Physical Properties of Two Biological Cushioning Materials from Wheat and Corn Starches[1]

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ABSTRACT

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Physical properties of two biological cushioning materials made from wheat and corn starch extrudates were compared with those of commercial plastic foam cushioning material. Characteristics measured included dimensions, bulk and true densities, and water absorption isotherms at 15, 25, and 40°C. Their properties under simple compression tests and stress relaxation tests were also examined. The C-shaped extrudate from corn starch showed more radial expansion than that of the wheat starch extrudate. But the bulk density and true density of the corn starch extrudates were significantly higher than those of the wheat starch extrudates. Both biological cushioning materials showed similar water absorption isotherms at three temperatures when the equilibrium moisture contents significantly increased as relative humidities increased. The S-shaped plastic foam exhibited lower bulk and true densities. Simple compression tests and stress relaxation tests showed that the biological materials had more unrecoverable plastic deformation than the plastic foams and also indicated a difference between the two extruded cushioning materials.

Loose-fill cushioning materials provide cost-effective protection for relatively lightweight products against shock or vibration during shipping and handling (Torok 1990). In addition to the important energy absorbing properties of cushioning materials, characteristics such as light weight, stability in ambient conditions, good resilience, and stress dissipation rate also should be considered. As cushioned packages play an increasing role in world commerce, flexible, closed-cell, expandable polystyrene foam materials are being used more and more. Disposal of used plastic cushioning materials, which are derived from petroleum sources, has become a public concern (Larson 1989, 1990). Biological cushioning materials, such as extrudates from wheat and corn starches, are now available. The objective of this study was to compare the physical properties of two biological cushioning materials with those of plastic foam materials by measuring dimensions, bulk and true densities, water absorption isotherms, and compression properties.

MATERIALS AND METHODS

Materials

Wheat starch (Midsol 50) manufactured by Midwest Grain Products (Atchison, KS) and corn starch (pearl corn starch) manufactured by A. E. Staley (Decatur, IL) were mixed with 3% polyethylene glycol and 0.5% silicon dioxide for 0.5 hr in a double-ribbon mixer (Wenger Mixer Mfg., Sabetha, KS) and sealed tightly in plastic bags for 12 hr before the extrusion process. The total mix was 50 kg for each type of starch. A Wenger X-20 single-screw extruder with a C-shaped die was used to process both the wheat and the corn starches under the operational conditions listed in Table I (Neumann and Seib 1993). The final formulation of feed material, extruder screw configuration, feed rate, die dimension, die zone temperature, and plate cutter were determined from previous runs conducted in the extrusion laboratory (Department of Grain Science and Industry) and in the physical properties laboratory (Department of Biological and Agricultural Engineering) at Kansas State University, Manhattan, KS.

The loose-fill plastic foam used in the comparisons was an expandable polystyrene material manufactured by Dow Chemical Company (PELANSPAN-PAC). This S-shaped foam is one of the most commonly used commercial cushioning materials.

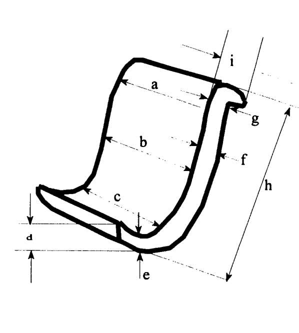
Methods

Dimensions, bulk and true densities, and water absorption isotherms at 15, 25, and 40°C were determined. Resilience and stress dissipation properties of the materials were measured using simple compression and stress relaxation tests.

A digital reading caliper (Manostate, Switzerland) was used

TABLE I
Operational Conditions of the Extruder

Extrusion Condition	Wheat Starch Mix	Corn Starch Mix
Feed screw speed (rpm)	15.0	15.0
Mixing cylinder speed (rpm)	150.0	150.0
Discharge temperature (°C)	90.0	96.0
Discharge moisture (%)	19.34	17.78
Shaft speed (rpm)	300	300
Motor load (%)	24.0	24.0
Knife drive speed, two blades (%)	40–50%	40–50%
Extrudate bulk density (wet)	18.58 kg/m^3	20.50 kg/m^3
Pressure (psig)	4,237 kPa	5,650 kPa
Barrel jacket conditions		
2nd to 4th	Cold water	Cold water
5th	Steam	Steam
6th	Cold water	Cold water



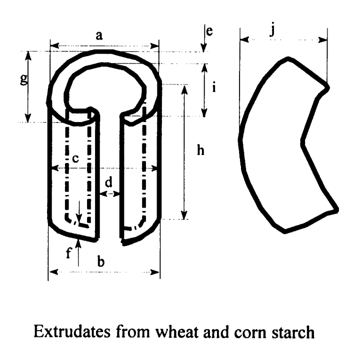


Fig. 1. Measurements made with a digital reading caliper of the dimensions of three types of cushioning materials. Measurements for each dimension were made at three different places and then averaged.

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to measure the dimensions of the three types of cushioning materials. Measurements for each dimension were made at three different places and then averaged (Fig. 1).

Bulk density was measured by releasing the materials from a funnel (300 mm at the top and 64 mm at the bottom) at a height 160 mm above the top of the measuring container (126 mm diameter × 165 mm height). Excess material was scraped off with a straightedge without shaking the container. The sample in the container was weighed and then recorded in kilograms per cubic meter. A Quantachrome multipycnometer was used to measure the true volume of solid materials by employing the Archimedes principle of fluid displacement. To assure maximum accuracy, helium gas was used because it is ideal for penetrating the finest pores. An analytical balance was used to ascertain the mass of the sample. Knowing the weight and volume of the sample, the true density (weight/volume) can be calculated.

Five saturated salt solutions were prepared according to standard practices (ASTM 1992) for maintaining constant relative humidity with aqueous solutions. They were placed in the bottom of desiccators to obtain relative humidities of ~11, 32, 52, 75, and 92%. Temperatures of 15, 25, and 40°C were obtained by putting the desiccators in refrigerated incubators (Fisher Isotemp, Fisher Scientific, Pittsburgh, PA) and allowing the samples to equilibrate for seven to ten days. Each experimental treatment (one temperature and one relative humidity) had two repetitions from each sample in each desiccator and was replicated once.

A universal testing machine (model 4502, Instron, Canton, MA) was used for the simple compression tests and stress relaxation tests. All the tests were conducted at ambient conditions: 23 ± 3°C and 45 ± 10% rh. In simple compression tests, the specimen was cut radially and longitudinally into pieces ~20 × 20 mm. The pieces were compressed using a cylinder probe 3 mm in diameter and 120 mm in length at 1.3 mm/min. Young's modulus was measured for each treatment sample. For the stress relaxation tests, whole samples were loaded into a cylinder 126 mm in diameter and 165 mm in height. The original load was set at 400 N. The sample was brought to the given deformation and kept constant to measure the load drop as a function of time (the amount of time necessary for load dissipation from 400 N to 147 N, ~37%).

The SAS (1989) software package was used for the statistical analysis. A general linear model procedure was used for analysis of variance. Least square means, followed by the general linear model procedure, were used to calculate the sample mean and variance and to give the smallest difference between two sample means that was statistically significant. All the significant differences were considered at the 5% probability level. Each test was replicated 10 times unless specified otherwise.

RESULTS AND DISCUSSIONS

Dimensions

The mean and standard deviation for each dimension of the foams are listed in Table II. The dimensions of the corn starch extrudates were slightly bigger than those of the wheat starch extrudate. A one-way analysis of variance for wheat and corn starch extrudates was conducted. The statistical results also are listed in Table II. These results show that all the significant differences appeared in the radial dimensions of the extrudates. Although both extrudates were produced under the same conditions with the same manufacturing equipment, the corn starch extrudate tended to have more radial expansion than the wheat starch extrudate. A comparison of the average standard deviations showed that the plastic foam had the least variation in dimensions, corn starch extrudate was second, and wheat starch extrudate had the most variation.

Bulk Density and True Density

Bulk and true densities were used to indicate the weight per unit of volume of the extrudates, as well as the porosity and amount of void space. In cushioning materials, light weight is a desirable characteristic for keeping transportation costs at a minimum. Extrudates from wheat starch were lighter than those of corn starch. Wheat and corn extrudates and the plastic foam showed significant differences in both bulk density and true density (Table III).

The bulk densities of the wheat and corn starch extrudates were approximately five times that of the plastic foam. On visual inspection, the corn starch extrudate showed larger cell sizes and thicker cell walls than the wheat starch extrudate. The extrudates from wheat starch were lighter than those from corn starch, although the latter had more radial expansion. This could be the result of the corn starch having thicker annulus. Those results reflected the difference between natural wheat and corn starches in terms of color, starch granule shape and composition, and amylose and amylopectin properties (Shi and Seib 1989). Polyethylene glycol and silicon dioxide enhance the arrangement of starch chains and, thus, increase the ratio of cell wall material to air space (Neumann and Seib 1993). However, the extrudates from wheat and corn starches were still much denser than the plastic foam (Table III). The plastic foams had much smaller cell size than wheat and corn starch extrudates and had the lowest bulk and true densities.

Moisture Absorption Isotherms

Equilibrium moisture isotherms indicate the water absorption properties of cushioning material when exposed to environments with different relative humidities. Of the three factors (material, relative humidity, and temperature), only material and relative humidity showed statistically significant effects on the equilibrium moisture content (EMC). Significant differences in interactions of relative humidity and material and of relative humidity and temperature were also present. The three-way interaction of the

TABLE II
Statistical Results for the Dimensions Measured on Plastic Foam and Two Starch Extrudates

	Plastic Foam		Corn Starch Extrudates		Wheat Starch Extrudates		
Dimension	Mean (mm)	SD[a]	Mean (mm)	SD	Mean (mm)	SD	Pr[b]
a	21.61	1.21	18.839	0.986	19.347	4.11	0.5181
b	22.54	0.913	18.574	1.05	17.856	2.88	0.2081
c	21.84	1.19	21.207	0.909	19.036	1.35	0.0001*[c]
d	14.08	1.41	4.310	0.723	4.815	2.93	0.1417
e	7.92	0.711	6.352	0.779	5.425	0.711	0.0013*
f	7.98	0.554	6.175	0.292	5.557	0.759	0.0054*
g	7.82	0.382	18.755	1.17	17.45	1.31	0.0054*
h	33.55	1.53	48.936	3.88	45.95	7.59	0.1255
i	13.10	1.50	11.529	0.555	11.53	1.79	0.9980
j	...	...	24.367	3.73	26.34	6.18	0.1322
Average	...	1.044	...	1.41	...	2.961	...

[a]Standard deviation.
[b]Probability.
[c]* = Significant at 5% probability level.

TABLE III
Bulk Density and True Density of Plastic Foam and Two Starch Extrudates

Density	Plastic Foam	Wheat Starch Extrudates	Corn Starch Extrudates
Bulk density			
Mean (kg/m^3)	3.6390	16.8410	19.4740
LSDG[a]	C	B	A
SD[b]	0.08	0.70	0.62
True density			
Mean (kg/m^3)	0.06332	0.7303	0.9037
LSDG	C	B	A
SD	0.01	0.10	0.08

[a]Least significant difference grouping, the material sharing the same letter are not significantly different.
[b]Standard deviation.

three factors was also significant. Moisture isotherms at 25°C are shown in Figure 2.

The original moisture contents were 10.1% (wb) for wheat starch extrudates and 9.99% (wb) for corn starch extrudates. The starch-based porous materials absorbed moisture at high relative humidities and lost moisture to the environment at low relative humidities. The relative humidities did have a great effect on the wheat and corn starch extrudates. The EMC of the two biological materials increased significantly with the increase of relative humidity. The EMC of wheat extrudates ranged from ~6% at 11% rh to 26% at 95% rh. The starch extrudate picked up almost three times more moisture at 95% rh. At the same relative humidity, wheat and corn starch extrudates had similar EMC absorption properties.

The EMC of the wheat and corn starch extrudates increased with a decrease in temperature. The rate of increase was somewhat higher when the temperature fell from 40 to 25°C, particularly at higher relative humidities of 75 and 95%, than when it decreased from 25 to 15°C. The EMC was generally higher at higher relative humidity. Relative humidities significantly affected not only the EMC of the wheat and corn starch extrudates, but also their structure. By visual inspection, after equilibrium was reached (7–10 days, depending on the controlled temperature), the wheat and corn starch extrudates had no significant change in size at 11 to 76% rh at all three temperatures. The extrudates were reduced in size and became very hard at 89–95% rh at 15–40°C. No mold growth was found at any relative humidity or temperature studied.

The EMC of the plastic foam was not significantly affected by relative humidity. It was highest at 40°C and lower at 25°C than at 15°C.

The above comparisons of the dimensions, bulk and true densities, and the EMC of the three materials showed significant differences between the plastic foam and the wheat and corn starch extrudates. The plastic foam was light in bulk density and more stable under different relative humidities. Wheat starch extrudate had lighter bulk and true densities and relatively smaller radial dimensions than corn starch extrudate. Both wheat starch and corn starch extrudates tended to pick up moisture from the environment and lose their porosity at high relative humidities.

Simple Compression Tests and Stress Relaxation Tests

Simple compression tests and stress relaxation tests were conducted to compare the compression properties of plastic foam with those of wheat and corn starch extrudates.

Young's modulus is an indication of the elastic deformation of a material before the plastic deformation or break occurs. It was calculated from the slope of the compression curve, plotted as the load versus deformation at the linear range. The test sample was compressed radially (direction A) and longitudinally (direction B). No significant differences in Young's moduli were found between any of the materials in either direction. These results are summarized in Table IV.

However, some differences can be observed from the simple compression curves. Figure 3 indicates that the plastic foam had a wide linear range, whereas the wheat and corn starch extrudates

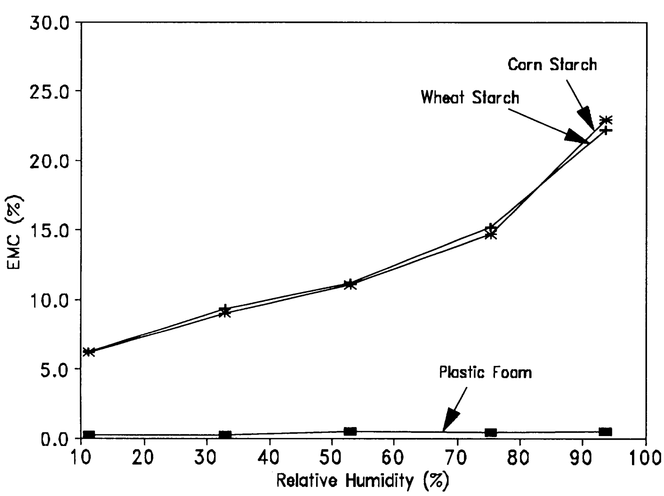

Fig. 2. Water absorption isotherms of plastic foam and corn and wheat starch extrudates at 25°C.

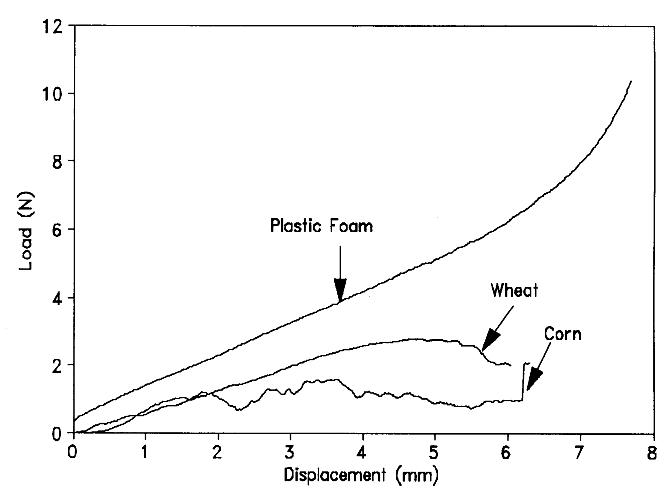

Fig. 3. Simple compression test curves of plastic foam and corn and wheat starch extrudates.

TABLE IV
Means and Standard Deviation (SD) of Young's Modulus with Least Significant Difference (LSD) Grouping Labeled for Plastic Foam and Two Starch Extrudates

	Young's Modulus[a]	
Materials	**Direction A**	**Direction B**
Plastic foam		
Mean (MPa)	1.5579	1.4045
SD (MPa)	0.2281	0.3578
LSDG	A a	A a
Wheat starch		
Mean (MPa)	1.5481	1.6616
SD (MPa)	0.7929	0.4626
LSDG	A a	A a
Corn starch		
Mean (MPa)	1.7901	1.6172
SD (MPa)	0.4310	0.4119
LSDG	A a	A a

[a] a = Materials with their means sharing the same letters are not significantly different. A = Compression directions with their means sharing the same letters are not significantly different.

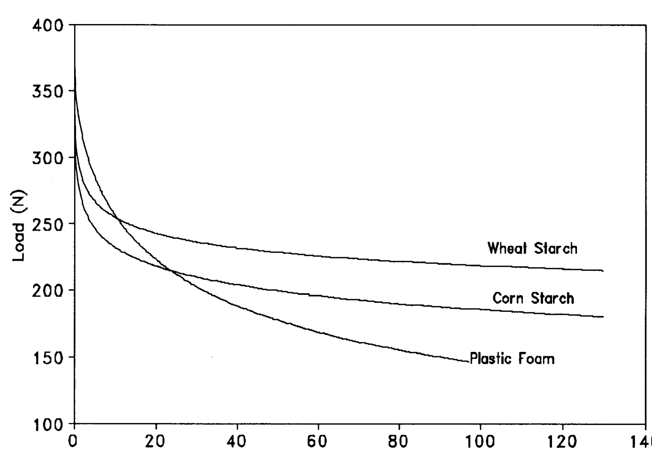

Fig. 4. Stress relaxation test curves of plastic foam and corn and wheat starch extrudates.

had a narrow linear range followed by a plastic deformation. The corn starch extrudates had the narrowest linear deformation of the three materials, followed by an irregular change of load when the deformation was increased further. Wheat starch extrudates underwent plastic deformation after passing the linear region. This could be a result of their differences in bulk density and cell wall thickness and brittleness.

As seen in Figure 4, the load dropped rapidly during the first 20 min, then dropped gradually and reached a relatively stable value. For wheat starch extrudate, that stable value was about 215 N, and for corn starch extrudate it was 180 N. At an original load of 400 N, the corn and wheat starch extrudates never exhibited a drop in load to 37%, even when given an extended period of time. The plastic foam exhibited the ability to continue to reduce the load over time. The load decayed to 147 N after 100 min. Given more time, the load could continue to dissipate and eventually reach a stable level less than 37%. This test showed that the wheat and corn starch extrudates were very "tough" compared to the plastic foam. This toughness indicated the plasticity of the materials. Once a load was added on the biological materials beyond the linear range of deformation, unrecoverable plastic deformation made the materials settle and resulted in slower stress dissipation. The higher bulk densities of the biological materials could also be a factor. The unrecoverable deformation is not desirable because it can generate a large head space inside the package and increase the potential for damage to the protected products during transportation and handling (Dow 1988).

CONCLUSIONS

The two biological materials showed significant differences in dimension (radial directions) and bulk and true densities, but not in EMC during water absorption isotherm tests. In the simple compression tests and stress relaxation tests, the two biological materials showed more plasticity than the plastic foam. Overall, the wheat starch extrudates were considered more desirable than corn starch extrudates. The plastic foam showed much lower bulk and true densities and lower EMC. These significant differences between the two biological materials, and between them and the plastic foam, indicated the need for further research to optimize extrusion conditions and material composition.

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LITERATURE CITED

AMERICAN SOCIETY OF TESTING MATERIALS. 1992. Standard practice for maintaining constant relative humidity by means of aqueous solutions. E104-85. Annual Book of ASTM Standards, Vol 08.03. The Society: Philadelphia.

DOW CHEMICAL CO. 1988. Cushioning: What's needed. Packaging 33:66-88.

LARSON, M. 1989. Cushioning packages fill more niches than ever. Packaging 35(4):39-43.

LARSON, M. 1990. Cushioning responds to hard knocks. Packaging 36(11):45-47.

NEUMANN, P. E., and SEIB, P. A. 1993. Starch-based biodegradable packing filler and method of preparing same. U.S. patent 5,208,267.

SAS. 1989. Software Release 6.07. SAS Statistical Analysis Package. SAS Institute: Cary, NC.

SHI, Y. C., and SEIB, P. A. 1989. Properties of wheat starch compared to normal maize starch. Page 215 in: Wheat is Unique. American Association of Cereal Chemists, Inc. St. Paul, MN.

TOROK, D. B. 1990. Cushioning: Protecting the product and environment. Material Handling Eng. 45(10):76-81.

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