Effect of Different Coarse Aggregate Sizes on the Propagation Characteristics of Acoustic Emission Waves in Concrete

Aiping Yu, Xiuxin Li, Zichen Cheng, Liyuan Liu, Jinxu Shi, Feng Fu FASCE

Corresponding author Feng.fu.1@city.ac.uk[1]

Abstract: In order to develop a new technology to effectively detect the sizes of the aggregate in existing concrete structure, the study of influence of coarse aggregate sizes on acoustic emission signals was performed. The specific surface areas of five coarse aggregate sizes (same mass) of 4.75-9.5 mm, 9.5-16 mm, 16-19 mm, 19-26.5 mm and 26.5-31.5 mm were measured by slurry wrapping method to calculate their effects on the three-phase microscopic components of concrete. In this paper, acoustic emission monitoring and parametric analysis were conducted on concrete samples with different coarse aggregate sizes by adopting the method of active-passive joint acoustic emission monitoring, and to explore the influence of excitation frequencies and coarse aggregate

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Aiping Yu Professor, College of Civil Engineering, Guilin Univ. of Technology, Guilin 541004, China. Email: apyu@glut.edu.cn

Xiuxin Li, Master's Candidate, College of Civil Engineering, Guilin Univ. of Technology, Guilin 541004, China. Email: 2120220791@glut.edu.cn

Zichen Cheng, Master's Candidate, College of Civil Engineering, Guilin Univ. of Technology, Guilin 541004, China. Email: 2120230852@glut.edu.cn

Liyuan Liu, Master's Candidate, College of Civil Engineering, Guilin Univ. of Technology, Guilin 541004, China. Email: 2120230886@glut.edu.cn

Jinxu Shi, Master's Candidate, College of Civil Engineering, Guilin Univ. of Technology, Guilin 541004, China. Email: 2120220821@glut.edu.cn

Feng Fu, Associate Professor, Dept. of Civil Engineering, School of Mathematics, Computer Science & Engineering, City, Univ. of London, Northampton Square, London EC1V 0HB, UK (corresponding author). ORCID: https:// orcid.org/0000-0002-9176-8159. Email: feng.fu.1@city.ac.uk

sizes on parameter variation of elastic waves in concrete. The results show that AE signals in the concrete will appear high frequency and low frequency interconversion characteristics, and the degree of diffraction, refraction, scattering and energy attenuation of AE signals in concrete samples are highly correlated to coarse aggregate sizes. The Energy Difference Index (*EDI*) values are most affected by elastic wave with AE signal of 50 kHz, followed by 100 kHz, and the least affected is 150 kHz. Based on the proportion of wavelet packet energy, we can establish a relationship model between the specific surface area of coarse aggregate and its evaluation index, which can quantitatively evaluate the influence of coarse aggregate size on AE elastic wave at three excitation frequencies, and provide theoretical basis and data support for optimizing the algorithm of AE system to locate the damage source.

Key words: active-passive joint acoustic emission monitoring; coarse aggregate size; frequency; wavelet packet analysis; energy difference index

1 Introduction

Acoustic emission (AE) is a passive non-destructive testing technology, which is based on the local sources in materials release energy quickly to produce instantaneous elastic waves. It has many advantages such as real-time, high efficiency and so on. In essence, AE is a kind of elastic wave with various frequencies, which has been widely used in many fields (Rodríguez and Celestino 2019, Yu et al. 2023, Liu et al. 2022, Baikla et al. 2019). The microstructure of the materials will affect the propagation characteristics of AE signal in concrete materials. Presuming continuous and homogeneous material characteristics when using AE technology to detect structures (Mao et al.

2022, Xu et al. 2018). Riyar and Bhowmik (2023) regard concrete as a homogeneous material, and studies the fracture behavior of concrete under the action of static force and fatigue load. Li et al. (2023) regards the whole fracture behavior of the rock as continuous and homogeneous, and monitor the fracture damage of the rock by using AE technology. However, in fact, the internal microstructure of materials in some areas is discontinuous and heterogeneous. Therefore, understanding the correct propagation characteristics of AE signals in different media materials is very important for the advancement of AE technology. In recent years, many scholars have made achievements in metal, rock materials by using AE technology (Ma et al. 2023, Fan et al. 2022, Wang et al. 2022). In relatively homogeneous materials such as metals and rocks, the propagation of elastic waves can be assumed to be continuous and homogeneous, that is, it is assumed that elastic waves propagate uniformly along the straight line in relatively homogeneous materials such as metals and rocks. Coarse aggregate, cement mortar and interface transition zone (ITZ) constitute three-phase of concrete structure materials (Colombero et al. 2018, Nežerka et al. 2019). The interface transition zone is closely related to the coarse aggregate size. And the three-phase composition of concrete makes it difficult for AE elastic wave to propagate uniformly along a straight line in concrete, which is one of the important challenges faced by AE nondestructive technology in concrete structures. However, the current AE system uses the fixed AE wave velocity value, which may cause a non-negligible error in locating the damage. To tackle this problem, many scholars have done research to explore the impact of different material compositions on AE signals. Chen and Liu (2007) studied the effect of the maximum aggregate size on failure performance of high-performance beams, and found that the aggregate size was positively correlated with the crack expansion scale. Some scholars have studied the failure mechanism and fracture process of concrete samples with different sand rates during compression loading by combining AE and CT techniques (Elaqra et al. 2007, Lee et al. 2020). Li et al. (2020) used the regional exhaustive localization method with modified wave velocity to study the source localization with different aggregate sizes concrete samples and found that this method has a higher positioning accuracy than traditional method. Wang et al. (2017) revealed the failure evolution process of concrete samples with different w/c ratios through the development rule of AE accumulated energy. In addition, some scholars have proposed to treat the AE damage source as a random variable, using the probability density field to reflect the crack morphology, which also provides the new idea for AE location of the damage source (Zhang and Yang 2022, Zhang et al. 2023). The above research shows that the propagation characteristics of elastic wave are closely related to the concrete composition materials. But these studies are difficult to be really applied to practical engineering. Therefore, we need to explore a practical way to reveal the essential relationship between the propagation characteristics of elastic wave and the three-phase composition of concrete.

In practical engineering, coarse aggregate is a key component of concrete. Under the same proportions of concrete mix, changes in coarse aggregate size inevitably lead to variations in the specific surface area of coarse aggregate size ratio, which also leads to the change of ITZ (Golewski 2018, Gao et al. 2022, Kong and Ge 2015). It also directly affects the propagation characteristics of elastic waves within concrete, which will result a great deviation of AE monitoring and locating results of damage source. The different of coarse aggregate size has a significant effect on the propagation characteristics of elastic waves in concrete materials (Kocur et al. 2010, Kocur et al.

2011, Leon and Chockalingam 2020,). Zhao et al. (2023) studied the effect of different coarse aggregates (particle size, volume fraction, etc.) on the failure process of concrete through experiments, revealing the relations between crack expansion scale and internal stress. Sagar et al. (2018) found that AE cumulative energy was positively correlated with coarse aggregate sizes. Jia et al. (2017) found that the change of coarse aggregate size would lead to changes in the interfacial transition zone. Wu et al. (2021) studied the propagation characteristics of elastic waves with different coarse aggregate sizes within concrete, and pointed out that the attenuation degree of elastic wave characteristic parameters (frequency, amplitude, and energy, etc.) was positively correlated with aggregate sizes. Previous studies have indicated that different particle sizes of coarse aggregates affect the propagation characteristics of elastic waves in concrete. In addition, the frequency of AE elastic waves collected varies with the different damage stages of concrete. Wei et al. (2023) found that AE signals collected by the AE system were concentrated within the range of 50-350 kHz under uniaxial compression tests. Furthermore, AE signals within the range of 100-125 kHz were consistently present throughout the entire loading process. Wang et al. (2022) found that the frequency of AE signals collected under axial compression failure conditions mainly concentrated in the four frequency bands: 0-50 kHz, 100-150 kHz, 200-250 kHz and 250-300 kHz. At the initial loading stage (0%-20% peak stress) and the approaching failure stage (90%-100% peak stress), that is, pore compaction, primary crack closure, micro-crack formation and macro-crack formation, the proportion of low-frequency (0-50 kHz) AE hits is larger. The proportion of high frequency (200-250 kHz and 250-300 kHz) AE hits increases significantly at the stage of approaching failure. At this stage, many micro-cracks are connected to form macro-cracks, and ITZ between cement mortar and coarse aggregate is cracked in a large area. At the certain stage (20%-80% peak stress), that is, the newly born micro-cracks crack steadily and develop into a number of micro-cracks at ITZ, the weakest part of the three-phase composition of concrete, many AE signals can be collected in the middle frequency band (100-150 kHz), and the proportion is very high. AE elastic waves with different frequencies have different propagation characteristics in different concrete materials. Therefore, while studying AE damage signals of concrete with different coarse aggregate sizes, it is also necessary to analyze the evolution process of elastic waves with different frequencies inside concrete materials.

Most of the previous studies focused on the effect of different aggregate sizes on acoustic emission. The qualitative research is mostly based on the quantitative analysis from the macro-characteristic parameters of coarse aggregate to the parameters of AE signals, which cannot be changed according to the macro-characteristic parameters. Furthermore, it is difficult to establish the relationship with the key factor (component change) of AE signal change, which leads to the great dispersion of test results. The main reason is that there is no quantitative analysis of the relationship between different aggregate size and ITZ, and the direct relationship between macro parameters of aggregate size and ITZ is not established, which makes it difficult to form a unified and reliable index standard. Meanwhile, we can establish the relationship between macro parameters of aggregate size and ITZ and analyze the propagation variation rule of AE signal in different components of concrete, which may reveal the evolution rule of aggregate size change on AE damage signal parameter change from the mechanism. Therefore, the study starts from the mechanism to explore a more unified regularity indicator to reveal the relationship between the propagation process of AE signals and three-phase components of concrete (coarse aggregate size) and frequency. The study aims to reveal the influence of coarse aggregate size and frequency on the propagation of AE signals and to quantify this relationship. The method of active-passive joint acoustic emission monitoring is adopted in this study. Arbitrary waveform generator (AWG) is used to excite AE waves simulation frequencies of 50, 100 and 150 kHz, which to simulate the AE signal frequency of concrete samples during failure process, and to monitor the AE signals of five groups of concrete with different coarse aggregate sizes. AE signal was analyzed by wavelet packet analysis method, and the relation model between the coarse aggregate size specific surface area and the energy difference index (*EDI*) of coarse aggregates was established based on energy ratio of wavelet packet, and to reveal the effects of coarse aggregate sizes on AE parameters.

2 Test program

2.1 Specimen design

The raw materials used in the test were Conch PO42.5 ordinary Portland cement, fine aggregate, coarse aggregate and water (Wang,2020, Cai 2019,Qian 2021). The fine aggregate is medium sand, and its fineness modulus, apparent density and accumulative density are 2.85, 2.653 kg/m^3 and 1530 kg/m^3, respectively. The coarse aggregate is crushed stone, and its apparent density and accumulative density are 2.752 kg/m^3 and 1643 kg/m^3 respectively. Coarse aggregate was divided into five groups: 4.75-9.5 mm, 9.5-16 mm, 16-19 mm, 19-26.5 mm, 26.5-31.5 mm. The samples cast into prismatic test blocks with the size of 150×150×300 mm^3, and 5 parallel samples were poured in each group. The proportions of concrete mix is 550.1:559.4:1038.8:209.0(cement: fine aggregate: coarse aggregate: water, kg/m^3) . Five groups of concrete prismatic samples are shown in Figure 1. All the samples were made in the same batch and were demoulded 24 hours after pouring, and placed in a standard curing environment (relative humidity >95%, temperature 20±2℃) for 28d.

2.2 Determination of coarse aggregate size specific surface area

In order to successfully quantify the coarse aggregate size and ITZ, and establish the numerical relationship model between AE waveform parameters and coarse aggregate size at different frequencies, the influence of frequency and coarse aggregate size on AE signal were studied by introducing the parameter of coarse aggregate size specific surface area. Specific surface area refers to the ratio of the total area of the material per unit mass, cm^2/g. In this paper, the coarse aggregate size specific surface area was measured by slurry wrapping method. It was assumed that the mass of slurry wrapping per unit area of concrete cube was the same as that of coarse aggregate, and the w/c ratio of cement paste was 0.6. The calculation formula of different coarse aggregate sizes surface area of is as follows (Liu and Liu 2020).

$$S_{a,i} = \frac{S_c}{M_c - m_c} \times \left(M_{a,i} - m_{a,i} \right) \tag{1}$$

Where i represents five different coarse aggregate, A~E; $S_{a,i}$ represents five different coarse aggregate sizes surface areas, cm^2; S_c represents concrete cube surface area with a side length of 100mm, cm^2; M_c and m_c represent the mass of the test cube before and after coating, respectively; $M_{a,i}$ and $m_{a,i}$ represent the mass of different coarse aggregate sizes before and after coating, respectively.

The calculation formula of specific surface area for different coarse aggregate sizes as follows (Liu and Liu 2020).

$$S_{s,i} = \frac{S_{a,i}}{M_{a,i}} \tag{2}$$

The test results of different coarse aggregates sizes specific surface area are shown in Table 1.

2.3 Test setup

The method of active-passive joint acoustic emission monitoring was used in the experiment. The active acoustic emission monitoring method uses ARB-1410 sonic instrument produced by American Physics Corporation (PAC) to excite AE waves of 50, 100 and 150 kHz. The frequency of the instrument can be up to 15 MHz. The excitation sensor selects the R3α, and its broadband frequency is 20-180 kHz. The amplitude of the excitation signal is 1.25 V, and the period is 5. The waveform diagram of AWG excitation signal was shown in Figure 2 (taking 50 kHz excitation signal as an example).

The passive acoustic emission monitoring method uses the full digital system Sensor Highway-III produced by PAC to collect AE signal. The AE sensor selects the PK15I with a resonant frequency of 150 kHz, and its broadband frequency is 80-200 kHz. Table 2 shows the detailed setting of AE monitoring system during the test.

In the experiment, the excitation sensor and AE sensor are attached in the middle of the 150 mm concrete cube with silica gel adhesive. AE elastic waves of three different frequencies are produced by the Arbitrary waveform generator. The AE excitation acts on the sample through the excitation sensor. After the AE signal inside the concrete samples is diffracted, refracted, scattered and attenuated, it is received by the AE system through the AE sensor on the other side. It is expected to obtain the analytical model correlating AE waveform parameters with different frequencies and coarse aggregate sizes, enabling quantitative analysis and evaluation of energy distribution in concrete with different coarse aggregate sizes. Figure 3 shows the schematic diagram of test process. To ensure consistency in the AE waveform signals elicited each time, the same step was used to excite AE signals at three different frequencies. Each group of test blocks were excited three times with the same frequency in the same step to assure the reliability of the results of experiments.

3 Analytical methods

AE waveform contains all the information of elastic waves, so AE waveform analysis is the most accurate method. AE waveform signals can be analyzed by fast Fourier transform (FFT) and wavelet packet transform (WPT). The acquired time-domain signal can be transformed into frequency-domain signal by FFT method and decompose the main-frequency and sub-frequency (Aggelis et al. 2011). However, compared with FFT, WPT method can decompose the signal according to the set frequency band width, and the obtained data information can reflect the energy ratio of corresponding frequency band, which can better characterize the local features of the signal (Fakharian and Naderpour 2022, Liu et al. 2023). Jahangir et al. (2022) used the energy proportion obtained from wavelet packet analysis to derive the damage index of prestressed concrete slabs. Wang et al. (2022) used wavelet packet decomposition to obtain the energy ratio of the lowest frequency band and the highest frequency band, and divided the damage stage of concrete material into three stages. Wang et al. (2018) studied the crack patterns of materials by investigating the portion of the release energy using wavelet packet decomposition and found that the speed of energy release is positively correlated with the frequency of stress wave. It shows that it is effective to analyze the internal energy change of concrete structure by using wavelet packet. Therefore, in order to obtain the analytical model for the relationship between elastic waves and coarse aggregate sizes with different frequencies, and to realize the quantitative analysis and evaluation of the energy ratio of concrete with different coarse aggregate sizes. Wavelet packet analysis of AE waveform received by concrete samples with different frequencies and coarse aggregate sizes is studied.

3.1 Wavelet packet analysis

WPT method can decompose the whole waveform signal according to the set frequency band width, and the data obtained after decomposition can adaptively select the matching frequency band, which can better reflect the energy distribution of the elastic wave in corresponding frequency band. The selection of wavelet function should have some basic properties such as orthogonality, time region and lossless signal reconstruction. The SymletsA wavelet function was proposed by Ingrid Daubechies (Daubechies 2009). SymletsA wavelet function is generally abbreviated as SymN (N= 2,3, ... , 8), which has excellent properties in continuity, filter length, support length, symmetry and orthotropy, etc (Zhang et al. 2019) . In addition, Sym8 wavelet basis function can better analyze the localization characteristics of signals when processing digital signals and reduce the distortion of signals in the process of analysis and reconstruction, so the Sym8 wavelet function is used here to process AE signals. Schematic diagram of three-layer wavelet packet process is shown in Figure 4, where S, H and L represent the original signal, the high frequency signal and the low frequency signal, respectively. Every time the original signal S is decomposed by one layer of wavelet packet decomposition, a high frequency signal H and a low frequency signal L obtained. After three-layer of wavelet packet decomposition, 2^3 sub-signals can be obtained, that is, 8 different frequency bands.

The maximum decomposition scale “j” is determined according to the sampling frequency (f_s) set by the AE system and the lowest effective frequency (f_{min}) of the AE sensor used. The maximum decomposition scale “j” is calculated from formula 3 (Lv 2021) .

$$j \le log_2 \frac{f_s}{2f_{min}} \tag{3}$$

Where f_s represents the sampling frequency setby the AE system during the experiment, 1000 kHz; f_{min} represents the minimum effective frequency of the PK15I AE sensor used during the experiment, 80 kHz.

After calculation by formula 3, the maximum decomposition scale j=3. Moreover, the setting of frequency band width is closely related to the size of sampling frequency, and the sampling frequency set by the AE system during the test is 1000 kHz. According to Nyquist theorem, the signal excitation frequency must be less than or equal to half of the sampling frequency, so the maximum frequency of AE signals that can be analyzed by the experiment is 500 kHz (Li et al. 2012) . The frequencies of AE signals excited by the test are 50, 100 and 150 kHz respectively, which are far less than 500 kHz. Therefore, after AE signals are partitioned by 3-layer wavelet packets, each frequency band width is 62.5 kHz, and the corresponding frequency bandwidth ranges of 8 frequency bands are shown in Table 3.

In addition, when selecting the frequency of AE wave, the interface value of bandwidth should be avoided as far as possible. The purpose is to reduce the distortion caused by signal analysis and reconstruction in a certain range when AE signal is decomposed by wavelet packet. Three frequencies of AE wave selected in the study are 50, 100 and 150 kHz.

3.2 Coarse aggregate size energy difference index

The Energy Difference Index (*EDI*) is defined as the degree of difference between the response energy of the samples of group A to D and the samples of Group E. *EDI* calculation formula was established as showed in formula 4 (Zamorano et al. 2023).

$$EDI=\sqrt{\sum_{u=1}^{n}\left(\frac{e_{i,u}-e_{h,u}}{e_{h,u}}\right)^{2}} \tag{4}$$

where $e_{i,u}$ represents the energy ratio of one of the sub-frequency bands of coarse aggregate size samples in groups A to D, $e_{h,u}$ represents the energy ratio of one of the sub-frequency band of group E with the largest coarse aggregate size, n represents the number of frequency band.

After the decomposition of the wavelet packet in group E, the energy ratio of 8 frequency bands is obtained. The energy ratio of each frequency band is recorded as $e_{h,u}$ (u=1, 2, 3, , 8). After the decomposition of group A~D, the energy ratio of 8 frequency bands can also be obtained. The energy ratio of each frequency band is recorded as $e_{i,u}$ (u=1, 2, 3, , 8). The calculation formula is shown in formula 4. *EDI* values represent the essential qualitative relationship of coarse aggregate size by comparing the energy difference between Group A ~ D coarse aggregate size and group E with the largest coarse aggregate size after wavelet packet decomposition. According to formula 4, the larger *EDI* value, the greater energy difference between this group and the largest group E (coarse aggregate size is 26.5-31.5 mm), and the obvious signal change between them. It is worth noting that before calculating *EDI*, for the sake of reducing the effect of noises on the calculate results, the energy ratio corresponding to the 8 frequency bands should be screened, and the energy ratio should be selected as the concentrated frequency band for calculation.

4 Test results and analysis

4.1 Wavelet packet energy ratio analysis

After wavelet packet decomposition, the influence of different frequencies and coarse aggregate sizes on elastic waves can be observed intuitively through the change of sub-frequency bands energy ratio. Energy ratio of wavelet packets in 8 frequency bands with different frequencies and coarse aggregate sizes are shown in Figure 5. Excitation signals of 50, 100, and 150 kHz exhibit maximum energy distribution in Band 1 (0 ~ 62.5 kHz), Band 2 (62.5 ~ 125 kHz), and Band 3 (125 ~ 187.5 kHz), respectively. It demonstrates that decomposing AE signal by using Sym8 wavelet function is reasonable and effective.

As shown in Figure 5. The frequencies received by AE instruments are mainly concentrated in Band 1-3(0 ~ 187.5 kHz) , the total energy ratio of Band 1~3 is more than 95% . Under the three frequencies, the energy distribution in each frequency band shows certain regular variations with changes in aggregate size.

For the frequency band with high energy ratio (Band1 ~ 3), it can visually present the variation patterns of energy ratio across 8 frequency bands with different coarse aggregate sizes. Energy ratio of 8 frequency bands of different coarse aggregate sizes at 50kHz excitation frequency was shown in Figure 5 (a). With increasing coarse aggregate size, the energy ratio in Band 1 increases, while it decreases in Band 2. It indicates a characteristic of high-to-low frequency transfer of 50 kHz elastic waves within the concrete interior. Energy ratio of 8 frequency bands of different coarse aggregate sizes at 100 kHz excitation frequency was shown in Figure 5 (b). With increasing coarse aggregate size, the energy ratio in Band 2 decreases, while the energy contributions in Band 1 and Band 3 increase. It indicates a characteristic of elastic waves transitioning from low to high frequencies and from high to low frequencies within concrete interior. Energy ratio of 8 frequency bands of different coarse aggregate sizes at 150 kHz excitation frequency was shown in Figure 5 (c). With increasing coarse aggregate size, the energy ratio in Band 3 decreases, while that in Band 2 increases, and Band 1 shows little change and does not exhibit a clear pattern of variation. It indicates a characteristic of high-to-low frequency transfer of 150 kHz elastic waves within the concrete interior, and the frequency transfer is step by step.

However, analyzing the energy distribution across the 8 frequency bands obtained solely from wavelet packet decomposition makes it difficult to quantitatively analyze the relationship between frequency, coarse aggregate size, and elastic waves using a unified standard, so further analysis is needed.

4.2 EDI analysis

Section 4.1 is the analysis of the energy ratio obtained from wavelet packet decomposition. Although the energy ratio of AE signals of samples with different coarse aggregate sizes shows obvious change rules at different frequencies, in order to reveal the essential relationship of elastic waves of different frequencies in the propagation of different coarse aggregate sizes with a unified rule index, the value *EDI*, an index of energy difference of coarse aggregate size, was studied and established. It can effectively characterize the propagation rules of AE signals in concrete, obtain numerical relationship models of different frequencies, different coarse aggregate sizes and AE waveform parameters, and realize quantitative analysis and evaluation of energy ratio of different coarse aggregate sizes. To reduce the influence of noise on the experimental results, we selected frequency bands with relatively concentrated energy ratio (Band 1-3) to calculate the *EDI* value.

Figure 6 shows the *EDI* value of different coarse aggregate size specific surface area under three frequencies. The calculation formula is shown in formula 4. It can be seen from Figure 6 that *EDI* values under three frequencies increases with the increase of the specific surface area, indicating a decrease with larger coarse aggregate sizes. Through fitting process of the first order function, three relational models can be obtained to describe *EDI* values of different frequencies and different coarse aggregate size specific surface area:

AE elastic wave excited at 50 kHz: y=4.2003x-0.7905, R^2=0.98

AE elastic wave excited at 100 kHz: y=1.6982x-0.2888, R^2=0.94

AE elastic wave excited at 150 kHz: y=1.3201x-0.2901, R^2=0.97

According to the three relational models, *EDI* value shows a linear increasing trend with the increase of specific surface area. This is because the different coarse aggregate sizes and frequencies will both affect the propagation of elastic waves within concrete, resulting in different degrees of redistribution of band energy with changes in coarse aggregate size and frequency. The smaller coarse aggregate size, the larger energy difference between group E, that is, the larger *EDI* value. Three relation models reveal the essential relationship of elastic wave with different frequencies in the propagation of different coarse aggregate sizes by a relatively uniform rule index, which can be used to quantitative analysis and evaluate the energy ratio of different coarse aggregate sizes.

Under three different frequencies, the goodness of fit R^2 of *EDI* values for different coarse aggregate sizes is extremely high, almost close to 1, which indicates that *EDI* value is highly correlated with specific surface area. Therefore, it is reasonable to use *EDI* value to quantitatively analyze the influence of coarse aggregate size on AE signal.

Three models show that *EDI* values increase linearly with the increase of coarse aggregate sizes specific surface area. From the slope of three relation models, it can be seen that *EDI* values under different frequencies are different. The slopes of the relationship model corresponding to the excitation frequencies of 50, 100 and 150 kHz are 4.2003, 1.6982 and 1.3201, respectively, which shows that the propagation characteristics of AE elastic wave are also different when the damage stage is different (frequency of signal source is different). And it can be inferred that concrete test blocks with different coarse aggregate sizes have different effects on signal sources with different frequencies at different damage stages.

By comparing the frequencies of three excitation sources, it can be found that *EDI* values of different coarse aggregate sizes are most affected by elastic wave with AE excitation signal of 50 kHz, followed by 100 kHz, and the least affected is 150 kHz. It shows that the frequency change will effect the propagation of elastic wave within concrete, and the degree of diffraction, refraction, scattering and energy attenuation of AE signals in concrete sample, will increase with the frequency increase. In other words, AE signal of each stage of concrete specimen failure has different attenuation degrees in the concrete interior. During the initial loading stage and approaching failure stage, AE signals are mainly low-frequency signals of 50 kHz. It shows that the AE signals produced by pore compaction, primary crack closure, micro-crack formation and macro-crack formation are greatly affected by coarse aggregate size. At the loading stage, AE signal in the middle frequency band (100 ~ 150 kHz) accounts for a high proportion. In this stage, the newly born micro-cracks crack steadily and develop into a number of micro-cracks at ITZ, the weakest part of the 3-phase composition of concrete. The essence is that the tip of the micro-crack gradually extends to the weaker paste in the concrete. Elastic waves generated by this process are relatively weak and is less affected by the size of coarse aggregate size.

5 Conclusion

In this paper, the influence of different frequencies and coarse aggregate sizes on AE signals were investigated and below conclusion can be made:

（1）Elastic waves have a characteristic of transitioning from low to high frequencies and from high to low frequencies within the concrete interior. With the change of coarse aggregate size, the wavelet packet energy ratio also presents a certain change rule. The degree of diffraction, refraction, scattering and energy attenuation of AE signal in samples is closely related to the coarse aggregate size.

（2）For the three frequencies investigated, *EDI* values increased with the increase of coarse aggregate specific surface area. Three relation models reveal the essential relationship of elastic waves of different frequencies in propagation of different coarse aggregate sizes with a unified rule index, and then effectively characterize the propagation rule of AE wave within concrete. It can provide theoretical basis and data support for subsequent optimization of damage source localization.

（3）According to the relationship model corresponding to the frequencies of the three AE excitation sources, *EDI* values of different coarse aggregate sizes is most affected by 50 kHz, followed by 100 kHz, and the least affected is 150 kHz. The frequency change will effect the propagation of elastic wave within concrete, and the degree of diffraction, refraction, scattering and energy attenuation of AE signals in concrete samples, will increases with the frequency increase.

（4）When using the AE system to detect the location of damage sources in concrete, we should consider the frequency of damage sources at different damage stages and effect of coarse aggregate size on the propagation characteristics of AE elastic waves. The algorithm for locating the damage source in the AE system can be optimized by considering the combination of three empirical equations, which can further optimize the location the damage source. In future engineering practices, other types of materials (such as coarse aggregate particle size and cement) can also be evaluated using the specific surface area measurement method we proposed, thereby effectively characterizing the propagation laws of acoustic emission waves within different types of concrete. In addition, other factors that will affect the AE propagation characteristics of elastic waves inside the concrete will also be considered in the study, such as concrete age, temperature, humidity, moisture content, sand rate, and steel reinforcement.

Data Availability Statement

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Tab.1 Different coarse aggregates sizes specific surface area

Group	Material	Mass before Coating(g)	Mass after Coating(g)	Added Mass(g)	Surface Area(cm^2)	Specific Surface Area(cm^2/g)
Concrete cube	concrete cube with sides of 100 mm	2200.0	2260.75	60.75	600.000	0.273
A	4.75-9.5 mm	1100.0	1167.60	67.60	667.654	0.607
B	9.5-16 mm	1100.0	1152.50	52.50	518.519	0.471
C	16-19 mm	1100.0	1143.00	43.00	424.691	0.386
D	19-26.5 mm	1100.0	1132.50	32.50	518.519	0.292
E	26.5-31.5 mm	1100.0	1122.00	22.00	217.284	0.198

Tab.2 Detailed setting of AE monitoring system

Test Parameter	Threshold (dB)	Sampling rate (MHz)	Sampling length	Amplifier Gain (dB)	PDT (μs)	HDT (μs)	HLT (μs)
Test value	35	1	1000	26	100	200	300

Where PDT is peak definition time, HDT is hit definition time, and HLT is hit locking time.

Tab.3 Corresponding frequency bandwidth range of 8 frequency bands

Band Number	Bandwidth(kHz)
1	0-62.5
2	62.5-125
3	125-187.5
4	187.5-250

5	250-312.5
6	312.5-375
7	375-437.5
8	437.5-500

Fig.1 Five groups of concrete prismatic samples

Fig.2 Time-domain waveform of 50 kHz excitation signal

Fig.3 Schematic diagram of test process

Fig.4 Schematic diagram of the three-layer wavelet packet process

Fig.5 Energy ratio of wavelet packets each frequency band with different frequencies and coarse aggregate sizes

Fig.5 (a) 50kHz

Fig.5 (b) 100kHz

Fig.5 (c) 150kHz

Fig.6 *EDI* value of different coarse aggregate size specific surface area under three frequencies.

Fig.6 (a) 50kHz

Fig.6 (b) 100kHz

Fig.6 (c) 150kHz