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Abstract: This article introduces a kind of composite material made of kapok fibre and polycaprolactone by the hot-pressing method. The effects of volume density, mass fraction of kapok fibre, and thickness on the sound-absorption performance of composites were researched using a singlefactor experiment. The sound-absorption performance of the composites was investigated by the transfer function method. Under the optimal process parameters, when the density of the composite material was 0.172 g/cm<sup>3</sup>, the mass fraction of kapok was 40%, and the thickness was 2 cm, the composite material reached the maximum sound-absorption coefficient of 0.830, and when the sound-absorption frequency was 6300 Hz, the average sound-absorption coefficient was 0.520, and the sound-absorption band was wide. This research used the box dimension method to calculate composites' fractal dimensions by using the Matlab program based on the fractal theory. It analysed the relationships between fractal dimension and volume density, fractal dimension and mass fraction of kapok fibre, and fractal dimension and thickness. The quantitative relations between fractal dimension and maximum sound-absorption coefficient, fractal dimension, and resonant sound-absorption frequency were derived, which provided a theoretical basis for studying sound-absorption performance. The results showed that kapok fibre/polycaprolactone composites had strong fractal characteristics, which had important guiding significance for the sound-absorption performance of kapok fibre composites.

**Keywords:** kapok fibre; polycaprolactone; composite materials; sound-absorption performance; fractal dimension

## 1. Introduction

Noise pollution belongs to one kind of environmental pollution, which is regarded as one of four major environmental problems in the world together with water pollution, air pollution, and light pollution. Noise pollution causes people's mood level and sleep quality to decline, and continues to slowly affect the human body system and increase the incidence of various diseases, even to a life-threatening level [1]. Secondly, noise will also accelerate the aging rate of conveyor belts, gears, bolts, and other mechanical structures, thus affecting the accuracy and service life of instruments and equipment, seriously affecting the safety of a building [2]. More and more scholars focus on developing environmentally friendly sound-absorbing materials and striving to improve their sound-absorption performance in recent years.

Lignocellulose insulation materials, natural materials, and recycled materials have been widely used in the field of sound-absorption in recent years. Tudor et al. [3] studied the sound-absorption coefficient of bark insulation board made of cork bark spruce and larch. The results showed that cork bark was an underrated material, and that compared with wood-based composites, engineered spruce bark was even better at absorbing sound than MDF, particleboard, or oriented particleboard. Tudor et al. [4] also analysed the acoustic performance of bark boards and found that the optimal density of bark boards



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to obtain the best sound-absorption coefficient was about  $350 \text{ kg/m}^3$ , and that these lightweight panels achieved better sound-absorption performance at a higher thickness (especially at lower frequencies). Smardzewski et al. [5] determined the normal surface impedance and sound-absorption coefficient of several woods from Europe and tropical regions, and the results showed that oak, ash, sapele, and pine had the highest soundabsorption coefficient at the frequency of 2 kHz. Asdrubali et al. [6] studied the acoustic properties of sustainable materials and found that sustainable products made from natural and recycled materials are effective substitutes for traditional synthetic materials. Fouladi et al. [7] used fresh coconut shell fibres and industrially prepared coconut shell fibres with an added binder as raw materials to study the sound-absorption coefficients of the two fibres as porous materials. The results showed that the industrially prepared fibres had poorer sound-absorption performance at low frequencies than fresh coconut shell fibres due to the addition of the binder. For commercial use, however, fibres must be mixed with additives to enhance properties such as hardness, antifungal, and flammability. Therefore, methods such as increasing air gaps or perforating plates should be used to improve the acoustic properties of industrially treated coconut shell fibres.

According to its formation mechanism and structure, porous sound-absorption materials can be divided into fibrous sound-absorption materials, granular sound-absorption materials, and foam plastic plates. When sound waves penetrate the surface of porous materials, the sound waves cause the vibration of the object, and then cause the vibration of the pores and gases inside the material. A large part of the sound energy can be consumed by the motion between the sound waves and the pore walls, and the transmission of sound waves is reduced due to the friction effect and viscous effect. The transmitting sound wave is weakened, thus achieving the purpose of sound insulation and absorption. At the same time, due to the different temperature of the pore wall and the small hole of the material, the gas will flow to realise heat exchange, and then lead to the loss of heat, resulting in the reduction in sound energy, to achieve the purpose of sound absorption. In addition, because of the influence of the frequency and friction of high frequency sound waves, the vibration speed of air particles will become faster, and then improve the speed of heat exchange; therefore, porous materials can achieve good sound-absorption effect in the range of high frequency sound waves.

Sound-absorbing materials have a wide range of application prospects, but the traditional sound-absorbing materials have many shortcomings, such as short service life, secondary pollution, performance instability, and so on. The emergence of new soundabsorbing materials makes up for the deficiency of traditional sound-absorbing materials to some extent [8]. Compared with traditional fibre sound-absorption materials, the soundabsorption coefficient of fibre sound-absorption composite materials is greatly improved, and many of them can reach more than 0.8, which makes up for the limitation of traditional fibre sound-absorption materials in the application range, to a large extent. Moreover, fibrous composites have less impact on the environment than conventional materials, generally have lower overall energy requirements for manufacturing and installing these materials, and are less harmful to human health. Replacing traditional sound-absorption materials with fibre composites has a significant impact on all phases of the building life cycle (construction, operation, end of life) [9].

Kapok fibre is a single cell fibre with a smooth surface, cylindrical shape, and no torsion. As a natural cellulose fibre, it is biodegradable and recyclable [10]. Due to its advantages such as softness, high hollow rate, anti-bacterial, and anti-mite, it has attracted extensive attention and has a good development prospect in the textile field [11]. Kapok is a kind of natural fibre, which has excellent sound-absorption performance due to its high degree of emptiness and small fibre diameter [12]. Because kapok fibre belongs to the short fibre category and is affected by its hollow structure, fibre strength is low, and has weak adhesion and poor elasticity; therefore, the technical difficulty of single spinning kapok yarn is high, and the application of economic benefits in textile and clothing is poor [13]. The large hollow structure of kapok fibre can be well utilised by making it into sound-

absorbing composite material, which has low technical requirements and high economic benefits. The research and development of kapok fibre products can not only reduce the over-dependence on oil and other non-renewable resources, but also respond to the national strategic goal of ecological environment protection and sustainable development [14].

Dresden Technical University in Germany [15] focused on the study of kapok fibre and wool fibre. By comparing their differences in heat insulation and sound insulation, it was finally concluded that kapok fibre material had better heat insulation and sound insulation performance than wool fibre material. Liu et al. [16] developed a sound-absorbing nonwoven composite material based on kapok fibre and hollow polyester fibre, and used the impedance tube method to study the sound-absorbing performance of kapok fibre nonwoven composite material in the low-frequency region of 100–500 Hz. Makki et al. [17] studied the sound-absorption properties of nonwoven, layered warp knitting, and layered double-layer fabric made of kapok fibre at frequencies from 100 to 5000 Hz. The results showed that the best sound-absorption effect was obtained by combining kapok nonwovens with double-layer fabric with a thickness of 11.25 mm. Azieyanti et al. [18] prepared reinforced polypropylene composites using jute and kapok fibres as raw materials and compared jute and kapok fibre-reinforced polypropylene sound insulation effect composites; the results showed that the performance of the composite material, along with the increase in the quality percentage of jute and kapok fibre, increased the filling amount to 30% when the performance of the composite material was best. Liu [19] used polyethene film to fabricate the kapok fibre nonwoven fabric. The research on the sound-absorption coefficient and specific surface impedance of composite materials in the frequency range of 100–2500 Hz was carried out using the impedance tube method. The results showed that the multilayer composite had better sound-absorption performance than the single-layer non-woven fabric at low frequency.

A fractal is defined as a mathematical object with a fraction (not an integer) dimension. In the 1990s, Yu proposed a method to determine the effective thermal conductivity of reinforced fibre materials and irregular porous materials, that is, the fractal theory method, but in the research process, the calculation method and process were too complex to be applied in practice. In 2001, Yu conducted another study on fractal calculation methods and published a paper [20] in which it was pointed out that the fractal characteristics of porous media could be described by a general model. Chen's [21] use of fluid science, fractal theory, the study of space structure of the fibre porous metal processing, the fractal model of flow resistance rate, and the effectiveness of the proposed model was verified by experiment, which showed that the fractal model could intuitively reflect the relationship between the geometric parameters and flow resistance rate of material. In order to design fibre-porous metal, sound-absorbing material provides a theoretical support. According to the heat conduction model of down fibre aggregate, Fu [22] calculated the fractal dimension of hollow polyester fibre under different volume fractions by the box-counting method and calculated the heat transfer coefficient of the aggregate. The predicted value calculated by the model was in good agreement with the measured value, which proved that the heat conduction model was effective. According to the box-counting method fractal theory, Lyu [23] calculated the fractal dimension of discarded feather/EVA sound-absorption composite material. By Matlab programming, the fractal dimension between the mass and density of discarded feathers was calculated, and then the relationship between the fractal dimension and the maximum sound-absorption coefficient was derived quantitatively.

Fractal geometric properties mainly included self-similarity, wholeness, fractal dimension, organisational depth, and recursion, which interweaved, reinforced, and supported each other [24]. Kapok fibre is the most hollow fibre, and its hollow structure is self-similar to the porous structure of the whole nonwoven fibres. In kapok fibre, the intercross and stacking of macromolecular chains are similar to the whole, and most macromolecular chains are six membered rings, benzene rings, and other molecular chains. The gap between macromolecular chains is similar to that of the whole porous. Kapok fibre sound absorption of the pore size and distribution of composite materials has obvious fractal characters; according to the fractal theory and image processing technology, intuitive characterisation of fibre morphology parameters can be directly extracted: one is the characterisation of porosity, a single pore area, fractal dimension, and pore number, pore structure parameters, such as the size and distribution of these parameters can reflect the pore; the second is the parameters that characterise the state of the fibre. These parameters can reflect the orientation distribution of the fibre. The relationship between structure and sound-absorption property, structure, and fractal dimension of kapok fibre sound-absorption composite was established. Finally, the fractal method is used to solve the sound-absorption performance of kapok fibre.

This article introduces a kind of composite material made of kapok fibre and polycaprolactone by the hot-pressing method. The effects of volume density, mass fraction of kapok fibre, and thickness on the sound-absorption performance of composites were researched using a single-factor experiment. The sound-absorption performance of the composites was investigated by the transfer function method. This research used the box dimension method to calculate composites' fractal dimension by using the Matlab program based on the fractal theory. It analysed the relationships between fractal dimension and volume density, fractal dimension and mass fraction of kapok fibre, and fractal dimension and thickness. The quantitative relations between fractal dimension and maximum soundabsorption coefficient, fractal dimension, and resonant sound-absorption frequency were derived, which provided a theoretical basis for studying sound-absorption performance.

### 2. Materials and Methods

## 2.1. Materials

Kapok fibre—the micronaire is rated A (Guangzhou CUHK Textile Co., Ltd., Guangzhou, China). Polycaprolactone (PCL)—800 mesh (Solvay Company, Dongguan, China).

#### 2.2. Equipment

The surface structure of the material was observed using a scanning electron microscope (Nippon Electronics Co., Ltd., Beijing, China). FA2004B, (Shanghai Precision Experimental Instrument Co., Ltd., Shanghai, China); Pressure Forming Machine, QLB-50D/QMN (Jiangsu Wuxi Zhongkai Rubber Machinery Co., Ltd., Wuxi, China); SW422/SW477, (Beijing Wangsheng Electronic Technology Co., Ltd., Beijing, China).

#### 2.3. Preparation of Composites

Using kapok fibre and polycaprolactone as raw materials, a kapok fibre/polycaprolactone composite material was prepared by the hot-pressing method. Kapok fibre and polycaprolactone were mixed in a particular proportion and pressed by QLB-50D/QMN press. Yang tested the influence of hot-pressing pressure on the sound-absorption coefficient of composite materials in the frequency range of 2000–6300 Hz, and found that the influence of hot-pressing pressure on the sound-absorption coefficient of composite materials was small. In a certain range, the increase in hot-pressing pressure could accelerate the flow of fibre and matrix in the die, improve the chamber of the material, and result in uniform composite molding and good appearance. At the same temperature, the lower hot-pressing pressure was not enough to make the polycaprolactone powder melt and flow between the fibres, resulting in the pressure pointing to the fibre-extrusion fibres, resulting in a large number of fibre-aggregation phenomena. Suitable hot-pressing pressure could allow the polycaprolactone matrix to overcome the resistance between the fibres and fill the gap between the fibres, so that the fibres in the material were evenly distributed. However, too-high pressure would damage the fibre and reduce the mechanical properties of the material. When the hot-pressing pressure was 10 MPa, the composite material was well formed, the noise reduction coefficient and the average sound-absorption coefficient were relatively high, and the overall sound-absorption performance of the material was excellent. Therefore, the most suitable hot-pressing pressure for the preparation of the composite material was 10 MPa [25]. The ideal hot-pressing processing parameters were as follows: The pressure was 10 MPa; the temperature was 130 °C and the time was 15 min. The volume density was 0.156, 0.172, 0.188, and 0.205 g/cm<sup>3</sup>, the mass fraction of kapok fibre was 30%, 40%, 50%, and 60%, and the thickness was 1.0, 1.5, 2.0, and 2.5 cm. The composite material was cut into circular samples with diameters of 100 and 30 mm according to the mold size for the sound-absorption performance test.

## 2.4. Testing of the Composites

## 2.4.1. Sound-Absorption Coefficient Test

The composite material was tested using a stationary standing wave tube. The composite material was placed in a sample bag at room temperature prior to the test. Test specifications were 010534-2:1998 and GB/T1869.2-2002; the experiment used the transfer function method. The SW422/SW477 impedance tube sound-absorption test system was shown in Figure 1.



Figure 1. Schematic diagram of the sound-absorption test.

Test environment setting: the temperature was 25  $^{\circ}$ C, sound speed was 346.11 m/s, atmospheric pressure was 101.325 Pa, relative humidity was 65%.

The sound-absorbing performance could be characterised by the average soundabsorption coefficient. In the experiment, the SW422/SW477 impedance sound-absorption test system was used to measure the sound-absorption coefficient of samples at different frequencies. The measured sound-absorption coefficient was the average of six tests, and then drew the material's sound-absorbing curve at various frequencies.

For materials, when the average sound-absorption coefficient is greater than 0.20, it is called sound-absorption material, and when the average sound-absorption coefficient is greater than 0.56, it is called efficient sound-absorption material [26]. The average sound-absorption coefficient was the arithmetic average of six sound-absorption coefficients at 125, 250, 500, 1000, 2000, and 4000 Hz frequencies. Equation (1) was used to calculate the average sound-absorption coefficient.

$$\alpha = \frac{\alpha_{125} + \alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000} + \alpha_{4000}}{6} \tag{1}$$

Generally speaking, materials with a noise reduction coefficient (NRC) greater than or equal to 0.20 were called sound-absorbing materials [27]. NRC was the average sound-absorption coefficient of 250, 500, 1000, and 2000 Hz. Equation (2) represented the calculation method of the noise reduction coefficient.

NRC = 
$$\frac{\alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000}}{4}$$
 (2)

### 2.4.2. Calculation of Porosity

The sound-absorption performance of composites is closely related to the porosity, which can be calculated indirectly according to the thickness and surface density of the sample [28]. Equation (3) was used to calculate the porosity.

$$\eta\% = \left(1 - \frac{G}{\rho \times \sigma}\right) \times 100 \tag{3}$$

In the formula:  $\eta$  was the sample's porosity (%), G was the model's surface density (G/cm<sup>2</sup>),  $\rho$  was the fibre's mixing specific gravity (G/cm<sup>3</sup>), and  $\sigma$  was the sample's thickness (m).

## 2.4.3. Fractal Characterisation

The sample's two-dimensional image was taken by a scanning electron microscope (Beijing Jeol Co. Ltd., Beijing, China) with a pixel size of  $1024 \times 1024$ . Additionally, the Matlab software (Matlab 2014) was used for a preprocessing series so that the image background was consistent and the picture was more precise. Then, the grey image was converted into a binary image that the computer could recognise, and Matlab's box-counting method was used to compute the sample's fractal dimension (see Appendix A for the program) [29].

The calculation method used in this experiment was the box-counting method. The principle was to take small cube boxes with a side length of  $\varepsilon$  and stack the boxes into the shape of a graph curve. Then, it was found that some boxes were empty, and some boxes contained part of the graph curve. Finally, the number of boxes containing the curve was denoted as N( $\varepsilon$ ) [30]. When  $\varepsilon \rightarrow 0$ , the fractal dimension of the curve could be obtained by using Equation (4):

$$D = -\lim_{\epsilon \to 0} \frac{\log N(\epsilon)}{\log \epsilon}$$
(4)

In the calculation process, the value of  $\varepsilon$  was not equal to 0, and N( $\varepsilon$ ) was also numerical. A line was obtained by the least square fitting and mapping, and the slope of the line gave the fractal dimension [31]. Matlab provided a wealth of visual graphical representation functions and convenient programming capabilities in the box-counting analysis process of two-dimensional digital images. Therefore, in this research, image processing, numerical analysis, and other operations were all performed using Matlab.

## 3. Results and Discussion

## 3.1. Influence of Process Parameters on the Sound-Absorption Coefficient

3.1.1. Influence of Volume Density on the Sound-Absorption Coefficient

The samples' thickness was 1.0 cm when the composite material maintained the hotpressing temperature at 130 °C, and the hot-pressing time was 15 min. The volume density was designed as 0.156, 0.172, 0.188, and 0.205 g/cm<sup>3</sup>. Figure 2 showed the influence of volume density on the sound-absorption coefficient.

The influence of volume density on the sound-absorption coefficient of composite materials; that is, extremely low or extremely high density is not conducive to the sound absorption of composite materials. When the volume density of the composite material was extremely low, the material's gap was large and the material became extremely loose. Therefore, when the sound wave passed through the composite material, there was not enough friction and vibration between the air. The sound wave had less resistance and less sound energy loss and even could pass directly through the material. The lack of friction and vibration airflow between fibre walls led to the reduction in sound loss. At high volume density, if the volume density of the composites increased, the number of fibres per unit volume would increase, and the pore structure between the fibres became more complex than that under the condition of low density. The built-in surface area increased, and the porosity decreased. Under the action of sound waves, the molecular chains of fibres

moved and consumed sound energy. When the volume density of composite material was very high, sound waves could not quickly go in the material, and the advantages of the porous sound-absorbing material would be eliminated due to the low porosity. As noted in Figure 1, the sound-absorption coefficient with the lowest volume density of kapok fibre in the low and mid-low range was also the lowest; that was, the sound-absorption coefficient increased with increasing volume density. This was because the denser composites (higher density and less open structure) behaved as reflective materials, absorbing lower frequencies of sound. In the middle and high-frequency part, the composites' sound-absorption performance became better and better with the composite material's decreased surface volume density. This was because the low density and high porosity allowed sound to enter the matrix more easily in order to dissipate, which helped improve the sound-absorption performance of the material. The volume density had extreme value, and the highest sound-absorption performance could be obtained. When the kapok fibre composite material's volume density was 0.172 g/cm<sup>3</sup>, the average sound-absorption coefficient reached 0.388, with a maximum range of sound-absorbing. Overall, when the volume density of the composite material was  $0.172 \text{ g/cm}^3$ , the sound-absorbing performance reached the highest [32].



**Figure 2.** Influence of volume density on sound-absorption coefficient: (**a**) sound-absorption coefficient, (**b**) average sound-absorption coefficient.

#### 3.1.2. Influence of Mass Fraction of Kapok Fibre on the Sound-Absorption Coefficient

The influence of mass fraction of kapok fibre on the sound-absorption coefficient was investigated. Under the unchanged conditions of other experimental conditions (hotpressing temperature 130 °C, time 15 min, volume density 0.172 g/cm<sup>3</sup>, thickness 1.0 cm), samples with a mass fraction of kapok fibre of 30%, 40%, 50%, and 60% were prepared, respectively, and their sound-absorption coefficients were measured. Figure 3 showed the influence of mass fraction on sound-absorption coefficients.

In the low and mid-low frequency regions, the sound-absorbing effect was better when the fibre mass fraction was larger. As the mass fraction increased, the sample's sound-absorption coefficient increased in a particular range. In the mid-high frequency and high-frequency regions, the sound-absorption effect became worse when the mass fraction was high. When the mass fraction of kapok fibre was 30%, the sample's maximum sound-absorption coefficient could reach 0.92. However, the sound-absorbing performance of sample with low-medium and low-frequency was not good, and the sound-absorbing results were good at high frequency.

The results showed that the excessive addition of kapok fibre made the composites too fluffy, the strength was low, and the forming effect was not good. However, when kapok fibre was too sparse, the material gap became more extensive, and the sound-absorbing effect was low. Based on the above analysis, the mass fraction of kapok fibre was 40% [32].



**Figure 3.** Influence of mass fraction on sound-absorption coefficient: (**a**) sound-absorption coefficient and (**b**) average sound-absorption coefficient.

3.1.3. Influence of Thickness on the Sound-Absorption Coefficient

To study the relationship between the sound-absorbing performance of kapok fibre composite materials and the thickness of composites, the sample's volume density was  $0.172 \text{ g/cm}^3$ , the hot-pressing time was 15 min, the hot-pressing temperature was 130 °C, and the mass fraction of the model was 40%. The samples' thickness was 1.0, 1.5, 2.0, and 2.5 cm, respectively. Figure 4 showed the influence of thickness on sound-absorption coefficient.



**Figure 4.** Influence of thickness on sound-absorption coefficient: (**a**) sound-absorption coefficient and (**b**) average sound-absorption coefficient.

As shown in Figure 4, as the thickness increased, the average sound-absorption coefficient would also increase. Its increasing trend was evident and showed a linear relationship. When the thickness increased, the peak of its sound-absorption coefficient would move to the low frequency region. When the thickness was 1.5 cm, the sound-absorption coefficient's peak frequency was 1600 Hz, and when the composite material increased the thickness to 2.5 cm, the frequency of the peak sound-absorption coefficient was reduced to 800 Hz. Additionally, the composite's thickness was 2.0 cm [32].

When the thickness of the composites increased, the air permeability of the composites would decrease, and the flow resistance would increase accordingly, thereby enhancing the sound-absorbing effect. When the material's thickness was reduced, the time and distance for the sound to pass through the composite would be shorter, and the sound wave could not be reflected and refracted multiple times, thereby reducing the sound-absorption coefficient of the composites. Consequently, the thickness of the material was

generally considered an essential factor in controlling sound-absorption performance. However, when the thickness of the material remained unchanged to a certain extent, the sound-absorption coefficient would be substantially unchanged [33].

## 3.2. Fractal Characterisation Results

## 3.2.1. Kapok Fibre Sound-Absorbing Composites Image Acquisition

The EOL-JSM-6460LV scanning electron microscope was used for the image acquisition of composite materials. The magnification of the image was 100 times. Afterimage processing took the basic fibre layer for pore structure analysis (sample 1#~17#). This processing method was based on the fact that the material was composed of multiple layers of randomly oriented fibres. Most of them were considered to be perpendicular to the average propagation direction of sound waves in the composite material. Some performances of a single layer (base plane fibre layer), such as sound-absorption coefficient, could reflect the entire composite material's performance.

The SEM images of composites with volume densities of 0.139, 0.155, 0.172, 0.188, 0.205, and 0.211 g/cm<sup>3</sup> were numbered from 1# to 6#, and were shown in Figure 5.



**Figure 5.** SEM images of composite materials with different volume densities. (**a**) 1# (0.139 g/cm<sup>3</sup>); (**b**) 2# (0.155 g/cm<sup>3</sup>); (**c**) 3# (0.172 g/cm<sup>3</sup>); (**d**) 4# (0.188 g/cm<sup>3</sup>); (**e**) 5# (0.205 g/cm<sup>3</sup>); (**f**) 6# (0.205 g/cm<sup>3</sup>).



The composites images with mass fraction of kapok fibre 30, 40, 50, and 60% were numbered as 7#–10#, respectively. The SEM images were shown in Figure 6.

**Figure 6.** SEM of composite materials with different kapok fibre mass fractions. (**a**) 7# 30%; (**b**) 8# 40%; (**c**) 9# 50%; (**d**) 10# 60%.

The SEM images with a thickness of 0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 cm were numbered as 11#–16# in Figure 7.





Figure 7. Cont.

(**b**)



**Figure 7.** SEM images of composite materials with different thicknesses. (**a**) 11# (0.5 cm); (**b**) 12# (1 cm); (**c**) 13# (1.5 cm); (**d**) 14# (2 cm); (**e**) 15# (2.5 cm); (**f**) 16# (3.0 cm).

## 3.2.2. Preprocessing of Composites Images

To obtain accurate data, it was necessary to process the SEM images. Matlab software realised the image preprocessing of each part. The following procedures were shown in Appendix A.

## 3.2.3. Image Binarisation

The process of converting multiple grayscale images into two grayscale images through a specific threshold was called image binarisation; that was, all pixels were set as black or white. The grey level of pores and their surrounding areas were significantly different; therefore, the points whose grey level was more significant than or equal to a threshold could be turned into white points, and those whose grey story was less than a threshold could be turned into black points through binarisation of the image by selecting appropriate entries [34]. The scanning electron microscope image (100 times magnification) of the sample was processed by Photoshop, and the binary image recognized by computer was obtained. The pre-processed image was shown in Appendix B Figure A1.

#### 3.2.4. Calculation of Fractal Dimension

This experiment used the box-counting method and Matlab programming to calculate the kapok fibre composite material's fractal dimension on the processed binary image (see Appendix A for the program) [35]. Appendix B Figure A2 showed the calculation results of the fractal dimension of composite materials with different volume densities, kapok fibre mass fractions, and thicknesses.

The square of linear correlation coefficient of each simulated composite material image was above 0.99 in 13 and 0.98 in 3. According to the calculation results of the fractal dimension of composite material volume density, fibre mass fraction, and thickness, the

composite material's pore size had fractal characteristics, and the fractal dimension of the sample hole was represented by the slope of the straight line.

# 3.3. Relationship between Fractal Dimension and Various Factors3.3.1. Influence of Volume Density on Fractal Dimension

Table 1 showed the relevant parameters of samples at different densities. Based on the table data, the researcher drew the relationship curve between the fractal dimension of the model and the maximum sound-absorption coefficient under various volume densities, as shown in Figure 8. Figure 8 could see that when the sample's volume density increased, the corresponding fractal dimension and the maximum sound-absorption coefficient usually showed a decreasing trend. In exploring the effect of volume density on the sound-absorption performance, as the volume density increased, the sound-absorbing curve of the peaks moved to low frequency; when the sample was  $0.172 \text{ g/cm}^3$ , volume density samples corresponding to the hole shape and aperture size combination made throughout the sound-absorbing performance were better in the absorption spectrum, the maximum sound-absorption coefficient of wave in the test frequency range, and the average sound-absorption coefficient was higher, but did not affect the overall trend.

Table 1. Relevant parameters of samples at different volumetric densities.

Sample Number	Composites Volume Density g∙cm <sup>-3</sup>	Maximum Sound Absorption Coefficient	Average Sound Absorption Coefficient	Fractal Dimension	The Square of the Correlation Coefficient R <sup>2</sup>
1#	0.139	0.940	0.326	1.888	0.998
2#	0.155	0.710	0.303	1.794	0.996
3#	0.172	0.800	0.365	1.874	0.998
4#	0.188	0.750	0.347	1.836	0.997
5#	0.205	0.680	0.323	1.855	0.998
6#	0.211	0.630	0.300	1.582	0.980



**Figure 8.** Relationship between fractal dimension and maximum sound-absorption coefficient of samples at different volumetric densities.

3.3.2. Influence of Mass Fraction of Kapok Fibre on Fractal Dimension

Table 2 showed the relevant parameters of different kapok fibre mass fraction samples. Based on the table's data, the relationship between the fractal dimension of models with different kapok fibre mass fractions and the maximum sound-absorption coefficient was drawn, as shown in Figure 9. As the kapok fibre's mass fraction increased, the sound-absorption coefficient and fractal dimension decreased gradually, indicating that the complexity of the internal structure of the composites decreased. In other words, the complexity of the kapok fibre composite material's internal system decreased as the fibre mass fraction increased.

Table 2. Relevant parameters of s	samples under	different kapok fibre	mass fractions.
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Sample Number	Quality Fraction of Kapok Fibre %	Maximum Sound Absorption Coefficient	Average Sound Absorption Coefficient	Fractal Dimension	The Square of the Correlation Coefficient R <sup>2</sup>
7#	30	0.940	0.308	1.774	0.995
8#	40	0.860	0.318	1.713	0.990
9#	50	0.770	0.322	1.745	0.994
10#	60	0.750	0.360	1.712	0.992



**Figure 9.** Relationship between sample fractal dimension and maximum sound-absorption coefficient under different kapok fibre mass fractions.

## 3.3.3. Influence of Thickness on Fractal Dimension

Table 3 showed the relevant parameters of specimens with different thicknesses. The relationship between the fractal dimension of models with different thicknesses and the resonant sound-absorption frequency was drawn based on the table's data, as shown in Figure 10.

Since the thickness significantly influenced the composite material's sound-absorption performance, as the thickness increased, the sound-absorbing curve expanded toward low frequencies. The relationship between the resonance sound-absorbing rate corresponding to the inflexion point was explained by the sound-absorption coefficient and the fractal dimension. The figure showed that the fractal dimension had a good correlation with the sound-absorbing resonance frequency. It showed that the turning point of the sound-absorbing performance of composite materials could be studied through the fractal dimension. That was, the resonance frequency point at which the sound-absorption performance of the material was greatly improved. When the composite's thickness increased, the fractal dimension of the response decreased. The resonance frequency corresponding to the turning point moved to the low frequency; this was because as the composite material's thickness increased, the length of the channel through which the sound waves enter the interior increased, and the hole depth increased, reducing its fractal dimension.

Sample Number	Thickness cm	Resonant Sound-Absorption Frequency	Average Sound-Absorption Coefficient	Fractal Dimension	The Square of the Correlation Coefficient R <sup>2</sup>
11#	0.5	6300	0.182	1.580	0.989
12#	1	4000	0.327	1.815	0.992
13#	1.5	2000	0.400	1.715	0.997
14#	2	1000	0.445	1.697	0.992
15#	2.5	800	0.465	1.697	0.992
16#	3	630	0.525	1.599	0.984

Table 3. Relevant parameters of specimens under different thicknesses.



**Figure 10.** Relationship between fractal dimension of specimen and resonant frequency under different thicknesses.

3.3.4. Relationship between Fractal Dimension and Average Sound-Absorption Coefficient

Figure 11 showed the relationship between the fractal dimension of samples 1#–17# and the average sound-absorption coefficient.



Figure 11. Scatter plot.

Due to the influence of deviation during image adoption, some images with considerable variation were selected for fitting, and Figure 12 showed the fitted curve. The curve obtained was as follows:

$$Y = 4.6 \times X^2 - 16.58X + 15.26 \tag{5}$$

In the formula, Y was the average sound-absorption coefficient and X was the fractal dimension.

As the thickness of the material increased, the resonance absorption frequency corresponding to the sound-absorption coefficient's inflexion point moved to lower frequencies. The fractal dimension of the corresponding response increased. As shown in Figure 13, the fractal dimension was matched with the resonance absorption frequency. The suitable curve was shown below:

$$Y = -2.37 \times 10^{-8} X^2 + 1.56 \times 10^{-4} X + 1.54$$
(6)

In the formula: Y was the fractal dimension; X was the resonant frequency.

This was in accordance with Equation (5), and designed the sound-absorbing performance parameters of composite materials. If the average sound-absorption coefficient was 1, the material's fractal dimension was 2.187 or 1.418. According to the fact that the fractal dimension was about 1.4, the composites had a simple internal structure and a small sound-absorption coefficient. Therefore, the fractal dimension was chosen as 2.187. The larger fractal dimension indicated that the complexity of the internal system of the composites was enhanced.



Figure 12. Fitting curve of average sound-absorption coefficient and fractal dimension.



Figure 13. Fitting curve of fractal dimension and resonance sound-absorption frequency.

This was in accordance with Equation (6), and designed the sound-absorbing performance parameters of composite materials. If a 125 Hz resonant sound-absorption frequency was needed, the fractal dimension of the material was 1.555. The experiment proved that with the decrease in the fractal dimension, the thickness of composite material increased, and the resonance frequency corresponding to the turning point moved to low frequency.

## 4. Conclusions

The composite material was prepared from kapok fibre and polycaprolactone by the hot-pressing method. The following conclusions were drawn:

- (1) Through single-factor experiments, composite material determined the optimal process conditions as follows. The composite material's volume density was 0.172 g/cm<sup>3</sup>, the mass fraction of kapok fibre was 40%, and the composite material's thickness was 2.0 cm. Therefore, this experiment obtained a porous sound-absorbing material with a high sound-absorption coefficient and absorption bandwidth. The maximum sound-absorption coefficient was 0.830, and the average sound-absorption coefficient was 0.520.
- (2) The box-counting method was used to calculate the kapok fibre/polycaprolactone sound-absorbing composite material's fractal dimension. The results showed that the kapok fibre/polycaprolactone composite material had strong fractal characteristics. By fitting the fractal dimension and average sound-absorption coefficient of the kapok fibre composites, the fitting curve was  $Y = 4.6 \times X^2 16.58X + 15.26$ . The right angle of fractal dimension and resonance sound-absorption frequency was  $Y = -2.37 \times 10^{-8} \times X^2 + 1.56 \times 10^{-4}X + 1.54$ , which provided the theoretical basis for the study parameter design of the sound-absorption performance of kapok fibre composite material, and had important guiding significance.
- (3) Kapok fibre sound-absorption composite material had the advantages of low production cost, light weight, simple process, and recycling. Therefore, this sound-absorbing composite material could be widely used in the building environment. In this paper, only the sound-absorption performance of kapok fibre sound-absorption composite material was studied. In practical application, other properties such as mechanical properties, antibacterial properties, thermal insulation properties, and so on need to be considered.

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## Appendix A

1. The calculation program of background elimination

- I1 = imread ('Original image.tif');
- I2 = imread ('Background images.tif');

I1 = rgb2gray (I1); % Image grayscale

I2 = rgb2gray (I2);

Img = imsubtract (I2, I1); Background differentiation

Img = 255/max (max (Img)).\*Img;

Img = imadjust (Img, (0.3, 0.9)); % local image enhancement, *x* value according to the actual situation

threshold = graythresh (Img); % the between-cluster variance method of OSTU threshold figure; subplot (131), imshow (I1); subplot (132), imshow (I2); subplot (133), imshow (Img); 2. Image enhancement calculation procedures I = imread ('Original image.tif'); % read in grayscale I = rgb2gray (I)Subplot (2,1,2), imhist (I), title ('gray histogram'); % for gray histogram 3. Image binarisation calculation procedures I = imread ('\*.bmp');BW = im2bw (I, 0.43); % Transformation threshold converted gray image into a binary image figure; imshow (BW); title ('Binary Image'); B = size (BW, 1); % returns the number of rows of I if mod  $(\log_2(B), 1) > 0$ ; % the mod function is a complementary function. Returns the remainder after dividing two numbers. The sign of the result is the same as the divisor error('The size of image must be 2^n'); end t = log2(B); % t is 2 to the power of t, which is the number of boxes  $s = 2^{(1:t)}$ ; % s is the box size Nr = zeros(1,t); % create a 1 line, zero matrix t column for k = 1:t; d = s(k);h = B/d;For m = 1:h %Cycle by line For n = 1:h % Cycle by column A = BW  $(d^{*}(m - 1) + (1:d), d^{*}(n - 1) + (1:d));$ mx = max(A(:));nr = mx;Nr(k) = Nr(k) + nr;end end end r = d./s; $x = \log(r);$ y = log(Nr);plot(x,y,+');lsline; p = polyfit(x,y,1); Xlabel ('ln (1/epsilon)'); Ylabel ('N (epsilon)'); Dm = p;hold on;  $z = y_{\cdot}/x$ ;

## Appendix B

1. Binarisation images of composites with different volume density, mass fraction, and thickness



**Figure A1.** (a) Volume density  $0.139 \text{ g/cm}^2$ ; (b) volume density  $0.155 \text{ g/cm}^2$ ; (c) volume density  $0.172 \text{ g/cm}^2$ ; (d) volume density  $0.188 \text{ g/cm}^2$ ; (e) volume density  $0.205 \text{ g/cm}^2$ ; (f) volume density  $0.211 \text{ g/cm}^2$ ; (g) kapok fibre 30%; (h) kapok fibre 40%; (I) kapok fibre 50%; (j) kapok fibre 60%; (k) thickness of 5 mm; (l) thickness of 1.0 cm; (m) thickness of 1.5 cm; (n) thickness of 2.0 cm; (o) thickness of 2.5 cm; (p) thickness of 3.0 cm.

2. Calculation results of the fractal dimension of composite materials with different volume density, mass fraction, and thickness.



Figure A2. Cont.



**Figure A2.** (a) Volume density  $0.139 \text{ g/cm}^2$ ; (b) volume density  $0.155 \text{ g/cm}^2$ ; (c) volume density  $0.172 \text{ g/cm}^2$ ; (d) volume density  $0.188 \text{ g/cm}^2$ ; (e) volume density  $0.205 \text{ g/cm}^2$ ; (f) volume density  $0.211 \text{ g/cm}^2$ ; (g) kapok fibre 30%; (h) kapok fibre 40%; (I) kapok fibre 50%; (j) kapok fibre 60%; (k) thickness of 5 mm; (l) thickness of 1.0 cm; (m) thickness of 1.5 cm; (n) thickness of 2.0 cm; (o) thickness of 2.5 cm; (p) thickness of 3.0 cm.

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