Degradable Foam Tray Based on High-concentration Dispersed Cellulose Fibers Obtained by a Hot-press Baking Process

Ruijuan Zhang[1,2], Yanqun Su[1,2,*], Tao Zhao[1,3], Jingang Liu[1,2],
Hongjie Zhang[1,2], Leilei Hou[1,2], Xianling Fu[1], Qi Chen[4]

1. *China National Pulp and Paper Research Institute Co., Ltd., Beijing,* 100102*, China*
2. *National Engineering Lab for Pulp and Paper, Beijing,* 100102*, China*
3. *Sinolight Specialty Fiber Products Co., Ltd., Langfang, Hebei Province,* 065008*, China*
4. *China National Intellectual Property Administration, Beijing,* 100088*, China*

Ruijuan Zhang, marster, engineer;
E-mail: suixinju1990@163.com

*Corresponding author:
Yanqun Su, professorate engineer;
research interest: green packaging materials and application of the nanocellulose fibers;
E-mail: yanqunsu@126.com

Abstract: Degradable industrial packaging foam trays made from cellulose fibers were fabricated using a hot-press baking process. Bleached softwood pulp fibers with a concentration of 30% were dispersed at a high speed under the action of a dispersant. The effects of the dispersant dosage of the fibers on the porosity, foam density, and static compression characteristics were discussed. Furthermore, the effects of the reinforcing adhesive including polyvinyl alcohol (PVA), and cassava starch on the physical and mechanical properties of the foam trays were studied, as well as the relationship between these properties and the microstructure of the foam trays. The dispersant enhanced the rheological and blistering properties of the fiber dispersion. As the dispersant dosage increased from 2% to 4%, the foam density gradually increased and the compressive strain performance and residual compressive strain of the foam trays decreased. Under the condition of constant dosage of dispersant, increasing the fiber proportion from 67% to 77% improved the porosity and foam density and slightly reduced the static compression performance. In additioton, the static compression resistance of the foamed materials was improved by increasing the PVA dosage since PVA was beneficial for improving the strength of the foam trays.

Keywords: degradable foam; cellulose fiber dispersion; cassava starch; polyvinyl alcohol

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1 Introduction

Buffer packaging, such as disposable foam packaging, is used to protect and preserve products during distribution and handling operations. The most popular buffer materials include expanded polystyrene (EPS), polyurethane, polyethylene, and polypropylene because of their light density, good strength, and low cost [1]. EPS is extensively used in single-use packages for the packing of commercial and electronic goods because it is lightweight, durable, and resistant to chemical or corrosive reactions [2]. These properties make EPS an excellent cushioning material. However, post-consumer petroleum-based products are difficult to recycle owing to their time-intensity and cost and are non-biodegradable, which causes concerns about the environmental impact of their manufacture and disposal. Therefore, it is necessary to develop alternative buffer materials using renewable and degradable resources. Bio-based materials, such as starch and cellulose, are possible alternatives in foam manufacture.

Cellulose fibers can be made into biofoams as the main component or as reinforcement for starch-based foams. Huang et al [3] produced foam buffer materials with 20% cationic starch, 5% polyvinyl alcohol (PVA), 74% beaten fiber slurry, and 1% magnesium stearate. Luo et al [4] prepared a porous wood-fiber-based cushioning material for packaging using poplar fiber and wood powder via hot-press molding. Ji-Young et al [5] fabricated ecofriendly cushioning materials with thermomechanical pulps (TMPs) from waste wood using a suction forming method. The buffer properties of the TMP cushion containing cationic starch were slightly less than those of EPS and much greater than those of the molded pulp. Ahmadzadeh et al [6] prepared cellulose-based nanoclay biocomposites as a substitute for synthetic polymer foam trays in food packaging materials. The preparation stage involved dissolution/regeneration and followed by lyophilization. The prepared cellulose nanocomposite foam is a potential alternative to the commercial synthetic foams used for packing food products. Li et al [7] prepared foam materials to demonstrate the feasibility of controlling the foaming-material structure using a standardized procedure. The procedure included draining the foam suspension.

Although these studies have demonstrated the feasibility of using plant fibers in the preparation of foams, the effect of fiber dispersion on the properties of foams has not been described in detail. When high-concentration pre-foaming material is baked in a mold and then foamed, this preparation method is not suitable for setting up the process of draining, which requires a good dispersion of pulp fibers at a higher concentration. In this study, degradable foam trays were prepared from cellulose fibers by hot-press and baking process, in which guar gum was used as dispersant, and PVA and cassava starch were used as strengthening adhesives. The focus was on investigating the effects of the dispersant dosage of the fibers on the porosity, foam density, and static compression characteristics. In addition, the effects of the reinforcing adhesive on the physical and mechanical properties of the foam trays were investigated.

2 Experiments

2.1 Materials and chemicals

Bleached softwood kraft pulp was sourced from Sinolight Specialty Fiber Products Co., Ltd. The PVA, guar gum, and cassava starch were obtained from Cangzhou Yida Flower Paper Printing Material Co., Ltd., and Yueyang Forest and Paper Co., Ltd., respectively. All chemicals (stearic acid and glycerol) used in this study were of analytical grade.

2.2 Methods

2.2.1 Dispersion of cellulose fibers

Softwood pulp fibers with a concentration of 30% were placed in a high-speed dispersion machine (shear line speed of 2−4.5 m/s). In the high-speed shear dispersion process, 2%−4% guar gum, based on the fiber weight, was added to the fiber agglomerates as dispersant. The mixture was dispersed at a shear line speed of 3 m/s for 20 min to obtain the dispersion of the cellulose fibers. The fiber dispersions obtained containing different dispersant dosages of guar gum are listed in Table 1.

2.2.2 Preparation of foam trays

To prepare each formulation (Table 2), the indicated

Table 1 Experimental factorial design

Samples	F2	F2.3	F2.5	F3	F4
Guar gum dosage (based on fiber weight)/%	2.0	2.3	2.5	3.0	4.0

Table 2 Experimental factorial design

Samples	Guar gum dosage (based on fiber weight)/%	Fiber dispesion (containing guar gum)/%	Cassava starch/%	PVA/%
F2-S23-P10	2.0	67	23	10
F2.5-S23-P10	2.5	67	23	10
F3-S23-P10	3.0	67	23	10
F4-S23-P10	4.0	67	23	10
F2.3-S23-P10	2.3	67	23	10
F2.3-S13-P10	2.3	77	13	10
F2.3-S13-P15	2.3	72	13	15
F2.3-S13-PF20	2.3	67	13	20

fiber dispersion was added with cassava starch, PVA aqueous solution, and additives (0.5% sodium dodecyl sulfate, 8% stearic acid, 15% glycerol, and 4% clay). The mixture was then stirred at a shear line speed of 3 m/s for 20 min using a high-speed dispersion machine to form a pre-foaming fiber paste. The paste (35−40 g) of each formulation was homogeneously layered on a plate with dimensions of 15 cm × 10 cm and a thickness of 2 mm. A lid was placed over the paste and thermopressing was performed using a heat press (HY-10THB, Shanghai Henyu Instrument Co., Ltd., Shanghai, China) equipped with temperature and pressure sensors. Hot pressed baking temperature and time were set at 180 ℃ and 5 min respectively. Finally, the foam trays were removed from the press, and unmolded after cooling for 2 min at room temperature. The prepared foam trays are shown in Fig. 1.

Fig. 1 Images of the prepared foam trays

2.2.3 *Measurement methods*

2.2.3.1 *Foaming rate*

The foaming rate, which is the percentage of the volume level increasing in the mixing system before and after foaming, reflects the air content in the foaming system, and can be calculated using Eq. (1):

$$\text{Foaming rate} = \frac{V_1 - V_0}{V_0} \times 100\% \qquad (1)$$

where V_0 and V_1 denote the volumes of the mixing system before and after foaming, respectively.

2.2.3.2 *Foam density*

Foam density was calculated as the ratio of weight and volume of the foam using Eq. (2):

$$\text{Foam density} = \frac{m}{V_2} \qquad (2)$$

where m and V_2 are the weight and volume of the foam tray, respectively.

2.2.3.3 *Porosity*

The foam porosity was calculated using Eq. (3):

$$\text{Porosity} = \left(1 - \frac{\rho}{\rho'}\right) \times 100\% \qquad (3)$$

where ρ is the density of the given foam sample and ρ' is the density of the corresponding unfoamed material. ρ' value was obtained using Eq. (4).

$$\rho' = \frac{1}{\sum_{i-1}^{n} (w_i/\rho_i)} \qquad (4)$$

where w_i is the mass fraction of each component in the foam sample; ρ_i is the density of each component in the fiber porous material. The densities of the fibers, cassava starch, and PVA were 1.50, 1.5 and 1.3 g/cm^3, respectively.

2.2.3.4 *Microscopic morphology observation*

A scanning electron microscope (SEM, s-3400N, Hitachi, Tokyo, Japan) was used to observe the microstructure of the foam materials at a voltage of 5.0 kV or 15.0 kV.

2.2.3.5 *Static compression performance*

The static compressive-strain performance characterizes the deformation of the foam tray under a static load. The compressive strain of foam trays at 130−220 kPa was selected as $\mathcal{E}_1$. The residual compressive strain $\mathcal{E}_2$ was indicated by a height change after 5 min unloading the 220 kPa load.

The $\mathcal{E}_1$ was calculated using Eq. (5):

$$\mathcal{E}_1 = \frac{h_0 - h_1}{h_0} \times 100\% \tag{5}$$

where h_0 is the original height of the sample and h_1 is the height when the sample is loaded.

The $\mathcal{E}_2$ was calculated by Eq. (6):

$$\mathcal{E}_2 = \frac{h_0 - h_2}{h_0} \times 100\% \tag{6}$$

where h_0 is the original height of the sample and h_2 is the height after 5 min unloading the 220 kPa load.

Compression-resilience characterizes the recovery performance of the foam tray after bearing a static load for a certain time and then unloading. In this test, the rebound rate $\mathcal{E}_3$ of compressive strain indicated the change of sample thickness after 30 min unloading 220 kPa load. The $\mathcal{E}_3$ was calculated by Eq. (7):

$$\mathcal{E}_3 = \frac{h_4 - h_3}{h_0 - h_3} \times 100\% \tag{7}$$

where h_0 is the original height of the sample, h_3 is the height of the sample while loading 220 kPa for 1 min, and h_4 is the height of the sample after 30 min unloading the 220 kPa load.

3 Results and discussion

For fibrous foam materials, high porosity and uniform pore distribution are important for endowing the foam with better cushioning properties. The mechanical properties of foam materials are related to their compressive performances. Therefore, good static compression performance can also provide good buffering performance for foam trays. The effects of the dispersant dosage of the fibers and reinforcing adhesive on the properties of the foam trays are discussed.

3.1 Effects of the dispersant dosage of the fibers on the properties of foam trays

When using a high-concentration pre-foaming paste to prepare fiber-based foam trays by foaming again and baking in the mold, it was not suitable to set up the process of draining, which required the pulp fibers to be well dispersed at higher concentrations. As shown in Fig. 2, the pulp fibers exhibited an obvious flocculation state before dispersion. After adding an appropriate amount of dispersant to the fibers and applying shearing force, the fibers were uniformly dispersed. Other components were added to the dispersed fibers to obtain uniform and fine foam after the pre-foaming treatment. From the fiber dispersion state and the actual observation of the pre-foaming process, with the increase of the amount of dispersant from 2% to 4%, there was no obvious difference in the uniformity of fiber dispersion, but the viscosity of fiber dispersion decreased with

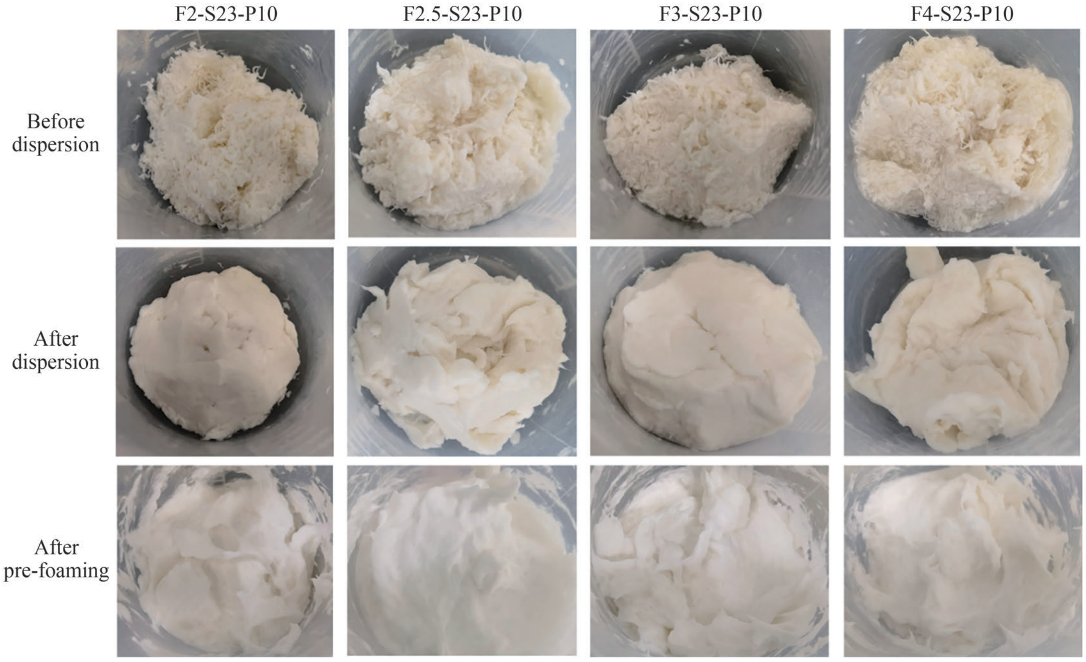

Fig. 2 Differences in states before and after fiber dispersion

dispersant dosage increasing, and the foaming property of fiber dispersion improved with the increase of dispersant dosage.

Although the fibers with different dispersant dosages could be uniformly dispersed, there were differences in the appearance and properties of the foam trays after foaming again and baking in the mold because of the differences in the rheology of the fiber pastes. Based on the morphological structure of the foam body (Fig. 3), the surface of the foam exhibited more small pores when the dispersant dosage was lower, and the number of small pores on the surface gradually decreased with increasing dispersant dosage. This may be related to the rheology of the foam paste. As the viscosity decreased, the bubble expansion resistance decreased; the bubbles could not be fixed, and it was easy to form pore mergers, resulting in a larger pore structure [4].

The dispersant dosage affected the formability and static compression performance of the foam material. As shown in Table 3 and Fig. 4, the change of dispersant dosage significantly affected the porosity and compressive resilience of the foam trays.

As the dispersant dosage increased from 2% to 4%, the porosity of the foam trays gradually decreased. Consequently, the foam density gradually increased, which is consistent with the results shown in the microscopic images of the foam trays in Fig. 3. As shown in Table 3 and Fig. 4, the static compressive strain properties and residual compressive strain of the foam trays decreased with increasing dispersant dosage. As shown in Fig. 4, for the same stress, when the dispersant dosage increased from 2% to 2.5% or 3% to 4%, the static compression strain decreased. The results also indicated that the higher the dispersant dosage, the higher the static compressive stress the foam could withstand with the same deformation. The residual compressive strain exhibited similar results. When the dispersant dosage increased from 2% to 2.5% or 3% to 4%, the residual compressive strain of the foam trays decreased, which indicates that a higher dispersant dosage results in better impact resistance. In addition, increasing the dispersant dosage improved the compression resilience of the foam trays.

3.2 Effects of reinforcing adhesive on the properties of foam trays

Although the main constituent of the degradable foam trays was cellulose fiber, a certain amount of adhesive is useful to improve the strength and reduce the occurrence of linting and dusting caused by the fine components of fibers. The adhesives used in this study

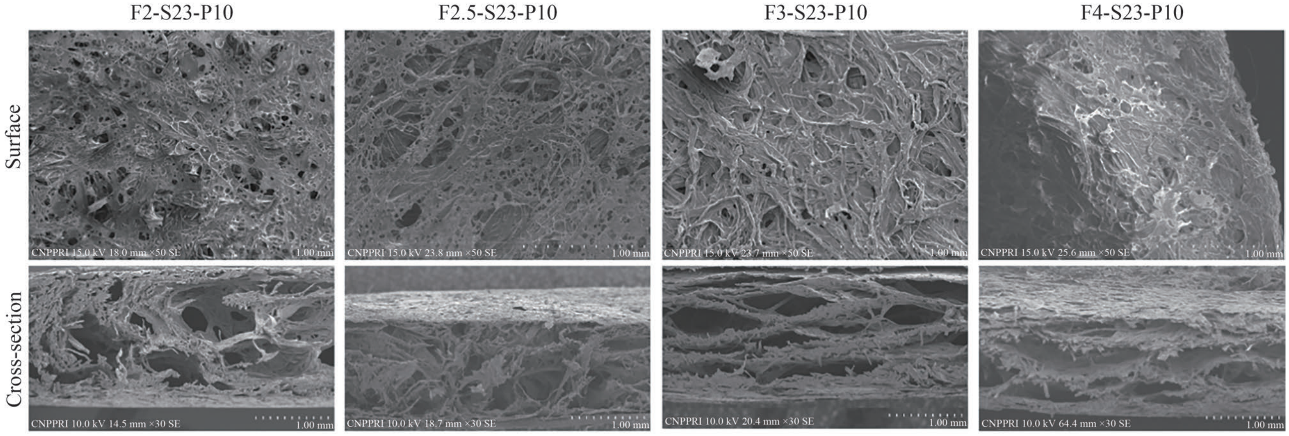

Fig. 3 SEM images of foam trays with different dispersant dosages

Table 3 Foam properties of foam trays with different dispersant dosages

Samples	Foaming rate/%	Foam density/(kg·m^{-3})	Porosity/%	Residual compressive strain/%	Compression-resilience/%
F2-S23-P10	200	196	86.7	33.1	34.7
F2.5-S23-P10	160	170	88.5	21.9	44.8
F3-S23-P10	250	198	86.6	30.9	39.4
F4-S23-P10	140	208	85.9	9.2	63.2

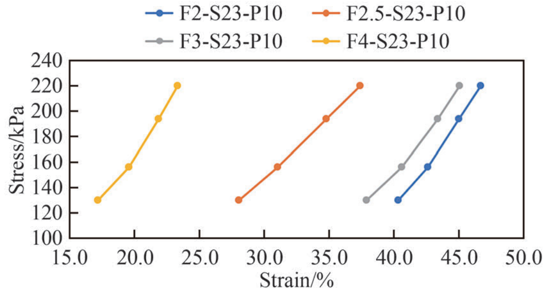

Fig. 4 Static compressive strain performance of foam trays with different dispersant dosages

were raw starch (cassava starch) and PVA. From the SEM images of foam trays with different adhesive dosages shown in Fig. 5, the change in the adhesive dosages had some effects on the morphological structure of the foam trays. Compared with F2.3-S23-P10 and F2.3-S13-P10, reduction in the cassava starch dosage reduced the porosity of the foam surface when the PVA dosage remained constant. The cross-section also clearly shows that the overall porosity decreased after reducing the cassava starch dosage. Simultaneously, the number of macropores was significantly reduced. When the cassava starch dosage remained constant, the porosity of the foam surface decreased as the PVA dosage continuously increased. The porosity displayed in the cross-section also decreased. This result shows that the porosity of the foam trays was reduced by reducing the cassava starch doasge or increasing the amount of fibers. Moverover, the porosity of the foam trays was also decreased by increasing the amount of PVA, which might be attribute to the excellent film-forming properties and high bonding strength of PVA.

The effects of increasing the adhesive dosage and reducing the amount of fiber on the properties of the foam trays are shown in Table 4. There is almost no effect of reducing the amount of cassava starch on the foaming rate. An increase in the PVA dosage slightly affected the foaming rate. The foaming rate decreased with increasing PVA dosage from 10% to 15%.

The change in the reinforcing adhesive affected the apparent and static compression properties of the foam trays. When the PVA dosage was constant and the cassava starch dosage was reduced, the porosity of the foam trays was slightly reduced, and the foam density slightly increased. However, the differences in compressive strain and compression-resilience performance were obvious. As shown in Fig. 6 and Table 4, the strain resistance of the foam trays increased significantly after

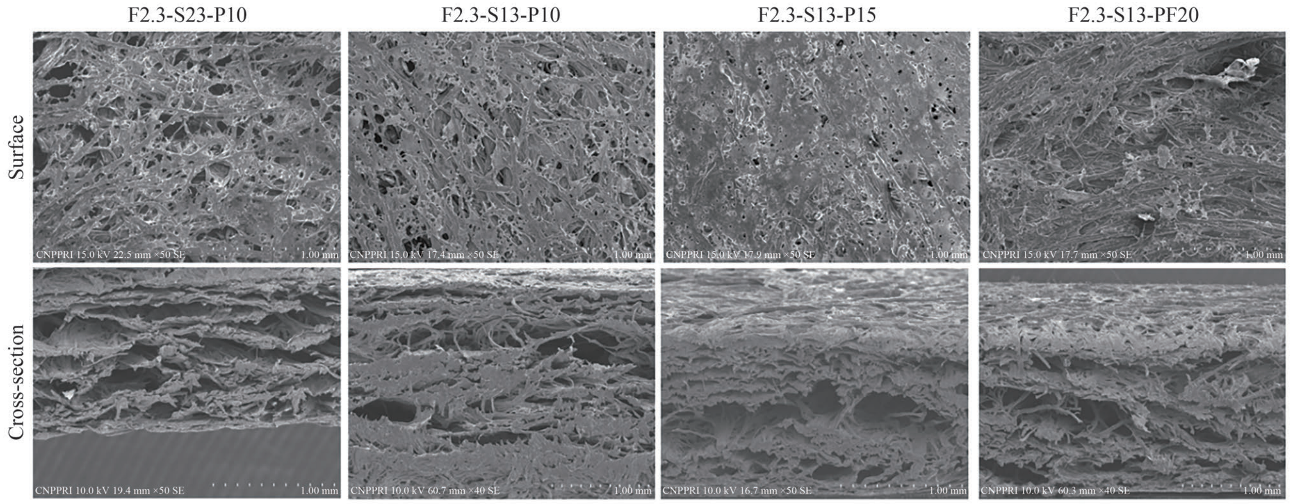

Fig. 5 SEM images of foam trays with different ratios of adhesive dosages

Table 4 Foam properties of foam trays with different ratios of adhesive dosages

Samples	Foaming rate/%	Foam density/(kg·m^{-3})	Porosity/%	Residual compressive strain/%	Compression-resilience/%
F2.3-S23-P10	200	202	86.3	36.4	30.6
F2.3-S13-P10	200	208	85.9	21.4	44.1
F2.3-S13-P15	150	230	84.4	23.7	46.3
F2.3-S13-PF20	175	257	82.6	22.8	41.4

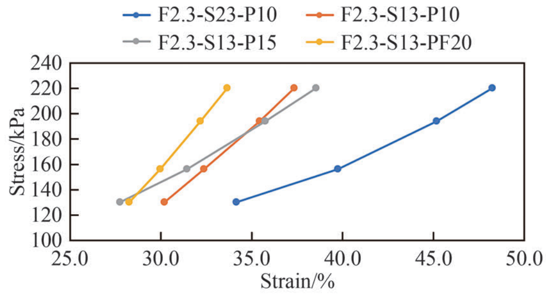

Fig. 6 Static compressive strain performance of foam trays with different ratios of adhesive dosages

reducing the starch dosage. Furthermore, the compression-resilience performance increased significantly, indicating that reduction of the starch dosage significantly improved the static compression buffer performance of the foamed trays. When the starch dosage was constant, the increase in the PVA dosage significantly reduced the porosity and increased the foam density of the foam trays, which was consistent with the pore structure shown in the microscopic photos (Fig. 5). These results may be related to the enhanced bounding strength of PVA. Since PVA was beneficial for improving the strength of the foam trays, the static compression resistance of the foamed materials was improved by increasing the PVA dosage, as shown in Fig. 6.

4 Conclusions

Degradable foam trays were prepared from cellulose fibers, PVA, and cassava starch by hot-press baking process. The bleached softwood pulp fibers were uniformly dispersed using different dispersant dosages. Different dispersant dosages affected the porosity, foam density, and static compression characteristics. From the fiber dispersion state and the actual observation of the foaming process, with an increase in the amount of dispersant from 2% to 4%, there was no obvious difference in the uniformity of the fiber dispersion; however, the viscosity of the fiber dispersion decreased with an increase in dispersant dosage. A higher dispersant dosage improved the foaming properties of the fiber dispersion. With an increase in the amount of dispersant from 2% to 4%, the porosity of the foam trays gradually decreased and the foam density gradually increased. Meanwhile, the compressive-strain performance and residual compressive strain of the material decreased.

In addition, changing the dosage of the reinforcing adhesive in the foam trays affected the physical and mechanical properties. When the amount of cassava starch was reduced or the amount of PVA increased, the porosity of the foam trays was reduced. When the amount of PVA was constant and the amount of starch was reduced, the foam density of the foam trays increased slightly. The changes in static compressive strain and compression-resilience performance were obvious. When the amount of cassava starch was unchanged and the amount of PVA was increased, the foam density of the foam trays significantly increased. Increasing the amount of PVA was beneficial to the static compression resistance of the foam trays.

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