Effects of Feed Compositions and Screw Configurations on the Properties of Biodegradable Loose-Fill Extruded Foams

Wai-Bun LUI¹ and Jinchyau PENG*²

Abstract

In this study, the main effort was to determine the effects of the extruder’s operating conditions on the physical, mechanical and chemical properties of corn/PVA extrudates. The operating conditions were feed compositions (FC; food grade corn grit, feeding grade corn grit), screw threads (ST; single, double), screw pitches (SP; narrow (3.5 mm), intermediate (5.0 mm), wide (6.5 mm)), and screw speeds (SS; 50 rpm, 60 rpm, 70 rpm). The experiment was a 2×2×3×3 factorial design. Samples of each treatment were collected and the physical, mechanical and chemical properties were measured and analyzed using the PROC ANOVA and PROC CORR of the SAS 6.0 software package. Experimental results indicated that: screw thread, feed composition, and screw pitch had a most significant effect on the radial expansion ratio and compressibility; whereas, screw speed had a most significant effect on the longitudinal expansion, water absorption index and compressibility, respectively.

Keywords] Feed compositions, Screw configurations, Biodegradable, Loose-fill, Extruded foams

I Introduction

Extrusion technology can be defined as a high-temperature short-time (HTST) process that combines several unit operations including mixing, kneading, shearing, cooking, shaping and forming (Harper, 1981). It has been applied in the production of ready-to-eat cereals, snacks, pet foods, confectionery products, textured vegetable protein, macaroni and chemreactors (Hayter et al., 1986; Harper, 1981; Dziezak, 1989; Miller, 1992; Peng et al., 1994). The ecological problems increase due to the excessive use of non-biodegradable expandable polystyrene as cushioning materials (Barenberg et al., 1990; Stdut, 1990; Narayan, 1994). Extrusion technology has been applied to cornstarch processing for many years (Chinnaswamy, 1988; Moore et al., 1990; Harper, 1981; Haper, 1991; Tsai, 1991). If extruded products from whole yellow dent corn are used for loose fill cushioning material, we can get low cost and biodegradable advantages (Andreas, 1989; Altieri et al., 1990; Bastioli et al., 1991; Tsai, 1991). Therefore, the research in the extruded cushioning materials, especially in the degradable cushioning extrudates, is an important and expanding aspect in extrusion technology.

Huge amount of non-biodegradable plastic products such as refuse and retail bags, fast-food containers, egg cartons, packaging films, and loose fillers are used in the past (Andreas, 1989; Roger, 1989; Barenberg et al., 1990; Narayan, 1994). For example, about 23 × 10⁶ kg of expandable polystyrene loose fill was consumed in the United States in 1988 (Frey and Star, 1988). Disposal of used plastic products has become a public concern because of their non-degradability (Barenberg et al., 1990; Naranya, 1994). Much effort has gone into producing environmentally friendly alternatives to plastic products from the incineration process (Altieri et al., 1990; Neumann et al., 1993). The use of starch in plastic production would greatly reduce the demand of petroleum as well as the negative impact in the environment caused by discarding non-biodegradable materials. This is because starch can be easily degraded into small molecules that can be metabolized by microorganisms such as bacteria, yeast and fungi (Mohsenin, 1986; Roger, 1989; Roper et al., 1990; Sachetto et al., 1991).

Moreover, Lacourse and Altieri (1989), Sachetto et al. (1991), Bastioli et al. (1991), and Neumann and Seib (1993) have patented technology to make biodegradable starch-based foams. Starch-based foam prepared from the mixture of 95% hydroxyproplated high amylose corn starch and 5% polyvinyl alcohol is used commercially as an alternative to polystyrene
loose fill material (Chinnaswamy, 1991; George, 1994). The mechanical properties of the starch-based foams from various mixtures have been studied by Hayter et al. (1986), Mohsenin (1986), Hutchinson et al. (1987), Chinnaswamy and Hanna (1988), Moore et al., (1990), Waburton et al. (1990~1992), Lourdin et al. (1995) and Bhatnagar and Hanna (1995). The power law correlation between mechanical properties and bulk density of starch-based foams was found by impact, compression, tension and the flexure tests (Hayter et al., 1986; Hutchinson et al., 1987; Waburton et al., 1992).

On the other hand, much more effort has been made to improve the mechanical properties of starch-based foams because an increase in starch levels decreases their compressibility, spring index, flexibility, and elasticity (Tsai, 1991). Still, starch-based plastic foams have poor mechanical properties compared to pure plastic foams (Tsai, 1991). The mechanical properties of starch-based foams are dependent on feed compositions and screw configurations, yet the effects of the above operating conditions have not been studied.

Therefore, in this study, two different feed compositions were used to produce corn grit-based extrudates with different screw configurations. The objective was to study the effects of feed composition and screw configuration in the physical, mechanical and the chemical properties of the corn grit-based foam extrudates.

II Materials and Methods

1. Materials

Food grade corn grit and feed grade corn grits were the basic raw materials for this study. The moisture content of the corn grits were adjusted to 13%, dry basis, before being blended with the polyvinyl alcohol (PVA).

Polyvinyl alcohol (PVA) used in this study was BF-17 from Chang Chun Petrochemical Co., Ltd. (Taiwan, R.O.C.). The molecular weight was 74800 and the degree of polymerization was 1700.

2. Extruder

A locally made single-screw extruder with a 45mm diameter and 165mm length was used. A 3.34mm cylindrical die was used to give continuous cylindrical rope-like extrudates.

3. Experimental design

The process variables were the operating conditions, screw thread (single, double), feed composition (food grade corn grit, feeding grade corn grit), screw pitch (narrow (3.5 mm), intermediate (5.0 mm) and wide (6.5 mm)), and screw speed (50 rpm, 60 rpm, 70 rpm). The proportions of the PVA and corn grits were fixed at 1:4. The die temperature was fixed at 90°C. The experiment was a 2×2×3×3 factorial design. Samples of each treatment were collected and the physical, mechanical and chemical properties were measured and analyzed.

4. Physical properties measurements

Moisture content was measured for each of the extrudates. First, measured a small container; and then measured 10 g of the material into the container; moreover, dried the samples for 24 h. in a 105-110°C oven; finally, measured the sample again, subtracted the weight of the container, and determined the moisture content using the following equation (1) (AOAC, 1984):

\[ M_n = \frac{(W_w - W_d)}{W_w} \times 100 \] ..............................(1)

where:

- \( M_n \) = moisture content (%) of material n
- \( W_w \) = wet weight of the sample, and
- \( W_d \) = weight of the sample after drying.

Radial expansion ratio of the extrudates was calculated by dividing the mean cross-section area of the extrudates by the cross-section area of the die nozzle. The mean cross-section area of the extrudates was estimated by taking the average of 50 measurements on randomly chosen extrudates. Each calculated value was a mean of 20 observations (Bhatnagar & Hanna, 1995).

Longitudinal expansions of the extrudates were obtained by dividing the average lengths by the corresponding weight (AOAC, 1984).

Bulk densities of the extrudates were determined using a seed displacement method. The 200ml rape seeds (Brassica capestris) were used as the displacement medium. The seeds were poured into a graduated cylinder (250 ml). The cylinder was tapped soundly 20 times. The weight of each sample was weighed with an electronic balance. The bulk density (g/m3) was calculated by dividing the weight of the extrudates by the volume displaced. Ten measurements were taken for each treatment (Bhatnagar & Hanna, 1995).

Water solubility indices were used to ascertain water solubility of the extrudates. Since it was difficult to grind the extrudates to exact size due to their plastic content, extrudates were ground for 1 min in a blender prior to the determination of water solubility indices. Water solubility indices were measured at room temperature and expressed as percentage on dry matter basis (AOAC, 1984).

5. Mechanical properties measurements

Compressibility of a sample was the force needed to create
2mm deformation, which was measured using an INSTRON 4464 universal testing machine (within 5kg static load cell). A 10cm² compression anvil (model 2830-011) was used to compress the sample to 2mm deformation at a loading rate of 30 mm/min (Altieri and Lacource, 1990; Wang et al., 1996). The initial gauge length of the samples was about 30 mm. A high value was attributed to a sample that was relatively hard, meaning it was less compressible, while a lower value was attributed to a sample that was easily compressed (Bhattacharjee and Hanna, 1995).

Spring index refers to the ability of a material to recover to its original shape after it has been deformed. The force required to initially compress the sample and the force required to recompress the same sample after 1 min of releasing the initial load were determined by an INSTRON 4464 universal testing machine employing the conditions used in measuring compressibility (Altieri and Lacource, 1990; Wang et al., 1996). Recovery of the sample was measured by dividing the recompression force after 1 min by the initial compression force. For an ideal elastic body, the value of spring index is 1. A higher recovery value corresponds to a material having better elastic characteristics or resiliency (Bhattacharjee and Hanna, 1995).

### 6. Biodegradability measurements

Biodegradability of the samples was measured by the modified BOD₃ test method used for testing the pollution of waste water (Roger, 1989). The proportion of the bio-chemical oxygen demand (BOD₃) to the chemical oxygen demand (COD) of the microorganism can be used as the standard index of the biodegradability. The samples of each treatment were mixed with the microorganism (E. coli). The biodegradability of the samples was determined by dividing the bio-chemical oxygen demand by the chemical oxygen demand (BOD₃/COD).

### 7. Statistical analysis

The experimental results were analyzed using statistical software SAS version 6.0 (SAS Institute Inc., Cary, NC, USA). The data were analyzed by procedure ANOVA and procedure CORR of the software package to determine the significance of the process variables and the correlation among the experimental properties, respectively (SAS, 1988).

### III Results and Discussion

#### 1. Physical properties

<table>
<thead>
<tr>
<th>Treatments</th>
<th>Operating Conditions</th>
<th>Screw Speed (rpm)</th>
<th>Feed compositions</th>
<th>Moisture Content</th>
<th>XIR(%)</th>
<th>Radial expansion ratio</th>
<th>Longitudinal expansion</th>
<th>Bulk density (g/mL)</th>
<th>Water solubility index</th>
<th>Water absorption index (g/dL)</th>
<th>Compressibility (MPa)</th>
<th>Spring index</th>
<th>Biodegradability (BOD₃/COD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1 1 1 1 1 2</td>
<td>11.65±1.07</td>
<td>70.6±1.65</td>
<td>15.1±1.07</td>
<td>0.08±0.01</td>
<td>12.21±0.13</td>
<td>5.79±0.02</td>
<td>0.17±0.01</td>
<td>0.04±0.03</td>
<td>0.06±0.13</td>
<td>0.40±0.15</td>
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<tr>
<td>2</td>
<td>2</td>
<td>2 2 2 2 2 2</td>
<td>11.65±1.07</td>
<td>70.6±1.65</td>
<td>15.1±1.07</td>
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<td>0.06±0.13</td>
<td>0.40±0.15</td>
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</tr>
<tr>
<td>3</td>
<td>3</td>
<td>3 3 3 3 3 3</td>
<td>11.65±1.07</td>
<td>70.6±1.65</td>
<td>15.1±1.07</td>
<td>0.08±0.01</td>
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<td>0.06±0.13</td>
<td>0.40±0.15</td>
<td></td>
</tr>
</tbody>
</table>

Where (1) Screw thread—1 | Single (2) Feed compositions—1 | Food grade corn grit (3) Screw pitch—1 | Narrow (4) Intermediate (5) Wide (4) Screw speed—1
50 rpm / 2 : 60 rpm / 3 : 70 rpm

Table 1 The extrudate’s experimental results of the factorial experiment.
pitch and 60 rpm screw speed (Table 1). However, the minimum value was obtained with single screw thread, food considerably more hydrophilic than most of the polymers used the moisture content in the starch phase of the melts probably increased as resin content increased.

Table 2 indicates the significance of process variables to extrudate’s experimental results. The change of screw thread (ST) had no significant effect on the moisture content of the extrudates. This may have been due to reformation resulting in some form of grafting of corn starches polymers and the plastics (PVA) polymers during the screw rotation (Lenk and Merrall, 1981; Moore et al., 1990; Chinnaswamy and Hanna, 1991; George, 1994). On the other hand, the effect of screw thread (ST) manifested itself in the moisture content through the ST*FC*SP*SS interactions.

The feed composition (FC) had no significant influence in the moisture content (Table 2). However, the influence of FC also manifested itself in the moisture content through the ST*FC*SP*SS interactions. Shogren and Willett (2002) mentioned that PVA was nearly as hygroscopic as starch, and the water would be expected to partition between the starch and PVA to a greater extent than in the other blends.

The screw pitch (SP) had significant effect on the moisture content at 5% level. The influence of SP also manifested itself in the moisture content through the ST*FC*SP*SS interactions.

The screw speed (SS) had no significant influence in the moisture content (Table 2). The influence of SS also manifested itself in the moisture content through the ST*FC*SP*SS interactions.

Table 2: The significance of process variables to extrudate’s experimental results.

<table>
<thead>
<tr>
<th>Operating Conditions</th>
<th>Moisture content</th>
<th>Radial expansion ratio</th>
<th>Longitudinal expansion ratio</th>
<th>Bulk density</th>
<th>Water solubility index</th>
<th>Water absorption index</th>
<th>Compressibility</th>
<th>Spring index</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pr&gt;F</td>
<td>Significance</td>
<td>Pr&gt;F</td>
<td>Significance</td>
<td>Pr&gt;F</td>
<td>Significance</td>
<td>Pr&gt;F</td>
<td>Significance</td>
</tr>
<tr>
<td>Screw thread (ST)</td>
<td>0.4362</td>
<td>NS</td>
<td>0.0001 **</td>
<td>0.0088 **</td>
<td>0.7692 NS</td>
<td>0.1259 NS</td>
<td>0.8884 NS</td>
<td>0.0001 **</td>
</tr>
<tr>
<td>Feed composition (FC)</td>
<td>0.1804</td>
<td>NS</td>
<td>0.0001 **</td>
<td>0.0878 NS</td>
<td>0.0054 **</td>
<td>0.0382 *</td>
<td>0.0143 *</td>
<td>0.0001 **</td>
</tr>
<tr>
<td>Screw pitch (SP)</td>
<td>0.0173</td>
<td>*</td>
<td>0.0002 **</td>
<td>0.3021 NS</td>
<td>0.0852 NS</td>
<td>0.1336 NS</td>
<td>0.2455 NS</td>
<td>0.0001 **</td>
</tr>
<tr>
<td>Screw speed (SS)</td>
<td>0.4079</td>
<td>NS</td>
<td>0.0547 NS</td>
<td>0.0076 **</td>
<td>0.0560 NS</td>
<td>0.6116 NS</td>
<td>0.0050 **</td>
<td>0.0001 **</td>
</tr>
<tr>
<td>ST*FC</td>
<td>0.6125</td>
<td>NS</td>
<td>0.0001 **</td>
<td>0.7668 NS</td>
<td>0.2642 NS</td>
<td>0.0662 NS</td>
<td>0.0005 **</td>
<td>0.0035 **</td>
</tr>
<tr>
<td>PC*SP</td>
<td>0.1408</td>
<td>NS</td>
<td>0.0001 **</td>
<td>0.0040 **</td>
<td>0.8652 NS</td>
<td>0.0731 NS</td>
<td>0.0001 **</td>
<td>0.2192 NS</td>
</tr>
<tr>
<td>SP*SS</td>
<td>0.2692</td>
<td>NS</td>
<td>0.0001 **</td>
<td>0.2704 NS</td>
<td>0.1571 NS</td>
<td>0.4828 NS</td>
<td>0.4205 NS</td>
<td>0.0001 **</td>
</tr>
<tr>
<td>ST*SS</td>
<td>0.1600</td>
<td>NS</td>
<td>0.0001 **</td>
<td>0.0137 *</td>
<td>0.1514 NS</td>
<td>0.4868 NS</td>
<td>0.0121 *</td>
<td>0.0001 **</td>
</tr>
<tr>
<td>ST<em>FC</em>SP*SS</td>
<td>0.0267</td>
<td>*</td>
<td>0.0001 **</td>
<td>0.0023 **</td>
<td>0.4572 NS</td>
<td>0.4405 NS</td>
<td>0.0001 **</td>
<td>0.01483 NS</td>
</tr>
</tbody>
</table>

**: means most significant difference (Pr < 0.01)
*: means significant difference (0.01 <Pr <0.05)
NS: means no significant difference (Pr > 0.05)

grade corn grit, narrow screw pitch and 60 rpm screw speed (Table 1). Shogren and Willett (2002) stated that starch was ST*FC*SP*SS interactions.

(2) Radial expansion ratio

A maximum value for the radial expansion ratio was obtained with the double screw thread, food grade corn grit, intermediate screw pitch and 70 rpm (Table 1). The minimum value was obtained with single screw thread, food grade corn grit, narrow screw pitch and 70 rpm (Table 1). Shogren and Willett (2002) reported that radial expansion of extruded starch foams could be described by the ratio of the cross-sectional area of the foam to the die cross-section (Rf/Rd)^2, where Rf was the radius of the foam and Rd was the radius of the die. It has been suggested that radial expansion of extruded starch is dependent on the melt elasticity.

The screw thread (ST) had a very significant effect on the radial expansion ratio of the extrudates. This may have been due to reformation resulting in some form of grafting of corn starches polymers and the plastics (PVA) polymers during the screw rotation (Lenk and Merrall, 1981; Moore et al., 1990; Chinnaswamy and Hanna, 1991; George, 1994). The effect of ST also manifested itself in the radial expansion ratio through the ST*FC, ST*SS and ST*FC*SP*SS interactions.

The feed compositions (FC) had a very significant influence in the radial expansion ratio (Table 2). The influence of FC also manifested itself in the radial expansion ratio through the ST*FC, FC*SP and ST*FC*SP*SS interactions. Generally, the radial expansion ratio increased
with increasing the resin content. Table 2 shows that the screw pitch (SP) had a most significant effect on the radial expansion ratio at 5% level. The influence of SP also manifested itself in the radial expansion ratio through the FC*SP, SP*SS and ST*FC*SP*SS interactions.

The screw speed (SS) had no significant influence in the radial expansion ratio (Table 2). The radial expansion ratio increased with the increase in the screw speed. The influence of SS also manifested itself in the radial expansion ratio through the SP*SS, ST*SS and ST*FC*SP*SS interactions. This could be explained by observing the decrease of the shear strain by the increase of resin content, which was the product of the shear rate and the residence time during the screw rotation (Griffin et al., 1984; Hayter et al., 1986; Bhatnagar and Hanna, 1995).

(3) Longitudinal expansion

A maximum value of the longitudinal expansion was obtained with a single screw thread, food grade corn grit, narrow screw pitch and 60 rpm (Table 1). However, the minimum value was obtained with double screw thread, feeding grade corn grit, wide screw pitch and 50 rpm (Table 1). Shogren and Willett (2002) mentioned that the longitudinal expansion which is a measure of expansion in the flow direction. Longitudinal expansion of expanded starch products is thought to be dependent on the viscous nature of the melt.

The screw thread (ST) had a very significant effect on the longitudinal expansion of the extrudates. This may have been due to reformation resulting in some form of grafting of corn starches polymers and the plastics (PVA) polymers during the screw rotation (Lenk and Merrall, 1981; Moore et al., 1990; Chinnaswamy and Hanna, 1991; George, 1994). The effect of ST also manifested itself in the longitudinal expansion through the ST*SS and ST*FC*SP*SS interactions.

The feed compositions (FC) had no significant influence in the longitudinal expansion (Table 2). The influence of FC also manifested itself in the longitudinal expansion through the FC*SP and ST*FC*SP*SS interactions. Shogren and Willett (2002) mentioned that addition of resin to normal corn starch increased the longitudinal expansion of the resulting foam. The addition of either polymer had effect on longitudinal expansion for this starch. Higher melt elasticity is generally associated with improved foaming properties. It is known that polymers which exhibit strain hardening during extension have improved foaming properties (Gendron et al., 2000), consistent with the extensional deformation experienced by the melt during bubble growth in the foaming stage. In this regard, it has been reported that the addition of as little as 10 wt% of one polymer into another can significantly alter strain hardening in poly (ethylene) blends (Schlund et al., 1987).

The screw pitch (SP) had no effect on the longitudinal expansion at 5% level. In this study, the results in table 2 may have been due to the short barrel length (165mm only) of the extruder without any heat control system. The heat control system was only at the surrounding of the die, so the heat energy cannot evenly spread through the barrel during the screw rotation. Thus, the SP had no significant effect on the longitudinal expansion. The influence of SP also manifested itself in the longitudinal expansion through the FC*SP and ST*FC*SP*SS interactions.

The screw speed (SS) had a most significant influence in the longitudinal expansion (Table 2). The influence of SS also manifested itself in the longitudinal expansion ratio through the ST*SS and ST*FC*SP*SS interactions. This could be explained by observing the decrease of the shear strain, which was the product of the shear rate and the residence time during the screw rotation (Griffin et al., 1984; Hayter et al., 1986; Bhatnagar and Hanna, 1995).

(4) Bulk density

The maximum value of the bulk density was obtained with a double screw thread, food grade corn grit, narrow screw pitch and 50 rpm (Table 1). The minimum value was obtained with single screw thread, food grade corn grit, narrow screw pitch and 70 rpm (Table 1). Shogren and Willett (2002) stated that bulk densities, which are dependent on sample geometry and reflect the space-filling properties of these shapes, were approximately one-half the magnitude of the foam densities for all formulations.

The screw thread (ST) had no significant effect on the bulk density of the extrudates.

The feed compositions (FC) had a very significant influence in the bulk density (Table 2). Shogren and Willett (2002) reported that the contraction between the polymers resulted in increased densities and reduced expansions. The observed contraction was probably due to a cooling rate, which was not rapid enough to prevent collapse. The presence of the resin phase was the dominant factor in determining foam properties.

The screw pitch (SP) had no effect on the bulk density at 5% level. In this study, the results in table 2 may have been due to the short barrel length (165mm only) of the extruder without any heat control system. The heat control system was only at the surrounding of the die, so the heat energy cannot evenly spread through the barrel during the screw rotation. Thus, the SP had no significant effect on the radial expansion.
The screw speed (SS) had no significant influence in the bulk density (Table 2). This could be explained by observing the decrease of the shear strain, which was the product of the shear rate and the residence time. Therefore, the bulk density increased (Griffin et al., 1984; Hayter et al., 1986; Bhatnagar and Hanna, 1995).

(5) Water solubility index

The maximum value of the water solubility index was obtained with a single screw thread, food grade corn grit, narrow screw pitch and 60 rpm (Table 1). The minimum value was obtained with double screw thread, feeding grade corn grit, narrow screw pitch and 70 rpm (Table 1). Shogren and Willett (2002) mentioned that one of the advantages of using extruded starch foams for loose-fill packaging applications is their water solubility. In certain applications, some degree of water resistance may have been desirable. Therefore, the water solubility index characteristics were determined.

Table 2 indicates the significance of process variables to extrudate’s experimental results. The screw thread (ST) had no significant effect on the water solubility index of the extrudates. This may have been due to reformation resulting in some form of grafting of corn starches polymers and the plastics (PVA) polymers (Lenk and Merrall, 1981; Moore et al., 1990; Chinnaswamy and Hanna, 1991; George, 1994).

The feed compositions (FC) had a significant influence in the water solubility index (Table 2). Shogren and Willett (2002) reported that the weight loss was greater for the starch/PVA foam, consistent with the water solubility of PVA. Foams with the lowest weight loss had the greatest water absorption. Weight loss also decreased with increasing polymer surface concentration.

The screw pitch (SP) had no effect on the water solution index at 5% level. In this study, the results in table 2 may have been due to the short barrel length (165mm only) of the extruder without any heat control system. The heat control system was only at the surrounding of the die, so the heat energy cannot evenly spread through the barrel during the screw rotation. Thus, the SP had no significant effect on the water solubility index.

The screw speed (SS) had no significant influence in the water solubility index (Table 2). This could be explained by observing the decrease of the shear strain during the screw rotation, which was the product of the shear rate and the residence time. Therefore, the water solubility index increased (Griffin et al., 1984; Hayter et al., 1986; Bhatnagar and Hanna, 1995).

(6) Water absorption index

The maximum value of the water absorption index was obtained with a double screw thread, food grade corn grit, intermediate screw pitch and 50 rpm (Table 1). The minimum value was obtained with double screw thread, feeding grade corn grit, intermediate screw pitch and 50 rpm (Table 1). Shogren and Willett (2002) reported that one of the advantages of using extruded starch foams for loose-fill packaging applications is their water solubility. In certain applications, some degree of water resistance may have been desirable. Therefore, the water absorption index characteristics were determined.

The screw thread (ST) had no significant effect on the water absorption index of the extrudates. This may have been due to reformation resulting in some form of grafting of corn starches polymers and the plastics (PVA) polymers during the screw rotation (Lenk and Merrall, 1981; Moore et al., 1990; Chinnaswamy and Hanna, 1991; George, 1994). The effect of ST also manifested itself in the water absorption index through the ST*FC, ST*SS and ST*FC*SP*SS interactions.

The feed compositions (FC) had a significant influence in the water absorption index (Table 2). The influence of FC also manifested itself in the water absorption index through the ST*FC, FC*SP and ST*FC*SP*SS interactions. This could be explained by observing the decrease of the shear strain during the screw rotation, which was the product of the shear rate and the residence time (Griffin et al., 1984; Hayter et al., 1986; Bhatnagar and Hanna, 1995). Shogren and Willett (2002) stated that resins which gave the lowest density foams tended to absorb less water. In general, the water absorption index decreased as the polymer surface concentration increased.

The screw pitch (SP) had no effect on the water absorption index at 5% level. In this study, the results in table 2 may have been due to the short barrel length (165mm only) of the extruder without any heat control system. The heat control system was only at the surrounding of the die, so the heat energy cannot evenly spread through the barrel during the screw rotation. Thus, the SP had no significant effect on the water absorption index. The influence of SP also manifested itself in the water absorption index through the FC*SP and ST*FC*SP*SS interactions.

The screw speed (SS) had a most significant influence in the water absorption index (Table 2). The water absorption index increased with the increase in the screw speed. The influence of SS also manifested itself in the water absorption index through the ST*SS and ST*FC*SP*SS interactions.
This could be explained by observing the decrease of the shear strain, which was the product of the shear rate and the residence time. Therefore, the water absorption index increased (Griffin et al., 1984; Hayter et al., 1986; Bhatnagar and Hanna, 1995).

2. Mechanical properties

(1) Compressibility

The maximum value of the compressibility was obtained with a double screw thread, feeding grade corn grit, wide screw pitch and 50 rpm (Table 1). The minimum value was obtained with single screw thread, food grade corn grit, intermediate screw pitch and 70 rpm (Table 1). Shogren and Willett (2002) mentioned that compressibility is a measure of foam’s ability to deform under load. Denser foams tend to have thicker cell walls and hence resist deformation better than lower density foams with thinner cell walls.

The screw thread (ST) had a very significant effect on the compressibility of the extrudates. This may have been due to reformation resulting in some form of grafting of corn starches polymers and the plastics (PVA) polymers during the screw rotation (Lenk and Merrall, 1981; Moore et al., 1990; Chinnaswamy and Hanna, 1991; George, 1994). The effect of ST also manifested itself in the compressibility through the ST*FC, ST*SS and ST*FC*SP*SS interactions.

The feed compositions (FC) had a most significant influence in the compressibility (Table 2). This may have been due to the breaking of hydrogen bonds in starch and plastics. Their reformation results in some form of grafting starch with plastics (Warburton et al., 1990; Chinnaswamy and Hanna, 1991; George, 1994). The influence of FC also manifested itself in the compressibility through the ST*FC, FC*SP and ST*FC*SP*SS interactions. This could be explained by observing the decrease of the shear strain during the screw rotation, which was the product of the shear rate and the residence time (Griffin et al., 1984; Hayter et al., 1986; Bhatnagar and Hanna, 1995).

Table 2 shows that the screw pitch (SP) had a very significant effect on the compressibility at 5% level. The effect of SP also manifested itself in the compressibility through the FC*SP, SP*SS and ST*FC*SP*SS interactions.

The screw speed (SS) had a significant influence in the compressibility (Table 2). The influence of SS also manifested itself in the compressibility through the ST*SS interactions.

(2) Spring index

The maximum value of the spring index was obtained with a double screw thread, food grade corn grit, wide screw pitch and 60 rpm (Table 1). Whereas, the minimum value was obtained at double screw thread, feeding grade corn grit, narrow screw pitch and 50 rpm (Table 1). Bhatnagar and Hanna (1995) reported that for all purposes, a perfect spring is an ideal elastic body, which will deform upon application of a load and regain its original shape after removal of the load. Further, a spring will bear the same load upon repeated application. Therefore, all foams produced were compared to an ideal spring by comparing their spring indices.

The screw thread (ST) had a significant effect on the spring index of the extrudates. This may have been due to reformation resulting in some form of grafting of corn starches polymers and the plastics (PVA) polymers during the screw rotation (Lenk and Merrall, 1981; Moore et al., 1990; Chinnaswamy and Hanna, 1991; George, 1994). The effect of ST also manifested itself in the spring index through the ST*SS interactions.

The feed compositions (FC) had no significant influence in the spring index (Table 2).

The screw pitch (SP) had no effect on the spring index at 5% level.

The screw speed (SS) had a significant influence in the spring index (Table 2). The influence of SS also manifested itself in the spring index through the ST*SS interactions.

3. Biodegradability

The maximum value of the biodegradability was reached with a single screw thread, food grade corn grit, wide screw pitch and 70 rpm (Table 1). Whereas, the minimum value was obtained with double screw thread, food grade corn grit, wide screw pitch and 50 rpm (Table 1).

4. The correlation coefficients among the experimental properties

Table 3 indicates that the moisture content negatively correlated with the water solubility index and very significantly.

On the other hand, the radial expansion ratio negatively correlated with the compressibility and significantly.

Furthermore, the longitudinal expansion positively correlated with the water solubility index and most significantly.
Meanwhile, the bulk density positively correlated with the compressibility and very significantly. The bulk density negatively correlated with the spring index and most significantly.

**IV Summary and Conclusions**

The results of the physical, mechanical and the biodegradable properties of the extrudates demonstrated the suitability of the experimental extrudates as cushioning material from the point of view of their physical, mechanical behavior, water solubility and high bulk densities. The results of the test of biodegradability showed that the experimental extrudates were biodegradable (BOD5/COD > 0.4). Therefore, the corn grit/PVA extruded foams developed in this study were suitable for use as biodegradable packaging loose fill materials. Finally, the experimental results indicated that:

1. Screw thread had a most significant effect on the radial expansion ratio, longitudinal expansion and compressibility, but had no significant effect on the moisture content, bulk density, water solubility index and water absorption index of the extrudates.

2. Feed composition had a most significant effect on the radial expansion ratio, bulk density and compressibility, but had no effect on the moisture content, longitudinal expansion, spring index and biodegradability properties of the extrudates.

3. Screw pitch had a most significant effect on the radial expansion ratio and compressibility, but had no effect on the longitudinal expansion, bulk density, water solubility index, water absorption index, spring index and biodegradable properties of the extrudates.

4. Screw speed had a most significant effect on the longitudinal expansion, water absorption index and compressibility, but had no effect on the moisture content, radial expansion ratio, bulk density, water solubility index and biodegradable properties of the extrudates.

**Acknowledgements**

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**References**


Andreas, M.L. (1989). The polyclean process. Iowa Corn Promotion Board Corn-Based Degradable Plastics Symposium, Des Moines, IA.


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**Table 3 The correlation among the extrudate’s properties.**

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Where MO: Moisture content; RE: Radial expansion ratio; LE: Longitudinal expansion; BD: Bulk density; WSI: Water solubility index; WAI: Water absorption index; COMP: Compressibility; SI: Spring index; BOD: Biodegradability; 1: means Pearson coefficient no; 2: means probability; 3: means significanation (**: means most significant different (Pr < 0.01) : *: means significant different (0.01 <Pr <0.05) ; NS: means no significant different (Pr > 0.05)
analytical chemists. 14th ed. Washington, DC.


Roger, E.J. (1989). Degradable plastics for the 90s. Iowa Corn Promotion Board Corn-Based Degradable Plastics Symposium, Des Moines, IA.


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