Applied Polymer
JOURNAL OF — SCIENCE

Polylactide Foams Prepared by a Traditional Chemical Compression-Molding Method

Yu Luo,[1] Jiuli Zhang,[1] Rongrong Qi,[1] Jiaqi Lu,[1] Xinli Hu,[1] Pingkai Jiang[2]

[1]School of Chemistry and Chemical Engineering, Shanghai Jiao Tong University, Dongchuan Road 800, Shanghai 200240, China
[2]Shanghai Key Lab of Electrical Insulation & Thermal Aging, Shanghai Jiao Tong University, Dongchuan Road 800, Shanghai 200240, China
Correspondence to: R. Qi (E-mail: rrqi@sjtu.edu.cn)

ABSTRACT: To reduce environmental pollution and oil shortages, biodegradable polylactide (PLA) from plants was used to replace synthetic plastic from petroleum. In this study, high-melt-viscosity PLA was achieved through the *in situ* reaction of carboxyl-ended polyester (CP) and solid epoxy (SE) first; then, PLA foams were successfully prepared by a chemical compression-molding method. The detailed foaming factors were also studied, including the decomposition temperature of the blowing agent, the foam temperature, and the open-mold temperature. The results reveal that the obtained PLA foams had good water absorption and degradable properties, and the foam density was low as 0.16 g/cm^3. Moreover, the effects of the CP/SE concentration and the AC content on the properties of the foams were also investigated. © 2013 Wiley Periodicals, Inc. J. Appl. Polym. Sci. 130: 330–337, 2013

INTRODUCTION

Because of increasing environmental concerns and decreasing fossil resources, polylactide (PLA) is getting more and more attention because of its environmentally friendliness and low price compared to other biodegradable materials.[1] PLA foams are also potential alternatives to common nondegradable foam materials for applications with short life spans because of their unique characteristics, especially in the biomedical, environmentally friendly packaging, and agriculture fields.[2,3] They also possess common properties similar to other foam materials, such as a light weight, low thermal conductivity, and acoustic absorption.[4,5]

The chemical compression-molding method is a traditional foam methods with the advantages of simple equipment and easy operation,[6] and many polymer foams, such as ethyl vinyl acetate, polyethylene, and polyvinyl chloride, have been prepared with this method.[7,8] Generally, commercial PLA is usually prepared through the condensation polymerization route, and the lower molecular weight of the obtained PLA leads to its low complex viscosity and melt strength. PLA foam materials are usually prepared through a physical foaming method, such as an extrusion foaming process or a supercritical CO$_2$ foaming method. Lee et al.[9] studied the expansion dependency of the amount of blowing agent and cell density on PLA resins by an

extrusion process, but its density was as high as 0.5 g/cm^3. Dong et al.[10] prepared biodegradable microcellular PLA/silk fibroin powder composites by a solution processing technique. Then, composites foams were successfully prepared by supercritical CO$_2$. Richards et al.[11] systematically investigated the effect that the blending of two biodegradable polymers [PLA and poly(hydroxybutyrate-*co*-valerate)] had on the thermal properties and morphology of the resultant foams blown with CO$_2$. Ema et al.[12] investigated the cellular structures of PLA-based nanocomposites in various ranges of foaming temperature and CO$_2$ pressures with scanning electron microscopy (SEM) and transmission electron microscopy. They found that PLA-based nanocomposite systems provided excellent nanocomposite foams because the dispersed nanoclay particles acted as nucleating sites for cell formation and cell growth. Georgiou et al.[13] made use of the supercritical CO$_2$ method to form degradable phosphate glass incorporated PLA composite foams that may be applied in bone tissue engineering.

To prepare foams by the chemical compression-molding method, it is necessary to increase the melt viscosity and strength of PLA because the low complex viscosity and melt strength of PLA are far from stable and cause rupturing bubbles during the foam process,[14] and various studies have recently been done to improve their melt rheological properties. For example, Di et al.[15] modified PLA with organized layered

Table I. PLA Compound Formulations and Mold-Opening Temperature for the Foaming Process

Sample		PLA (wt %)	Ac (wt %)	ZnO (wt %)	CP (wt %)/SE (wt %)	Mold-opening temperature (°C)
Effect of the mold-opening temperature	O1	69.2	7.7	7.7	7.7/7.7	120
	O2	69.2	7.7	7.7	7.7/7.7	100
	O3	69.2	7.7	7.7	7.7/7.7	80
Effect of the CP/SE concentration	C1	76	8	8	4.0/4.0	100
	O2	69.2	7.7	7.7	7.7/7.7	100
	C3	57.1	7.2	7.2	14.4/14.4	100
Effect of the AC content	A2	77.6	2.6	2.6	8.6/8.6	100
	B2	75	4.2	4.2	8.3/8.3	100
	O2	69.2	7.7	7.7	7.7/7.7	100
	D2	66.2	9.6	9.6	7.3/7.3	100

silicates to improve their melt viscosity, and nanocomposite foams were successfully prepared; Gu et al.[16] first oligomerized a low-molecular-weight, hydroxyl-terminated prepolymer with a lactic acid monomer and then obtained a high-molecular-weight PLA with a high complex viscosity with 1,6-hexamethylene diisocyanate as a chain extender. Dominik et al.[17] proposed the concept of preparing open-cell foams from PLA and PS or PLA and PMMA blends, in which the blends were prepared by the polymerization of either styrene or methyl methacrylate in a PLA matrix to constitute interpenetrating polymer networks. The melt viscosity of PLA could also be increased by γ-irradiation and electron-beam-irradiation crosslinking or chemical crosslinking;[18,19] Mitomo et al.[20] first reported that about an 84% gel fraction was obtained when PLA was irradiated at 50 kGy in the presence of 3% triallyl isocyanurate. Nevertheless, the radiation apparatus is expensive, and the PLA products must be in the form of thin plates to get enough energy from the radiation to initiate the crosslinking reactions in the irradiation crosslinking of PLA materials; this limits its practical applications in the field of foams. Nijenhuis et al.[21] obtained a gel fraction of 100% at high peroxide (dicumyl peroxide) concentrations (13–25 wt %) and high curing temperatures (192°C) in crosslinking research of PLA. Although studies with increasing viscosities and melt strengths of PLA are essential for preparing PLA foams, many other factors should be taken into consideration to obtain ideal foam materials. On the other hand, few studies in past years have been reported in which PLA foams were prepared by a chemical compression-molding method.

Our previous studies[22] indicated that the complex viscosity of PLA could be significantly increased (over two orders of magnitude) by the *in situ* crosslinking reaction of carboxyl-ended polyester (CP) and solid epoxy (SE) during the blending process. Thus, in this study, degradable PLA foam articles were successfully prepared through a chemical compression-molding process, and the lowest foam density of 0.15 g/cm³ was obtained. Furthermore, the effects of various factors, such as the matching of the CP/SE crosslinking reaction temperature and the blowing agent [azodicarbonamide (AC)] decomposition temperature, foam temperature, and open-mold temperature, on the foaming process are discussed in detail. The effects of the CP/SE and AC content on the properties of the foams, such as the density, mechanical properties, water absorption, degradation, and morphology of the foams, were also investigated.

EXPERIMENTAL

Materials

PLA [3051D, number-average molecular weight = 93,500 g/mol, melt flow rate (210°C, 2.16 kg] = 25 g/10 min, specific gravity = 1.25 g/cm³) was purchased from NatureWorks LLC (Houston, TX).

CP (P5980, weight-average molecular weight = 3000 g/mol as determined by gel permeation chromatography) and SE (E903, epoxy equivalent = 700 g/mol as determined by the technical parameters) were kindly supplied by DSM (Heerlen, Holland).

AC was manufactured by Shanghai Xiangyang Chemical Co., Ltd. (Shanghai, China).

Zinc oxide (ZnO) was an industrial-grade product purchased from Shanghai Yuanji Chemical Co., Ltd. (Shanghai, China).

Antioxidants 1010 and 168 were purchased from Ciba Specialty Chemicals (Shanghai, China).

Sample Preparation

To keep the samples sufficiently dry, the drying conditions of samples (PLA, CP, and SE) were as follows. PLA pellets were dried *in vacuo* at 60°C for 12 h before they were used.[23] CP and SE powders were dried *in vacuo* at 50°C for 12 h before blending. Then, the PLA compounds were mixed with the ingredients according to the formulation in Table I at 150°C with a Haake Rheocord Torque Rheometer 90 (Mess-Technic GmbH, Germany, Sankt Augustin). The mixing temperature was set at 150°C, the rotor speed was 60 rpm, and the mixing time was 5 min. Then, the compounds were taken out of the mixing chamber to form a sheet and stored at room temperature for 24 h before foaming. Finally, the compounds were pressed in a closed mold (145 × 145 × 6 mm³) with a pressure of 16 MPa for 10
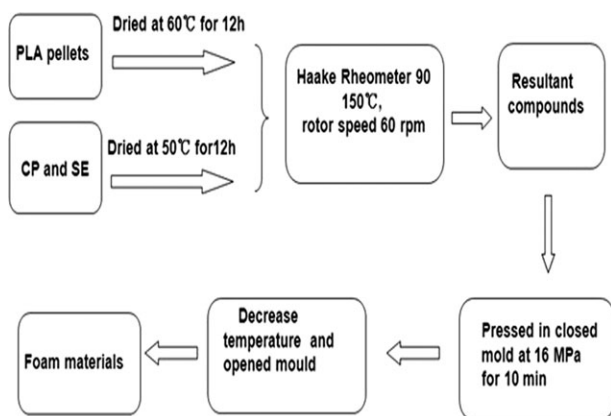
Scheme 1. Process of preparing PLA foams.

min, and then, the PLA foams were obtained through the decrease of the mold temperature to a certain value. Then, the mold was opened. The prepared foams were kept at room temperature 24 h for structural characterization and property measurements. The detailed foaming process is shown in Scheme 1.

Thermogravimetric Analysis (TGA)

TGA was conducted on a TGA7 thermal analysis system from PerkinElmer Co. (Waltham, MA) at a heating rate of 20°C/min under a flowing nitrogen atmosphere. The temperature scan ranged from room temperature to 400°C.

Rheological Properties

For the study of PLA and its composite rheological behaviors, the samples were pressed into 1 mm thick plates at 180°C. The rheological measurement was carried out on a Gemini 200 rheometer (Bolin Instruments, Inc., East Brunswick, NJ). A frequency sweep for the samples was carried out under nitrogen at 190°C with 25-mm plate–plate geometry, and the sample gap was set at 0.5 mm. A strain sweep test was initially conducted to determine the linear viscoelastic region of the materials. The strain and angular frequency range used during testing were 5% and 0.01–100 rad/s, respectively. Gemini 200 software was used to acquire the data.

The rheological measurements (the vulcanization and blowing characteristics) for the precured PLA compounds were conducted with a moving die processability tester (i.e., an moving die rheometer (MDR); model UCAN-2030, U-Can Dynatex, Inc., Nantou, Taiwan) according to ASTM D 5289. The MDR was equipped with a pressure sensor at the upper die. It could detect the pressure of the PLA compound during the PLA vulcanization in the mold.

Mechanical Testing

The density was calculated from the mass and volume of the cylinder specimens with a surface skin according to ISO 845-1988. The void fraction (VF) was calculated by the equation VF = 1 − ρ_f/ρ, where ρ is density of the unfoamed sample and ρ_f is density of the foamed sample. The hardness was measured with a Shore C durometer according to ISO 2439-1980 (TH200, force = 144 g, Cany Precision Instruments Co., Ltd., Shanghai, China). The stress–strain properties (tensile strength and elongation at break)

were determined on a universal electromechanical tester (Instron 4465, Instron Corp., Grove City, PA) at room temperature (25 ± 2°C) according to ASTM D 3574-86 and a tensile speed of 50 mm/min. At least five sample replicates were tested to obtain the average values of the different properties.

SEM

The cellular morphological analysis was carried out on freeze-fractured samples in liquid nitrogen and the corresponding cross sections with a sputtered gold coating, and the core layer of foam was observed by SEM (model S-2150, Hitachi, Chi City, Japan).

The areas of the cells were manually traced from the SEM micrographs with JMicroVision 1.2.7 software.[24] The individual cell size was then calculated by approximation of the cells as circular shapes. The average size of the cells and the average wall thickness were calculated from a survey of over 40 cells.

Thermal Properties

Differential scanning calorimetry (DSC) was carried out with a TA instrument (Q2000, TA Instruments, New Castle, DE) at a heating rate of 10°C/min, under a nitrogen flux.

Water Absorption Properties

The water absorption percent was calculated according to GB/T 18942.1-2003 with a specimen size of 150 × 150 × 25 mm³. After the specimen totally immersed in water for 96 ± 1 h, we took it out and wiped the water off of the surface and then kept it for 3 min before testing. The water absorption percentage was determined by eq. (1) as follows:

$$\varphi = (m_2 - m_1)/m_1 \times 100\% \tag{1}$$

where ϕ is the water absorption percentage of the PLA foams, m_1 is the weight of the specimen before immersion, and m_2 is the weight of the specimen after immersion.

Degradable Properties

The degradable properties of the PLA foams were calculated according to ASTM D 2126-1999 with a specimen size of 100 × 100 × 25 mm³. After the specimen was totally immersed in NaOH solution (1 mol/L) for a week, it was taken out, and we wiped the solution off of the surface and then kept it for 24 h before testing.[25] The degradation percentage was determined by eq. (2) as follows:

$$A = (M_1 - M_2)/M_1 \times 100\% \tag{2}$$

where A is the degradation percentage, M_1 is the weight of the specimen before immersion, and M_2 is the weight of the specimen after immersion.

RESULTS AND DISCUSSION

In this study, a traditional chemical compression-molding method (with dicumyl peroxide as the curing agent and AC as the blowing agent) was used to prepare PLA foam materials directly. Although various conditions, including the foam temperature, curing agent content, and blowing agent concentration, were used to prepare the PLA foams, the experiment still failed because of the low complex viscosity of PLA. So, we must
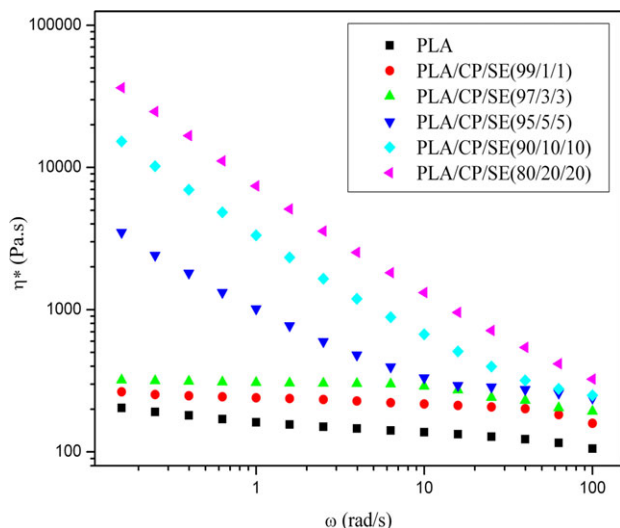
WILEYONLINELIBRARY.COM/APP **WILEY** ONLINE LIBRARY

Figure 1. Viscosity (η^*) values of the PLA and PLA/CP/SE composite.[22] [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

increase the complex viscosity of PLA to obtain ideal PLA foams. In previous studies, we found that the complex viscosity of PLA could be greatly improved by the *in situ* reaction of CP and SE (depicted in Figure 1). As shown in Figure 1, the viscosity of PLA increased significantly (over two orders of magnitude) with increasing CP/SE loading, especially in the low-frequency region. This phenomenon was closely associated with the crosslinking reaction of CP and SE and the reaction between SE and PLA.[22] On the basis of previous results, PLA foams were prepared through a chemical compression-molding method.

Process Conditions

The effects of the process conditions on the PLA foam material are discussed according to the formulation shown in Table I.

Effect of the Activators. The temperature is very critical in the production of PLA foams because it affects the decomposition rate of the chemical blowing agent (AC), the reaction between SE and CP, and the melt viscosity of the polymer, which will further directly influence cell nucleation, growth, and stabilization and the retention of foams.[26,27] In general, a suitable process for producing foams is that the chemical blowing agent can start to decompose when the melting and crosslinking of PLA have occurred. Our previous studies[22] revealed that the proper reaction temperature of SE and CP was 180°C, whereas the decomposition temperature of AC was beyond 200°C. This means that the decomposition of AC did not start when the reaction of SE and CP was completed. To tune the reaction temperature and obtain the optimum foaming parameters, effective additives have to be added to regulate the decomposition temperature of AC. Previous works[28,29] indicated that certain amounts of ZnO could decrease the decomposition temperature and accelerate the decomposition rate of AC. From the decomposition behavior of AC (Figure 2), one can see that ZnO can effectively decrease the decomposition temperature of AC, and the starting decomposition temperature went to 180°C

when the weight ratio of AC to ZnO was 1/1; this was consistent with the crosslinking reaction temperature of CP/SE.

Effect of the Temperature on the Relationship between the CP/ SE Vulcanization and Blowing Agent Decomposition. Generally speaking, matching the rate of vulcanization and the blowing agent decomposition is the key to producing perfect foams because bubble expansion is accomplished through heating, and they need to be stabilized by the simultaneous crosslinking of the polymers.[30] Liu[31] investigated the kinetics of blowing and crosslinking reactions and measured the crosslinking reaction, the blowing rate constants, and the activation energy by rheometry. Because the decomposed gas either dissolved under high pressure or formed microbubbles in the matrix and the rheometric torque was basically consistent with the crosslinking degree of matrix, the effect of the temperature on the curing characteristics of the preprepared sample (C2) was investigated and is shown in the rheographs curves at different temperature (Figure 3).

As shown in Figure 3, both the CP/SE vulcanization and blowing agent AC decomposition accelerated with increasing temperature. The crosslinking reaction of CP and SE was rapidly complete in 150 s at 190°C; this was earlier than that the decomposition of the blowing agent AC ($\sim$ 200 s). Moreover, at 190°C, both the crosslinking reaction of CP and SE and the decomposition rate of AC were too quick for the gas to diffuse and grow, so it was difficult to obtain a good PLA foam. When the temperature was 170°C, the decomposition of AC started at a time of 450 s and finished in 600 s, whereas the reaction of CP and SE was not yet completed after 600 s. However, at 180°C, the blowing agent started to decompose at a time of 250 s, and the complex viscosity of the composite material increased to an extent that part of the CP and SE had completed the reaction. This situation was beneficial for the bubbles to grow and stabilize. Therefore, a temperature of 180°C for 10 min may be suitable for the production of PLA foams.
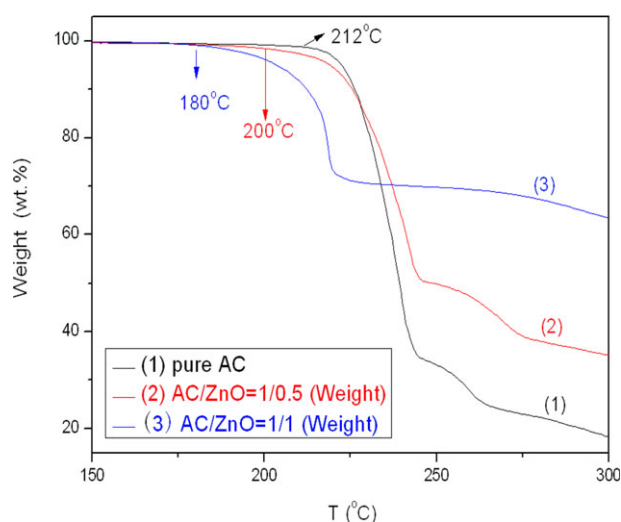

Figure 2. TGA curves of (1) AC, (2) 1/0.5 AC/ZnO, and (3) 1/1 AC/ZnO. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]
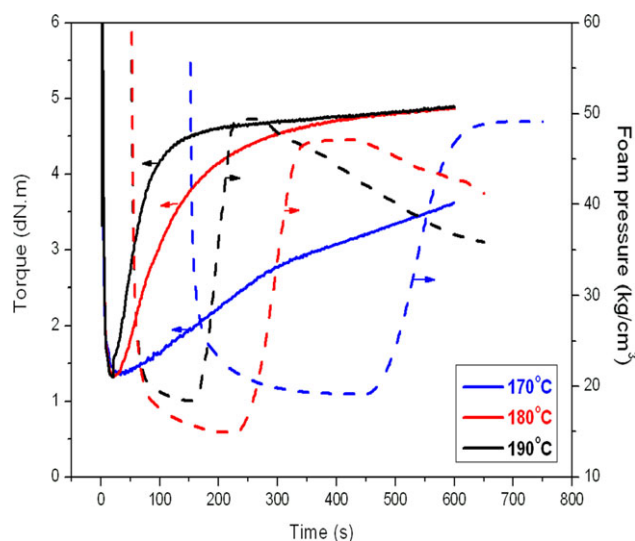
Figure 3. Rheographs and blowing curves of C2 at different temperatures (solid-torque, dash-foam pressure). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Effect of the Mold-Opening Temperature. Although the previous works indicate that the optimum process conditions for the PLA foams were 180°C for 10 min, the PLA foams still could not be obtained by the opening of die directly at 180°C because the complex viscosity of PLA was not high enough. It is well known that for PLA melt fluid, the lower temperature is, the higher viscosity is. Therefore, to acquire ideal foams, the mold should be quickly cooled and opened at temperatures from the glass-transition temperature (T_g) to the melting temperature of PLA after it is reacted at 180°C for 10 min. The DSC results for pure PLA and the compound without blowing agent are given in Figure 4. As shown in Figure 4, pure PLA and the compound without blowing agent showed the same thermal performances.
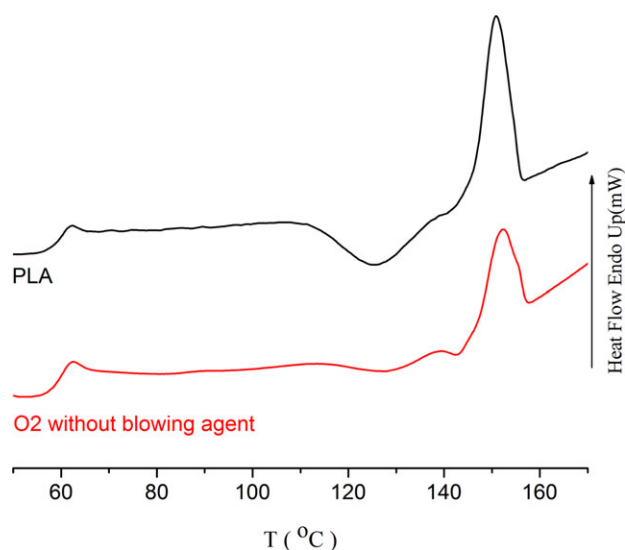

Figure 4. DSC thermograms of the compounds without blowing agent. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table II. Effects of Different Mold-Opening Temperatures on the Properties of the PLA Foams

Sample	Density (g/cm^3)	VF (%)	Average size of the cells (μm)	Average wall thickness (μm)
O1	0.15	88	210	40
O2	0.16	78.8	180	50
O3	0.16	78.8	105	103

Foaming temperature = 180°C. O2 as an example.

Also, there were three peaks for T_g (58°C), temperature of crystallization on cooling (T_{cc}) (125°C), and the melting temperature (150°C), respectively.

On the basis of many pre-experiments, the optimum mold-opening temperature was set to 80–120°C because a low viscosity would have led to the rupture of bubbles when the temperature was higher than 120°C, and not enough bubbles grew when the temperature was lower than 80°C. The results for different mold-opening temperatures are listed in Table II. From Table II, one can see that the foam density increased with decreasing open-mold temperature, and VF showed the opposite phenomenon. This was because the complex viscosity of PLA increased with decreasing temperature; this was not good for gas diffusion in the matrix.[32] On the other hand, PLA was in a high-elastic state in the range of 80–120°C, and the material deformed easily under an external force; this was also beneficial for the formation and growth of bubbles and, further, for foam preparation. Nevertheless, foams were not easily formed below 80°C because the temperature was close to the T_g and could freeze the movement of chain segments. From the SEM micrographs of the PLA foams processed at different mold-opening temperatures (Figure 5), one can see that PLA foams with a closed-cell structure with few open cells were successfully prepared, and the wall thickness of the foams had some differences. The foam wall could easily rupture at a high temperature (120°C), and this resulted in the merging of bubbles. As shown in Figure 5 and Table II, the average size was large and the average thickness was thin at 120°C. This was because the partly cooled crystal also hindered gas diffusion (120°C was close to the T_{cc}). However, the foam wall was too thick, and the size of the cell was small at a low temperature (80°C), whereas relatively uniform bubbles were obtained at 100°C. This was because an appropriate low temperature improved the viscosity of PLA at 100°C. So, 100°C was used as the optimum mold-opening temperature in the following experiments.

Effect of the CP/SE Concentration and AC Content on the Properties of the PLA Foams. From the previous experiments, the optimum processing conditions for the PLA foams were as follows: foaming temperature = 180°C for 10 min and open-mold temperature = 100°C. Here, the influence of the CP/SE concentration and blowing agent content on the properties of the PLA/CP/SE composite foams are discussed under these conditions.

Effect of the CP/SE Concentration on the Properties of the PLA/CP/SE Composite Foams. From previous results, we know
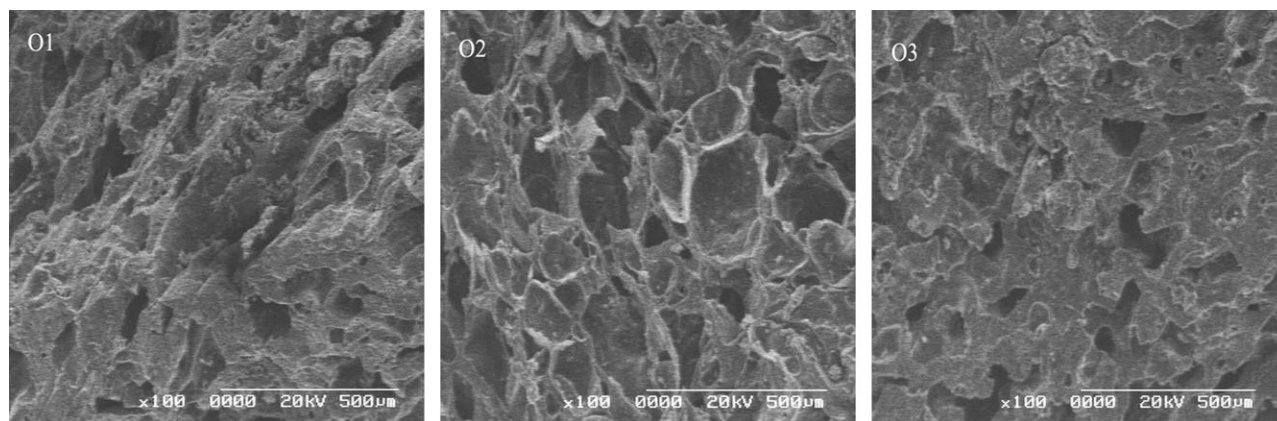
Figure 5. SEM micrographs of the PLA foams as a function of the opening-molding temperature: (O1) 120°C, (O2) 100°C, and (O3) 80°C.

that PLA foams can be successfully obtained because of the high complex viscosity of PLA by the *in situ* reaction of CP/SE and the optimum foaming conditions. To study the effect of the CP/SE concentration on the properties of PLA foams, PLA foams with different CP/SE concentrations (Table I) were prepared. In the reaction of CP and SE, PLA could react with SE simultaneously and accomplish the process of crosslinking. Thus, the wall thickness of the bubbles increased, and the size of the cells decreased with increasing CP/SE concentration because the complex viscosity of the composite increased with increasing CP/SE concentration (Figure 6 and Table III), and better foams could be obtained when the CP/SE concentration was 7.7/7.7 w/w.
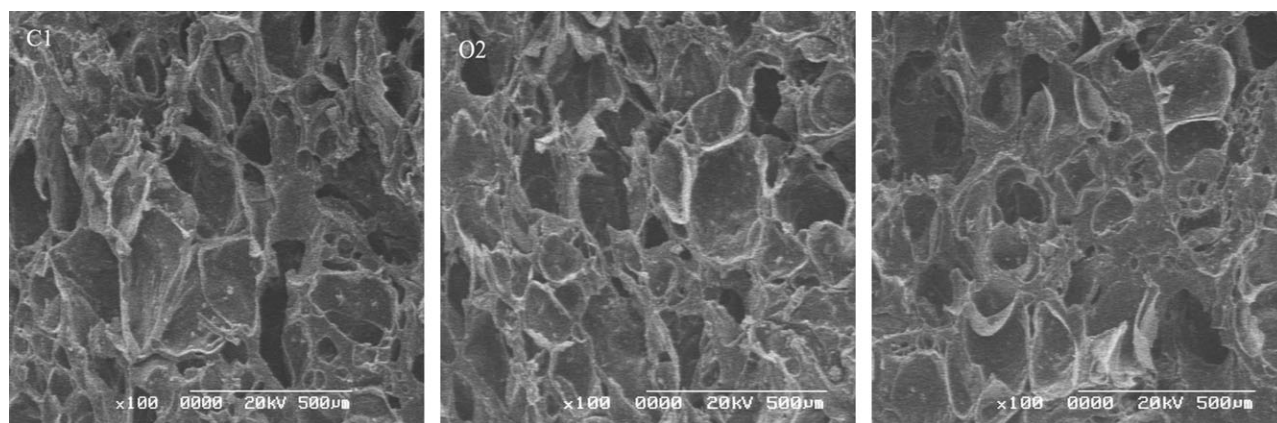

Figure 6. SEM micrographs of the PLA foams as a function of the CP/SE concentration: (C1) CP/SE = 4.0/4.0 wt %, (O2) CP/SE = 7.7/7.7 wt %, and (C3) CP/SE = 14.4/14.4 wt %.

Table III. Effect of the CP/SE Concentration on the Properties of the PLA Foams

	Sample			
	C1	C2	C3	Pure PLA
Density (g/cm^3)	0.15	0.16	0.17	1.25
VF (%)	88.0	87.2	86.4	—
Average size of the cells (μm)	140	125	100	—
Average wall thickness (μm)	35	50	60	—
Hardness C	37	40	43	—
Tensile strength (MPa)	28.3 ± 1.7	29.0 ± 1.8	30.4 ± 2.8	54.9 ± 4.2
Water absorption (%)	10.9	10.1	9.6	0.5
Degradation (%)	83.6	75.7	63.0	47.1

Foaming temperature = 180°C, open-mold temperature = 100°C.

Table IV. Effect of the AC Content on the PLA Foam Properties

Sample	A2	B2	C2	D2	Pure PLA
Density (g/cm^3)	0.52	0.30	0.16	0.17	1.25
VF (%)	58.4	76.0	87.2	86.4	—
Hardness C	48	46	40	45	—
Tensile strength (MPa)	35.1 ± 2.0	31.3 ± 2.3	29.0 ± 1.8	23.9 ± 2.0	54.9 ± 4.2
Water absorption (%)	4.2	6.6	10.1	10.2	0.5
Degradation (%)	73.4	74.7	75.7	75.8	47.1

Foaming temperature = 180°C, open-mold temperature = 100°C.

To understand the properties of the PLA foams, the density, VF, hardness, and tensile strength of the foams were studied. Moreover, PLA is a kind of degradable material that is sensitive to heat, water, and relative humidity.[25] Therefore, the water absorption percentage and degradation percentage were also investigated (Table III). From the results in Table III, we found that the density, hardness, and tensile strength of the foams increased with increasing CP/SE concentration, whereas the VF, water absorption percentage, and degradation percentage decreased. This was because the extent of crosslinking increased with increasing concentration of CP/SE; this made the gas diffusion in the PLA melt matrix difficult and led to a higher foam density, hardness, and tensile strength. When the concentration of CP/SE was lower, more homogeneous bubbles with thinner walls were obtained; this made it easy for them to absorb water and degrade. On the other hand, the degradation of foams decreased with increasing CP/SE concentration because CP/SE was not prone to degradation. Moreover, as shown in Table III, the degradation of all of the PLA foams was greater than that of pure PLA; this indicated that the foam was conducive to degradation.

Effect of the Content of Blowing Agent on the PLA Foam Composite Properties. To further investigate effect of the blowing agent content on the PLA foams, PLA foams with different AC contents (Table I) were prepared, and the results are shown in Table IV. As shown in Table IV, the density and hardness of the PLA foams decreased first and then increased with the increasing AC content. The VF of PLA showed the opposite phenomenon. This was because gas emissions increased with increasing AC content, and then, the foam density decreased. However, when gas emissions reached saturation, the surplus amount of liberated gas from the decomposing AC made some bubbles break down, and this led the foam density and hardness to slightly increase. This was similar to Sun et al.'s work.[33] In general, the lower the foam density is, the lower tensile strength is. For sample D2, the relationship of the foam density and tensile strength were not satisfied by this regularity. The reason was the surplus amount of AC. A minimum foam density of 0.16 g/cm^3 was obtained when the AC amount was 10 phr. With increasing blowing agent content, the water absorption percentage and degradation percentage increased, similar to those of foam density. Furthermore, a lower foam density made the volume and contact area of the foams with water and NaOH solution increase; this is favorable for the absorption of water by foam composites and degradation.

CONCLUSIONS

PLA foams were successfully prepared by a traditional chemical compression-molding method. The important results follows:

1. CP/SE obviously improved the melt viscosity and elasticity of PLA; this laid the foundation for preparing PLA foams.
2. ZnO lowered the decomposition temperature of AC, and the optimum process conditions for the foams were foaming at 180°C for 10 min and opening the mold at 100°C.
3. With increasing CP/SE concentration, the density, hardness, and tensile strength of the PLA foams increased, whereas the water absorption percentage and degradation percentage decreased.
4. With increasing AC, the density and hardness of the foams first decreased and then increased. Although the water absorption and biodegradable properties increased with decreasing density, when the AC amount was 7.7 (wt %), a minimum foam density of 0.16 g/cm^3 was obtained.

REFERENCES

1. Garlotta, D. *J. Polym. Environ.* **2001**, *9*, 63.
2. Giannelis, E. P.; Vaia, R. A. *Adv. Mater.* **1996**, *8*, 29.
3. Mathieua, L. M.; Mueller, T. L.; Bourbana, P. E.; Pioletti, D. P.; Muller, R.; Mansona, J. E. *Biomaterials* **2006**, *27*, 905.
4. Alexandre, M.; Dubois, P. *Mater. Sci. Eng.* **2000**, *28*, 1.
5. Narayan, R. *Am. Chem. Soc. Symp. Ser.* **1992**, *476*, 1.
6. Zhang, Y.; Kontopoulou, M.; Ansari, M.; Hatzikiriakos, S.; Park, C. B. *Polym. Eng. Sci.* **2011**, *51*, 1145.
7. Verdejo, R.; Mills, N. J. *J. Biomech.* **2004**, *37*, 1379.
8. Demir, H.; Sipahioglu, M.; Balkose, D.; Ulku, S. *J. Mater. Process. Technol.* **2008**, *195*, 144.
9. Lee, S. T.; Kareko, L.; Jun, J. *J. Cell. Plast.* **2008**, *44*, 293.
10. Dong, J. K.; Deng, X.; Zhen, X. Z.; Kaushik, P.; Dae, S. B.; Jin, K. K. *Macromol. Mater. Eng.* **2009**, *294*, 620.

11. Richards, E.; Rizvi, R.; Chow, A.; Naguib, H. *J. Polym. Environ.* **2008**, *16*, 258.

12. Ema, Y.; Ikeya, M.; Okamoto, M. *Polymer* **2006**, *47*, 5350.

13. Georgiou, G.; Mathieu, L.; Pioletti, D. P.; Bourban, P. E.; Månson, J. A.; Knowles, E. J. C.; Nazhat, S. N. *J. Biomed. Mater. Res. B* **2007**, *80*, 322.

14. Park, E. S.; Cho, H. C.; Kim, M. N.; Yoon, J. S. *J. Appl. Polym. Sci.* **2003**, *90*, 1802.

15. Di, Y.; Iannace, S.; Maio, E. D.; Nicoais, L. *J. Polym. Sci. Part B: Polym. Phys.* **2005**, *43*, 689.

16. Gu, S. Y.; Yang, M.; Yu, T.; Ren, T. B.; Ren, J. *Polym. Int.* **2008**, *57*, 982.

17. Dominik, K.; Masahiro, O. *Macromol. Mater. Eng.* **2011**, *296*, 770.

18. Burdick, J. A.; Frankel, D.; Dernell, W. S.; Anseth, K. S. *Biomaterials* **2003**, *24*, 1613.

19. Bananalbandi, A.; Hill, D. J.; Donnell, J. H. *Polym. Degrad. Stab.* **1995**, *50*, 297.

20. Mitomo, H.; Sasada, K.; Nishimura, K. *J. Polym. Environ.* **2004**, *12*, 95.

21. Nijienhuis, A. J.; Grijpma, D. W.; Pennings, A. *J. Polymer* **1996**, *37*, 2783.

22. Zhang, J. L.; Li, G.; Su, Y. Z.; Qi, R. R.; Ye,D. D.,Yu, J.; Huang, S. W. *J. Appl. Polym. Sci.* **2012**, *123*, 2996.

23. Ho, K. G.; Pometto, A. L.; Hinz, P. N. *J. Environ. Polym. Degrad.* **1999**, *7*, 83.

24. Roduit, N. JMicroVision: Image analysis toolbox for measuring and quantifying components of high-definition images. Version 1.2.7. Available at: http://www.jmicrovision.com.

25. Kim, D. J.; Kim, S. W.; Kang, H. J. *J. Appl. Polym. Sci.* **2001**, *81*, 2443.

26. Amon, M.; Denson, C. D. *Polym. Eng. Sci.* **1984**, *24*, 1026.

27. Tai, H. J.; Wang, J. B. *J. Cell. Plast.* **1997**, *33*, 304.

28. Sudduth, R. D. *Polym. Eng. Sci.* **1996**, *36*, 2135.

29. Tai, H. J.; Wang, J. B. *J. Cell Plast.* **1997**, *3*, 304.

30. Lim, K. S.; Jang, S. G.; Lee, S. I.; Lee, K. H. *Macromol. Res.* **2008**, *16*, 218.

31. Liu, C. *Polym. Mater. Sci. Eng.* **2005**, *21*, 244.

32. Rubinstein, M.; Colby, R. Polymer Physics; Oxford University Press: New York, **2003**; p 112.

33. Sun, Q.; Huang, B.; Ji, J. *Adv. Mater. Res.* **2011**, *290*, 1805.