

Article

Damage Evolution Characteristics of Steel-Fiber-Reinforced Cellular Concrete Based on Acoustic Emission

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Abstract: In order to investigate the steel fiber parameters on the damage characteristics and crack evolution of cellular concrete materials, uniaxial compression–acoustic emission combined tests were carried out on steel-fiber-reinforced cellular concrete (SFRCC) with different steel fiber contents (0%, 0.5%, 1%, 1.5%, and 2%) and different porosities (10% and 20%). The material damage evolution characteristics were analyzed by acoustic emission parameters and IB values, and the crack types were identified using Gaussian mixture clustering method (GMM) pairs. The results show the following: the inclusion of steel fibers increased the compressive strength of cellular concrete by 19.8~46.3% at 10% porosity, and by 37.1~102.2% at 20% porosity; the addition of steel fibers significantly increased the density and intensity of the acoustic emission signals; the decreasing tendency of the IB value at the peak stress slowed down with the increase in the amount of steel fibers, and the steel fibers could effectively inhibit the crack development; crack classification results show that the proportion of shear cracks in all stages of cellular concrete increased significantly after the addition of steel fibers.

Keywords: steel-fiber-reinforced cellular concrete; acoustic emission; IB value; Gaussian mixture model; crack identification; damage characteristics



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1. Introduction

Cellular concrete is a lightweight and porous material composed of cement paste, aggregates, and voids, typically produced by introducing gas into the concrete matrix through mechanical or chemical methods. The unique cellular structure imparts low density and high porosity to the material, enhancing its thermal insulation, noise reduction, and energy absorption properties [1–3]. These characteristics have facilitated its widespread application in areas such as wall insulation, tunnel engineering, and structural damping systems [4–6].

Despite these advantageous properties, the broader application of cellular concrete is restricted by its relatively poor mechanical performance, limited durability, and the complexity of its manufacturing process. To address these challenges, extensive experimental studies have been conducted, revealing that the mechanical properties of cellular concrete are primarily governed by factors such as the cementitious material content, water-to-binder ratio, curing conditions, aggregate gradation, and pore structure characteristics [7–13]. Among these, the water-to-binder ratio has a particularly significant impact. A lower water-to-binder ratio increases the density of the cement matrix, thereby promoting pozzolanic reactions and resulting in the formation of additional C-S-H gel, which enhances strength [8,9]. The inclusion of mineral admixtures, such as silica fume, fly ash, and

rice husk ash, has been shown to improve both the early-age performance and long-term durability of cellular concrete by increasing the cementitious content and reducing the water-to-binder ratio. These admixtures also refine pore size distribution and enhance pore uniformity, thereby improving the material's thermal insulation performance [10,11]. In addition, the use of higher strength aggregates enhances the strength of porous concrete, and the shape of the aggregate also influences the compressive strength since the larger the specific surface area of the aggregate, the more adhesion is created between the aggregate and the cement paste [12,13].

In recent years, the use of lightweight particulate materials (e.g., polystyrene EPS [14,15], expanded perlite [16], super absorbent polymer (SAP) [17], and foam glass particles [18]) to form pores instead of blowing agents has become a desirable option. By using lightweight particles to partially or completely replace aggregates, thus increasing the porosity and improving the lightweight properties of concrete, the shape, size, and homogeneity of pores are stably controlled, and the preparation process is optimized. Deng [17] first proposed the use of spherical SAP to make porous coagulation in 2012 and investigated its mechanical response under quasi-static and high strain rates. The results showed that the porosity had a significant effect on the damage mode, compressive strength, elastic modulus and critical strain. Other studies have found [19] that concrete prepared with water-absorption-saturated SAP slowly releases water during curing and promotes hydration reactions, thereby increasing the strength of the cement paste matrix and further enhancing the overall strength of porous concrete. Thereafter, Zhang [20] replaced part of the cement with silica fume and waste marble powder based on SAP porous concrete and investigated the effects of pore size and porosity of SAP on its compressive, flexural and splitting strengths. Zhang [21] found that SAP porosity in the range of 40% to 60% had a significant effect on the energy dissipation capacity, and the higher the porosity, the better the energy dissipation. The above studies have made some progress in improving the mechanical properties, durability and fabrication process, and provided some novel ideas, but porous concrete still faces low structural strength, which limits its application in fields such as blast and impact resistance and military protection.

In recent decades, steel fibers have been widely used in concrete due to their excellent crack resistance. Steel fibers can significantly improve the mechanical properties and durability of concrete, and can increase the strength and ductility, inhibit the extension of visible cracks, and enhance its post-cracking behavior. Therefore, researchers have incorporated steel fibers into porous concrete to obtain steel-fiber-reinforced composites that combine the characteristics of both. For example, Cao [22] carried out the dynamic strength, impact toughness and damage modes of steel fiber synergistically reinforced cellular concrete (SFSRCC) under uniaxial high strain rate. Wang [23] investigated the compressive and splitting tensile behaviors of cellular concrete with three different shapes of steel fibers—bending, straight-end, and hooked-end—and found that the compressive strength and tensile strength were closely related to the volume fraction and the length-to-diameter ratio of steel fibers, and the straight-end steel fiber reinforcement of cellular concrete is less than end-hooked steel fibers and bent steel fibers. LEE [24] carried out the effect of micro steel fibers on the compression and bending toughness of lightweight aggregate concrete, and pointed out that the addition of 0.25% of micro steel fibers can be better dispersed in the concrete to limit the expansion of cracks, and significantly improve the strength and toughness of compression and bending. The above literature shows that steel-fiber-reinforced porous materials can realize the complementary advantages of different materials. However, there are fewer studies on the microscopic damage mechanism, and further research is still needed.

With the continuous development of non-destructive monitoring technology, acoustic emission (AE) technology provides a means of microscopic damage analysis with unique advantages in damage detection of reinforced concrete structures. The damage evolution of concrete can be inferred by measuring and analyzing the AE signals (AE ringing counts, AE energy, amplitude, rise time, etc.) emitted during the loading process. For example, Anastasios C [25] evaluated the effect of damage caused by fire exposure on the mechanical properties of steel-fiber-reinforced concrete using the variation in parameters such as AE hit rate. Jin [26] classified the AE signals monitored in the early reaction of alkali-activated slag waste brick mortar into three phases of reaction acceleration, reaction stabilization, and volumetric shrinkage through the use of a mechanistic learning approach; Korda [27] performed AE monitoring of concrete and concrete containing SAP in the fresh and hardened phases and showed that higher intensity AE signals could easily distinguish shrinkage cracking, while the signals of settlement, hydration, and internal curing mechanisms overlap the signals more strongly. In terms of concrete damage mechanisms, Ohtsu [28] proposed the use of RA and AF in AE parameters for evaluating the crack damage mechanisms of concrete materials, which were categorized into two types of cracks, tension and shear, by dividing the curves; subsequently, the researchers, based on RA-AF correlation analysis method, introduced Gaussian mixture modeling (GMM) in the mechanical learning to make up for the defect of inconsistent delineation boundaries in the RA-AF method [29–31]; e.g., Li [32] investigated the damage state of recycled concrete under load ratings improved by basalt fibers based on the acoustic emission cluster analysis method, and revealed the effect of basalt fibers on the damage pattern of recycled concrete. Yue [33] used acoustic emission monitoring and mechanical learning algorithms to detect the crack expansion pattern and damage process within the fracture zone of steel fiber concrete under three-point bending test, and proposed a new tensile-plastic damage ontological model for steel fiber concrete based on the relevant results. The above literature shows that the AE technique has significant advantages in the study of concrete material damage; however, the acoustic emission is usually affected by the nature of the material, the service environment, the propagation path and other factors, and the reflected acoustic emission signals contain different forms of information, and there is a lack of research on the microscopic damage of steel-fiber-reinforced porous materials.

In summary, the addition of steel fibers to cellular concrete can make up for the lack of its mechanical properties, but most of the research focuses on its static and dynamic properties and durability, and there are fewer studies on the evolution of AE damage in terms of fine-scale damage, especially fewer studies on the fine-scale study of steel-fiber-reinforced cellular concrete (SFRCC) using SAP as the pore space. Therefore, a total of five groups of SFRCC specimens with different steel fiber contents and two different porosities were fabricated to carry out uniaxial compression and combined with AE counting to study the mechanical properties and crack damage evolution laws of SFRCC materials under static compression. The steel fiber reinforcement mechanism is explained from the fine view aspect by AE parameter analysis, IB value and GMM. Provide theoretical basis for the application of steel fiber porous materials in engineering.

2. Materials and Test Methods

2.1. Sample Materials and Preparation

The specimen components were mainly cementitious materials, aggregates, steel fibers, water, water reducing agent and super absorbent polymer (SAP). The cementitious material is a mixture of PO 42.5 ordinary silicate cement, silica fume and waste marble powder, and the use of silica fume and marble powder to replace part of the cement can significantly improve the mechanical and durability properties of cellular concrete [20], the ratio of the

three is 0.85:0.1:0.05. The coarse aggregate adopts the well-graded basalt crushed stone with a particle size of 2~10 mm, and the fine aggregate adopts the fineness modulus of 2.3 and the maximum particle size of 1 mm river sand; the water is laboratory water. Liquid polycarboxylate superplasticizer (PS) is used to improve the ease of SFRCC, PS water reduction rate of 25%. Steel fibers are used in rows of end-hooked steel fibers, and the physical and mechanical properties are shown in Table 1. Saturated SAP is the use of particle size 1.5~2 mm of dry SAP soaked in 0.75 mol/L NaCl solution for 8 h to prepare, after saturation of SAP with a diameter of 7.5~8 mm. According to the literature [34–36], the optimum steel fiber dosage in steel fiber concrete is 1.0~1.5%, and the optimum dosage in SFRCC is not clear. For porosity, too high porosity will be detrimental to its mechanical properties. Therefore, the volumetric doping of steel fibers was set at 0%, 0.5%, 1%, 1.5%, and 2%, and the porosity was set at 10% and 20%. Table 2 shows the mix proportion of SFRCC, in which the numbers after SAP and S are porosity and steel fiber content, respectively. For example, SAP10S10 is a specimen with porosity of 10% and steel fiber content of 1%.

Table 1. Table of physical and mechanical properties of steel fiber.

Length (mm)	L/D Ratio	Tensile Strength (MPa)	Density (g/cm ³)	Modulus of Elasticity (GPa)
35	70	1250	7.85	200

Table 2. Mix proportions of SFRCC.

	SAP10S ^{0/5/10/15/20}	SAP20S ^{0/5/10/15/20}
Cement	435.9	387.4
Silica fume	51.3	45.6
Waste marble powder	25.6	22.8
Coarse aggregate	725.8	725.8
Sand	695.5	618.3
Water	169.2	150.4
PS	3.5	3.1
SAP	98.8	197.6
Steel fiber	0/39.3/78.6/117.9/157.2	0/39.3/78.6/117.9/157.2

Figure 1 illustrates how to prepare the SFRCC samples. The specific steps are as follows: coarse and fine aggregates, cementitious materials into the mixer, anhydrous mixing dry mixing for 2 min, followed by saturated SAP into the continuation of dry mixing for 1 min; finally, the solution of water and PS fully mixed with steel fibers together with the addition of the continuation of the mix for 3 min; after mixing, the specimens were loaded into standard cube molds in two batches and cured in the room for one day. Subsequently, the specimens were demolded and placed in a standard curing room to a standard age of 28 days.

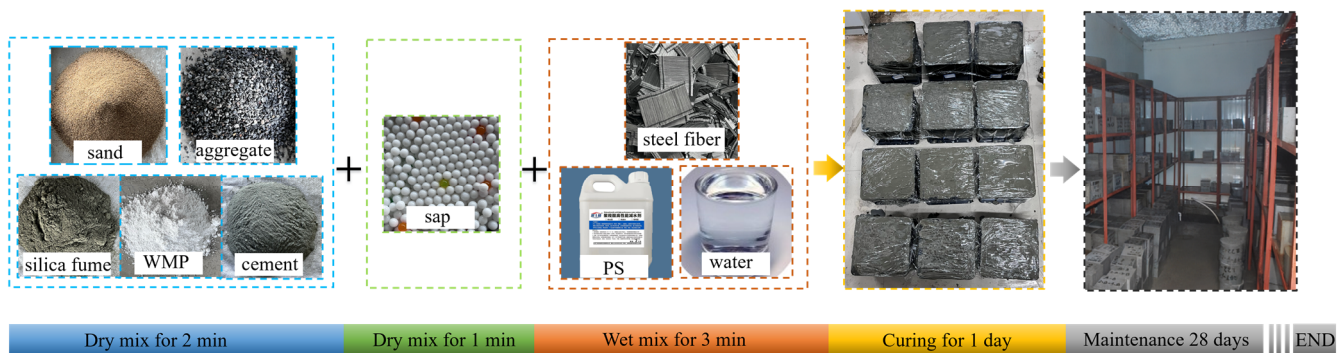


Figure 1. SFRCC raw materials and preparation process.

2.2. Experimental Setup and Testing System

The experimental system used in this study comprised a loading system and an acoustic emission (AE) data acquisition system, as illustrated in Figure 2. A microcomputer-controlled electro-hydraulic servo compression tester model YAW-5000 manufactured by SUNS TECHNOLOGY Company in Shenzhen, China, was used to conduct uniaxial compression tests on the specimens. The tests were conducted under displacement-controlled loading, with a loading rate of 0.5 mm/min. The machine automatically recorded the load–deflection curves and displayed them in real time on the monitor.

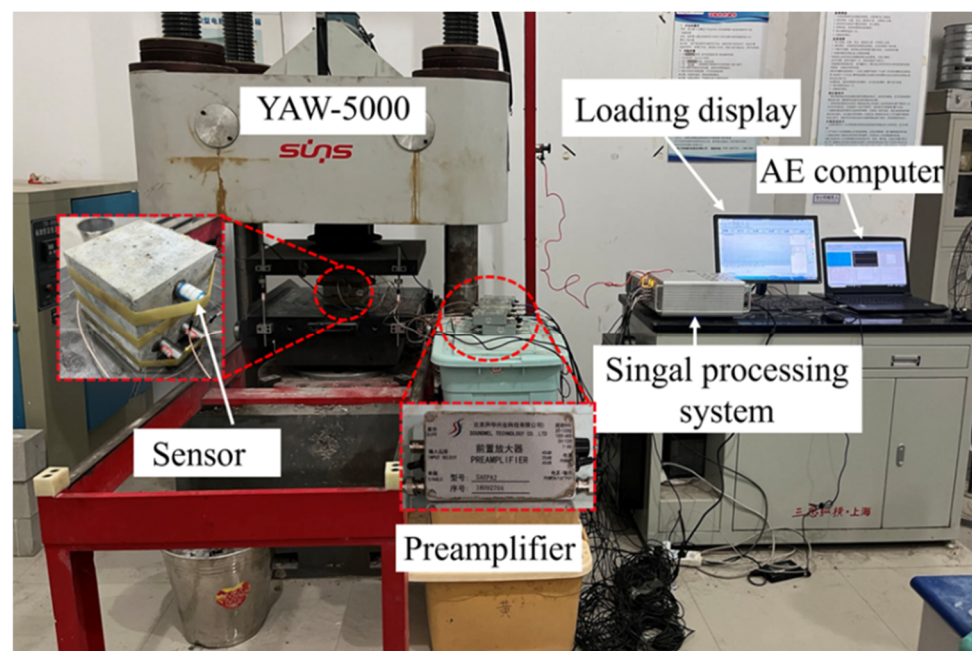


Figure 2. Test setup.

The acoustic emission signals were collected using the SAEU3H acoustic emission system produced by QCAE Company, Guangzhou, China. For three-dimensional localization of AE sources, at least three sensors not located on the same plane are required. In this study, four SR40M sensors were arranged on the surface of the cubic specimens. These sensors operate within a frequency range of 15–70 kHz and have a resonant frequency of 40 kHz. The front-end amplifier sampled signals at a frequency of 1 kHz. To minimize interference from noise generated by the testing machine and other sources during the experiments, the amplifier threshold was set to 40 dB. The amplifier transmitted the amplified signals to a converter, which converted them into digital signals that were subsequently sent to

a computer for recording and analysis of AE parameters. The parameters of AE signals, including amplitude, hit count, and energy, are illustrated in Figure 3.

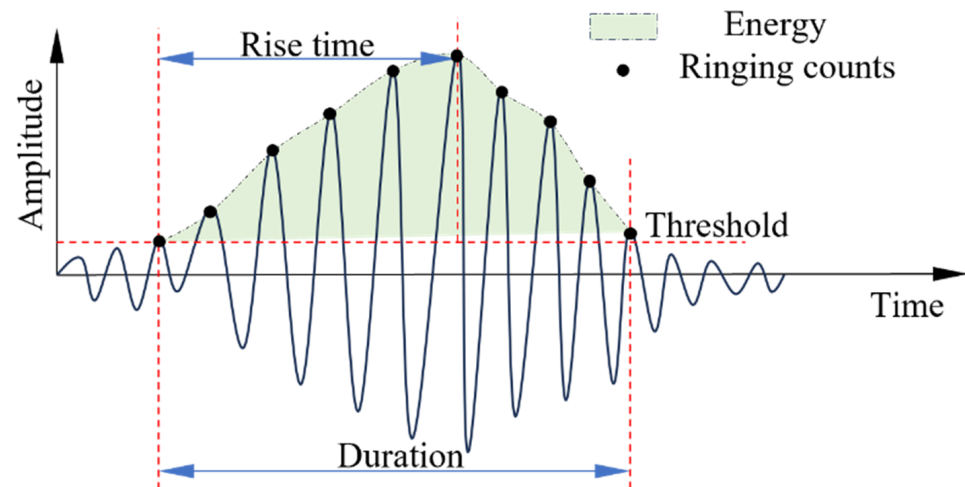


Figure 3. Schematic diagram of AE parameters.

3. Analysis of Results

3.1. Analysis of SFRCC Mechanical Properties

3.1.1. Stress–Strain Curve

The stress–strain curves of SFRCC specimens are shown in Figure 4. As observed in Figure 4a, the stress–strain curve of SAP10S0 exhibits a steeper slope in the initial loading phase compared to the other specimens, indicating that the introduction of steel fibers created more weak interface regions. The internal pores and defects of the specimen lead to greater deformation under the same stress conditions. In the elastic phase, the stress–strain curve of the specimens with steel fibers has a smaller slope compared to SAP10S0, and as the steel fiber content increases, the slope reduction becomes more pronounced. In the post-peak phase, the stress–strain curve of SAP10S0 rapidly drops, displaying obvious brittle failure characteristics. However, the curve for specimens with steel fibers decreases more slowly than that of SAP10S0, and the decrease becomes even more gradual as the steel fiber content increases, demonstrating better ductility.

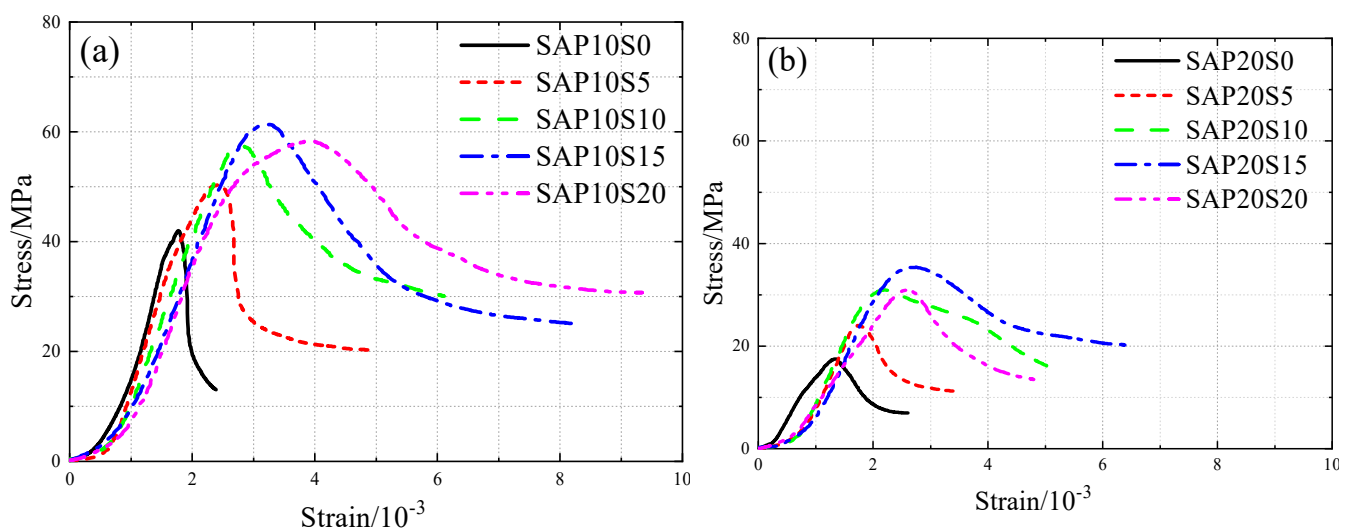


Figure 4. Stress–strain curves of SFRCC specimens: (a) 10% porosity; (b) 20% porosity.

Comparing Figure 4a,b, the stress–strain behavior of cellular concrete with 20% porosity after adding steel fibers is similar to that of the 10% porosity concrete, though the enhancement effect differs. This suggests that adding steel fibers at a volume content of 0.5% to 2% can improve the peak compressive strength, deformation resistance, and ductility of cellular concrete. Excessive steel fiber content may enhance the ductility of concrete but has a limited effect on increasing its strength, which is consistent with the findings of Zhao [37].

3.1.2. Compressive Strength

The results of peak stress and peak strain of SFRCC specimens are shown in Figure 5. As can be seen in Figure 5a, it can be seen that with the increase in steel fiber doping, the peak strength shows a tendency of increasing and then decreasing, while the peak strain increases all the time. Specifically, the average compressive strengths of specimens with 10% pore space and 0.5/1/1.5/2% steel fiber content were 50.26 MPa, 57.36 MPa, 61.40 MPa, and 58.27 MPa, respectively, which were 19.8%, 36.7%, 46.3%, and 38.8% higher than that of SAP10S0 (41.97 MPa); when the porosity is 20%, the compressive strength of SAP20S10/15/20 is 23.99 MPa, 30.93 MPa, 35.37 MPa, and 30.92 MPa, which is 37.1%, 76.8%, 102.2%, and 76.8% higher than the SAP20 compressive strength value of 17.49 MPa. The peak strength first increases and then decreases, to form a three-dimensional spatial system, the distribution of steel fibers is more uniform and bear part of the load, slowing down the formation and expansion of cracks, thus increasing the compressive strength of the specimen. However, with the high dosage of steel fibers, the agglomeration phenomenon between steel fibers retains a part of the air, resulting in a decrease in compressive strength [38,39].

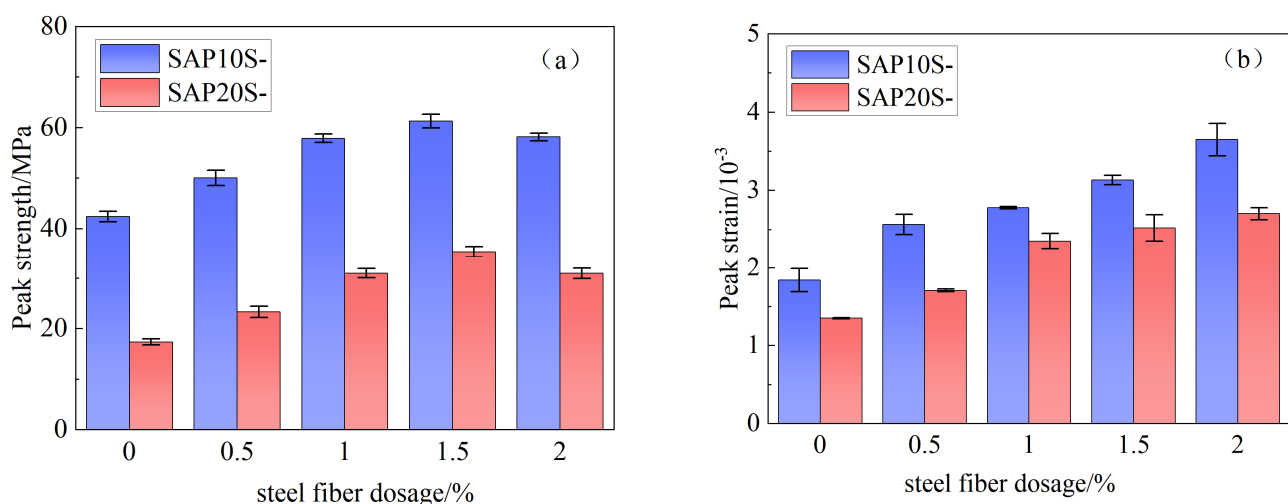


Figure 5. Characteristics of SFRCC specimens: (a) peak strength; (b) peak strain.

For the specimens with a porosity of 20%, the strength of all five groups is lower than that of SAP10S0, indicating that while the addition of steel fibers improves the deformation resistance and ductility of cellular concrete, it cannot fully compensate for the strength loss caused by high porosity. Additionally, as shown in Figure 5b, the peak strain increases with the steel fiber content, indicating that the steel fibers enhance the deformation resistance and ductility of cellular concrete.

3.1.3. Energy Absorption Capacity

The energy absorption capacity (toughness) of concrete under compression is defined as the area under the stress–strain curve at different stress or strain levels. As shown

in Figure 6a, referring to the studies by Zhou [40] and Poon C S [41], the toughness of SFRCC is evaluated using the area under the stress–strain curve at 0.6 times the peak stress during the descending branch. Figure 6b presents the toughness calculation results for each specimen. As expected, the toughness index is significantly dependent on the steel fiber content. As the steel fiber content increases, the overall toughness improves, indicating that SFRCC has a higher energy absorption capacity than cellular concrete. This can be attributed to the crack-resisting effect of the steel fibers during loading. For the same steel fiber content, the toughness decreases with increasing porosity, suggesting that excessive porosity reduces the energy absorbed by the specimen. Furthermore, a regression equation was established based on the experimental results to represent the relationship between steel fiber content and toughness index.

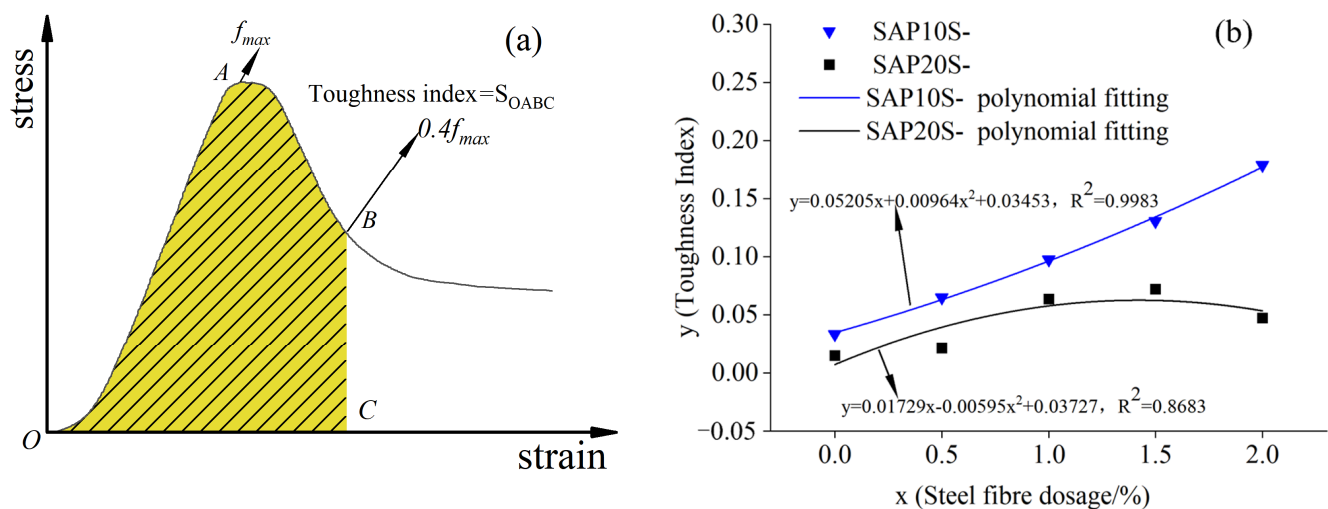


Figure 6. Energy absorption capacity: (a) calculation schematic; (b) toughness calculation results.

3.1.4. Damage Analysis

The uniaxial compression failure results of SFRCC are shown in Figure 7. The failure modes can be classified into two types: splitting and shear. Splitting failure occurs when there is little or no steel fiber content. In cellular concrete, the high porosity leads to a relatively low tensile strength. When local tensile stress exceeds the material's tensile strength, cracks rapidly propagate along the normal direction, connecting the pores and resulting in splitting failure. This is observed in specimens such as SAP10S0/SAP20S0/SAP10S5, where cracks primarily occur in areas of localized tensile stress concentration within the concrete and appear as vertical cracks along the loading direction. Shear failure occurs when the steel fiber content is sufficient. After adding a certain amount of steel fibers, the concrete's tensile strength and resistance to crack propagation are enhanced, making it more difficult for the material to form through cracks under localized tensile stress. The steel fibers convert the stress concentration areas into distributed zones, altering the crack development path and making shear failure the dominant failure mode. This is observed in specimens like SAP10S20/SAP20S20, where cracks no longer concentrate in a single direction but are distributed randomly, leading to a more intact structural failure.



Figure 7. SFRCC compression destruction mode.

3.2. AE Characteristic Parameter Analysis

Acoustic emission (AE) parameters are closely related to the internal damage of concrete specimens. Under the same material and loading conditions, AE characteristics are stable for samples from the same batch. In this experiment, the effects of steel fiber content and porosity on AE parameters were analyzed by comparing SAP10S0/10/15 and SAP20S0/10/15.

3.2.1. AE Ring Count

Figure 8 shows the variation in AE ringing counts in SFRCC specimens. From Figure 8a–c, it can be seen that the addition of steel fibers resulted in a more intensive overall AE activity, especially in stages III and IV, and this phenomenon can also be found by comparing Figure 8d–f. This is due to the weakening of crack connectivity within the concrete matrix, and the interaction between the steel fibers and the matrix leads to the release of more AE signals. Figure 8 shows that the specimen has less acoustic emission activity in the pore compaction stage (I), where cracks start to form due to the compression of the internal pores with the original defects. Entering the crack development stage (II), the AE signal increases significantly per unit time, and the internal damage develops initially, at which time the steel fibers play a bridging role in the crack, transferring the stress from the proximal end of the crack to the distal end, and reducing the stress concentration, at which time the microcracks continue to be generated and continue to develop. In the rapid crack expansion stage (III) and damage stage (IV), due to the continuous increase in load, the local deformation of steel fibers perpendicular or inclined to the crack triggers physical processes such as slipping and pulling out of the ends of the steel fibers, releasing a large number of AE signals.

In addition, comparing Figure 8a–f, it can be found that the total number of AE cumulative ringing counts of 10% porosity SFRCC specimens is larger than the AE cumulative ringing counts of 20% porosity SFRCC specimens, and that higher porosity specimens show less AE activity overall. This is because the acoustic wave emitted during microcrack generation is refracted, reflected and absorbed by the pores during its propagation inside the material, so that its signal strength is gradually weakened, and the more complex internal pore structure of the material has a stronger effect on the signal attenuation, and the pore structure of the 20% porosity specimen makes a part of the attenuated sig-

nal strength less than the threshold value set by the AE probe, thus reducing the AE events [42–44].

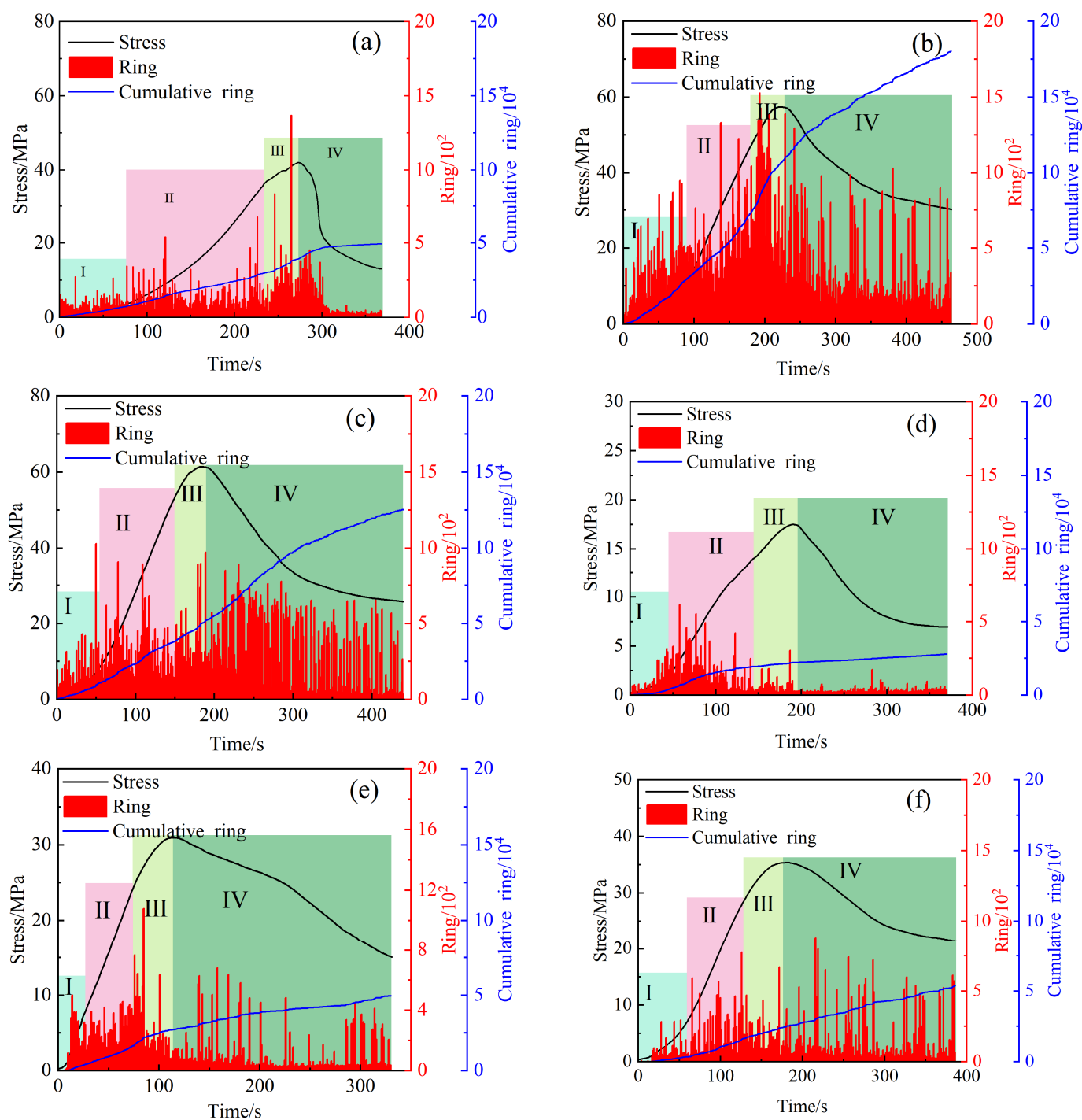


Figure 8. SFRCC AE ringing count variation graph. (a) SAP10S0; (b) SAP10S10; (c) SAP10S15; (d) SAP20S0; (e) SAP20S10; (f) SAP20S15.

3.2.2. Energy

AE energy is another important indicator for assessing the degree of damage during the loading process. It reflects the intensity of AE activity and is roughly proportional to the size of the cracks. Figure 9 shows the variation in energy, cumulative energy, and stress over time. From Figure 9, it is evident that there is a strong correlation between AE energy and AE ring count. High energy values in a unit time correspond to regions

with dense ring counts. This is because each AE signal is associated with an energy value, and when the ring count increases within a unit time, the energy typically increases as well.

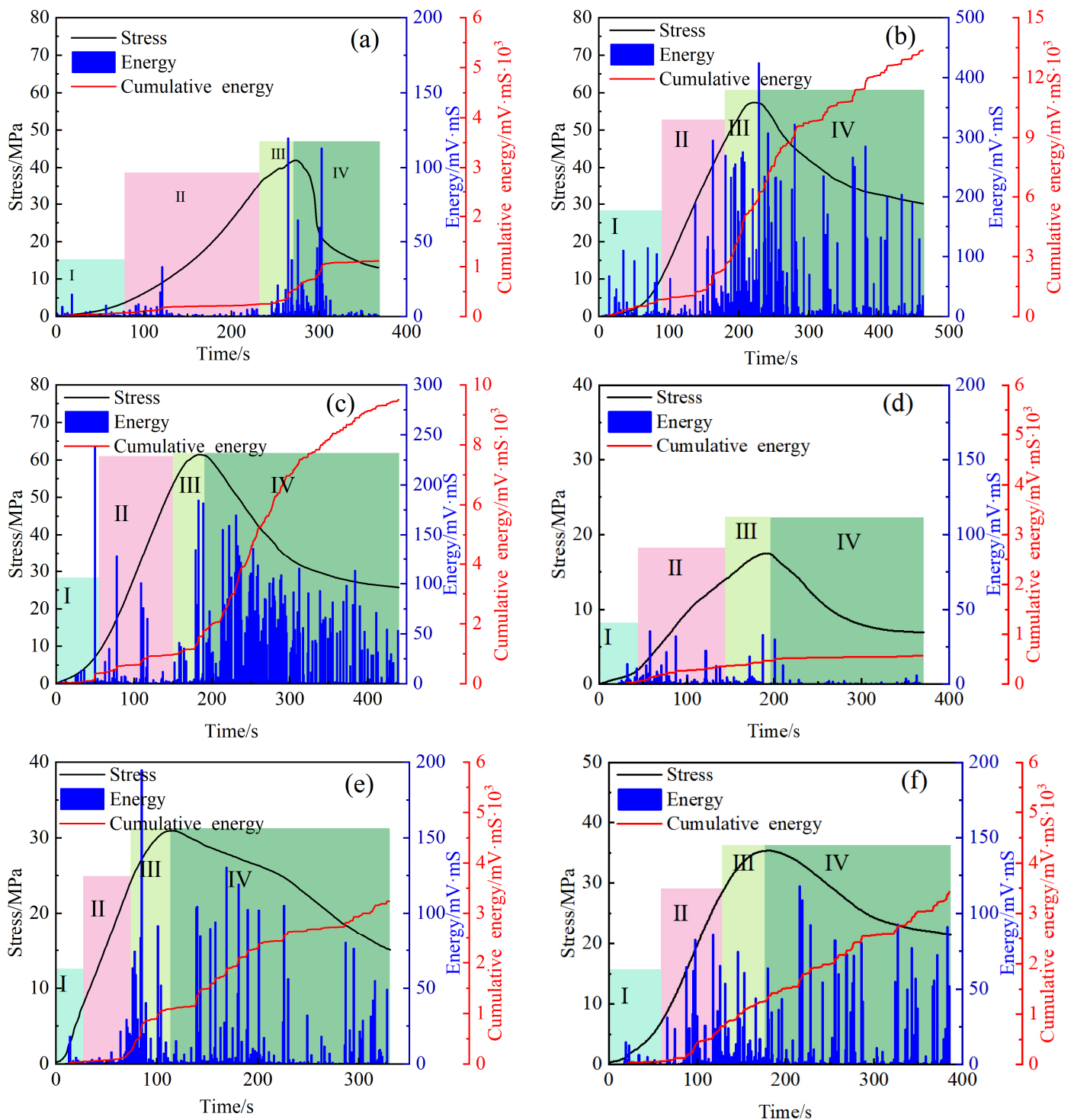


Figure 9. SFRCC AE energy variation plot. (a) SAP10S0; (b) SAP10S10; (c) SAP10S15; (d) SAP20S0; (e) SAP20S10; (f) SAP20S15.

For cellular concrete specimens (SAP10S0 and SAP20S0), the cumulative energy curve grows minimally before the peak stress, then sharply increases after the peak stress, accompanied by high-density energy activity. This indicates that, in the absence of steel fibers, the main fractures inside the specimen occur at the peak stress, where internal

cracks propagate along the aggregates and merge into macroscopic cracks, showing clear brittle failure characteristics. After the addition of steel fibers, the energy density in stages I and II is significantly higher than that of the cellular concrete, but still lower than in stages III and IV. This suggests that the contribution of steel fibers is relatively small during stages I and II [45], with their bridging and toughening effects becoming more pronounced as cracks continue to expand and open (i.e., stages III and IV). In stages III and IV, steel fibers dissipate a substantial amount of energy through mechanisms such as local bending, stretching, and sliding. According to KJ Trainor's [46] research, the energy dissipation in this stage can account for 35% to 48% of the total dissipated energy.

3.2.3. IB Value

The IB-value method was developed from the b-value method in the field of seismology because the acoustic emission phenomenon in concrete materials has a similar mechanism to seismic waves and the frequency and amplitude distributions of the acoustic emission signals are in accordance with the Gutenberg–Richter [47] formula in seismology, and therefore, the IB-value has been widely used to assess the damage and rupture of rock and concrete structures. The principle is that in the energy release within the material, microcracks produce low amplitude signals, while macro cracks are accompanied by high amplitude signals, the IB value is calculated by analyzing the distribution of the AE amplitude to reflect the cyclic process of crack development and expansion. The formula of the IB value is shown in Equation (1):

$$IB = \frac{\log_{10} N(\mu - \alpha_1 \sigma) - \log_{10} N(\mu + \alpha_2 \sigma)}{(\alpha_1 + \alpha_2) \sigma} \quad (1)$$

where N is a segment of the acoustic emission signal for which the IB value is calculated; μ and σ are the standard deviation and mean of the amplitude distribution of a segment of the acoustic emission signal; α_1, α_2 is a constant that depends on the amplitude distribution of the AE events; $N(\mu - \alpha_1 \sigma)$ is the number of events with amplitude greater than $\mu - \alpha_1 \sigma$; and $N(\mu + \alpha_2 \sigma)$ is the number of events with amplitude greater than $\mu + \alpha_2 \sigma$.

The IB value curves of the SFRCC specimens are shown in Figure 10. As can be seen in Figure 10a–c, the IB values of the specimens have an obvious decreasing trend at the peak load, indicating that macroscopic cracks appear in the specimens at this time, which corresponds to the energy changes in Figures 8 and 9. After the addition of steel fibers, the overall fluctuation of IB value decreases with the increase in steel fiber content, which is because steel fibers inhibit the generation of many macroscopic cracks, and the inhibition effect is more significant with the increase in its content, and this phenomenon is consistent with the failure damage mode of the specimen. Similar conclusions were reached in the studies of Tang [48] and Jiao [49]. In addition, at 20% porosity, the trend of IB value after adding steel fibers is more gentle than that of 10% porosity specimens, indicating that the inhibition effect of steel fibers on crack extension is more significant at higher porosity.

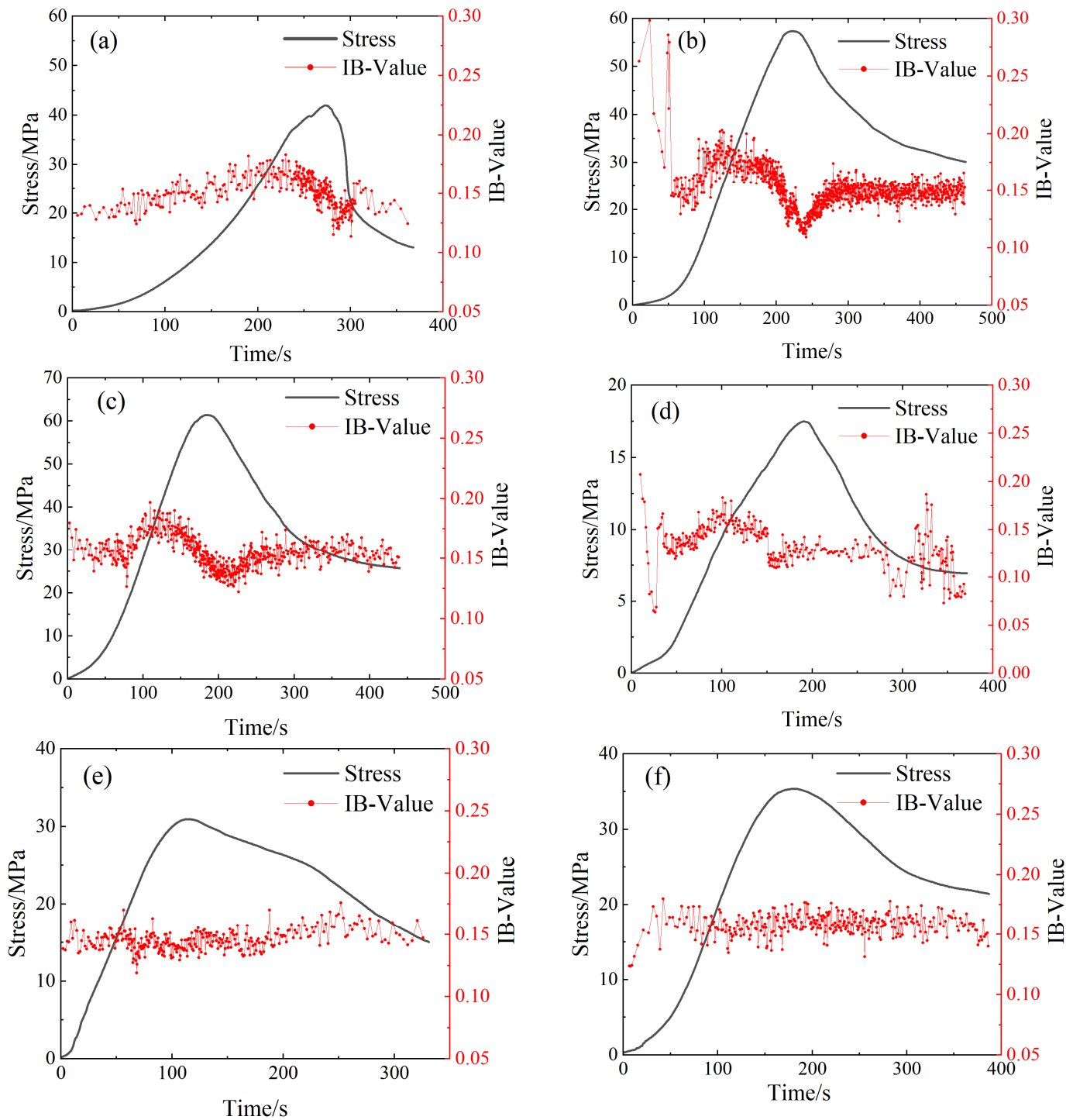


Figure 10. Plot of changes in SFRCC compression IB values. (a) SAP10S0; (b) SAP10S10; (c) SAP10S15; (d) SAP20S0; (e) SAP20S5; (f) SAP20S10.

3.2.4. AE Location

The localization points in Figures 11 and 12 are calculated based on the Geiger time-difference localization method of the AE system. In brief, the 3D position is inverted from the position of the rupture source by the time difference in the arrival of the P-wave received by the sensor, and the phases are segmented by the time of appearance of the localization points, which corresponds to the phases in Figures 8 and 9.

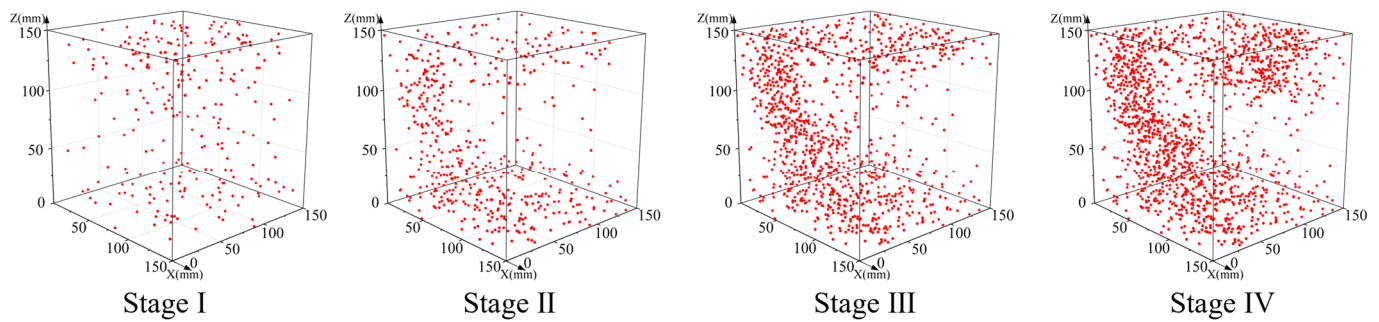


Figure 11. SAP10S0 compression damage location map.

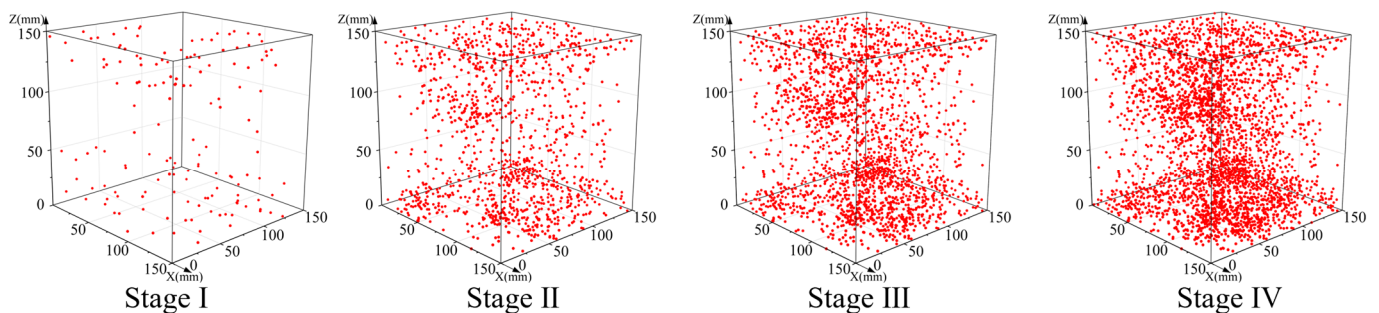


Figure 12. SAP10S10 compression damage location map.

The uniaxial compression damage localization maps for the SAP10S0 and SAP10S15 specimens are shown in Figures 11 and 12. From the analysis, it can be seen that SAP10S15 exhibits more damage localization points in the initial stage compared to SAP10S0. This may be due to the introduction of initial damage by the steel fibers. As cracks develop, in Stage II, a clustering phenomenon is observed, with SAP10S15 showing more damage points. This is because the steel fibers help organize crack propagation and promote the redistribution of internal stresses, resulting in more micro-damage localization points [50]. In Stage III, for the SAP10S10 specimen, clustering points are observed along the diagonal, indicating the formation of longer cracks. For the SAP10S15 specimen, the three-dimensional steel fiber network structure leads to more micro-damage points. This could be due to local tensile stresses causing some steel fiber tips to detach, leading to more damage points at the internal interfaces. This phenomenon is more pronounced in Stage IV. By comparing Figures 11 and 12, it is evident that steel fibers prevent large cracks, promoting the redistribution of internal stresses and enhancing the toughness of the concrete as well as crack propagation. Specifically, the damage localization points in cellular concrete are more concentrated, while SFRCC exhibits more uniformly distributed damage points.

4. SFRCC Materials Crack Identification

4.1. GMM Clustering Principle

The AE characteristics are associated with the cracking mode of concrete members, where tensile cracking due to pure tensile stress occurs in the early stage of loading, while shear cracking occurs in the later stage of loading, i.e., the cracking mode of the material usually changes from tensile mode to shear mode when damage is about to occur. Therefore, the use of AE to monitor the type of cracking can determine the stress stage at which the material is located, which is of great engineering significance for the structure for early warning of cracking.

Gaussian mixture model (GMM) is a widely used clustering algorithm in machine learning, which has been applied in many fields such as concrete crack recognition, image segmentation, speech recognition, pattern recognition and anomaly detection, etc. GMM is a clustering method based on a probabilistic model, which can be regarded as a combination of multiple Gaussian distributions, and each Gaussian distribution corresponds to a different parameter. In the algorithm of GMM, the received AE signal $X = \{x_1, x_2, \dots, x_K\}$ is weighted by K Gaussian-based probability densities, defined as in Equation (2):

$$P(x) = \sum_{k=1}^K \pi_k N(x_k | \mu_k, \sigma_k) \quad (2)$$

where $N(x_k | \mu_k, \sigma_k)$ denotes the single Gaussian distribution function, x_k is the sample vector, μ_k is the mean, σ_k is the variance, and π_k is the weighting coefficient between individual single Gaussians and satisfies $\sum_{k=1}^K \pi_k = 1$.

In order to be able to determine which Gaussian distribution any AE signal belongs to, the probability of assigning the sample points to the respective Gaussian model they belong to is obtained by multiplying the probabilities, and the maximum product is considered to be consistent with the clustering result, i.e., the maximum likelihood (ML) criterion. The ML criterion can be obtained from the maximum likelihood parameter by Expectation Maximization (EM) to obtain the maximum likelihood parameter. The steps of the EM algorithm are as follows:

- (1): Set the initial values of the parameters π_k, μ_k, σ_k , and compute the log-likelihood function $\ln P(x | \pi, \mu, \sigma)$ and the posterior probability γ_{jk} .
- (2): Update the computation of π_k, μ_k, σ_k according to the posterior probability γ_{jk} .
- (3): Recalculate the log-likelihood function $\ln P(x | \pi, \mu, \sigma)$ according to the updated parameter π_k, μ_k, σ_k , and check whether the log-likelihood function converges (1×10^{-5}); if it converges, end the computation; if it does not converge, repeat step (2).

$$\ln P(x | \pi, \mu, \sigma) = \sum_{k=1}^K \ln \left\{ \sum_{k=1}^K \pi_k N(x_k | \mu_k, \sigma_k) \right\} \quad (3)$$

$$\gamma_{jk} = P(z = k, y_j | \mu, \sigma) = \frac{P(z = k, y_j | \mu, \sigma)}{\sum_{k=1}^K P(z = k, y_j | \mu, \sigma)} = \frac{\pi_k N(y_j | \mu_k, \sigma_k)}{\sum_{k=1}^K \pi_k N(y_j | \mu_k, \sigma_k)} \quad (4)$$

$$\mu_k = \left(\sum_{j=1}^K \gamma_{jk} y_j \right) / \left(\sum_{j=1}^K \gamma_{jk} \right) \quad (5)$$

$$\sigma_k^2 = \left(\sum_{j=1}^K \gamma_{jk} (y_j - \mu_k)^2 \right) / \left(\sum_{j=1}^K \gamma_{jk} \right) \quad (6)$$

$$\pi_k = \sum_{j=1}^K \frac{\gamma_{jk}}{K} \quad (7)$$

4.2. Crack Damage Evolution Law

According to the principle of crack clustering identification in Section 4.1, use MATLAB version 2021a to write a GMM cluster analysis program to identify the clusters of AE data. Figure 13 shows the crack clustering diagram of the SAP10S0 specimen at each stage; from left to right in Figure 13 are the three-dimensional density map of the a posteriori probability of cracks, two-dimensional density map and crack classification results map, in which the red area of the three-dimensional and two-dimensional density maps indicates

higher probability density, and the blue area indicates lower probability density, and the right hand side of the crack classification results map shows that the RA value of tension cracks is mainly distributed in the range of 0~1.5 ms/v. The right side of the crack classification results shows that the RA values of the tension cracks are mainly distributed in the range of 0~1.5 ms/v, and are distributed nearly vertically, and the RA values of the shear cracks are distributed in the range of 1.5~8 ms/v, located in the lower right side of the tension cracks as a whole, and are dispersed in the distribution; the results of the tension and shear cracks of the rest of the specimens are plotted in Figures 14 and 15.

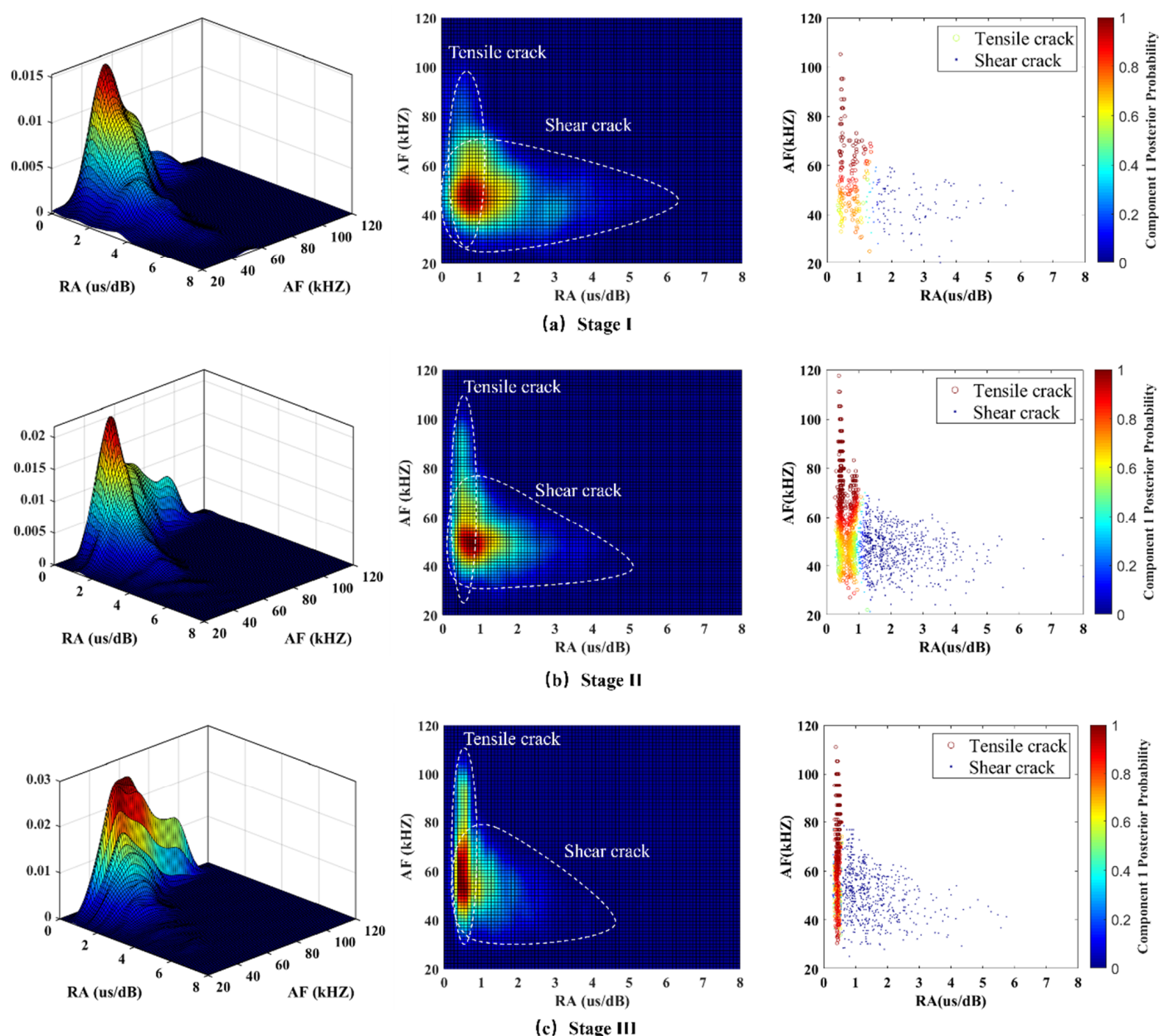


Figure 13. *Cont.*

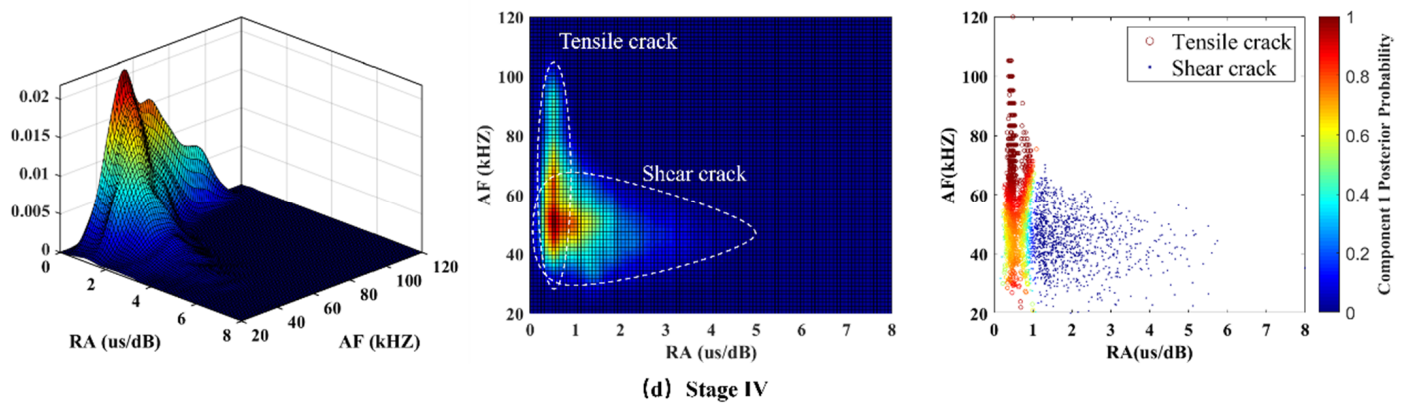


Figure 13. SAP10S0 specimen GMM classification results. (a) Stage I; (b) Stage II; (c) Stage III; (d) Stage IV.

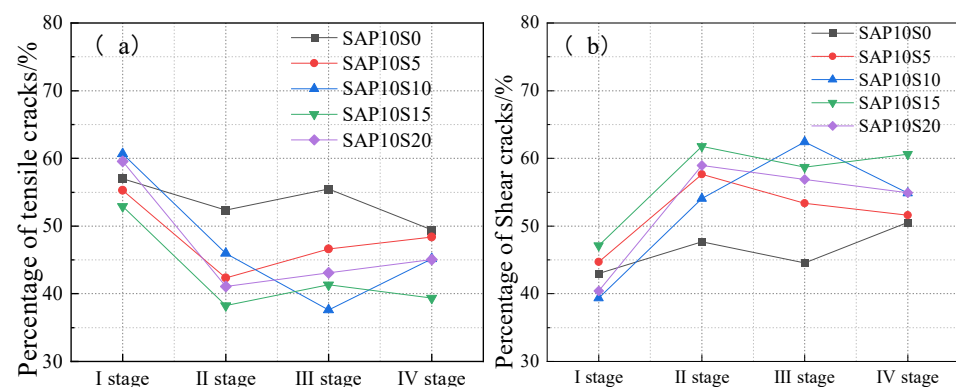


Figure 14. Percentage cracking of SFRCC specimens with 10% porosity: (a) crack shear; (b) tensile crack.

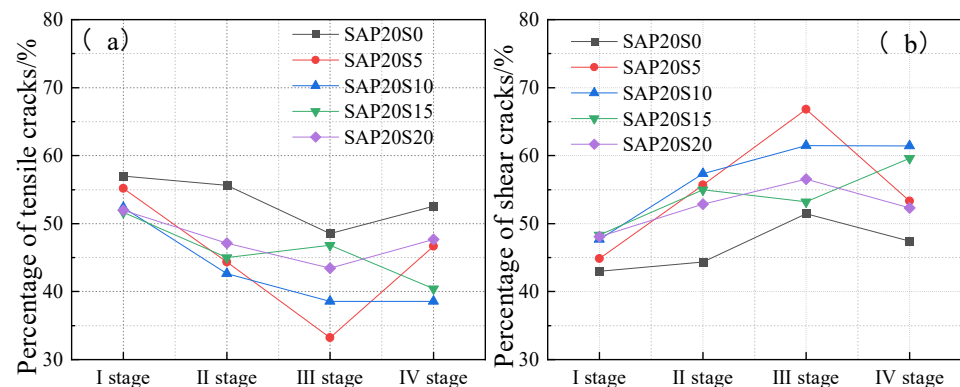


Figure 15. Percentage cracking of SFRCC specimens with 20% porosity: (a) crack shear; (b) tensile crack.

The crack classification results of SFRCC specimens at each stage are shown in Figures 12 and 13. For cellular concrete with different porosities (10% and 20%), the percentage of shear cracks increased at all stages with the addition of steel fibers, and the overall trend of shear crack percentage increased with time. In stage I, the shear crack percentage of all specimens was below 50%, indicating that the cracks were dominated by tensile cracks in this stage. In stage II, the shear crack percentage of SFRCC specimens is significantly higher than that of ordinary cellular concrete, indicating that the cracks gradually transition from tensile to shear in this stage, and the addition of steel fibers accelerates and strengthens this transition process, and shear cracks begin to dominate; in stages III and IV, the shear

crack percentage of SFRCC specimens continues to maintain a high level, and at this time, the specimens mainly focus on the shear cracks until the structure of the specimens is completely destroyed. The specimen structure was completely destroyed. The introduction of steel fibers significantly reduced the proportion of tension cracks within the concrete, while increasing the proportion of shear cracks. The presence of steel fibers replaced single cracks that were easily penetrated by more microcracks and introduced the physical mechanism of shear slip of steel fibers, which altered the crack propagation pattern and enhanced the structural performance.

5. Discussion

As shown in Figure 16a, the addition of steel fibers in the SFRCC can be regarded as a four-phase system of aggregate, mortar, steel fibers and interfacial transition zone, in which the interfacial transition zone where steel fibers and mortar are combined is weaker compared with aggregate and mortar, and thus is prone to being damaged preferentially under the action of loading. Due to the high toughness and tensile strength of steel fibers, crack expansion to the steel fiber–mortar interface transition zone first formed the so-called “pseudo-debonding” crack segments [51]. At this time, the AE signal is characterized by a low amplitude, low frequency, and short duration, mainly occurring in the crack tip of the tensile stress concentration. With the increase in load, the steel fiber bridging cracks will be subjected to pullout force, shear stress, and positive stress, of which the composition of positive and shear stresses are chemical adhesive force, friction force, and mechanical occlusion force (Figure 16b), and at this time, the crack expansion process needs to continually overcome the adhesive bond between the steel fibers and mortar, which leads to friction and slippage of the steel fibers and the substrate jointing surface until the bond at the union loosens and completely fails. During this process, a high amplitude, medium to high frequency, and long duration shear-type AE signal is released, which becomes more pronounced as the load increases. As the stress continues to grow, cracks penetrate through the aggregate and matrix, forming through cracks.

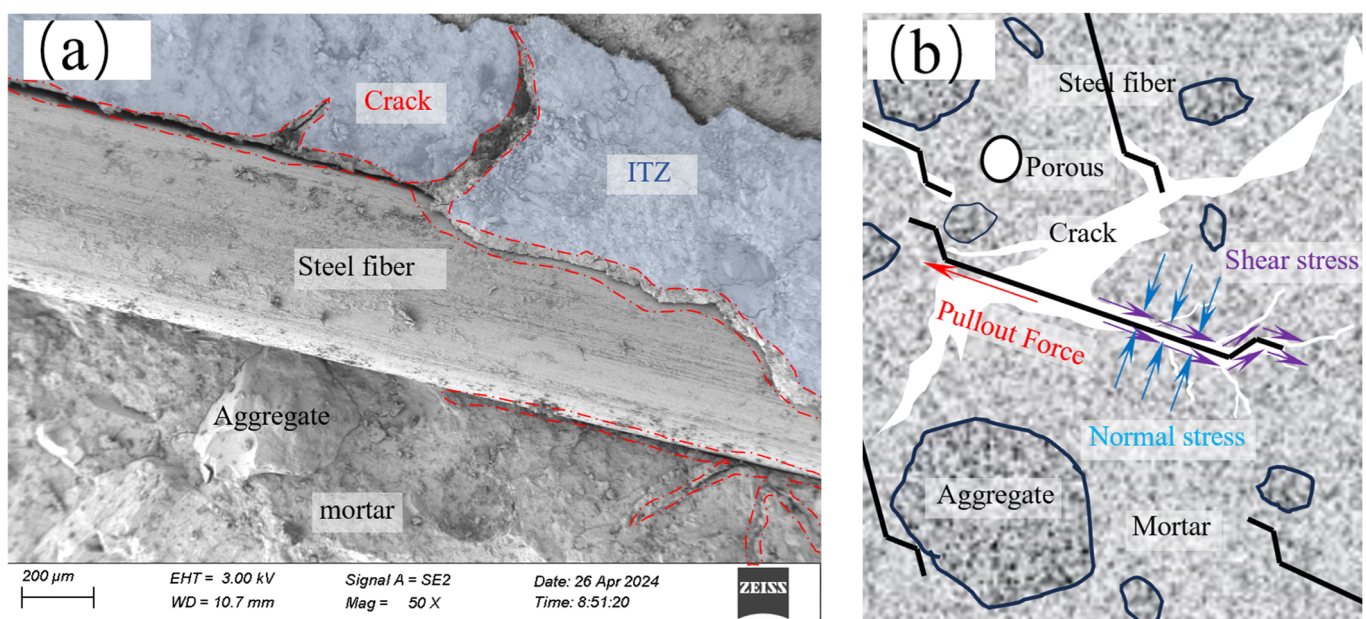


Figure 16. (a) SFRCCC electron micrograph; (b) schematic diagram of SFRCCC bridge cracking action.

In the GMM crack classification results, the incorporation of steel fibers increases the proportion of shear cracks within the porous concrete and macroscopically exhibits the shear damage characteristics of fragmentation but not dispersion. From an engineering application point of view, shear damage is more advantageous than tension damage because it is less prone to sudden breakage or fragmentation, and the material is more likely to retard crack extension by absorbing energy and undergoing mitigation mechanisms such as slip and friction. This ductility improves the resistance of the structure to damage under extreme loads (e.g., seismic or impact loads), and its structure degrades gradually rather than fails suddenly, which facilitates monitoring and maintenance and improves the safety of the structure.

6. Conclusions

In this paper, the mechanical properties and AE damage evolution law of SFRCC by steel fiber admixture and porosity were investigated, and the crack transformation law of SFRCC at each stage was studied in combination with GMM for crack classification, and the main conclusions are as follows:

(1) The brittleness, compressive strength, ductility, and deformation resistance are significantly improved after adding steel fibers in cellular concrete; the peak strength of SFRCC shows the law of increasing and then decreasing with the increase in steel fiber dosage, and the optimal dosage is 1.5%; the strength of SFRCC with 20% porosity is lower than that of SAP10S0, which indicates that steel fibers in the case of high porosity cannot completely compensate for the strength brought by the porosity loss.

(2) According to the AE signal parameter, the failure process of SFRCC was divided into four stages: pore compaction, stable crack development, rapid crack expansion, and post-peak damage; the addition of steel fibers in cellular concrete significantly increased the AE signal activity, and the pulling action of steel fibers led to an increase in the AE activity, which was more pronounced in the stages III and IV.

(3) The decrease in specimen IB values at load corresponds to the appearance of macroscopic cracks in the specimens; the range of fluctuation of IB in 20% porosity SFRCC specimens is weakened, indicating that the inhibitory effect of steel fibers on the crack extension is more significant at higher porosities.

(4) The RA values of tension cracks were mainly distributed in the range of 0–1.5 ms/v, and those of shear cracks were distributed in the range of 1.5–8 ms/v; the addition of steel fibers to cellular concrete resulted in a larger proportion of shear cracks than that of cellular concrete at all stages of the specimen, and the addition of steel fibers increased the proportion of internal shear cracks.

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