

Structure and morphology of baked starch foams

R. L. Shogren*, J. W. Lawton, W. M. Doane^{†‡} and K. F. Tiefenbacher[§]

Plant Polymer Research Unit, US Department of Agriculture, Agricultural Research Service, National Centre for Agricultural Utilization Research, 1815 N. University Street, Peoria, IL 61604, USA

(Received 21 July 1997; accepted 13 November 1997)

Baked starch foams were characterized by several physical methods in order to better understand the relationship between process parameters and starch foam structure. In this process, a thin-walled object such as a plate is formed by heating a starch batter inside a closed mould. Normal corn and potato starches are gelatinized by this treatment but some swollen granules remain. The foams have a dense outer skin and a less dense interior with large, mostly open cells. Overall foam density and strength increase with increasing starch concentration, molecular weight and amylose content. Foam flexibility tends to increase with decreasing density. Plates made from tuber starches such as potato have lower densities and higher flexibilities than those made from cereal starches such as corn. Starch foams are useful as disposable food packaging and serving articles which can be composted after use. © 1998 Published by Elsevier Science Ltd. All rights reserved.

(Keywords: starch; foam; biodegradable)

INTRODUCTION

The use of starch as a biodegradable base material for disposable articles such as plates, utensils and bags is desirable as an environmentally friendly alternative to the present use of non-degradable petroleum-based plastics such as polyethylene and polystyrene^{1–7}. Although the latter can be recycled, this is often difficult and expensive due to contamination of plastic articles with food and collection costs. Totally biodegradable starch-based plastics can be composted into a useful mulch rather than being entombed in landfills. In addition, starch is a widely available biopolymer and, at \$0.25–0.60 kg⁻¹, is less expensive than polyethylene and polystyrene (\$0.80–1.50 kg⁻¹).

Expanded starch-based foams have been prepared since the 1970s by extrusion of grains or starch with water^{8–11}. High temperatures and shear within the extruder barrel cause the starch–water mixture to melt into a plastic-like consistency. Water serves as the blowing agent as it expands upon exiting the extruder. For example, expanded snack foods and cereals are prepared in this manner. More recently, starch foam packing ‘peanuts’ and sheeting have been prepared using a similar process and have begun to penetrate the market formerly occupied entirely by expanded polystyrene foam packing^{12–14}. It is, however, difficult to prepare shaped objects such as a plate from starch foam because the heat required to soften the foam and mould it into the desired shape will cause the starch to lose moisture and raise its glass transition temperature to levels above the decomposition temperature (~200°C)¹⁵.

Recently, a new process for preparing shaped foam articles from starch has been described^{6,7}. This involves

baking a starch–water batter in a hot mould. A starch-formed article is fashioned as the starch gelatinizes, expands and dries. In this report, baked starch foams were characterized by several physical methods in order to better understand how variables such as amylose content, starch concentration, starch type, molecular weight and temperature influence starch foam structure and properties. The effects of humidity and time on the mechanical properties of baked starch foams were also studied.

MATERIALS AND METHODS

Materials

Normal corn starch (27% amylose) was Buffalo 3401 from CPC International, Englewood Cliffs, NJ and had a moisture content of 10–12%. Waxy maize starch (18% moisture) was Amioca from National Starch and Chemical, Bridgewater, NJ. High amylose corn starches (12% moisture) containing 50 and 70% amylose were Amaizo 5 and Amylomaize VII from American Maize-Products, Hammond, IN. Wheat starch (16.6% moisture) was AYTEX-P3201-8 from Ogilvie Mills, Minnetonka, MN. Tapioca starch (18.6% moisture) was Staley No. 1 from A. E. Staley Mfg., Decatur, IL. Guar gum and magnesium stearate were from Sigma Chemical, St Louis, MO.

Methods

Preparation of foam trays. Starch, guar (1% based on starch weight) and magnesium stearate (2% based on starch weight) were mixed in the dry state using a Kitchen Aid mixer with a wire whisk attachment. Guar was added to increase batter viscosity and therefore prevent starch from settling during preparation. Magnesium stearate was added to facilitate release of baked starch foams from the mould surface. Distilled water was then added to the starch and the batter was mixed on medium speed for 20 min. The amount

* To whom correspondence should be addressed. Phone: 309-681-6354, Fax: 309-681-6691

[†] Bradley University, Peoria, IL 61604 (current address)

[‡] Franz Haas Machinery of America, Richmond, VA 23231

[§] Franz Haas Machinery of America, Richmond, VA 23231

of added water necessary to give a batter with the desired solids content was calculated by: % solids = starch dry wt./ (starch moist wt. + added water wt.)

Starch foam trays were prepared using a lab model baking machine (model LB TRO) supplied by Franz Haas Machinery of America, Richmond, VA. This machine essentially consists of two heated steel moulds, the top of which can be hydraulically lowered to mate with the bottom half for a set amount of time. Dimensions of the mould were 217 mm long, 134 mm wide, 19 mm deep and 3 mm (plate separation). mould temperatures were set at 175–235°C as described in Section Section 3. Actual temperatures at the mould surface were approximately 10°C lower as measured using a Temp-Sure Digital Pyrometer TS-200. The minimum amount of starch batter required to form a complete tray (see Section Section 3) was added to the bottom half of the mould after which the top was closed. Baking times were the minimum required to avoid a soft or bubbled tray and depended strongly on the formulation (see Section Section 3). After baking, trays typically contained 2–4% moisture. The presence of higher moisture levels normally caused puffing and distortion of trays due to release of pressurized steam within the tray after mould opening.

Testing of trays

Trays were equilibrated at 20, 50 and 85% relative humidity (R.H.) at 23°C for 7 days prior to mechanical testing. The 20% R.H. environment was achieved by placing a saturated solution of sodium acetate in a large glove box. For 85% R.H., a Hotpack constant humidity oven was used. Equilibration at 50% R.H. and testing was carried out in a special room maintained at that humidity. Humidities were checked in each environment using a Vaisala humidity metre HMI 31 which was calibrated with saturated LiCl and NaCl. Trays maintained at 20 and 85% R.H. were placed in ziplock polyethylene bags and then were removed one by one for testing (in a room maintained at 50% R.H.)

Flexural testing was performed in the three point bending mode using an Instron model 4201 Universal Testing Machine. Foam specimens 76 mm square were cut out of the plates and thicknesses were measured using a digital micrometer. Elastic bending moduli were determined following ASTM D790 using the equation:

$$E = (dF/dL \times c^3)/(4 \times b \times a^3) \quad (1)$$

where dF/dL is the initial slope of the force *versus* deformation curve, c is the support span (50.8 mm), b is the sample width (76.2 mm) and a is the sample thickness. Crosshead speed was 25 mm min⁻¹.

Ultimate properties (breaking stress and strain) could not be measured using the three-point bending method since most specimens did not break. Tensile methods were also deemed to be unsuitable because foam samples could not be gripped without severe deformation. It was found that whole plates subjected to a circular load usually showed a clear break and thus the ultimate or maximum force (F_m) and deformation to F_m (L_m) could be measured. The apparatus consisted of a cylindrical steel probe ($d = 35$ mm diam.) and an annular base ($D = 80$ mm inside diameter). The probe was lowered onto the tray until a load of 0.5 N was reached and then lowered at 30 mm min⁻¹. Instron series IX materials testing software, version 5, was used to calculate F_m , L_m and E . Data reported were an average of results from two different baking runs with four or five trays tested per run. Foam densities were calculated by foam

weight/volume of foam (calculated from dimensions). Average standard deviations in the measurement of density, F_m , L_m and E were 4.4, 15, 14, and 13%, respectively.

Scanning electron microscopy

Tray samples were mounted on aluminium stubs with graphite filled tape and vacuum coated with gold/palladium. Specimens were then examined with a Jeol JSM 6400V scanning electron microscope.

X-ray diffractometry

X-ray diffraction analysis of the surface of starch foam trays was performed with a Philips 1820 diffractometer operated at 40 kV, 30 mA with graphite filtered CuK $_{\alpha}$ radiation and a theta compensating slit. Data were acquired in 0.05° 2 θ , 4 s steps.

RESULTS AND DISCUSSION

The process of foaming a starch batter inside a heated, closed mould can be divided into several steps. First, the temperature of the starch–water mixture inside the mould rises above the starch gelatinization temperature or to the boiling point. Next, the starch gelatinizes and becomes a thick paste at which point the steam trapped in the paste expands causing the paste to fill the mould and begin to exit the vents around the edge of the mould. As this happens, a small amount of pressure (~1 bar) builds inside the mould thus increasing the internal temperature and accelerating the exit of steam and excess starch paste from the mould. During the final and longest step, the starch foam gradually dries to 2–4% moisture as water slowly escapes through the vents.

In order for foam formation to occur, starch pastes must have certain rheological characteristics. First, the starch paste must have sufficient elastic strength so that expanding steam bubbles are trapped in the paste rather than breaking with the consequent collapse of the foam. It has been found, for example, that a corn starch–water dispersion that has been jet-cooked will only form a dried film rather than a foam after baking. Jet-cooking completely disrupts starch granules giving a more fluid starch paste. This points to the need for swollen starch granules to give the starch paste sufficient elastic strength for foam expansion. Similarly, very low molecular weight oxidized starches will not foam when baked (data not shown). Secondly, the viscosity of the starch paste must increase rapidly after expansion to stabilize the foam structure and prevent collapse as water evaporates. This increase in viscosity occurs readily in the mould as the expanding paste encounters the hot mould surface and begins to dry.

Table 1 examines the effect of amylose content on the baking conditions and properties of corn starch foamed trays. It is clear that required batter volume, baking time and foam density all increase with increasing amylose content. These observations can be explained based on the rates at which the different starches swell, form a viscoelastic paste and expand into a foam.

Waxy maize (0% amylose) gelatinizes and fills the mould very rapidly (within ~5 s after filling) compared to ~25 s for normal corn starch. This is consistent with viscoamylograph data for 5% starch dispersions in water which show that waxy maize develops maximum viscosity at ~70°C compared to ~95°C for normal corn starch¹⁶. It is thought that the formation of amylose–lipid complexes during the heating of corn starch–water dispersions acts as a physical

Table 1 Effect of amylose content on the processing conditions and properties of baked corn starch foams

% Amylose	Batter volume (/mL)	Baking time (/s)	Density (/g cm ⁻³)	F _m (/N)	L _m (/mm)	E (/MPa)
0	27	75	0.082	30	4.7	60
27	55	115	0.16	75	3.8	180
50	80	180	0.35	140	6.2	380
70	80	200	0.40	160	6.6	470

Abbr: F_m: maximum force; L_m: deformation to F_m; E: modulus of elasticity; tests performed after 7 days at 50% R.H.

Note: Solids contents of all batters were 33%; baking temperatures were 205°C

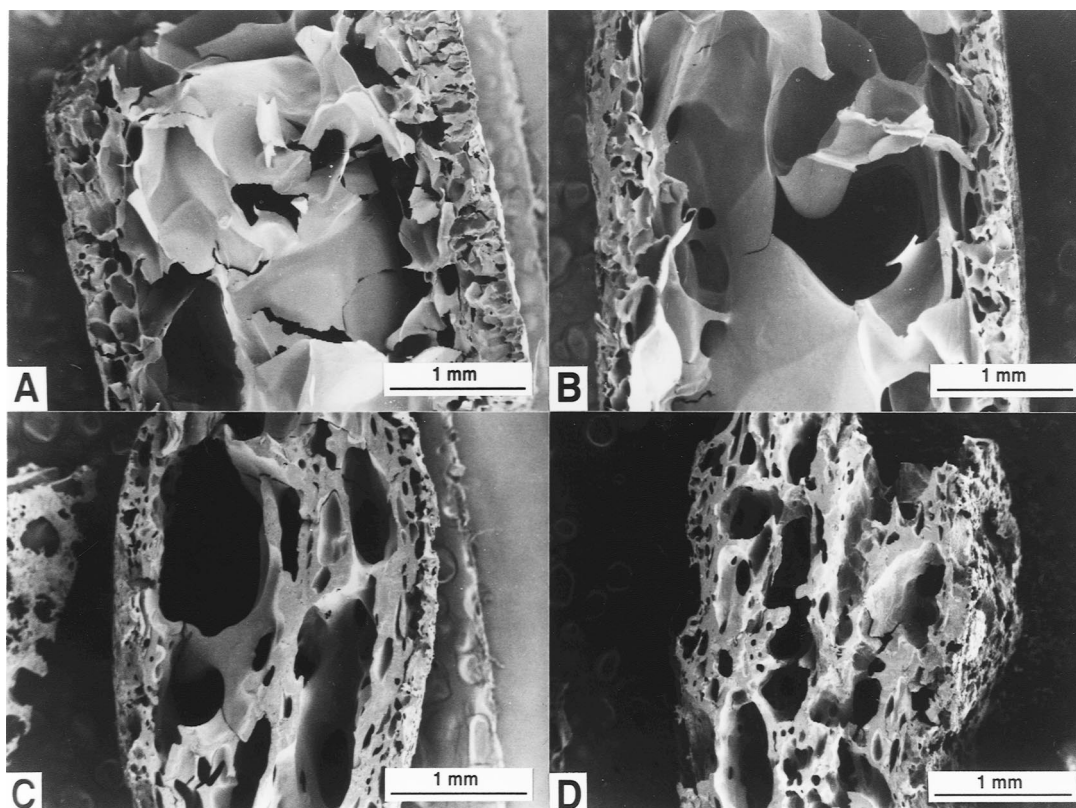


Figure 1 Scanning electron micrographs of cross-sections of baked foam plates made from waxy maize starch (A), normal corn starch (B), high (50%) amylose corn starch (C) and high (70%) amylose corn starch (D)

cross-link therefore making the granules more resistant to swelling. Entanglements between the long, linear amylose molecules may also slow swelling. Partly swollen granules will have fewer inter-granular contacts or entanglements and thus less elastic character and less ability to hold a steam bubble. Also, the more time required for gelatinization, the more water will have escaped from the batter, thus increasing melting temperature and paste viscosity and further reducing the rate of foam expansion. High (50–70%) amylose starches have melting endotherms which extend to temperatures above 110°C so that they swell only slightly when heated with excess water under atmospheric pressure¹⁷. As a result, these starches require long baking times and do not swell enough to fill the mould evenly. Thus, low amylose starches which gelatinize and swell rapidly have the shortest baking time and lowest density while the opposite is true for high amylose starches.

Table 1 also indicates that the strength and rigidity of starch foams (as represented by F_m, E) are highly correlated with density and hence amylose content. This is expected since higher densities mean that more starch, the load bearing component, is present, compared to air. The

flexibility of the tray, as represented by L_m, seems to be slightly higher for waxy maize than normal corn starch. This is unexpected since it is known that the elongation to break of starch films normally increases as amylose content increases¹⁸. In this case, differences in morphology between waxy and normal corn starch foams may account for the difference in properties. For example, waxy starch foams have much lower densities, a more expanded outer skin and thinner cell walls (Figure 1) than normal corn starch foams. Apparently, a thinner 'film' of starch can flex more easily without breaking than a thicker one. This can be explained by examining the relationship between deflection of a beam in bending (L) and the breaking strain of the material in the outer curvature of the beam (ε):

$$L = \epsilon D^2 / 6a \quad (2)$$

where D is the support span and a is the thickness. Thus, the thinner the beam or 'film' the greater the deflection at break. Rigid polyurethane¹⁹ and polyethylene²⁰ foams also showed increased tensile elongation with decreased density although no reasons were given. Although Table 1 suggests that L_m is higher for foams containing 50 and 70% amylose,

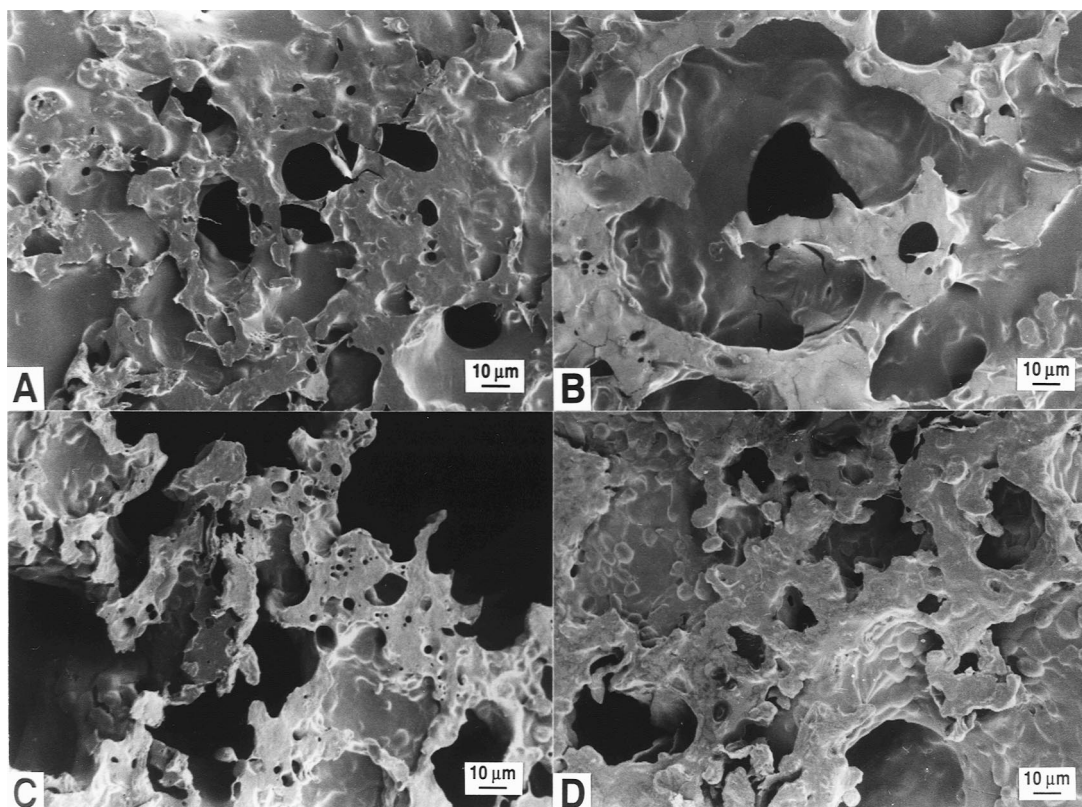


Figure 2 Scanning electron micrographs of surfaces of baked foam plates made from waxy maize starch (A), normal corn starch (B), high (50%) amylose corn starch (C) and high (70%) amylose corn starch (D)

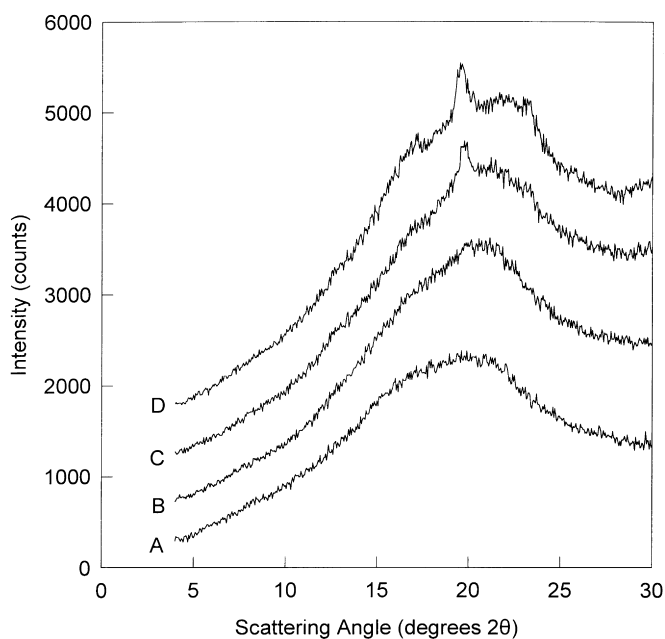


Figure 3 X-ray diffractometer scans of baked foam plates made from waxy maize starch (A), normal corn starch (B), high (50%) amylose corn starch (C) and high (70%) amylose corn starch (D)

these data may not be meaningful since the surface of these foams were irregular and contact between the probe and the surface was not initially uniform.

Scanning electron micrographs of baked corn starch foams containing 0 to 70% amylose are shown in *Figure 1*.

From the cross-sectional views it is apparent that the foams have dense outer skins with a much less dense interior. The outer skin is more dense because, being close to the hot mould, the starch paste dries rapidly and therefore cannot expand very extensively. The interior of the foam contains

Table 2 Effect of starch concentration on the properties of normal corn starch foams

% Solids	Batter volume (/mL)	Baking time (/s)	Density (/g cm ⁻³)	Fm (/N)	Lm (/mm)	E (MPa)
27	53	125	0.14	63	4.7	142
33	53	125	0.16	70	3.8	175
40	53	135	0.21	90	3.5	235
45	53	140	0.34	170	3.2	450

Abbr: Fm: maximum force; Lm: deformation to Fm; E: modulus of elasticity; tests performed after 7 days at 50% R.H.; baking temperatures were 205°C

Table 3 Properties of baked foams prepared from acid degraded corn starch

Molarity of H ₂ SO ₄ (/M)	Batter volume (/mL)	Baking time (/s)	Density (/g cm ⁻³)	Fm (/N)	Lm (/mm)	E (MPa)
0	53	117	0.17	93	4.0	190
0.05	57	120	0.14	61	3.7	141
0.50	60	130	0.12	45	5.3	158

Abbr: Fm: maximum force; Lm: deformation to Fm; E: modulus of elasticity; tests performed after 7 days at 50% R.H.

Note: Starch was treated with aqueous sulfuric acid for 10 min and washed prior to baking; solids contents of all batters were 33%; baking temperatures were 205°C

mostly large, open cells due to the large amounts of water venting outside the mould and consequent cell rupture. The high amylose starch foams have irregular cross-sectional shapes due to the incomplete filling of the mould. Their densities are also higher, reflecting the low degree of swelling and incomplete gelatinization of the high amylose starches (see below).

Scanning electron micrographs of baked corn starch foam surfaces are shown in *Figure 2*. Some remnants of starch granules can be seen on the surfaces of all the foams. Those granules in direct contact with the mould probably dry so rapidly that they do not swell significantly. Areas somewhat below the surface of waxy and normal corn starch foams appear more homogeneous, suggesting that granule swelling is more extensive there. Granules are much more evident on the surfaces of foams prepared from high amylose starches due to incomplete gelatinization. All the starch foams have many holes on the surface, possibly due to steam and air voids or shrinkage and rupture on drying.

Figure 3 shows X-ray powder diffraction scans of the surfaces of baked foams prepared from corn starches having different amylose contents. Both the foams prepared from waxy and normal starch have amorphous scattering patterns, indicating that the crystalline structure of the starch has been disrupted in these samples. This is expected since the melting temperatures of waxy and normal corn starch in excess water (70 and 63°C) based on peaks in d.s.c. endotherms^{15,21} are less than the temperature of the starch paste in the mould (100–120°C). Some native B-type crystalline structure (as evidenced by maxima at 17, 21.8 and 23.3° 2θ) remains in the 70 and 50% amylose foams. This is also expected since the melting endotherm for high amylose corn starch in excess water extends from 60 up to 120°C. The sharp maxima at 19.5° for the high amylose starch foams reflect the formation of crystalline amylose–lipid complexes²². Interestingly, these are not present in the case of normal corn starch.

Table 2 shows the effects of starch concentration on the properties of corn starch foams. Increasing the starch solids in the batter results in an increase in baking time and tray density. As starch solids content is increased, starch paste viscosity increases thus decreasing the rate of steam bubble expansion. This leads to higher densities. Similar to data in *Table 1*, Fm and E are seen to increase with increasing

density. Interestingly, the flexibility of the tray (as measured by Lm) seems to increase with decreasing density. This may be related to the observation that starch films or foams having thin walls are more flexible than those having thick walls as discussed above. The effects of starch concentration on the properties of plates made from corn and other starches are described in more detail in a separate manuscript²³.

Modulus data in *Table 2* can be fit to an empirical power law equation of the form²⁴:

$$E = E_0(\rho/\rho_0)^n \quad (3)$$

where E_0 is the modulus of unfoamed gelatinized starch, ρ_0 is the density of unfoamed starch (1.5) and ρ is the density of the foam. Plotting $\ln E$ versus $\ln \rho/\rho_0$ one obtains $E_0 = 3000$ MPa and $n = 1.28$ ($r^2 = 0.998$). This value of E_0 is in rather good agreement with a value of 3500 MPa obtained for the bending modulus of extruded wheat starch sheets at 11% moisture²⁵. This implies that the modulus of a starch foam can be predicted given density data. In addition, foams prepared from different types of starch (see data in *Table 1* and 6) have moduli which closely follow equation (3). It should be noted that values of E_0 will change with humidity (see *Table 6*) and that measured values of E are over-estimates of the true foam modulus due to the sandwich structure.

A relation between the breaking stress (σ) and density analogous to equation (3) can also be written:

$$\sigma = \sigma_0(\rho/\rho_0)^m \quad (4)$$

σ was estimated from measured values of Fm using equations for bending of a slab under circular loading (see Appendix A)²⁶. By plotting $\ln \sigma$ versus $\ln \rho/\rho_0$, values of $\sigma_0 = 60$ MPa and $m = 1.12$ were obtained ($r^2 = 0.99$). An ultimate strength of 60 MPa is somewhat larger than the tensile strength of extruded corn starch ribbons (40 MPa)²⁷ and the flexural strength of plasticized corn starch sheets (30–60 MPa)²⁵. σ_0 will vary with a number of factors such as humidity, starch type and molecular weight.

Table 3 shows the effect of reduction in molecular weight of corn starch by acid treatment on the properties of foam trays. It is seen that trays prepared from starch treated with higher concentrations of sulfuric acid (lower molecular

Table 4 Effect of baking temperature on properties of baked normal corn starch foams

Baking temperature ($^{\circ}\text{C}$)	Batter volume (/mL)	Baking time (/s)	Density ((g cm^{-3}))	F_m (/N)	L_m (/mm)	E (/MPa)
175	55	150	0.16	79	3.9	146
205	55	115	0.16	69	3.8	145
235	55	100	0.17	85	4.3	162

Abbr: F_m : maximum force; L_m : deformation to F_m ; E : modulus of elasticity; tests performed after 7 days at 50% R.H.

Note: Baking temperatures given are set temperatures; actual mould temperatures were about 10° less; solids contents of all batters were 33%

Table 5 Processing parameters for starch foam trays prepared from different starches

Starch type	Baking temperature ($^{\circ}\text{C}$)	Batter volume (/mL)	Baking time (/s)
Corn	205	47	112
Wheat	205	56	132
Potato	200	33	115
Tapioca	200	26	102

Note: Baking temperatures given are set temperatures; actual mould temperatures were about 10°C less; solids contents of all batters were 33%

weights) have lower densities and strengths. This is consistent with the idea that the lower molecular weight starches will have lower paste viscosities and therefore allow more rapid and extensive expansion of the starch foams.

Table 4 shows the effect of baking temperature on the properties of baked corn starch foams. Clearly, baking time decreases with increasing baking temperature since higher temperatures will increase the rate of starch gelatinization and the rate of drying of the tray. Mechanical properties of the foams seem to change very little with baking temperature.

Table 5 shows baking conditions used to prepare foam trays from different types of starch. In general, more batter and longer baking times were required for cereal starches (corn, wheat) than for tuber starches (potato, tapioca). Tuber starches gelatinize more rapidly (at lower temperatures) than cereal starches¹⁶. As a result, trays made with tuber starches have lower densities (0.11) than those made from cereal starches (0.16–0.19) (*Table 6*). On an equal weight basis, foams made with potato starch have the highest values of F_m and L_m , probably due to the high molecular weights of potato starch and its relatively high dispersibility in hot

water¹⁶. The strength of the foams is greatest at moderate humidities (50%) because brittleness and ease of fracture occur at low humidities and higher water absorption and softness at high humidities. Flexibility of the starch foams increases with humidity due to water absorption and consequent plasticization of the starch. A commercially available expanded polystyrene foam has a lower density and somewhat greater strength and flexibility than the starch foams (*Table 6*). Reasons for the difference in properties probably include the smaller pore size, smaller wall thickness and closed cells of the polystyrene foam.

Data in *Table 7* illustrate the effect of aging time on the properties of baked corn and potato starch foams. Both strength and flexibility are seen to decrease as the foams are aged at 23°C and 50% humidity. Physical aging, the process in which starch chains relax into a lower energy and lower free volume state, is likely responsible for the deterioration in mechanical properties¹⁵.

In summary, foam containers of various shapes such as plates, cups, clamshells or package cushioning can be prepared by baking a starch batter inside a hot mould. These foams have a dense outer layer and a less dense core containing mostly open cells. Although starch crystallinity is mostly destroyed during baking, some swollen granules remain bound within a starch matrix.

The density and mechanical properties of the foams can be controlled by changing the batter formulation. Batters which gelatinize rapidly (at low temperatures) such as those containing a starch with low amylose content, a low starch solids content or a lower molecular weight, tend to give less dense foams with lower compression strength and higher flexibility. Foams made from cereal starches, which contain lipids and proteins that can complex with amylose and decrease solubility and starch swelling, have higher densities than the tuber starches. Compared to expanded

Table 6 Effect of starch type and relative humidity on properties of baked starch foams

Starch type	Relative humidity (%)	Density ((g cm^{-3}))	F_m (/N)	L_m (/mm)	E (/MPa)
Normal corn	20	0.15	47	2.3	220
Normal corn	50	0.16	79	3.9	160
Normal corn	85	0.17	26	5.2	105
Wheat	20	0.18	43	1.9	201
Wheat	50	0.19	76	3.2	158
Wheat	85	0.19	22	3.9	101
Potato	20	0.11	38	2.9	108
Potato	50	0.11	72	6.3	92
Potato	85	0.12	34	5.6	49
Tapioca	20	0.12	39	2.5	95
Tapioca	50	0.12	50	3.6	89
Tapioca	85	0.13	16	3.5	49
Expanded polystyrene foam plate	45	0.09	130	5.3	280

Abbr: F_m : maximum force; L_m : deformation to F_m ; E : modulus of elasticity; tests performed after 7 days

Note: Solids contents of all batters were 33%

Table 7 Effect of time on the properties of baked starch foams

Starch type	Density (/g cm ⁻³)	Time (/day)	Fm (/N)	Lm (/mm)
Normal corn	0.19	7	90	3.8
Normal corn	0.19	28	86	3.4
Normal corn	0.17	90	70	3.2
Normal corn	0.18	172	78	3.5
Potato	0.11	7	69	6.3
Potato	0.11	28	69	5.7
Potato	0.11	83	59	5.0
Potato	0.11	170	55	4.6

Abbr: Fm: maximum force; Lm: deformation to Fm; tests performed at 50% R.H.; solids contents of all batters were 33%

polystyrene foam, starch foams have higher densities and lower strengths, especially at extremes of low and high humidities. Work to improve the strength of baked starch foams over a range of humidities is currently under way.

Containers made from starch foams will be inherently sensitive to water since starch is a very hydrophilic polymer. For some applications, such as plates or containers for dry foods, this is not a concern. For other applications, such as drink cups, a water resistant coating would be necessary. Coatings based on polysaccharide derivatives as well as biodegradable polyesters have been developed²⁸⁻³². These have water resistance which is sufficient to protect the starch foam for periods of hours to days³³.

ACKNOWLEDGEMENTS

The technical assistance of Elizabeth Bissett and Lee Baker is gratefully acknowledged. This work was conducted under Cooperative Research and Development Agreement (CRADA) No. 58-3K95-M-228 with Franz Haas Machinery of America.

APPENDIX A:

Calculation of maximum stress (σ) in a slab loaded along a knife edge at $r = b$ and supported at $r = a$ ²⁶:

$$\sigma = 6M_f/t^2$$

$$M_f = Fm/(8\pi)[(1 - \nu)(1 - b^2/a^2) - 2(1 + \nu)\ln(b/a)]$$

ν = Poisson's ratio (~ 0.35), t = foam thickness

REFERENCES

- Koch, H., Roper, H. and Hopcke, R., *Roy. Soc. Chem., Spec. Publ.*, 1993, **134**, 157.
- Swanson, C. L., Shogren, R. L., Fanta, G. F. and Imam, S. H., *J. Environ. Polym. Degrad.*, 1993, **1**, 155.
- Mayer, J. M. and Kaplan, D. L., *Trends Polym. Sci.*, 1994, **2**, 227.
- Narayan, R., in *Polymers from Agricultural Coproducts*, ed. M. L. Fishman, R. B. Friedman and S. J. Huang. American Chemical Society, Washington, DC, 1994, p. 2.
- Shogren, R. L., Fanta, G. F. and Doane, W. M., *Starch/Stärke*, 1993, **45**, 276.
- Tiefenbacher, K. F., *J. Macromol. Sci., Pure Appl. Chem.*, 1993, **A30**, 727.
- Tiefenbacher, K. F., *Kontakt Stud.*, 1994, **425**, 27.
- Colonna, P., Tayeb, J. and Mercier, C., in *Extrusion Cooking*, ed. C. Mercier, P. Lindo and J. M. Harper. American Association of Cereal Chemists, St Paul, MN, 1989, p. 247.
- Lai, L. S. and Kokini, J. L., *Biotechnol. Prog.*, 1991, **7**, 251.
- Harper, J. M., in *Developments in Carbohydrate Chemistry*, ed. R. J. Alexander and H. F. Zobel. American Association of Chemists, St Paul, MN, 1992, p. 37.
- Mercier, C., Charbonniere, R., Gallant, D. and Guilbot, A., in *Polysaccharides in Food*, ed. J. M. V. Blanshard and J. R. Mitchell. Butterworths, London, 1979, p. 153.
- LaCourse, N. L. and Altieri, P. A., US Patent No. 4863655, 1989.
- Altieri, P. A., Tormey, B. C. and Rose, R. R., Eur. Patent Appl. No. EP 0712883, 1996.
- Tatarka, P. D., in *Proceedings of the Society of Plastics Engineers 53rd Annual Technical Conference*, 1995.
- Shogren, R. L., *Carbohydr. Polym.*, 1992, **19**, 83.
- Swinkels, J. J. M., *Starch/Stärke*, 1985, **37**, 1.
- Colonna, P. and Mercier, C., *Phytochem.*, 1985, **24**, 1667.
- Wolff, I. A., Davis, H. A., Cluskey, J. E., Gundrum, L. J. and Rist, C. E., *Ind. Eng. Chem.*, 1951, **43**, 915.
- Lifshitz, J. M., *Polym. Eng. Sci.*, 1983, **23**, 144.
- Brown, N., in *Failure of Plastics*, ed. W. Brostow and R. D. Corneliussen. Hanser, New York, 1986, p. 289.
- Russell, P. L., *J. Cereal Sci.*, 1987, **6**, 133.
- Zobel, H. F., *Starch/Stärke*, 1988, **40**, 1.
- Lawton, J. W., Shogren, R. L. and Tiefenbacher, K. F., to be submitted to *Cereal Chem.*, 1997.
- Throne, J. L., *Thermoplastic Foams*. Sherwood Publishers, Hinckley, OH, 1996, p. 425.
- Kirby, A. R., Clark, S. A., Parker, R. and Smith, A. C., *J. Mater. Sci.*, 1993, **28**, 5937.
- Girkmann, K., in *Civil Engineering Reference Book*, Vol. 1, 2nd edn., ed. J. Comrie. Butterworths, London, 1961, p. 379.
- Shogren, R. L. and Jasberg, B. K., *J. Environ. Polym. Degrad.*, 1994, **2**, 99.
- Haas, F., Haas, J. and Tiefenbacher, K., PCT Int. Appl. WO 94/13734, 1994.
- Tomka, I. and Schmidlin, S., PCT Int. Appl. WO 90/01043, 1990.
- Shogren, R. L. and Lawton, J. W., US Patent Appl. Serial No. 08/591923, 1996.
- Kemmish, J. and Montador, J., PCT Int. Appl. WO 95/15260, 1994.
- Gruber, P., Kolstad, J., Ryan, C. and Iwen, M., PCT Int. Appl. WO 94/08090, 1993.
- Shogren, R. L., *J. Environ. Polym. Degrad.*, 1997, **5**, 91.