Properties of Protective Loose-Fill Foams

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ABSTRACT: This study compared the performance of eight commercial starch and expanded polystyrene (EPS)-based loose-fill foam products. Density of starch-based foams is higher, by a factor of two to three times, than either EPS-based ones. Compressive stress of most starch-based foams did not differ significantly from 0.0893 MPa value for virgin EPS foam. EPS- and starch-based foams have predominantly a closed and open cellular structure, respectively. Resiliency or elastic recovery of starch-based foams had values between 69.5 and 71.25%, which is about 10% lower than virgin EPS foam. Friability of both starch- and EPS-based foams was between 2 and 6 wt %, but starch-based foams broke into a fine dust, whereas EPS-based foams broke into large fragments. After conditioning at 20, 50, and 80% r.h., 23°C and 50% r.h., 35°C, the water content for starch-based foams averaged 6.0, 9.5, 14, and 8.5 wt %, respectively. The mechanical properties of starch-based foams were more sensitive to changes in relative humidity and temperature than EPS-based foams, but the higher amount of absorbed moisture did not compromise its mechanical integrity. © 1998 John Wiley & Sons, Inc.* J Appl Polym Sci **67:** 1157–1176, 1998

Key words: loose-fill; density; compressive stress; friability; resiliency; starch

INTRODUCTION

Expanded polystyrene (EPS), shredded newsprint and cardboard, excelsior, popcorn, flour, and starch are the most common materials used to make protective packing products. Their function is to provide cushioning, protection, and stabilization of articles packaged for shipping. EPS-based loose-fill foam products have enjoyed a steady growth in this application over the last three decades, but became targeted recently in the solid waste disposal debate. Consumers are demanding and legislators are mandating the use of environmentally benign products.[1–4] Starch-based loose-fill foams are biodegradable and have competed well with EPS-based loose-fill even though starch-based loose-fill costs approximately $21 per cubic meter delivered, which is about 30% higher than the price of EPS-based loose-fill.[4] A recent comparative study by the Minnesota Office of Waste Management (MOWM) claims that starch-based loose-fill is a reasonable alternative to EPS-based loose-fill if composting infrastructures exist and EPS foam recycling is impractical.[3] Another study found that traditional synthetic polymer-based cushioning products provided better protection with less material than popcorn or cellulosic materials.[5] Little quantitative data has been published that compares the properties of EPS- and starch-based loose-fill, and no information is available that discusses foam performance vs. temperature and relative humidity.[1,2,6,7] This study is designed to provide data on starch-based foams that could be useful in producing environmentally friendly and economically competitive products.

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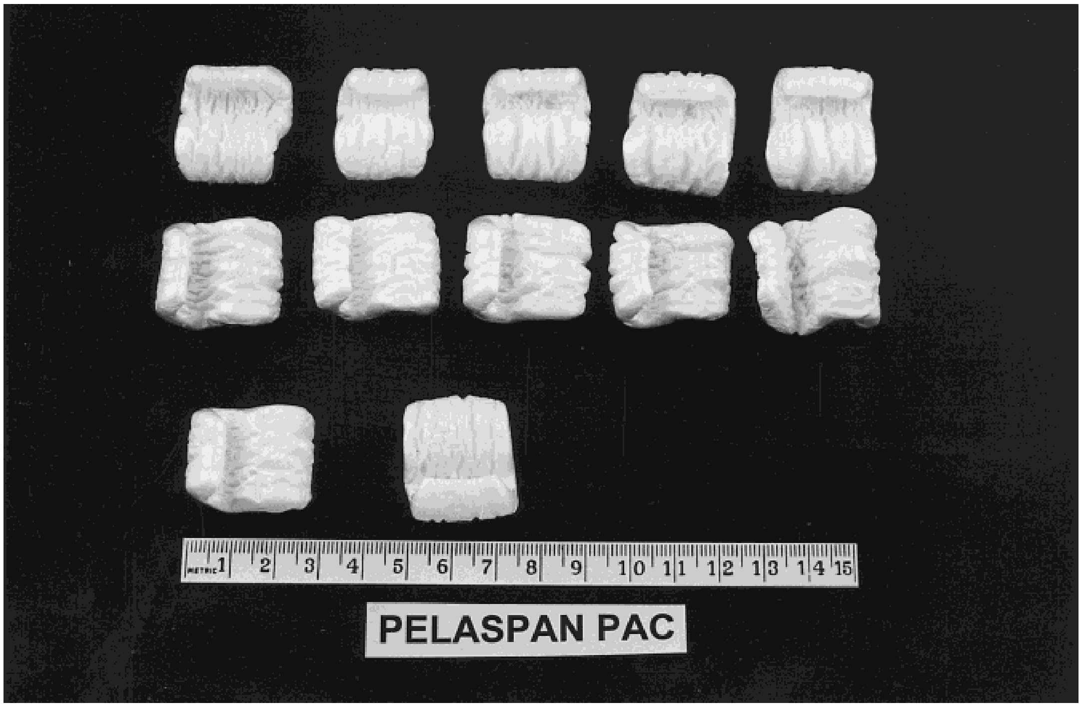

Figure 1 Photograph of PELASPAN PAC.

Seven properties and the response of these properties to changes in temperature and humidity were studied. These properties are moisture, cell structure, foam and bulk density, compressive stress, resiliency, and friability. On a statistical basis, significant differences between commercial EPS- and starch-based loose-fill products on an "as-received" or unconditioned basis and between "as-received" and after conditioning for each loose-fill product are described by confidence intervals.

EXPERIMENTAL

Materials

The two synthetic materials were virgin EPS PELASPAN PAC by American Excelsior Co. of Arlington, TX, and recycled EPS FLO-PAK S by Free-Flow Packaging Corp. of Redwood City, CA. The six starch foams were CLEAN GREEN by Clean Green Packing Co. of Minneapolis, MN; ENVIROFIL by EnPac of Wilmington, DE; ECO-FOAM by American Excelsior Co. of Arlington, TX; FLO-PAK BIO 8 by Free-Flow Packaging Corp. of Redwood City, CA; RENATURE by Storopack, Inc. of Cincinnati, OH; and STAR-KORE by Uni-Star Industries, Ltd. of Canton, IL. Photographs illustrating the size and shape of each of eight commercial loose-fill foam specimens are found in Figures 1–8. PELASPAN PAC has a three-dimensional "S" shape with height, width, and length dimensions of 14, 23, and 29 mm. FLO-PAK S has a hollowed three-dimensional "figure 8" shape with dimensions of 12, 16, and 38 mm. CLEAN GREEN has a cylindrical shape with dimensions of 20, 20, and 35 mm. ENVIROFIL also has a cylindrical shape with dimensions of 22, 22, and 46 mm. ECO-FOAM has a cylindrical shape with shark-skinned or melt-fractured surfaces with dimensions of 17, 17, and 35 mm. FLO-PAK BIO 8 has a solid "figure 8" or fused dual-cylindrical shape with dimensions of 15, 27, and 25 mm. RENATURE has a cylindrical shape with dimensions of 19, 19, and 38 mm. STAR-KORE has a curled cylindrical shape with split ends with dimensions of 17, 17, and 44 mm. The starch used in CLEAN GREEN is wheat, in ENVIROFIL is corn, in ECO-FOAM is hydroxypropylated high amylose corn, in FLO-PAK BIO 8 and RENATURE is corn or wheat, and in STAR-KORE is methyl acrylate grafted corn. Specific additives used in these products were not identified. Small quantities of additives such as polyvinyl alcohol, glycerol, polyethylene glycol, or silicon dioxide may influence mechanical properties and moisture sensitivity.[4,6,7]

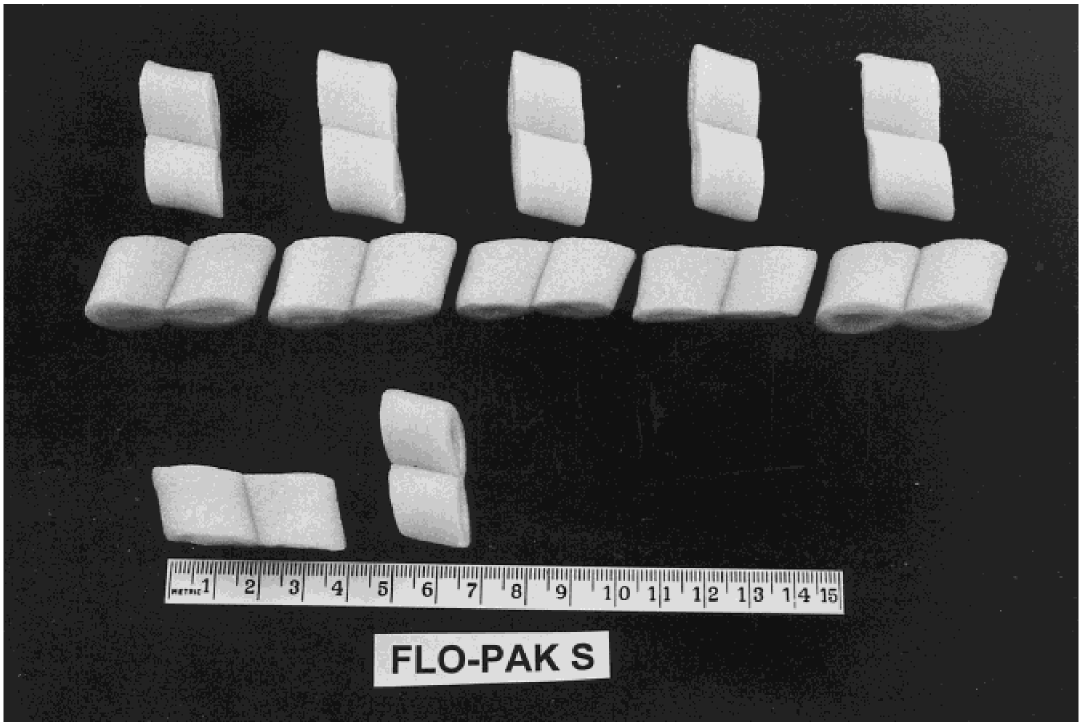

Figure 2 Photograph of FLO-PAK S.

These commercial loose-fill products are manufactured in one of three methods. Virgin EPS loose-fill is produced in a multistep process. Partly expanded polystyrene beads are made by incorporating blowing agents into styrene before polymerization or extrusion compounded into polysty-

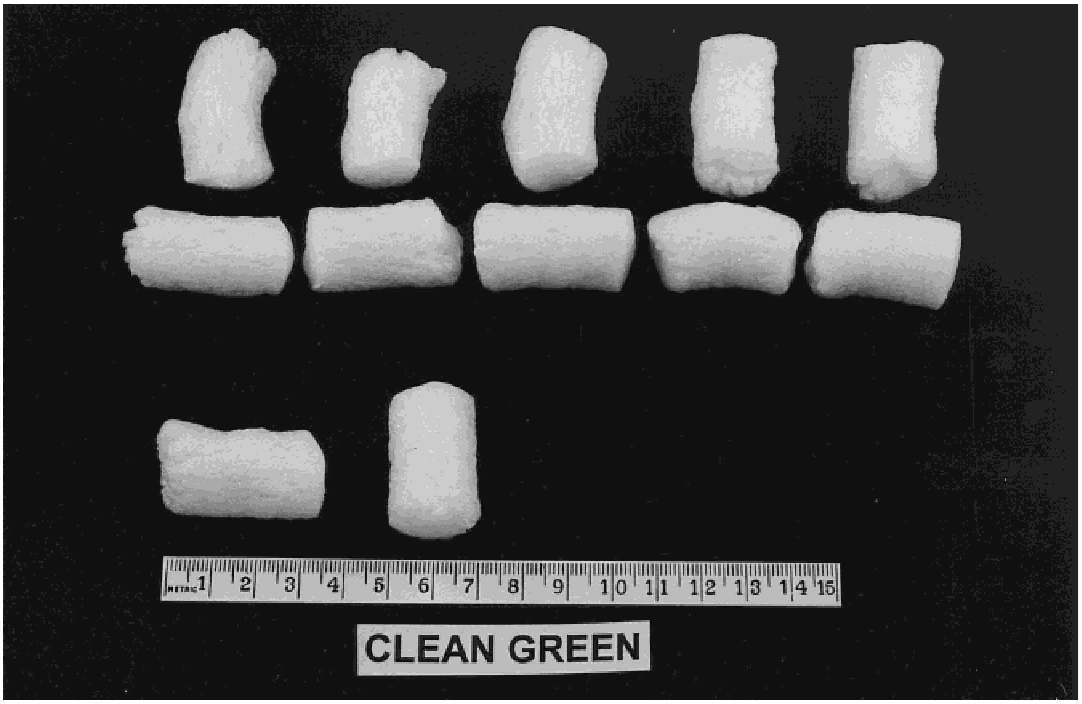

Figure 3 Photograph of CLEAN GREEN.

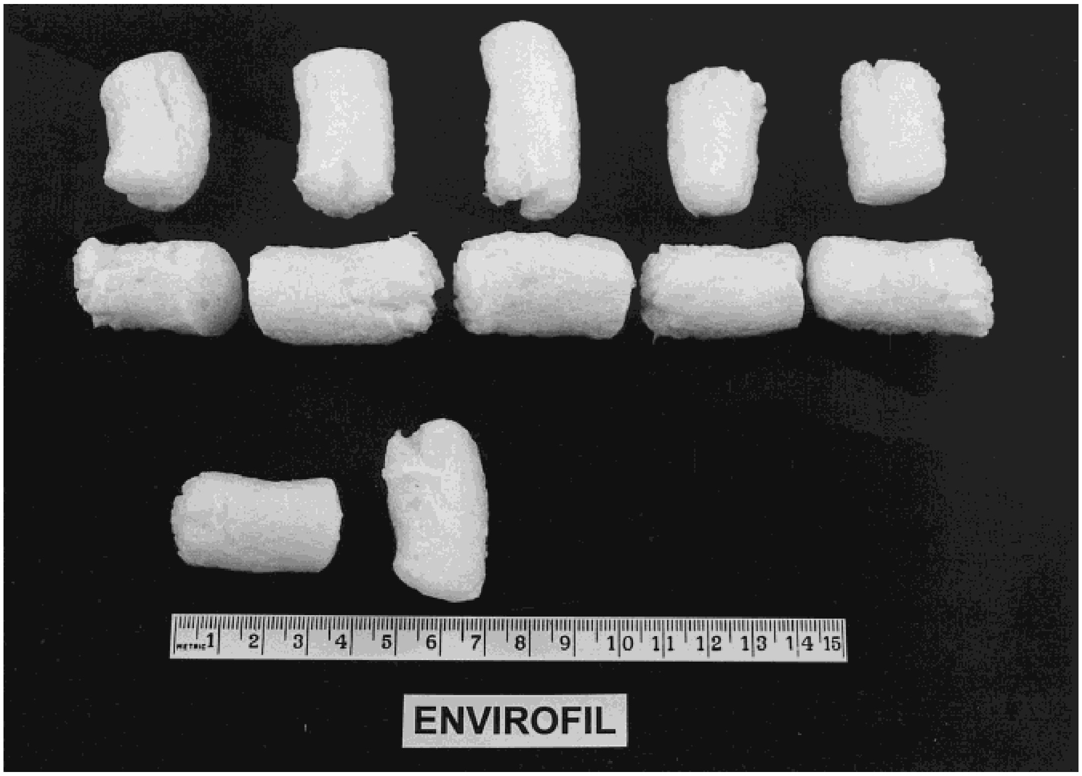

Figure 4 Photograph of ENVIROFIL.

rene after polymerization. These foam beads are subsequently expanded into loose-fill with steam and quenched below T_g for a day to allow air to diffuse into the cells. To achieve the desired foam density, the expansion and quenching process is repeated two or three times.[8,9] Recycled EPS is made from reclaimed post-consumer and industrial-expanded polystyrene foam products. The ground EPS and blowing agents are melt compounded in an extruder, partly expanded, and cut into loose-fill pieces. Foam density can be further reduced by postextrusion expansion and quenching.[10] Starch-based loose-fill is manufactured, usually in a one-step process, via an extrusion cooking process. Granular starch and water are fed into an extruder, usually a twin screw, where heat and shear causes the starch to gelatinize. Water, released as steam at the die of the extruder, is the primary blowing agent. Complete expansion or density reduction takes place immediately after the product exits the extruder.[11]

Loose-fill specimens were conditioned for 1 week at each of the following conditions: 20% r.h., 23°C; 50% r.h., 23°C; 80% r.h., 23°C; and 50% r.h., 35°C in a Model 518 Automatically Controlled Environmental Chamber, ETS Electro-Tech Systems, Inc., Glenside, PA. The temperature and humidity tolerances were ±3% r.h. and ±1°C.

Properties

The moisture content was measured with a Mettler DL35 Karl Fisher Titrator. Mettler DO301 Drying Oven (Mettler Instrument Corp., Hightstown, NJ), set at 180°C, was used to evaporate the moisture from the specimens.[12,13] Averages were calculated from two EPS foam specimens and three to six starch foam specimens.

Cell structure was determined to assess the relative amount of open and close cells in the foam. Test protocols followed ASTM D 2856–87, Procedure C. Beckman Air Comparison Pycnometer, Model 930 (Beckman Instruments, Inc., Scientific and Process Instruments Division, Fullerton, CA) was used.[14] One unaltered foam specimen was used per test. Averages were calculated from five to seven EPS and starch foam specimens.

Foam density is the weight-to-volume ratio of an individual loose-fill foam specimen. Foam density describes the reduction in density of the solid material that is attributable to the expansion process. A set of five specimens was weighed using a

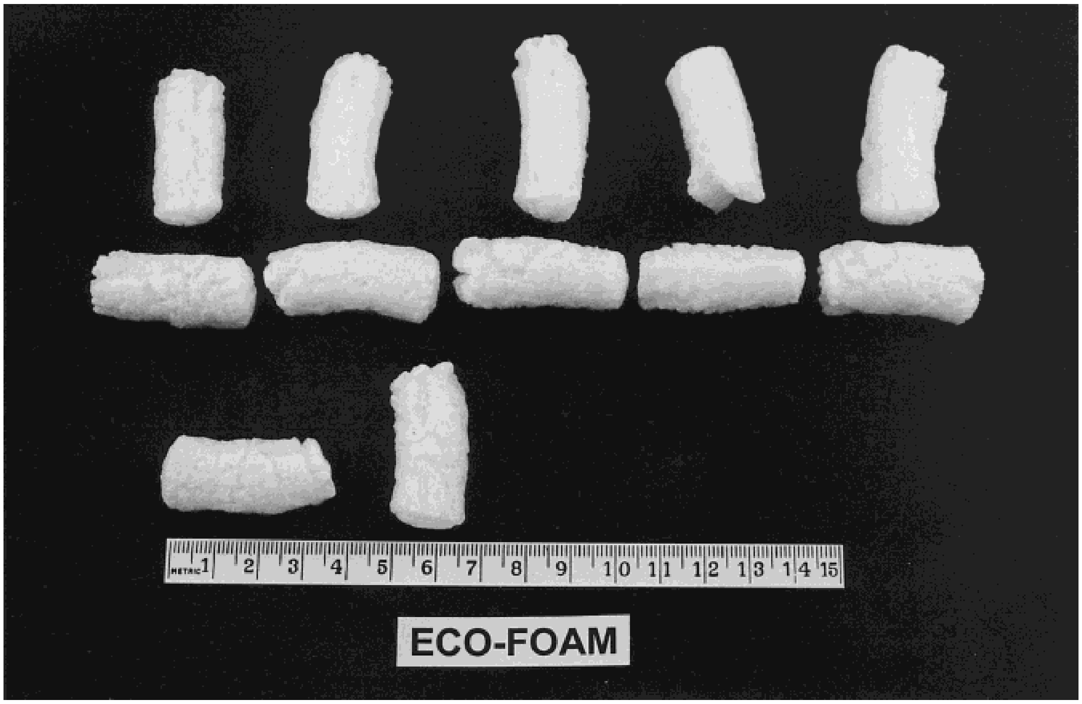

Figure 5 Photograph of ECO-FOAM.

Sartorius A200S analytic balance. These specimens were placed at regular intervals in a 250-mL graduated cylinder with a known volume of nominal 220 micron, P-010 solid glass spheres (Potters Industries Inc., Brownwood, TX). The total volume of glass spheres and foam specimens

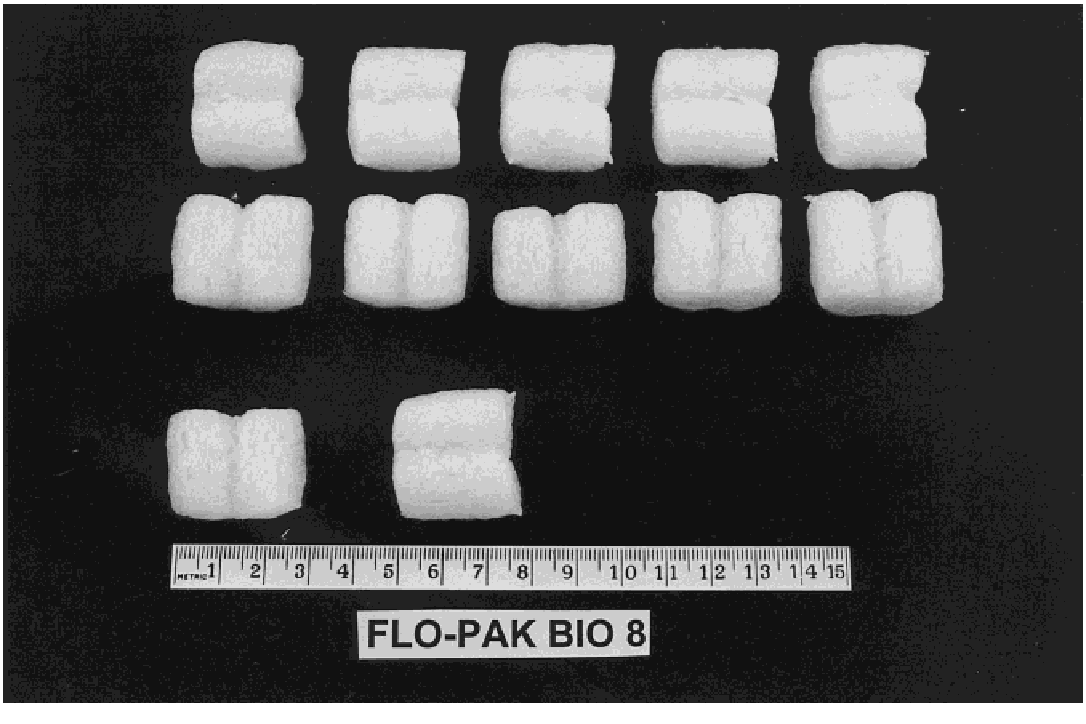

Figure 6 Photograph of FLO-PAK BIO 8.

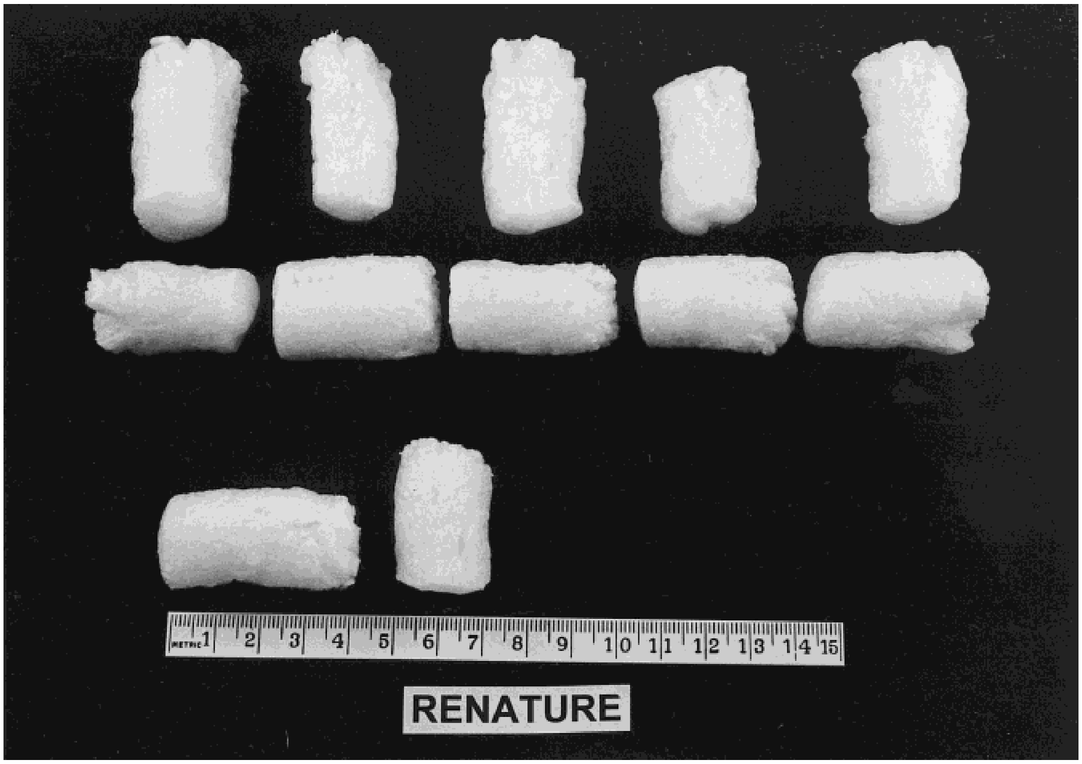

Figure 7 Photograph of RENATURE.

are recorded after tapping the graduated cylinder for 1 min. Foam density is calculated from the mass divided by the displaced volume. Averages were calculated from five to seven sets of EPS foam specimens and three sets of starch foam specimens.

Bulk density is the weight-to-volume ratio of a large quantity of loose-fill foam. Bulk density is a function of material and foam densities and the packing efficiency of the foam. Foams that have a high packing efficiency will have similar foam and bulk densities, whereas foams that have a low packing efficiency will have a bulk density that is significantly lower than its foam density. To measure bulk density, loose-fill foam was poured into the tarred beaker. Mettler PM4800 analytic balance was used to measure the foam weight and a 3-liter graduated glass beaker was used to measure its volume. Averages were calculated from ten sets of EPS and starch foam specimens.

Compressive stress and resiliency describe the mechanical integrity of the foam. The compressive stress is the amount of applied stress necessary to depress the surface of the foam by 3 mm. Resiliency is the percentage of elastic recovery after 3 mm deflection. A steel probe (0.635 cm diameter) mounted under a crossarm of an Instron Model 4201 with a 1 kN static load cell, type 2518–806 (Instron Corp., Canton, MA), was used. In each test, two foam specimens were stacked one on top of the other and oriented such that their largest dimension was perpendicular to the probe shaft. Two foam specimens were used instead of one to minimize the resistance provided by the solid Instron base. Depending on the product tested, the initial height of the two-foam stack varied between 20 and 46 mm. By lowering the piston to the foam surface, an initial load of 0.5 N was applied on the top specimens for approximately 5 s. From this point, the probe was lowered at a rate of 30 mm/min. for a distance of 3 mm. The maximum load was recorded. After 60 s has elapsed, a relaxation load was recorded. Compressive stress was calculated as the maximum load/cross-sectional area of the probe. Resiliency is the percentage of the compressive force after the 60-s hold period divided into the maximum force required to compress the foam 3 mm.[7] Averages were calculated from five sets of EPS and starch foam specimens.

Friability describes the percentage of foam fragmentation after tumbling the foam in a 190 × 197 × 197 mm box with 19 cubic mm solid

Figure 8 Photograph of STAR-KORE.

wooden blocks for a duration of 10 min. Using a set of 12 specimens in their original size and shape, friability tests were conducted according to the methods described in ASTM C 421–88.[15] Averages were calculated from three sets of EPS foam specimens and two to three sets of starch foam specimens.

Confidence Intervals

Confidence intervals are calculated from small sample t-test of hypothesis that aid in the determination of statistically significant differences between population averages from small samples.[12,13] The t-test uses a pooled sample variance estimate, s_p^2, expressed by:

$$s_p^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} \qquad (1)$$

where s_1^2 and s_2^2 is the variance and n_1 and n_2 is the number of specimens in samples 1 and 2. It is constructed by centering a t distribution about the difference between two property averages and calculating the distance to the critical region bounded by the positive and negative critical t values according to:

$$(\bar{x}_1 - \bar{x}_2) \pm t_{\alpha/2}\sqrt{s_p^2\left(\frac{1}{n_1} + \frac{1}{n_2}\right)} \qquad (2)$$

where $\bar{x}_1$ and $\bar{x}_2$ are the small sample property averages and $t_{\alpha/2}$ is based on $(n_1 + n_2 - 2)$ degrees of freedom.[16] Ninety-fifth percent level of significance or α risk of 0.05 was selected. This implies a 1 in 20 chance that the difference between these two property averages exceeds the upper limit or is below the lower limit. These critical t-statistic values are published in tables.[17] For degrees of freedom of 2, 3, 4, 5, 7, 8, 10, 12, and 18, $t_{\alpha/2}$ is 4.303, 3.182, 2.776, 2.571, 2.365, 2.306, 2.228, 2.179, and 2.101, respectively. The difference between averages is included within the lower and upper bounds of the confidence interval. If zero is included in the interval, then both property averages have no statistically significant difference.

Three important assumptions must be satisfied to use the two-sample confidence interval properly. Because the t statistic was used in the construction of confidence intervals, it is assumed that the sampled populations have approximately normal distributions, have equal variances, and have been selected in a random and independent fashion.[17] All commercial loose-fill samples, approximately 10 cubic feet in size, were acquired from production runs at the respective manufacturers. Each test used a different, randomly selected foam specimen. Commercial loose-fill populations are expected to have similar property variances and normal frequency distributions. However, the assumption of equal population variances can be relaxed if equal sample sizes are used in the comparison of the respective property averages.[17] All property averages were compared with the same or similar number of test specimens.

RESULTS AND DISCUSSION

Tables I–VII summarizes each of the seven performance properties for the eight commercial loose-fill products. Tables are divided into six primary columns. The first column lists the trade names of the two EPS-based foams followed by the six starch ones. The remaining five primary columns contain property information for each foam product measured at the following temperatures and relative humidities: as-received, 20, 50, and 80% r.h., 23°C and 50% r.h., 35°C. These five columns are further subdivided into three secondary columns. These columns contain the average, one standard deviation and the 95% confidence interval.

Analysis of the data consists of two comparisons to the "as-received" foam. The first comparison is summarized under the primary column entitled "As Received" and the secondary column entitled "Foams," where the difference between the property of PELASPAN PAC is compared with FLO-PAK S and starch based loose fill. The second comparison is detailed in the remaining four primary columns and secondary columns entitled "Condition," where the difference between the as-received property of each foam is compared with itself after conditioning. Each 95% confidence interval consists of three numbers. The top number represents the upper confidence limit (U.C.L.). The middle number is the difference between two sample averages. The bottom number denotes the lower confidence limit (L.C.L.). Those confidence intervals that do not intersect zero are considered statistically significant and are highlighted with a box.

Moisture Content

EPS-based PELASPAN PAC and FLO-PAK S did not show any appreciable change in moisture content after being conditioned at various humidities and temperatures. The only exception was a statistically significant decrease in moisture content after conditioning at 20% r.h., 23°C for PELASPAN PAC. The moisture content, ranging between 0.05 and 1.2 wt %, is similar to the range of values previously reported, but more than the approximate 0.10 wt % water absorption for solid injection molded polystyrene homopolymer.[8,18] Because polystyrene does not absorb appreciable amounts of moisture, the air inside the cell is expected to equilibrate via a diffusion process with the moisture in the ambient environment. No difference in moisture content or response to humidity and temperature changes was observed between the virgin and recycled EPS foams.

Averaging approximately 6 wt % moisture, all starch-based foams contain significantly more water than do EPS-based foams "as-received" from the manufacturer. Starch, unlike the nonpolar polystyrene, is very hygroscopic. The moisture content of starch varies with relative humidity. After conditioning at 20% r.h., 23°C, most starch-based foams had a moisture content similar to the unconditioned specimens, except ECO-FOAM. All starch-based foams contain significantly more water after equilibrating at 50 and 80% r.h., 23°C and 50% r.h., 35°C, averaging 9.5, 14, and 8.5 wt %, respectively. The hydroxy-propylated high amylose cornstarch and additives used to make ECO-FOAM are more sensitive to moisture than the unmodified corn and wheat starches used by the other manufacturers.[6,7] All starch-based foams absorb an increasing quantity of water as humidity increased. Some foams absorbed more water than others. At these conditions, ECO-FOAM had a moisture content higher by 1 to 2% above the other starch-based foams. Foams consisting of a chemically modified starch, such as ECO-FOAM, showed a greater tendency to absorb and retain more moisture than chemically unmodified ones. These results are expected because the substitution of bulky hydroxypropyl groups for hydroxyl groups do reduce chain packing and crystallization in a similar fashion that hydroxyethyl groups have been shown to do in wheat starch.[19] The difference in moisture content between 35 and 23°C at 50% r.h. was about 1% for the starch-based foams. These results show a response similar to the sorption isotherms of native high amylose corn starch films measured at different temperatures.[20] FLO-PAK BIO 8, ENVIRO-FIL, and RENATURE are believed to consist of corn starch, whereas CLEAN GREEN is believed

Table I Moisture Content (%)

	As Received[a]			23° 20% R.H.[b]			23°C 50% R.H.[b]			23°C 80% R.H.[b]			35°C 50% R.H.[b]		
Trade Name	Mean	Standard Deviation	Foam: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.
Pelaspan Pac	0.99	0.10	— — —	0.05	0.03	−0.61 −0.94 −1.28	1.22	0.11	0.70 0.23 −0.24	0.45	0.31	0.47 −0.45 −1.55	1.08	0.05	0.45 0.10 −0.26
Flo-Pak S	0.85	0.30	0.84 −0.14 −1.11	1.08	0.88	3.05 0.23 −2.59	1.10	0.07	1.19 0.25 −0.69	0.55	0.09	0.65 −0.30 −1.26	0.86	0.10	0.97 0.01 −0.95
Star-Kore	6.27	0.18	5.75 5.28 4.82	6.64	0.34	0.99 0.37 −0.25	9.73	0.29	4.01 3.46 2.91	13.40	0.49	7.97 7.13 6.29	8.72	0.16	2.84 2.45 2.06
Flo-Pak Bio 8	5.60	0.39	5.43 4.61 3.80	6.08	0.16	1.09 0.48 −0.15	9.49	0.27	4.56 3.89 3.21	14.08	0.35	9.21 8.48 7.75	8.55	0.49	3.79 2.95 2.10
Eco-Foam	6.00	0.15	5.41 5.01 4.61	6.66	0.09	0.94 0.66 0.38	10.31	0.48	5.12 4.31 3.51	16.18	0.63	11.21 10.18 9.14	9.97	0.15	4.31 3.97 3.63
Envirofil	6.21	0.21	5.76 5.22 4.68	6.53	0.05	0.67 0.32 −0.03	9.45	0.28	3.81 3.24 2.67	14.28	0.36	8.74 8.07 7.39	8.20	0.30	2.58 1.99 1.40
Renature	6.45	0.14	5.84 5.46 5.09	6.25	0.01	0.02 −0.20 −0.43	9.36	0.47	3.70 2.91 2.12	14.29	0.32	8.40 7.84 7.27	8.45	0.13	2.31 2.00 1.69
Clean Green	6.20	0.12	5.45 5.21 4.97	6.13	0.01	0.11 −0.07 −0.24	9.19	0.08	3.18 2.99 2.80	13.96	0.26	8.06 7.76 7.47	8.35	0.26	2.44 2.15 1.86

[a] Under the "As Received" Column, the moisture content of Pelaspan Pac is compared to the moisture content of Flo-Pak S and the starch loose-fill foams. The confidence interval for each comparison is found under the "Foam" Column. If statistically significant, this interval is highlighted with a box.

[b] Under the four temperature and humidity columns, the moisture content of each foam product is compared to the "as received" moisture content of itself. The confidence interval for each comparison is found under the "Condition" Column. If statistically significant, this interval is highlighted with a box.

Table II Open Cell Content (%)

	As Received			23° 20% R.H.			23°C 50% R.H.			23°C 80% R.H.			35°C 50% R.H.		
Trade Name	Mean	Standard Deviation	Foam: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.
Pelaspan Pac	16.9	4.0	— — —	17.0	1.6	4.4 0.1 −4.1	12.5	4.0	0.8 −4.4 −9.6	17.5	4.4	6.0 0.6 −4.8	13.4	2.0	0.9 −3.5 −7.8
Flo-Pak S	37.4	9.1	28.7 20.5 12.3	26.4	3.4	−1.4 −11.0 −20.6	35.7	6.3	8.8 −1.7 −12.2	29.1	3.3	1.3 −8.3 −17.9	33.1	4.4	5.6 −4.3 −14.2
Star-Kore	98.7	1.2	85.2 81.8 78.4	97.5	0.0	0.1 −1.2 −2.5	98.3	0.0	0.9 −0.4 −1.7	98.7	0.3	1.3 0.0 −1.3	99.0	0.0	1.6 0.3 −1.0
Flo-Pak Bio 8	98.8	0.3	85.2 81.9 78.6	98.7	0.2	0.3 −0.1 −0.5	98.9	0.1	0.4 0.1 −0.2	99.4	0.0	0.9 0.6 0.3	98.8	0.0	0.3 0.0 −0.3
Eco-Foam	98.2	0.6	84.6 81.3 78.0	97.2	0.2	−0.4 −1.0 −1.6	97.8	0.5	0.4 −0.4 −1.2	99.2	0.3	1.7 1.0 0.3	98.8	0.0	1.2 0.6 0.0
Envirofil	97.9	0.6	84.3 81.0 77.7	98.1	0.3	0.8 0.2 −0.4	98.8	0.3	1.5 0.9 0.3	99.2	0.4	1.9 1.3 0.7	99.0	0.1	1.7 1.1 0.5
Renature	97.6	0.7	84.0 80.7 77.4	97.2	0.3	0.4 −0.4 −1.2	97.9	0.4	1.1 0.3 −0.5	98.9	0.1	2.0 1.3 0.6	99.0	0.1	2.1 1.4 0.7
Clean Green	96.5	0.3	82.9 79.6 76.3	96.4	0.4	0.4 −0.1 −0.6	98.1	0.2	1.9 1.6 1.3	98.0	0.7	2.2 1.5 0.8	97.8	0.4	1.7 1.3 0.9

Table III Foam Density (g/cc)

	As Received			23° 20% R.H.			23°C 50% R.H.			23°C 80% R.H.			35°C 50% R.H.		
Trade Name	Mean	Standard Deviation	Foam: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.
Pelaspan Pac	0.0079	0.0010	— — —	0.0075	0.0003	0.0006 −0.0004 −0.0014	0.0096	0.0014	0.0032 0.0017 0.0002	0.0085	0.0006	0.0017 0.0006 −0.0005	0.0095	0.0010	0.0029 0.0017 0.0004
Flo-Pak S	0.0072	0.0006	0.0003 −0.0007 −0.0016	0.0074	0.0004	0.0009 0.0002 −0.0005	0.0075	0.0008	0.0012 0.0003 −0.0006	0.0080	0.0003	0.0014 0.0008 0.0001	0.0097	0.0007	0.0033 0.0025 0.0016
Star-Kore	0.0203	0.0008	0.0139 0.0125 0.0110	0.0194	0.0007	0.0007 −0.0010 −0.0027	0.0206	0.0001	0.0016 0.0003 −0.0010	0.0222	0.0005	0.0034 0.0019 0.0004	0.0204	0.0006	0.0164 0.0000 −0.0162
Flo-Pak Bio 8	0.0167	0.0004	0.0102 0.0088 0.0074	0.0163	0.0007	0.0009 −0.0004 −0.0016	0.0168	0.0006	0.0012 0.0001 −0.0011	0.0195	0.0007	0.0040 0.0027 0.0146	0.0180	0.0009	0.0028 0.0012 −0.0003
Eco-Foam	0.0209	0.0017	0.0149 0.0130 0.0111	0.0198	0.0005	0.0018 −0.0011 −0.0040	0.0191	0.0004	0.0010 −0.0018 −0.0046	0.0258	0.0009	0.0080 0.0049 0.0187	0.0210	0.0004	0.0029 0.0001 −0.0027
Envirofil	0.0226	0.0013	0.0164 0.0147 0.0130	0.0219	0.0006	0.0017 −0.0007 −0.0030	0.0221	0.0012	0.0025 −0.0004 −0.0033	0.0239	0.0014	0.0045 0.0014 −0.0018	0.0209	0.0000	0.0005 −0.0017 −0.0039
Renature	0.0214	0.0004	0.0149 0.0135 0.0122	0.0203	0.0008	0.0004 −0.0011 −0.0025	0.0210	0.0005	0.0006 −0.0004 −0.0015	0.0239	0.0010	0.0041 0.0025 0.0077	0.0217	0.0010	0.0021 0.0003 −0.0014
Clean Green	0.0216	0.0005	0.0151 0.0137 0.0123	0.0209	0.0005	0.0005 −0.0006 −0.0018	0.0218	0.0003	0.0012 0.0003 −0.0006	0.0274	0.0007	0.0072 0.0059 0.0045	0.0221	0.0002	0.0014 0.0005 −0.0003

Table IV Bulk Density (kg/cu. m)

	As Received			23° 20% R.H.			23°C 50% R.H.			23°C 80% R.H.			35°C 50% R.H.		
Trade Name	Mean	Standard Deviation	Foam: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.
Pelaspan Pac	3.296	0.141	— — —	3.449	0.079	0.261 0.153 0.046	3.382	0.123	0.211 0.086 −0.039	3.415	0.067	0.224 0.119 0.015	3.418	0.059	0.223 0.122 0.020
Flo-Pak S	3.542	0.141	0.379 0.246 0.113	3.428	0.080	−0.006 −0.114 −0.222	3.510	0.079	0.076 −0.032 −0.140	3.473	0.073	0.037 −0.069 −0.174	3.756	0.077	0.321 0.214 0.107
Star-Kore	8.834	0.208	5.705 5.538 5.371	8.590	0.164	−0.068 −0.244 −0.420	8.594	0.209	−0.044 −0.240 −0.436	9.121	0.140	0.453 0.287 0.121	8.906	0.169	0.250 0.072 −0.106
Flo-Pak Bio 8	8.971	0.232	5.856 5.675 5.494	8.378	0.173	−0.401 −0.593 −0.785	8.787	0.158	0.003 −0.184 −0.371	9.450	0.118	0.652 0.479 0.306	8.766	0.108	−0.035 −0.205 −0.375
Eco-Foam	9.129	0.430	6.134 5.833 5.520	8.648	0.164	−0.175 −0.481 −0.787	8.762	0.164	−0.061 −0.367 −0.673	10.154	0.211	1.344 1.025 0.707	8.608	0.192	−0.208 −0.521 −0.834
Envirofil	10.808	0.395	7.791 7.512 7.233	10.240	0.176	−0.281 −0.568 −0.856	10.359	0.208	−0.152 −0.449 −0.746	11.096	0.258	0.601 0.288 −0.026	10.665	0.201	0.151 −0.143 −0.438
Renature	11.131	0.334	8.076 7.835 7.594	10.330	0.235	−0.530 −0.801 −1.073	10.079	0.108	−0.819 −1.052 −1.285	11.204	0.196	0.331 0.073 −0.184	10.499	0.167	−0.384 −0.632 −0.880
Clean Green	11.312	0.496	8.359 8.016 7.673	10.681	0.204	−0.275 −0.631 −0.987	11.000	0.190	0.041 −0.312 −0.665	12.683	0.209	1.729 1.371 1.013	11.107	0.304	0.182 −0.205 −0.591

Table V Compressive Strength (MPa)

	As Received			23° 20% R.H.			23°C 50% R.H.			23°C 80% R.H.			35°C 50% R.H.		
Trade Name	Mean	Standard Deviation	Foam: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.
Pelaspan Pac	0.0893	0.0408	— — —	0.1048	0.0116	0.0592 0.0155 −0.0283	0.0820	0.0216	0.0403 −0.0073 −0.0549	0.0865	0.0113	0.0409 −0.0028 −0.0465	0.0739	0.0172	0.0303 −0.0154 −0.0611
Flo-Pak S	0.0410	0.0089	−0.052 −0.0483 −0.0914	0.0441	0.0046	0.0134 0.0031 −0.0073	0.0480	0.0023	0.0165 0.0070 −0.0025	0.0459	0.0076	0.0170 0.0049 −0.0072	0.0437	0.0051	0.0133 0.0027 −0.0078
Star-Kore	0.0671	0.0120	0.0217 −0.0222 −0.0661	0.0864	0.0102	0.0356 0.0193 0.0031	0.0731	0.0125	0.0238 0.0060 −0.0118	0.0676	0.0068	0.0148 0.0005 −0.0137	0.0802	0.0154	0.0332 0.0131 −0.0070
Flo-Pak Bio 8	0.0565	0.0088	0.0103 −0.0328 −0.0759	0.0643	0.0052	0.0183 0.0078 −0.0028	0.0566	0.0024	0.0095 0.0001 −0.0093	0.0441	0.0031	−0.0028 −0.0124 −0.0221	0.0561	0.0082	0.0121 −0.0004 −0.0128
Eco-Foam	0.0612	0.0050	0.0143 −0.0281 −0.0705	0.0721	0.0047	0.0180 0.0109 0.0038	0.0546	0.0078	0.0029 −0.0066 −0.0161	0.0517	0.0087	0.0008 −0.0095 −0.0198	0.0651	0.0102	0.0157 0.0039 −0.0078
Envirofil	0.0858	0.0068	0.0392 −0.0035 −0.0462	0.0897	0.0234	0.0290 0.0039 −0.0212	0.0832	0.0071	0.0075 −0.0026 −0.0127	0.0785	0.0199	0.0143 −0.0073 −0.0290	0.0910	0.0251	0.0321 0.0052 −0.0216
Renature	0.1051	0.0107	0.0593 0.0158 −0.0277	0.1032	0.0204	0.0218 −0.0019 −0.0256	0.0893	0.0143	0.0026 −0.0158 −0.0342	0.0714	0.0065	−0.0208 −0.0337 −0.0466	0.0951	0.0168	0.0105 −0.0100 −0.0305
Clean Green	0.0927	0.0121	0.0473 0.0034 −0.0405	0.0922	0.0136	0.0183 −0.0005 −0.0193	0.0859	0.0043	0.0065 −0.0068 −0.0201	0.0724	0.0043	−0.0070 −0.0203 −0.0336	0.0943	0.0054	0.0152 0.0016 −0.0121

Table VI Resiliency (%)

	As Received			23°C 20% R.H.			23°C 50% R.H.			23°C 80% R.H.			35°C 50% R.H.		
Trade Name	Mean	Standard Deviation	Foam: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.
Pelaspan Pac	78.1	1.5	— — —	79.6	0.9	3.3 1.6 −0.2	79.3	1.2	3.3 1.3 −0.7	78.5	0.9	2.3 0.4 −1.4	77.3	0.9	1.1 −0.7 −2.5
Flow-Pak S	82.5	0.9	6.3 4.5 2.7	85.1	1.1	4.0 2.5 1.0	82.7	1.0	1.6 0.2 −1.3	84.0	1.4	3.2 1.5 −0.2	78.9	4.1	0.7 −3.6 −7.9
Star-Kore	71.2	1.0	−5.0 −6.8 −8.7	63.8	0.3	−6.4 −7.5 −8.5	70.2	1.3	0.7 −1.1 −2.8	62.9	0.7	−7.1 −8.3 −9.6	70.7	1.2	1.0 −0.5 −2.1
Flo-Pak Bio 8	70.9	1.1	−5.3 −7.2 −9.1	62.8	0.9	−6.7 −8.1 −9.6	70.1	1.1	0.8 −0.8 −2.4	63.5	1.5	−5.4 −7.4 −9.3	66.4	0.9	−3.0 −4.5 −5.9
Eco-Foam	70.7	0.8	−5.6 −7.4 −9.1	64.3	1.2	−4.9 −6.4 −7.9	69.0	4.5	3.0 −1.7 −6.4	61.8	2.8	−5.8 −8.8 −11.8	70.0	0.7	0.4 −0.7 −1.8
Envirofil	70.8	0.5	−5.6 −7.3 −8.9	62.5	2.5	−5.6 −8.2 −10.9	67.8	0.9	−1.9 −2.9 −4.0	66.2	2.3	−2.2 −4.6 −7.0	69.2	0.8	−0.6 −1.5 −2.5
Renature	69.5	0.5	−6.9 −8.5 −10.2	61.9	2.2	−5.2 −7.6 −10.0	67.2	0.6	−1.5 −2.3 −3.2	66.8	0.7	−1.9 −2.8 −3.7	68.0	1.3	−0.1 −1.5 −3.0
Clean Green	70.9	1.0	−5.3 −7.2 −9.0	64.3	0.7	−5.4 −6.6 −7.8	68.8	1.0	−0.6 −2.1 −3.5	65.8	2.7	−2.1 −5.1 −8.1	71.1	0.5	1.3 0.2 −1.0

Table VII Friability (%)

	As Received			23° 20% R.H.			23°C 50% R.H.			23°C 80% R.H.			35°C 50% R.H.		
Trade Name	Mean	Standard Deviation	Foam: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.	Mean	Standard Deviation	Condition: 95% U.C.L. Difference 95% L.C.L.
Pelaspan Pac	4.313	3.318	— — —	3.608	2.165	5.645 −0.705 −7.056	4.134	0.368	7.716 −0.179 −8.073	6.065	4.490	10.701 1.752 −7.197	7.602	2.881	10.333 3.289 −3.754
Flo-Pak S	0.546	0.550	1.624 −3.767 −9.157	0.086	0.058	0.425 −0.460 −1.346	0.467	0.270	1.301 −0.079 −1.459	0.047	0.036	0.383 −0.500 −1.382	0.534	0.669	1.375 −0.013 −1.401
Star-Kore	2.389	1.653	4.019 −1.923 −7.865	0.437	0.367	0.762 −1.953 −4.667	1.077	0.698	2.780 −1.312 −5.405	1.419	0.715	1.917 −0.970 −3.857	6.673	0.922	7.317 4.283 1.249
Flo-Pak Bio 8	0.003	1.340	2.831 −4.310 −11.450	0.180	0.086	2.434 0.177 −2.080	0.444	0.177	4.554 0.440 −3.674	0.841	0.737	3.685 0.838 −2.009	4.520	2.461	10.772 4.517 −1.739
Eco-Foam	0.582	0.196	1.597 −3.731 −9.058	0.251	0.202	0.121 −0.331 −0.782	0.070	0.751	0.831 −0.512 −1.855	2.471	0.394	2.954 1.889 1.184	3.631	0.726	4.255 3.049 1.844
Envirofil	0.279	0.246	1.299 −4.034 −9.367	0.075	0.056	0.201 −0.204 −0.609	0.251	0.296	0.739 −0.027 −0.794	1.524	0.144	1.702 1.245 0.788	3.042	3.011	7.605 2.763 −2.079
Renature	0.244	0.935	1.457 −4.068 −9.594	0.129	0.071	1.387 −0.115 −1.618	0.110	0.116	2.091 −0.134 −2.359	1.391	0.034	2.646 1.147 −0.353	4.691	3.459	10.189 4.446 −1.296
Clean Green	0.410	0.157	1.422 −3.902 −9.227	0.125	0.047	−0.023 −0.286 −0.549	0.250	0.330	0.506 −0.160 −0.827	1.612	0.492	2.029 1.201 0.374	3.473	0.851	4.448 3.062 1.676

to consist of wheat starch. Unmodified corn and wheat starch have very similar water absorption characteristics. Results, shown in Table I, are consistent with the adsorption isotherms previously reported for corn and wheat starch powders.[21] Though additives such as polyvinyl alcohol and hydrophilic plasticizers may be present in small quantities, they can affect moisture absorption of these products.

Cell Structure

Open cells in foams occur if at least part of one wall is missing, creating an opening onto adjacent cells.[22] The open-cell content of PELASPAN PAC is low. The reason for its predominately closed-cell structure is a consequence of its method of manufacture. Polystyrene foam beads, which contain either dissolved gas or chemical blowing agents, are expanded by steam and aged for a day below the glass transition temperature to allow air to diffuse into the cells. Repeating this expansion process a few times reduces bulk density and minimizes the presence of open cells because the cell walls are expanded just enough to prevent cell wall rupture.[8,9] After conditioning, the open-cell content of PELASPAN PAC did not change significantly.

The open-cell content of FLO-PAK S is higher than PELASPAN PAC. Recycled EPS loose fill is partly expanded by the extrusion process before steam expansion, which may make it more difficult to control the expansion and cell wall integrity.[10] After conditioning, FLO-PAK S did not show significant changes in open-cell content, except after conditioning at 23°C and 20% r.h.

All starch-based foams have higher open-cell content than either EPS-based foam. Considering the manufacturing process used, it is not surprising that starch-based foams have more open cells. The expansion is attributable to the escape of water as steam during the extrusion process, resulting between 96 and 99% open cells. Steam can easily rupture the cell walls because thermoplastic starches have poor melt strength. After exposure to high humidities and temperatures, most foams exhibited a statistically significant, but trivial increase, about 1.0%, in open-cell content. Commercial starch-based foams have an open cellular structure. This differs from patents that claim hydroxypropylated high amylose foams as having a closed-cell structure, but the method used to make this assessment was not disclosed.[6,7]

Foam Density

Foam density describes the density of an individual expanded loose-fill foam specimen. PELASPAN PAC has a foam density of 0.0079 g/cc vs. 1.0 g/cc for nonexpanded polystyrene homopolymer. During the manufacturing process, the density of polystyrene has been reduced by a factor greater than 125. After conditioning, foam density of PELASPAN PAC usually did not change. However, after conditioning at 50% r.h., 23 and 35°C, the foam density increased. The relative increase in foam density between as-received and these conditions range between 20 and 35%. With a foam density of 0.0072 g/cc, FLO-PAK S was not significantly different from PELASPAN PAC. Its response to conditioning was similar, especially at 80% r.h., 23°C and 50% r.h., 35°C. The loss of air from the foam, particularly at the higher conditioning temperature, may be the reason for the higher foam density.

The foam density of starch-based products was much higher than EPS-based ones. These values ranged between 0.0167 and 0.0209 g/cc for STARKORE, FLO-PAK BIO 8, and ECO-FOAM and between 0.0214 and 0.0226 g/cc for ENVIROFIL, RENATURE, and CLEAN GREEN. These products are approximately two to three times more dense than EPS-based foams. This disparity is attributable to the large difference in density between polystyrene and starch and a lower expansion factor. Dry, unmodified granular starch has a nominal density of 1.5 g/cc. During the extrusion process, the starch density has been reduced by factors ranging between 60 and 90. Open cells created during expansion will prevent the foam from continuing the expansion.

After conditioning at 20 and 50% r.h., 23°C and 50% r.h., 35°C, the changes in foam density were not statistically significant. After conditioning at 80% r.h., 23°C, however, the density of all starch-based foams increased significantly except ENVIROFIL. The relative change in foam density between as-received and 80% r.h., 23°C ranges between 10 and 30%. This result is attributable to the weight gain from the increased water absorption and the shrinkage in the foam volume because of the higher water content. Water plasticizes starch by disrupting the inter- and intrachain bonding among adjacent starch molecules, which are responsible for its brittle, rigid network. Shrinkage can be caused by the relaxation of internal stresses that have been frozen into the foam during the extrusion manufacturing process. Shrinkage can be influenced by many factors besides moisture content such as starch type, derivatization, an amylose/amylopectin ratio, presence of water soluble additives such as polyvinyl alcohol and glycerin, extrusion process parameters such as temperature and pressure, and the shape of the foam.

Bulk Density

Bulk density is more complex than specific density. Bulk density takes into account not only material and foam densities, but also packing efficiency, which depends on size, shape, and uniformity of the loose fill. Packing efficiency describes how well the loose fill fills the voids among adjacent foam specimens and can be measured by the ratio of bulk density to foam density. If this ratio is equal to one, the efficiency is very high because no voids exits among adjacent foam specimens. A low packing ratio can be achieved from irregular shaped foams. A loose-fill product with low packing is most desirable because the end-user reduces material consumption and saves shipping costs.

The bulk density of PELASPAN PAC is a very low 3.3 kg/m^3. After conditioning, the bulk density of PELASPAN PAC increased. This change was significant for all conditions except 50% r.h., 23°C. On a relative basis, the increase ranged between 3 and 5%. At 3.5 kg/m^3 the bulk density of FLO-PAK S is higher than PELASPAN PAC by 7.5%. Conditioning did change the bulk density of FLO-PAK S, but the change was less than 6%. The packing ratio of as-received PELASPAN PAC is 0.417 vs. 0.492 for FLO-PAK S. After conditioning at 50% r.h., 35°C, this ratio decreased to 0.360 and 0.387, respectively.

All starch-based foams have a significantly higher bulk density by a factor of two to three than either EPS-based foam. As shown in Figure 9, the starch-based foams cluster into two bulk density groups. STAR-KORE, FLO-PAK BIO 8, and ECO-FOAM have bulk densities between 8.8 and 9.1 kg/m^3 and between 10.8 and 11.3 kg/m^3 for ENVIROFIL, RENATURE, and CLEAN GREEN. As shown in Figure 10, foam density of starch-based foams correlated well with bulk density. The correlation coefficient for this relationship is 0.97. The bulk density of 10.9 kg/m^3 for ECO-FOAM has been previously reported and this is slightly higher with the 9.1 to 10.1 kg/m^3 values found in this study.[1] The packing ratio of the starch-based foams was between 0.435 and 0.538. STAR-KORE and ECO-FOAM had the lowest packing ratio of 0.435 and 0.437, respectively, below the value for FLO-PAK S. At 0.538, FLO-PAK BIO 8 had the highest packing ratio and at 0.0167 g/cc the lowest foam density. Irregular cylindrical shapes impart products with lower packing ratios than does uniform cylindrical or dual cylindrical shapes with two similar dimensions.

After conditioning at 20 and 50% r.h., 23°C and 50% r.h., 35°C, all starch-based foams exhibited a decrease in bulk density. This decrease was small but significant in many instances. RENATURE had the largest decrease. For the bulk density to decrease, the starch foams probably expanded or swelled slightly during conditioning as the retrogradated amylose chains relaxed. After conditioning at 80% r.h., 23°C, bulk density, like foam density, increased significantly except ENVIROFIL and RENATURE. The increase in bulk density can be attributed to both the increase in moisture content and the apparent shrinkage of the foam due to plasticization of the starch by the absorbed water. Packing ratios did change after conditioning; however, these changes followed the changes in bulk and foam density.

Compressive Stress

Compressive stress is the maximum force required to compress the foam 3 mm. High compressive stress implies foams resist compression. Compressive stress of PELASPAN PAC averaged 0.0893 MPa. As expected, no significant changes in this property were observed with respect to changes in relative humidity. At 0.041 MPa, FLO-PAK S did have a much lower compressive stress than PELASPAN PAC. This can be attributed, in part, to the "hollowed figure eight" shape, which requires less force to compress than a solid would. Molecular weight deterioration of the recycled polystyrene and the cell structure of the foam may also contribute to its lower strength.[9,22] Like PELASPAN PAC, FLO-PAK S did not show any significant changes in compression stress with respect to changes in relative humidity.

The compressive stress of starch-based foams does not significantly differ from PELASPAN PAC. As-received FLO-PAK BIO-8, STAR-KORE, ECO-FOAM and ENVIROFIL have lower values between 0.0565 and 0.0853 MPa, whereas CLEAN GREEN and RENATURE have higher values of 0.0927 and 0.1051 MPa. PELASPAN PAC, however, combined a high compressive

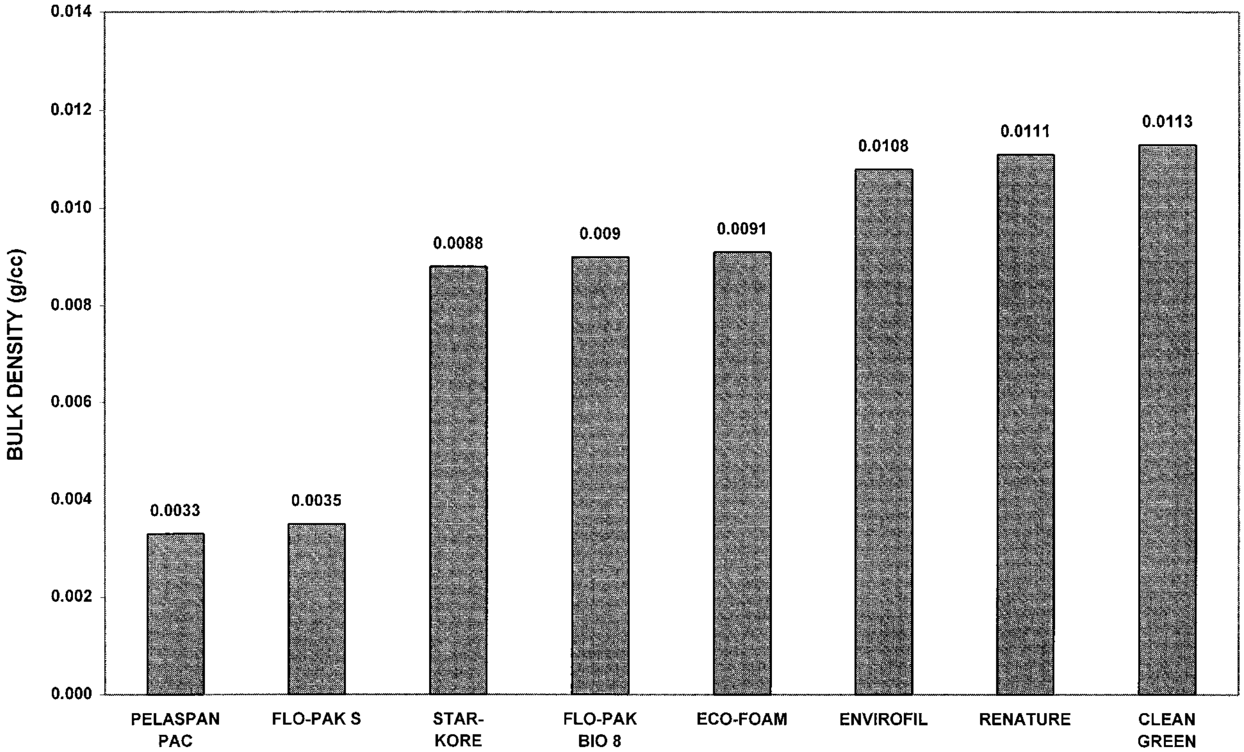

Figure 9 Bulk density of commercial loose-fill foams.

stress with a desirable low foam density. All starch-based foams had a compressive stress greater than that of FLO-PAK S.

Compressive stress of starch-based foams was generally insensitive to changes in relative humidity. At 20% r.h. and 23°C, only the chemically modified starch-based foams, ECO- FOAM and STAR-KORE, significantly increased compressive stress by 17 and 28%, respectively. At 80% r.h., 23°C, FLO-PAK BIO-8, RENATURE, and CLEAN GREEN significantly decreased compression stress by 22 to 32%. The higher moisture content in these products was sufficient to lower their resistance to compression. Although the chemically modified STAR-KORE and ECO-FOAM and the unmodified ENVIROFIL absorbed 13 to 16 wt % water at this condition, compressive stress did not significantly change. Chemically modified starches produced foams with good resistance to compression over a broad humidity range.

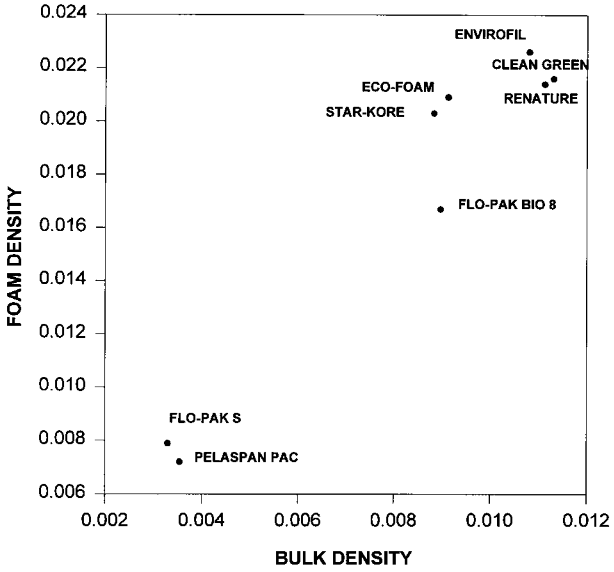

Figure 10 Foam and bulk density of commercial loose-fill foams.

Resiliency

Resiliency describes the ability of the foam to recover to its original form after deformation. Resiliency less than 100% implies that the polymer was strained beyond its elastic limit, for example, by cell wall rupture, which prevents the foam from recovering to its original state.

PELASPAN PAC has a resiliency of 78.1%. No significant differences in resiliency were attributable to changes in relative humidity. At 82.5%, the resiliency of FLO-PAK S was not significantly different from PELASPAN PAC. Their response to changes in relative humidity and temperature were not significant, with one exception.

The resiliency of starch-based foams with values between 69.5 and 71.2% are, as a group, about 10% lower on a relative basis than PELASPAN PAC. One study reports the permanent set of EPS and ECO-FOAM as 20 and 25.4%, respectively.[1] These values are consistent with the resiliencies measured for these materials. After conditioning, the resiliency of all starch-based foams were significantly lower, with values between 60 and 70%. Although starch-based foams absorbed 13 to 16 wt % moisture after conditioning at 80% r.h. and 23°C, the 62 to 67% resiliency retained is sufficient for the product to function.

Friability

Fragmentation of loose fill during handling and use is an important product quality concern among end-users. Friability of as-received PELASPAN PAC was 4.3%. FLO-PAK S had a lower friability of 0.54%, but is not significantly different because of the variability in the test. After conditioning, the friability of these EPS-based foams did not change significantly.

The friability of as-received starch-based foams ranged between 0.003 and 2.3%. Although these values are lower than EPS-based foams, they are not significantly different. After conditioning, the friability of these starch-based foams increased significantly when exposed to 80% r.h. and 23°C and 50% r.h. and 35°C, except FLO-PAK BIO 8 and RENATURE.

In the MOWM report, after abrasion starch products "produce a noticeable fine dust" and EPS produced "large fragments."[23] Although quantitative results were not given, these observations are consistent in the manner in which these products broke down after testing. Irregular-shaped specimens fragmented into large pieces. Quantitatively, starch- and EPS-based foams fragmented similarly at 2 to 6 wt %, but starch-based foams broke down into a fine dust, whereas virgin EPS-based foams broke into large fragments.

CONCLUSIONS

Although the use of natural materials, such as starch, in loose-fill products has been praised for a biodegradability and environmentally safe image, these products have been unfairly criticized for their perceived inferiority compared with EPS loose-fill products. EPS- and starch-based foams have differences, but the differences do not compromise performance.

These products differ with respect to composition and method of manufacture. Foam and bulk densities, which are higher by a factor of two to three times than either EPS-based foams, are attributable to the density of starch, which is 50% higher than polystyrene homopolymer and to the direct water-to-steam expansion process, which creates a predominately open cellular structure that stops foam expansion. EPS-based foams are expanded by a process that produces a foam with a very low density and a predominately closed cellular structure. Though EPS-based foam density increased after conditioning in some instances, this product was much less dense than starch-based foams. Foam density of starch-based products significantly increased between 10 and 30% after conditioning at high humidity.

Starch-based foam loose-fill is very hygroscopic. After conditioning at 20% r.h., 23°C, these materials contained approximately 6 wt % water, an amount that is similar to the quantity of water that remains in the foam after manufacture. After conditioning at 50 and 80% r.h., 23°C and 50% r.h., 35°C, water content averaged 9.5, 14, and 8.5 wt %, respectively. ECO-FOAM, which is made from hydroxypropylated high amylose corn starch, absorbs between 1 and 2 wt % more water than the other starch-based foams.

Compressive stress of PELASPAN PAC averaged 0.0893 MPa combined with a desirable low foam density. The compressive stress of most starch-based foams did not differ significantly from PELASPAN PAC. As-received FLO-PAK BIO-8, STAR-KORE, ECO-FOAM, and ENVIRO-FIL have lower values between 0.0565 and 0.0853 MPa, whereas CLEAN GREEN and RENATURE have higher values of 0.0927 and 0.1051 MPa. All starch-based foams have higher compressive stress than FLO-PAK S. Chemically modified starches yielded foams with good retention of compressive stress over a broad humidity range.

The resiliency of starch-based foams with values between 69.5 and 71.2% are, as a group, about 10% lower on a relative basis than PELASPAN PAC. Although starch-based foams absorbed 13 to 16 wt % moisture after conditioning at 80% r.h. and 23°C, these products retained between 62 and 67% resiliency.

Both starch- and EPS-based foam fragmentation amounted to 2 to 6 wt %, but starch-based foams broke down into a fine dust, whereas EPS-based foams broke into large fragments.

All starch-based foams have a significantly higher foam and bulk density and open cell and moisture content than EPS-based foam. Both product types have similar compressive stress, resiliency, and friability. Starch-based foams were more sensitive to changes in relative humidity and temperature than EPS-based foam, but the higher amount of absorbed moisture did not compromise its mechanical integrity.

Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by USDA implies no approval of the product to the exclusion of others that may be suitable. The authors thank G. D. Grose and M. K. Redman for their technical contributions.

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