Physical and Mechanical Properties of Soy Protein-Based Plastic Foams

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ABSTRACT: Flexible plastic foams using soy protein isolate (SPI), soy protein concentrate (SPC), and defatted soy flour (DFS) were produced by interacting proteins with glycerol-propylene oxide polyether triol (polyol), surfactant, triethanolamine (cross-linking agents), tertiary amine (catalyst), and water (blowing agent). The density, compressive stress, resilience, and dimensional stability of foams with SPI, SPC, and DFS increased as the initial concentration of soy protein increased. The foam density increased with increasing weight percentage of SPI, SPC, and DFS. The resilience values of SPI containing foam increased with the increasing addition of SPI up to a maximum 30% SPI addition. An increase in SPI up to 20% caused an increase in the compressive stress (225 kPa) in comparison to control polyurethane foam (187 kPa). The control foam and foam containing 20% DFS had a similar load-deformation relationship. The foam containing 20% SPI and SPC also exhibited a similar shape, but with a higher compressive stress. The compressive stress of all foams was steeply increased after 55% strain, since the foams completely collapsed upon compression.

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KEY WORDS: Compressive stress, defatted soy flour, polyurethane foam, soy protein concentrate, soy protein isolate, soy protein plastics.

The uses of soy proteins for nonfood products have increased as a result of increasing concern for the environmental safety of nonbiodegradable synthetic products used in safety packing and cushioning applications. Soy protein is a viable renewable resource for producing environmentally safe industrial products. Due to their structural characteristics, soy proteins have immense potential as adhesives, films, packaging, and reinforced composite materials (1). However, expanded utilization of soy proteins for industrial uses is limited owing to the lack of desirable properties in native proteins and the strong competition from synthetic petroleum-based products. The use of renewable sources in the polyurethane industry has attracted the attention of many researchers (2,3). Many studies have focused on the incorporation of carbohydrates into the plastic matrix (4–6).

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Recently, the use of soy protein in the polyurethane industry has attracted much attention. Researchers have already reported success with the incorporation of protein into polyurethane systems (7–9). Soy protein-based plastic foam has the attributes of light weight, excellent strength/weight ratio, superior insulating abilities, and energy-absorbing ability (including shock, vibration, and sound) (10). They can be used as partial replacements of safety packing material and cushion material for furniture. The increased strength, improved flame resistance, and enhanced biodegradability of the proteins have attracted attention from the plastics industry (11).

One advantage of using soybeans in nonfood applications is the low cost, as soy protein products are a relatively inexpensive vegetable source of protein. Soy protein products are classified into three major groups: defatted soy flour (DFS), soy protein concentrate (SPC), and soy protein isolate (SPI). These groups are based on protein content, which ranges from 50 to over 90%. Since the methods used for the isolation, separation, refining, and drying of proteins from soybeans significantly affect their functional properties, each type of soy protein has its own characteristics and uses. To produce an economical packaging foam, it is less expensive to use DFS ($0.30/lb) than SPC ($0.70/lb) or SPI ($1.40/lb).

The use and production of chlorofluorocarbon (CFC) blowing agents is restricted and is being phased out because of their adverse effect on the stratospheric ozone layer (12). In a recent study, water which reacts with isocyanate and produces carbon dioxide was used as the blowing agent for the manufacture of flexible urethane foams (7). The objectives of the present study were to investigate the effects of soy protein products, such as DFS, SPC, and SPI, on water-blown plastic foam and foam properties including density, compressive stress, resilience, and dimensional stability.

MATERIALS AND METHODS

Materials. DFS and SPI were provided by Archer Daniels Midland Co. (Decatur, IL). SPC was supplied by Central Soya (Fort Wayne, IN). Other components used in the flexible polyurethane foams were toluene diisocyanate (Olin TDI 80, Olin Corp., Stamford, CT), glycerol-propylene oxide polyether triol (ALCOL LHT-42; Arco Chemical Co., Newton, PA), tertiary amine (DABCO; Aldrich Chemical Co.,

Milwaukee, WI), triethanolamine (Aldrich Chemical Co.), surfactant (L-560; Union Carbide Co., Danbury, CT), and distilled water.

Foam preparation. A modified standard mixing procedure for making soy protein-incorporated polyurethane foams as described by Bailey and Critchfield (8) was used. The effects of the following variables in the foam formulation on the properties of polyurethane foams were studied. They were determined in a preliminary study to ensure that all foam products could be produced within 10 min. These include concentrations of DFS, SPC, and SPI in parts per hundred foam formulation for flexible polyurethane foams (0, 10, 20, and 30). Other factors in foam formulation such as the catalyst, surfactant, cross-linking agent, and isocyanate index were fixed (Table 1). Polyether polyol, tertiary amine, soy protein products, cross-linking agent, and blowing agent, as shown in Table 1, were sequentially weighed and added into a 1.0-L stainless steel container and mixed throughly with a glass rod for 5 min or until smooth. Then the mixture was left at room temperature for 2 min to degas. After degassing, polymeric isocyanate was rapidly added and stirring continued for another 15 s. Finally, the reacting mixtures were poured immediately into aluminum foil boxes ($1500 \times 825 \times 500$ mm) and allowed to rise at room temperature. Foams were removed from aluminum boxes after 1 h and allowed to cure at 25°C for 1 wk before test specimens were cut with a band saw (24 teeth/in. × 12 in.).

Foam property measurements. Densities of the samples were determined using American Society of Testing and Materials (ASTM) procedure D 1622-88. Test specimens ($100 \times 100 \times 50$ mm) were calipered and weighed and calibrations were made to determine the density in kg/m^3. Foam samples with dimensions of $200 \times 200 \times 20$ mm were placed on flat plates. Compression was measured at 10% deformation on a Texture Analyzer (TA.XT2; Texture Technologies Corp., Scarsdale, New York) with a data acquisition system. The compressive stress was calculated by dividing the load by the initial cross-sectional area of the specimen. The resilience and stress deformation tests were determined using simple compression tests. Six specimens were tested parallel to foam rise and average values were reported. Thermal effects on weight and volume changes of foams containing SPI, SPC, and DFS were carried out for 14 d at 75°C and 5% relative humidity.

TABLE 1
Foam Formulations for Soy Protein-Based Foam Incorporated with Polyurethane[a]

Ingredients	Parts by weight
Glycerol-propylene oxide polyether triol (polyol)	90, 80, 70, 60
Soy proteins (SPI, SPC, or DFS)	0, 10, 20, 30
Tertiary amine (catalyst)	0.5
Surfactant (L-560)	1.0
Triethanolamine (cross-linking agent)	0.5
Water	3.5
Polymeric MDI	6.5

[a]SPI, soy protein isolate; SPC, soy protein concentrate; DFS, defatted soy flour; MDI, methylene-4,4′-diphenyldiisocyanate.

Scanning electron microscopy. The samples were dried in a vacuum oven at 60°C for 12 h and cooled in a desiccator to prevent absorption of moisture. Cross-sections of samples were sliced horizontally using a blade. Each specimen was fixed to a stub with silver conducting paint and coated with gold with a Cressington 108 auto sputter coater for 2 min. A 2.5 kV volt and a 20 mA current were applied for 2 min to deposit a conductive layer 30 nm in thickness over the specimen. The specimen was examined with an ISI-60 scanning electron microscope at 15 kV.

Statistics. A least-significant difference (LSD) was applied to compare the means of the foam properties of different treatments and different types of biomass (SPI, SPC, and DFS). Differences were considered statistically significant at $P < 0.05$.

RESULT AND DISCUSSION

Density. The density of a water-blown flexible foam is governed by the weight per volume of the plastics making up the matrix of the foam and the gases trapped in the foam cells. In foams, light weight is required for keeping transportation costs at a minimum. Table 2 shows the effect of SPI, SPC, DFS, and the blowing agent on the density of polyurethane foams. The foam density increased with increasing weight percentage of soy protein products. Figure 1 shows scanning electron micrographs of DFS-, SPC-, and SPI-containing polyurethane foams. DFS-containing foam had a great expansion with large air gaps and over foam densities than those of foams containing SPC and SPI (Fig. 1A). This might have been caused by less active hydrogen atoms reacting with the isocyanate for DFS as compared to SPI and SPC. Since SPI- and SPC-containing foams expanded with small and uniform cell size, the foam density was increased (Figs. 1B and C).

Compressive stress. Compression tests were conducted at 10% deformation to compare the compressive stress of plastic foam with soy protein products. The compressive stress of a foam is defined as the maximum compressive stress level the foam can withstand for a very short time at a fixed point in the compression loading cycle (5). Figure 2 shows the compressive stress at 10% deformation for foams containing SPI, SPC, and DFS under compressive loads where the specimen was compressed parallel to the foam rise direction. An increase in the addition of SPI, SPC, and DFS increased compressive stress. In particular, an increase up to 20% in SPI caused an increase in the compressive stress, after which the increase started to level off. It is expected that SPI, up to the 20% addition, might have

TABLE 2
Densities of Foams Containing SPI, SPC, or DFS

Density	Added soy protein (%)[b]			
(kg/m^3)	0	10	20	30
DFS	19.8	21.8	23.5	27.7
SPC	19.8	22.3	26.6	29.1
SPI	19.8	24.6	28.2	32.4

[a]See Table 1 for abbreviations.
[b]Means were averages of six specimens ($P < 0.05$).

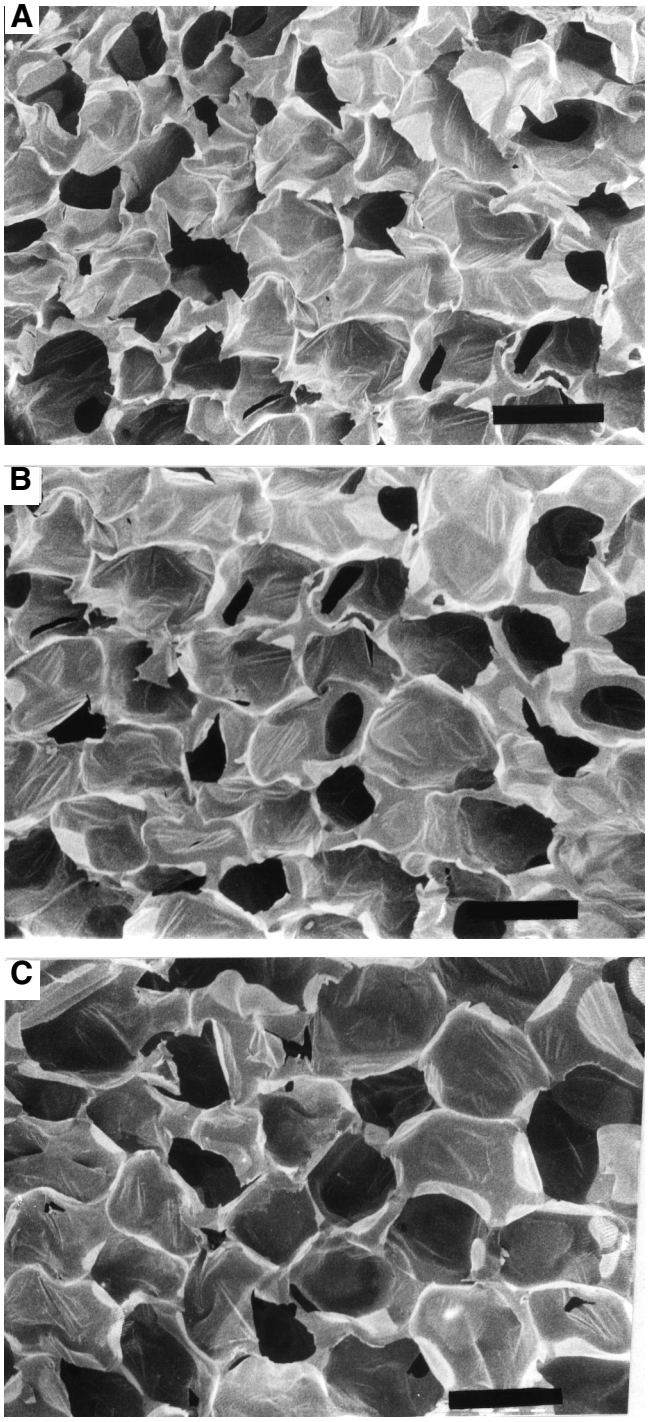

FIG. 1. Scanning electron micrographs of soy protein-based plastic foams. (A) foam containing 30% defatted soy flour (DFS); (B) foam containing 30% soy protein concentrate (SPC); and (C) foam containing 30% soy protein isolate (SPI). Magnification bars: A–C = 500 µm.

reacted with the isocyanate and other components in the foam formulation and contributed to the strength of the foam structure. Further addition of SPI above 20% might have exhausted the availability of the isocyanate to interact with soybean protein. The additional soy proteins may have interfered with the reaction between isocyanate and water and weakened the foam

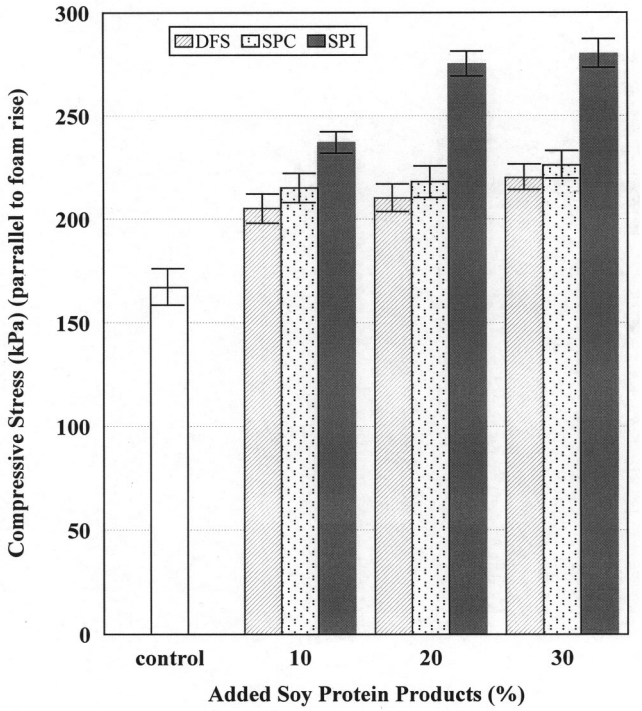

FIG. 2. Compressive stress at 10% deformation for foams containing SPI, SPC, or DFS. Means were averages of six specimens ($P < 0.05$). See Figure 1 for abbreviations.

structure. These results indicated that foams containing soy protein products possess considerable mechanical strength.

Resilience. Resilience is a very important property of flexible foams since it could apply to packaging material and cush-

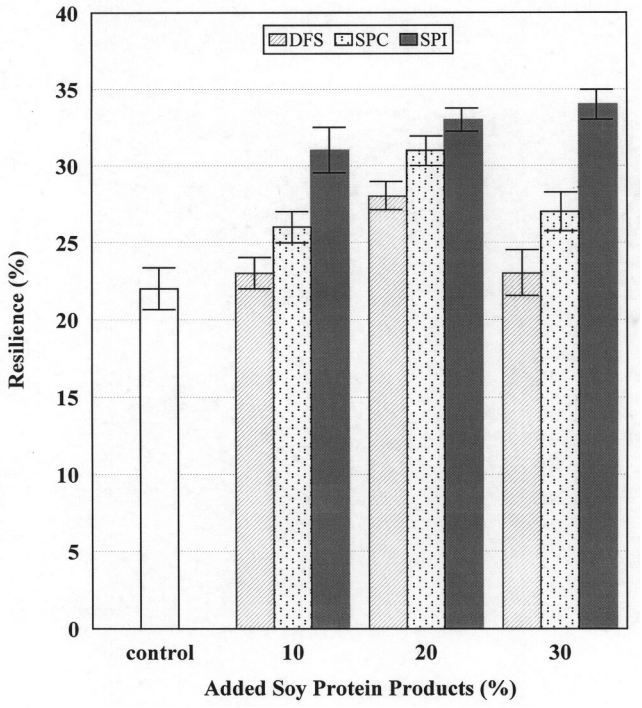

FIG. 3. Resilience of foams containing SPI, SPC, or DFS. Means were averages of six specimens ($P < 0.05$). See Figure 1 for abbreviations.

TABLE 3
Effect of Thermal Aging Polyurethane Foams Containing SPI, SPC, and DFS at 75°C and 5% Relative Humidity[a]

Control		SPI			SPC			DFS		
Concentration (%)	(PU)	10	20	30	10	20	30	10	20	30
Weight change (%)										
Day 1	−1.04	−1.34	−2.00	−2.10	−1.26	−1.48	−1.57	−1.08	−1.26	−1.29
Day 7	−1.32	−2.14	−2.37	−2.37	−1.65	−1.81	−1.98	−1.49	−1.66	−1.87
Day 14	−1.86	−2.29	−2.59	−2.64	−1.94	−2.12	−2.31	−1.73	−1.95	−2.08
Volume change (%)										
Day 1	0.23	0.20	0.25	0.28	0.24	0.42	0.42	0.22	0.37	0.24
Day 7	0.84	0.35	0.37	0.42	0.38	0.56	0.88	0.72	0.61	1.37
Day 14	0.48	0.42	0.24	0.23	0.61	0.63	0.94	1.06	1.29	1.47

[a]See Table 1 for abbreviations.

ioning material. This property is particularly important in determining the degree of comfort in a cushion material. Figure 3 shows that foams containing SPI, SPC, and DFS all have higher resilience values when compared to those of the polyurethane control foam. For SPI, the resilience values increased with an addition of up to 30% more SPI. For SPC and DFS, the maximal resilience occurred at 20% SPI addition. Foam containing 30% SPI had a better effect on foam resilience (34%) than those of 20% SPC and 20% DFS (27 and 23%, respectively). These results indicated that foams containing soy protein products have potential as partial replacements of safety packing material and cushion material.

Dimensional foam stability. Dimensional stability is the most important property considered for low-density foam (3). Table 3 shows the effect of thermal-aging polyurethane foams containing SPI, SPC, and DFS at 75°C and 5% relative humidity. The weight loss for all foams never exceeded 3%. All soy protein-based foams had greater weight losses than did the control foams during thermal aging. The foam containing SPI showed the greatest weight loss with increasing additions of SPI. Weight loss increased with aging time and with increasing concentrations. During thermal aging, changes in volume increased as aging time increased. The foam containing SPI showed less change in volume than did the control foam and foams containing SPC and DFS. These results indicated that the foam properties in safety packing and cushioning applications were improved by adding SPI.

The load–deformation properties of plastic foam are among the most important factors for cushioning materials. Figure 4 shows the behavior of the load–deformation, stress–strain relationship under indentation for plastic foams containing 20% of SPI, SPC, and DFS, respectively. The load–deformation curves of foams can be divided into three regions. At lower strains (0–15%), the foam deformed in a linear-elastic manner and was reversible. This initial linear elasticity region was due to the elastic bending of the cell walls and the struts comprising the foam matrix. The control foam and the foam containing 20% DFS had similar load–deformation relationships. The foam containing 20% SPI also exhibited a similar shape, but with a higher compressive stress. At the second region (15–55% strain), foams containing soy protein had slightly increased compressive stress. When the stress–strain curve of a foam contains a considerable plateau stress region, it will have a low comfort value. Therefore, the addition of 20% SPI, SPC, and DFS into the flexible foam system appeared to increase the foam comfort value. The compressive stress of all foams steeply increased after 55% strain, since the foams completely collapsed upon compression.

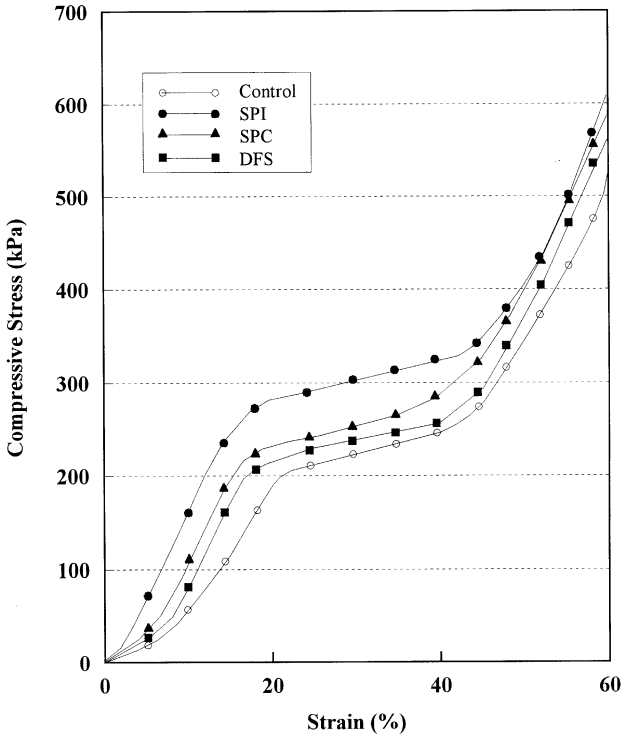

FIG. 4. Typical stress–strain curves of flexible foams containing 20% SPI, SPC, or DFS. Means were averages of six specimens ($P < 0.05$). For abbreviations see Figure 1.

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