HGCA

PROJECT REPORT No. 209

PACKAGING MANUFACTURED FROM STARCH-BASED MATERIALS (STARPAC PROJECT)

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by

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ABSTRACT

The aims of the studies were to examine the performance of wheat flour in packaging materials and compare it with the most effective synthetic plastic packaging, expanded polystyrene (EPS). Expanded foams were prepared from wheat flour by two processing systems and the foams were evaluated by impact and compression tests used on EPS. The processing methods involved extrusion cooking, either with direct expansion or a novel technique, based on the formation and expansion of cooked pellets of flour. The two methods were studied in parallel so that the factors controlling the performance of flour-based foam could be studied in detail on directly expanded foams, while the novel technique was being developed.

Samples of expanded foam were produced as sheets or cylinders by direct extrusion and used as vehicles for assessing the effects of structure, moisture and a small range of synthetic additives on the stability and cushioning performance of starch-based foams. Measurements at The University of Reading, Department of Biomimetics, using compression and impact-testing equipment, showed that the most important factors influencing the cushioning power of flour-based foams were their cellular structure and the moisture content within the cell walls. Fine cell structures, prepared by a novel idea of adding extra nucleating substances to the wheat flour during extrusion cooking, gave large improvements in the cushioning curves, so that they matched those of expanded polystyrene (EPS). Moisture levels in the foam between 12 and 14% w/w gave the best performance. Lower levels became too brittle at <10% moisture and higher levels, >15%, tended to become too soft and had too little resistance to collapse. It was shown that the maximum expansion of wheat flour was obtained with hard endosperm varieties with low protein such as the feed wheat Brigadier.

It was recognised that the control of moisture absorption or loss would be important in the wider usage of flour-based foams. Therefore, a range of additives was tested in the extruded foams, including hydrolysed fractions of acetylated polyvinyl alcohol (PVA), polyglycerols (PEG), glycerol and citric acid. The effect of these materials on water activity in the extrudates was very small within the ranges of additions (1-5%) which could be used without reducing the expansion and foam quality. Some benefits could be obtained with these materials in plasticising the foams so that they were less brittle under dry conditions down to 10% moisture, but it was shown that the expensive PVA materials did little to improve the foams with respect to moisture control.

Experiments to develop novel methods for manufacturing blocks of foam from wheat flour were carried out with extruded pellets manufactured from wheat flour. Small spherical extruded pellets, 2-3 mm in diameter, were produced which could be expanded to 9-10 ml/g by the rapid application of heat. Preliminary experiments in fluidised hot air rigs showed that the pellets lost too much moisture during expansion, becoming dry and brittle, and having no adhesion between the expanded spheres. Attempts to stick them together by wetting them with steam, water sprays or viscous glue failed to produce blocks, except when the glue was used. Even then the blocks were too dense and hard for packaging. Alternative heating systems were examined with an autoclave at 160-190°C and microwave systems in plastic moulds. The autoclave failed to give any expansion for the pellets, although it showed that the pellets softened and flowed at 170 °C. The use of high power microwaves gave tight packing of expanded beads, but the water still tended to escape and leave the foams too hard and brittle. Addition of high melting temperature waxes was tried but they had no beneficial

effect. It was concluded therefore that the formation of starch-based foams from extruded pellets was not feasible for a commercial process at present.

The main benefits of the research studies carried out in this project are in the improvement of the understanding of requirements for the manufacture of good quality expanded foams from wheat flour which can match EPS in performance. Wheat flour foams have equal cushioning powers to EPS when the texture and moisture levels are in the optimum ranges.

The studies have also developed a better understanding of the stability of wheat flour foams in relation to relative humidity in storage conditions and the efficacy of a number of low cost additives, in particular waste paper fibres. Wheat flour foams were shown to be completely biodegradable and the dry foam could be crushed and recycled in the extrusion cooking process at a lower energy level than raw flour.

SUMMARY OF THE PROJECT

1. INTRODUCTION

The extrusion cooking of starch from wheat flour and potato flakes has been shown to produce new molecular forms of the biopolymers polymers, which resemble synthetic polymers in their functionality. The native polymers of starch present in wheat flour consist of the relatively small amylose (200 kD) and the large branched amylopectin (1000 MD) molecules. Extrusion cooking breaks down the molecules of amylopectin to the range 1-5 MD, lowering the viscosity of the polymer melt and improving its flow and film forming properties. After processing the large branched starch polymers become more like synthetic materials such as polystyrene and polyethylene in terms of size and shape. However, the starch polymers are more hydrophilic and must be plasticised and solvated by water, whereas the synthetic materials are hydrophobic and are solvated by non-polar compounds.

Processing starch polymers by shear and plasticisation can lead to the formation of a soft plastic deformable material at moisture levels of above 10 % w/w. Lower moisture levels reduce the mobility of the polymers and eventually they become immobile in the hard glassy state at about 8 % moisture. At this point the starch polymer mass becomes hard and brittle.

Packaging materials that are used to protect products during transit are made in the form of expanded foams, which deform and absorb energy on impact. They should be resilient and recover after the load has been removed and not fracture to give irreversible deformation. The formation of foams from starch polymers can be achieved by direct extrusion of a molten polymer fluid from the die of an extruder. An alternative method investigated in this project, envisaged a two-stage pellet process. In the latter case, the starch polymers are melted to form a fluid and extruded at <100°C to form an unexpanded rope of starch melt, which can be cut into small pellets. The pellets are manufactured at 30% moisture and initially they have a rubbery viscoelastic character. On drying to about 10% moisture they become glassy at ambient temperatures and are stable for long periods. They can be expanded into foam by rapid heating to 150-170°C, whereupon the starch glass melts to form a viscoelastic fluid once more, and the superheated water nucleates as bubbles to expand the foam structure. This phenomenon has been exploited in the snack industry for many years in products such as prawn crackers.

Currently, several companies are manufacturing loose fill packaging from starch-based raw materials - wheat flour, maize starch and potato starch/flour - by the direct extrusion method. It was proposed in the STARPAC project to attempt to use the pellet-based technology to develop moulded packaging. In a parallel study it was also proposed to examine the critical factors affecting performance of starch-based foams in comparison with EPS foams. No information has been published about the factors affecting the performance of starch-based foams. These products have been developed by empirical methods (1) and as indicated by a number of patents. The use of wheat flour was not covered well during the large patenting exercises of Warner Lambert begun in 1982 (2) as shown by the granting of a later patent by Buhler (3). There is a difficult area of prior art concerning wheat flour extrusion because of the use of extrusion cookers to produce foams for pet foods; biscuits and snacks for all types form the basis, which weakens any patent coverage.

Synthetic EPS packaging is currently made by either direct expansion or by a pellet technique based on polystyrene pellets using a blowing agent, pentane, to obtain their expansion. The pellets are manufactured by extrusion as small beads containing the hydrocarbon. The beads are expanded by steam heating within a mould. The expanding beads fill the space within the mould until a solid body in formed. It is planned to investigate procedures for expanding starch-based pellets within a mould to produce the same types of product.

2. EXPERIMENTAL

2.1 Experimental plans for the development of pellets and expanded foam blocks

Small bead-like pellets were manufactured from wheat flour on a long barrel extruder to provide stocks of samples for testing. After establishing optimum extrusion conditions for pellets with good expansion, they were characterised by measuring the degree of processing of the starch in the pellets. The best samples were used to examine methods for forming blocks of expanded foams similar to those formed from polystyrene beads. These were included in hot air rigs to fluidise and expand the pellets, microwave ovens and plastic moulds, and any other ideas arising during the project such as high-pressure autoclave systems and rice cake machines (5).

Other materials were to be added to the wheat flour pellets to improve their texture using new ideas developed in the parallel studies on directly expanded extruded foams

2.2 Experimental plans for the study of the performance of starch in packaging foams using directly expanded foams

CCFRA manufactured experimental foams from wheat flour, which were assessed for physical and cushioning performance by The University of Reading. These samples were characterised for cellular structure by image analysis and conditioned with moisture to permit a study of the plasticisation of the foam with moisture. The effects of additives were examined on the same types of foam. Two types of additive were studied:

1. Materials such as talc and chalk powders added at levels of 1-7% w/w to act as nucleating sites to increase bubble numbers and produce finer textures in the extrudates.
2. Materials such as glycerol and polyvinyl alcohol derivatives, which might help to plasticise the starch at lower water levels and also control water uptake and loss. Some trials were also carried out with waste paper, following good reports from industry.

CCFRA also determined the effects of a number of additives by preparing cylindrical shaped extrudates similar to the current commercial products to complement the work at The University of Reading.

3. KEY RESULTS

3.1 Manufacture of pellets from wheat flour

Pellets were manufactured from soft wheat flour, which could be expanded to a specific volume of 9-10 ml/g. For good expansion it was shown that the degree of processing of the flour should be sufficient to melt the crystalline structures of the starch granules but not to disperse them into an amorphous mass. It appears that some granular structure is required for the expansion process. This meant that the starch polymer could not be degraded as much as in direct expansion and therefore their flow and expansion in the melt were restricted. The largest expansion of individual beads was 9-10 ml/g compared with expansions of up to 20 ml/g for directly expanded materials such as wheat and maize starches. However, it was hoped that, by forming a block from the expanded beads, the overall specific volume for the foam would be much greater and might be as high as 30 ml/g and even more if different shapes were used.

3.2 Attempts to form a block of packaging material by expanding the pellets

The formation of a block of expanded starch foam from the best two samples of pellets was attempted by three main techniques. The first technique was based on a fluidised bed to expand the beads followed by a steaming and collection of the moist beads in a mould. However, the expanded beads lost too much moisture and became brittle and hard. On steaming they could be moistened but although they took up water to 18-20% they did not stick together in a firm block. The use of a viscous paste made from ground pellets and water was shown to stick the expanded pellets together in a block, but on drying to 10-12% moisture the block was found to be too firm with little cushioning power. Several variations on the use of water sprays and adhesive materials were explored but all were unsuccessful.

The second technique employed was based on the use of microwave heating of pellets in a plastic mould. This gave excellent expansion of the pellets to 10-12 ml/g, but the water tended to escape through the seals of the moulds and leave the pellets firm and dry. The pellets were expanded in a confined space so that the beads expanded against one another to give firm areas of contact by deforming the contact zones. However, on removing from the moulds, either before or after exposure to moisture, the block crumbled into individual pellets. Trials with the addition of high melting point waxes at 3-5% levels gave a strong binding in the blocks but once again the blocks were too hard for packaging materials.

In the third technique it was proposed to heat the pellets in a metal mould inside a large industrial autoclave at 150-190 °C so that their whole matrix would be softened. On releasing the autoclave pressure it was hoped to cause expansion of the pellets in a hot humid atmosphere so that they pressed firmly against each other to form contact points. In practice no expansion occurred in the moulds when the pellets melted. At the highest temperatures the pellets flowed together before the autoclave was opened.

Other techniques were considered such as the rice cake making machinery and the use of a special propellant such as the hexane used in EPS, but on close examination no other method appeared to be practical for the manufacture of packaging materials.

The conclusion on the first part of the project was that it was practical to make small pellets from wheat flour, which could be expanded, into foams, with specific volumes of c.10 ml/g. However, practical methods examined to form these expanding foam beads into blocks of packing material failed to produce any useful products.

3.3 Factors affecting the performance of expanded packaging foams made from wheat flour.

The study of factors affecting the cushioning power of starch-based packaging was divided into two areas: structural features and chemical additives to modify the physical performance of starch polymers.

Sheets of foam were prepared at CCFRA from wheat flours under a range of processing conditions. The equipment used was similar to that employed for the manufacture of flat bread products. In order to test the sheets in a standard impact tester they had to be made with a smooth surface and even cross-section. This requirement restricted the expansion that was about 10 ml/g for most of the study. After the initial examination of the variations that could be achieved on flour, the cellular structure of foams was modified by increasing the number of cells in the foam by adding nucleating substances such as chalk or talc powders. These foams were prepared with roughly the same expansion but had a wide variation in texture scores from 3-10 on a scale of 1-10. The University of Reading was able to measure the cellular morphology of the foams in terms of cell wall thickness by image analysis of cross-sections (4).

The initial examination of the cushioning power of experimental wheat flour foams was made with extruded flour conditioned to c.12% moisture. These foams had cell wall thickness of 10-17 μm and specific volumes for 4 to 10 ml/g, compared with 2μm and 50 ml/g, respectively, for EPS. The flour foams have a greater energy absorbing capacity, but less rebound resilience, than

EPS foams. Close observation of the foams after testing revealed that they tended to fracture more than EPS foam under compressive and impact testing.

Addition of talc or chalk at 1 to 3% improved the wheat flour foams by reducing the cell wall thickness to 4-5 μm. The resilience was improved significantly and the cell walls did not fracture under compression but exhibited plastic deformation in a similar manner to EPS foams. The texture scores for the number of cells per unit volume were increased by the addition of the nucleating substances from 2 to 6, 9 and 10 at 1, 3 and 7% additions, respectively. This physical change in the extruded starch improved the flour foam so that it almost matched the cushioning curves for EPS foam despite being twice as dense.

The effect of moisture on the flour foam was studied by conditioning the foams for several days under conditions from 10 to 80% RH. At low RH the starch foams came to equilibrium at moistures <10% and displayed some brittle fracture characteristics. These fractures completely disappeared at 50% and 60% RH, when the moisture levels in the foams rose to 11-12%, both for the finely textured and coarse foams, and compression curves indicated only plastic deformation. For general performance during usage as a packaging material the wheat flour foams gave good results in the range 50 to 80% RH. Under these conditions the moisture level in the foam varies between 10 and 15% w/w.

However, if the moisture levels move outside this range the foams may become either too brittle or too soft for good performance. Therefore, some materials were examined which it was thought might help to plasticise the foams in the dryer conditions or to stiffen their structures at higher water levels. These materials were added to the flour during extrusion and were used at levels up to 5%. Their effect on the compressibility of flour foams and their ERH at a standard moisture level of 10 or 15% were measured. Surprisingly the materials tested, PVAs, PEG, and glycerol, had little effect on ERH and only PVAs had any significant effect on the plasticisation of the foam at low moisture to prevent brittleness. The addition of waste paper fibres appeared to improve the resilience of the starch foams and had a larger effect at low RH than PVAs.

In the later trials supplies of a hard milling feed wheat became available. This gave better expansion in the extruder and enabled the specific volume of the wheat flour extrudate to be increased to 20 ml/g. A feedstock of ground extrudates was used to demonstrate that the packaging could be recycled. In the second processing step the energy consumption was reduced and the degraded starch expanded to the same values as the flour with a lower shear screw design.

The addition of waste paper was examined in the extrusion of wheat flour at levels up to 20%. It tended to depress the expansion at the highest level but gave fine textures and improved resilience in the starch foam. The cushioning curves were improved by moving the minimum in deceleration to higher impact energy levels and broadening the whole curve for impact testing so that they were superior to EPS.

4. SUMMARY & CONCLUSIONS

The manufacture of blocks of foam from extruded pellets of wheat flour has been attempted using the puffing apparatus employing hot air expansion and steam conditioning. This technique has not been successful because the expanded beads of wheat flour extrudate had little or no adhesive properties even when moistened by the condensation of steam. Attempts to force the expanding pellets to bind together in moulds by expansion with microwaves were not successful because the moisture was lost during expansion and the expanded beads became too dry. The addition of additives with the beads during expansion either failed to produce a block or made it too hard. At present it is concluded that the expansion of pellets of wheat flour with water does not appear to be likely to produce foam products comparable to those made with EPS.

Valuable information was obtained on the factors affecting the performance of directly extruded foams, which are being used in the packaging industry. It was shown that two factors dominate the performance of wheat-based foams, the structure and the moisture level. Both are extremely

important in matching the cushioning performance of EPS foams. Fine structures with cell walls of similar thickness to EPS can be produced by adding talc or chalk to wheat flour. These structures display plastic deformation and good cushioning power over a range of moisture levels from 10-15%. These foams give good performance which matches the cushioning curves for EPS over a wide range of impact energies, which might be encountered in use as a packaging material. The wheat flour foams gave a similar performance to EPS at specific volumes of 8-12.5 ml/g compared with 50 g/ml for EPS. In general the wheat flour foam had greater energy absorbing capacity than EPS.

Information collected concerning additives suggests that the use of PVA derivatives and PGE does not improve the quality of the starch foams for their packaging performance either by the modification of the physical properties or for the control of moisture in the foams.
It is concluded that wheat-based foams can be manufactured which give excellent performance as packaging materials provided their manufacture is controlled to give a fine cellular structure, a high expansion and a moisture content between 10 and 15 %. These foams appear stable within atmospheric conditions of 50-80% RH but problems may arise outside this range due to brittleness at the lower RH and softness and collapse at the higher RH. None of the chemical additives tested helped to improve performance in these areas but addition of waste paper appeared to improve resilience. Additions of 10-20% waste paper fibres gave a synergistic effect with the wheat flour helping the nucleation of gas cells and shifting the minimum deceleration value to higher impact energies. The combined wheat/paper product is also completely biodegradable and preliminary tests also showed that it could be recycled in the extrusion cooker after coarse grinding to obtain a feedstock.
In summary, for the research on wheat flour foams, it has been demonstrated that excellent packaging materials can be made from wheat flour by extrusion cooking with a small amount of low cost materials acting as the functional additives. The performance of the best quality foams is determined by the cell morphology and some synergistic interactions from newspaper fibre. These foams can be manufactured by using the high shear processing and the simple additives. After usage the foams can be mixed with water to give a low volume slurry which can be allowed to biodegrade or be compressed and recycled to form more foam at lower energy extrusion conditions.

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METHODS AND RESULTS

1. EXPERIMENTAL

1.1 Raw materials

A soft wheat flour, c. 9.0 % protein and 13.5 % moisture was purchased from an UK miller. Later a hard feed wheat, Brigadier, with similar protein and moisture contents was purchased to improve expansion.

Two powders were used for the nucleation of bubbles: creta preparata (calcium carbonate) and talc. These materials were characterised for their particle size.

Other additives examined included acetylated polyvinyl alcohol derivatives (PVAs, Alcotex F88-4, 78, 72.5 and 552P, from Honeywell & Stein), polyethylene glycol (PEG, Honeywell & Stein), glycerol and citric acid. PVAs were available in four different types, each having been manufactured with a different degree of hydrolysis. All the additives were used at levels of 2.5 and 5% w/w of the dry mix.

Waste paper pulp was prepared by milling wet newspapers through a shearing section on the twin screw extruder or obtained from a paper mill.

1.2 Manufacturing pellets

The extrusion processing used to manufacture pellets was a low shear process on an APV MPF 50 25L/D, twin screw extruder, which formed a dense extrudate exiting the dies at 95-100 °C.

1.2.1 Single pass extrusion for pellets

Table 1: Process conditions for extrusion cooking of wheat flour

Variable	Settings
Powder feed	Wheat flour
Screw configuration:	Screw D (Appendix1, low shear)
Total feed rate (g/min):	In range 150 to 400 g/min
Process moisture (%):	in range 27 to 33
Dies, number, diameter (mm)	4, 1.5
Screw speed (rpm):	in range 90 to 100
Barrel temp. zones (°C):	Typically from feed inlet 40, 75, 130, 95, to 70 at the die

The extrudates were cut at speeds of 1400 to 1800 rpm with a twin blade knife to form small beads. These were dried at 60°C for 30 min and then at 40°C overnight to give glassy pellets with moisture contents of 8-10%.

1.3 High shear extrusion processing for directly expanded foams

The second type of extrusion processing was high shear, high feed rate, low moisture processing (Table 2) for the production of directly expanded material. This type of processing was to produce a highly expanded extrudate containing the additives and also in the experiment to produce different textures. It was carried out on an APV MPF 50 15 L/D twin screw extruder.

1.3.1 Manufacture of sheets of foam

The wheat flour was processed at high shear to degrade the starch and extruded through a slit die using shutters to keep the surfaces flat and smooth.

Table 2: Extrusion cooking processing conditions for sheets of foam

Variables	Settings
Powder feeds:	Wheat flour plus additives
Screw configuration:	Screw C
Die	Dog bone slit, 55 mm x 1.5 mm with adjustable shutters to control thickness
Total feed rate (g/min):	600
Process moisture (%):	In range 15 to 20
Screw speed (rpm):	In range 250 to 400
Barrel temp. zones (°C):	30, 50, 70, 120, 150

1.3.2 Manufacture of directly expanded material: circular dies

The conditions for all the cylindrical extrudate samples made in these trials closely resembled those shown below. For some of the mixes, small modifications were made to the moisture and /or screw speed, in order to improve the stability of the process.

Table 3: Extrusion cooking processing conditions for cylindrical extrudates

Variables	Settings
Feeds:	Wheat flour plus additives
Screw configuration:	Screw B
Dies: number, diameter, (mm)	2 , 4
Total feed rate (g/min):	600
Process moisture (%):	16
Screw speed (rpm):	250
Barrel temp. zones (°C):	30, 50, 70, 120, 150

The collets were cut and collected after cooling to ambient temperatures. They were conditioned with moisture to obtain samples with moisture contents in the range 10-14 % w/w.

1.4 Trials for pellet expansion and forming into blocks

1.4.1 Expansion of pellets

The pellets were examined for their ability to expand by heating in either a 1000W microwave oven at full power for 15-20s or in a fluidised bed of hot air at c. 200°C for 10-15s. The expansion was measured by direct displacement of glass beads in a standard measuring cylinder and expressed as specific volume in ml/g.

1.4.2 Techniques for the formation of packaging blocks from the pellets

The attempts to form the pellet into blocks were made both during and after expansion. The techniques examined are listed in Table 4.

Table 4: List of techniques investigated for block formation

Code	Technique	Special requirement	Additives
A	Microwave	800W	10-20% Barriercoat DC1718 wax (Dussek Campbell)
B	Microwave	1000W	as A
C	Hot air	Test rig A	ground extrudate 20% paste w/w, in water
D	Hot air	Test rig B	as C
E	Autoclave	150-190 °C	None
F	Spraying	Ambient/dryer	ground extrudate 5% paste w/w, in water

1.5 Examination of extrudate for compressibility and water activity at specific moisture levels.

Experiments were carried out on the directly expanded collets to assess the effects of additives on water activity and compressibility.

1.5.1 Water activity

A set of extrudates was selected and prepared for testing. Each sample was first ground to a coarse powder and then conditioned in a Trimcote bread dough prover to one of two moisture levels, 10% or 15%. The temperature in the prover was between 30-40°C and the relative humidity set at 70%. The samples were analysed in a Novasina Water Activity meter.

1.5.2 Compressibility

The collets made in the above trials were tested on a Stable Micro Systems TA-XT2 texture analyzer to assess their suitability for packaging. The test regime was similar to the British Standard for the testing of packaging, comprising four compression and recovery cycles, each to 25% strain on each cycle at 20 mm/min.

1.6 Measurements of extrusion cooking variables for process and extrudate

In all extrusion trials the following variables were measured during the processing:

1. SME (specific mechanical energy), estimated from the recorded motor current (torque value).
2. Die pressure and temperature, recorded with a combined temperature and pressure probe in the die head cavity.
3. Feed and moisture flow rates from pumps and powder feeder.

Measurements made on the extrudates included the following:

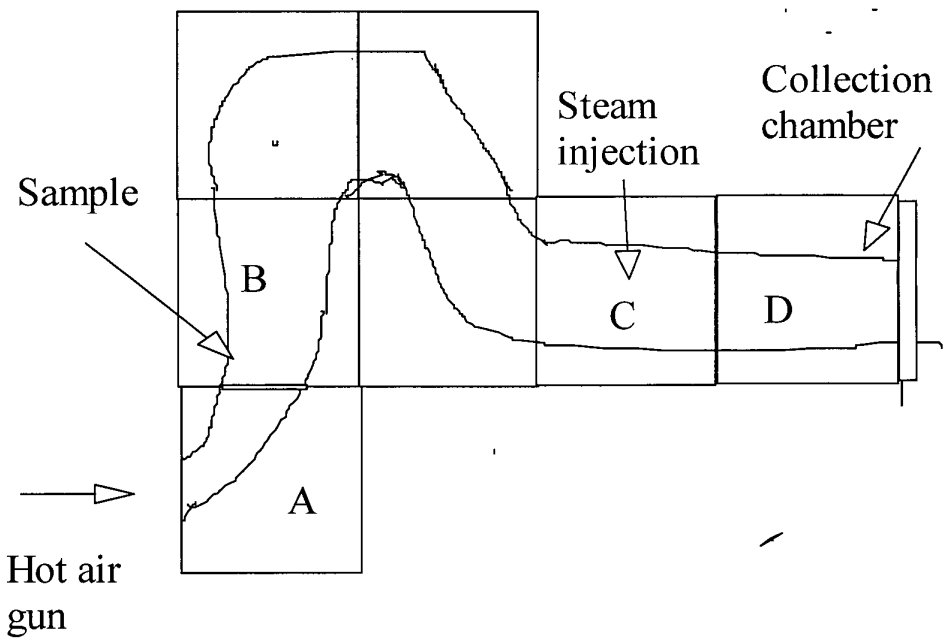
1. Moisture content by oven drying at 100°C.
2. Specific volume by displacement of glass beads.
3. Dimensions by measurements with vernier calipers.
4. Cellular texture by image analysis (The University of Reading)
5. Texture score by visual comparison with reference standards on scale 1-10 where

Texture score = 1.12 $\log_e$ (Cell numbers per g) – 4.1

1.7 Construction of the fluidised bed expansion apparatus (The puffer)

In the expansion apparatus (Fig.1), the heating chamber (B) has been fitted to the heating gun via horizontal entry port (A) and the conical vessel has been extended so that the expanding pellets can be carried on the air stream to a mould (D). During their passage to the mould there is a small chamber (C) which can be opened or closed by screen and has ports at the top and bottom for the addition of additives or steam. A sample of pellets will be loaded into A via a small port and expanded in a batch process.

Fig.1: Diagram of test rig used to expand pellets



2. RESULTS AND DISCUSSION

2.1 Expansion of pellets

Pellets manufactured as in 3.2, were examined for their expansion in hot air. The materials were manufactured from 100% soft wheat flour with a degree of cook of 25% (Guy and Horne 1988) Their pellets showed increases from 0.7ml/g in the pellet to 9-10ml/g as the foam. The performance of the pellets was not affected by storage in plastic bags for the duration of the project (2.5yr).

2.2 Manufacture of blocks of packaging materials from expanded pellets.

The puffing apparatus was used to expand the pellets from 0.7 ml/g to 8-9 ml/g specific volume.

Expansion of the wheat flour pellets was achieved in the fluidised bed of the puffing apparatus and the expanded beads were blown over the dam into chamber B for further treatments. The main problem at this stage was that the beads were too dry, having lost c. 5% moisture during expansion so that their residual moisture levels were c. 5- 6% w/w. At this moisture level the beads were crisp and brittle and would not stick together.

Experiments were carried out to cool the beads and to add steam to wet their surfaces before the final compression into the mould. Preheating the metal puffing apparatus to >100°C prevented condensation on the apparatus and allowed the steam to moisten the pellets. The effect of the added moisture was to soften the pellets so that they became plastic. Moisture could be added in this way to such an extent that the beads even began to shrink. However, the moistened beads did not have any significant adhesive properties and could not be formed into a block.

An alternative approach was adopted in which the pellets were expanded in the fluidised bed and then mixed with an aqueous paste of powdered extrudate and water as described in the techniques. The proportion of paste to expanded beads was important in achieving a good adhesion between the beads without having excessive levels of moisture to cause the beads to shrink. The best conditions were found to use 10% of a 20% paste of ground beads. This gave a good binding effect on drying the blocks at 60°C. However, the blocks were too dense to be used as a packaging material.

In the experimental studies the blocks had to be rehumified to 10-12% moisture to ensure that the starch polymers were in the plastic state.

These studies have shown that in order to form a block of foam from expanding beads of wheat flour glass the following conditions must be fulfilled:

1. the beads must be heated to melt the starch polymer glass and allow the expansion of the plastic fluid form of the starch
2. the expanded starch beads made from flour are not sticky even when moistened so much that they shrink, and therefore must be either treated with an external adhesive, or expanded in a sealed system so that they retain their moisture. This would require that they expand like puffed wheat or rice to form a block in which the expanding spheres are forced together to give areas of deformation, which adhere together on cooling.
3. the starch polymer system must be equilibrated to c. 12% moisture to obtain a plastic deformable state for packaging.

Two other techniques were examined to form blocks from the pellets.

2.3 Manufacture of expanded foams by direct expansion extrusion

The manufacture of expanded foams by extrusion from a slit die was successful in that it produced a series of sheets of foam with the same overall expansion as measured by specific volume (7.2 to 9.0 ml/g), but with a range of texture quality from coarse to fine.

Table 5: Examples of expanded foam sheets prepared for analysis of cushioning power

Sample, EN 281	%, Talc	Specific Volume, Ml/g	Texture score, 0-10	Linear density g/m	Area density, g/m^2	Width, Mm	Thickness mm
S7	0	8.4	2	91.5	1.28	71.38	14.0
S8	0	8.7	2	92.4	1.31	70.75	14.7
S9	7	7.2	10	52.1	0.82	63.88	6,4
S11	7	9.0	10	58.1	0.83	69.63	8.3
S12	1	8.6	6	77.5	1.11	69.75	9.2
S15	3	8.5	9	71.3	1.04	68.63	10.5

Fig. 2: Impact testing results from The University of Reading

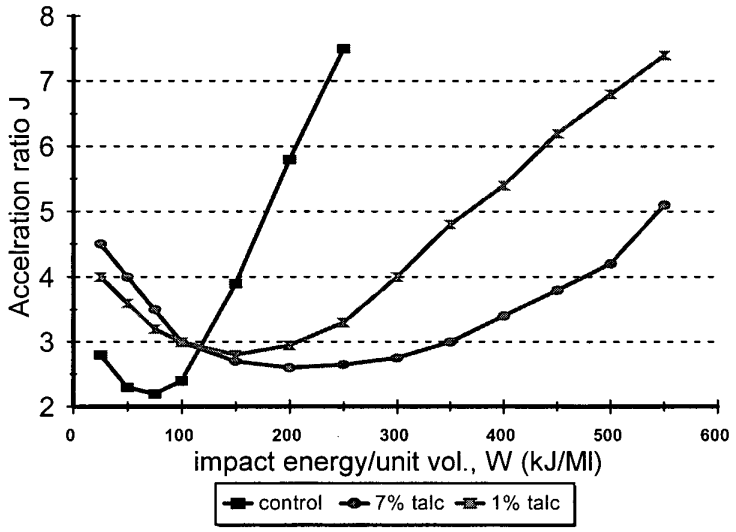
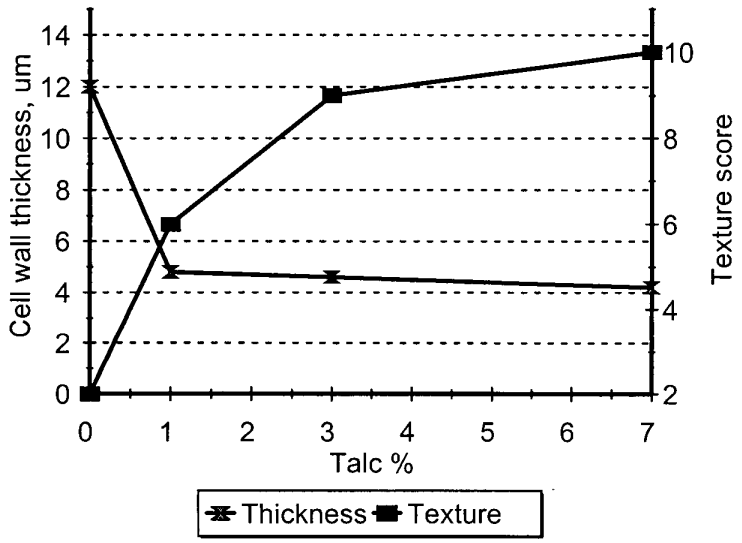


Fig. 3: Effect of talc in wheat flour foams



In Fig.2 the foams were conditioned at 50% RH which gave moisture levels of 10.7 to 11.5% w/w in the foams. At higher RH values the equilibrium moisture in the starch increased so that it was as high as 14% w/w at 80% RH. This increase in moisture lowered the minimum for the impact curves whilst retaining the general shape. There is an improvement in a material as its minimum falls until it becomes too soft and then it tends to lack resilience and can be squashed. Wheat flour foams were shown to be satisfactory up to 15% moisture in compression tests. They will tend to fail in very high RH conditions > 80% RH which may be found in equatorial regions. Fuller details of the impact testing are reported by Jeronimidis et al.(1999) to EPRSC.

2.4 Compression and water binding tests on cylindrical extrudates

Tests were carried out on cylindrical collets of expanded wheat flour containing different levels of moisture and different types and levels of additives (PVAs, PEG, and glycerol). Standard compression tests, in which the cylinders were compressed repetitively four times, did not show up any significant differences in packaging performance due to any of the additives. There was a small reduction in recovery between compressions (measured by the ratio of the areas under the third and first peaks of the force-time curve) with increasing moisture from 10 to 15% w/w.

The additives had only a small effect on ERH, although the ERH of all the samples changed markedly with moisture. Samples containing different additives did not have significantly different ERH values at the same moisture. This was a disappointing result as it had been hoped that the PVAs would enhance the moisture binding properties. However, it was noted that at the 5% level PVA tended to reduce the brittleness of samples at 10% moisture levels.

3. SUMMARY AND CONCLUSIONS

The manufacture of blocks of foam from extruded pellets of wheat flour has been attempted using the puffing apparatus employing hot air expansion and steam conditioning. This technique has not been successful because the expanded beads of wheat flour extrudate had little or no adhesive properties, even when moistened by the condensation of steam. They required a relatively high level of moisture to become sticky and at that stage they also began to shrink and lose their expansion. It was found that the addition of slurry of ground extrudate could act as a glue to bind the expanded beads together. The blocks of beads were stabilised by drying to set the glue but could be rehumidified to obtain a soft plastic state at 12-14% moisture. However, the blocks of pellets were too dense to give any useful cushioning properties and did not meet the objectives.

It was concluded that the expansion of pellets should be attempted in an apparatus that would force the pellets to be in contact with each other at the peak of their expansion. This would give binding areas where the pellets made firm contacts with each other while still plastic. It is thought that the alternative to using a glue would be to expand the pellets in a steam chamber like rice cakes. A small test chamber is being considered at present.

The information which has been collected concerning additives suggests that the use of PVA derivatives and PGE does not improve the quality of the starch foams for their packaging performance either by the modification of the physical properties or for the control of moisture in the foams.

Reference

Guy, R.C.E. and Horne, A.W. (1988) Degree of cook in extruded products. FMBRA Bulletin No. 1, 25-34.

APPENDIX 1: Extruder screw configurations

SCREW	A		B		C
FS	8"	FS	10"	FS	10"
FP-30°	3	FP-45°	7	FP-45°	7
SL	2"	SL	8"	SL	7"
FP-60°	4	P-90°	2	P-90°	2
RP-60°	3	TSS	2"	TSS	2"
SL	2"	P-90°	2	P-90°	2
FS	5"	RP-45	4	RP-30°	6
FP-60°	3	SL	2"	SL	2"
SL	2"				
FP-30°	4				
SL	2"				

Where:

P is a paddle 0.5" wide
R or F is reversing or forwarding.
30°, 45°, 60°, 90° is the angle of the paddle to its upstream neighbor.
FS is feed screw.
SL is single lead screw.
TSS is twin start feed screw.

Screw A is a low shear screw with the cooking section near the feed end.
Screw B is the Chorleywood Standard Screw Configuration (CSSC), a moderately high shear configuration.
Screw C is a high shear configuration.