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

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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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15 sizes on parameter variation of elastic waves in concrete. The results show that AE signals in the

16 concrete will appear high frequency and low frequency interconversion characteristics, and the

17 degree of diffraction, refraction, scattering and energy attenuation of AE signals in concrete samples

18 are highly correlated to coarse aggregate sizes. The Energy Difference Index (*EDI*) values are most

19 affected by elastic wave with AE signal of 50 kHz, followed by 100 kHz, and the least affected is

20 150 kHz. Based on the proportion of wavelet packet energy, we can establish a relationship model

21 between the specific surface area of coarse aggregate and its evaluation index, which can

22 quantitatively evaluate the influence of coarse aggregate size on AE elastic wave at three excitation

23 frequencies, and provide theoretical basis and data support for optimizing the algorithm of AE

24 system to locate the damage source.

25 **Key words:** active-passive joint acoustic emission monitoring; coarse aggregate size; frequency;

26 wavelet packet analysis; energy difference index

27 1 Introduction

28 Acoustic emission (AE) is a passive non-destructive testing technology, which is based on the local

29 sources in materials release energy quickly to produce instantaneous elastic waves. It has many

30 advantages such as real-time, high efficiency and so on. In essence, AE is a kind of elastic wave

31 with various frequencies, which has been widely used in many fields (Rodríguez and Celestino

32 2019, Yu et al. 2023, Liu et al. 2022, Baikla et al. 2019). The microstructure of the materials will

33 affect the propagation characteristics of AE signal in concrete materials. Presuming continuous and

34 homogeneous material characteristics when using AE technology to detect structures (Mao et al.

35   2022, Xu et al. 2018). Riyar and Bhowmik (2023) regard concrete as a homogeneous material, and

36   studies the fracture behavior of concrete under the action of static force and fatigue load. Li et al.

37   (2023) regards the whole fracture behavior of the rock as continuous and homogeneous, and monitor

38   the fracture damage of the rock by using AE technology. However, in fact, the internal

39   microstructure of materials in some areas is discontinuous and heterogeneous. Therefore,

40   understanding the correct propagation characteristics of AE signals in different media materials is

41   very important for the advancement of AE technology. In recent years, many scholars have made

42   achievements in metal, rock materials by using AE technology (Ma et al. 2023, Fan et al. 2022,

43   Wang et al. 2022). In relatively homogeneous materials such as metals and rocks, the propagation

44   of elastic waves can be assumed to be continuous and homogeneous, that is, it is assumed that elastic

45   waves propagate uniformly along the straight line in relatively homogeneous materials such as

46   metals and rocks. Coarse aggregate, cement mortar and interface transition zone (ITZ) constitute

47   three-phase of concrete structure materials (Colombero et al. 2018, Nežerka et al. 2019). The

48   interface transition zone is closely related to the coarse aggregate size. And the three-phase

49   composition of concrete makes it difficult for AE elastic wave to propagate uniformly along a

50   straight line in concrete, which is one of the important challenges faced by AE nondestructive

51   technology in concrete structures. However, the current AE system uses the fixed AE wave velocity

52   value, which may cause a non-negligible error in locating the damage. To tackle this problem, many

53   scholars have done research to explore the impact of different material compositions on AE signals.

54   Chen and Liu (2007) studied the effect of the maximum aggregate size on failure performance of

55   high-performance beams, and found that the aggregate size was positively correlated with the crack

56   expansion scale. Some scholars have studied the failure mechanism and fracture process of concrete

57   samples with different sand rates during compression loading by combining AE and CT techniques

58   (Elaqra et al. 2007, Lee et al. 2020). Li et al. (2020) used the regional exhaustive localization method

59   with modified wave velocity to study the source localization with different aggregate sizes concrete

60   samples and found that this method has a higher positioning accuracy than traditional method. Wang

61   et al. (2017) revealed the failure evolution process of concrete samples with different w/c ratios

62   through the development rule of AE accumulated energy. In addition, some scholars have proposed

63   to treat the AE damage source as a random variable, using the probability density field to reflect the

64   crack morphology, which also provides the new idea for AE location of the damage source (Zhang

65   and Yang 2022, Zhang et al. 2023). The above research shows that the propagation characteristics

66   of elastic wave are closely related to the concrete composition materials. But these studies are

67   difficult to be really applied to practical engineering. Therefore, we need to explore a practical way

68   to reveal the essential relationship between the propagation characteristics of elastic wave and the

69   three-phase composition of concrete.

70   In practical engineering, coarse aggregate is a key component of concrete. Under the same

71   proportions of concrete mix, changes in coarse aggregate size inevitably lead to variations in the

72   specific surface area of coarse aggregate size ratio, which also leads to the change of ITZ (Golewski

73   2018, Gao et al. 2022, Kong and Ge 2015). It also directly affects the propagation characteristics of

74   elastic waves within concrete, which will result a great deviation of AE monitoring and locating

75   results of damage source. The different of coarse aggregate size has a significant effect on the

76   propagation characteristics of elastic waves in concrete materials (Kocur et al. 2010, Kocur et al.

4

77   2011, Leon and Chockalingam 2020,). Zhao et al. (2023) studied the effect of different coarse

78   aggregates (particle size, volume fraction, etc.) on the failure process of concrete through

79   experiments, revealing the relations between crack expansion scale and internal stress. Sagar et al.

80   (2018) found that AE cumulative energy was positively correlated with coarse aggregate sizes. Jia

81   et al. (2017) found that the change of coarse aggregate size would lead to changes in the interfacial

82   transition zone. Wu et al. (2021) studied the propagation characteristics of elastic waves with

83   different coarse aggregate sizes within concrete, and pointed out that the attenuation degree of elastic

84   wave characteristic parameters (frequency, amplitude, and energy, etc.) was positively correlated

85   with aggregate sizes. Previous studies have indicated that different particle sizes of coarse

86   aggregates affect the propagation characteristics of elastic waves in concrete. In addition, the

87   frequency of AE elastic waves collected varies with the different damage stages of concrete. Wei et

88   al. (2023) found that AE signals collected by the AE system were concentrated within the range of

89   50-350 kHz under uniaxial compression tests. Furthermore, AE signals within the range of 100-125

90   kHz were consistently present throughout the entire loading process. Wang et al. (2022) found that

91   the frequency of AE signals collected under axial compression failure conditions mainly

92   concentrated in the four frequency bands: 0-50 kHz, 100-150 kHz, 200-250 kHz and 250-300 kHz.

93   At the initial loading stage (0%-20% peak stress) and the approaching failure stage (90%-100%

94   peak stress), that is, pore compaction, primary crack closure, micro-crack formation and macro-

95   crack formation, the proportion of low-frequency (0-50 kHz) AE hits is larger. The proportion of

96   high frequency (200-250 kHz and 250-300 kHz) AE hits increases significantly at the stage of

97   approaching failure. At this stage, many micro-cracks are connected to form macro-cracks, and ITZ

98   between cement mortar and coarse aggregate is cracked in a large area. At the certain stage (20%-

99   80% peak stress), that is, the newly born micro-cracks crack steadily and develop into a number of

100   micro-cracks at ITZ, the weakest part of the three-phase composition of concrete, many AE signals

101   can be collected in the middle frequency band (100-150 kHz), and the proportion is very high. AE

102   elastic waves with different frequencies have different propagation characteristics in different

103   concrete materials. Therefore, while studying AE damage signals of concrete with different coarse

104   aggregate sizes, it is also necessary to analyze the evolution process of elastic waves with different

105   frequencies inside concrete materials.

106   Most of the previous studies focused on the effect of different aggregate sizes on acoustic emission.

107   The qualitative research is mostly based on the quantitative analysis from the macro-characteristic

108   parameters of coarse aggregate to the parameters of AE signals, which cannot be changed according

109   to the macro-characteristic parameters. Furthermore, it is difficult to establish the relationship with

110   the key factor (component change) of AE signal change, which leads to the great dispersion of test

111   results. The main reason is that there is no quantitative analysis of the relationship between different

112   aggregate size and ITZ, and the direct relationship between macro parameters of aggregate size and

113   ITZ is not established, which makes it difficult to form a unified and reliable index standard.

114   Meanwhile, we can establish the relationship between macro parameters of aggregate size and ITZ

115   and analyze the propagation variation rule of AE signal in different components of concrete, which

116   may reveal the evolution rule of aggregate size change on AE damage signal parameter change from

117   the mechanism. Therefore, the study starts from the mechanism to explore a more unified regularity

118   indicator to reveal the relationship between the propagation process of AE signals and three-phase

119   components of concrete (coarse aggregate size) and frequency. The study aims to reveal the

120   influence of coarse aggregate size and frequency on the propagation of AE signals and to quantify

121   this relationship. The method of active-passive joint acoustic emission monitoring is adopted in this

122   study. Arbitrary waveform generator (AWG) is used to excite AE waves simulation frequencies of

123   50, 100 and 150 kHz, which to simulate the AE signal frequency of concrete samples during failure

124   process, and to monitor the AE signals of five groups of concrete with different coarse aggregate

125   sizes. AE signal was analyzed by wavelet packet analysis method, and the relation model between

126   the coarse aggregate size specific surface area and the energy difference index (*EDI*) of coarse

127   aggregates was established based on energy ratio of wavelet packet, and to reveal the effects of

128   coarse aggregate sizes on AE parameters.

129   **2 Test program**

130   *2.1 Specimen design*

131   The raw materials used in the test were Conch PO42.5 ordinary Portland cement, fine aggregate,

132   coarse aggregate and water (Wang,2020, Cai 2019,Qian 2021). The fine aggregate is medium sand,

133   and its fineness modulus, apparent density and accumulative density are 2.85, 2.653 kg/m^3 and

134   1530 kg/m^3 , respectively. The coarse aggregate is crushed stone, and its apparent density and

135   accumulative density are 2.752 kg/m^3 and 1643 kg/m^3 respectively. Coarse aggregate was divided

136   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

137   cast into prismatic test blocks with the size of 150×150×300 mm^3, and 5 parallel samples were

138   poured in each group. The proportions of concrete mix is 550.1:559.4:1038.8:209.0(cement: fine

139   aggregate: coarse aggregate: water, kg/m^3) . Five groups of concrete prismatic samples are shown

140   in Figure 1. All the samples were made in the same batch and were demoulded 24 hours after pouring,

141   and placed in a standard curing environment (relative humidity >95%, temperature $20\pm2℃$) for

142   28d.

2.2 Determination of coarse aggregate size specific surface area

144   In order to successfully quantify the coarse aggregate size and ITZ, and establish the numerical

145   relationship model between AE waveform parameters and coarse aggregate size at different

146   frequencies, the influence of frequency and coarse aggregate size on AE signal were studied by

147   introducing the parameter of coarse aggregate size specific surface area. Specific surface area refers

148   to the ratio of the total area of the material per unit mass, cm^2/g. In this paper, the coarse aggregate

149   size specific surface area was measured by slurry wrapping method. It was assumed that the mass

150   of slurry wrapping per unit area of concrete cube was the same as that of coarse aggregate, and the

151   w/c ratio of cement paste was 0.6. The calculation formula of different coarse aggregate sizes surface

152   area of is as follows (Liu and Liu 2020).

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

154   Where i represents five different coarse aggregate, A~E; $S_{a,i}$ represents five different coarse

155   aggregate sizes surface areas, cm^2; S_c represents concrete cube surface area with a side length of

156   100mm, cm^2; M_c and m$_c$ represent the mass of the test cube before and after coating, respectively;

157    $M_{a,i}$ and $m_{a,i}$ represent the mass of different coarse aggregate sizes before and after coating,

158   respectively.

159   The calculation formula of specific surface area for different coarse aggregate sizes as follows (Liu

8

160   and Liu 2020).

161
$$S_{s,i} = \frac{S_{a,i}}{M_{a,i}} \tag{2}$$

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

163   *2.3 Test setup*

164   The method of active-passive joint acoustic emission monitoring was used in the experiment.

165   The active acoustic emission monitoring method uses ARB-1410 sonic instrument produced by

166   American Physics Corporation (PAC) to excite AE waves of 50, 100 and 150 kHz. The frequency

167   of the instrument can be up to 15 MHz. The excitation sensor selects the R3α, and its broadband

168   frequency is 20-180 kHz. The amplitude of the excitation signal is 1.25 V, and the period is 5. The

169   waveform diagram of AWG excitation signal was shown in Figure 2 (taking 50 kHz excitation signal

170   as an example).

171   The passive acoustic emission monitoring method uses the full digital system Sensor Highway-III

172   produced by PAC to collect AE signal. The AE sensor selects the PK15I with a resonant frequency

173   of 150 kHz, and its broadband frequency is 80-200 kHz. Table 2 shows the detailed setting of AE

174   monitoring system during the test.

175   In the experiment, the excitation sensor and AE sensor are attached in the middle of the 150 mm

176   concrete cube with silica gel adhesive. AE elastic waves of three different frequencies are produced

177   by the Arbitrary waveform generator. The AE excitation acts on the sample through the excitation

178   sensor. After the AE signal inside the concrete samples is diffracted, refracted, scattered and

179   attenuated, it is received by the AE system through the AE sensor on the other side. It is expected to

180   obtain the analytical model correlating AE waveform parameters with different frequencies and

181   coarse aggregate sizes, enabling quantitative analysis and evaluation of energy distribution in

182   concrete with different coarse aggregate sizes. Figure 3 shows the schematic diagram of test process.

183   To ensure consistency in the AE waveform signals elicited each time, the same step was used to

184   excite AE signals at three different frequencies. Each group of test blocks were excited three times

185   with the same frequency in the same step to assure the reliability of the results of experiments.

186   **3 Analytical methods**

187   AE waveform contains all the information of elastic waves, so AE waveform analysis is the most

188   accurate method. AE waveform signals can be analyzed by fast Fourier transform (FFT) and wavelet

189   packet transform (WPT). The acquired time-domain signal can be transformed into frequency-

190   domain signal by FFT method and decompose the main-frequency and sub-frequency (Aggelis et

191   al. 2011). However, compared with FFT, WPT method can decompose the signal according to the

192   set frequency band width, and the obtained data information can reflect the energy ratio of

193   corresponding frequency band, which can better characterize the local features of the signal

194   (Fakharian and Naderpour 2022, Liu et al. 2023). Jahangir et al. (2022) used the energy proportion

195   obtained from wavelet packet analysis to derive the damage index of prestressed concrete slabs.

196   Wang et al. (2022) used wavelet packet decomposition to obtain the energy ratio of the lowest

197   frequency band and the highest frequency band, and divided the damage stage of concrete material

198   into three stages. Wang et al. (2018) studied the crack patterns of materials by investigating the

199   portion of the release energy using wavelet packet decomposition and found that the speed of energy

200   release is positively correlated with the frequency of stress wave. It shows that it is effective to

201   analyze the internal energy change of concrete structure by using wavelet packet. Therefore, in order

202   to obtain the analytical model for the relationship between elastic waves and coarse aggregate sizes

203   with different frequencies, and to realize the quantitative analysis and evaluation of the energy ratio

204   of concrete with different coarse aggregate sizes. Wavelet packet analysis of AE waveform received

205   by concrete samples with different frequencies and coarse aggregate sizes is studied.

206   *3.1 Wavelet packet analysis*

207   WPT method can decompose the whole waveform signal according to the set frequency band width,

208   and the data obtained after decomposition can adaptively select the matching frequency band, which

209   can better reflect the energy distribution of the elastic wave in corresponding frequency band.

210   The selection of wavelet function should have some basic properties such as orthogonality, time

211   region and lossless signal reconstruction. The SymletsA wavelet function was proposed by Ingrid

212   Daubechies (Daubechies 2009). SymletsA wavelet function is generally abbreviated as SymN (N=

213   2,3, ... , 8), which has excellent properties in continuity, filter length, support length, symmetry and

214   orthotropy, etc (Zhang et al. 2019) . In addition, Sym8 wavelet basis function can better analyze the

215   localization characteristics of signals when processing digital signals and reduce the distortion of

216   signals in the process of analysis and reconstruction, so the Sym8 wavelet function is used here to

217   process AE signals. Schematic diagram of three-layer wavelet packet process is shown in Figure 4,

218   where S, H and L represent the original signal, the high frequency signal and the low frequency

219   signal, respectively. Every time the original signal S is decomposed by one layer of wavelet packet

220   decomposition, a high frequency signal H and a low frequency signal L obtained. After three-layer

221   of wavelet packet decomposition, 2^3 sub-signals can be obtained, that is, 8 different frequency bands.

222 The maximum decomposition scale "j" is determined according to the sampling frequency (f_s) set

223 by the AE system and the lowest effective frequency (f_{min}) of the AE sensor used. The maximum

224 decomposition scale "j" is calculated from formula 3 (Lv 2021) .

225
$$j \leq log_2 \frac{f_s}{2f_{min}} \tag{3}$$

226 Where f_s represents the sampling frequency setby the AE system during the experiment, 1000 kHz;

227 f_{min} represents the minimum effective frequency of the PK15I AE sensor used during the experiment,

228 80 kHz.

229 After calculation by formula 3, the maximum decomposition scale j=3. Moreover, the setting of

230 frequency band width is closely related to the size of sampling frequency, and the sampling

231 frequency set by the AE system during the test is 1000 kHz. According to Nyquist theorem, the

232 signal excitation frequency must be less than or equal to half of the sampling frequency, so the

233 maximum frequency of AE signals that can be analyzed by the experiment is 500 kHz (Li et al.

234 2012) . The frequencies of AE signals excited by the test are 50, 100 and 150 kHz respectively,

235 which are far less than 500 kHz. Therefore, after AE signals are partitioned by 3-layer wavelet

236 packets, each frequency band width is 62.5 kHz, and the corresponding frequency bandwidth ranges

237 of 8 frequency bands are shown in Table 3.

238 In addition, when selecting the frequency of AE wave, the interface value of bandwidth should be

239 avoided as far as possible. The purpose is to reduce the distortion caused by signal analysis and

240 reconstruction in a certain range when AE signal is decomposed by wavelet packet. Three

241 frequencies of AE wave selected in the study are 50, 100 and 150 kHz.

242 ***3.2 Coarse aggregate size energy difference index***

243 The Energy Difference Index (*EDI*) is defined as the degree of difference between the response

244 energy of the samples of group A to D and the samples of Group E. *EDI* calculation formula was

245 established as showed in formula 4 (Zamorano et al. 2023).

246
$$EDI = \sqrt{\sum_{u=1}^{n} \left(\frac{e_{i,u} - e_{h,u}}{e_{h,u}} \right)^2} \qquad (4)$$

247 where $e_{i,u}$ represents the energy ratio of one of the sub-frequency bands of coarse aggregate size

248 samples in groups A to D, $e_{h,u}$ represents the energy ratio of one of the sub-frequency band of group

249 E with the largest coarse aggregate size, n represents the number of frequency band.

250 After the decomposition of the wavelet packet in group E, the energy ratio of 8 frequency bands is

251 obtained. The energy ratio of each frequency band is recorded as $e_{h,u}$ (u=1, 2, 3, , 8). After the

252 decomposition of group A~D, the energy ratio of 8 frequency bands can also be obtained. The energy

253 ratio of each frequency band is recorded as $e_{i,u}$ (u=1, 2, 3, , 8). The calculation formula is shown

254 in formula 4. *EDI* values represent the essential qualitative relationship of coarse aggregate size by

255 comparing the energy difference between Group A ~ D coarse aggregate size and group E with the

256 largest coarse aggregate size after wavelet packet decomposition. According to formula 4, the larger

257 *EDI* value, the greater energy difference between this group and the largest group E (coarse

258 aggregate size is 26.5-31.5 mm), and the obvious signal change between them. It is worth noting

259 that before calculating *EDI*, for the sake of reducing the effect of noises on the calculate results, the

260 energy ratio corresponding to the 8 frequency bands should be screened, and the energy ratio should

261 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

14

282 size, the energy ratio in Band 2 decreases, while the energy contributions in Band 1 and Band 3

283 increase. It indicates a characteristic of elastic waves transitioning from low to high frequencies and

284 from high to low frequencies within concrete interior. Energy ratio of 8 frequency bands of different

285 coarse aggregate sizes at 150 kHz excitation frequency was shown in Figure 5 (c). With increasing

286 coarse aggregate size, the energy ratio in Band 3 decreases, while that in Band 2 increases, and Band

287 1 shows little change and does not exhibit a clear pattern of variation. It indicates a characteristic of

288 high-to-low frequency transfer of 150 kHz elastic waves within the concrete interior, and the

289 frequency transfer is step by step.

290 However, analyzing the energy distribution across the 8 frequency bands obtained solely from

291 wavelet packet decomposition makes it difficult to quantitatively analyze the relationship between

292 frequency, coarse aggregate size, and elastic waves using a unified standard, so further analysis is

293 needed.

294 *4.2 EDI analysis*

295 Section 4.1 is the analysis of the energy ratio obtained from wavelet packet decomposition. Although

296 the energy ratio of AE signals of samples with different coarse aggregate sizes shows obvious

297 change rules at different frequencies, in order to reveal the essential relationship of elastic waves of

298 different frequencies in the propagation of different coarse aggregate sizes with a unified rule index,

299 the value *EDI*, an index of energy difference of coarse aggregate size, was studied and established.

300 It can effectively characterize the propagation rules of AE signals in concrete, obtain numerical

301 relationship models of different frequencies, different coarse aggregate sizes and AE waveform

302 parameters, and realize quantitative analysis and evaluation of energy ratio of different coarse

303   aggregate sizes. To reduce the influence of noise on the experimental results, we selected frequency

304   bands with relatively concentrated energy ratio (Band 1-3) to calculate the *EDI* value.

305   Figure 6 shows the *EDI* value of different coarse aggregate size specific surface area under three

306   frequencies. The calculation formula is shown in formula 4. It can be seen from Figure 6 that *EDI*

307   values under three frequencies increases with the increase of the specific surface area, indicating a

308   decrease with larger coarse aggregate sizes. Through fitting process of the first order function, three

309   relational models can be obtained to describe *EDI* values of different frequencies and different

310   coarse aggregate size specific surface area:

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

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

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

314   According to the three relational models, *EDI* value shows a linear increasing trend with the increase

315   of specific surface area. This is because the different coarse aggregate sizes and frequencies will

316   both affect the propagation of elastic waves within concrete, resulting in different degrees of

317   redistribution of band energy with changes in coarse aggregate size and frequency. The smaller

318   coarse aggregate size, the larger energy difference between group E, that is, the larger *EDI* value.

319   Three relation models reveal the essential relationship of elastic wave with different frequencies in

320   the propagation of different coarse aggregate sizes by a relatively uniform rule index, which can be

321   used to quantitative analysis and evaluate the energy ratio of different coarse aggregate sizes.

322   Under three different frequencies, the goodness of fit R^2 of *EDI* values for different coarse aggregate

323   sizes is extremely high, almost close to 1, which indicates that *EDI* value is highly correlated with

324   specific surface area. Therefore, it is reasonable to use *EDI* value to quantitatively analyze the

325   influence of coarse aggregate size on AE signal.

326   Three models show that *EDI* values increase linearly with the increase of coarse aggregate sizes

327   specific surface area. From the slope of three relation models, it can be seen that *EDI* values under

328   different frequencies are different. The slopes of the relationship model corresponding to the

329   excitation frequencies of 50, 100 and 150 kHz are 4.2003, 1.6982 and 1.3201, respectively, which

330   shows that the propagation characteristics of AE elastic wave are also different when the damage

331   stage is different (frequency of signal source is different). And it can be inferred that concrete test

332   blocks with different coarse aggregate sizes have different effects on signal sources with different

333   frequencies at different damage stages.

334   By comparing the frequencies of three excitation sources, it can be found that *EDI* values of different

335   coarse aggregate sizes are most affected by elastic wave with AE excitation signal of 50 kHz,

336   followed by 100 kHz, and the least affected is 150 kHz. It shows that the frequency change will

337   effect the propagation of elastic wave within concrete, and the degree of diffraction, refraction,

338   scattering and energy attenuation of AE signals in concrete sample, will increase with the frequency

339   increase. In other words, AE signal of each stage of concrete specimen failure has different

340   attenuation degrees in the concrete interior. During the initial loading stage and approaching failure

341   stage, AE signals are mainly low-frequency signals of 50 kHz. It shows that the AE signals produced

342   by pore compaction, primary crack closure, micro-crack formation and macro-crack formation are

343   greatly affected by coarse aggregate size. At the loading stage, AE signal in the middle frequency

344   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

365 wave within concrete, and the degree of diffraction, refraction, scattering and energy attenuation of

366 AE signals in concrete samples, will increases with the frequency increase.

367 （4）When using the AE system to detect the location of damage sources in concrete, we should

368 consider the frequency of damage sources at different damage stages and effect of coarse aggregate

369 size on the propagation characteristics of AE elastic waves. The algorithm for locating the damage

370 source in the AE system can be optimized by considering the combination of three empirical

371 equations, which can further optimize the location the damage source. In future engineering

372 practices, other types of materials (such as coarse aggregate particle size and cement) can also be

373 evaluated using the specific surface area measurement method we proposed, thereby effectively

374 characterizing the propagation laws of acoustic emission waves within different types of concrete.

375 In addition, other factors that will affect the AE propagation characteristics of elastic waves inside

376 the concrete will also be considered in the study, such as concrete age, temperature, humidity,

377 moisture content, sand rate, and steel reinforcement.

378 Data Availability Statement

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

380 ***request.***

381 **Conflicts of Interest**

382 The authors declare no potential conflicts of interest with respect to the research, authorship, and/or

383 publication of this article.

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508 .

509 **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

510 **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

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

512 **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

513

514   **Fig.1 Five groups of concrete prismatic samples**

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

516   **Fig.3 Schematic diagram of test process**

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

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

520   **Fig.5 (a) 50kHz**

521   **Fig.5 (b) 100kHz**

522   **Fig.5 (c) 150kHz**

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

524   **Fig.6 (a) 50kHz**

525   **Fig.6 (b) 100kHz**

526   **Fig.6 (c) 150kHz**