Effect of Batter Solids and Starch Type on the Structure of Baked Starch Foams

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ABSTRACT

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The effects of starch type on the properties of baked starch foams were investigated. Starch types used for baking were normal corn, normal potato, waxy corn, high-amylopectin potato, wheat, and tapioca. Solids content of the starch batters used to bake foam trays ranged from 25 to 45%. Processing parameters and physical properties of the foams were examined. Starch-foamed trays were formed by heating a starch batter inside a closed mold. Scanning electron micrographs showed that the thin-walled foamed trays have a dense outer skin and a less dense interior with large cells. The weight of the foamed trays and density of the foam depended on the amount of batter cooked inside the mold, the percent solids of the batter, and the type of starch used. The high-amylopectin starches made the lightest trays, while the normal cereal starches made the heaviest trays. Baking time depended on percent solids of the batter, the batter volume added to the mold, and starch type. The normal cereal starches had the longest baking times and the high-amylopectin starches had the shortest baking times Strength and flexibility of the trays are correlated with tray weight and foam density. Heavier trays had greater strength and less flexibility than did lighter trays. Physical properties of the trays can be tailored to meet specific criteria by changing the starch type used and the batter solids.

Currently, there is a great deal of interest in the manufacture of single-use articles such as plates, packaging foams, cups, and containers from biodegradable materials (Doane et al 1992). Although many biodegradable synthetic and natural materials have excellent mechanical properties, they are currently quite expensive ($4–10/kg) when compared with nonbiodegradable polymers currently on the market ($0.80–1.20/kg for polyethylene and polystyrene). Because of its low initial cost, thermoplastic starch is receiving a great deal of attention as a possible ingredient for disposable items. Starch, alone or with other ingredients, is now being used to manufacture packing peanuts (P. D. Tatarka, *unpublished data*). These packaging foams have excellent properties and now have captured 20–25% of the market.

Starch foams are generally manufactured with an extruder (Harper 1981, Harper and Tribelhorn 1992). Foaming of the thermoplastic starch by extrusion is achieved as the starch melt exits the extruder die. Superheated water flashes off in the form of steam and acts as a blowing agent for the starch or starch-based material. Even though these starch foams have excellent properties, they are difficult to shape into items such as cups, plates, bowls, and clam shells.

There is another process for making starch foams wherein the items are both foamed and shaped in the same step during the manufacturing process (Tiefenbacher 1993, Haas et al 1994, Shogren et al 1997). The process, which is closely related to the baking of waffles and wafer cookies, is capable of manufacturing many different thin-walled materials. A batter of ungelatinized starch, alone or with other ingredients and water, is injected into heated molds. The temperatures of the heated molds are substantially higher than the gelatinization temperature of starch, usually in the range of 145–225°C. During the heating of the batter, water vapor is released which both foams the batter and allows the foamed article to be dry when it exits the mold. Baking times vary with the ingredients (40–230 sec). The relationship between structure, morphology, and mechanical properties of these foams has been described (Shogren et al 1998a,b). These studies also investigated the morphology of the foams as they pertain to corn, wheat, tapioca, and potato starches. This article describes how changing the starch batter solids level affects the properties of the foam trays made from starches from different sources.

MATERIALS AND METHODS

Materials

Normal potato starch was purchased from Avebe (Veendam, Holland). Amylopectin potato starch was a gift from Lyckeby Stärkelsen (Kristianstad, Sweden). Normal corn starch (Buffalo 1304) was purchased from CPC International (Englewood Cliffs, NJ). Amylopectin (waxy) corn starch (Amioca) was purchased from National Starch and Chemical Co. (Bridgewater, NJ). Tapioca starch was purchased from A. E. Staley Co. (Decator, IL). Wheat starch was purchased from Sigma Chemical Co. (St. Louis, MO). Guar gum and magnesium stearate were reagent-grade and purchased from Sigma.

Pasting Profile Determination

The pasting viscosity and temperature-time profile of the starches were determined using a Rapid ViscoAnalyser (model RVA-4, Foss North America, Inc., Eden Prairie, MN). The standard heating profile of the RVA software (Thermocline for Windows, ver. 2.0, Newport Scientific Pty. Ltd., Warriewood, NSW, Australia) was used to produce pasting curves based on 4 g (14% mb) of starch. The heating profile started at 50°C with stirring speed at 960 rpm for 10 sec, then stirring speed was reduced to 160 rpm for the duration of the procedure. Heating continued from 50 to 95°C in 3.7 min and was held at 95°C for 2.5 min. Then cooling commenced to 50°C in 3.8 min.

Amylose Determination

Amylose content of the starches were determined as described by Knutson (1986). Amylose content reported is the average of two analyses.

Baking

Starch, guar (1%, starch weight basis), and magnesium stearate (2%, starch weight basis) were mixed dry using a standard mixer (model KSM5, Kitchen Aide, St. Joseph, MI) with a wire whisk attachment. The material was dry-mixed on a low setting until the guar was dispersed into the starch. Guar was added to increase batter viscosity so the starch did not settle out of the batter. Magnesium stearate was added as a release agent so the trays would not stick to the mold. A batter was formed by adding water to the

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dry mixture and stirring at medium speed (setting 3) for 10 min. The amount of water added to give the desired batter solids content was calculated as: % Solids = (starch dry wt + guar wt + magnesium stearate wt) / (starch as-is wt + guar wt + magnesium stearate wt + added water wt).

A laboratory baking machine (model LB TRO, on loan from Franz Haas Machinery of America, Richmond, VA) was used to bake the starch trays. The machine has two heated steel molds. The top mold is hydraulically lowered to meet the bottom mold during baking. Baking temperatures of the top and bottom molds were set at 200°C. Actual temperature at the mold surfaces was ≈10°C lower, as measured by a Temp-Sure digital pyrometer. A 60-cm^3 plastic syringe with an enlarged opening was used to dispense the batter into the opened heated molds. Enough batter was drawn up into the syringe and dispensed into the mold to just fill the mold after foaming and form a complete tray. The mold was closed and the batter was baked into trays. The time needed to bake the trays was adjusted for each of the batters, depending on solids content. The amount of batter needed to make a complete tray was determined by first over-filling the mold. On subsequent injections, less batter was added to the mold until a tray could not be formed. The amount used on the preceding injection that just formed a tray was used to make all the trays for testing. Two replicates of each batter were made for the starches.

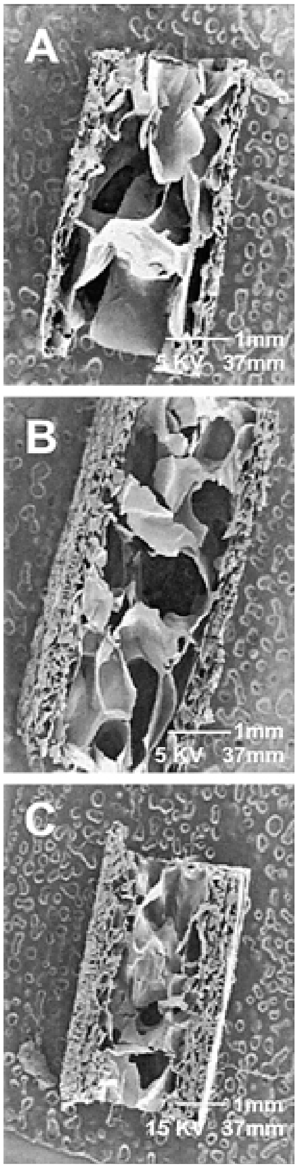

Fig. 1. Scanning electron micrographs of cross sections of baked trays made from normal corn starch. Batter solids content: 25% (**A**), 33% (**B**), and 45% (**C**).

Tray Testing

After baking, the trays were conditioned for one week at 23°C and 50% rh before mechanical testing. Three-point bending flexural tests were performed on the trays using a universal testing machine (Instron model 4201). Foam specimens 76 mm^2 were cut out of the trays and the thicknesses were measured using a digital micrometer. Elastic bending moduli were determined after the three-point bend test (D790) (ASTM 1998). Crosshead speed was 25 mm/min and the support span was 50.8 mm. The reported data are the average of four cut-out specimens.

Ultimate properties (breaking stress and strain) could not be measured using a three-point bending test. Whole trays subjected to a circular load usually showed a clear break and therefore ultimate properties could be measured. This test was performed with the universal testing machine equipped with a cylindrical probe (35 mm diameter) and a cylindrical base (80 mm i.d.). The probe was lowered onto the tray until a load of 0.5 N was reached, and then lowered at 30 mm/min until the tray failed. Testing software (Instron series IX, vers. 5) was used to calculate the maximum load at failure (F_m) and displacement at failure (L_m). The reported data are an average of four tested trays. Density of the conditioned foamed trays were calculated by dividing tray volume (98 cm^3) into the weight.

Scanning Electron Microscopy

Tray samples were mounted on aluminum stubs using graphite-filled tape and vacuum coated with gold/palladium. Specimens were examined with a scanning electron microscope (JEOL JSM 6400V).

RESULTS AND DISCUSSION

Batter baked into light foam trays has moisture contents of 1–3% right out of the mold. The cross section of the trays had the appearance of a sandwich (Fig. 1) with dense outer skin and a foam interior. Dimensions of the mold were: 217 mm long, 134 mm wide, and 19 mm deep with a 3-mm upper and lower plate separation. Enough batter was needed so that, upon baking, the batter foams

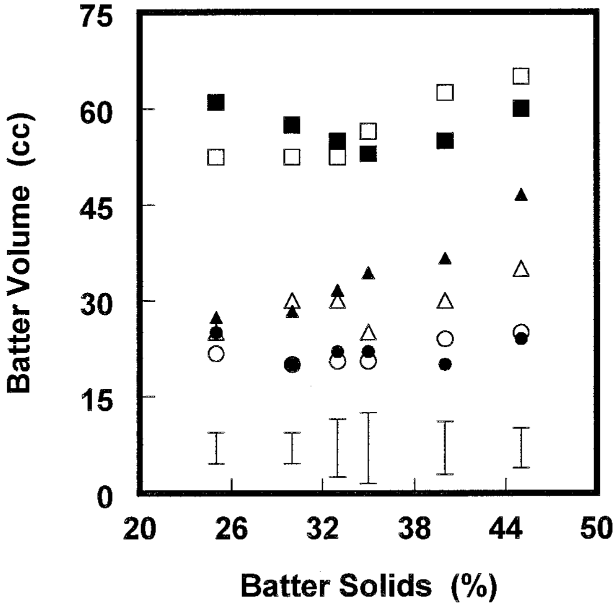

Fig. 2. Effect of batter solids on the amount of batter need to form a complete tray. Normal corn (■), wheat (□), normal potato (▲), tapioca (Δ), high-amylopectin potato (●), and waxy corn (○). Bars indicate mean ± average standard deviation.

and fills the mold and a complete tray is formed. If too little batter was added, no foaming took place and a complete tray was not formed. If too much batter was added, large amounts of batter were extruded through the steam vents and wasted. A small amount of batter needs to be extruded through the steam vents to build pressure inside the mold. If no pressure develops, no foaming takes place in the mold.

The amount of batter needed to fill the mold and form a complete tray varied with both the starch type and percent solids of the batter (Fig. 2). Generally, for most of the starch types tested, the amount of batter needed to fill the mold and make a complete tray increased as the percent solids of the batter increased, especially with elevated batter solids. The lower the solids content of the batter, the less batter was needed to fill the mold and make a complete tray. This is the opposite of what we expected. It would be expected that the batter with lower solids content, with less solid mass, would need a greater volume of batter to form the same tray. It appears, however, that batters with lower solids content have a greater ability to foam, thereby needing less solids to fill the same volume. Starch type also affected the amount of batter needed to fill the mold. This could be due to the different rheological characteristics of the starches. For foaming to take place inside the mold, the starch paste must have certain rheological characteristics. The temperature of the starch-water mixture inside the mold needs to rise above the starch gelatinization temperature. The gelatinized starch paste needs to have sufficient elastic strength so that the expanding steam bubbles are trapped in the paste rather than breaking and collapsing the foam. These two events have to occur before the hot temperatures of the mold surfaces dry out the surface of the starch paste and sets the starch so that no further expansion can occur. Gelatinization temperatures of the starches are all in the 53–85°C range (Thomas and Atwell 1999). The gelatinization temperature ranges are comparable for the starches and are probably not the sole basis for the great differences in the amount of batter needed to form the trays. More important to the forming of the trays would be initial pasting temperatures and the speed at which viscosity develops. Initial paste viscosity temperature for potato, tapioca, waxy corn, normal corn, and wheat starch are 65, 69.4, 71.1, 66.2, 73.6, and 67°C, respectively. Measurements were made with an RVA. There is a difference among the starches in the amount of time needed for the starches to start to develop viscosity (Fig. 3). The speed at which viscosity develops in the different starches is also important. The normal cereal starches need >2 min from initial viscosity development to peak viscosity (Table I) during RVA pasting, whereas potato, tapioca, and high-amylopectin starches viscosity increased quickly after the initial pasting began. Reaching paste viscosity quickly in the mold would also be important; this would allow the batter to trap more water vapor. This, in turn, gives the batter time to foam and fill the mold before too much water escapes. Potato, tapioca, and the high-amylopectin starches have higher relative viscosities compared with those of corn and wheat starch (Whistler and BeMiller 1997). This greater viscosity and elasticity would enable the high-viscosity starch paste to trap more steam, allowing for greater expansion. With normal corn and wheat starch batter, it is believed that foam expansion is impeded by the low viscosity of the initial paste. This would mean that more batter would be needed to form a tray to compensate for the lower foaming volume on the normal corn and wheat starches. The amount of amylose content of the starches can also have an effect on the foaming of the trays (Wang 1997). The ability of the starches to foam, as measured by the volume of batter needed to form a tray, decreased as amylose content decreased (Table I). The high-amylopectin starches with little or no amylose foamed to make a complete tray with very little batter as compared with normal potato and tapioca starches. Tapioca starch, with less amylose than potato starch, generally took less batter to form a tray than did potato starch (Fig. 2). The normal cereal starches took more batter to form a complete tray than did potato starch, as expected due to potato starch having greater swelling and foaming abilities (Wang 1997).

Baking time varied with both percent solids and starch type (Fig. 4). This is probably a function of batter volume, water, and starch type. As the percent solids of the batters increased, there is less water to paste the starch. Limited amounts of water increase the gelatinization temperature range of starch (Hoseney 1994). Therefore, longer baking times are needed to gelatinize and paste the starch, develop viscosity, and form a tray. Starches that need more batter volume to form a complete tray would require even longer baking times to fully cook the starch and evaporate the water. Less water in the batter would also increase the paste viscosity inside the mold, which would make the paste more resistant to foam expansion.

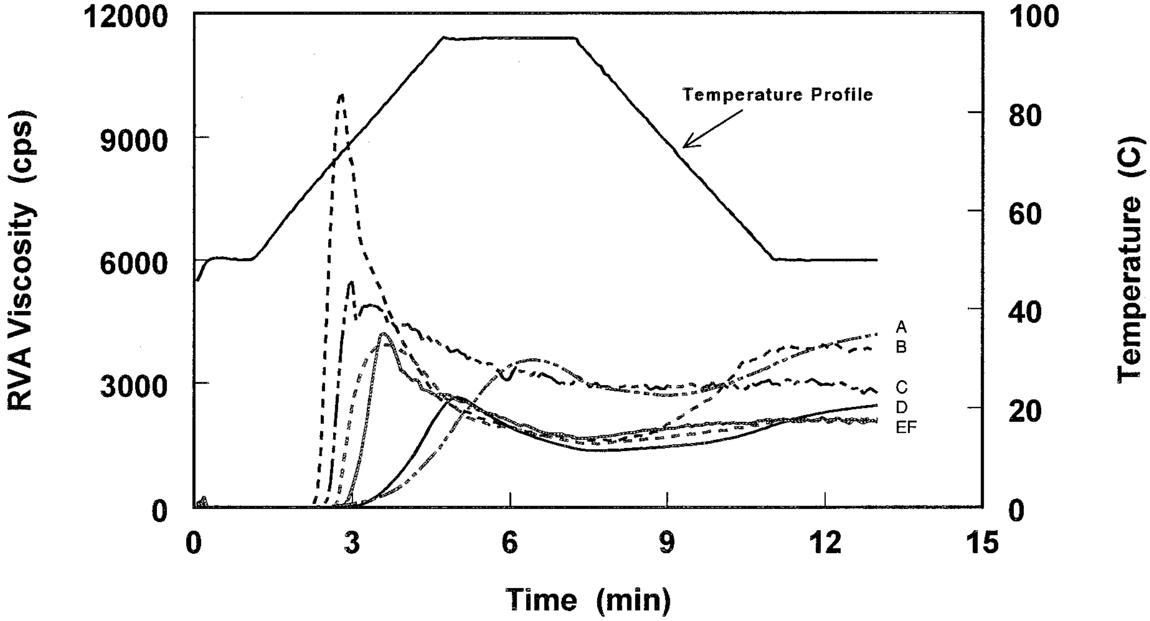

Fig. 3. Rapid ViscoAnalyser (RVA) pasting profiles of normal corn starch (D), waxy corn starch (E), normal potato starch (B), tapioca starch (F), wheat starch (A), and high-amylopectin potato starch (C).

As expected, tray weights and tray densities increased as percent solids of the batter increased (Fig. 5). As starch solids are increased, starch paste viscosity increases, thus decreasing the rate of steam bubble expansion, which leads to higher densities.

Strength (F_m), (Fig. 6) is highly correlated with the density. The strength of the tray increases as tray density increases. This would be as anticipated because greater tray density would mean more starch (the load-bearing material) is present in the tray. A relationship between breaking stress (σ) and density can be fitted to an empirical power law equation (Throne 1996):

$$\sigma = \sigma_0(\rho/\rho_0)^m \quad (1)$$

where σ_0 = breaking stress of unfoamed gelatinized starch; ρ_0 = density of unfoamed starch (1.5 g/cm^3); ρ = density of the foam; and m = a unitless empirical exponent. The value for σ was estimated from measured values of F_m using equations for bending a slab under circular loading as described by Shogren et al (1998b). By plotting ln vs. ln (ρ/ρ_0), for all data, values of σ_0 = 52 MPa and m = 1.03 were obtained (r^2 = 0.94). An ultimate strength of 52 MPa is comparatively higher than the tensile strength of extruded corn starch ribbons (40 MPa) (Shogren and Jasberg 1994) but still in the 30–60 MPa range for plasticized corn starch sheets (Kirby et al 1993). The greater predicted strength could be due to the sandwich structure of the foam. Also, strength will vary with factors such as humidity and molecular weight of the starch.

The individual starch data could also be fitted to the power law equation. Equation-predicted values for σ_0 from the individual starch data were not statistically different from the aforementioned 52 MPa obtained from the overall averaged strength data, except for the value obtained for high-amylopectin potato starch. By fitting the power law equation to the high-amylopectin potato starch, a value of 188 MPa was predicted for σ_0. This value is probably too high to be valid. The equation is likely to be overly influenced by the first two low density data points. By examining Fig. 5, we see that, at greater densities, the strength values for high-amylopectin potato starch falls on the regression line obtained from all the data. However, when plotting just the high-amylopectin potato starch data, the strength of the starch at low density points makes the slope greater. The greater slope would lead to predicting greater strength values for the unfoamed starch.

The maximum displacement (L_m) at yield (tray failure) decreases as density increases (Fig. 7). The reason for this can be seen in the scanning electron micrographs (Fig. 1) of corn starch trays made with low and high solids batter. Less dense starch trays (low solids batter) have thinner outer skins than denser trays, and the light trays have less interior foam than the heavier trays. Even though corn starch is depicted in Fig. 1, all the starches showed the same trend. Thinner outer skins and less interior foam mass would give lighter trays more ability to bend and flex with the force before the trays failed. Starch type also affected maximum displacement of the trays. Trays made with different starches but with the same density did not vary greatly in how much displacement they could withstand before failure occurred. The exception were the wheat starch trays which showed a greater ability to flex at greater densities that the other starch trays. Previously (Shogren et al 1998b), we reported that the flexibility of wheat starch was not much different than that of corn. In that work, only one batter solids level was used to make the trays, and a different wheat starch was used, which may account for the difference. Maximum displacement of the corn starch trays did not change much with tray density. The displacement was ≈4 mm, regardless of the tray density.

The elastic bending modulus (E) increased as foam density increased (Fig. 8). This is to be expected. As the foam increases in density, the cell walls of the foams become thicker and the outer layers of the foams become thicker (Fig. 1). Thicker walls would be expected to make a stiffer baked foam. The E for the individual starch trays were negatively correlated with displacement (Fig. 9). This is to be expected, as a starch foam with a lower E would make a more flexible tray. Even though E was an indicator of tray displacement for individual starches used, it could not be used to estimate tray displacement without knowing the starch type.

TABLE I
Properties of Starch Batters and Paste

Sample	Batter Vol.[a] (cm^3)	Amylose (%)	Time to Initial Viscosity[b] (min)	Time to Peak Viscosity (min)
Normal corn	55	21.3	2.93	5.03
Normal potato	32	23.8	2.26	2.83
Tapioca	30	16.7	2.4	3.6
Wheat	53	25.3	2.46	6.47
Waxy corn	21	0.0	2.73	3.57
Waxy potato[c]	22	2.6	2.2	2.97

[a] Volume of a 33% solids batter needed to make a complete tray.
[b] Rapid ViscoAnalyser measured above the base line.
[c] High-amylopectin potato starch.

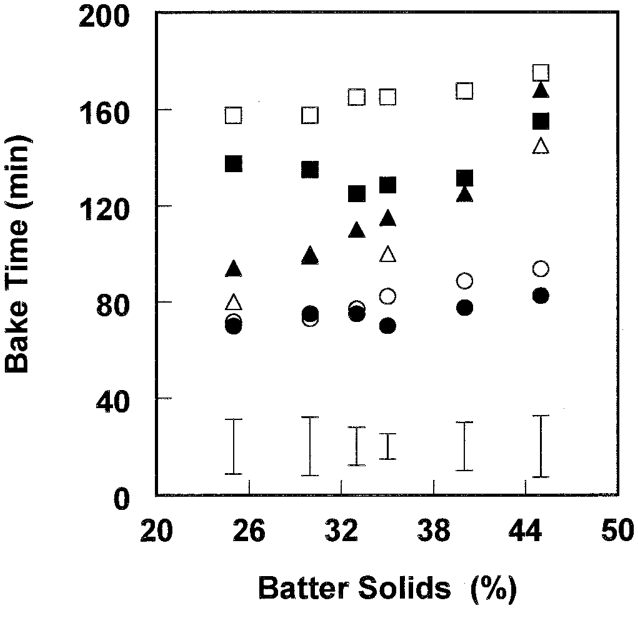

Fig. 4. Effect of batter solids on baking time. Normal corn (■), wheat (□), normal potato (▲), tapioca (Δ), high-amylopectin potato (●), and waxy corn (○). Bars indicate mean ± average standard deviation.

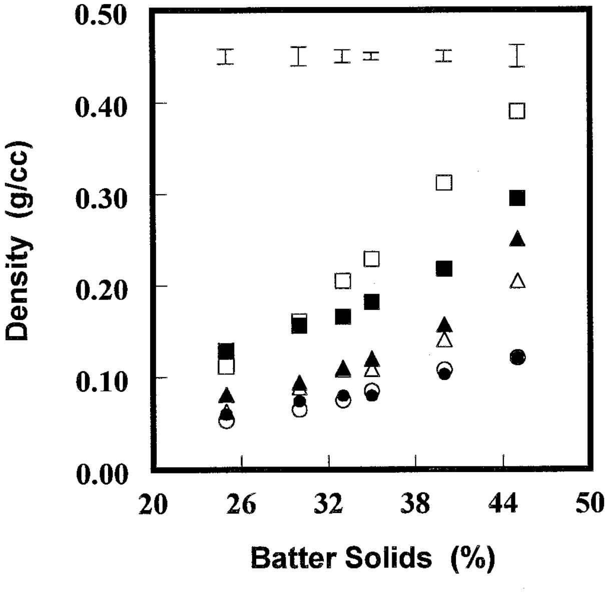

Fig. 5. Effect of batter solids on density of starch foam. Normal corn (■), wheat (□), normal potato (▲), tapioca (Δ), high-amylopectin potato (●), and waxy corn (○). Bars indicate mean ± average standard deviation.

The data in Fig. 8 were fitted to an empirical power law equation analogous to Eq. 1 (Throne 1996):

$$E = E_0 (\rho/\rho_0)^n \quad (2)$$

where E_0 = elastic modulus of unfoamed gelatinized starch; ρ_0 = density of unfoamed starch (1.5 g/cm^3); ρ = density of the foam; and n = unitless empirical exponent. Plotting ln E vs. ln ρ/ρ_0 for all the data, E_0 = 3,428 MPa and n = 1.45 (r^2 = 0.96). The value of E_0 is in close agreement with the value of 3,500 MPa obtained from the bending modulus of extruded wheat starch at 11% moisture (Kirby et al 1993). This indicates that the modulus of starch foams can be predicted, given density data. By fitting the individual starch foams to the power law equation, estimates of E_0 could be calculated. These estimates were not significantly different than the estimate obtained with all the data. This may be due to the small number of points used for the estimates predicted from the individual starch points. The data could have been equalized by the use of a generic value for unfoamed starch of 1.5 g/cm^3 that was used for all calculations.

CONCLUSIONS

The type of starch used for the production of baked foams influences both the processing and the flexural properties of the foams. In general, the tray properties fell into three groups, depending on the starch type used: high-amylopectin starches, normal cereal starches, and tuber starches. The high-amylopectin starches baked the fastest and needed the least amount of batter to make adequate foam trays. Smaller amounts of batter could be used to make trays with the high-amylopectin starches because these starches had

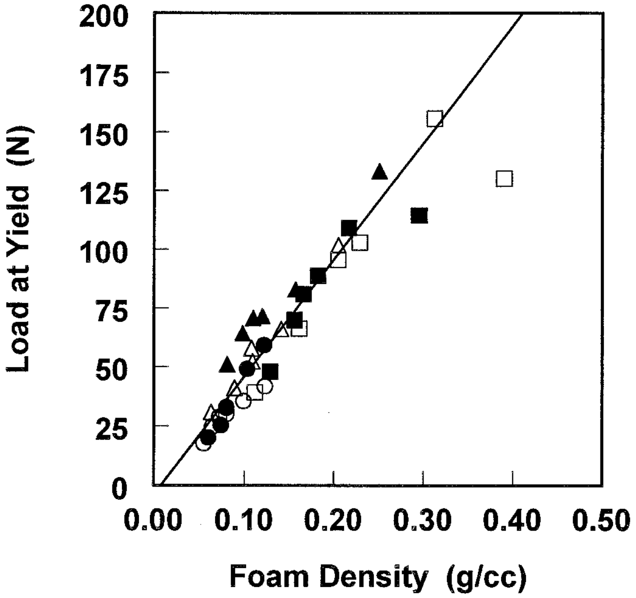

Fig. 6. Effect of foam density on breaking strength of trays. Normal corn (■), wheat (□), normal potato (▲), tapioca (△), high-amylopectin potato (●), and waxy corn (○). R^2 = 0.95.

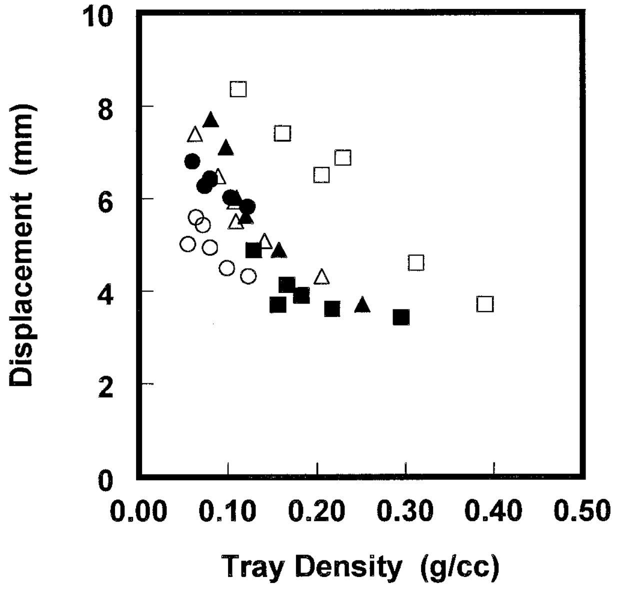

Fig. 7. Effect of foam density on total tray displacement at break. Normal corn (■), wheat (□), normal potato (▲), tapioca (△), high-amylopectin potato (●), and waxy corn (○).

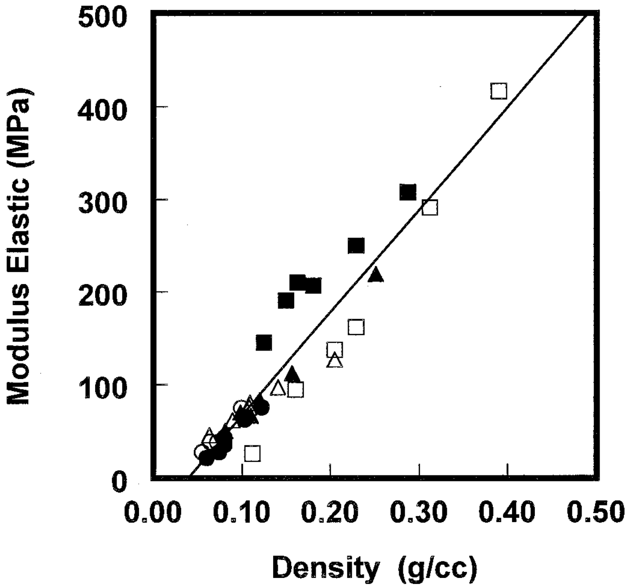

Fig. 8. Effect of foam density on elastic bending modulus of trays. Normal corn (■), wheat (□), normal potato (▲), tapioca (△), high-amylopectin potato (●), and waxy corn (○). R^2 = 0.95.

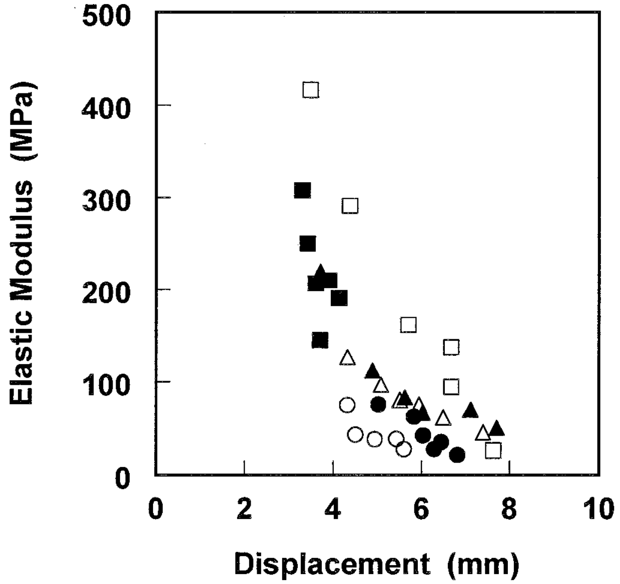

Fig. 9. Correlation of total tray displacement with elastic bending modulus. Normal corn (■), wheat (□), normal potato (▲), tapioca (△), high-amylopectin potato (●), and waxy corn (○).

greater foaming capacity and could foam to fill the mold. Due to their low densities, trays made with the high-amylopectin starches are weaker than trays made with the other starches. Normal corn starch and wheat starch generally took longer to bake. Because of the deficiency in foaming, the normal cereal starches needed more batter to make adequate trays. Because trays made with normal corn starch and wheat starch needed more batter, they were heavier than trays made with other starches. Baking times of the tuber starches using different percent solids showed the greatest variation. Potato starch batters with low solids had baking times much lower than comparable normal corn starch batters, but potato starch batters with high solids had baking times greater than comparable normal corn starch batters. Tuber starch trays were stronger and more flexible than comparable trays made with normal cereal starches and high-amylopectin starches. Within a starch type, the amount of batter used to make a tray affected both processing and tensile properties of the trays. Greater amounts of batter took longer to bake and made stronger, less flexible trays. Solids content in the batters followed the same trend; as solids content increased, trays took longer to bake and were stronger but less flexible.

Starch type, in addition to percent solids of the batter and batter volume, produced a wide variety of tray properties. This information can be useful in the production of trays for different types of applications and economic conditions.

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