Sound absorption properties of multi-layer structural composite materials based on waste corn husk fibers

Lihua Lyu, Jing Lu, Jing Guo, Yongfang Qian, Hong Li, Xinyi Zhao and Xiaoqing Xiong

Abstract
In order to find a reasonable way to use the waste corn husk, waste degummed corn husk fibers were used as reinforcing material in one type of composite material. And polylactic acid particles were used as matrix material. The composite materials were prepared by mixing and hot-pressing process, and they were processed into the micro-slit panel. Then, the multi-layer structural sound absorption composite materials were prepared sequentially by micro-slit panel, air cavity, and flax felt. Finally, the sound absorption properties of the multi-layer structural composite materials were studied by changing flax felt thickness, air cavity depth, slit rate, and thickness of micro-slit panel. As the flax felt thickness varied from 0 to 10 mm in 5 mm increments, the peak of sound absorption coefficient shifted to low frequency. The sound absorption coefficient in the low frequency was improved with the air cavity depth varied from 0 to 10 mm in 5 mm increments. With the slit rate increased from 3% to 7% in 2% increments, the peak of sound absorption coefficient shifted to high frequency. With the thickness of micro-slit panel increased from 2 to 6 mm in 2 mm increments, the sound absorption bandwidth was broaden, and the peak of sound absorption coefficient was increased and shifted to low frequency. Results showed that the highest sound absorption coefficient of the multi-layer structural composite materials was about 1 under the optimal process conditions.

Keywords
Waste corn husk, micro-slit panel, multi-layer structural material, sound absorption

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Introduction
With the development of industrialization and modernization, noise pollution is becoming more and more serious. Noise is defined as unwanted sound. The main sources of noise in life are traffic and industrial machines. In a sustaining noise environment, we may have hearing impairments and effect our life. Therefore, it is important to research on sound absorption materials.

Corn is one of the most widely distributed crops in the world. But, corn is an example of major crops that result in generation of huge amounts of waste from its cultivation and processing. The sound absorption coefficient of the waste corn husk fibers was tested, so the waste corn husk fibers could be made into sound-absorbing material.

In 1975, Maa used the perforated constants to determine the acoustic impedance. The perforated constants

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were related to the size of the perforated diameter and the thickness of the viscous boundary layer. Later, Maa\textsuperscript{10} established the calculation model to forecast the sound absorption coefficient of double-layer structural micro-perforated panels. According to Maa’s theory, it was necessary to make the smaller perforated diameter and the larger perforated rate to make the better sound absorption performance. Qian et al.\textsuperscript{11} used micro-electromechanical system (MEMS) technology to process the micro-perforated plate with smaller perforated diameter and the larger perforated rate, and found that the sound absorption property of the micro-perforated panel was more superior with broaden sound absorption bandwidth, but the perforated diameter was smaller and the cost was higher. Therefore, scholars have carried out the micro-perforated panel with bigger perforated diameter and porous materials on the back of micro-perforated panel. And another acoustic element-micro-slit panel had been received the attention of researchers.\textsuperscript{12} Maa\textsuperscript{13} studied the sound absorption characteristics of micro-slit panel and found that it had good sound absorption performance with appropriate structural parameters. Mao and Wang\textsuperscript{14} discussed the sound absorption mechanism, calculation formula of acoustic impedance, and sound absorption coefficient of the micro-slit panel and found that they were similar to that of the micro-perforated panel. And they showed that methods and theories of the micro-perforated panel were used to describe the sound absorption performance of the micro-slit panel. Zhang and Lu\textsuperscript{15} studied the sound absorption characteristics of micro-slit sound absorbers at normal incidence of sound waves. The interaction between the physical structure parameters of the micro-slit panel was discussed. And this provided an effective design for the design of micro-slit sound absorbers reference.

In the field of acoustic engineering, there are a few factors which contributed much for the sound absorption properties of a material. One of the important factors which determines the sound absorption properties of materials is thickness.\textsuperscript{16} In practice, air cavity has been introduced in the research of perforated metal acoustic ceiling tiles. For the purpose of appearance sake, modifications to the original design were required to achieve the same acoustic performance.\textsuperscript{17}

In recent years, sound absorption properties of multi-layer nonwovens were studied. Çelikel and Babaarslan\textsuperscript{18} had studied sound absorption properties of three-layered multi-layer nonwovens, and the results showed that they had good sound absorption properties. Yang et al.\textsuperscript{19,20} had studied the structural parameters of multi-layer nonwovens that affect sound absorption properties, and the results showed that with thickness of nonwovens, the increase in the thickness of air cavity and layers of nonwovens can improve the sound absorption coefficient in the low-frequency range. Yang et al.\textsuperscript{21} studied sound absorption properties of multicomponent polyester nonwoven materials by using Materiacustica impedance tube. These provided a reference for us to study sound absorption properties of multi-layer structural composite materials.

This article used polylactic acid particles (PLAs) and waste corn husk fibers to prepare multi-layer structural composite materials by mixing and hot-pressing process. The aim of this work was to study the effects of structural parameters on the sound absorption properties of composite materials. The optimal sound absorption conditions of composite materials was studied by changing flax felt thickness, air cavity depth, slit rate and thickness of micro-slit panel, and the optimal structural parameters were also studied. In order to think about the requirements of materials in construction safety, flame retardant properties were considered, and the flame retardant properties of micro-slit panel were simply tested.

**Experiment**

**Materials**

PLAs (provided by Xiangye waste plastic materials management department of Dongguan) with diameter of 2–4 mm and melting point of 165°C are shown in Figure 1.

The chemical compositions of waste corn husk fibers (provided by Shandong Province) were cellulose of 38.57%, hemicellulose of 45.14%, lignin of 10.73%, and pectin of 5.56%. Flax felt with 5 mm thickness and the density 0.117 g/cm\(^3\) was fabricated by acupuncture in laboratory.

**Chemicals**

Urea (provided by Tianjin quartz factory), sodium hydroxide (provided by Tianjin Kermel Chemical Reagent Co, Ltd.), hydrogen peroxide (provided by Tianjin Kermel Chemical Reagent Co, Ltd.), hydrochloric acid (provided
ammonium polyphosphate (provided by Qingdao HaiHua flame retardant materials Co, Ltd.), pentaerythritol (provided by Tianjin Kermel Chemical Reagent Co, Ltd.), and 13X and 4A zeolites powder with diameter 2–4 μm (provided by Henan huanyu molecular sieve Co, Ltd.) were used.

Fabrication of multi-layer structural composite materials

Fabrication of waste corn husk fibers

In the pre-treatment of urea and hydrogen peroxide experiment, the waste corn husk was soaked into a mixture (bath ratio 1:15) of concentration of urea 6 g/L and concentration of hydrogen peroxide 8 g/L for 40 min, kept at 30°C in water bath (bath ratio 1:15), washed with hot distilled water of 100°C. In the treatment of sodium hydroxide experiment, the waste corn husk was soaked into the solution (bath ratio 1:15) of concentration of sodium hydroxide 2% at 100°C for 30 min. Then, it was washed with cold distilled water of 30°C and finally dried at 100°C. Waste corn husk fibers are shown in Figure 2.

Fabrication of flame retardant micro-slit panel based on waste corn husk fibers and PLA

The PLA was melted using SK-160B two-roll mixer heated at 165°C, and then the waste corn husk fibers with length of 10 mm, ammonium polyphosphate and pentaerythritol (2:1), and co-agonist with 13X zeolite were added and mixed. The mixture was consolidated in a hot panel press machine type QLB-50D/Q forming panels. The panels were cooled, and the flame retardant composites were obtained.

Process: mixing of raw materials → blending and masticating → coating and removing agent → preheating of hot press → constant temperature pressurization → cooling setting → stripping → fiberboard.

The technology conditions were listed: hot processing temperature at 165°C, hot processing time for 5 min, hot processing pressure of 10 MPa, mass fraction of waste corn husk fibers were made by flame retardant treatment accounting for 45%, mass fraction of flame retardant with ammonium polyphosphate and pentaerythritol accounting for 10%, mass fraction of co-agonist with 13X zeolite 3%, and the mass fraction of waste corn husk fibers and ammonium polyphosphate was 10:1 with flame retardant treatment of waste corn husk fibers.

According to previous studies, the flame retardant and mechanical properties were optimal with this parameter. The test of flame retardant property was done according to standard GB/T 8924-2005 on an LFY-606B digital oxygen index detector.

Finally, the flame retardant micro-slit panel (1.15 g/cm³) was drilled by using NHY-W prototype machine with different slit rate (Slit rate was defined as the ratio of slit area to composite surface area.16) and air cavity depth. Figure 3 shows two sizes of the micro-slit panels, one with the diameter of 3 cm was tested from 1600 to 6400 Hz and the other with the diameter of 10 cm was tested from 0 to 1600 Hz. The aim of different slit length and distance was keeping the same slit rate in the same test.

Design of multi-layer structural sound absorption composite materials

In order to broaden the sound absorption band, the composites had better sound absorption properties. One way was to
machine a smaller hole or diameter to improve the sound absorption coefficient and broaden the sound absorption band. Another way was to use multi-layer structural composite materials with series. The multi-layer structural sound absorption composite materials were prepared by flame retardant micro-slit panel, flax felt, and air cavity sequentially. The flax felt was close to the micro-slit panel to obtain the multi-layer structural composite materials. The diagram of multi-layer structural sound absorption composite materials is shown in Figure 4.

Sound absorption mechanism of constituent of composite materials

The sound absorption mechanism of micro-slit panel sound absorption is similar to that of micro-perforated panel sound absorption, which is based on the principle of resonance sound absorption, and under the action of sound wave, the sound energy is lost due to viscous damping and heat conduction and the vibration and friction of air on the opening wall. The rest of the sound energy passes through flax felt, and when the sound wave is incident on the surface of the flax felt, a part of the sound wave will be reflected, while the rest will enter the flax felt. When the sound wave propagates in the flax felt, it will cause air in the material to vibrate and cause friction between the air and the fiber to form viscous resistance, and the sound energy will be converted into heat energy and dissipated.

We think the optimal sound absorption properties that have the higher peak value of sound absorption coefficient and the sound absorption bandwidth were wider at low frequency. We used single factor analysis method, determined the density of the micro-slit panel (1.15 g/cm³) and the density of the flax felt (0.117 g/cm³), and studied the optimal sound absorption conditions of composite materials studied by changing flax felt thickness, air cavity depth, slit rate, and thickness of micro-slit panel. By means of range analysis, we determined structural parameters of the multi-layer structural sound absorption composite materials: flax felt thickness varied from 0 to 10 mm in 5 mm increments; air cavity depth varied from 0 to 10 mm in 5 mm increments; slit rate varied from 3% to 7% in 2% increments; the thickness of micro-slit panel varied from 2 to 6 mm in 2 mm increments. In order to study the sound absorption coefficient at the frequency from 0–100 Hz if it can reach 0.2, we did not ignore the frequency from 0–100 Hz.

Sound absorption coefficient testing of multi-layer structural sound absorption composite materials

The sound absorption coefficient testing of multi-layer structural sound absorption composite materials was done under the atmospheric condition of 22°C and 68% of relative humidity (GB/T 18696. 2-2002). SW422/SW477 impedance tube sound absorption test system was used, according to transfer function method. The sketch of SW422/SW477 impedance tube sound absorption test system is shown in Figure 5.

Results and discussion

Flame retardant composite materials

According to the technology conditions, the flame retarded composite materials were obtained, and the limiting oxygen index was 35.2%. As its limiting oxygen index was more than 32%, flame retarded composite materials have good flame retardant properties.

When the composite materials are heated, ammonium polyphosphate and pentaerythritol undergo esterification reaction to generate incombustible gases, which are filled into the generated carbon layer to expand and foam the molten carbon layer. After the reaction is completed, a dense foam carbon layer is formed, and because the carbon layer is difficult to burn, it has the functions of heat insulation and oxygen insulation, which can achieve flame retardant effect.
Effect of flax felt thickness on sound absorption coefficient

Figure 6 shows the sound absorption coefficient curves of multi-layer structural composite materials with thickness of micro-slit panel of 2 mm, slit width of micro-slit panel of 1 mm, slit rate of micro-slit plate of 5%, and air cavity depth of 5 mm. When the flax felt thickness changed from 0 to 10 mm in 5 mm increments, as seen from Figure 6, the peak value of sound absorption coefficient was 0.96 and shifted to low frequency. The low-frequency sound absorption properties of multi-layer structural composite materials were significantly improved with the increase of flax felt thickness. However, they decreased at the frequency of 2000, 2500, and 3150 Hz.

The thickness of flax felt had little effect on the sound absorption properties of the high-frequency band, and the influence on the maximum sound absorption coefficient was also small. The reason is as the low-frequency sound waves were absorbed into the deep layer of the material, the sound wave grew through the channel of the material pore with the increase in thickness from 0 to 10 mm in 5 mm increments, and the more the barrier was flexed by the pores, the more the acoustic energy loss and the more the sound absorption coefficient increased. When the thickness was increased to a certain value, the sound absorption coefficient would be stable.26 Considering the indoor construction, the flax felt thickness should not be too thick. So the optimal thickness of flax felt was 10 mm.

Effect of air cavity depth on sound absorption coefficient

Figure 7 shows the sound absorption coefficient curves of multi-layer structural composite materials. The thickness and slit width of micro-slit panel were 2 and 1 mm, respectively. In addition, the slit rate of micro-slit panel was 5%, flax felt thickness was 10 mm, and the air cavity depth changed from 0 to 10 mm in 5 mm increments.

As seen from Figure 7, with the increase in air cavity depth from 0 to 10 mm in 5 mm increments, the peak value of sound absorption coefficient shifted to low frequency and decreased. The low-frequency sound absorption properties of multi-layer structural composite materials were significantly improved with the increase of air cavity depth from 0 to 10 mm in 5 mm increments. The peak value of sound absorption coefficient decreased from 0.96 at 2500 Hz to 0.83 at 1600 Hz with the increase in air cavity depth. The sound absorption performance of composite materials of air cavity depth 5 mm was considered optimally, the peak value of sound absorption and the sound absorption properties at low frequencies. Then, the sound absorption coefficient was increased after 3000 Hz for the specific characteristic of flax felt, and it could increase the sound absorption properties in the middle- and high-frequency ranges.27

The appearance of the air cavity could achieve the effect of increasing the thickness of the material in the middle- and low-frequency bands.28 When the sound waves pass through the material and reach the rigid back cover of the sound-absorbing instrument, the sound waves were reflected back and forth between the back side of the material and the rigid back cover, and the sound waves were generated. The energy was lost, and the sound energy was lost by continuously converting into heat energy, so that the sound absorption performance of the material in the low-frequency band was remarkably improved.

Effect of slit rate on sound absorption coefficient

Figure 8 shows the sound absorption coefficient curves of multi-layer structural composite materials with thickness of
micro-slit panel of 2 mm, slit width of micro-slit panel of 1 mm, air cavity depth of 5 mm, and flax felt thickness of 10 mm, when slit rate of micro-slit plate was 3%, 5%, and 7%.

As seen from Figure 8, with the increase of slit rate, the peak value of sound absorption coefficient shifted to high frequency and the absorption bandwidth was broadened. The peak value of sound absorption coefficient was 0.96. The average sound absorption showed an increasing trend. Although the low slit rate was beneficial to the sound absorption coefficient in low-frequency range, the sound absorption bandwidth was narrow. The peak value of the resonance sound absorption coefficient changed little. Then, after the rest of the parameters are determined, the slit rate can be found to be an optimal value of 5% under the condition that the bigger the slit rate, the better the effect. The slit rate is too small, the sound absorption effect is very poor in the high-frequency region, and the sound absorption band is narrow; if the slit rate is too large, although the sound absorption band is broadened, it is not conducive to practical applications. Therefore, under the premise of meeting the requirements of use, the slit rate can be appropriately increased to increase the width of the sound absorption band.

Sound absorption coefficient of the micro-slit panel was similar to the micro-perforated panel. With the increase of slit rate, the resonance frequency moved to the high frequency, so the peak value of sound absorption coefficient shifted to high frequency; the acoustic impedance was unchanged, so the peak value of sound absorption coefficient was unchanged; when the sound absorption band became wider, the sound absorption coefficient increased, which was larger than the decrease caused by the decrease of the peak value of the sound absorption coefficient.

**Effect of thickness of micro-slit panel on sound absorption coefficient**

Figure 9 shows the sound absorption coefficient curves of multi-layer structural composite materials with slit width of micro-slit panel of 1 mm, air cavity depth of 5 mm, flax felt thickness of 10 mm and slit rate of micro-slit panel of 5%, when thickness of micro-slit panel was 2, 4, and 6 mm.

As seen from Figure 9, as the thickness of micro-slit panel increased from 2 to 6 mm in 2 mm increments, the peak value of sound absorption coefficient increased from 0.82 to 1, and the sound absorption coefficient was shifted to low frequency, but the absorption bandwidth was narrowed.

Although the thickness of micro-slit panel was beneficial to the peak value of sound absorption coefficient in low-frequency range, the sound absorption bandwidth was narrow. Changing the thickness of micro-slit panel could not obtain high sound absorption coefficient and wide sound absorption bandwidth at the same time. Therefore, the thickness of micro-slit panel had an optimal value of 4 mm, when the rest of the parameters were determined. Changing the thickness of micro-slit panel was to change the depth of the slit, which mainly affected the low-frequency sound absorption performance of the sound-absorbing structure. With the increase in the thickness of micro-slit panel, the position of the maximum sound absorption coefficient moved toward the low frequency. The larger the peak value, the clearer the graph and the narrower the bandwidth.

**Sound absorption coefficient curves under the optimal process condition**

Figure 10 shows the sound absorption coefficient curves of multi-layer structural composite materials under the optimal process conditions (slit width of micro-slit panel of 1 mm, air cavity depth of 5 mm, flax felt thickness of 10 mm, slit rate of micro-slit panel of 5%, and thickness of micro-slit panel of 4 mm). The highest sound absorption coefficient of the multi-layer structural composite materials reached 1 at 2000 Hz.

The sound absorption mechanism of micro-slit panel was similar to that of micro-perforated panel, which was
based on the principle of resonance sound absorption; under the action of sound wave, the sound energy was lost due to viscous damping and heat conduction and the vibration and friction of air on the opening wall.23 The rest of the sound energy passed through flax felt, and when the sound wave was incident on the surface of the flax felt, a part of the sound wave would be reflected, while the rest would enter the flax felt. When the sound wave propagated in the flax felt, it would cause air in the material to vibrate and cause friction between the air and the fiber to form viscous resistance, and the sound energy was converted into heat energy and dissipated.24

**Conclusion**

Waste corn husk fibers were used as reinforcement material, and PLAs were used as matrix material. The flame retarded composites were fabricated by mixing and hot-pressing method, and they were processed into the micro-slit panel. The limiting oxygen index of the micro-slit panel was 35.2%. Then, the multi-layer structural sound absorption composite materials were prepared by micro-slit panel, air cavity, and flax felt sequentially. With the increase in flax felt thickness and air cavity depth, the low-frequency sound absorption properties of multi-layer structural composite materials were significantly improved. And, within limits, the peak of sound absorption coefficient shifted to high frequency, and the sound absorption bandwidth was broaden with the increase of slit rate. Then, with the increase of thickness, the peak value of sound absorption coefficient increased, and the sound absorption coefficient was shifted to low frequency. But the absorption bandwidth was narrowed. Under the optimal process conditions (slit width of micro-slit panel of 1 mm, air cavity depth of 5 mm, flax felt thickness of 10 mm, slit rate of micro-slit plate of 5%, and thickness of micro-slit plate of 4 mm), the multi-layer structural composite materials had good sound absorption properties, and the sound absorption coefficient reached 1 at 2000Hz.

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