Research Article

Influence of Propagation Distance on Characteristic Parameters of Acoustic Emission Signals in Concrete Materials Based on Low-Frequency Sensor

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Acoustic emission is a nondestructive testing technology based on the propagation of transient elastic waves captured by acoustic emission sensors. The acoustic emission signal depends not only on the distance and quality of the propagation path of the transient elastic wave but also on the sensitivity and frequency bandwidth of the receiving sensor that converts the transient elastic wave into a voltage signal. The frequency range of damage signals in concrete materials is generally in the low-frequency band. If high-frequency sensors are used, the low sensitivity to low-frequency signals will cause measurement errors, while the bandwidth of general commercial acoustic emission sensors is relatively narrow. Therefore, a high-sensitivity, low-frequency acoustic emission sensor is proposed, whose bandwidth is almost four times that of commercial sensors. Based on the customized sensor, we quantitatively analyzed the influence of propagation distance on the characteristic parameters of acoustic waves propagating in concrete. The results show that the different propagation modes of acoustic waves in concrete have different attenuation with the propagation distance, related to the position relationship between the acoustic source and the sensor and the propagation path and path quality. This result gives us a better understanding of the propagation mechanism of acoustic emission signals in concrete materials.

1. Introduction

Concrete material has become the most widely used building material in the world because of its low cost and easy production [1, 2]. However, due to external factors, such as environmental life span, natural disasters, stress, and fatigue, many structures suffer from damage or cracking that leads to the degradation of concrete structure performance, the significant decline of bearing load capacity, and even the collapse of the structures [3].

The application of acoustic emission technology in concrete materials has been for more than 60 years. Acoustic emission is a nondestructive testing technology that can evaluate the internal damage of structures without destroying the tested components. It has been successfully applied to the health monitoring of steel structures [4], rock [5], and concrete structures [6, 7]. Acoustic emission has the ability of continuous real-time monitoring [8], can accurately locate the damage, and can provide early warning for the internal invisible crack damage of concrete structure in the early stage [9]. Therefore, it is one of the most widely used detection technologies in concrete structure health monitoring.

Acoustic emission technology is based on the propagation of transient elastic waves. When cracks occur in concrete structures, transient elastic waves will be released and detected by acoustic emission sensors installed on the surface of concrete materials [10]. In general, elastic waves can be described by a set of parameters to digitize the transient [11]. Because cracks are usually the premise of
acoustic wave generation, the waveform parameters recorded by the sensor carry the information of crack mode and fracture process, which can truly and effectively reflect the degree and activity of internal damage in concrete and the location of concrete damage. Therefore, the investigation of acoustic emission characteristic parameters is the basis of concrete structure performance research.

Some indices that have been successfully employed to characterize concrete damage are based on waveform parameters. Figure 1(a) shows a typical waveform of an acoustic emission signal with the basic parameters. The amplitude means the maximum amplitude when the acoustic wave crosses the threshold and is used to measure the acoustic source’s type and size in concrete [12]. The amplitude attenuation determines the distance scope that each sensor can monitor [13]. The amplitude of the AE signal is the value processed by the software, and the unit is dB. In contrast, the voltage amplitude of the waveform is only the amplified original voltage without unit conversion. Vélez et al. [14] found that different acoustic emission signals can be distinguished by amplitude range. The threshold is used to filter the noise signals [15]. Rise time is when the received signal crosses the threshold to reach the maximum amplitude [16]. AE energy is another version of AE signal strength and can assess the severity of damage [17]. Figure 1(b) shows a frequency spectrum of an AE signal after fast Fourier transformation. The characteristic parameter peak frequency is the frequency of the maximum magnitude of the spectrum, which can be influenced by the sensor distance [16]. Parameters such as amplitude, frequency, and energy have been used to characterize damage [18–20]. The b-value method based on acoustic emission amplitude distribution can identify the fracture stage of concrete materials [21–23]. The RA value is defined as the ratio of rise time to waveform peak amplitude, which can be used to classify crack modes, predict the structural performance, and evaluate its remaining life [24, 25]. Based on the acoustic velocity, the location of the source is obtained by the time delay of the corresponding signals received by multiple sensors placed at different positions [26, 27]. The location allows estimating which part of the concrete structure needs maintenance, essential for large-scale concrete structures. Therefore, it is necessary to find out the propagation law of acoustic waves and their characteristic parameters in concrete materials, which is the premise of the research on the internal damage of concrete structures. However, due to the inherent heterogeneity of concrete materials, with the increase of acoustic wave propagation distance, the shape of the waveforms will be seriously distorted by some factors, such as dispersion [28] and scattering [29], and the calculation of acoustic emission parameters is expected to be affected. Therefore, it is necessary to quantitatively analyze the influence of propagation distance on a series of characteristic parameters.

As the core component of the acoustic emission system, the acoustic emission sensor plays a vital role in concrete structure health monitoring because its sensitivity determines the accuracy of monitoring results. Robinson [30] conducted uniaxial compression tests on various mortar and concrete samples and found that the two primary frequencies of concrete acoustic emission signals are in the low-frequency band. Ohtsu [31] and Lovejoy [32] found concrete’s suitable acoustic emission detection frequency range is between 20 and 100 kHz. Yuyama et al. [33] compared the data detected by 30 kHz, 60 kHz, and 150 kHz resonant frequency sensors and concluded that the sensitivity of the acoustic emission sensor with the resonance frequency of 30 kHz is the highest. Therefore, we customized an acoustic emission sensor with a resonant frequency of 30 kHz in this paper.

Generally, the acoustic emission sensor with high sensitivity is a narrowband resonant piezoelectric sensor, which is only sensitive to the signals in the frequency band near the resonant frequency and has low sensitivity to the signals in other frequency bands. Hence, if high-frequency sensors are used, measurement errors will be caused by the low sensitivity to low-frequency signals. In contrast, the frequency bandwidth of the general commercial acoustic emission sensors is relatively narrow, leading to inaccurate monitoring results. Therefore, a wide-band low-frequency sensor with high sensitivity is proposed.

We employed the acoustic velocity, signal amplitude, rise time, waveform, and spectrum to describe acoustic wave characteristics during propagation in concrete samples. We adopted the pencil lead breaking to replace the acoustic source. Based on the customized sensor, we quantitatively analyzed the influence of propagation distance on the characteristic parameters of acoustic waves propagating in concrete with three different strength grades (C30, C40, and C50). Due to the positional relationship between the acoustic source and the sensor, we discussed the two cases when the wavefront is perpendicular and parallel to the sensor axis. The discrepancy of the detection results in the two cases was analyzed by the RMSD method. Finally, the factors that may cause waveform changes were summarized and analyzed.

2. Materials and Methods

2.1. Concrete Sample Preparation. To investigate the influence of propagation distance on the characteristic parameters of acoustic waves propagating in concrete with different strength grades, we adopted concrete strength grades C30, C40, and C50, and six concrete samples were prepared for each strength grade. During the preparation of concrete specimens, we used ordinary Portland cement 42.5. Limestone size 5 to 25 mm and standard river quartz sand were employed as coarse aggregate and fine aggregate, respectively. A chemical retardant polycarboxylate superplasticizer was used to improve the workability of the concrete. Table 1 lists the mixed proportion of components in three different strength grades of concrete. Consistent with the Chinese standard, specimen sizes of 400 × 100 × 100 mm were cast. The samples were demolded 24 h after casting and cured in a standard condition room at a temperature of ±20°C with a relative humidity of 95% for 28 days.

2.2. Acoustic Emission Sensor. To collect low-frequency concrete damage signals more accurately, low-frequency and wide-band acoustic emission sensors with high sensitivity
were tailored for signal acquisition [34–36]. The shape and dimensions of the sensor are a cylinder with a diameter of 25 mm and a height of 45 mm, as illustrated in Figure 2. An acoustic emission sensor generally comprises a sensing element, a matching layer, and a backing layer. In this paper, the commercial PMN-PT piezoelectric ceramic material with a diameter of 12 mm and a thickness of 28 mm was used as the sensitive element of the acoustic emission sensor. The matching layer is made of alumina ceramic material, with a diameter of 17.5 mm and a thickness of 0.6 mm. The backing layer is a mixture of epoxy resin, curing agent, and tungsten powder with a mass ratio of 4:1:1.5. The structural diagram of the acoustic emission sensor is shown in Figure 3.

Figure 4 shows the frequency spectrum measured by breaking the pencil lead ($\Phi = 0.5$ mm, $L = 2.5$ mm) on the aluminum plate at an angle of 30° with the acoustic emission sensor [37, 38]. It can be found that the frequency response range is mainly between 0 and 100 kHz. The commercial AE sensor (R3a) produced by the American Physical Acoustics Company (PAC) has a resonant frequency of about 25 kHz. It is noted that its frequency response range (15–25 kHz) is relatively narrow. The frequency spectrum measured by the customized AE sensor shows that before the improvement, the sensor’s resonant frequency was about 47 kHz, and the frequency response range was between 30 and 55 kHz. In contrast, after the improvement, the resonant frequency is about 45 kHz and the frequency response range is between 20 and 60 kHz. It can be found that although the amplitude of the frequency spectrum of the customized sensor decreases slightly, the frequency response range becomes wider, and the peak frequency and frequency response range shift to low frequency. The frequency response range increases by 60% compared with that before the improvement, almost four times that of the commercial AE sensor. At the same time, the amplitude is consistent with the commercial AE sensor, which means that it can monitor more low-frequency signals and be more sensitive to low-frequency signals, to make the monitoring results more accurate than the commercial sensor.

The expansion of the frequency response range is realized by adjusting the content of tungsten powder in the backing layer. It is reported that the expansion of the frequency response range is at the expense of sensor amplitude sensitivity [39]. It is found that when the mass ratio of epoxy resin, curing agent, and tungsten powder is 4:1:1.5, the amplitude sensitivity of the sensor is consistent with that of the commercial sensor. At the same time, the frequency response range is improved by nearly 60%.

2.3. Experimental Equipment. Micro-II acoustic emission acquisition system produced by PAC was employed to process the acoustic emission characteristic parameters/waveforms in real time. The threshold and preamplifier of the acoustic emission acquisition system were set to 40 dB, and the sampling rate was set to 1MSPS. Vaseline is used as a coupling agent at the contact between the acoustic emission sensor and the concrete surface to ensure good signal reception.

2.4. Experimental Method. To investigate the influence of propagation distance on acoustic velocity, signal amplitude, rise time, waveform, and frequency spectrum of acoustic wave, the pencil lead breaking tests were carried out on the surface of the concrete with three different strength grades C30, C40, and C50 at different distances from the sensor.

![Figure 1: (a) Typical waveform and (b) typical frequency spectrum of an acoustic emission signal.](image)
Figure 2: Photos of acoustic emission sensors.

Figure 3: Structural diagram of acoustic emission sensor.

Figure 4: Frequency spectrum of acoustic emission sensor.
For the positional relationship between the acoustic source and the sensor, in some cases, especially for the samples in the laboratory, the waveform is usually perpendicular to the sensor axis (Figure 5(a)). In contrast, for structural components, the waveform is generally parallel to the sensor axis (Figure 5(b)) [40]. In this paper, the two cases were discussed, respectively. In the actual experiment, when the waveform is perpendicular to the sensor axis, the acoustic source and the sensor are located on the opposite side of the prismatic beam sample, as shown in Figure 6(a), while when the waveform is parallel to the sensor axis, the acoustic source and the sensor are located on the same side of the prismatic beam sample, as shown in Figure 6(b). The pencil lead fracture tests were carried out at the positions marked by the number in the circle in the figure. The propagation distances from the sensor are 100 mm, 150 mm, 200 mm, 250 mm, and 300 mm, respectively. To ensure the accuracy of the data, the pencil lead fracture is carried out three times at each point to obtain the mean value. When two sensors are used, the reception of the same acoustic source will have a time delay due to the different positions of the two sensors. Based on the distance difference of the propagation path and the time delay, the ratio of the two is the acoustic velocity [41]. The calculation formula is as follows:

\[ v = \frac{\Delta S}{\Delta t} = \frac{S_i - S_0}{t_i - t_0} \]  

where \( \Delta S \) represents the distance difference between the two sensors and the acoustic source and \( \Delta T \) represents the time difference between the two sensors receiving the same signal. \( S_0 \) and \( t_0 \) denote the reference time and distance detected by the position fixed sensor; the pencil lead breaking point is at the edge of the sensor. Therefore, the distance between the sensor and the pencil lead breaking point is fixed, and the time when the sensor receives the pencil lead breaking signal is almost the same. To obtain accurate results, we take the radius of the sensor 12.5 mm as the distance from the pencil lead breaking point to the sensor in our calculation. \( S_i \) and \( t_i \) denote the time and distance detected by the position changeable sensor to produce a distance difference of 100 mm, 150 mm, 200 mm, 250 mm, and 300 mm.

The photos of acoustic velocity measurement are shown in Figure 7.

Root mean square deviation (RMSD) method is usually adopted as a damage metric by researchers because it can better reflect the changes of structural damage [42–44]. This method is a data processing algorithm based on the difference between two states. It is a common mathematical statistics method. In this paper, we used this method to evaluate the deviation of characteristic parameters of acoustic emission signals collected at different distances and initial measurement positions. The calculation equation is as follows:

\[ \text{RMSD} = \sqrt{\frac{\sum_{i=1}^{n} (R_i - R_i^0)^2}{\sum_{i=1}^{n} (R_i^0)^2}} \]  

where \( R_i^0 \) is the measured values of the characteristic parameters of the acoustic emission signal at the first measurement position (i.e., the distance of 100 mm from the sensor) and \( R_i \) is the corresponding values of characteristic parameters detected at different distances from the sensor.

3. Results and Discussion

3.1. Case 1: When the Wavefront Is Perpendicular to the Sensor Axis

Figures 8(a)–8(c), respectively, illustrates the variation curves of acoustic velocity, amplitude, and rise time of acoustic emission signals propagating in three different strength grades of concrete (C30, C40, and C50) with the increase of propagation distance when the waveform is perpendicular to the sensor axis. The results show that in the concrete with the same strength grade, with the increase of the propagation distance, the acoustic velocity and amplitude decrease, while the rise time increases. Under the same propagation distance in concrete with different strength grades, increasing the concrete strength grade, the acoustic velocity and amplitude increase, while the rise time decreases.

Based on equation (2), the RMSD indexes of acoustic velocity, amplitude, and rise time are derived, and the results are shown in Figures 9(a)–9(c). It can be seen from the RMSD spectra that in the concrete with the same strength grade, the RMSD value arises with the increase of the propagation distance, which indicates that relative to the signal characteristic parameters detected at the initial distance of 100 mm, the deviation of the signal characteristic parameters detected at other farther distances gradually increases. However, the deviation increment decreases with the increase of concrete strength grade. The characteristic parameter deviation of the signal in the concrete with strength grade C30 is the largest, while the deviation is the smallest in the concrete with strength grade C50.

Figures 10(a)–10(c) show the time-domain spectra of acoustic emission signals detected at different distances from the sensor in three different strength grades of concrete (C30, C40, and C50). The figures represent the concrete strength grade and the distance between the acoustic source and the sensor, and the distance unit is mm. From the figures, we can see the change process of amplitude and rise time with the increase of propagation distance more intuitively. It can be found that in the concrete with the same strength grade, the waveform voltage decreases with propagation distance. It takes longer for the signal to reach the maximum amplitude at reception [45], and the convergence speed of the waveform slows down, which leads to an extension of the signal duration. According to acoustic wave theory, the longer the acoustic wave duration time, the narrower the spectrum [39]. It also can be seen that under the same propagation distance in concrete with different strength grades, with the increase of concrete strength grade, the voltage of the waveform increases while the rise time decreases. The result is consistent with the previous variation trend of signal amplitude and rise time [46]. In addition, with the increase of concrete strength grade, the waveform becomes more regular, and the degree of signal distortion decreases.
Based on the Fourier transform method, the frequency domain spectra of acoustic emission signals detected at different distances from the sensor in three different strength grades of concrete (C30, C40, and C50) are shown in Figures 11(a)–11(c). It can be found that the resonant frequency of the sensor is around 45 kHz, and the frequency response range is approximately 20 to 60 kHz. In the concrete with the same strength grade, with the increase of propagation distance, the amplitude of the spectrum gradually decreases. In addition, with the concrete strength grade increase, the offset of the peak frequency decreases, the frequency response range narrows, and the frequency component shifts to low frequency.

It is worth noting that, compared with the measurement results of the high-frequency sensor [47], the spectral response range does not change significantly. It is mainly due to the small attenuation of the low-frequency signal in concrete materials, proving that the improved low-frequency sensor is more suitable for the health monitoring of internal damage of concrete structures than the commercial sensor.

3.2. Case 2: When the Wavefront Is Parallel to the Sensor Axis. Figures 12(a)–12(c), respectively, show the variation curves of acoustic velocity, amplitude, and rise time of acoustic
emission signals propagating in three different strength grades of concrete (C30, C40, and C50) with the increase of propagation distance when the wavefront is parallel to the sensor axis. The same trend as the wavefront is perpendicular to the sensor axis. In the concrete with the same strength grade, with the increase of the propagation distance, the acoustic velocity and amplitude decrease, while the rise time increases. Under the same propagation distance in concrete with different strength grades, increasing the concrete strength grade, the acoustic velocity and amplitude increase, while the rise time decreases. Figures 13(a)–13(c) illustrate the RMSD indexes of the three characteristic parameters. In the concrete with the same strength grade, the RMSD value increase with the propagation distance, the deviation of the signal characteristic parameters increases. In contrast, the deviation increment decreases with the increase of concrete strength grade.

To compare the deviation of characteristic parameters of the signal in the two cases (when the wavefront is perpendicular and parallel to the sensor axis), we calculated the maximum RMSD of each characteristic parameter and listed it in Table 2. The values of acoustic velocity, amplitude, and rise time listed in the table correspond to the signal characteristic parameters detected at the sensor’s initial distance of 100 mm.

We can observe that when the wavefront is perpendicular to the sensor axis, the acoustic velocities in the concrete with strength grades C50, C40, and C30 detected at the initial distance of 100 mm from the sensor are 5272 m/s, 4784 m/s, and 4495 m/s, respectively. In contrast, when the wavefront is parallel to the sensor axis, the corresponding acoustic velocities are 2850 m/s, 2607 m/s, and 2351 m/s, respectively. The acoustic velocity ratios of the former and the latter are 54%, 54.5%, and 52.3%, respectively. As a general rule, when acoustic waves propagate in solid media, there are several propagation modes such as longitudinal wave, transverse wave, surface wave, and so on. The longitudinal wave has the fastest propagation speed, and there is a specific ratio relationship between the acoustic velocities of different modes in the same material. For example, the transverse wave velocity is about 60% of the longitudinal wave velocity, and the surface wave velocity is about 90% of the transverse wave velocity [41, 48]. According to the rule, the position relationship between the acoustic source and the
Figure 10: Time domain spectra of acoustic emission signals in concrete with strength grade. (a) C30, (b) C40, and (c) C50.

Figure 11: Frequency domain spectra of acoustic emission signals in concrete with strength grade. (a) C30, (b) C40, and (c) C50.
sensor, and the corresponding values of acoustic velocity detected at the same distance from the sensor, it can be concluded that when the wavefront is perpendicular to the sensor axis, the dominated propagation mode corresponds to the longitudinal wave. In contrast, the dominate propagation mode corresponds to the surface wave when the wavefront is parallel to the sensor axis.

From Table 2, we can also find that the longitudinal wave’s initial acoustic velocity and amplitude are more significant than the surface wave’s. At the same time, the rise time is shorter than that of the surface wave. Moreover, the RMSD values of the longitudinal wave are larger than the surface wave, which indicates that the attenuation of all parameters of the longitudinal wave in concrete is larger than that of the surface wave. It is noted that the amplitudes of the longitudinal wave in concrete with strength grade C50, C40, and C30 detected at the initial distance of 100 mm from the sensor are 94.5 dB, 93 dB, and 91 dB, respectively. In contrast, the corresponding amplitudes of the surface wave are 92 dB, 89 dB, and 88 dB, respectively. Although the initial amplitudes of the longitudinal wave are greater than those of the surface wave, the attenuation of the longitudinal wave is faster than that of the surface wave. Therefore, according to this development trend, the surface wave should travel
farther than the longitudinal wave. The result gives us enlightenment that, compared with the three-dimensional location in concrete structure, the two-dimensional location can monitor a larger range, and the spacing of sensors can be larger.

The results of the time-domain spectra of acoustic emission signals detected at different distances from the sensor in three different strength grades of concrete (C30, C40, and C50) when the wavefront is parallel to the sensor axis are presented in Figures 14(a)–14(c). It can be found that the same trend as the wavefront is perpendicular to the sensor axis. In the concrete with the same strength grade, the waveform voltage decreases with propagation distance, while the rise time increases. Under the same propagation distance in concrete with different strength grades, with the increase of concrete strength grade, the voltage of the waveform increases while the rise time decreases. In addition, with the increase of concrete strength grade, the waveform becomes more regular, and the degree of signal distortion decreases.

The frequency domain spectra of acoustic emission signals detected at different distances from the sensor in three different strength grades of concrete (C30, C40, and C50) when the wavefront is parallel to the sensor axis are shown in Figures 15(a)–15(c). It can be seen that the peak frequency at the distance of 100 mm from the sensor and frequency response range are almost the same as when the wavefront is perpendicular to the axis of the sensor. In the concrete with the same strength grade, with the increase of propagation distance, the amplitude of the spectrum gradually decreases, the frequency response range narrows, and the frequency component shifts to low frequency. In addition, with the concrete strength grade increase, the offset of the peak frequency decreases.

To compare the deviation of the dominant frequency in the two cases (when the wavefront is perpendicular and parallel to the sensor axis), we calculated the maximum RMSD of each frequency spectrum and presented it in Table 3. The table also lists the peak frequency (100 mm) and (300 mm) corresponding to the peak frequencies detected at the distance of 100 mm and 300 mm from the sensor, respectively.

The results show that in the concrete with the same strength grade, with the increase of propagation distance, the peak frequency of the spectrum shifts to low frequency. Under the same propagation distance in concrete with different strength grades, with the increase of concrete strength grade, the RMSD value decreases, indicating that the attenuation of the peak frequency decreases. Comparing the two cases, we found that the RMSD value of the longitudinal wave is larger than that of the surface wave, indicating that the attenuation of the peak frequency of the longitudinal wave in concrete is larger than that of the surface wave.

Figure 16 shows the photos of concrete surfaces with different strength grades prepared in this experiment. Comparing the surface of concrete prismatic beam samples with different strength grades, we can see that with the increase of concrete strength grade, the number and size of holes on the surface and inside of concrete samples decrease,
and the concrete samples become denser. This process will form many randomly distributed pores and slender cracks during the pouring and hardening of concrete samples. Therefore, when the acoustic wave propagates inside the concrete samples, it will reflect and refract, and the energy will be attenuated [46, 49, 50]. In general, the longitudinal wave mainly propagates inside the concrete sample. Besides reflection and refraction, dispersion and scattering also occur when it propagates. Dispersion is primarily due to the strong impedance mismatch of the constituent phase [51],

Table 3: The variation of peak frequency and RMSD index in two cases.

| The relation between the wavefront and the sensor | The concrete strength grade | Peak frequency (100 mm) | Peak frequency (300 mm) | RMSD of dominant frequency |
|--------------------------------------------------|---------------------------|-------------------------|-------------------------|----------------------------|
| Perpendicular                                    | C30                       | 42.96                   | 30.27                   | 29.5                       |
|                                                  | C40                       | 43.94                   | 32.22                   | 26.7                       |
|                                                  | C50                       | 44.92                   | 35.15                   | 21.7                       |
| Parallel                                         | C30                       | 42.96                   | 31.25                   | 27.2                       |
|                                                  | C40                       | 44.92                   | 33.2                    | 26                          |
|                                                  | C50                       | 44.92                   | 35.26                   | 21.5                       |

Figure 15: Frequency-domain spectra of acoustic emission signals in concrete with strength grade. (a) C30, (b) C40, and (c) C50.

Figure 16: (a–c) Photos of concrete surfaces with different strength grades. (a) C30, (b) C40, and (c) C50.
while scattering [52] will lead to wave redirection and change the arrival time of some wave components. These results eventually lead to energy decrease, which is reflected in the significant reduction of acoustic velocity and amplitude parameters. The surface wave mainly propagates on the surface of the concrete sample. In the process of mold vibration, a thin layer of cement paste or mortar will be formed on the surface of the concrete sample, which is beneficial to the propagation of surface waves. Therefore, the attenuation of the surface wave’s acoustic velocity and amplitude parameters is small. In addition, the waveform deviates seriously from its initial shape, which may be related to the shape and size of the concrete sample because it reflects at the boundary and is further distorted by the sample geometry. These factors gradually accumulate with the increase of acoustic wave propagation distance.

4. Conclusion

In this paper, high-sensitivity, low-frequency acoustic emission sensors with broad frequency bands were tailored according to the frequency characteristics of damage signals in concrete material. Acoustic velocity, signal amplitude, rise time, waveform, and frequency spectrum were employed as characteristic parameters to describe the changes of acoustic wave characteristics during propagation in concrete samples. Based on the customized sensor, we quantitatively analyzed the influence of propagation distance on the characteristic parameters of acoustic waves propagating in concrete with three different strength grades (C30, C40, and C50). We discussed the two cases when the wavefront is perpendicular and parallel to the sensor axis. The discrepancy of results in the two cases was investigated by the RMSD method. Conclusions are as follows.

(1) In preparing the highly sensitive low-frequency acoustic emission sensors, we found that when the mass ratio of epoxy resin, curing agent, and tungsten powder is 4:1:1.5, the amplitude sensitivity of the acoustic emission sensor is consistent with that of the commercial sensors. At the same time, the bandwidth is almost four times that of the commercial sensor, which means that it can monitor more low-frequency signals and make the monitoring results more accurate than the commercial sensor.

(2) We find the same variation trend of acoustic emission characteristic parameters in the two cases. In the concrete with the same strength grade, with the increase of the propagation distance, the acoustic velocity and amplitude decrease, while the rise time increases. Under the same propagation distance in concrete with different strength grades, with the increase of the concrete strength grade, the acoustic velocity and amplitude increase while the rise time decreases. From the waveform spectrum, we can see the changes of these parameters more intuitively.

(3) From the frequency spectrum, we can find that in the concrete with the same strength grade, with the increase of propagation distance, the amplitude of the spectrum gradually decreases, the frequency response range narrows, and the frequency component shifts to low frequency. Under the same propagation distance in concrete with different strength grades, the offset of the peak frequency decreases with the concrete strength grade increase.

(4) Based on the above analysis, we can conclude that the different propagation modes of acoustic waves in concrete have different attenuation with the propagation distance, which is related to the position relationship between the acoustic source and the sensor and the propagation path and path quality.

Data Availability

The data generated or used during the study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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References

[1] M. Ohtsu, “The history and development of acoustic emission in concrete engineering,” Magazine of Concrete Research, vol. 48, no. 177, pp. 231–330, 1996.
[2] H. A. Elfergani, R. Pullin, and K. M. Holford, “Damage assessment of corrosion in prestressed concrete by acoustic emission,” Construction and Building Materials, vol. 40, pp. 925–933, 2013.
[3] M. Ohtsu, “Quantitative AE techniques standardized for concrete structures,” Advanced Materials Research, vol. 13-14, pp. 103–192, 2006.
[4] A. Marfo, Y. Luo, and Z. A. Chen, “Quantitative acoustic emission fatigue crack characterization in structural steel and weld,” Advances in Civil Engineering, vol. 2013, Article ID 461529, 6 pages, 2013.
[5] Y. Chen, Y. G. Yang, F. Gao, and X. X. Zhang, “Researches on damage evolution and acoustic emission characteristics of rocks,” Advances in Civil Engineering, vol. 2018, Article ID 3108065, 7 pages, 2018.
[6] S. Shahiron, N. M. Bunnori, M. N. Nor, and S. R. Basi, “Health index evaluation on acoustic emission signal for concrete structure by intensity analysis method,” Advanced Materials Research, vol. 403-408, pp. 3729–3733, 2012.
Advances in Civil Engineering

[7] A. Carpinteri, G. Lacidogna, and N. Pugno, “Structural damage diagnosis and life-time assessment by acoustic emission monitoring,” *Engineering Fracture Mechanics*, vol. 74, no. 1-2, pp. 273–289, 2007.

[8] D. G. Aggelis, E. Z. Kordatos, M. Strantzaki, D. V. Soulioti, and T. E. Matikas, “NDT approach for characterization of sub-surface cracks in concrete,” *Construction and Building Materials*, vol. 25, no. 7, pp. 3089–3097, 2011.

[9] D. G. Aggelis, “Classification of cracking mode in concrete by acoustic emission parameters,” *Mechanics Research Communications*, vol. 38, no. 3, pp. 153–157, 2011.

[10] K. M. Holford, “Acoustic emission in structural health monitoring,” *Key Engineering Materials*, vol. 413-414, pp. 15–28, 2009.

[11] K. M. Holford, M. J. Eaton, J. J. Hensman, R. Pullin, S. L. Evans, N. Dervilis, and K. Worden, “A new methodology for automating acoustic emission detection of metallic fatigue fractures in highly demanding aerospace environments: an overview,” *Progress in Aerospace Sciences*, vol. 90, pp. 1–11, 2017.

[12] G. F. Ma and Q. J. Du, “Structural health evaluation of the prestressed concrete using advanced acoustic emission (AE) parameters,” *Construction and Building Materials*, vol. 250, pp. 1–17, Article ID 118860, 2020.

[13] N. B. Burud and J. M. C. Kishen, “Response based damage assessment using acoustic emission energy for plain concrete,” *Construction and Building Materials*, vol. 269, Article ID 121241, 2021.

[14] W. Vélez, F. Matta, and P. Ziehl, “Acoustic emission monitoring of early corrosion in prestressed concrete piles,” *Structural Control and Health Monitoring*, vol. 22, no. 5, pp. 873–887, 2015.

[15] J. G. Xu, *Nondestructive evaluation of prestressed concrete structures by means of acoustic emissions monitoring*, Ph.D. thesis, 2008.

[16] D. G. Aggelis and T. E. Matikas, “Effect of plate wave dispersion on the acoustic emission parameters in metals,” *Computers & Structures*, vol. 98-99, pp. 17–22, 2012.

[17] M. Ohtsu, M. Uchida, and T. Okamoto, “Damage assessment of reinforced concrete beams qualified by acoustic emission,” *ACI Structural Journal*, vol. 99, pp. 411–417, 2002.

[18] G. K. Kocur and T. Vogel, “Classification of the damage condition of preloaded reinforced concrete slabs using parameter-based acoustic emission analysis,” *Construction and Building Materials*, vol. 24, no. 12, pp. 2332–2338, 2010.

[19] C. U. Grosse and L. M. Linzer, “Signal-based AE analysis,” in *Acoustic Emission Testing*, C. Grosse and M. Ohtsu, Eds., pp. 53–99, Springer, Berlin, Germany, 2008.

[20] T. Shirotani, Edited by C. Grosse, Ed., “Parameter analysis,” in *Acoustic Emission Testing*, M. Ohtsu, Ed., pp. 41–51, Springer, Berlin, Germany, 2008.

[21] I. S. Colombo, I. G. Main, and M. C. Ford, “Assessing damage of reinforced concrete beam using b-value analysis” of acoustic emission signals,” *Journal of Materials in Civil Engineering*, vol. 15, no. 3, pp. 280–286, 2003.

[22] J. H. Kurz, F. Finck, C. U. Grosse, and H.-W. Reinhardt, “Stress drop and stress redistribution in concrete quantified over time by the b-value analysis,” *Structural Health Monitoring*, vol. 5, no. 1, pp. 69–81, 2006.

[23] A. Farhidzadeh, Dehghan-Niri, S. Salamone, B. Luna, and A. Whittaker, “Monitoring crack propagation in reinforced concrete shear walls by acoustic emission,” *Journal of Structural Engineering*, vol. 139, no. 12, pp. 116–134, 2013.

[24] Rilem Technical Committee, “Recommendation of RILEM TC 212-ACD: acoustic emission and related NDE techniques for crack detection and damage evaluation in concrete,” *Materials and Structures*, vol. 43, no. 9, pp. 1187–1189, 2010.

[25] S. Shahidan, R. Pullin, N. Muhamad Bumori, and K. M. Holford, “Damage classification in reinforced concrete beam by acoustic emission signal analysis,” *Construction and Building Materials*, vol. 45, pp. 78–86, 2013.

[26] C. Grosse, H. Reinhardt, and T. Dahm, “Localization and classification of fracture types in concrete with quantitative acoustic emission measurement techniques,” *NDT & E International*, vol. 30, no. 4, pp. 223–230, 1997.

[27] N. M. Nor, N. M. Bumori, A. Ibrahim, S. Shahidan, and S. N. M. Saliha, “An investigation on acoustic wave velocity of reinforced concrete beam in-plane surface cracks,” in *Proceedings of the 2011 IEEE 7th International Colloquium on Signal Processing and its Applications*, pp. 19–22, Penang, Malaysia, March, 2011.

[28] J. T. Verbis, S. E. Kattis, S. V. Tsinopoulos, and D. Polyzos, “Wave dispersion and attenuation in fiber composites,” *Computational Mechanics*, vol. 27, no. 3, pp. 244–252, 2001.

[29] D. G. Aggelis, S. V. Tsinopoulos, and D. Polyzos, “An iterative effective medium approximation (IEMA) for wave dispersion and attenuation predictions in particulate composites, suspensions and emulsions,” *Journal of the Acoustical Society of America*, vol. 116, no. 6, pp. 3443–3452, 2004.

[30] G. S. Robinson, “Methods of detecting the formation and propagation of microcracks in concrete,” in *Proceedings of the International Conference on Structure of Concrete and its Behavior under Load. Cement and Concrete Association*, pp. 131–145, London, UK, September, 1965.

[31] M. Ohtsu, “General remarks on applications,” in *Acoustic Emission Testing*, C. Grosse and M. Ohtsu, Eds., pp. 203–209, Springer, Berlin, Germany, 2008.

[32] S. C. Lovejoy, “Development of acoustic emissions testing procedures applicable to conventionally reinforced concrete deck girder bridges subjected to diagonal tension cracking,” Ph. D. thesis, Oregon State University, the United States, 2006.

[33] S. Yuyama, K. Yokoyama, K. Niitani, M. Ohtsu, and T. Uomoto, “Detection and evaluation of failures in high-strength tendon of prestressed concrete bridges by acoustic emission,” *Construction and Building Materials*, vol. 21, no. 3, pp. 491–500, 2007.

[34] S. F. Huang, M. M. Li, D. Y. Xu, M. J. Zhou, S. H. Xie, and X. Cheng, “Investigation on a kind of embedded AE sensor for concrete health monitoring,” *Research in Nondestructive Evaluation*, vol. 24, no. 4, pp. 202–210, 2013.

[35] D. Y. Xu, S. F. Huang, L. Qin, L. C. Lu, and X. Cheng, “Monitoring of cement hydration reaction process based on ultrasonic technique of piezoelectric composite transducer,” *Construction and Building Materials*, vol. 35, pp. 220–226, 2012.

[36] Y. S. Xu, J. Qu, F. Lu, L. Li, X. Cheng, and S. F. Huang, “Acoustic emission characteristics of plain concrete under three-point bending,” *Advanced Materials Research*, vol. 1030-1032, pp. 974–977, 2014.

[37] K. Jemielniak, “Some aspects of acoustic emission signal preprocessing,” *Journal of Materials Processing Technology*, vol. 109, no. 3, pp. 242–247, 2001.

[38] M. R. Gorman, “Plate wave acoustic emission,” *Journal of the Acoustical Society of America*, vol. 90, no. 1, pp. 358–364, 1991.

[39] W. Zhang, H. Jia, G. Gao, X. Cheng, P. Du, and D. Xu, “Backing layers on electroacoustic properties of the acoustic
emission sensors,” Applied Acoustics, vol. 156, pp. 387–393, 2019.
[40] D. E. W. Stone and P. F. Dingwall, “Acoustic emission parameters and their interpretation,” NDT & E International, vol. 10, no. 2, pp. 51–62, 1977.
[41] A. G. Beattie, Acoustic Emission Non-destructive Testing of Structures Using Source Location techniques, SAND2013-7779, Sandia National Laboratories, Albuquerque, NM, New Mexico, 2013.
[42] V. Giurgiutiu and A. Zagrai, “Damage detection in thin plates and aerospace structures with the electro-mechanical impedance method,” Structural Health Monitoring, vol. 4, no. 2, pp. 99–118, 2005.
[43] K. K.-H. Tseng and A. S. K. Naidu, “Non-parametric damage detection and characterization using smart piezoceramic material,” Smart Materials and Structures, vol. 11, no. 3, pp. 317–329, 2002.
[44] C. Liang, F. P. Sun, and C. A. Rogers, “An impedance method for dynamic analysis of active material systems,” Journal of Intelligent Material Systems and Structures, vol. 8, no. 4, pp. 323–334, 1997.
[45] D. Polyzos, A. Papacharalampopoulos, T. Shiotani, and D. G. Aggelis, “Dependence of AE parameters on the propagation distance,” Journal of Acoustic Emission, vol. 29, pp. 57–67, 2011.
[46] D. Aggelis, T. Shiotani, A. Papacharalampopoulos, and D. Polyzos, “The influence of propagation path on elastic waves as measured by acoustic emission parameters,” Structural Health Monitoring, vol. 11, no. 3, pp. 359–366, 2011.
[47] Y. Q. Liu, W. L. Wang, L. Qin, S. F. Huang, and X. Cheng, “Influence of source distance on the characteristics of AE signal from cement-based materials,” Applied Mechanics and Materials, vol. 90-93, pp. 1698–1701, 2011.
[48] G. T. Shen, Acoustic Emission Technology and Application, SciencePress, Beijing, China, 2015.
[49] W. Punurai, J. Jarzynski, J. Qu, K. E. Kurtis, and L. J. Jacobs, “Characterization of dissipation losses in cement paste with diffuse ultrasound,” Mechanics Research Communications, vol. 34, no. 3, pp. 289–294, 2007.
[50] K. Tharmaratnam and B. S. Tan, “Attenuation of ultrasonic pulse in cement mortar,” Cement and Concrete Research, vol. 20, no. 3, pp. 335–345, 1990.
[51] D. G. Aggelis and T. P. Philippidis, “Ultrasonic wave dispersion and attenuation in fresh mortar,” NDT & E International, vol. 37, no. 8, pp. 617–631, 2004.
[52] M. L. Cowan, K. Beaty, J. H. Page, Z. Liu, and P. Sheng, “Group velocity of acoustic waves in strongly scattering media: dependence on the volume fraction of scatterers,” Physical Review A, vol. 58, no. 5, pp. 6626–6636, 1998.