Effects of Micronized Fibers on the Cushion Properties of Foam Buffer Package Materials

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Foam buffer package materials composed of plant fibers have been a focus of research in recent years because of their environmentally beneficial ability to become fully disintegrated. In this study, bleached bagasse pulp was micronized using a PFI mill, and foam buffer materials were prepared using the micronized fiber. The effects of the beating degree of micronized fibers on the dimensional stability, moisture absorption, static compression, and dynamic compression characteristics were discussed. Results showed that, in both the static and the dynamic compression experiments, the buffer properties improved with an increasing beating degree. The buffer materials made of highly micronized fiber were stronger under pressure and impact. Specifically, the highly micronized fiber's ability to absorb energy curing impact was improved, demonstrating that it can support a higher compression and impacting load in a certain deformation scope. However, during the drying process, the dimensional stability of the samples also declined with an increasing beating degree. The moisture absorption of the samples improved when the beating degree was increased.

Keywords: Micronized fiber; Cushion properties; Foam cushioning package material

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INTRODUCTION

With the shortage of raw materials and increasingly stringent environmental requirements, sustainability has become an important principle for the packaging industry. As a sustainable packaging material, plant fiber foaming material can replace polystyrene foam (EPS) transport buffer packaging materials, and its added environmental benefits make it a likely candidate for increased use in the future (Chen *et al.* 2012). Currently, the most common environmentally friendly degradable buffer materials are molded pulp and honeycomb paperboard products. A buffer cavity structure to improve the protective properties of materials was established using papermaking technology. However, such buffer materials have the disadvantages of poor elasticity, poor elastic modulus, greater cushion coefficient friability, and higher specific weight. In addition, their production cost exceeds the price of plastic foam material, a factor that also restricts their wide application.

Foam buffer package material that is made of plant fibers (agricultural waste, waste paper, cardboard, or other plant fiber materials) and starch additive is a new type of green packaging material (Noguchi *et al.* 1998; Chang and Hung 2003; Ganjyal *et al.* 2004; Geng 2004; Soykeabkaew *et al.* 2004; Nabar and Narayan 2006). Its advantages include the use of simple manufacture technology, low cost, wide material sources, and better shock isolation performance in comparison to molded pulp products (Gao *et al.* 2008). It can be used in the production of shockproof lining, replacing EPS filling

particles and approximating the performance of EPS products. In comparison to Styrofoam (Thickness: 40 mm), the foam buffer materials exhibit a similar static buffering performance. Moreover, the maximum rebounds of the foam buffering materials were found to be 95%, which is higher than the 90% value found for Styrofoam (Chen *et al.* 2012). Because the buffer material has a low environmental impact, it offers an effective solution to the contradiction between the demands of economic growth, the reality of resource scarcity, and concerns about environmental pollution. Therefore, in recent years, along with an increasing concern and attention to the problem of environmental pollution, buffer materials made of plant fibers have become the focus of research and development. Most research focuses on preparation technologies. Scientists have investigated factors that affect the performance of starch/fiber blend buffer materials. They found that starches are highly compatible with fibers. Meanwhile, flexural strength, compressive strength, and other mechanical properties of these buffer materials improved with increased fiber content. Furthermore, they modified fibers using an alkaline treatment to obtain better rheological properties (Ganjyal *et al.* 2004; Kaisangsri and Kerdchoechuen 2014; Liu *et al.* 2014). In order to enhance the stability of foam materials while reducing their density, some researchers combined surfactants with hydrophobic celluloses or paper pulps. In addition, the low density cellulose-based foam had a density as low as 10 mg/cm^3, which meant that this material could be fabricated using existing papermaking infrastructure, thus avoiding the cost of new technology (Dong *et al.* 2009). The modified blend incorporated threads such as banana, agave, and coconut fiber with material waste such as polyurethane foams, corn starch, and potato starch to produce composites that reduced the overall swelling and improved strength and dielectric properties, whilst maintaining favorable cushion performance (Aguilar-Palazuelos *et al.* 2010).

However, researchers also have noticed that the properties of foam buffer material made from unbeaten pulp are weak because of the poor bonding strength between the plant fibers. Long fibers without beating processing were only suited for bulky materials because the internal contact area was limited (Karademir *et al.* 2012). Therefore, if the plant fibers were first treated by beating and then by cutting and/or crushing (hydration), they became water-absorbent, swollen, and fibrillated to a broom-like morphology (fine fibrillation). The morphology of the original fibers was changed and the intertwining among fibers was enhanced, satisfactorily meeting the application requirements for molded foam buffer materials (Zhu and Xia 2007). Therefore, this kind of fiber processing technology makes sense and may serve a useful purpose in many future applications.

Micronized fiber is extensively refined fiber. The fine degree of fibrillation of pulp fiber can be improved through the medium-consistency beating process. Fine fibrillation includes external fine fibrillation and internal fine fibrillation. For the external fine fibrillation and splitting, the fiber is split longitudinally, with brooms at the two ends and it becomes devillicate-fluffing, which can increase the fiber surface area and promote hydrogen bonding between fibers. For the interior of the fibers, the water absorbing swelling of the fiber causes the breakage of the hydrogen bonds of adjacent cellulose chains within concentric layers in the secondary wall. It also damages the side chain connections, thus reducing the cohesion of fibers, decreasing the rigidity of the fiber and increasing its plasticity. Therefore, the fiber becomes soft and malleable (Wai *et al.* 1985; Chen *et al.* 1997). This paper mainly focuses on improving fine fibrillation of pulp fibers through the medium-consistency beating process. The effect of beating degree on the size

stability, moisture absorption, static compression, and dynamic compressive properties of foam buffer packaging material are discussed.

EXPERIMENTAL

Materials

Bleached bagasse pulp was obtained from Guangxi Nanning Sugar Industry Co., Ltd; CS-8 cationic starch was obtained from Guangxi Mingyang Biochemical Technology Co., Ltd; sodium bicarbonate AR, was obtained from Chengdu Kelong Chemical Reagent Factory; polyvinyl alcohol, AR, was obtained from Chengdu Kelong Chemical Reagent Factory; and magnesium stearate, industrial-grade, was obtained from Sinopharm Chemical Reagent Co., Ltd.

Equipment

The KRK-D16 standard pulp fluffer was produced by Japan KRK Co., Ltd. The 2511-B PFI pulp grinder was produced by Japan KRK Co., Ltd. The YQ-Z-13 pulp beating degree tester was produced by Sichuan Changjiang Papermaking Instrument Co., Ltd. The INSTRON 8801 material-testing system was produced by the Instron (Shanghai) Test Equipment Trading Co., Ltd. The Y02-2/ZF dynamic compression tester was produced by northwest machinery factory. The WMX-Ⅲ-A microwave oven was produced by Shaoguao Keli experimental instruments Co., Ltd. The 101-Z thermostatic drier was produced by Shanghai Laboratory Instrument Works Co., Ltd.

Methods

Beating of bleached bagasse pulp

First, the dryness of the air-dried bleached pulp was measured. Then, 30 g of bleached pulp was weighed and immersed in water at 25 ºC for more than 4 h. The slurry was then dissociated for 10 min in the KRK-D16 standard pulp fluffer. After that, the slurry was concentrated to 20 to 30%, weighed, and diluted to 10%. The diluted slurry was subjected to a beating treatment in the 2511-B PFI pulp grinder.

Preparation of foam buffer materials

According to the results of previous experiments (Zhu 2012), a 20% cationic starch and 5% aqueous solution of polyvinyl alcohol was mixed into a paste for 30 min. Afterwards, 74% beaten fiber slurry and 1% of magnesium stearate was added to the paste and stirred until it reached a uniform consistency. The solids content of paste was 20%. After the mixture was cooled to room temperature, 5.5% sodium bicarbonate (a percentage of solids) as a foaming agent was added. After being stirred and mixed until uniform, the mixture was moved into the mold. The mixture was foamed into buffer materials in a microwave oven for 5 min. The foamed buffer materials were moved from the mold into the drying oven until the materials had become fully dried. Finally, the buffer properties of the prepared foam buffer materials were measured.

The preparation process is shown in Fig. 1:

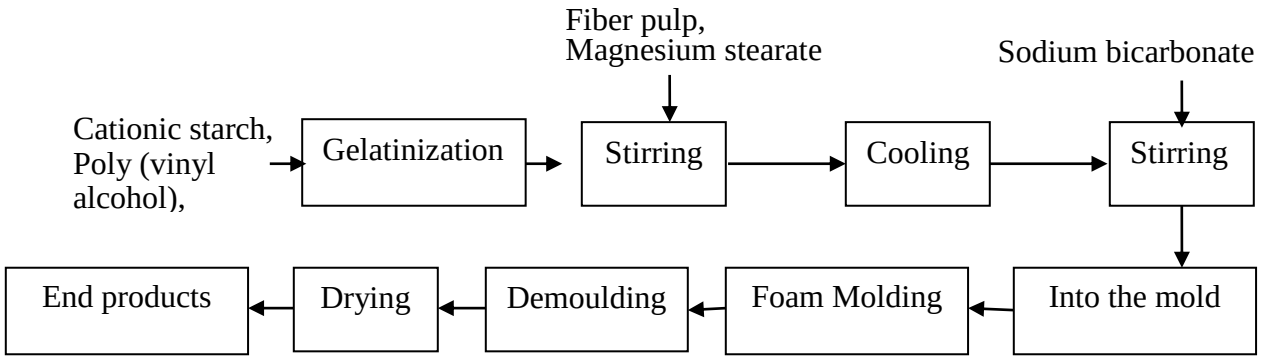

Fig. 1. The flow chart of the preparation of foam buffer materials

Measurements

(1) Measurement of the beating degree

Two grams of oven dry pulp slurry was diluted with water and dissociated with the fluffer for 3 min. Then, it was diluted with water to 1000 mL and stirred until uniform. After that, the beating degree of the slurry was measured using the YQ-Z-13 pulp beating degree tester.

(2) Measurement of the volumetric change rate

According to the Chinese National Standard GB/T 8811-2008, which dictates the dimension stability test method for rigid foam (Zhu and Chen 2008), microwave-foamed buffer material samples were placed under 70 °C temperature conditions for 24 h. The specimen's size before and after the treatment was measured. The volumetric change rate was calculated according to Eq. 1,

$$\varepsilon_v = \frac{V_t - V_0}{V_0} \times 100\% \quad (1)$$

where ε_v is the volumetric change rate (%), V_0 is the volume of the sample before treatment in cm^3, and V_t is the volume of the sample after treatment in cm^3.

(3) Measurement of moisture absorption

The foam buffer materials were fully dried and weighed. Then they were placed under a temperature of 25 °C with a relative humidity of 60% for 1, 3, 6, 12, 24, and 36 h. Samples were weighed after each time period, and the amount of moisture absorption was calculated (Shi and He 2008).

To reduce the influence of sample quality on the absorption ability, the unit mass moisture absorption was calculated according to Eq. 2,

$$Q = \frac{M_t - M_0}{M_0} \times 100\% \quad (2)$$

where Q is the moisture absorption of samples (%), M_0 is the quantity of the sample after being dried (g), and M_t is the quantity of the sample after absorbing moisture (g).

(4) Measurement of static compression properties

The static compression properties were measured according to Chinese National Standard GB 8168-2008, Method A, which is the static compression test method for buffer package materials (Huang *et al*. 2008a). In the experiment, the load applied to the samples was gradually increased at a velocity of 12 (±3) mm/min along the thickness direction. The compression force and its corresponding deformation during the sample compression process were recorded, enabling the stress-deformation curve to be acquired. To eliminate the influence of the size of the foam buffer material, the stress-deformation curve was converted into the stress-strain curve according to Eqs. 3 and 4,

$$\sigma = \frac{P}{A} \times 10^6 \quad (3)$$

where σ is the compression force (Pa), P is the compression load (N), and A is the loading area (mm^2).

$$\varepsilon = \frac{T - T_i}{T} \times 100\% \quad (4)$$

where ε is the compressive strain (%), T is the thickness of the sample before compression in mm, and T_i is the thickness of the sample after compression in mm.

(5) Measurement of dynamic compression properties

According to the dynamic compression test method for buffer package materials, Chinese National Standard GB/T 8167-2008 (Huang *et al*. 2008b), 1.5-, 2-, 3-, 4-, and 5-kg heavy punches were selected for the experiments. The heavy punches continuously impacted the samples 5 times from a height of 50 cm. The interval between each shock pulse was no less than 1 min. The maximum acceleration of each shock was recorded, and the average of the last 4 repetitions was used as the maximum acceleration. Thus, the maximum acceleration and static stress curves were found and converted into the buffer coefficient-static stress curve.

The static stress was calculated using Eq. 5,

$$\sigma_{st} = \frac{Mg}{A} \times 10^4 \quad (5)$$

where σ_{st} is the static stress (Pa), M is the mass of the punch (kg), g is the acceleration of gravity (m/s^2), and A is the surface area of the sample that underwent shock (mm^2).

RESULTS AND DISCUSSION

Effect of Beating Degree on Dimensional Stability

To determine the effects of the beating degree of micronized fiber on the dimensional stability of the prepared foam buffer materials, pulps with different beating degrees were used in this study. The results are shown in Table 1.

Table 1. Effect of Beating Degree of Micronized Fibers on the Volumetric Change Rate

Beating degree (ºSR)	Weight (g)	Length (cm)	Width (cm)	Height (cm)	Volume (cm^3)	Density ($g \cdot cm^{-3}$)	Volumetric change rate (%)
18	48.33	10.3	10.2	3.9	409.7	0.118	-4.3
60	45.27	10.2	10.1	3.9	401.8	0.113	-6.2
73	46.14	10.3	10.2	3.8	399.2	0.116	-6.8
80	45.96	10.3	9.6	3.8	375.7	0.122	-12.3
84	44.42	10.2	9.7	3.6	356.2	0.124	-16.8

*The size of demolded samples was 10.5 cm × 10.2 cm × 4 cm

After drying, the foam buffer material made of micronized bleached bagasse pulp fibers shrank, and the volumetric change rate was significantly improved with the increasing of beating degree.

The plant fiber fibrillation and fine fibrillation and splitting degree increased with a growing beating degree, and the fines content also increased; therefore, the accessible hydroxyl groups of the cellulose correspondingly increased. During the drying process, the dehydration of plant fiber products and increased hydrogen bonding caused the fibers to move closer together. The larger amount of accessible hydroxyl groups made the foam buffer materials shrink and higher beating degrees caused more shrinkage, while the volumetric change was also larger.

Effect of Beating Degree on Moisture Absorption

Different beating degrees of bleached bagasse pulp were chosen to make foam buffer materials and the moisture absorption in fully dry conditions at room temperature was studied. The results are shown in Fig. 2.

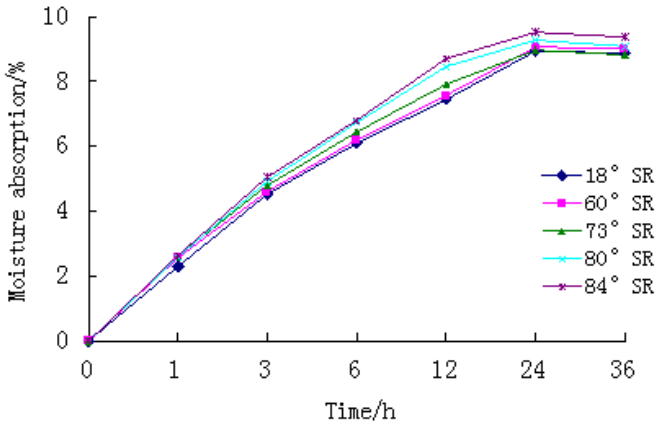

Fig. 2. Effects of the beating degree of micronized fibers on moisture absorption

Figure 2 shows that moisture absorption significantly increased over time under the conditions of 25 °C and 60% relative humidity. For the first 12 h, the increase in moisture absorption of foam buffer materials was relatively quick. Afterwards, the

growth of moisture absorption slowed. At about 24 h, the moisture absorption reached its maximum. That was because more accessible hydroxyl groups were generated during the beating process. The hydroxyl groups are water-absorbing groups, which can cause the foam buffer material to absorb more moisture. In addition to bagasse fibers, the other raw material, cationic starch, also contained large amounts of hydrophilic accessible hydroxyl groups. Both of them can cause the produced foam buffer material to absorb moisture more easily. Moreover, the pore structure in the foam buffer material surface is prone to physical absorption, so the pores are also important factors influencing the moisture absorption.

Effect of the Beating Degree on Static Compression Performance

Different beating degrees of micronized fibers were chosen to make foam buffer materials, and random sampling was used to measure static compression performance according to GB/T 8168-2008. The stress-strain curves of the samples prepared with different beating degrees are shown in Fig. 3.

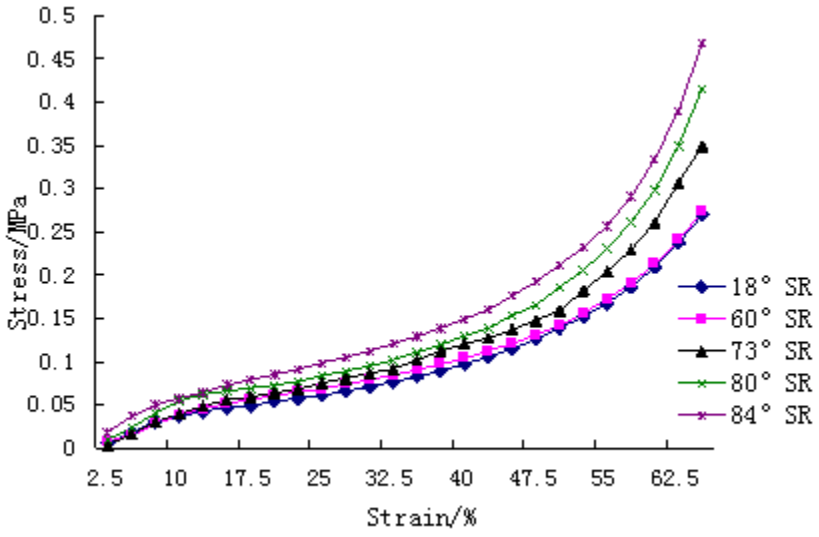

Fig. 3. Stress-strain curves of the samples prepared with micronized fibers of different beating degrees

Figure 3 shows that the static compressive stress-strain curve of foam buffer materials can be divided into three stages: the 0 to 10% strain range is the small strain elastic deformation zone with an essentially linear stress-strain curve; from 10 to 50%, the strain range is known as the platform area (or the yield). In the latter region, the stress force change is not large when the strain sharply changes and the curves remain relatively flat. After 50%, the curve becomes exponential as the strain increases and the stress forces sharply grow towards infinity; this is known as the compaction area (or density).

Under the same strain condition, the stress significantly grew with an increase in the beating degree. This illustrates that the beating process helps to improve the bonding force between fibers, which made the buffer material more absorbent of static pressure energy. Therefore, the buffer performance was significantly enhanced. This is because long beating times can make fibers broom and cause splitting. Large amounts of hydroxyls were generated on the fibers, which increased the hydrogen bonding between

the fibers and caused the fibrous structure to combine more tightly. This action made the mechanical strength of the foam buffer material increase and allowed it to withstand higher pressure.

Effect of the Beating Degree on Dynamic Compression Performance

The effects of different beating degrees of micronized fibers on the dynamic compression performance were determined. The static stresses of different heavy punches were calculated according to Eq. 5, and the results are shown in Table 2. The G_m-σ_{st} curves of foam buffer materials were prepared with micronized fibers of different beating degrees as shown in Fig. 4.

Table 2. Dynamic Compression Data

Mass of heavy punch (kg)	Static stress (kPa)	Drop height (cm)	Thickness of the sample (cm)
1.5	1.47	50	3.8
2.0	1.96		
3.0	2.94		
4.0	3.92		
5.0	4.90		

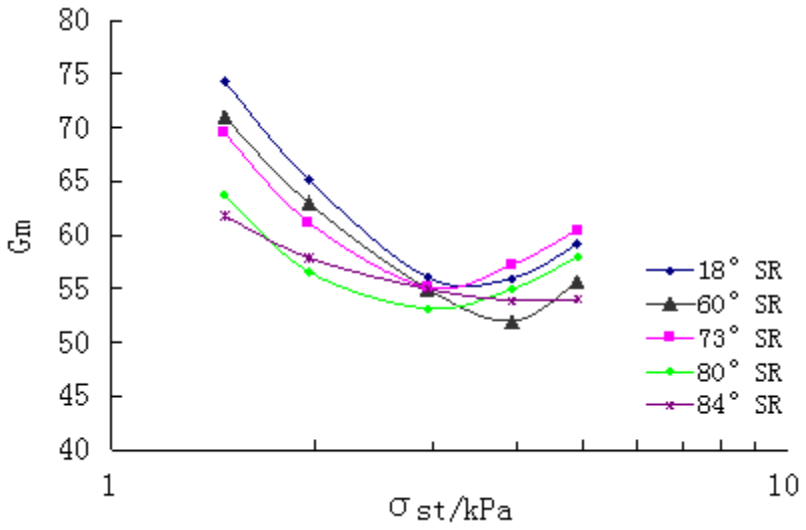

Fig. 4. The G_m-σ_{st} curves of foam buffer materials prepared with micronized fibers of different beating degrees

Figure 4 shows that the maximum acceleration-static stress curves of the foam buffer materials of different beating degrees had the same trend; they all initially decreased with increasing static stress and then increased. The minimum value appeared near static stresses of 2.94 to 3.92 kPa. The mechanical properties of plant fiber buffer packaging materials are controlled by the fiber strength, the bonding degree of the fiber

network, and the strength of the bonds. Without bonding, no fiber network is formed. In the forming process of buffer materials, cellulosic fibers have a tendency to bond with each other when dried. Mechanical interlocking increases in relation to the surface area of the particles (Taipale *et al.* 2010). During dewatering, the contraction of the fibrils pulls the fibers closer together and promotes the formation of direct hydrogen bonds between the surfaces. Due to their large specific surface area, well-dispersed cellulosic fibrils enhance the bonding between plant fibers and distribute stress peaks under loading. The refining of pulp can increase the bonding ability of the fibers. The greater the beating degree, the smaller the maximum acceleration value, which illustrates that the beating treatment can improve the bonding strength between fibers and prompt the formation of high-strength fiber structures. The strength of paper can also be enhanced through the addition of water-soluble hydrophilic dry-strength additives such as starch. Therefore, the buffer materials can absorb more energy. In the case of the same impact acceleration, foam buffer materials made from fibers of higher beating degrees can bear larger impact loads.

CONCLUSIONS

1. The dimensional stability declined with an increasing beating degree after the drying process. The longer the beating process, the higher the volumetric change rate.

2. The foam buffer materials made from micronized fibers easily absorbed moisture in the air at room temperature. Within 12 h, the moisture absorption of foam buffer materials increased rapidly with time. After that, the rate of moisture absorption slowed. At about 24 h, the moisture absorption reached the maximum limit.

3. Under the same strain conditions, the stress significantly increased with an increasing beating degree. The higher the beating degree, the larger the stress. The beating processing helps improve the bonding force between fibers, which makes the buffer material better able to absorb the energies of the static pressure.

4. The greater the beating degree, the smaller the maximum acceleration value, which illustrates that the beating treatment can improve the bonding strength between fibers to form a high-strength fiber structure, which can absorb more energy. Under the same impact acceleration, foam buffer materials made from higher beating degrees can bear larger impact loads.

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