THE IMPACT BEHAVIOR OF ECOFRIENDLY CELLULOSIC FIBER-BASED PACKAGING COMPOSITES

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Abstract. Wood–fiber composites with densities of 80, 90, and 100 kg·m^{-3} were created using a single-component polyurethane that was foamed by steam injection. The impact behavior of the composite was studied by static and dynamic tests. The dynamic impact curves of the composites were concave and upward. Decreasing densities or increasing resin content resulted in better dynamic cushioning properties. The minimum static cushioning coefficients were much lower and increased more slowly than the minimum dynamic cushioning coefficients with increases of density. Mathematical relations for minimum static and dynamic cushioning coefficients and densities were established. With the increase of initial dynamic shock stress the residual thickness–peak acceleration curve shifted to reduced residual thickness and higher peak acceleration. Dynamic maximum stresses were much higher and increased more sharply than static maximum stresses. These results can be used to optimize the structure and properties of the composites and evaluate the potential of applications in the packaging industry.

Keywords: Impact behavior, cellulosic fiber-based packaging composites, cushioning coefficients, peak acceleration.

INTRODUCTION

The problems of resource shortages and environmental pollution cause great concern worldwide. The perception of environmental risks associated with the traditional use by the packaging industry of highly persistent expanded polystyrene (EPS) foam plastics has fostered rapid development of new biodegradable cushioning materials from bioplastics (Arif et al 2007) and other biodegradable raw materials (Sang and Hettiarachchy 1999). Because of high production costs or other difficulties in the production of these new biodegradable cushioning materials, little has been reported about their practical applications for the packaging industry.

Cellulose is the most widely used natural biopolymer in the world. The potential advantages of cellulosic fiber-based materials, apart from their environmental gains, are low cost, not dependent on petroleum sources, available from renewable resources, and ability to replace some synthetic polymers (Wua et al 2009). For this reason, ecofriendly cellulosic fiber-based cushioning materials are desirable as a niche alternative for conventional foam materials (Hornberger et al 1997). Of these materials, molded pulp (Noguchi et al 1997), corrugated fiberboard (Yukiomi 2005), and honeycomb

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boards (Wang 2008) are the most widely used biodegradable cushioning materials in packaging industry. However, the preparation processes of these packaging materials are limited by slow processes of water removal (Lee and Ding 2000; Huo and Saito 2009).

For this reason, great effort had been recently applied to develop new cellulosic fiber-based packaging composites (CFMCs) by a new method of rapid steam injection technology (only 90 s preparation time) as reported previously (Liu et al 2008). The physicochemical characteristics of the composites were studied and the static compressive properties analyzed. Static compressive tests simulate the static compressed conditions of the materials in the packaging process, but this cannot indicate the actual cushioning process because the materials are dynamically compressed by products during packaging. Hence, to investigate the cushioning properties of the composites in all aspects, dynamic shock-absorbing tests are required. Dynamic shock tests are extremely important for a realistic evaluation of the cushioning properties of the materials (Hornberger et al 1997). In dynamic shock tests, the peak acceleration and cushioning coefficient are generally used to evaluate dynamic cushioning properties and hence to optimize the structural design of packaging materials (Wang 2008).

In this work, further investigations of the impact behavior of CFPCs were carried out. Dynamic and static cushioning properties of the composites were compared, and the relationships between cushioning properties and the composite structure were investigated.

MATERIALS AND METHODS

Materials

Chinese red pine (*Pinus massoniana* Lamb.) fibers were supplied by Jiangxi Oasis Wood-based Panels Co Ltd (Jiangxi, China). The fibers were prepared using a pressurized disc refiner in an medium-density fiberboard production line and were supplied in clumps. The fibers had size distributions as follows: 1) 4%, screened through $\leq$14 mesh (1.43-mm opening) sieve; 2) 80%, retained on 14-100 mesh sieves; and 3) 16%, retained on $\geq$100 mesh (0.154-mm opening) sieve. Before preparation of the composites, the fibers were at about 10% MC. The resin (MPU-20) used is an organic-soluble single-component polyurethane that was supplied by the Jingjiang City Specific Adhesive Factory (Jiangsu, China) with a density of 1150 $kg \cdot m^{-3}$ and dynamic viscosity of 8-20 $Pa \cdot s$.

Specimen Preparation

The resin was diluted with 4:1 (by weight) ethyl acetate for ease of dispersion. The resin was sprayed onto the fibers in a sealed plastic container to obtain an addition of 10-20% resin on an oven-dry fiber basis. The steam injection molding former was self-designed (Liu et al 2008) and the steam injection process included loading a mold with a measured amount of fiber/resin with a target thickness of 0.05 m and densities of 80, 90, and 100 $kg \cdot m^{-3}$ (oven-dry basis). Steam at about 400-700 kPa was injected into the mold, causing the resin to foam and crosslink to a solid state. After a holding time of 60 s, the composite was released from the mold and air-dried for 24 h.

Testing Methods

The dynamically tested samples were impacted by 0.7-27 kg hammers falling 3 m, chosen to stimulate impacts experienced by the composites in packaging applications. In these tests, peak acceleration is defined as the acceleration transferred to a protected product at a specific impact (Wang 2008). Dynamic shock tests followed D1596 (ASTM 1997). Static compressive tests were done according to GB/T8168 (GB/T 1987) at a speed of 0.2 $mm \cdot s^{-1}$. All specimens for the tests were preconditioned at room temperature (20 $\pm$ 2°C) and 64 $\pm$ 4% RH for 48 h according to ISO2233 (ISO 1986). During the dynamic shock process, signal outputs from the data collection system located in the mass block were recorded. The relationships among dynamic cushioning factor, static stress, maximum stress, and peak acceleration are described in Eqs 1-3 (Wang 2008):

$$S_m = S_s G_m \tag{1}$$

$$C = \frac{G_m t}{H} = \frac{S_m}{E} \tag{2}$$

$$e = \frac{x}{t} \tag{3}$$

where C is dynamic cushioning factor; S_s, static stress (kPa); S_m, maximum stress (kPa); G_m, peak acceleration; e, compressive strain; x, thickness of cushioning material after impact (m); t, thickness of cushioning material before impact; E, energy absorption ($kJ{\cdot}m^{-3}$); and H, drop height (m).

RESULTS AND DISCUSSION

Dynamic Impact Behavior

The relative experimental errors were estimated as ±5% for the dynamic shock tests. Figure 1 showed that the density of the composites had a significant effect on the relationship between peak acceleration and static stress. It was concluded that the composites exhibited obvious nonlinear characteristics similar to other typical cushioning materials, eg conventional EPS foams (Miltz et al 1989) and molded pulps (Eagleton and Marcondes 1994). It was found that the peak acceleration vs static stress curve from 80 $kg{\cdot}m^{-3}$ samples showed an upward trend, and the 90 $kg{\cdot}m^{-3}$ samples showed a relative slight upward trend. The 100 $kg{\cdot}m^{-3}$ sample, however, exhibited a downward trend. These results indicated that with increasing density, the minimum peak acceleration increased and also occurred at higher stress (as shown in Fig 1). Lower peak acceleration reduces the probability of impact damage to products, resulting in better protection (Wang 2008). The results suggested that the composites with lower densities absorbed more shock energy and had better cushioning efficiencies under the same shock stress conditions. This trend agrees well with static compressive tests in previous work (Liu et al 2008) and for molded pulp materials (Noguchi et al 1997) but is opposite the trend observed for paper honeycomb sandwich panels (Wang 2008).

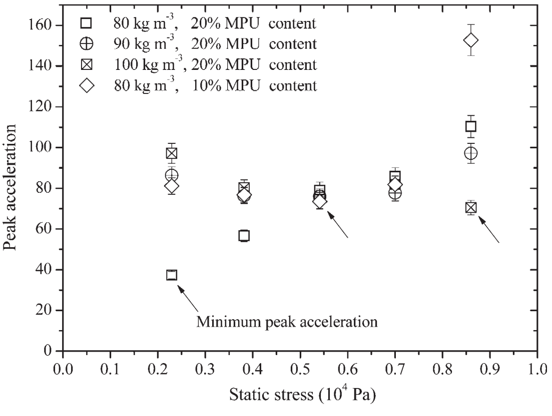

Figure 1. Dependence of technical conditions on peak acceleration–static strain curves.

Figure 1 indicated that decreasing the resin from 20 to 10% increased the minimum peak acceleration. This showed that composites with higher resin levels have better cushion efficiencies or can reduce shock acceleration under the same shock stress conditions. Additional resin in the matrix provided more efficient foaming and grafting reactions. This conclusion has also been supported by static compressive tests (Liu et al 2008).

In the relationship of peak acceleration and static strain, the 80 and 90 $kg{\cdot}m^{-3}$ samples had the same minimum peak acceleration of 31.67 ± 1.58 at a static strain of 2%, while the 100 $kg{\cdot}m^{-3}$ sample had a minimum peak acceleration of 85.82 ± 4.29 at a static strain of 0.4% (Fig 2). Composites with higher densities have higher rigidities but less elasticity and therefore poorer shock absorbing properties. From Fig 2, the 80 $kg{\cdot}m^{-3}$ sample with 10% resin had a minimum peak acceleration of 67.46 ± 3.37 at a static strain of 13%, which was greater than that obtained by using 20% resin. This can be explained in that reducing resin content resulted in lower grafting and foaming reactions, resulting in poorer mechanical strength as well as poorer energy absorbance.

Figure 3 showed dependence of shock strain on the peak acceleration–residual thickness curves of the 80 kg·m^{-3} samples. It was found that by varying the initial shock strain, residual thicknesses of the composites decreased nearly linearly with an increase of peak acceleration. As initial shock strain increased from 2.29 to 8.60 kPa, the peak acceleration–residual thickness curves were shifted to a higher peak acceleration and also a smaller residual thickness. The explanation is that higher initial shock strain resulted in more shock energy applied per unit area of the test samples even at the same density. The results suggested that the composites were best suited for packaging small but not heavy products.

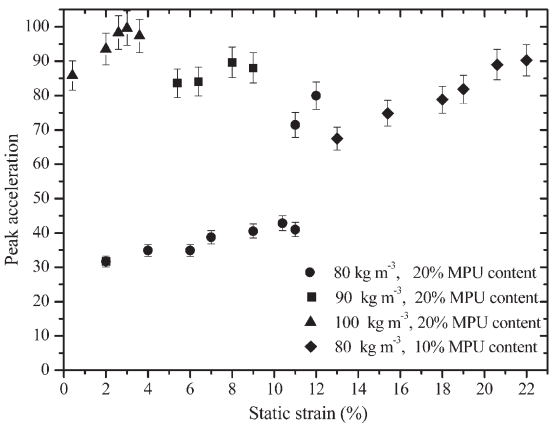

Figure 2. Dependence of technical conditions on peak acceleration–static stress curves.

Comparisons of Dynamic and Static Cushioning Coefficients

The cushioning coefficient is the one of most important parameters for defining cushioning properties in the design of packaging materials. As can be seen from Eq 2, a lower cushioning coefficient indicated that a test sample absorbs more shock energy per unit volume. Hence the minimum cushioning coefficient is desired for optimal design of cushioning materials (Gruenbaum and Miltz 1983). In this article, the minimum cushioning coefficient (*Mcc*) is derived from the minimum static cushioning coefficient (*Mscc*) and the minimum dynamic cushioning coefficient (*Mdcc*), and is considered as a metric for the evaluation of cushioning properties of the composites.

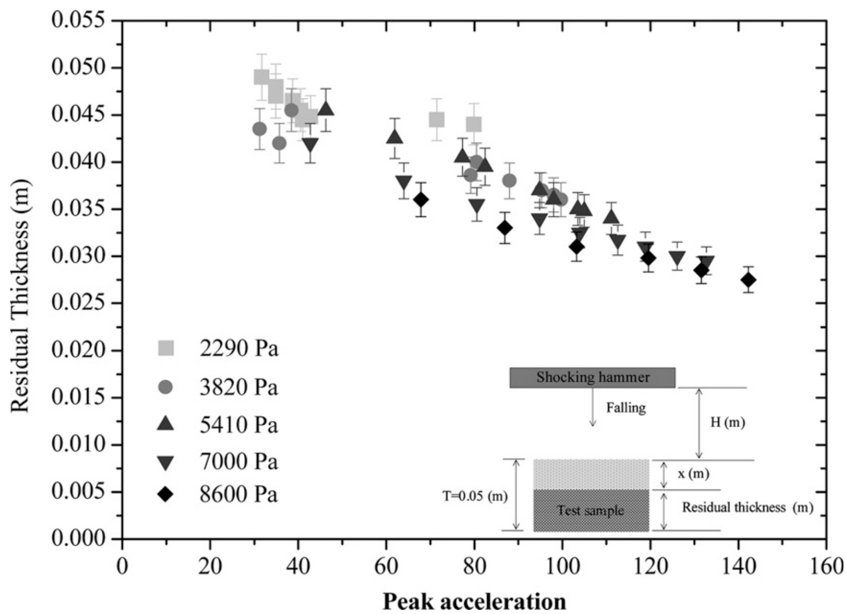

Figure 3. Dependence of initial shock strain on the peak acceleration–residual thickness curves.

Figure 4 suggested that the *Mcc* of the composites was different when they were tested by the two methods described previously and that *Mscc* of the test samples was much lower than *Mdcc*. This can be explained by noting that in the static compressive process, the test sample absorbed the deformation energy more slowly in a relatively longer time, while in dynamic shock, the test sample absorbed energy in a very short impact period. In the static and the dynamic processes, there were different possible mechanisms of foam void deformation. It was also observed that *Mscc* increased more slowly with an increase of density than *Mdcc*.

Data were processed to find mathematical relations between *Mcc* (eg *Mscc*, *Mdcc*) and densities. As seen in Fig 5, it was found that the calculated Y_1 value has a linear and Y_2 a second-degree parabolic relationship with densities from 80 to 100 kg·m^{-3} with an R^2 value of 1.00. These relationships can be described by Eqs 4 through 8:

$$Y_1 = Exp(0.8\ Mdcc) \quad (4)$$

$$Y_1 = A_0 + B\rho \quad (5)$$

where A_0 is –98700, B is 1230, and ρ is density.

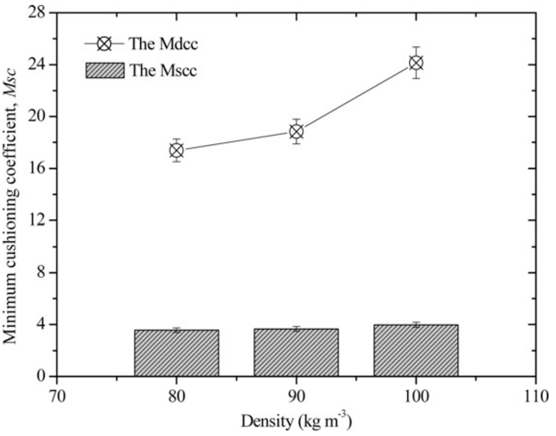

Figure 4. The comparisons of the minimum static cushioning coefficient (*Mscc*) and the minimum dynamic cushioning coefficient (*Mdcc*) for different densities.

Therefore, Eq 6 can be derived from Eqs 4 and 5 showing that *Mdcc* had a logarithmic trend with density.

$$Mdcc = 1.25\ln(-98700 + 1230\rho) \quad (6)$$

In addition, Eq 9 can be derived from Eqs 7 and 8, in which *Mscc* has a logarithmic trend with density.

$$Y_2 = Exp(0.8\ Mscc) \quad (7)$$

$$Y_2 = K_0 + A\rho + B\rho^2 \quad (8)$$

where K_0 is 145, A is –3.13, and B is 0.0193;

$$Mscc = 1.25\ln(145 - 3.13\rho + 0.0193\rho^2) \quad (9)$$

Comparisons of Maximum Stress

According to Eq 1, the maximum stress is determined by the peak acceleration and static stress during dynamic shock. Figure 6 illustrates the variations of maximum stresses response to compressive strains in the 80 kg·m^{-3} test samples in static compression and dynamic shock. The results showed that maximum stresses of the composites tested by dynamic shock were much higher than those obtained by static compression. Eq 10 shows the mathematical relation between maximum stress (S_m) and compressive strain (e) in dynamic shock:

$$S_m(e) = -17.9 + 21.7 \times e - 0.524 \times e^2 + 0.0138 \times e^3 \quad (10)$$

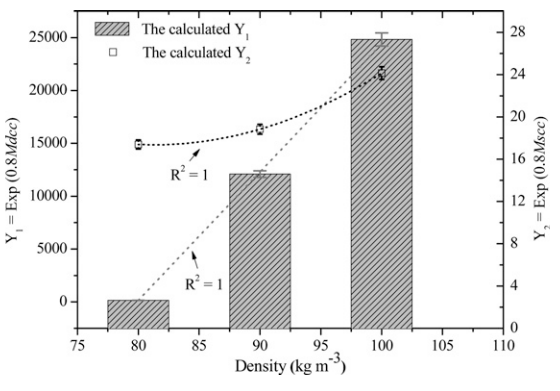

Figure 5. The mathematical relations of minimum cushioning coefficients (*Mcc*) and density.

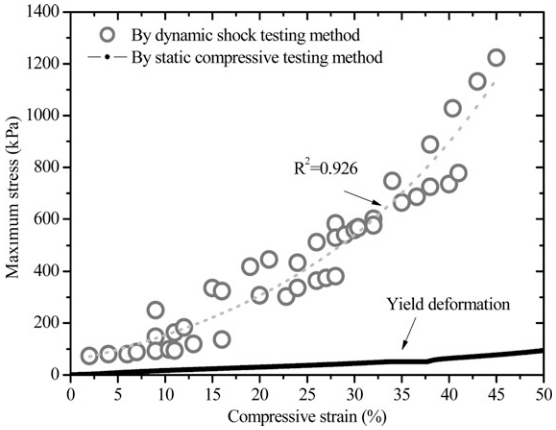

Figure 6. The experimental comparisons of dynamic shock tests and static compressive tests on the maximum stress–compressive strain curves.

However, the maximum stress of the 80 kg·m^{-3} test sample by static compression increased more slowly compared with that from dynamic shock. It should also be noted that the yield-deformation stage observed in static compression was verified in a previous study (Liu et al 2008). This was similar to that of a paper honeycomb sandwich (Wang et al 2009). These results can be explained in that the accelerations produced during dynamic shock caused greater stress when compared with compression at 0.2 mm·s^{-1} during static compression.

Technical–Economic Impact Analysis

The new cushioning CFPCs are biodegradable and recyclable compared with nonbiodegradable foam plastics. The prevalent biodegradable cushioning products of molded pulp (Asensio and Nerín 2006) and corrugated pulp (Biancolini and Brutti 2003) on the market are mainly manufactured by vacuum or hydraulic pressure molding (Lee and Ding 2000; Huo and Saito 2009). The other biodegradable product of honeycomb paperboard (Wang and Wang 2008), however, has considerably more complex process flows and is marginally recyclable. Honeycomb paperboard has a longer production time compared with the new cellulosic composite preparation (only about 90 s). The production cost of this new composite, including raw material, chemical agents, equipment depreciations, utilities, and labor costs, is about 2.5-3.0 RMB·kg^{-1} (0.36-0.44 US$·kg^{-1}). The production of CFPCs has a considerably lower cost than the common biodegradable products. The composites are recyclable at end-of-life and were better suited for packaging smaller products as supported by the results. Industrial–agricultural wastes such as waste wood, rice straw, or bagasse available in rural areas are considered as potential raw materials and will be studied in the future.

CONCLUSIONS

To determine the cushioning properties of the CFPCs, resin content and density were investigated for their effects on impact behavior. Cushioning coefficients were obtained by static compression and dynamic shock. The results showed that, with increasing density, minimum peak acceleration increased and occurred at higher stresses. Additional resin resulted in better cushion efficiencies because of acceleration under the same shock stress conditions. In dynamic shock, the peak acceleration–residual thickness curves shifted to higher peak accelerations and had smaller residual thicknesses as initial shock strain increased from 2.29 to 8.60 kPa. Residual thickness decreased nearly linearly with an increase in peak acceleration. *Mscc* of the test samples were much lower than *Mdcc*. Mathematical relations were established between the minimum cushioning coefficient (*Mcc*) and density. The maximum stresses in dynamic shock were much higher than those obtained by static compression. Because of the ease of manufacture, low environmental pollution, and low cost, the composites are market-competitive and show promise as a new cushioning material for the packaging industry.

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