, and the model number is SC-HY-PZT-2.0. This active detection system integrates signal generator and oscilloscope, and real-time filtering can be performed in the process of data acquisition. In addition, this system can generate a variety of excitation signals, including sweep, pulse, and other arbitrary signals. In this paper, the authors mainly used sweep wave as excitation signals. Sweep signal is essentially a sine wave with continuously changing frequency, it can perform a linear dynamic frequency sweep for the structure. The characteristics of sweep excitation are simple and fast, and it can conveniently measure the frequency and dynamic characteristics of the system.

In this experiment, the height of the concrete-filled GFRP tube column is 300 mm and the diameter is 150 mm. The grouting concrete label is C30. Two piezoelectric SAs were embedded in the specimen, and the distance between

FIGURE 4: Composition of an active detection system based on piezoelectric transducers.

the piezoelectric actuator and piezoelectric sensor was 220 mm; we can see this information from Figure 3. During the test, SA (actuator) transmits the signal as a driver and SA (sensor) receives the signal as a sensor. In order to remove the influence of noise, real-time filtering was performed in the whole process of the test. At the same time, to eliminate signal distortion caused by accidental errors, the data was not saved until the waveform was stable by multiple excitations.

The monitoring signal was selected as a swept sine wave. In the process of wave propagation, due to different materials having a different frequency response ranges to the signal [56], we need to carry out several pretests before the formal test to determine the frequency range of sweep signals. Firstly, a large range sweep frequency wave (such as 1 kHz–500 kHz) was employed to excite the SA (actuator), and the time-domain waveform of the collected signal was observed, and it could be found the time period where the signal amplitude was larger, and then the approximate sweep range corresponding to this period could be calculated according to the sweep time. And then the calculated sweep range was used to excite. The above process was repeated to gradually reduce the sweep range until a suitable frequency range was finally determined. According to this method, the final sweep frequency range selected was 100 kHz–200 kHz, the signal duration was 0.5 s, the voltage was 10 V, and the mode was linear sweep frequency. The advantage of swept sine waves as a monitoring signal is that the changing frequency can meet the changing requirements of concrete strength. The parameters of signal acquisition and filtering are given in Table 2. In this experiment, real-time data was recorded and saved every 24 hours until the concrete curing period reached 28 days.

4. Experimental Results

4.1. Frequency-Domain Responses of Received Signals. The received part of the original signal is shown in Figure 5. As can be seen from Figure 5, the signal shows a distinct peak around 0.35 s. As the concrete age increases, the strength of the concrete increases with the hydration reaction,

TABLE 2: The parameters of signal acquisition and filtering.

Incentive parameters		Acquisition parameter		Filtering parameter	
Voltage	10 V	Frequency	1 MHz	Filter	Butterworth
Range	100 kHz–200 kHz	Length	512 k	Type	Bandpass
Frequency	0.2 kHz	Sampling time	524 ms	Order	5
Step size	1 ms	Trigger mode	Normal	Range	100 kHz–200 kHz

FIGURE 5: The received signal of the sensor.

FIGURE 6: Continued.

FIGURE 6: STFT time-frequency diagram, (a) day 1, (b) day 5, (c) day 9, (d) day 13, (e) day 19, (f) day 25, and (g) day 28.

FIGURE 7: The frequency at the energy peak point.

which is more conducive to the propagation of stress waves in the concrete. Therefore, the signal amplitude is also increasing with the concrete age, which is consistent with the test results of [34] from Kong et al. And, in this experiment, the same SAs as in paper [34] were used. However, this conclusion is contrary to the results obtained by Gu et al. in [38] who used single frequency harmonics as the excitation signal. One mortar and three

concrete cylinders instrumented with embedded piezoelectric transducers were tested by using the proposed method in [38]. And the experimental results show that the harmonic amplitude dropped with the strength development of the concrete specimens at early ages. This difference may be related to factors such as the signal source, concrete specimens, signal monitoring system, and the antinoise performance of SAs. Overall, all of these

FIGURE 8: The power spectral density: (a) 1 d, (b) 3 d, (c) 5 d, (d) 7 d, (e) 9 d, (f) 11 d, (g) 13 d, (h) 16 d, (i) 19 d, (j) 22 d, (k) 25 d, and (l) 28 d.

test results show that as the concrete age strength increases, the signal amplitude changes in a certain pattern. In consequence, it can be preliminarily indicated that the detection method can effectively monitor the hydration process of concrete.

In order to understand the frequency components of the original signal, it is necessary to perform frequency domain analysis. The fast Fourier transform is performed on the original signal, and the obtained partial Short Time Fourier Transform (STFT) time-frequency diagram is as shown in Figure 6.

It can be seen from the STFT time-frequency diagram that, in the linear sweep range of 100 k~200 k, the signal energy was concentrated in the local frequency band, which also indicated that the concrete has resonated in some local frequency bands. And it can be found that the frequency dispersion of concrete was more serious within 1~14 days. In the frequency range 140 kHz~180 kHz, there was energy accumulation. This indicated that the concrete in the GFRP tube was undergoing a stable hydration reaction during this period, and the strength increased rapidly. In addition, it can be seen from the STFT spectrogram that the natural

frequency of the concrete began to stabilize slowly within 14 days to 28 days, and the frequency dispersion phenomenon began to decrease gradually, which indicated that the strength of the concrete was also beginning to stabilize.

The frequencies at the energy peak points in the respective STFT frequency domain graphs were extracted and plotted in Figure 7. As can be seen from Figure 7, the frequencies at the energy peak points were relatively scattered before the 14th day, and most of them were substantially less than 169.5 kHz. After the 14th day, the frequencies at the energy peak points of concrete were basically concentrated around 169.5 kHz, and this concentration effect was more and more stable. Through the above analysis, we can roughly determine the propagation frequency of the longitudinal wave in concrete used in this test was 169.5 kHz.

4.2. Power Spectral Density Analysis. The power spectral density analysis method was used to calculate and analyze the original signals of 28 days, and the respective power spectral density curves were obtained as shown in Figure 8. In order to clearly compare the changes in power spectral density, the power spectral density was extracted during the concrete early age when the propagation frequency of the longitudinal wave is 168.0 kHz, as shown in Figure 9. It can be seen from the figure that the early concrete strength development process can be roughly divided into three stages. In the first 4 days, the power spectrum density of the concrete is small, between $559.6 \mu\text{V}^2/\text{Hz}$ and $824.2 \mu\text{V}^2/\text{Hz}$, and the dispersion frequency band is wide. At this time, the hydration reaction in the concrete is ongoing, the concrete is not completely compacted, and the internal structure is not completely stable. When the stress wave passes through the concrete, a large amount of energy attenuation occurs in the unstable medium, and the energy distribution is also wide.

Within 5 to 14 days, the power spectral density increased with a very fast rate, reaching $2938.7 \mu\text{V}^2/\text{Hz}$ (about 90% of the maximum power spectral density). Moreover, the distribution of power spectral density has also begun to concentrate on 169.0 kHz~170 kHz. From 15 days to 28 days, the internal structure of the concrete is basically stable, and the amplitude of the received stress wave changes very little. Both the time domain signal and the frequency domain signal exhibit only a distinct peak. The power spectral density is stable in the range of $3102.6 \mu\text{V}^2/\text{Hz}$ ~ $3213.1 \mu\text{V}^2/\text{Hz}$ and is concentrated in the frequency range of 169.0 kHz~170.0 kHz. At the age of 28 days, the strength of the concrete is approximately 85% of the design strength.

4.3. Wavelet Packet Energy Analysis. By performing wavelet packet energy analysis on the signal collected by the sensor within 28 days, the wavelet packet energy variation of the signal during the concrete 28 days age can be obtained, as shown in Figure 10. It can be seen from the figure that, similar to the power spectral density curve, as the age increases, the energy change trend of the sensor monitoring signal can be divided into three stages.

FIGURE 9: The power spectral density.

FIGURE 10: The result of wavelet packet energy.

The first stage is from day 1 to day 4. The energy of the sensor monitoring signal reaches $1.845 \times 10^4 \text{ V}^2$ on the fifth day, reaching 11.28% of the maximum intensity of $16.355 \times 10^4 \text{ V}^2$ during the age. The second stage is from day 5 to day 14, the sensor monitoring signal energy increases rapidly and finally reaches $14.292 \times 10^4 \text{ V}^2$, reaching 87.38% of the maximum intensity of $16.355 \times 10^4 \text{ V}^2$ during the concrete 28 days age. The third stage is from day 15 to day 28, and the energy of the sensor monitoring signal fluctuates in a small range from $14.423 \times 10^4 \text{ V}^2$ to $16.355 \times 10^4 \text{ V}^2$.

5. Conclusions

In this paper, two piezoelectric SAs were embedded in the concrete-filled GFRP tube column specimen, and the changes of concrete strength in 28-day age were monitored and analyzed based on the piezoelectric active sensing method. The experimental results show that the frequency dispersion of concrete is more serious at the beginning. As

the age increases, the propagation frequency of the longitudinal wave in concrete gradually stabilizes and eventually ends at around 169.5 kHz. By analyzing the power spectral density and wavelet packet of the signal between a pair of embedded SAs, three strength growth periods were clearly verified. The first stage is from 1 to 4 days, and the concrete strength increases slowly, only reaching about 11% of the maximum strength of the 28 days age. The second stage is from 5 to 14 days. At this stage, the power spectral density and wavelet packet energy change greatly, and the strength of the concrete increases rapidly. And on the 14th day, the strength reached about 90% of the maximum strength of the age. The third stage is from 15 to 28 days, when the concrete strength is only slightly increased, and the change is minor. The wavelet packet energy and power spectral density of the signal also reach the maximum and are close to stability. Comparing and analyzing the received signal energy of the sensor and the power spectral density function of the stress wave of the concrete specimen, it can be found that the energy value and power spectral density value of the stress wave have the same trend with age strength in the three stages. Therefore, wavelet packet energy analysis and power spectral density analysis are feasible for strength monitoring of concrete age.

Data Availability

All data can be found in the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

Authors' Contributions

W. Y. provided guidance and methodology; X. Y. and S. L. conceived and designed the experiments, analyzed the data, and wrote the paper; X. Y. and S. L. performed the experiments; and X. Y., S. L., and C. W. proofread and revised the paper. All authors have read and agreed to the published version of the manuscript.

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