

# Physical Properties of Extruded Wheat Starch-Additive Mixtures

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## ABSTRACT

Cereal Chem. 75(3):325–330

The effects of the addition of fatty acids, monoglycerides (MG), and wheat germ oil (WGO) on the level of crystallinity and the crystalline structure of extrusion-cooked wheat starch have been studied using twin-screw extruders. Measurements of water solubility and water absorption indices were made on the extrudates, together with specific mechanical energy (SME) consumption and die pressure for the extruder. MG and the fatty acids added to a level of 4% caused an increase in  $V_{\text{hydrate}}$  type

crystallinity. WGO addition to a level of 8% caused no change in crystallinity, although the  $E_{\text{hydrate}}$  type was favored at lower moisture contents. All additives caused a decrease in SME and an increase or maximum in die pressure. WGO behaved differently than MG and fatty acids in that its addition caused the water solubility index and expansion to increase, as previously observed for other oils added to flours.

Starch crystallizes into one of four polymorphs, A-, B-, C-, or V-type (Zobel 1964). Stable  $V_{\text{hydrate}}$  ( $V_h$ ) complexes (strong diffraction peaks at  $13.0$  and  $20.0^\circ 2\theta$  [0.68 and 0.44 nm] respectively; medium peak at  $7.4^\circ 2\theta$  [1.2 nm]) result when starches are extruded in the presence of lipids or emulsifiers (Mercier et al 1979, Colonna et al 1987, Galliard and Bowler 1987). A metastable variant of the  $V_h$  type, designated  $E_{\text{hydrate}}$  ( $E_h$ ) (strong diffraction peak at  $18.5^\circ 2\theta$  [0.48 nm] and medium strength peaks at  $12.0$  and  $6.9^\circ 2\theta$  [0.74 and 1.28 nm], respectively), has also been reported (Zaslow 1963, Mercier et al 1979). The  $E_h$  variant is formed under conditions of reduced water availability and higher temperatures and is converted to the stable  $V_h$  type by increasing the moisture content of the extrudate (Mercier et al 1979).

Variations in extrusion processing conditions (temperature, moisture content, and the addition of emulsifiers) are significant in influencing the physicochemical properties of extrudates, possibly by affecting the specific mechanical energy (SME) of the system (Meuser et al 1987, Ollett et al 1990, Hu et al 1993). Previous studies of fatty acid and monoglyceride (MG) addition have used manioc (Mercier et al 1980, Colonna and Mercier 1983) and corn starches (Bhatnagar and Hanna 1994a,b), although Malkki et al (1984) and Galloway et al (1989) added MG to wheat flour, and Hu et al (1993) added MG to corn meal. They found that a decrease in water solubility, expansion, and SME accompanied the formation of the amylose-lipid complexes. Malkki et al (1984) found a decrease in die pressure, whereas Hu et al (1993) found an increase in die pressure with increasing level of MG addition. Schweizer et al (1986) added linoleic acid and soya oil to wheat flour and noted that the extrusion behavior of flours could not be extrapolated from that of starches. This is borne out in that Mercier et al (1980) found little change in water-soluble carbohydrates on adding a range of fats and oils to manioc starch, whereas Pan et al (1992) adding soybean oil to rice, and Badrie and Mellows (1992) adding soybean oil to cassava flour, found maxima in solubility and expansion at a level of 3–4% oil addition. Mohammed (1990) added corn oil to maize and found an increase in expansion up to the 4% level of addition.

In this article, the effect of addition of wheat germ oil (WGO) on the level of crystallinity and the crystalline structure, expansion, and water solubility of extrusion-cooked wheat starch has been studied using a pilot-scale twin-screw extruder under different conditions

of extrusion moisture content and barrel temperature. The results are compared with the literature on extrusion of fatty acids and MG, and with some experiments using a laboratory-scale twin-screw extruder.

## MATERIALS AND METHODS

### Materials

Wheat starch was supplied by ABR Foods Ltd. (Hull, U.K.), MG (Dimodan PV) from Grindsted Products (Bury St. Edmunds, U.K.), and WGO, myristic, palmitic, and stearic acids from Sigma (Poole, U.K.).

Starch with fatty acids and MG was fed as a premixed feedstock. The moisture content of the starch was adjusted to 24% by spraying the required amount of water onto the starch in a laboratory mixer (Kenwood Major). The starch was equilibrated overnight in polyethylene bags before slowly spraying the fatty acids or adding the MG onto the starch at 0, 1, 2, and 4% levels in the laboratory mixer.

### Extrusion Cooking

Wheat starch and WGO were extruded on an intermeshing, corotating pilot-scale (APV Baker MPF-50/25) extruder. Three temperature profiles were used: 30–60–90–100–125°C, 30–60–110–130–150°C, 60–90–120–150–175°C. Water injected downstream from the solid feed port gave moisture contents of 22, 25, and 28% (wb). WGO was added at concentrations relative to starch of 0, 4, and 8% at a port adjacent to the water feed. MPF-50 extruder screw and feed rate were kept constant at 300 rpm and 40 kg/hr, respectively. Extrusion was performed using a single 3-mm diameter die.

Extrusion cooking of premixed feedstock of starch with fatty acids or MG was performed on a laboratory-scale (MPF-19/25) twin-screw extruder. The temperature profile was 40–75–110–125°C. The MPF-19 extruder was operated at a constant screw speed of 300 rpm and a feed rate of 2.6 kg/hr; it was equipped with a single 4-mm diameter die.

Extrusion experiments were duplicated. In both extruders, die pressure was measured using a pressure transducer (0–3,000 psi, Dynisco Ltd., U.K.) in the die plate before the discharge orifice. Readings were recorded (MPF-50) or noted (MPF-19) every 30 sec for at least 5 min under steady conditions of pressure, torque, and temperature, which was generally achieved after  $\approx 10$ –20 min. SME was calculated using the equation (Hu et al 1993):

$$\text{SME (kWhr/kg)} = \left[ \frac{\text{screw speed (rpm)} \times \text{power (kW)} \times \text{torque (\%)} \times 100}{\text{max. screw speed (rpm)} \times \text{feed rate (kg/hr)}} \right]$$

### X-ray Diffraction

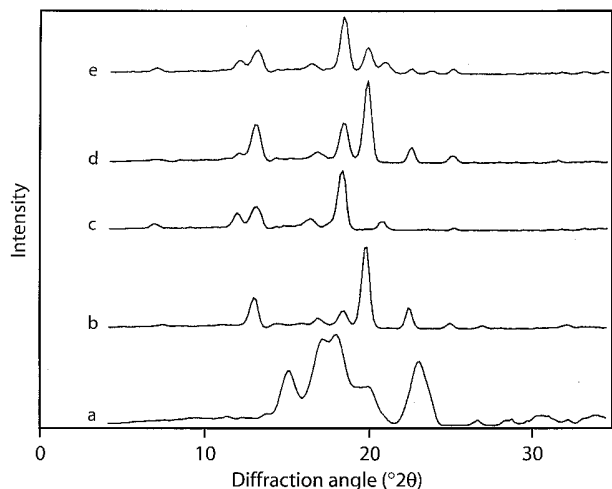
X-ray powder diffraction measurements were made using  $\text{CuK}\alpha$  radiation with a 0.154-nm wavelength. The diffractometer

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was a Philips Scientific PW 1820 vertical goniometer with an Anton Paar TTK camera. Data were collected using a proportional detector, then stored and processed on a personal computer using Philips PC-APD (Version 3.6b) automated powder diffraction software. Samples were scanned over the range 4.0–35.0° 2θ (2.21–0.26 nm), at a speed of 0.01° 2θ/sec and step size of 0.15° 2θ, at 24°C and 44% rh. Before X-ray analysis, samples were equilibrated at 44% rh in a desiccator over a saturated solution of K<sub>2</sub>CO<sub>3</sub> for 30 days. No significant retrogradation occurred during equilibration. The percentage crystallinity of the samples was calculated from the ratio of the area under the diffraction peaks to the total area under the whole diffraction pattern (Hermans and Weidinger 1961). Amorphous background patterns were generated, fitted to, and subtracted from each diffraction pattern by means of



**Fig. 1.** X-ray diffraction patterns: unextruded wheat starch A type (a), extruded V<sub>h</sub> type (b), extruded E<sub>h</sub> type (c), mixed V<sub>h</sub> and E<sub>h</sub> type (d), mixed E<sub>h</sub> and V<sub>h</sub> type (e).

the PC-APD software. Measurements were made on three aliquots from each sample.

### Expansion

The diameter of extrudates was measured as described earlier (Kirby et al 1988) as the mean of 10 random measurements using vernier callipers.

### Water Solubility and Water Absorption Indices

Water solubility (WSI) and water absorption (WAI) indices were determined by a modification of the method of Anderson et al (1969). The extrudates were first milled to a mean particle size of ≈180–250 μm. A 2.5-g sample was dispersed in 25 g of distilled water, using a glass rod to break up any lumps. After stirring for 30 min, the dispersions were rinsed into tared centrifuge tubes made up to 32.5 g and then centrifuged at 3,000 × g for 10 min. The supernatant was decanted for determination of its solids content, and the sediment was weighed and expressed as a percentage of the dry solids in the 2.5-g sample to give the WSI. After decanting the supernatant, the remaining gel or sediment was weighed and expressed relative to the weight of the dry sample to give the WAI. Two replicate measurements were made.

### Statistics

Treatment of the data to find the least significant differences at 5% ( $P < 0.05$ ) was performed using Minitab software (State College, PA).

## RESULTS AND DISCUSSION

Unextruded wheat starch gave characteristic A-type starch diffraction patterns (Zobel 1964) (Fig. 1a). The crystalline structures (S) found in extrudates subjected to different processing conditions are shown in Tables I and II and Fig. 1. The V<sub>h</sub> polymorph was formed exclusively in extrusion of starch with MG or fatty acids. Mercier et al (1980) found a mixture of E<sub>h</sub> and V<sub>h</sub> types for fatty acids and MG added to starch at a moisture content of 21%

**TABLE I**  
Crystallinity (%) and Crystalline Structure<sup>a</sup> of Extrudates Produced on a Laboratory-Scale Extruder<sup>b</sup>

| Additive       | Addition Level (%) |                 |                |     |                |    |                |    |                |    |
|----------------|--------------------|-----------------|----------------|-----|----------------|----|----------------|----|----------------|----|
|                | 0                  |                 | 0.5            |     | 1              |    | 2              |    | 4              |    |
|                | S                  | C               | S              | C   | S              | C  | S              | C  | S              | C  |
| Myristic acid  | V <sub>h</sub>     | 2c <sup>c</sup> | ...            | ... | V <sub>h</sub> | 5e | V <sub>h</sub> | 4f | V <sub>h</sub> | 4f |
| Palmitic acid  | V <sub>h</sub>     | 2c              | ...            | ... | V <sub>h</sub> | 5e | V <sub>h</sub> | 5e | V <sub>h</sub> | 3d |
| Stearic acid   | V <sub>h</sub>     | 2c              | ...            | ... | V <sub>h</sub> | 5e | V <sub>h</sub> | 4f | V <sub>h</sub> | 5e |
| Monoglycerides | V <sub>h</sub>     | 2c              | V <sub>h</sub> | 3d  | V <sub>h</sub> | 5e | V <sub>h</sub> | 5e | V <sub>h</sub> | 5e |

<sup>a</sup> S = crystalline structure. V<sub>h</sub> = V<sub>hydrate</sub> type. C = crystallinity (%). Standard deviation ± 0.5%.

<sup>b</sup> Extrusion performed on an intermeshing, corotating laboratory-scale (MPF-19/25) twin-screw extruder with 125°C final zone temperature, 24% moisture content (wb).

<sup>c</sup> Values followed by the same letter are not significantly different ( $P < 0.05$ ).

**TABLE II**  
Crystallinity (%) and Crystalline Structure<sup>a</sup> of Extrudates Produced Under Different Conditions on a Pilot-Scale Extruder<sup>b</sup>

| Final Zone Temperature (°C) | Moisture Content (% wb) | Wheat Germ Oil Level (%)       |                 |                                |    |                |    |
|-----------------------------|-------------------------|--------------------------------|-----------------|--------------------------------|----|----------------|----|
|                             |                         | 0                              |                 | 4                              |    | 8              |    |
|                             |                         | S                              | C               | S                              | C  | S              | C  |
| 125                         | 22                      | E <sub>h</sub>                 | 2e <sup>c</sup> | V <sub>h</sub> /E <sub>h</sub> | 1f | E <sub>h</sub> | 1f |
| 125                         | 25                      | V <sub>h</sub>                 | 1f              | E <sub>h</sub>                 | 1f | E <sub>h</sub> | 1f |
| 150                         | 22                      | E <sub>h</sub>                 | 1f              | E <sub>h</sub>                 | 1f | E <sub>h</sub> | 1f |
| 150                         | 25                      | V <sub>h</sub>                 | 1f              | V <sub>h</sub>                 | 1f | V <sub>h</sub> | 1f |
| 175                         | 22                      | E <sub>h</sub> /V <sub>h</sub> | 1f              | E <sub>h</sub> /V <sub>h</sub> | 2e | E <sub>h</sub> | 1f |
| 175                         | 25                      | V <sub>h</sub>                 | 1f              | V <sub>h</sub>                 | 1f | V <sub>h</sub> | 1f |

<sup>a</sup> S = crystalline structure. V<sub>h</sub> = V<sub>hydrate</sub> type. E<sub>h</sub> = E<sub>hydrate</sub> (a metastable variant of the V<sub>h</sub> type). C = crystallinity (%). Standard deviation ± 0.5%.

<sup>b</sup> Extrusion performed on an intermeshing, corotating pilot-scale (MPF-50/25) extruder.

<sup>c</sup> Values followed by the same letter are not significantly different ( $P < 0.05$ ).

and an extrusion temperature of 200°C. They found an amorphous response for starch extruded with oils and fats. Bhatnagar and Hanna (1994a) found the V<sub>h</sub> form solely for fatty acid, tristearin, and MG addition to corn starch extruded at 110°C and 19% moisture, although they pointed out that the V-type complex for starch extrusion with tristearin was due to native lipids in the starch.

In extrusion of starch with WGO, the V<sub>h</sub> polymorph (Fig. 1b) occurred preferentially at lower temperatures and higher moisture contents than did the E<sub>h</sub> variant (Fig. 1c), although mixtures containing dominance of either variant were also observed (Fig. 1d and e). This behavior is broadly consistent with complex formation with native lipids in the starch. Barnes (1983) gives the free fatty acid composition of WGO as 6%, from which it follows that 4 and 8% WGO addition to starch in these experiments is equivalent to only 0.24 and 0.48% addition of amylose-complexing moieties.

The crystallinity of unextruded wheat starch was 17 ± 0.5%. Table I shows the crystallinity of extrudates (C%) with different fatty acid additives. The low level of crystallinity illustrated that the bulk of the material in the extrudates was amorphous. The crystallinity of starch extrudates produced by the MPF-19 extruder was 2% with no added MG or fatty acids. Crystallinity increased significantly (*P* < 0.05) to 5% with fatty acid or MG addition at the 1% level, thereafter generally remaining constant (Table I). The crystalline material in extrudates produced without fatty acids can be attributed to the complexation of amylose solubilized by gelatinization with native lipids (0.8–1.2% dwb) in wheat starch

(Galliard and Bowler 1987). Increased levels of crystallinity in the samples extruded with MG and fatty acids were due to the crystallization of amylose-lipid complexes and the reduction in their degradation due to the lubricating effect of the additives. The latter is demonstrated by the significant (*P* < 0.05) decrease in SME with addition of ≥1% fatty acid and MG (Table III), as shown in earlier studies of MG additions to maize (Hu et al 1993) and wheat flour (Malkki et al 1984). The crystallinity of maize extrudates doubled on adding 1% MG (Cairns et al 1997). The crystallinity of starch-WGO extrudates remained low at 1–2%, regardless of the level of WGO added (Table II), which indicated that no further complexing occurred from WGO components.

The die pressure for starch extrusion with fatty acids increased (*P* < 0.05) with addition up to the 2% level, whereafter it decreased (*P* < 0.05) to the 4% level. Die pressure increased (*P* < 0.05) with an increase in MG as observed by Hu et al (1993), and with an increase in WGO (Table IV). SME decreased only marginally (*P* < 0.05 in most cases) with increasing level of WGO addition to starch (Table III), although the values in the absence of WGO were already low. In contrast, the SME fell progressively in all cases of MG or fatty acid addition. Conde-Petit and Escher (1995) observed that triglycerides and MG decreased SME and increased melt viscosity for potato starch extrusion. This is in agreement with the present results if a Poiseuille relationship is assumed between melt viscosity and die pressure. In contrast, Malkki et al (1984) observed a decrease in die pressure with a decrease in SME for MG addition to wheat flour. The MPF-19 extruder

**TABLE III**  
Specific Mechanical Energy (SME) (kWhr/kg) for Extrusion of Wheat Starch-Additive Mixtures

| Additives and Extrusion Conditions <sup>a</sup> | Additive Level (%) |       |       |        |       |
|---|--------------------|-------|-------|--------|-------|
|   | 0                  | 1     | 2     | 4      | 8     |
| Myristic acid                                   | 0.32a <sup>b</sup> | 0.20b | 0.18c | 0.15d  | ...   |
| Palmitic acid                                   | 0.32a              | 0.18b | 0.17b | 0.12c  | ...   |
| Stearic acid                                    | 0.32a              | 0.16b | 0.13c | 0.10d  | ...   |
| Monoglycerides                                  | 0.32a              | 0.21b | 0.19c | 0.13d  | ...   |
| Wheat germ oil                                  |                    |       |       |        |       |
| 125°C/22%                                       | 0.13a              | ...   | ...   | 0.13a  | 0.11b |
| 125°C/25%                                       | 0.12a              | ...   | ...   | 0.11ab | 0.10b |
| 125°C/28%                                       | 0.11a              | ...   | ...   | 0.10ab | 0.09b |
| 150°C/22%                                       | 0.12a              | ...   | ...   | 0.11ab | 0.10b |
| 150°C/25%                                       | 0.11a              | ...   | ...   | 0.10ab | 0.09b |
| 150°C/28%                                       | 0.10a              | ...   | ...   | 0.09ab | 0.08b |
| 175°C/22%                                       | 0.11a              | ...   | ...   | 0.10ab | 0.09b |
| 175°C/25%                                       | 0.10a              | ...   | ...   | 0.09ab | 0.08b |
| 175°C/28%                                       | 0.09a              | ...   | ...   | 0.09a  | 0.07b |

<sup>a</sup> Final zone temperature (°C)/extrusion moisture content (% wb).

<sup>b</sup> Values followed by the same letter in the same row are not significantly different (*P* < 0.05).

**TABLE IV**  
Die Pressure (MPa) for Extrusion of Wheat Starch-Additive Mixtures

| Additives and Extrusion Conditions <sup>a</sup> | Additive Level (%) |      |      |      |      |
|---|--------------------|------|------|------|------|
|   | 0                  | 1    | 2    | 4    | 8    |
| Myristic acid                                   | 1.4a <sup>b</sup>  | 2.0b | 2.7c | 2.2b | ...  |
| Palmitic acid                                   | 1.4a               | 2.7b | 3.2c | 2.5b | ...  |
| Stearic acid                                    | 1.4a               | 1.6a | 2.8b | 2.1c | ...  |
| Monoglycerides                                  | 1.4a               | 1.5a | 1.9b | 3.3c | ...  |
| Wheat germ oil                                  |                    |      |      |      |      |
| 125°C/22%                                       | 2.4a               | ...  | ...  | 3.5b | 6.7c |
| 125°C/25%                                       | 2.2a               | ...  | ...  | 2.9b | 5.3c |
| 125°C/28%                                       | 2.1a               | ...  | ...  | 2.2a | 3.9b |
| 150°C/22%                                       | 2.1a               | ...  | ...  | 3.3b | 3.4b |
| 150°C/25%                                       | 2.0a               | ...  | ...  | 2.9b | 3.1b |
| 150°C/28%                                       | 1.9a               | ...  | ...  | 2.6b | 2.9c |
| 175°C/22%                                       | 2.1a               | ...  | ...  | 2.8b | 3.1c |
| 175°C/25%                                       | 1.9a               | ...  | ...  | 2.5b | 2.8c |
| 175°C/28%                                       | 1.9a               | ...  | ...  | 2.4b | 2.6b |

<sup>a</sup> Final zone temperature (°C)/extrusion moisture content (% wb).

<sup>b</sup> Values followed by the same letter in the same row are not significantly different (*P* < 0.05).

exhibited higher values of SME than did the MPF-50 extruder under equivalent conditions, as observed previously with extrusion of maize-MG mixtures (Cairns et al 1997). Similarly, the difference in scale and die arrangements between the extruders does not permit a quantitative comparison of die pressures.

Meuser et al (1987) related WSI to SME and product temperature. Kirby et al (1988) confirmed the breakdown of maize structure necessary for high solubility and high expansion that occurred at high SME. On this basis, fatty acids and MG added to starch decreased SME and would, therefore, be expected to lead to low solubility and low expansion, as observed in previous studies on starches (Faubion and Hosney 1982; Bhatnagar and Hanna 1994a,b) and cereal flours (Faubion and Hosney 1982, Malkki et

al 1984, Schweizer et al 1986, Galloway et al 1989, Hu et al 1993, Ryu et al 1994). WSI of starch with fatty acid or MG extrudates initially decreased markedly ( $P < 0.05$ ) with 1% addition, then became almost constant (Table V), as observed by Malkki et al (1984). The relationship between WSI and SME is illustrated in Fig. 2.

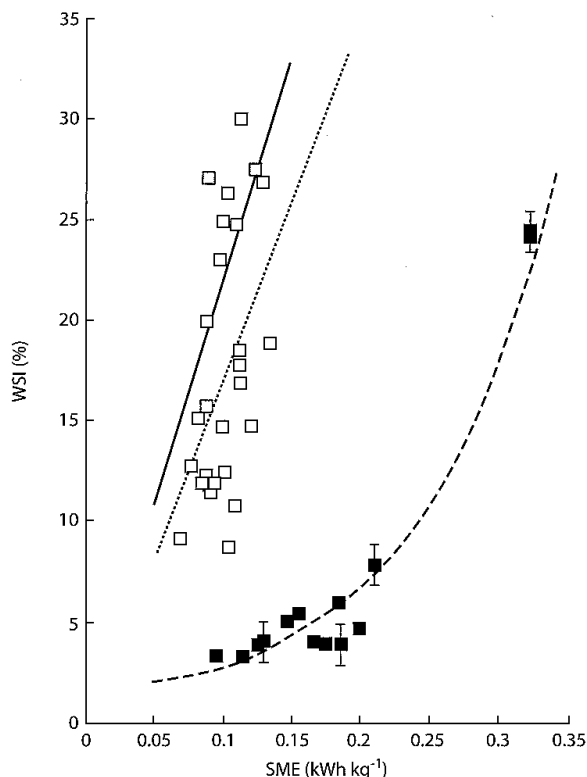
WSI results at the 2% addition level may be compared with those of Mercier et al (1980) where water-soluble carbohydrates were 90% for extruded manioc starch, falling to 30% for MG addition, and between 35 and 50% for the addition of fatty acids. The WAI increased significantly ( $P < 0.05$ ) for MG or fatty acid addition at the 1% level and remained nearly constant or decreased ( $P < 0.05$ ) on further addition to 4% (Table VI).

In contrast to fatty acid and MG addition, the changes in WSI were smaller but still significant ( $P < 0.05$ ) in response to an increase in WGO (Table V). When data from different moisture content and temperature conditions are considered, the WSI increases with increasing SME (Fig. 2). Interestingly, the WSI data for maize grits from an earlier study (Kirby et al 1988) using an APV Baker MPF-50/15 extruder, fall closest to the starch and WGO data set. A slight but significant ( $P < 0.05$ ) decrease in WAI was observed in most cases on adding WGO (Table VI).

Radial expansion increased with the level of added WGO or showed a maximum at the 4% level of addition ( $P < 0.05$ ) (Table VII). Badrie and Mellowes (1992) reported a maximum WSI and expansion in cassava flour at 4% addition of soybean oil. Pan et al (1992) similarly reported maxima for WSI and expansion at 3% level of addition of soybean oil to rice flour. Osman et al (1961) found that soybean oil did not complex with amylose. Mohamed (1990) observed an increase in expansion for up to 4% corn oil addition to maize grits. However, Mercier et al (1980) found that various fats and oils did not complex with manioc starch, and the extrudate solubility remained largely that of the starch alone. Similarly, Bhatnagar and Hanna (1994a) found that tristearin did not change expansion or water-soluble carbohydrate in extruded corn starch at a 4% level of substitution. Schweizer et al (1986) found that 2% soya oil added to wheat flour slightly increased the complexed starch relative to that in flour alone and decreased its solubility.

Conde-Petit and Escher (1995) pointed out that the lubrication effect of mono- and tri-glycerides does not depend on their complexation ability. Therefore, the decrease in SME on WGO addition would not necessarily be expected to lead to a decrease in WSI, as observed for MG and fatty acids, which is associated with complex formation. An equation for SME was given by Hu et al (1993) based on that given by Harper et al (1971):

$$SME = C_{\mu} N \omega^2 / Q + Q \mu_m / K_f$$



**Fig. 2.** Water solubility index (WSI) as a function of specific mechanical energy (SME). — = Maize extrusion (Kirby et al 1988). ■ (---) = Myristic acid, palmitic acid, stearic acid, or monoglycerides; □ (---) = wheat germ oil (WGO). Standard deviation bars appear on some data only for clarity.

**TABLE V**  
Water Solubility Index (WSI) (%) for Extrusion of Wheat Starch-Additive Mixtures

| Additives and Extrusion Conditions <sup>a</sup> | Additive Level (%) |      |      |       |       |
|---|--------------------|------|------|-------|-------|
|   | 0                  | 1    | 2    | 4     | 8     |
| Myristic acid                                   | 24.5a <sup>b</sup> | 4.6b | 3.9c | 4.9b  | ...   |
| Palmitic acid                                   | 24.5a              | 5.9b | 3.8c | 3.1d  | ...   |
| Stearic acid                                    | 24.5a              | 5.4b | 3.9c | 3.4d  | ...   |
| Monoglycerides                                  | 24.5a              | 7.8b | 3.7c | 4.0c  | ...   |
| Wheat germ oil                                  |                    |      |      |       |       |
| 125°C/22%                                       | 18.8a              | ...  | ...  | 26.9b | 30.0c |
| 125°C/25%                                       | 14.6a              | ...  | ...  | 17.8b | 24.8c |
| 125°C/28%                                       | 10.7a              | ...  | ...  | 12.1b | 15.6c |
| 150°C/22%                                       | 27.4a              | ...  | ...  | 24.6b | 26.2c |
| 150°C/25%                                       | 16.8a              | ...  | ...  | 12.4b | 19.9c |
| 150°C/28%                                       | 8.8a               | ...  | ...  | 11.7b | 15.3c |
| 175°C/22%                                       | 18.5a              | ...  | ...  | 22.9b | 27.1c |
| 175°C/25%                                       | 14.9a              | ...  | ...  | 12.4b | 12.8b |
| 175°C/28%                                       | 11.8a              | ...  | ...  | 11.9a | 9.2b  |

<sup>a</sup> Final zone temperature (°C)/extrusion moisture content (% wb).

<sup>b</sup> Values followed by the same letter in the same row are not significantly different ( $P < 0.05$ ).

where  $C$  is a constant;  $\mu_m$  and  $\mu_b$  are melt viscosity and average viscosity (Pa sec), respectively, over the filled channels in the barrel;  $N$  is the number of filled flights;  $\omega$  is the screw speed (per sec);  $Q$  is output rate ( $m^3/sec$ ); and  $K_f$  is the die conductance ( $m^3$ ). The second term represents the die pressure and it increased with MG and WGO addition, which may be attributed to a viscosity increase in the material in the die, probably due to a reduction in temperature as a result of less viscous energy dissipation in the barrel. The behavior of the first term is, however, not well specified. The term  $\mu_b$  will effectively decrease because of the reduced friction for all the additives. The value of  $N$  was not measured in this study, but Hu et al (1993) observed that  $N$  increased with MG addition by dead stopping the extruder. The dominance of the decrease in the first term (the barrel contribution to SME) is consistent with the decrease in SME with all additives. However, the second term (the die contribution) may increase when pumping a more viscous material.

The difference in expansion and solubility behavior between the WGO and the MG and fatty acid systems could be due to their ability to complex. The die contribution to the SME increased to a greater or lesser extent with an increasing level of the additives, and it appears that without the protective effect of complex formation, increased starch degradation occurred at the die (as shown in increased WSI). This explanation may not be correct; the results of Colonna and Mercier (1983) showed that, although copra and soya lecithin added to manioc starch slightly increased the water solubility, they decreased the molecular degradation of the starch as measured by intrinsic viscosity. However, the importance of SME in determining expansion has been cited through its effect on product temperature (Garber et al 1997) and starch degradation (Kirby et al 1988). Kokini et al (1992) related expansion to pressure drop at the die as the driving force for expansion and, in-

versely, to viscosity of material at the die. An increase in die pressure was observed for MG and WGO addition to starch, which show different expansion behavior with increasing level of addition.

## CONCLUSION

WGO behaved differently than MG and fatty acids when extruded with wheat starch. While all additives caused a decrease in SME, WSI increased generally for WGO addition, in contrast to fatty acids and MG addition, for which WSI decreased, as reported in the literature. Radial expansion increased for WGO addition, contrary to what has been reported in the literature for MG and fatty acid addition. The results for WSI and expansion for WGO addition to wheat starch are, however, consistent with those reported in the literature for oil addition to flours, although they are at variance with the near constant solubility reported for oil addition to other starches.

The SME has been approximated as the sum of contributions from the barrel and dies. Complexing and noncomplexing additives reduced the friction in the barrel, decreasing the barrel contribution to SME, although the die contribution to SME increased in those cases where an increase in die pressure was observed. The barrel SME term appeared to dominate over the pressure contribution, with the result that the overall SME decreased. The increase in solubility with decreasing SME for WGO addition was in contrast to the data for fatty acid and MG addition and may have occurred because of an increase in SME contribution from the die. In the absence of complex formation, which may protect against mechanical degradation, it is suggested that the degradation occurs at the die for starch-WGO mixtures. However, other published evidence points to reduced degradation on adding fats

TABLE VI  
Water Absorption Index (WAI) for Extrusion of Wheat Starch-Additive Mixtures

| Additives and Extrusion Conditions <sup>a</sup> | Additive Level (%) |      |      |      |      |
|---|--------------------|------|------|------|------|
|   | 0                  | 1    | 2    | 4    | 8    |
| Myristic acid                                   | 4.2ab              | 6.7b | 6.2c | 5.8d | ...  |
| Palmitic acid                                   | 4.2a               | 6.8b | 6.6b | 6.9c | ...  |
| Stearic acid                                    | 4.2a               | 6.7b | 6.9b | 6.7b | ...  |
| Monoglycerides                                  | 4.2a               | 6.8b | 6.9b | 4.8c | ...  |
| Wheat germ oil                                  |                    |      |      |      |      |
| 125°C/22%                                       | 7.3a               | ...  | ...  | 7.2a | 7.1a |
| 125°C/25%                                       | 8.0a               | ...  | ...  | 7.6b | 7.3c |
| 125°C/28%                                       | 9.0a               | ...  | ...  | 7.9b | 7.4c |
| 150°C/22%                                       | 7.7a               | ...  | ...  | 7.9a | 7.3b |
| 150°C/25%                                       | 8.5a               | ...  | ...  | 8.0b | 7.5c |
| 150°C/28%                                       | 9.5a               | ...  | ...  | 8.2b | 7.7c |
| 175°C/22%                                       | 8.2a               | ...  | ...  | 7.8b | 7.5c |
| 175°C/25%                                       | 8.5a               | ...  | ...  | 8.1b | 7.8c |
| 175°C/28%                                       | 9.0a               | ...  | ...  | 8.4b | 7.3c |

<sup>a</sup> Final zone temperature (°C)/extrusion moisture content (% wb).

<sup>b</sup> Values followed by the same letter in the same row are not significantly different ( $P < 0.05$ ).

TABLE VII  
Expansion Ratio for Extrusion of Wheat Starch-Wheat Germ Oil (WGO) Mixtures

| Final Zone Temperature (°C) | Extrusion Moisture Content (% wb) | WGO Level (%)     |       |       |
|-----------------------------|-----------------------------------|-------------------|-------|-------|
|                             |                                   | 0                 | 4     | 8     |
| 125                         | 22                                | 5.9a <sup>a</sup> | 10.1b | 7.4c  |
| 125                         | 25                                | 5.8a              | 9.3b  | 5.2c  |
| 125                         | 28                                | 5.0a              | 8.3b  | 5.2a  |
| 150                         | 22                                | 5.3a              | 10.1b | 10.0b |
| 150                         | 25                                | 5.2a              | 8.2b  | 7.8c  |
| 150                         | 28                                | 4.8a              | 7.9b  | 6.8c  |
| 175                         | 22                                | 4.8a              | 9.9b  | 10.5c |
| 175                         | 25                                | 4.5a              | 8.2b  | 8.0b  |
| 175                         | 28                                | 4.1a              | 7.8b  | 7.8b  |

<sup>a</sup> Values followed by the same letter in the same row are not significantly different ( $P < 0.05$ ).

to starch. In general, highly expanded extrudates require a high SME for starch degradation, and a high die pressure favors the driving force for expansion. The increase in SME dissipation at the die to compensate for that normally occurring in the barrel may, therefore, facilitate expansion of uncomplexed starch, although the pressure and viscosity conditions alone may favor expansion. The association of high solubility with high expansion for starch mixtures with WGO was consistent with published data on extrusion of starchy materials.

#### ACKNOWLEDGMENTS

We acknowledge the financial support by the Commonwealth Scholarship Commission in the U.K. to N. Singh and other funding from the BBSRC. We gratefully acknowledge the facilities provided by N. D. Frame of APV Baker, Peterborough, U.K.

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[Received June 24, 1997. Accepted January 21, 1998.]