# Dietary fibres and their properties:- the possibility of fibre lowering the glycaemic index of foods post extrusion.

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## Abstract

A series of experiments were devised in order to establish the relationship between fibre addition to an extruded breakfast cereal base recipe and the physical, chemical and nutritional qualities of the breakfast cereals. A twin screw extruder was used for all experiments. Preliminary investigations using, guar gum and inulin additions, illustrated that screw configuration was important in determining the physical properties (degree of expansion, firmness and crunchiness) of the extruded products. Thus a screw configuration featuring a reverse screw and mixing zone within the barrel was selected for the larger research study.

In the extended experimental design guar gum, inulin, wheat bran, swede fibre, and hi-maize were added to a base recipe at; 5, 10 and 15 % of total dry ingredient content. A further experiment was completed to investigate the synergistic effects of adding differing fibres in combination.

Results illustrated that soluble dietary fibres (for instance guar and inulin) created a porous, less firm, but crispier breakfast cereals than the insoluble fibres, which generally produced denser, harder products. The inclusion of fibre into the extruded breakfast cereals did not affect the chemical composition of the breakfast cereal significantly ($P \leq 0.05$) when taking into account the diluting factor of adding the fibre into the base recipe. However moisture loss / retention on extrusion varied significantly ($P \leq 0.05$) between fibre combinations. Thus the moisture loss of samples containing guar or inulin were greater than those samples containing wheat bran and swede fibre. The process of extrusion did not significantly effect the amount of protein, starch or fibre in the samples when the extruded samples were compared to the control samples. Pasting properties of samples were evaluated using the Rapid Visco Analyser. This was conducted to try to determine associations between starch pasting properties (gelatinisation events) of the raw and extruded samples and the physical or nutritional quality of the products. However, the results did not show clear associations.

An *in vitro* analysis was conducted to determine the effect of fibre addition on starch breakdown and subsequent release of reducing sugars. Breakfast cereals which included wheat bran, guar and swede fibre all showed a reduced rate of starch degradation compared to the control ($P \leq 0.05$). These fibres appeared to inhibit the rate of enzyme degradation of starch, in effect increasing the amount of slowly digestible starch in the breakfast cereals. Cereal samples containing inulin did not show this pattern. Generally the rate of inhibition was related to the amount of fibre added to the base recipe. When used in combinations, samples containing inulin and hi-maize were not significantly different to the control in terms of reducing sugar release, whereas inclusion of guar gum significantly reduced this release.

In conclusion, the addition of selected fibres can be used effectively as a method of manipulating the starch degradation rates of extruded breakfast cereals. This has nutritional implications in terms of glycaemic index and loading of breakfast cereals. Further work is required to develop clearer associations between the events of starch gelatinisation during extrusion and the potential glycaemic response.

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## List of publications arising from this research project

1. Brennan, M.A., Monro, J.A., & Brennan, C.S. (2008) Effect of inclusion of soluble and insoluble fibres into extruded breakfast cereal products made with reverse screw configuration. *International Journal of Food Science and Technology.* **42: (IN PRESS)**.

2. Brennan M.A., Merts, I., Monro, J., Woolnough, J. & Brennan, C.S. (2008) Impact of guar and wheat bran on the physical, and nutritional, quality of extruded breakfast cereals. *Starch* **60**: 248-256.

3. Brennan, M.A., Woolnough, J.W., Monro, J.A., Merts, I. & Brennan, C.S. (2008) Guar and bran fibre reduces the potential glycaemic impact of extruded breakfast cereals. IN Proceedings of Nutritional Society of New Zealand Volume 32 (Eds C.S. Brennan) Massey University Press, ISSN 0110-4187. pp.

4. Brennan, M.A., Woolnough, J.W., Monro, J.A., Merts, I. & Brennan, C.S. (2007) Glycaemic control of extruded breakfast cereals: use of dietary fibres. *Asia Pacific Journal of Clinical Nutrition.* **16:** S82.

# Chapter 1 Introduction

## *1.1 The definition of dietary fibre*

Historically the term dietary fibre (DF) has been used to define a collection of plant based cell wall materials. However, more recently there has been an attempt to improve the specificity of terms leading to the following definition was developed by a committee of members of the American Association of Cereal Chemists (AACC).

"Dietary fibre is the edible parts of plants or analogous carbohydrates that are resistant to digestion and absorption in the human intestine with complete or partial fermentation in the large intestine. DF includes polysaccharides, oligosaccharides, lignin, and associated plant substances. DF promotes beneficial physiological effects, such as laxation, and/or blood cholesterol attenuation, and/or blood glucose attenuation"
(Anon., 2001).

The above definition links the chemical composition of fibre to its physiological effects. At the same time it includes all non-starch polysaccharides resistant to digestion in the small intestine and are fermentable in the large intestine (celluloses, hemicelluloses, pectins, modified celluloses, oligosaccharides, and polyfructans such as inulin, gums, and mucilages). It also includes oligosaccharides and polysaccharide components bound to the plant cell wall (lignin, waxes, cutin, and suberin). Materials with analogous characteristics to DF are included in the new definition under the term of analogous carbohydrates.

A non-exhaustive list of the constituents of DF is summarised in Figure 1.1 which relates actual plant components to demonstrable physiological effect.

**Figure 1.1 Constituents of dietary fibre**

**(adapted from Brennan and Tudorica 2007)**

**DIETARY FIBRE**

**Non-starch polysaccharides and resistant oligosaccharides**

- Cellulose
- Hemicellulose
- Arabinoxylans
- Arabinogalactans
- Polyfructose
- Inulin
- Oligofructans
- Galactooligosaccharides
- Gums
- Mucilages
- Pectins

**Analogous carbohydrates**

- Indigestible dextrins
- Resistant maltodextrins
- Resistant potato dextrins
- Synthesized carbohydrate compounds
- Polydextrose
- Methyl cellulose
- Hydroxypropylmethyl cellulose
- Indigestible (resistant) starches

**Lignin**

**Substances associated with the non-starch-polysaccharides and lignin complex in plants**

- Waxes
- Phytates
- Cutin
- Saponins
- Suberin
- Tannins

## *1.2 Physicochemical properties of dietary fibre*

DF has been considered to be an inert carbohydrate fraction with little nutritional value, however current research has shown it as an essential component of the human diet. The consumption of foods rich in DF has been associated with decreased risks of developing diet related chronic diseases (WHO, 2003) and the physiological effects are usually compared with the intakes or contents of total dietary fibre (TDF).

However, the reliance on TDF fractions is simplistic as DF refers to a large number of substances encompassing very diverse macromolecules, which also exhibit a large variety of physico-chemical properties. As a result of compositional variations, different sources of DF have different metabolic and physiological effects depending upon the chemical and physical properties of the DF.

An understanding of these characteristics is useful in predicting the physiological response to specific fibres and is outlined in Tables 1.1 and 1.2 below (Adapted from Schneeman, 1999). As a consequence, DF can be classified either according to their chemical structure (origin) or the ability to combine with water (solubility).

**Table: 1.1 Characteristics of dietary fibre and their relationship to small intestinal functions**

| **Characteristic** | **Effect on small intestine** | **Physiological implication** |
|---|---|---|
| Dispersibility in water | Increases volume in the intestinal contents; dilution of compounds. | Associated with slower digestion of carbohydrate and lipid, which promotes nutrient absorption more distal in the intestine and is associated with reduction of plasma cholesterol and blunting the glucose and insulin response to a carbohydrate load and satiety. |
| Bulk | Expands bulk material phase of contents; alters mixing of contents. | |
| Viscosity | Slows gastric emptying; alters mixing and diffusion. | |
| Adsorb/bind compounds | Increased excretion of bile acids and other bound compounds. | Associated with plasma cholesterol reduction. |

Adapted from Schneeman, 1999

**Table: 1.2 Characteristics of dietary fibre and their relationship to large intestinal functions**

| **Characteristic** | **Effect on large intestine** | **Physiological implication** |
|---|---|---|
| Dispersibility in water | Provides an aqueous phase for penetration of microbes. | Increases microbial breakdown of polysaccharide structure. |
| Bulk | Increases material entering the large intestine; affects mixing of contents. | Provides substrate for micro flora; aids laxation. |
| Adsorb/bind bile acids | Increase the amount of bile acids in the large bowel. | Excretion is increased; opportunity for microbial modification of bile acids. |
| Fermentability | Growth of micro flora; microbial adaptation to polysaccharide substrates. | Increased microbial mass and products of metabolism. |

Adapted from Schneeman, 1999

## *1.3 Structural aspects of dietary fibre*

Dietary fibre includes primarily polysaccharides, but also oligosaccharides and substances from plant cell walls associated with the non-starch polysaccharides (Figure 1). The common characteristics are that these escape digestion in the small intestine and reach the large intestine, where a proportion undergo fermentation; hence the intrinsic effects on metabolism and disease risk are likely to be mediated through their properties as they pass through the gastrointestinal tract. The large majority of DF constituents are represented by carbohydrates: poly and oligosaccharides (Robertson *et al*., 2000). Similar to oligosaccharides, polysaccharide molecules are composed of glycosil units in linear or branched arrangements. The degree of polymerisation (DP), varies from less than 100 (only a few of them) to 10,000-15,000 (e.g. cellulose) with the majority of DF having a DP ranging between 200 and 3000. Each type of polysaccharide is characterised by its monosaccharide unit and the nature of the linkages between them.

The simplest structure is that of homoglycans, where all the glycosyl (monosaccharide) units are the same; for example, both cellulose and β-glucan have as monosaccharide residue glucose. In cellulose the linkages are β (1-4) with a linear structure, whereas in β-glucan, β (1-4) linkages are interspersed with 1-3 linkages resulting in a kinked structure.

Heteroglycans are composed of two or more different monosaccharide units, larger repeating sequences being common in polysaccharides of bacterial origin. Examples of heteroglycans are: hemicelluloses having a monosaccharide backbone consisting of xylan, galactan or mannan with side chains of arabinose or galactose (e.g. arabinoxylans), or pectins with a galacturonic acid core esterified to a varying extent with methoxyl groups.

The physical properties of polysaccharides are dominated by their conformation (sometimes described as ordered or disordered 'random coil' chain geometry) and the way they interact with one another. The chemical structures and chain conformations of DFs dictate their physical characteristics, which may have profound effects on their physiological role as constituents of digest, and may induce both local and systemic responses. Some of the most important physical characteristics of DF include: hydration properties, solubility/dispersability in water, rheological properties, bulk due to nondigestibility, the ability to adsorb or bind bile acids, fermentability by gut microflora and surface area characteristics.

## *1.4 Hydration properties of dietary fibres*

The majority of polysaccharides contain glycosil residues that have hydroxyl groups, and each hydroxyl group has the capacity to hydrogen bind to one or more water molecules. Therefore, glycans possess a strong affinity for water and readily hydrate when water is available (hydrophilic molecules). In aqueous systems, polysaccharide particles can take up water, swell, and undergo partial or complete dissolution.

Different hydration characteristics of DFs are related to their chemical structure. For instance, swelling values range from 5.65 ml/g for resistant starch (Novelose) to 10.45 ml/g for citrus fibre, and water retention capacity range from 2.95 g/g for Novelose to 10.66 g/g for citrus fibre (Robertson *et al.*, 2000). It has also been suggested that some values were lower than expected and this may be due to processing condition and consequent matrix structure breakdown (Robertson *et al.*, 2000). Processes such as grinding, drying, heating and extrusion can modify the physical properties of the fibre matrix and consequently affect their hydration properties (Guillon and Champ, 2000). Several examples of hydration characteristics for various DFs are presented in Table 1.3. Hydration characteristics of DF have been studied by many researchers in relation to both physiological effects (original DF hypothesis) and also to various technological aspects related to their presence into foods. Water appears to be bound to polysaccharides with differing strengths and in varying amounts. The water binding properties of DF have been determined by filtration (water holding capacity), centrifugation (water binding capacity) and even by freeze drying.

**Table 1.3 Hydration characteristics of some Dietary Fibres**

| **Source of fibre** | **Treatment** | **Particle size** (µm) | **Swelling** (mlg$^{-1}$) | **Water retention** (g water * g$^{-1}$ dry pellet) | **Water absorption** (ml water*g$^{-1}$dry DF) |
|---|---|---|---|---|---|
| Sugar beet fibre | - | 385 | 21.4 | 22.6 | 8.8 |
| | - | 205 | 15.9 | 19.2 | 7.3 |
| | Native | - | 10.8 | 6.1 | - |
| | depectinated-drastic drying | 27.6 | 14.0 | - | - |
| Citrus fibre | - | 540 | 15.7 | 10.4 | 7.0 |
| | - | 139 | 10.4 | 10.7 | 4.6 |
| Apple fibre | - | 540 | 9.6 | 6.9 | 3.8 |
| | - | 80 | 5.6 | 7.1 | 2.7 |
| Pea hull | - | 67 | 7.5 | 3.94 | |
| | Native | - | 6.2 | 4.2 | |
| | depectinated and freeze dried | - | 11.8 | 7.2 | |
| Wheat bran | - | 900 | 11.9 | 6.8 | 1.0 |
| | - | 320 | 5.9 | 3.0 | 0.9 |
| | Native | - | 7.0 | 7.0 | |
| | Delignified | - | 11.0 | 10.4 | |
| | Extruded | - | 9.0 | 4.4 | |
| Oat bran | - | - | 5.5 | 3.5 | |
| Resistant starch | | | | | |
| Novelose | - | 40 | 5.6 | 2.9 | 3.0 |
| Eridania | - | 84 | 7.4 | 3.1 | 3.9 |

(adapted from Guillon and Champ, 2000; Robertson *et al.*, 2000; Grigelmo-Miguel and Martin-Belloso, 1999).

The swelling and water retention capacities of DF provide a general view of the hydration characteristics, and provide useful information for designing extruded DF enriched breakfast cereal. High water holding capacity suggests that these materials can be used not only as DF enrichment, but also as functional ingredients to reduce calories, avoid syneresis and modify the viscosity and texture of the final product.

Water absorption is thought to provide more information on DF utilisation, in particular its substrate pore volume, and may be useful in understanding DF behaviour during the transit of the gastrointestinal tract (Guillon and Champ, 2000). Faecal bulking capacity of DF is related to both their water absorption/retention characteristics and their impact on microbial proliferation (Davidson and McDonald, 1998). However this is not entirely true. For instance DFs such as pectin have high water capacity when compared with wheat bran, but the latter has a more pronounced effect on faecal bulking as it is poorly fermentable and therefore retains its structure in the colon.

## *1.5 Solubility of dietary fibres*

Generally speaking, solubility is considered as a major factor in functional and nutritional properties of DF. The solubility of polysaccharides is a consequence of their internal structure and the stability of those structures. Most of the polysaccharides exist in some sort of helical shape (BeMiller and Whisler, 1996). Some polysaccharides have a structure in which the chains may adopt regular, ordered conformations and pack together into crystalline-solid assemblies; the polymer is likely to be more stable in the solid state than in solution (Guillon and Champ, 2000). The chemical regularity of a chain increases the strength of the links, conferring insolubility thus leading to resistance to enzymatic attack. Thus, linear structures such as cellulose (with its flat ribbon-like conformation) may undergo only limited degradation during enzymic degradation, because the structure is nearly inaccessible to enzyme penetration. If the structure is more irregular, or branches are present in the structures, the links tend to be weaker and prone to degradation. The majority of polysaccharides exist in this form and enables rapid hydration so that these polysaccharides are regarded as soluble. Another factor that alters solubility is charge on the chains. Neutral polysaccharides such as cellulose and starch have a strong tendency for self-association; the existence of charged groups within the molecule (as in pectins) promotes solubility due to electrostatic repulsion, which inhibits the formation of ordered arrangements. However, the negatively charged polysaccharide may associate in the presence of metal ions that can bind to the chain and balance their charge. Temperature also plays an important role in the stability of the ordered assemblies; some materials insoluble in cold water will dissolve as the temperature increases because it opens up the molecular structure.

The determination of solubility of DF is important from a classificational point of view. One widely used classification is that of water-soluble (and gel-forming viscous DF) and water insoluble DF. Many of the physiological effects of fibre appear to be based on this property. For instance, soluble viscous DFs are associated with carbohydrate and lipid metabolism and are highly fermentable, while insoluble DF generally contributes mainly to faecal bulk improving bowel habits (Jenkins *et al*., 2001; Kritchevsky, 2001)

Water-soluble DFs are frequently used in the food industry primarily to modify/control the flow properties of liquid food products (textural properties). They are commonly known as gums or hydrocolloids and because they have the capacity to produce viscosity and form gels, they are often used in very small concentrations of between 0.25 to 0.5% (Brennan, 2005). Developing viscosity is one of the most important physical properties of soluble DF not only from the perspective of food application but also regarding several physiological effects.

The viscosity of solutions of polysaccharides is dependent on the intrinsic characteristics of the polysaccharides (molecular weight, shape of the molecules, the presence and magnitude of charges of these hydrated molecules, and the conformations they adopt in the solvent), as well as their concentration and temperature of solution. Viscosity, directly related to hydration properties and solubility, is one of the most important physical properties of DF from both physiological and technological points of view. DFs, which have the ability to form viscous solutions/gels, can change the rheology of the intestinal contents, and are known to produce local responses along the gastrointestinal tract (Brennan, 2005).

The differing effects of soluble and insoluble dietary fibre components on the glycaemic impact of foods (blood glucose levels) are showed in Table 1.4. There is a general agreement from peer-reviewed publications that the addition of certain fibre components may have a beneficial effect both on an *in vitro* and an *in vivo* basis. Most of the knowledge shows a reduction in glucose levels associated with fibres such as guar gum, psyllium fibre and beta glucan (those fibres which are known to affect the viscosity profile of foods). It is possible therefore that the association between viscosity altering behaviour of the gums and the effect on starch digestibility are associated. This point will be discussed in more depth later in subsequent sections.

**Table 1.4 The effect of DFs on glycaemic and insulinaemic responses - studies *in vivo* and *in vitro***

| Dietary fibre/ level used | Studies *in vivo* | | Studies *in vitro* | | Reference |
|---|---|---|---|---|---|
| | **Glucose/insulin levels** | **GI** | **Glucose/ reducing sugars** | **GI/ HI** | |
| Guar gum<br>(2.5, 7.5, 12.5g) | ↓* insulin<br>↓ glucose | - | - | - | (Torsdottir *et al.*, 1989) |
| Guar gum 20g/100kcal *vs* 4g/100kcal<br>(on healthy subjects) | ↓ plasma glucose | ↓ GI (with aprox. 30%) | - | - | (Benini *et al.*, 1995) |
| Guar gum (molecular weights and particle sizes) healthy volunteers | no effect on plasma glucose level<br>↓ plasma insulin | - | - | - | (Ellis *et al.*, 1991) |
| Guar gum at 20 or 40 g/kg (on pigs) | ↓ blood glucose | - | - | - | (Ellis *et al.*, 1995) |
| Guar gum 3.4% on dmb<br>(on dogs) | no effect on plasma glucose | - | - | - | (Diez *et al.*, 1998) |
| Guar gum, xanthan gum, methilcellulose, wheat bran - 70g (on rats) | ↓ blood glucose for meals containing viscous DF | - | - | - | (Cameronsmith *et al.*, 1994) |
| Guar gum *In vitro* and *in vivo* (on pigs) | ↓ blood glucose | - | ↓glucose produced | - | (Brennan *et al.*, 1996) |
| Guar gum, xanthan gum, CMC, water insoluble DF, water soluble DF, resistant starch (dialysis tubings) | - | - | ↓glucose | - | (Ou *et al.*, 2001) |
| Guar gum (molecular weights) 7.6g *per* serving - NIDDM patients | ↓ blood glucose<br>↓ blood insulin | - | - | - | (Gatenby *et al.*, 1996) |
| Guar gum (60g TDF of which 15g were guar gum *vs* 16g TDF) | ↓ blood glucose level | ↓ GI | - | - | (Lafrance *et al.*, 1998) |
| Guar gum 6.3g *per* serving | ↓ blood glucose<br>↓ blood insulin | - | - | - | (Fairchild *et al.*, 1996) |
| Inulin<br>10 g fed half way through the meal | No effect<br>↓ blood glucose | - | - | - | (Rumessen *et al.*, 1990) |
| Inulin (15g/day)<br>(patients with type 2 diabetes) | No effect | - | - | - | (Alles *et al.*, 1999) |
| Inulin<br>8g/day | ↓ fasting blood glucose | - | - | - | (Yamashita *et al.*, 1984) |
| Inulin 10g/day (on healthy volunteers) | ↓ fasting insulin level | - | - | - | (Jackson *et al.*, 1999) |
| Pectin<br>Liquid diet 2.5% | ↓ maltose absorption | - | - | - | (Chun *et al.*, 1989) |
| Pectin 3.4%on dmb<br>(on dogs) | no effect on plasma glucose | - | - | - | (Diez *et al.*, 1998) |

| | | | | | |
|---|---|---|---|---|---|
| Cellulose 10% | ↓ blood sugars (-5%) | - | - | - | (Mahapatra *et al.*, 1988) |
| Cellulose 3.4%on dmb (on dogs) | no effect on plasma glucose | - | - | - | (Diez *et al.*, 1998) |
| I. Psyllium and mixture psyllium-citrus pectin (2.2g)<br>II. Sugar beet fibre (6g) and cellulose (2g) | I. no effect<br>II. ↓ blood glucose level<br>↓ blood insulin level | - | - | - | (Frape and Jones, 1995) |
| Sugar beet fibre (on healthy subjects) | ↓ blood glucose level | - | - | - | (Thorsdottir *et al.*, 1998) |
| Psyllium 2.5% | reduced fasting glucose levels | - | - | - | (Watters and Blaisdell, 1989) |
| Psyllium 7.4 g (healthy volunteers) | ↓ insulin level<br>↓ blood glucose level | - | - | - | (Rigaud *et al.*, 1998) |
| Psyllium 15g (healthy volunteers) | ↓ blood glucose level | - | - | - | (Cherbut *et al.*, 1994) |
| Wheat bran 15g (healthy volunteers) | no effect | - | - | - | (Cherbut *et al.*, 1994) |
| Wheat bran 12g/day | flatten glucose | - | - | - | (Kritchevsky, 1988) |
| Wheat bran (6%) In pigs | No significant effect on blood glucose or insulin levels | - | Increased the rate of hydrolysis | - | (Leclere *et al.*, 1993) |
| Beet fibre (6%) In pigs | No significant effect on blood glucose or insulin levels | - | Decreased *in vitro* hydrolysis | - | (Leclere *et al.*, 1993) |
| Sugar beet fibre 15g (healthy volunteers) | ↓ blood glucose level | - | - | - | (Cherbut *et al.*, 1994) |
| Pea fibre | Flatten glucose | - | - | - | (Hamberg *et al.*, 1989a; Hamberg *et al.*, 1989b) |
| β-glucan from oats (4, 6 and 8g) (NIDDM subjects) | ↓ blood glucose level<br>↓ blood insulin level<br>estimate of 50% decrease in GI | - | - | - | (Tappy *et al.*, 1996) |
| β-glucan from barley foods and cellulose from wheat foods 21-38 gTDF/day | No effect on glucose level | - | - | - | (McIntosh *et al.*, 1991) |
| β-glucan from barley *in vivo* (10 healthy volunteers) and *in vitro* | ↓ blood glucose level<br>↓ blood insulin level | ↓ GI | ↓ reducing sugars released | ↓ HI | (Granfeldt *et al.*, 1994) |
| β-glucan from oats (9 healthy volunteers) | No effect on glucose or insulin levels | no effect on GI | - | - | (Granfeldt *et al.*, 1995) |
| Oat bran - β-glucan *in vivo* and *in vitro* | ↓ blood glucose level<br>↓ blood insulin level | | ↓ sugars released | | (Holm and Björck, 1992) |
| Oat bran - β-glucan | | | ↓ sugars | | (Hudson *et al.*, 1992) |
| β-glucan : oat and barley products | ↓ blood glucose<br>↓ blood insulin levels | - | - | - | (Liljeberg *et al.*, 1996) |
| β-glucan from oats (review paper) | ↓ blood glucose level (50% reduction for 10% β-glucan) | - | - | - | (Wursch and PiSunyer, 1997) |

### *1.6 Glycaemic Index in relation to dietary fibre content and breakfast cereals*

The concept of the glycaemic index (GI) is based on the postprandial increase in the plasma glucose concentration (ie, the glycaemic response) from a fixed amount of available carbohydrate in a test food with the glycaemic response elicited from the same amount of carbohydrate in a standardised reference food (eg, glucose or white bread). Generally, carbohydrate rich food products (those derived from wheat flour material) are regarded as high GI food products due to the ease of starch digestibility from cereal food products. In turn, diets of high GI foods have been linked to increased weight gain, lack of insulin and blood glucose control, and increased levels of obesity (Brennan, 2005).

Clinical studies have shown that diets rich in soluble fibres such as guar gum, pectin and sugar beet fibres, result in lower post-prandial blood glucose and insulin levels (Jenkins *et al.,* 1987). Non-soluble NSP have a limited effect on dietary glycaemic index (Jenkins *et al.,* 1997). Soluble NSP such as from pulses, vegetables, whole fruits, oats and barley form gelatinous gels within the stomach which delay gastric emptying and enzymatic digestion, the latter by forming a physical barrier around the carbohydrate (Jenkins and Wolever, 1978), whereas insoluble NSP have little effect on gastric emptying and no effect on glucose absorption. High fibre/high NSP diets are therefore not necessarily synonymous with low glycaemic index foods (Jenkins and Wolever, 1983).

The glycaemic index and carbohydrate composition of commercially available breakfast cereals are showed in Table 1.5. As the table shows, the DF content of breakfast cereals varies dramatically. Cellulose has been the most widely used NSP in household food products including breakfast cereals, wholemeal bread and brown rice. Since cellulose is insoluble, these foods have the same glycaemic index whether or not their DF content was increased (Jenkins and Wolever, 1983). Kelloggs All-Bran, an extruded wheat bran product, is an exception to this. Despite its high insoluble fibre content, it has a low glycaemic index (Foster-Powell and Miller, 1995), the reason for this is not understood but could be linked to complexion of fibre and carbohydrate altering starch digestibility. However it is possible to affect the digestibility of starch in breakfast cereal products by altering the soluble DF composition of extruded breakfast cereals (Brennan *et al.,* 2008).

**Table 1.5 Glycaemic index of commercially available breakfast cereals**

| **Breakfast product** | **GI[1] (glucose =100)** | **GI[1] (bread=100)** |
|---|---|---|
| All bran (Kellogg's) | 42 ± 5 | 60 ± 7 |
| Bran flakes (Kellogg's) | 74 | 106 |
| Cheerios (General Mills, Canada) | 74 | 106 ± 9 |
| Coco Pops (Kellogg's) | 77 | 110 |
| Cornflakes (Kellogg's) | 81 ± 3 | 116 ± 5 |
| Rice Bubbles (Kellogg's) | 87 ± 4 | 124 ± 6 |
| Weetbix (Sanitarium) | 69 | 99 |

[1] Two GI values are shown for each food one in which glucose sugar was used as the reference food and one in which white bread was used as the reference food.
(Adapted from Foster-Powell *et al.,* 2002)

Wolever *et al*. (1986) have reported that dietary carbohydrates can impact on the glycaemic response of the next meal, such that the glycaemic response to a lunch time meal is less when it is preceded by a low, compared to a high, glycaemic index breakfast. Björck and Elmståhl (2003) have also reported a glycaemic impact of dietary fibre from one meal to another, where an evening meal rich in indigestible carbohydrates, with a low glycaemic index will result in an improved glucose tolerance the following morning. It is therefore possible that the provision of a low GI breakfast cereal could have advantages in the regulating the glycaemic impact of meals throughout the day.

However, extruded breakfast cereals (Table 1.5) tend to be regarded as high GI food products. This is in part due to the high carbohydrate content of the cereals, and also in part related to the extrusion process which alters the chemical composition of the food product, and the digestibility of the starch within the carbohydrate food products.

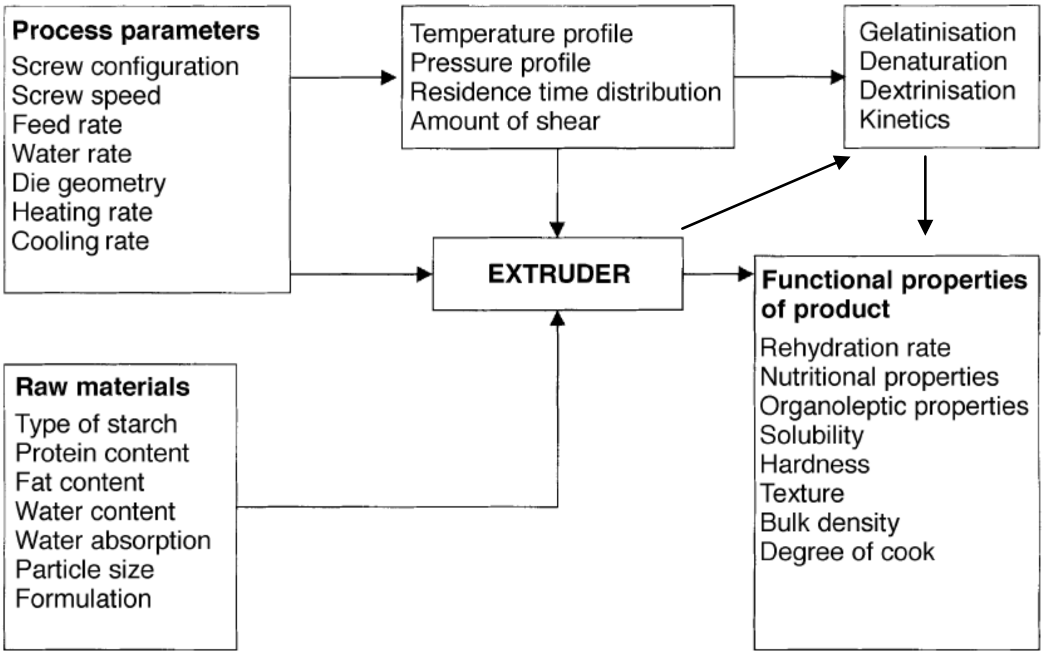
### *1.7 Extrusion processing and its impact on food quality*

Extrusion cooking can be regarded as a continuous process, however this is relatively simplistic. Extrusion processing of foods is characterised by the relatively short time of the process, the high shear environment in which processing occurs and the high temperatures, typically 140 to 160 ºC for snack and breakfast cereals, generated during processing. There are three major classes of extruders based on screw-type: single-screw extruders are common for their lower capital and operating costs. Intermeshing twin-screw in either counter rotating or co-rotating styles (Miller and Mulvaney, 2000) are far more expensive to install but offer superior versatility. The screw in the barrel constantly rotates during extrusion processing of the food materials. The food material is propelled forward under a continuous pressure and shear. At the end of the screw the product is forced through a die, that acts as a restrictive orifice. As the food is transported down the barrel the product is sheared, the process inherently causing back-mixing (Klein and Tadmor, 1970). The intermeshing twin-screw extruders have a shifting residence time of the product in the barrel. The counter-rotating screws, especially, produce a positive displacement pumping mechanism (Janssen, 1978). Co-rotating twin-screw can create a residence time distribution between the counter-rotating twin-screw and the single-screw mechanism.

The extruder has a die assembly at the end of the screw-barrel system, through which the product is forced. The product As temperature and shear increase down the barrel starchy materials melt due to high temperature (above 100 ºC) and shear. Pressures above the vapour pressure of water in the melt prevent the formation of bubbles in the barrel but as the hot melt leaves the die, the very rapid. pressure reduction as the melt leaves the die means that the melt expands at the die face as water in the melt flashes into steam. The rate of expansion depends on the rheological and thermal properties of the melt and on the geometry of the shaping die insert (Guy, 2001). The expanded extrudate is usually cut by a rotating knife on the outer face of the die. The the light crisp expanded pellets can then be coated with sugar, flavour or coloured molasses (Fast and Caldwell, 2000).

Extrusion cooking is used for a wide range of products. Pet food (dry, semi-dry, canned), expanded snacks, breakfast cereals, pastas and infant foods. The rheology of the pastes within the extruder has a significant influence of the product characteristics (bubble growth rate, degree of expansion, shape). Differences in flow rate and hence product characteristics can be created by changing the process parameters of die pressure drop, screw flow dynamics or screw energy consumption. Figure 1.2 shows different factors that have an influence on the extrusion cooking process.

**Figure 1.2: Interaction of raw material properties, process variables and product**



(adapted from Chessari and Sellahewa, 2001)

Humans cannot easily digest ungelatinised starch. During extrusion cooking, complete gelatinisation may not occur but digestibility will be improved due to partial gelatinisation and fragmentation of starch (Wang *et al.,* 1993). Extrusion can be regarded as a pre digestion of starch as the branches of amylopectin are susceptible to shear forces and can be cleaved from the main chain causing a change in the functionality of the ingredient. These shorter branches could cross link forming novel, indigestible linkages and therefore lower the glycaemic index (Theander and

Westerlund, 1987). Amylose and amylopectin have both been found to be reduced in molecular weight by extrusion (Politz *et al.,* 1994a). It has also been documented that extrusion of wheat starch can be optimised to maintain molecular weight (Poliz *et al.,* 1994b). High amylose rice has been extruded into noodles with a reduced glycaemic index (Panlasigui *et al.,* 1992).

### *1.8 Influence of dietary fibres in breakfast cereals*

The presence of non-starch polysaccharides in a meal have been reported to reduce postprandial sugar and lipid levels, the bio-availability of micronutrients, assist weight reduction and increase stool output (Read and Eastwood, 1992). These effects can be explained by the physiological action of non-starch polysaccharides. However as already mentioned, not all NSPs have the same properties. For example guar gum reduces postprandial glycaemia, but has little effect on stool bulking. In contrast, wheat bran and cellulose are better as laxative agents. A reason for the differences is the physical and chemical characteristics of the individual non-starch polysaccharides (Read and Eastwood, 1992).

Several researchers have established that eating breakfast is associated with an improved memory in the morning (Hall *et al.,* 1989). Children between 11-13 years having a breakfast could remember more words after 30 minutes, compared to children without (Morris and Sarll, 2001). The effect has also been confirmed for adults but has disappeared for both 90-120 minutes after the meal (Foster *et al.,* 1998). The rapid rise in blood glucose after breakfast provides these high mental functions. After two hours the memory still correlates with the glucose level (Sunram-Lea *et al*., 2001).

## *1.9 Objectives of this study*

The importance of breakfast cereals in our daily diet, combined with the potentially high glycaemic index status of extruded breakfast cereals, makes it an ideal food product to attempt to alter their nutritional quality through manipulation of product formulation.

The study was designed to investigate the effect of defined dietary fibre components on the physical chemical characteristics, and nutritional quality, of fibre enriched extruded snack products. A specific objective was to determine the effect of fibre inclusion on the apparent glycaemic index of extruded snack foods.

# Chapter 2 Materials and Methods

## *2.1 Materials*

Extruded breakfast cereals were made using a base recipe incorporating wheat flour (wholemeal or high ratio white flour), maize grits and oat meal (Tables 2.1, 2.2, 2.3). High ratio white wheat flour and wholemeal flour were obtained from Goodman Fielder NZ (Auckland, New Zealand). Non-starch polysaccharide (fibre) was added at 15% wheat flour replacement level. Wheat bran (bakers bran obtained from Marsanta foods Ltd; Auckland, New Zealand) and fine guar gum (Hawkins Watts Ltd; Auckland New Zealand) were used. The oatmeal used in the study was Flemings 'Thistle Oatmeal' obtained from Blue Bird Foods Ltd (Auckland, New Zealand), maize grits were 220 specification produced by Corson (Gisborne, New Zealand). Inulin used was Fibruline chicory inulin obtained from Cosucra Chaussée de la Sucreries (Fontenay, Belgium). National Starch (Auckland, New Zealand) provided hi-maize 1043 a natural unmodified, high amylose maize starch. Swede fibre was provided by Crop and Food (Palmerston North, New Zealand).

The recipes used for each of the studies in the thesis are shown in Tables 2.1, 2.2 and 2.3.

**Table 2.1 Recipes used to determine the effect of extrusion on wheat bran and guar gum using wholemeal (WM) and high ratio (HR) flours: results in Chapter 3**

| | WM flour (g) | HR flour (g) | Maize grits (g) | Oat meal (g) | Fibre (g) |
|---|---|---|---|---|---|
| WM control | 650 | | 200 | 150 | 0 |
| WM + 5% fibre | 600 | | 200 | 150 | 50 |
| WM +15% fibre | 500 | | 200 | 150 | 150 |
| HR control | | 650 | 200 | 150 | 0 |
| HR + 5% fibre | | 600 | 200 | 150 | 50 |
| HR + 15% fibre | | 500 | 200 | 150 | 150 |

**Table 2.2 Recipes using high ratio (HR) flour as a base used to determine the effect of extruder configuration (Chapter 4) and the effect of inclusion of soluble and insoluble fibres (Chapter 5)**

| | HR flour (g) | Maize grits (g) | Oat meal (g) | Fibre (g) |
|---|---|---|---|---|
| Control | 650 | 200 | 150 | 0 |
| 5% fibre | 600 | 200 | 150 | 50 |
| 10% fibre | 550 | 200 | 150 | 100 |
| 15% fibre | 500 | 200 | 150 | 150 |

**Table 2.3 Recipes using high ratio (HR) flour as a base used to determine any synergistic effect of combining dietary fibres**

| | HR flour (g) | Maize grits (g) | Oat meal (g) | Fibre 1 (g) | Fibre 2 (g) |
|---|---|---|---|---|---|
| Control | 650 | 200 | 150 | 0 | 0 |
| 15% fibre | 500 | 200 | 150 | 75 | 75 |

### *2.2 Extrusion process parameters*

Material was extruded using a twin screw extruder (Clextral BC21 twin screw co-rotating, self wiping extruder Clextral; Firminy Cedex, France), barrel diameter horizontal 46 mm, vertical 25 mm with a screw diameter of 24.7 mm, die diameter was

3 mm with set temperature points within barrels of 40, 60, 80, 100, 140 160 and 180 °C. Screw speeds, feed rates, water rates and the screw configurations used are given in Table 2.4. The torque and pressure of barrel and die during the different production runs are given in Tables 2.5, 2.6, 2.7. An automated cutter set at 200 rpm was used to obtain oval product shapes under constant cutting speed.

**Table 2.4 Extruder processing parameters**

| | **Screw speed (rpm)** | **Feed rate (Kg/h)** | **Water rate (L/h)** | **Screw configuration** |
|---|---|---|---|---|
| Reverse screw as used in Chapter 3 | 315 | 6.75 | 0.29 | 200 mm forward, 13 mm pitch<br>200 mm forward, 10 mm pitch<br>25 mm reverse, 7 mm pitch<br>50 mm forward, 10 mm pitch<br>225 mm forward, 7 mm pitch |
| Straight screw as used in Chapter 4 | 455 | 9.76 | 0.25 | 200 mm forward, 13 mm pitch<br>250 mm forward, 10 mm pitch<br>250 mm forward, 7 mm pitch |
| Reverse screw as used in Chapters 4, 5, 6 | 321 | 7.14 | 0.24 | 200 mm forward, 13 mm pitch<br>200 mm forward, 10 mm pitch<br>25 mm reverse, 7 mm pitch<br>50 mm forward, 10 mm pitch<br>225 mm forward, 7 mm pitch |

**Table 2.5 Torque and pressure of barrel and die during the production of samples using wholemeal (WM) and high ratio (HR) flours as a base to determine the effect of extrusion on wheat bran and guar gum (Chapter 3)**

| | **Apparent Torque (Nm)** | **Pressure thrust (bar)** | **Pressure at die (bar)** | **Temperature at die (°C)** |
|---|---|---|---|---|
| Control WM | 6 | 66 | 75 | 125 |
| WM +5% guar | 5.7 | 85 | 92 | 125 |
| WM +15% guar | 6.5 | 85 | 95 | 125 |
| WM +15% bran | 6.4 | 89 | 76 | 125 |
| Control HR | 5.5 | 50 | 65 | 125 |
| HR +5% guar | 5.4 | 60 | 72 | 125 |
| HR +15% guar | 6.6 | 76 | 85 | 125 |
| HR +15% bran | 5.5 | 6.2 | 75 | 125 |

**Table 2.6 Torque and pressure of barrel and die during the production of samples to determine the effect of straight screw extrusion**

| | **Apparent Torque (Nm)** | **Pressure thrust (bar)** | **Pressure at die (bar)** | **Temperature at die (°C)** |
|---|---|---|---|---|
| Control | 2.1 | 101 | 118 | 138 |
| Bran 5% | 2.9 | 108 | 116 | 137 |
| Bran 10% | 3.7 | 150 | 158 | 141 |
| Bran 15% | 3.6 | 150 | 154 | 143 |
| Inulin 5% | 3.1 | 112 | 116 | 140 |
| Inulin 10% | 3.8 | 92 | 101 | 139 |
| Inulin 15% | 3.9 | 80 | 98 | 138 |

**Table 2.7 Torque and pressure of barrel and die during the production of samples to determine the effect of adding a 25mm reverse screw element during extrusion**

| | Apparent Torque (Nm) | Pressure thrust (bar) | Pressure at die (bar) | Temperature at die (°C) |
|---|---|---|---|---|
| Control | 4.0 | 31 | 51 | 133 |
| Bran 5% | 4.4 | 35 | 55 | 134 |
| Bran 10% | 5.0 | 42 | 59 | 133 |
| Bran 15% | 5.0 | 46 | 62 | 133 |
| Inulin 5% | 4.0 | 45 | 62 | 130 |
| Inulin 10% | 4.0 | 49 | 60 | 129 |
| Inulin 15% | 4.5 | 41 | 59 | 130 |
| Guar gum 5% | 5.0 | 45 | 64 | 128 |
| Guar gum 10% | 5.0 | 49 | 69 | 129 |
| Guar gum 15% | 5.6 | 53 | 73 | 129 |
| Hi-maize 5% | 4.8 | 41 | 60 | 129 |
| Hi-maize 10% | 5.9 | 50 | 67 | 129 |
| Hi-maize 15% | 4.7 | 39 | 58 | 128 |
| Swede 5% | 5.1 | 46 | 64 | 128 |
| Swede 10% | 5.5 | 45 | 60 | 128 |
| Swede 15% | 5.5 | 43 | 64 | 129 |
| Bran + guar | 5.7 | 66 | 79 | 132 |
| Inulin + guar | 5.5 | 61 | 75 | 132 |
| Hi-maize + guar | 5.8 | 57 | 71 | 133 |
| Bran + inulin | 4.9 | 52 | 68 | 132 |
| Bran + hi-maize | 4.8 | 52 | 67 | 132 |
| Inulin + hi-maize | 4.4 | 38 | 56 | 133 |

### *2.3 Physico-chemical properties of raw base mix and extruded products*

Moisture determinations of raw product base and extruded products were conducted according to the American Association of Cereal Chemists (AACC) methodology (AACC 2000) and moisture loss during extrusion calculated by the difference from raw and extruded samples.

The size of 20 extruded pellets were measured using Vernier callipers (Mitutoyo; Tokyo, Japan).

Percentage expansion of the samples was determined using the formula:

$$\%\ \text{Expansion} = \frac{(\text{Average Cereal Extrudate Diameter})}{(\text{Diameter of Die})} \times 100$$

Weight of 1 L of extruded product was recorded to give the bulk density. Product volume was determined by poppy seed displacement method applied to 1L of product.

Product density was then determined according to the formula:

$$\text{Product density (kg/m}^3\text{)} = \frac{\text{sample weight (g)} \times 1000\ \text{(mL/L)} \times 1000\ \text{(L/m}^3\text{)}}{\text{sample volume (mL)} \times 1000\ \text{(g/kg)}}$$

### *2.4 Determination of pasting properties*

The pasting properties of both the raw cereal bases and the extruded food products were determined using a Rapid Visco Analyser (RVA-4; Newport Scientific, Warriwold, Australia). Samples were milled according to the manufacturers guidelines and were subjected to the standard 1 profile (Samman *et al.,* 2006). The computer software Thermocline for Windows (Newport Scientific, Warriewood, Australia) was used to analyse the pasting profiles of graphs obtained. All samples were analysed in duplicate.

### *2.5 In vitro starch determination*

*In vitro* starch hydrolysis was conducted. The food samples (2.5 g), either raw base product or milled extruded food product were mixed with 30 mL of water. Alpha amylase (Sigma – A3176) was added to the mixture and the pH adjusted to 2.5. Samples were held at 37 °C (10 minutes). Pepsin was then added (1 mL of 10 % solution in 0.05 M HCl) and kept at 37 °C for 30 minutes. Two ml of 1M NaHCO3 was added, and the pH adjusted to 6. At time zero a 1 ml aliquot was taken, and 0.1 ml of amyloglucosidase was added to prevent end product inhibition of pancreatic α-amylase then 5 ml 2.5 % pancreatin supernatant in 0.1 M maleate buffer pH 6 was added. The 1ml aliquots were taken at 20 minutes, 60 minutes and 120 minutes. The 1 ml aliquot was mixed with 4 ml ethanol in a tube and then centrifuged before reducing sugar was measured in the supernatant.

### *2.6 Resistant starch determination*

After removing the final aliquot at 120 minutes, the remaining digestion slurry was centrifuged at 4000 rpm for 10 minutes. The supernatant was discarded and the residue freeze dried. The residue was weighed, finely ground and returned to the tube where 2 ml dimethyl sulphoxide (DMSO) was added and the residue dispersed and heated at 100 °C for 10 minutes. Acetate buffer pH 5.2 (8 mL) containing 0.1 mL amyloglucosidase was added (made to 20 mL mark) mixed and incubated at 50 ºC for 30 minutes. The solution was centrifuged at 4000 rpm for 5 minutes, and an aliquot of the supernatant was taken for reducing sugar analysis.

### *2.7 Reducing sugar analysis with 3,5-dinitrosalicylic acid (DNS)*

DNS reagent was made by dissolving 10 g DNS in 200 mL 2 M NaOH with warming and vigorous stirring, and 300 g sodium potassium tartrate tetrahydrate in 500 mL distilled water. The two solutions were mixed and made to 1 L.

An aliquot of 0.05 mL of sample in ethanol was transferred into a tube with 0.25 mL enzyme solution A (1 % invertase and 1 % amyloglucosidase in acetate buffer pH 5.2), then mixed and allowed to stand for 10 minutes at room temperature. Then 0.75 mL DNS mixture (0.5 mg/ml glucose: 4 M NaOH: DNS reagent mixed in ratio 1:1:5) was added to the tube. The tube was covered with foil and heated at 95 to 100 ºC for 15 minutes. The tube was then cooled before adding 4 mL of water, and the absorbance was measured at 530 nm.

### *2.8 Protein Determination using the Kjeldahl Method*

Approximately 1 g sample was accurately weighed into a digestion tube. Two Kjeldahl tablets (each containing 3.5 g $K_2$ $SO_4$ and 0.0035 g Se) and 15 mL concentrated sulphuric acid were added. The tube was heated in a digestion block to 420 ºC until the solution became clear and then removed from the heat block after a further 20 minutes. The tube was cooled, and approximately 70 mL hot distilled water were added, before it was placed in a distillation unit. A conical flask containing 25 mL of 4 % boric acid solution (containing indicator) was placed under the condenser outlet. 30 mL of 40 % NaOH was dispensed in to the digestion tube and distilled for 4 minutes. The resulting ammonium borate solution was titrated against 0.1 M hydrochloric acid, to a mauve/grey end point.

### *2.9 Texture analysis of extruded products*

Texture profile analysis was performed according to the methodology described by Bourne (1978). Samples of the breakfast cereal products were measured with a texture analyser (TA-TEX32, Stable Micro Systems, Surrey, UK). An aluminium cylinder of 35 mm diameter (P/35; Stable Micro Systems, Surrey, UK) was used and the test- speed was adjusted to 1 mm/sec. Cereals were axially compressed to 50 % of the original height with 5 g trigger force. The force required to compress the sample 50 % was recorded as the hardness of the cereal product. The number of peaks recorded during the 50 % compression were recorded as the crispiness of the product. The results were analysed using the software, Texture Expert version 2.0 (Stable Micro Systems, Surrey, UK). All measurements were performed twenty times.

### *2.10 Total fibre determination*

Total dietary fibre was determined using the Total Dietary Fibre assay kit from Megazyme International (Wicklow, Ireland). The sample was weighed into a 400 mL beaker, 40 mL MES-TRIS pH8.2 buffer was added and stirred on a magnetic stirrer until there were no lumps. While stirring at a slow speed, 50 µL α-amylase was added. The beaker was covered with aluminium foil and then incubated for 35 minutes at 95 to 100 °C in a shaking water bath. After cooling to 60 °C, the foil cover was removed, the gel in the bottom and the ring on the side wall were scraped with a spatula and the side walls rinsed with 10 mL distilled water. Protease solution (100 µL ) was added and the beaker covered with foil and incubated for 30 minutes at 60 °C in a shaking water bath. The beaker was placed on a stirrer and the foil removed before 5 mL 0.561 N HCl was added. The pH was adjusted to between 4.1 to 4.8. While stirring, 200 µL amyloglucosidase was added, the beaker was covered with foil and incubated for 30 minutes at 60 °C in a shaking water bath. Ethanol (225 mL 95 %) pre heated to 60 °C was added to the beaker which was then covered with foil and left for 1 hour at room temperature to allow precipitation to take place. A fritted crucible containing acid washed, pre ashed celite was tared. The bed of celite was evenly distributed using 78 % ethanol and suction was applied to draw the celite onto the fritted glass as an even mat. The digest was filtered through the crucible using 78 % ethanol to rinse the beaker. Using a vacuum the residue was successively washed with two 15 mL portions of 78 % ethanol, 95% ethanol and acetone. The crucible was dried overnight at 103 °C. The crucible was cooled in a dessicator for approximately 1 hour before weighing to obtain fibre content. The residue was then analysed for protein using the Kjeldahl method (as in 2.8).

### *2.11 Total starch determination.*

Total starch was determined using the Total Starch assay kit from Megazyme International (Wicklow, Ireland). The sample (1 g) was suspended in 5 mL ethanol (80 %) and incubated at 80 °C for 5 minutes, the resulting suspension was centrifuged (using an IEC Centra MP4R centrifuge) for 10 minutes at 3000 rpm (approximately1000 g), the supernatant was discarded. Two mL DMSO was used to resuspend the pellet, this suspension was heated in a boiling water bath for 5 minutes after which 3 mL MOPS buffer/thermostable α-amylase solution was added, the sample was mixed with a vortex mixer and boiled for 6 minutes (stirred after 2 and 4 minutes). The heated sample was then placed in a 50 °C water bath and 4 mL sodium acetate added followed by amyloglucosidase (0.05 mL, 20 U), mixed using a vortex and then re-incubated at 50 °C for 30 minutes. The contents were then transferred to a 100 mL volumetric flask and made to volume with distilled water. The flask was mixed well and an aliquot withdrawn. The aliquot was centrifuged at 3000 rpm for 10 minutes. And duplicate aliquots (0.1 mL) of the diluted solution were transferred to the bottom of a glass test tube to which 3 mL of GOPOD-reagent were added before incubation at 50 °C for 20 minutes. The control samples were analysed with glucose standard solution with a water blank. Absorbance of samples was measured at 510 nm.

### *2.12 Statistical analysis*

Unless otherwise stated all analysis were done in triplicate, and mean ± standard deviation (SD) values are presented. Analysis of variance (ANOVA) of the results was performed using the Minitab 13 statistical software package (Minitab Inc., State College, Pennsylvania, US) followed by Tukey's test. Significance was defined as $P<0.05$.

# Chapter 3 The effect of wheat bran and guar gum on some physical chemical and nutritional qualities of extruded cereal products

## *3.1 Introduction*

The extrusion process has a considerable effect on the structure and nutritional quality of food products. A series of experiments were conducted to determine the characteristics of the extruded breakfast cereals made with a hi-ratio flour base and with a wholemeal flour base. Additionally two dietary fibres (guar gum and bran) were included into both of the recipes at a 15 % (w/w) replacement value for flour in order to determine the effect of fibre addition on the physical, chemical and nutritional characteristics of the two bases.

## *3.2 Materials and Methods*

The high ratio white flour, bran and inulin materials used in this series of experiments are detailed in Section 2.1. The recipe used for the manufacture of extruded products is detailed in Table 2.1. Table 2.4 shows the extruder processing parameters used, and Table 2.6 reports the pressure and temperature conditions of the extruder during product manufacture. The methods used to determine the physical, chemical and starch digestibility properties of the extruded products are those as detailed in Chapter 2.

## *3.2 Results*

Table 3.1 shows the amount of moisture in the raw base and extruded samples for both raw and extruded samples.

**Table 3.1: Moisture content of raw and extruded breakfast cereal products made from wholemeal (WM) and high ratio (HM) flour bases**

| | **Extruded** | **Raw (non-extruded)** |
|---|---|---|
| WM control | 8.86 $^{c}$ ±0.05 | 12.65 $^{c,d}$ ±0.10 |
| WM + 15% wheat bran | 8.95 $^{c}$ ±0.03 | 12.56 $^{c,d}$ ±0.03 |
| WM + 15% guar gum | 8.88 $^{c}$ ±0.15 | 12.73 $^{c}$ ±0.03 |
| HR control | 10.20 $^{a}$ ±0.13 | 13.97 $^{a}$ ±0.0 |
| HR + 15% wheat bran | 9.46 $^{b}$ ±0.03 | 13.57 $^{b}$ ±0.01 |
| HR + 15% guar gum | 9.52 $^{b}$ ±0.06 | 13.50 $^{b}$ ±0.03 |

Within columns each attribute means different letter are significant different ($P \leq 0.05$).

Previous research has indicated that white flour has a greater water holding capacity compared to wholemeal flour (Cauvan and Young, 2007). Table 3.1 shows that the high ratio flour samples had higher moisture content than wholemeal samples. In the wholemeal samples, the addition of fibre did not affect the moisture content of either the raw or extruded product. However, for the samples with the high ratio base, fibre addition reduced the moisture content of the products. The loss of moisture during extrusion (the difference between raw and extruded samples expressed as a percentage based on raw sample moisture content) is shown in Figure 3.1. The control wholemeal samples lost significantly more moisture during extrusion than the high ratio control samples. In the wholemeal base samples, inclusion of bran resulted in a lower moisture loss than inclusion of guar gum, whereas in the high ratio sample this trend was reversed.

**Figure 3.1: Moisture loss (%) during extrusion process**

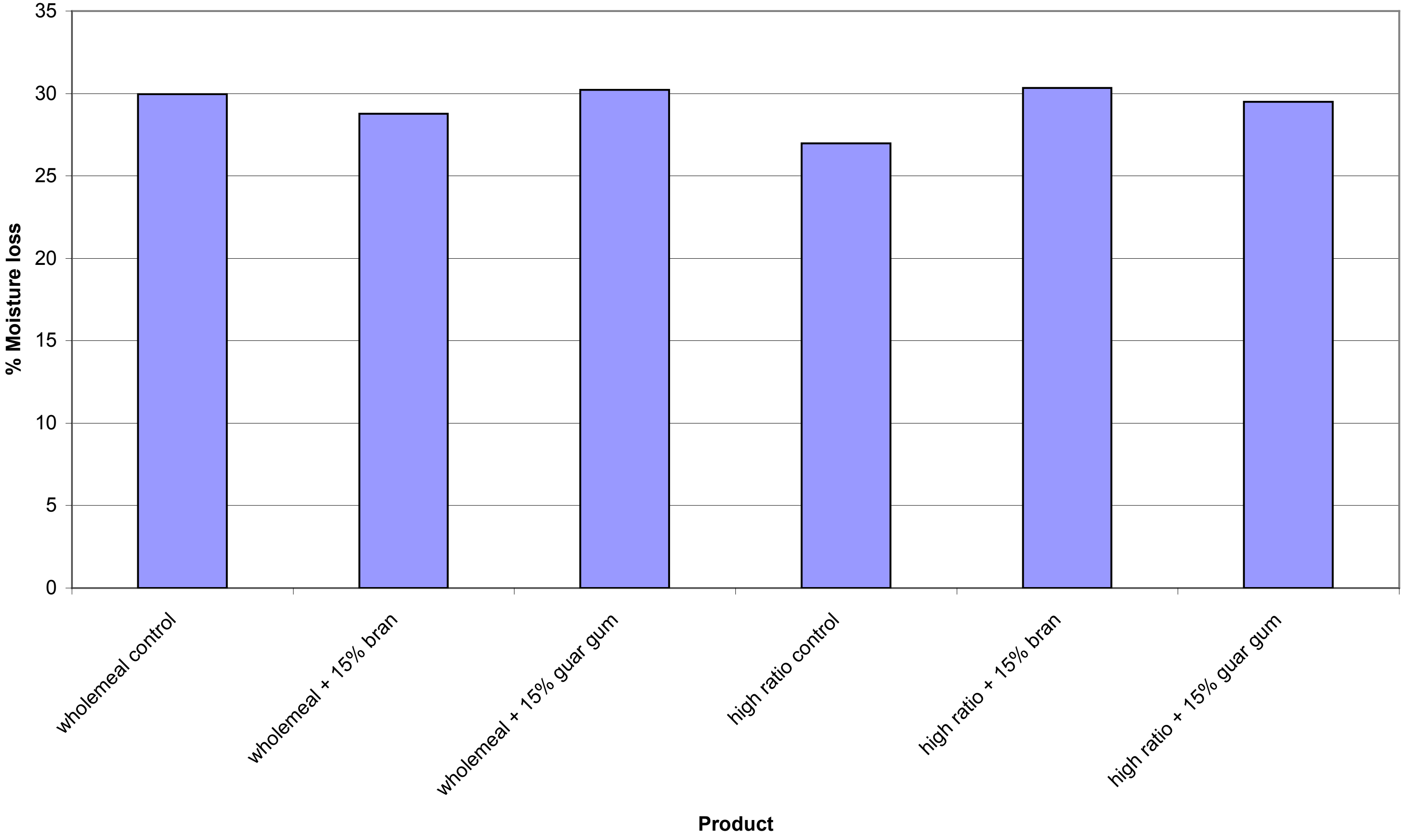
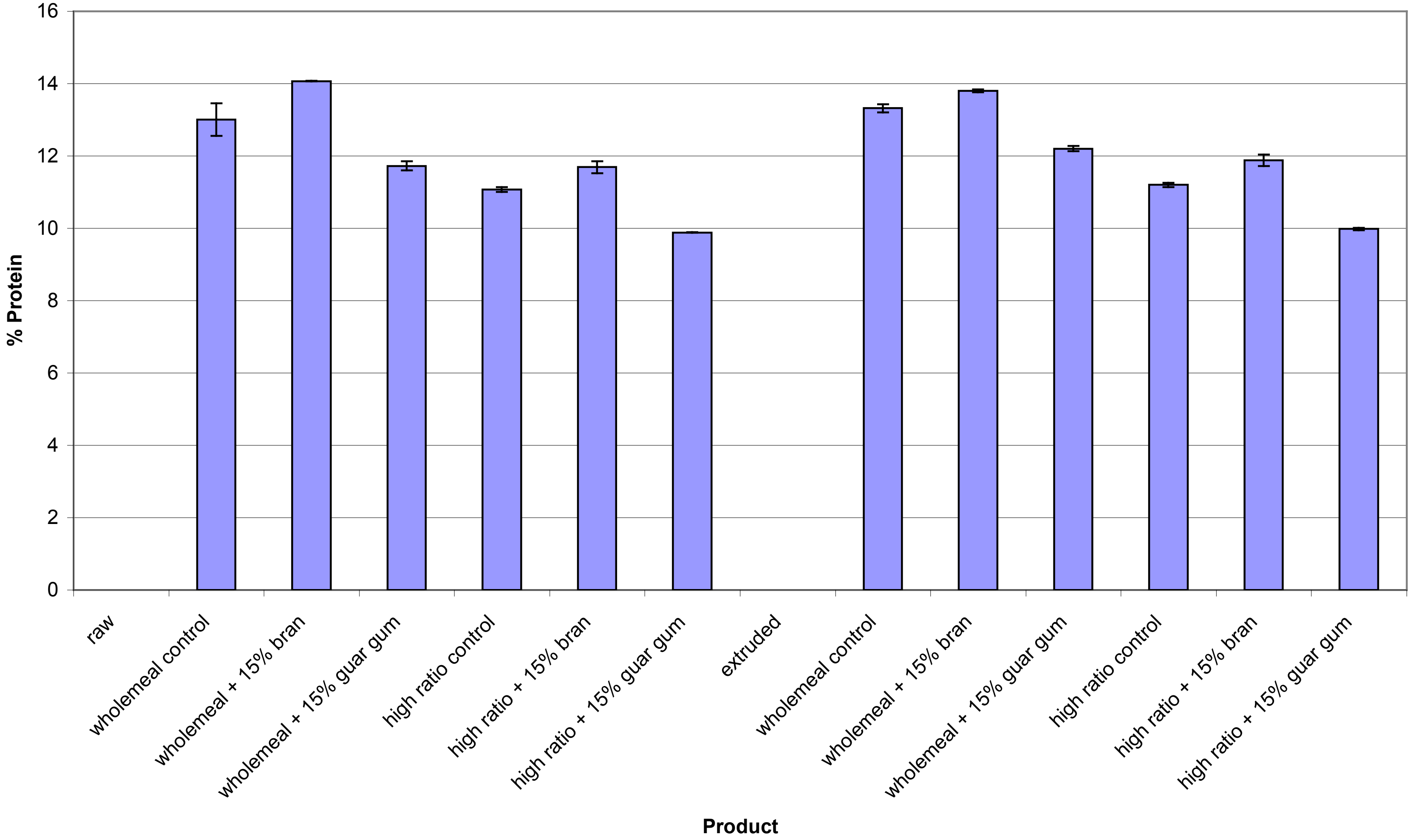


**Figure 3.2: Protein content (dry matter basis) of raw and extruded cereal products**



The protein content of the raw and extruded cereal products was analysed to determine the effect of extrusion process on the protein content (DMB) of products. There was little variation between the raw and the extruded cereal products was observed (Figure 3.2), showing that the protein content of breakfast cereal products is unlikely to be altered by the extrusion process as expected due to the physical nature of the process rather than chemical reactions.

The pasting properties of both the raw and extruded samples were evaluated using the Rapid Visco Analyser (RVA) in order to determine the effects of the extrusion process on the different flour bases with and without fibre addition. Table 3.2 shows that raw samples containing high ratio flour as a base had higher cold peak areas than wholemeal bases. Associated with this, the peak and final viscosities of the high ratio flour samples were higher than the viscosities of the wholemeal base samples.

In both the wholemeal and high ratio flour base mixes the inclusion of bran reduced peak and final viscosity compared to the control samples (associated with the reduction of starch content with the bran inclusion). Guar gum inclusion increased cold peak, peak and final viscosities associated with the ability of guar to increase product viscosity. Extruded control breakfast cereals and samples containing 15 % bran showed an increase in cold peak area (indicating that starch gelatinisation had occurred and amylose / amylopectin re-association to produce extended visco-elastic networks). Peak and final viscosities of these breakfast cereal samples decreased on extrusion (compared to the raw samples). Peak and final viscosities of the 15 % guar gum enriched breakfast cereals were reduced compared to the raw breakfast cereal base mixtures, illustrating that some starch gelatinisation had occurred. However these values were still higher than those of the control and 15 % bran added samples.

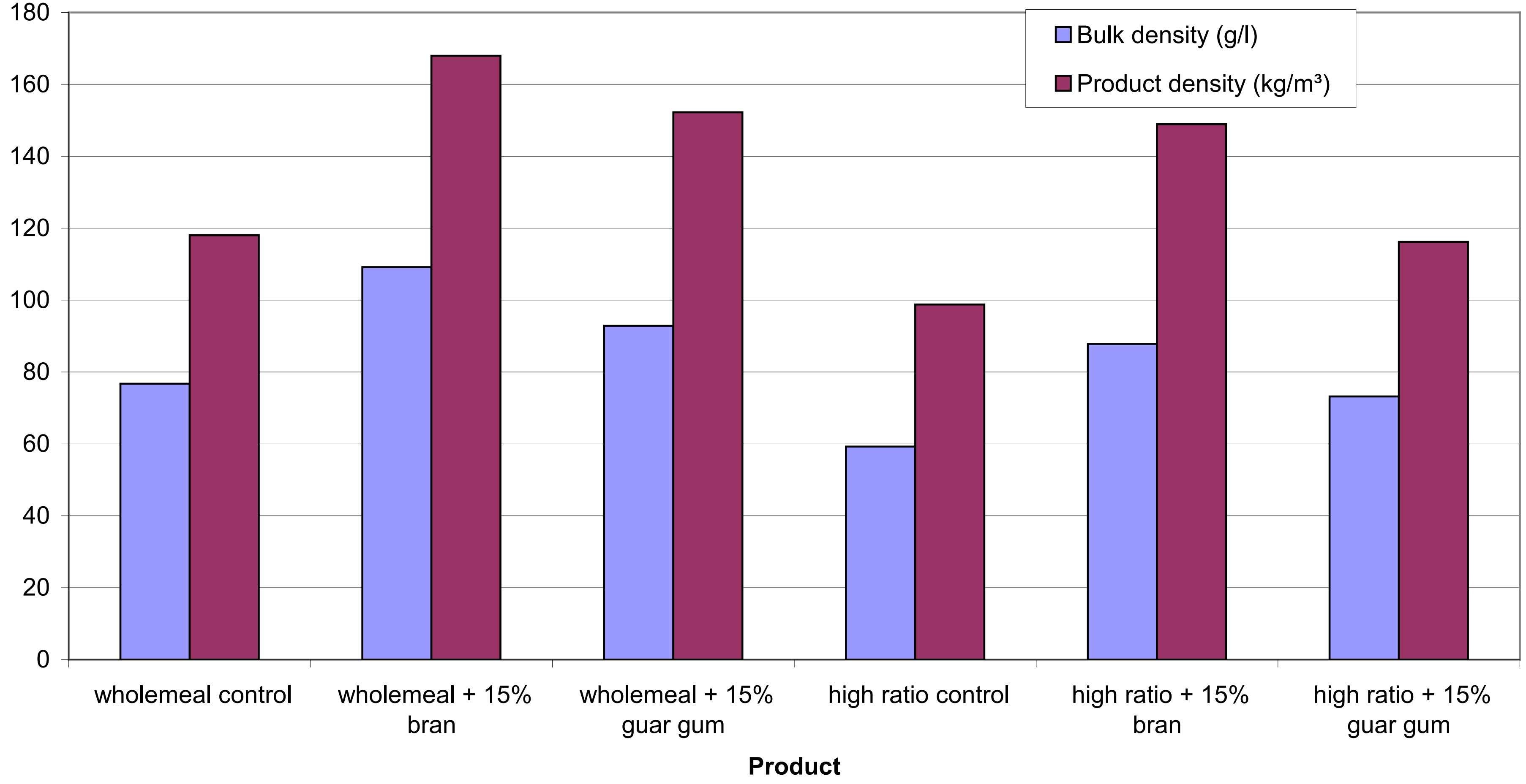
**Table 3.2: Pasting properties of high ratio (HR) and wholemeal (WM) flour bases with guar and bran replacement before and after extrusion**

| | **Raw Peak (cp)** | **Final Viscosity (cp)** | **Cold Peak Area (cp)** |
|---|---|---|---|
| Raw | | | |
| WM control | 499.00 $^{e}$ ±26.87 | 781.00 $^{f}$ ±55.15 | 28.12 $^{\mathrm{I}}$ ±3.73 |
| WM + 15% wheat bran | 338.50 $^{h}$ ±3.54 | 571.50 $^{h}$ ±17.68 | 22.66 $^{\mathrm{I}}$ ±2.49 |
| WM + 15% guar gum | 2914.00 $^{b}$ ±14.14 | 3532.50 $^{b}$ ±3.54 | 355.55 $^{e}$ ±19.50 |
| WM + 5% guar gum | 1354.50 $^{c}$ ±27.58 | 1989.50 $^{d}$ ±37.48 | 83.50 $^{j}$ ±5.24 |
| HR control | 566.50 $^{d}$ ±12.02 | 893.50 $^{e}$ ±16.26 | 37.69 $^{\mathrm{I}}$ ±8.44 |
| HR + 15% wheat bran | 371.00 $^{g}$ ±15.56 | 614.00 $^{g}$ ±28.28 | 19.95 $^{\mathrm{I}}$ ±0.41 |
| HR + 15% guar gum | 5362.00 $^{a}$ ±66.47 | 5316.00 $^{a}$ ±45.25 | 916.88 $^{a}$ ±43.23 |
| HR + 5% guar gum | 1509.00 $^{c}$ ±182.43 | 2027.00 $^{c}$ ±151.32 | 60.12 $^{k}$ ±4.85 |
| Extruded | | | |
| WM control | 75.50 $^{k}$ ±3.54 | 52.00 $^{m}$ ±0.00 | 154.97 $^{g}$ ±6.19 |
| WM + 15% wheat bran | 64.00 $^{l}$ ±2.83 | 44.00 $^{n}$ ±0.00 | 146.03 $^{h}$ ±6.58 |
| WM + 15% guar gum | 1311.00 $^{c}$ ±15.56 | 491.00 $^{\mathrm{I}}$ ±7.07 | 1936 $^{b}$.12 ±0.41 |
| WM+ 5% guar gum | 329.50 $^{h}$ ±27.58 | 156.00 $^{k}$ ±7.07 | 508.74 $^{d}$ ±53.28 |
| HR control | 74.00 $^{k}$ ±4.24 | 70.50 $^{l}$ ±36.06 | 121.40 $^{\mathrm{I}}$ ±28.60 |
| HR + 15% wheat bran | 93.00 $^{j}$ ±2.83 | 50.00 $^{m}$ ±1.41 | 194.14 $^{f}$ ±7.56 |
| HR + 15% guar gum | 451.50 $^{f}$ ±9.19 | 326.50 $^{j}$ ±26.16 | 629.72 $^{c}$ ±20.19 |
| HR + 5% guar gum | 186.50 $^{\mathrm{I}}$ ±34.65 | 88.50 $^{l}$ ±16.26 | 322.79 $^{e}$ ±5.61 |

Within columns each attribute means different letter are significant different (*P*≤0.05).

Bulk density and product density of the extruded breakfast cereals are shown in Figure 3.3. Bulk density was greater in the wholemeal base compared to the high ratio flour.

**Figure 3.3: Product and bulk density values of extruded high ratio and wholemeal flour bases with guar gum and bran replacement**



The addition of 15% fibre increased both the bulk and product density compared to the respective control breakfast cereals. In both recipes bran gave a greater increase in bulk and product density than the addition of guar gum. The expansion ratios of the breakfast cereals were determined (Figure 3.4) and the expansion ratio was greater for the high ratio flour recipes than the wholemeal base control. The inclusion of 15 % bran into the high ratio base was the only sample that resulted in less expansion, whilst the inclusion of bran and guar gum in the wholemeal samples and guar gum in the high ratio sample showed no difference from the controls. The reduction in expansion ratio for the samples containing 15 % bran fibre is related to the increased density of these samples as observed in (Figure 3.3).

The carbohydrate digestibility of the breakfast cereals is shown in Figure 3.5, illustrating the proportion of readily and slowly digestible carbohydrate as well as resistant carbohydrate as measured in the raw bases. The wholemeal samples with the addition of bran and guar reduced the amount of readily digestible carbohydrate compared to the control sample. No difference was observed between the samples and amount of slowly digested and resistant starch. Similarly, no difference was observed in the digestibility profiles of high ratio control and high ratio bases with 15% bran. However, the inclusion of guar gum, reduced the amount of readily and slowly digestible carbohydrate contents whilst increasing the resistant starch content. Extrusion increased the amount of readily digestible carbohydrate compared to the raw mixes (Figure 3.6). In both the wholemeal and high ratio flour bases the readily and slowly digestible carbohydrate fraction were similar between control and the 15 % bran sample. However, the inclusion of 15 % guar gum reduced the readily digestible carbohydrate fraction in both base recipes.

Figure 3.4: Expansion values of extruded high ratio and wholemeal flour bases with guar and bran replacement

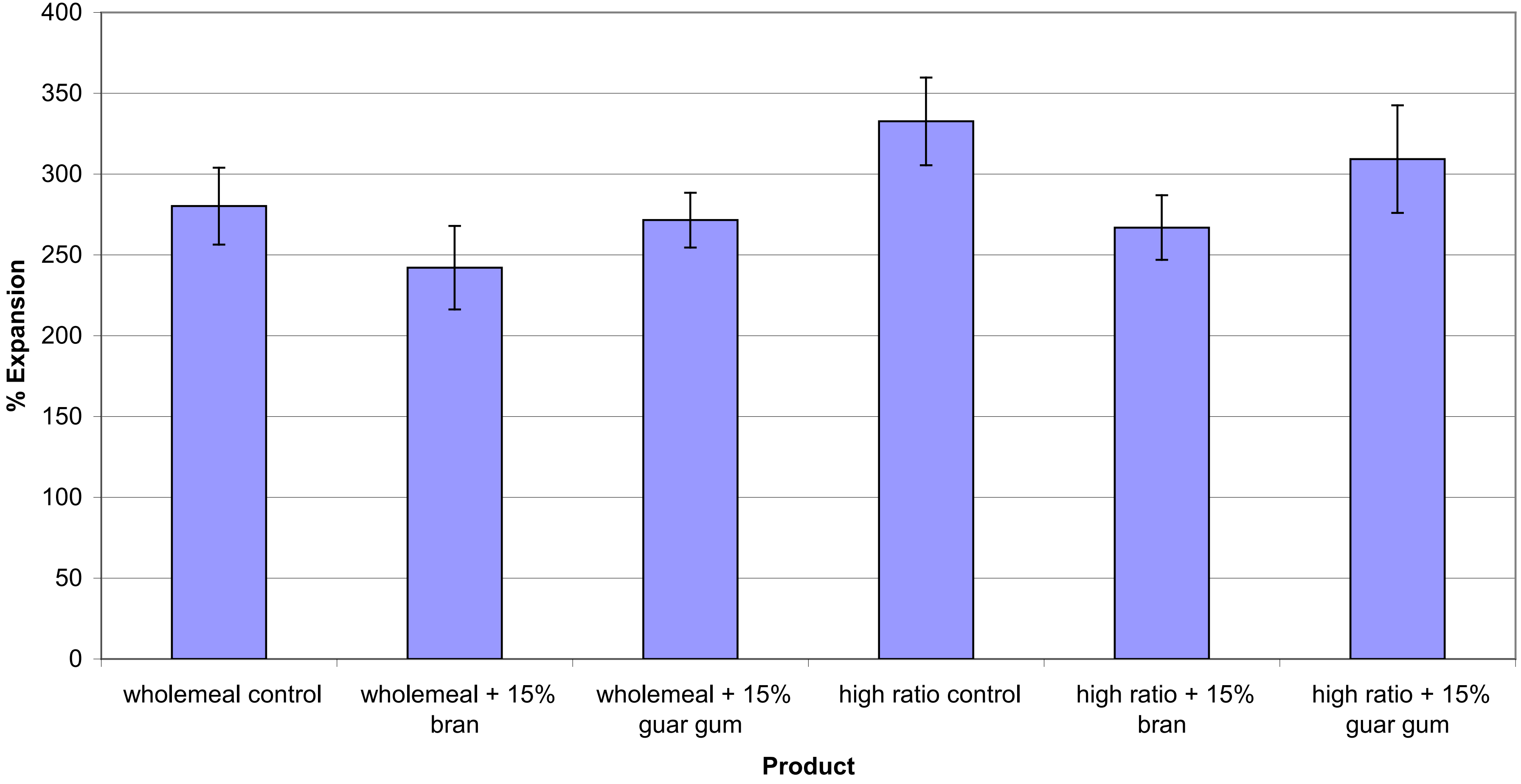


**Figure 3.5: Carbohydrate digestibility of high ratio and wholemeal flour bases with guar gum and bran replacement before extrusion**

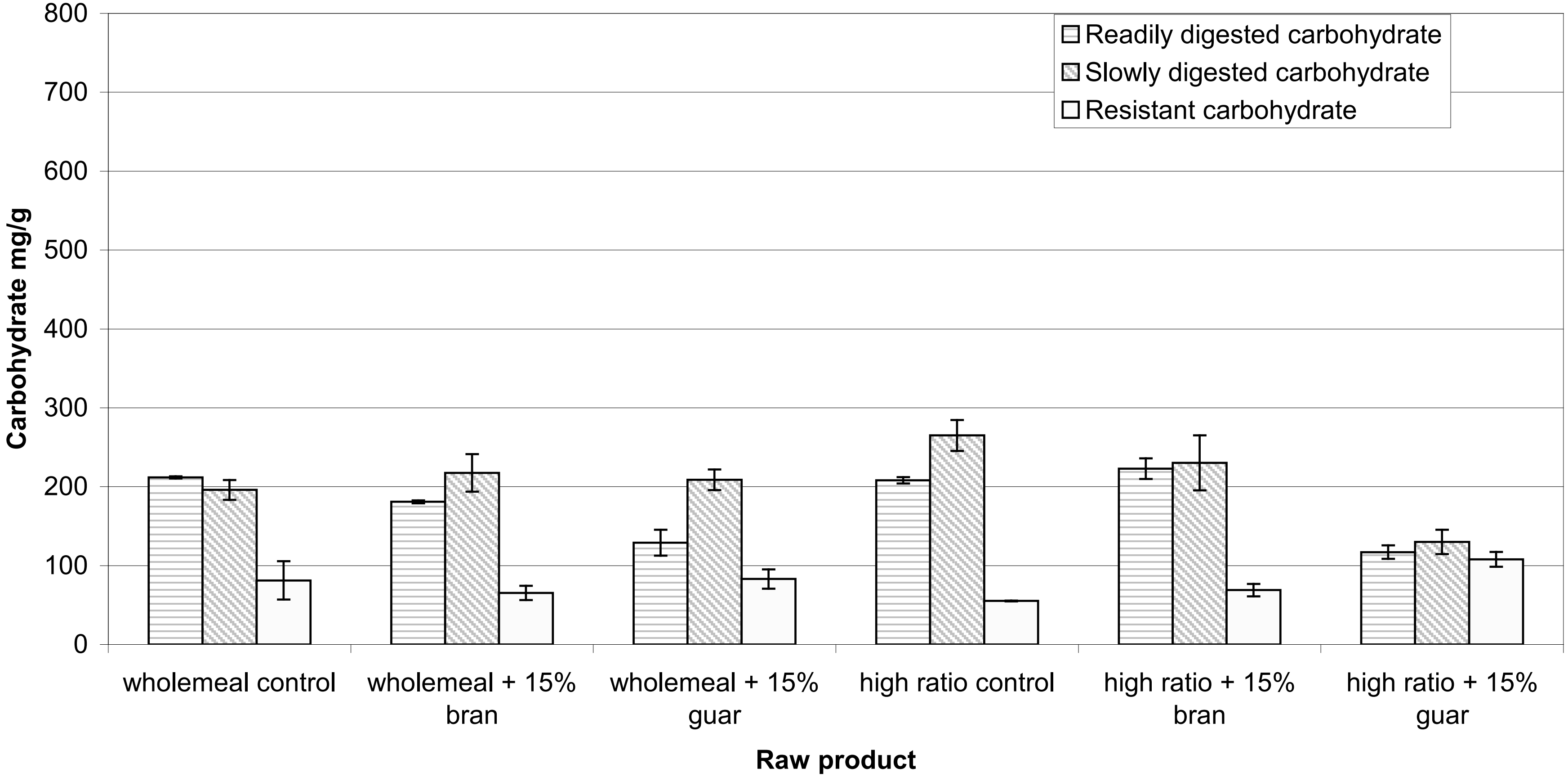
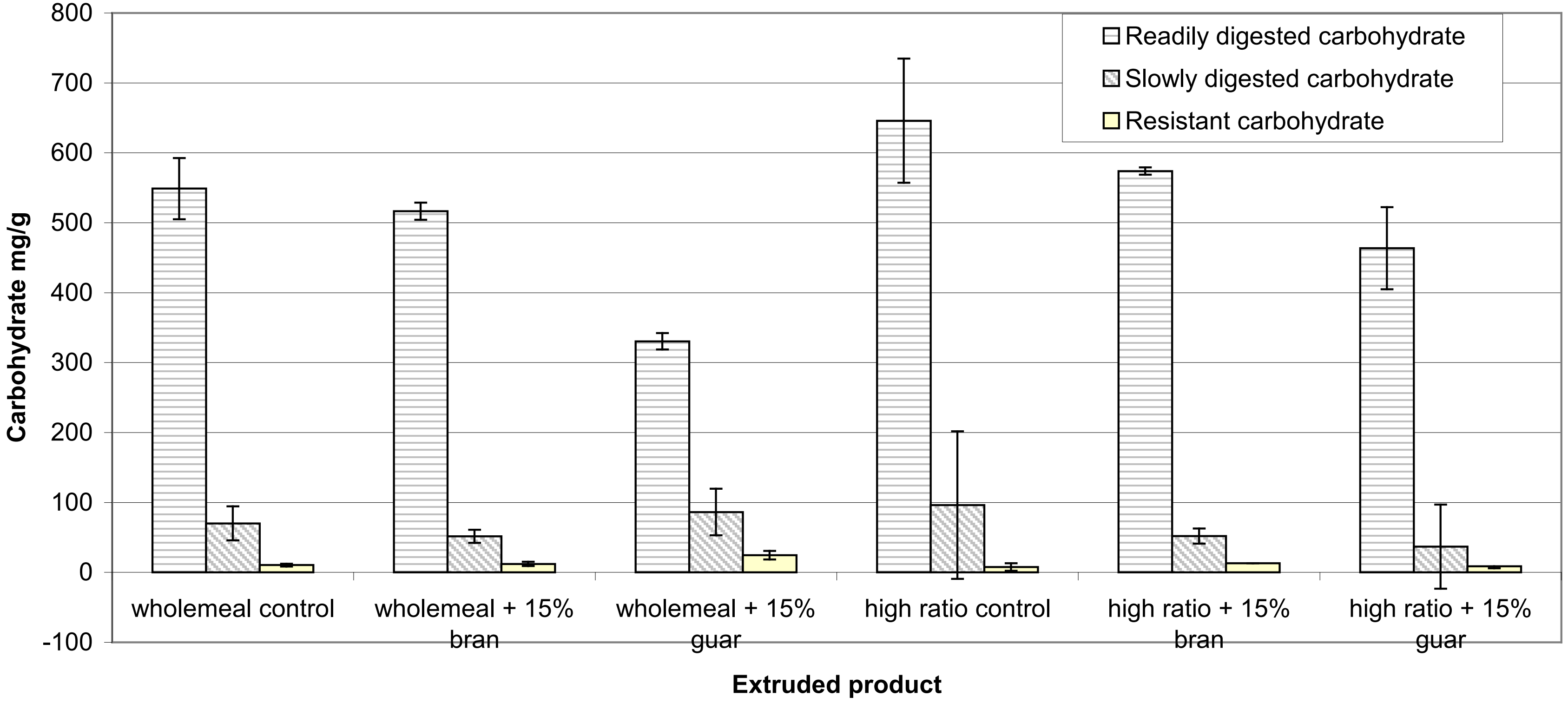


Figure 3.6: Carbohydrate digestibility of high ratio and wholemeal flour bases with guar and bran replacement before extrusion



## *3.4 Discussion*

In both the raw bases and the extruded products, samples derived from the wholemeal base exhibited lower moisture contents than the high ratio wheat flour bases. Wholemeal flours contain a higher amount of non starch polysaccharides compared to the relatively refined high ratio white wheat flours. As mentioned in the introduction, non starch polysaccharides have the ability to hold water in greater amounts than starch. Hence these results can be explained by product composition. The extrusion process did not affect the protein content of the extruded breakfast cereal samples. This is to be expected as the extrusion process involves changes to the physical state of food components, rather then chemical (enzymatic) processing.

The viscosity profiles of extruded and raw samples differed as did those of the wholemeal and high ratio control samples. The difference between the wholemeal and high ratio control samples can be attributed to higher starch levels in the high ratio samples, and hence greater gelatinisation effects leading to increased viscosity properties (Samman *et al.*, 2006). The inclusion of bran in the wholemeal and high-ratio bases lowered the peak and final viscosity profiles, this is likely to be due to the dilution effect that the NSPs in the wholemeal samples have on overall starch content and is supported by previous observations by Samman *et al.* (2006). However, the inclusion of guar gum increased the viscosity profiles of both raw and extruded samples compared to the control. Rojas *et al.* (1999) showed similar results when investigating the pasting properties of different flour systems.

The ease of starch digestibility was greatly enhanced by the extrusion process, and this supports the observation of Foster-Powell and Miller (2002) that extruded products generally yield higher glycaemic index foods. However, the results from this study demonstrate that the inclusion of bran and guar gum to flour bases can manipulate the ease of starch digestibility and reduce the amount of readily digestible starch in the extruded products. Both guar gum and bran have been used in non-extruded food products to reduce the glycaemic impact of foods (Ellis *et al*., 1991; Fairchild *et al.,*1996; Brennan *et al.,* 1996). The use of these DFs in controlling the digestibility of starch in extruded products creates an opportunity to reduce the high glycaemic impact of extruded food products by careful selection of raw materials.

### *3.5 Conclusion*

The extrusion process increased the amount of readily digestible carbohydrates of the samples. High ratio samples produced more readily digestible carbohydrate fractions compared to the wholemeal base samples. The inclusion of bran into either the wholemeal or high ratio bases did not affect the amount of readily digestible carbohydrates compared to the control. The inclusion of guar gum into either the wholemeal or high ratio bases reduced the amount of readily digestible carbohydrates compared to the control.

# Chapter 4 The effect of extruder configuration on the physico-chemical and nutritional characteristics of high ratio wheat flour samples with added bran and inulin fibre

## *4.1 Introduction*

As mentioned previously, extruders can be configured differently with the use of forward or reverse screw configurations. Changing the configuration of the extruder alters the energy input to the system by changing the mixing stages, feed rate and product resonance time. These parameters affect the overall pressure and temperature aspects of the extruder.

Following on from the experiments presented in Chapter 3, a base recipe incorporating high ratio flour was selected for the remaining experiments. In the next set of experiments the effects of varying extruder conditions on the physico-chemical and nutritional quality of fibre enriched high ratio wheat flour bases were analysed. Two fibres were selected based on their solubility. Bran (as an example of an insoluble fibre) and inulin (as an example of a highly soluble fibre ingredient).

Two screw configurations of the extruder were used. The first configuration was a straight screw configuration, where the extruder was used to form the product with forward pitched flights used. The other configuration used was a reverse screw configuration, where a reverse pitched flight was placed in the screw configuration in order to increase mix and shear during extrusion (Table 2.4).

## *4.2 Materials and Methods*

The high ratio white flour, bran and inulin materials used in this series of experiments are detailed in Section 2.1. The recipe used for the manufacture of extruded products is detailed in Table 2.2. Table 2.4 shows the extruder processing parameters used, and Table 2.6 reports the pressure and temperature conditions of the extruder during product manufacture. The methods used to determine the physical, chemical and starch digestibility properties of the extruded products are those as detailed in Chapter 2.

## *4.3 Results*

The moisture contents of control, bran (5, 10 and 15% addition), and inulin (5, 10 and 15% addition) of raw and extruded samples are shown in Figure 4.1. No differences were observed between the reverse and straight screw configurations. The extrusion process resulted in a reduction of moisture. Although not consistent, a tendancy was observed for the reverse screw configuration reducing the moisture content of the product more than a straight screw configuration (Figure 4.2). Although there was no difference between the straight and reverse screw samples, there was a pattern that bran addition to the recipe base reduced expansion ratio (Figure 4.3).

The product and bulk density values (Figures 4.4 and 4.5 respectively) illustrate that the addition of fibre to both straight and reverse screw configurations increased product density values. The use of reverse screw configuration reduced density values compared to the straight screw configuration.

**Figure 4.1: Moisture content of raw and extruded samples from the reverse screw and straight screw configuration**

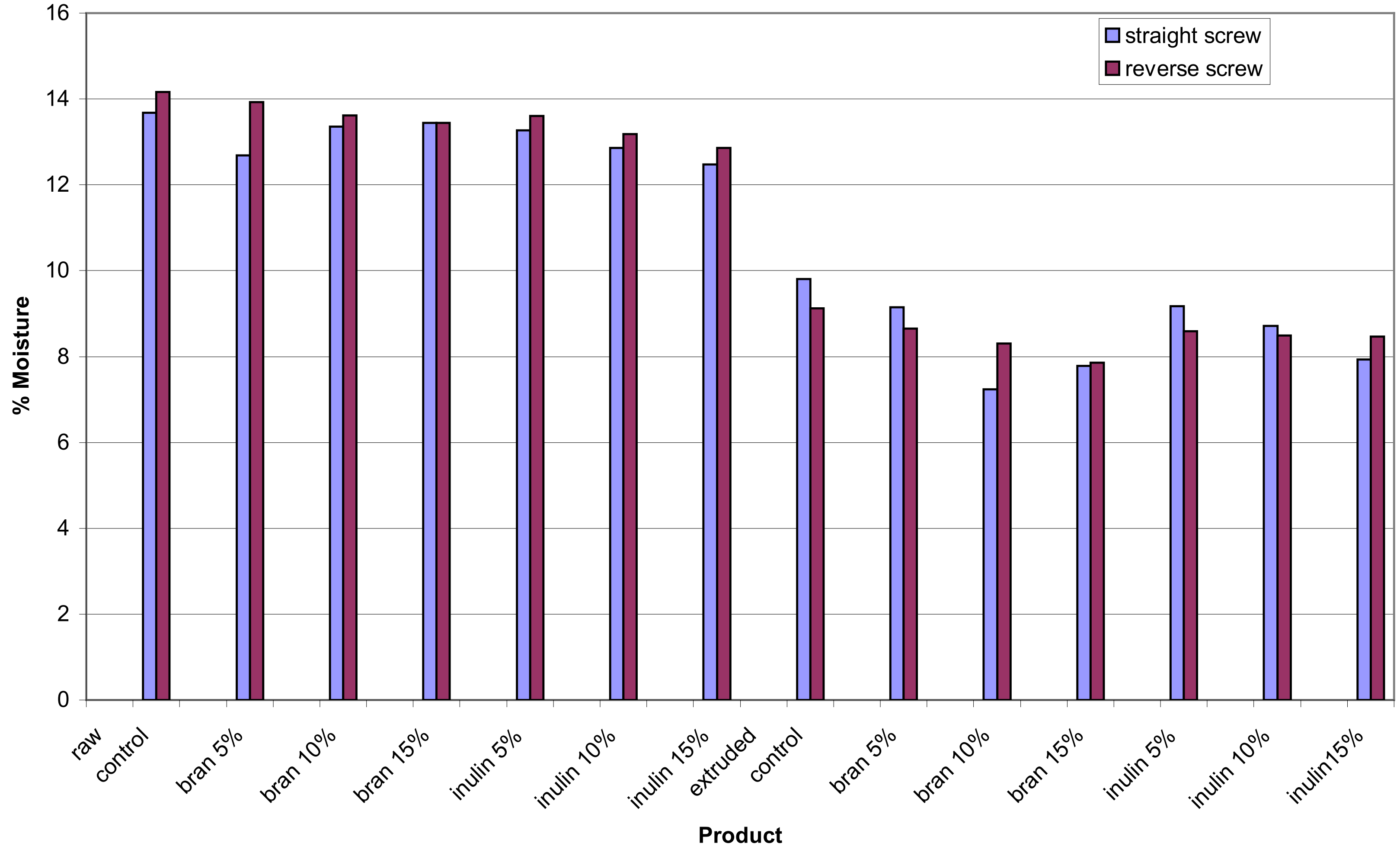


Figure 4.2: Moisture loss from the reverse screw and straight screw configurations of fibre enriched breakfast cereals

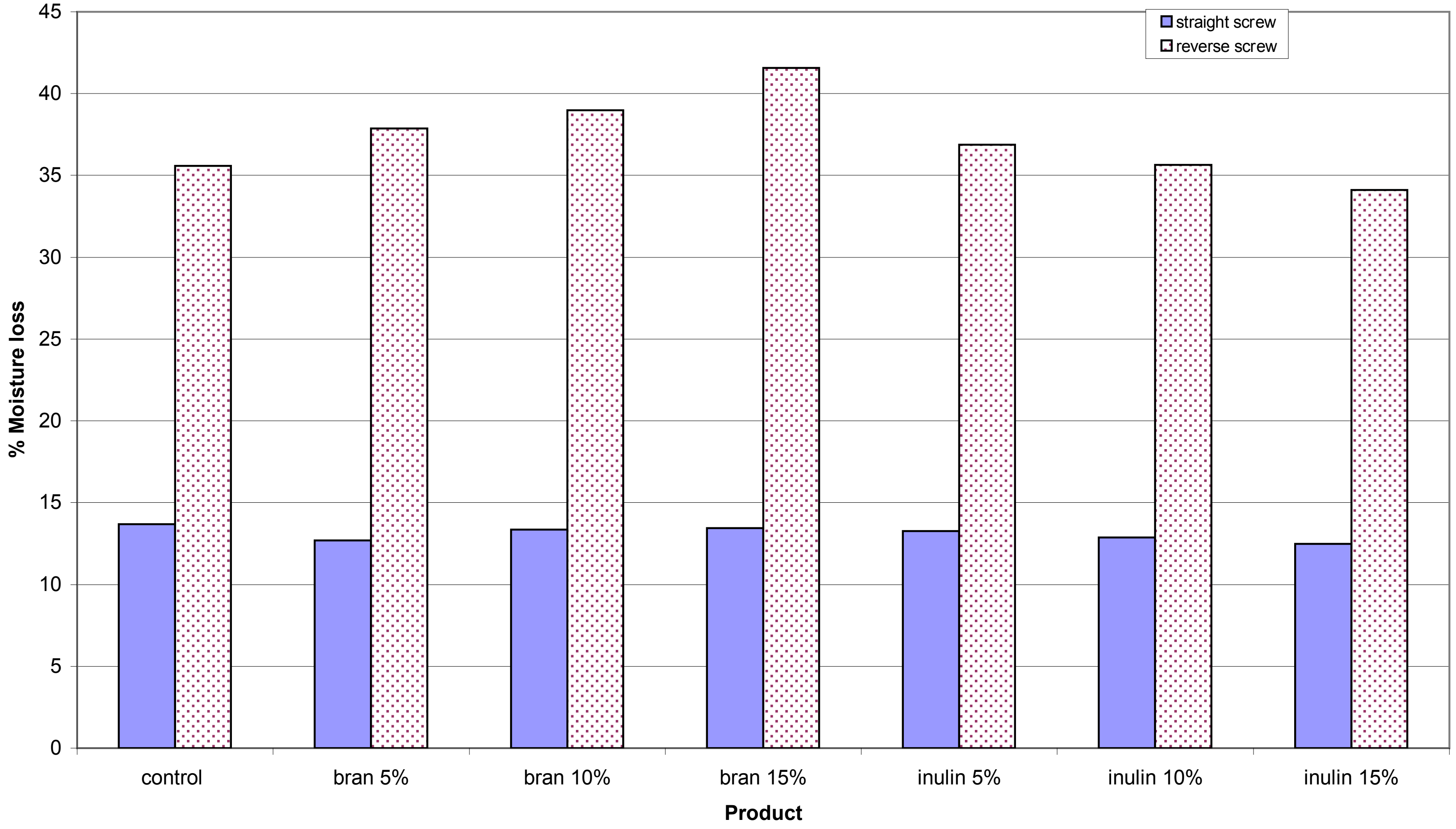


Figure 4.3: The effect of reverse and straight screw configurations on the expansion ratio of fibre enriched breakfast cereal products

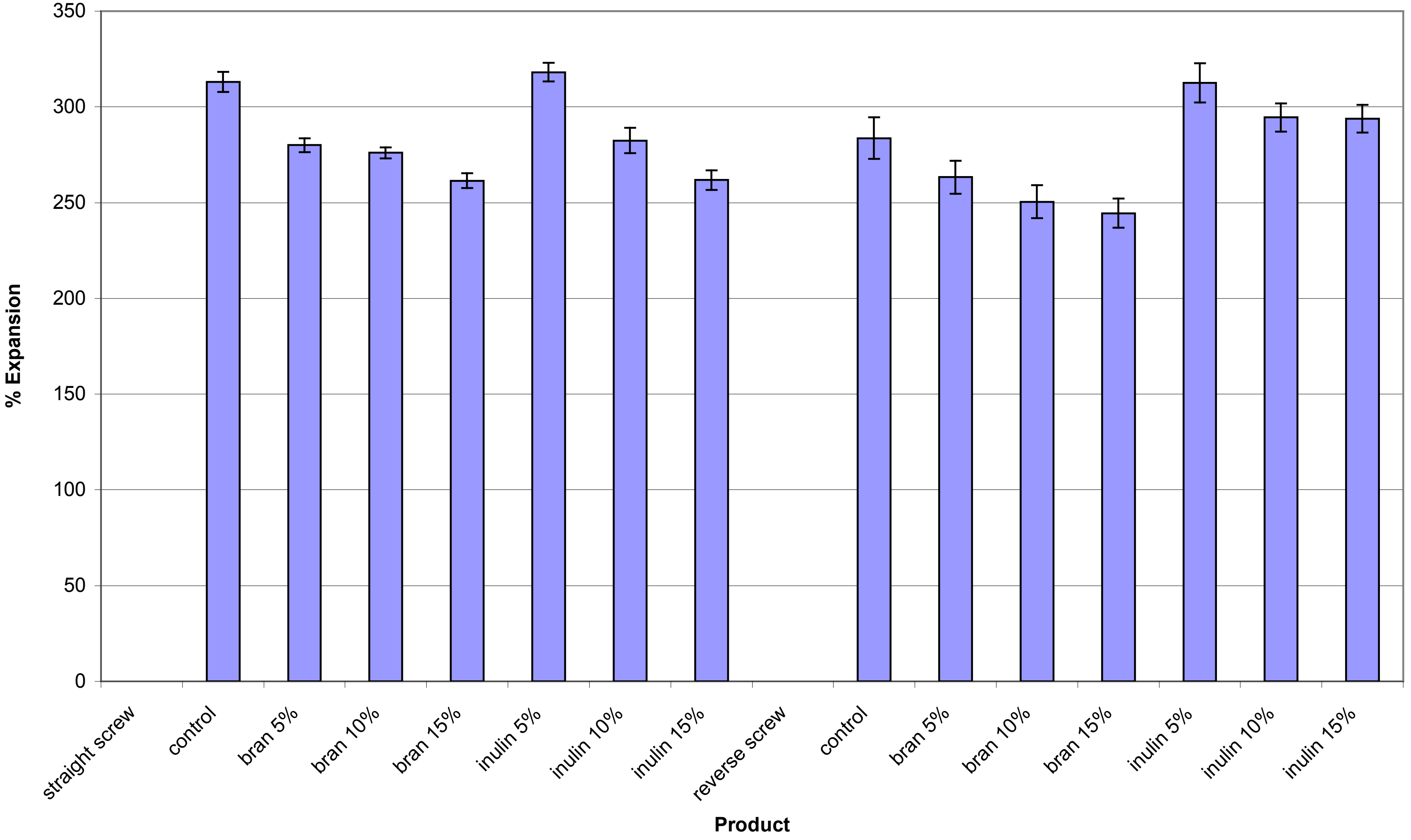


**Figure 4.4: The effect of reverse and straight screw configurations on the product density of fibre enriched breakfast cereal products**

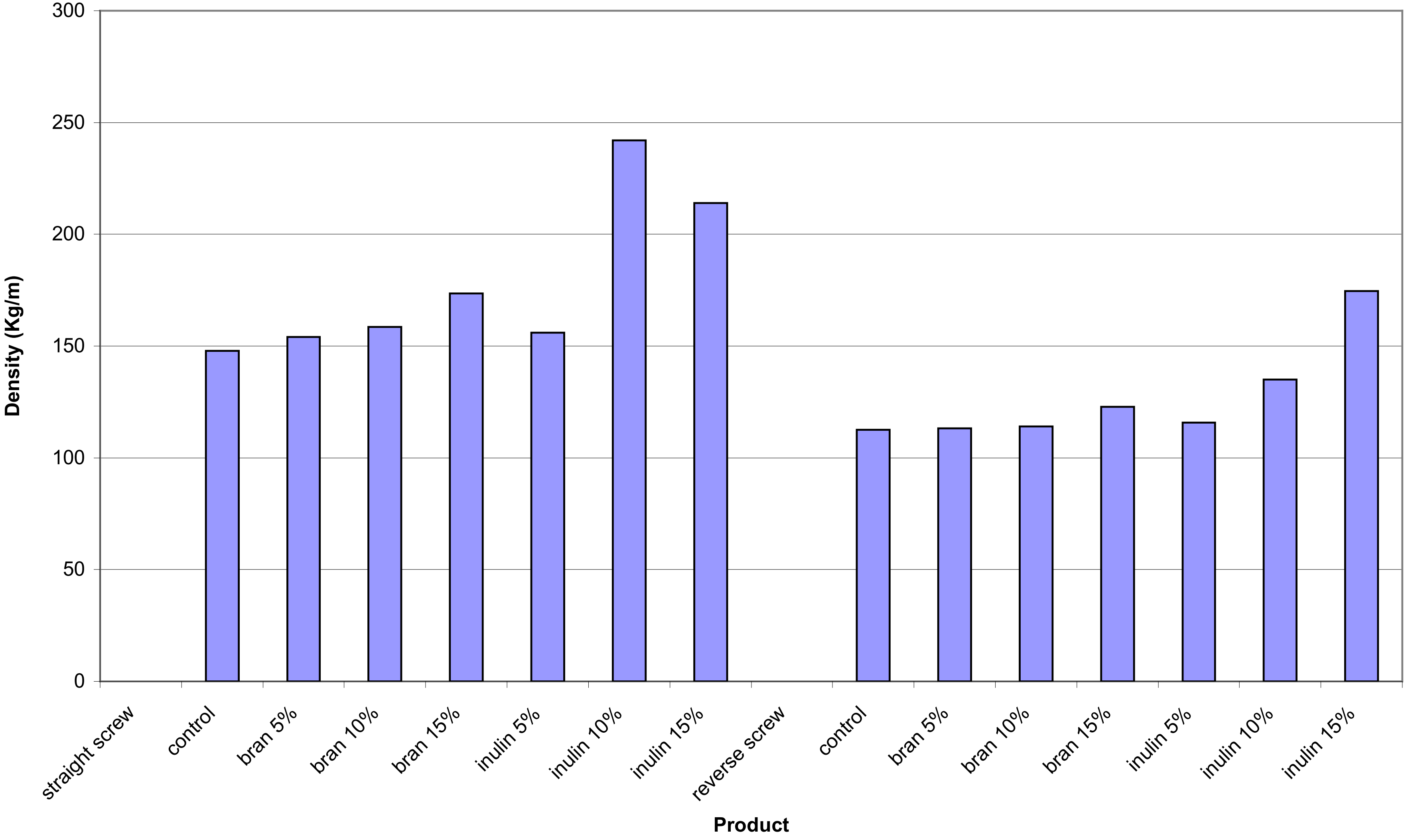


**Figure 4.5: The effect of reverse and straight screw configurations on the bulk density values of fibre enriched breakfast cereal products**

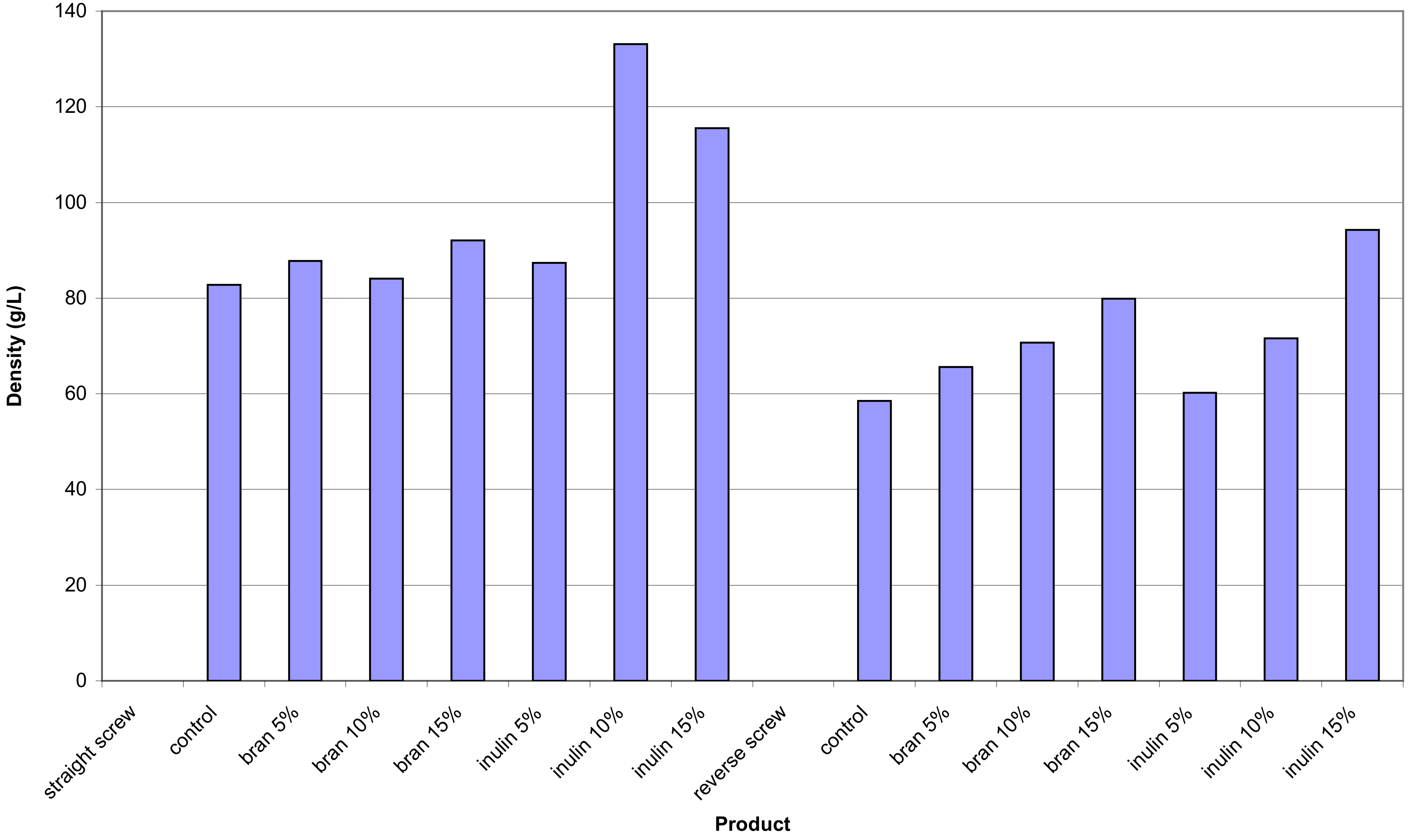


**Table 4.1: The pasting properties of raw and extruded fibre enriched samples from reverse and straight screw configurations**

| | Cold peak | Peak viscosity | Final viscosity | Cold peak area |
|---|---|---|---|---|
| Raw | (cp) | (cp) | (cp) | (cp) |
| Control | 6.50$^{h}$ ±0.71 | 572.00$^{a}$ ±26.87 | 905.50$^{a}$ ±41.72 | 24.32$^{i}$ ±2.17 |
| Bran 5% | 5.00$^{I}$ ±0.00 | 557.00$^{a}$ ±16.97 | 892.00$^{b}$ ±28.28 | 21.03$^{I}$ ±0.44 |
| Bran 10% | 6.50$^{h}$ ±3.54 | 464.00$^{b}$ ±5.66 | 743.00$^{c}$ ±12.72 | 25.59$^{i}$ ±7.17 |
| Bran 15% | 7.00$^{h}$ ±1.41 | 353.00$^{c}$ ±1.41 | 564.00$^{d}$ ±24.04 | 22.59$^{i}$ ±1.85 |
| Inulin 5% | 3.50$^{j}$ ±0.71 | 468.00$^{b}$ ±8.49 | 728.50$^{c}$ ±4.95 | 18.62$^{i,j}$ ±1.51 |
| Inulin 10% | 2.50$^{j}$ ±2.12 | 349.00$^{c}$ ±24.04 | 543.00$^{d}$ ±39.60 | 16.28$^{j}$ ±2.00 |
| Inulin 15% | 2.00$^{j}$ ±0.00 | 278.00$^{d}$ ±31.11 | 420.00$^{e}$ ±16.97 | 15.45$^{j}$ ±0.63 |
| Straight screw extruded | | | | |
| Control 1 | 143.00$^{a}$±9.90 | 120.50$^{g}$ ±23.33 | 93.50$^{g,h}$ ±12.02 | 212.28$^{c}$ ±33.70 |
| Bran 5% | 132.00$^{b}$ ±1.41 | 130.50$^{f}$ ±0.71 | 98.00$^{g}$ ±1.41 | 247.64$^{b}$ ±1.44 |
| Bran 10% | 116.00$^{c}$ ±2.83 | 114.50$^{g}$ ±2.12 | 93.50$^{h}$ ±3.54 | 238.43$^{c}$±10.61 |
| Bran 15% | 122.00$^{c}$ ±7.07 | 117.00$^{g}$ ±5.66 | 91.50$^{h}$ ±2.12 | 249.66$^{a,b}$ ±6.44 |
| Inulin 5% | 141.50$^{a}$ ±2.12 | 142.00$^{e,g}$ ±2.83 | 110.00$^{f}$ ±4.24 | 255.10$^{a}$ ±4.15 |
| Inulin 10% | 99.00$^{d}$ ±7.07 | 113.50$^{g}$ ±3.54 | 113.00$^{f}$ ±1.41 | 182.53$^{d}$ ±7.29 |
| Inulin 15% | 75.00$^{e}$ ±1.41 | 81.00$^{h}$ ±1.41 | 84.50$^{I}$ ±0.70 | 141.72$^{e}$ ±10.19 |
| Extruded reverse screw | | | | |
| Control | 101.50$^{d}$ ±2.55 | 89.50$^{j}$ ±8.60 | 47.17$^{l}$ ±0.24 | 174.50$^{d,e}$±20.77 |
| Bran 5% | 53.00$^{g}$ ±0.71 | 49.50$^{m}$ ±1.06 | 43.00$^{m}$ ±0.00 | 123.62$^{h}$ ±1.61 |
| Bran 10% | 55.00$^{g}$ ±0.71 | 51.00$^{m}$ ±0.71 | 44.00$^{m}$ ±0.00 | 128.50$^{h}$ ±1.38 |
| Bran 15% | 68.00$^{f}$ ±2.12 | 63.50$^{l}$ ±1.77 | 49.00$^{k}$ ±1.41 | 155.15$^{f}$ ±2.40 |
| Inulin 5% | 76.00$^{e}$ ±0.71 | 63.00$^{l}$ ±2.83 | 43.50$^{m}$ ±1.06 | 135.47$^{g}$ ±0.91 |
| Inulin 10% | 97.00$^{d}$ ±3.54 | 70.00$^{k}$ ±4.24 | 48.50$^{k,l}$ ±0.35 | 143.45$^{g}$ ±5.61 |
| Inulin 15% | 100.00$^{d}$ ±0.00 | 98.50$^{I}$ ±3.18 | 53.00$^{j}$ ±0.71 | 151.50$^{f}$ ±0.87 |

Within columns each attribute means different letter are significant different ($P \leq 0.05$).

Figure 4.6 shows the effect of the reverse and straight screw configuration on product hardness. The control samples of extruded breakfast cereals produced by both the reverse and straight screw configurations were similar in hardness values. However, the reverse screw configuration reduced the hardness of the breakfast cereals containing bran (and more emphatically inulin) compared to the straight screw samples. This may be associated with the product densities and moisture losses of the samples. Figure 4.7 shows that the number of peaks observed by compressing the breakfast cereal products were similar between the two batches. Within the reverse screw configuration, addition of fibre increased the number of peaks observed in the samples (especially with the addition of inulin). The increase in peaks recorded during compression relates to the brittleness of the product, each peak corresponding to an individual fracture event. Thus an increase in the number of peaks observed indicates an increase in product crispiness.

Figure 4.8 shows the effect of reverse and straight screw configuration on carbohydrate digestibility. The control extruded products were not different at 20 and 60 minutes. However, the amount of available carbohydrate at 120 minutes was greater for the straight screw rather than reverse screw configuration. The use of both bran and inulin at all levels significantly reduced the amount of available carbohydrate compared to the control samples. The values of readily available carbohydrate at 20 minutes was significantly higher in the reverse screw configuration than the straight screw configuration. The straight screw samples with the addition of bran produced variable results without a clear effect could be found between digestion time and inclusion rates. In the reverse screw samples the readily available carbohydrates reduced in relation to concentration of bran inclusion but increased with raising inulin levels.

Figure 4.6: The effect of reverse and straight screw configurations on the hardness of fibre enriched breakfast cereal products

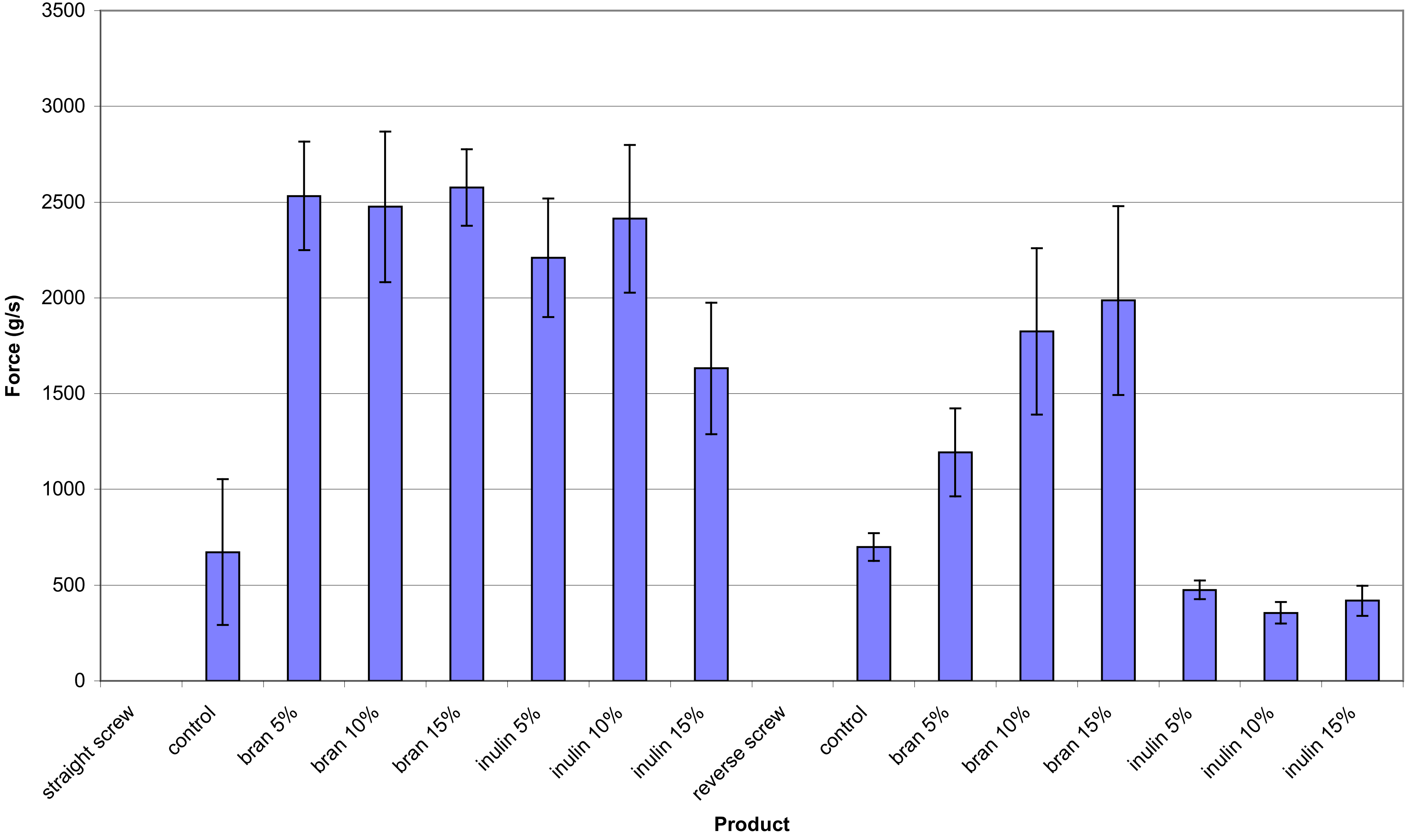


**Figure 4.7: The effect of reverse and straight screw configurations on the crispiness of fibre enriched breakfast cereal products**

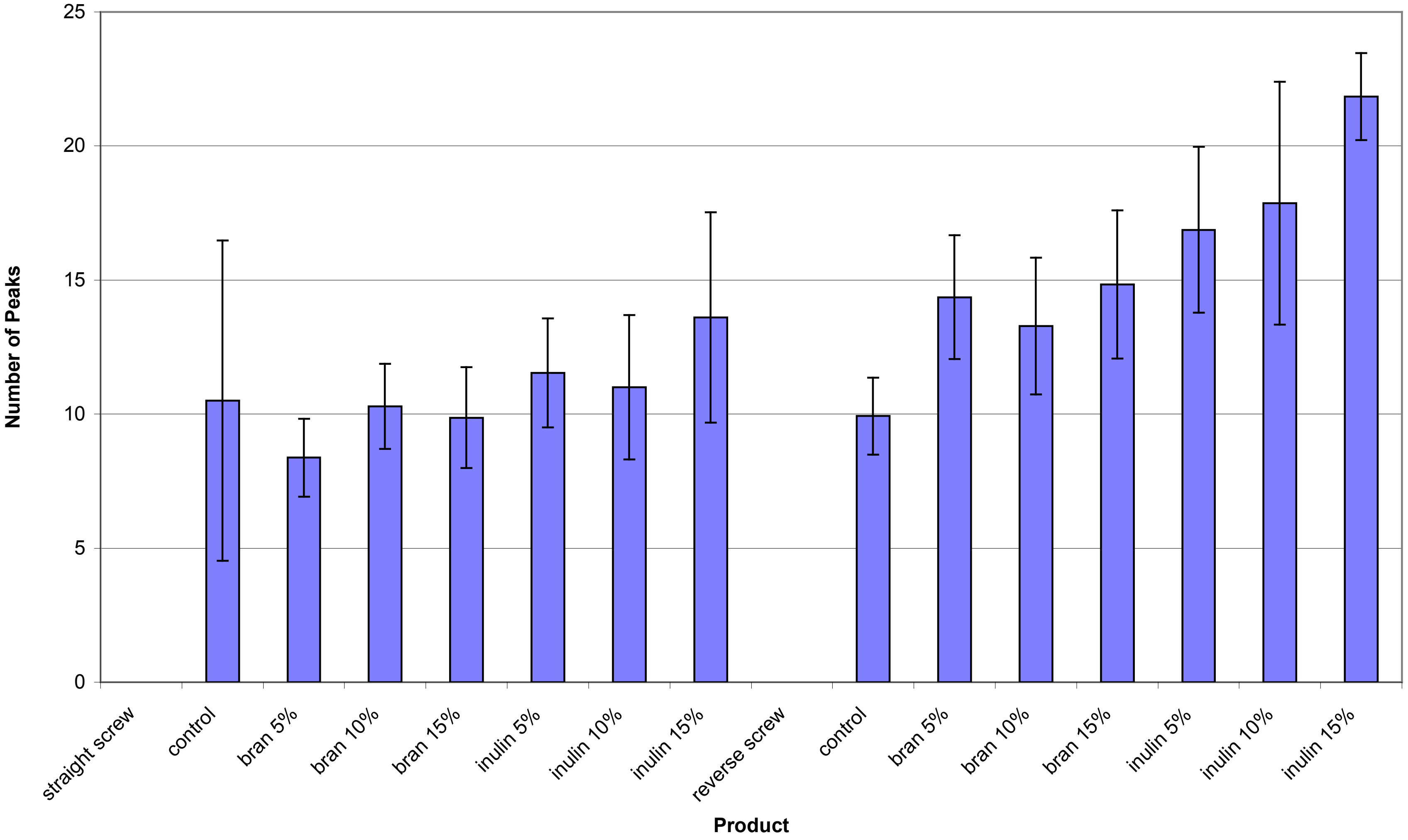
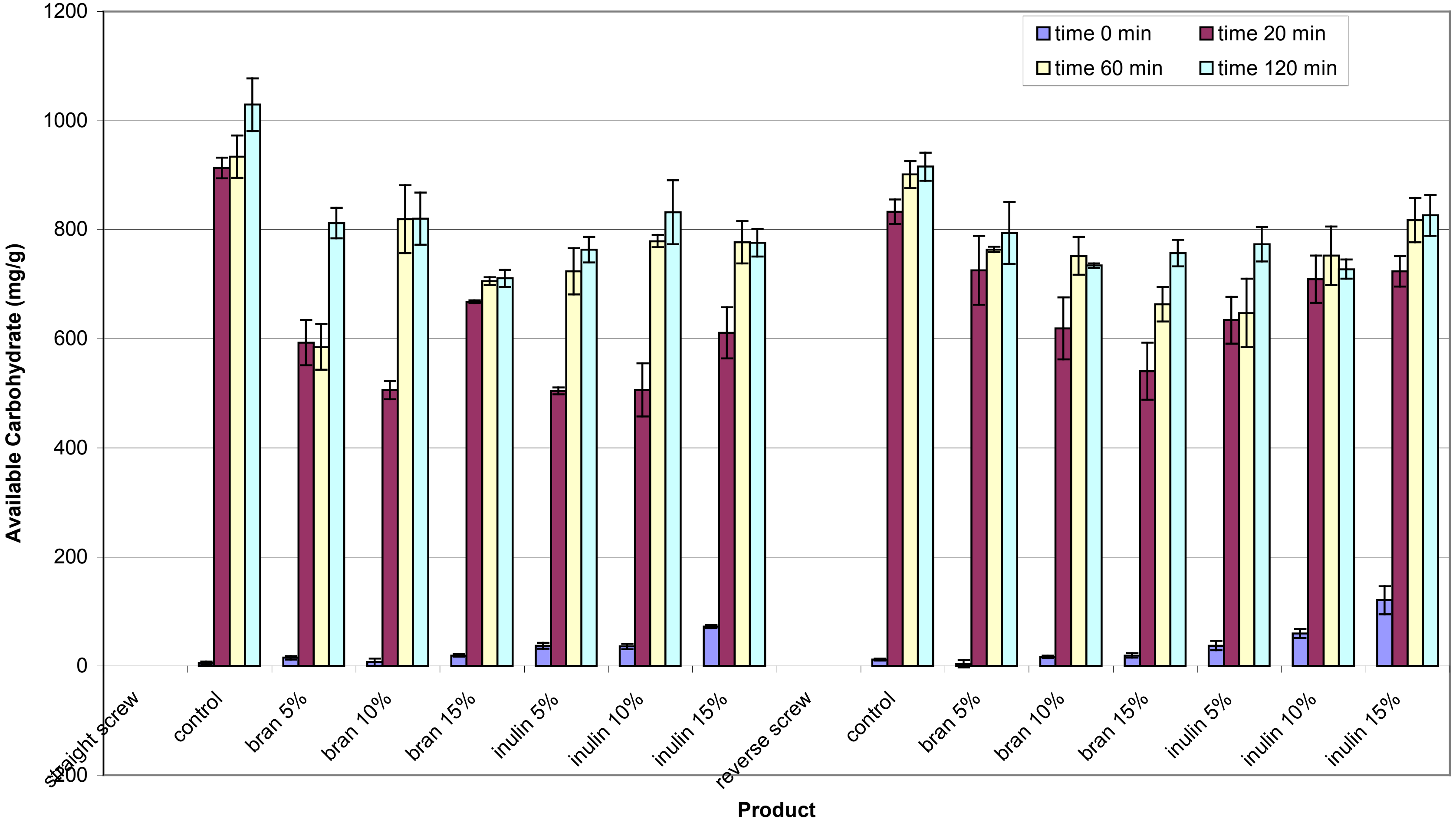


**Figure 4.8: Carbohydrate digestibility of extruded bran and inulin enriched breakfast cereal products from straight and reverse screw configurations**



## *4.4 Discussion*

Previous research has shown that greater pressure and shear in an extrusion system can increase the amount of amylose leaching and the fragmentation of amylose and amylopectin components into short chain products (Case *et al.,* 1992; Politz *et al.,* 1994 a,b). This in turn has been shown to lead to increased starch retrogradation (Case *et al.,* 1992). The results from this chapter illustrate that moisture loss during the extrusion process was greater in samples with a reverse screw configuration compared to straight screw configuration. This is to be expected due to the greater shear in such a system potentially increasing the incompatible regions of water and retrograded starch, hence making the water easier to drive off during the extrusion process (Guy, 2001).

Such an incompatibility of systems has been shown to exist by the research of Tolstoguzov (2003a, 2003b). Despite the effect on moisture loss, no clear effect could be observed between reverse screw or straight screw configuration and expansion ratio. The pasting properties of extruded cereal products, such as peak and final viscosity values, were reduced by the use of reverse screw configuration compared to the straight screw configuration. This supports the concept that the extrusion process reduces the chain length of starch, and hence the viscosity altering potential of complex hydrocolloids (Alverez-Martinez *et al*, 1998).

The bulk and product density increased with the addition of fibre when compared to the control base samples. This is most likely to be due to the water holding capacity of the fibres interfering with the structure formation process during extrusion. Although hardness of the control samples were similar between the reverse and straight screw configurations, the reverse screw configurations reduced the hardness of the fibre enriched samples. Thus inclusion of bran increased the hardness of extruded cereal products, while the addition of inulin reduced the hardness of the extruded cereal products.

The amount of readily digestible carbohydrate fractions increased with the use of reverse screw configuration compared to the straight screw configuration. This may be related to the fragmentation (dextrinisation) of starch granules (Case *et al.,* 1992). However, how this relates to the previous research indicating that extrusion can create higher levels of resistant starch needs to be investigated. The amount of digestible carbohydrate fractions (at all time points) decreased with the addition of fibre components (compared to the control samples). Similar observations have been seen with fibre inclusions into cold extruded products such as pasta (Tudorica *et al.,* 2002). Fibre components have also been used in a number of other food systems to alter the profile of carbohydrate digestibility (Ellis *et al.,* 1995; Brennan *et al.,* 1996; Bourdon *et al.,*, 1999).

## 4.6 Conclusion

It is clear from the current results that fibres can be utilised in the extrusion process to manipulate the nutritional content of extruded products. Both inulin and wheat bran can be used in the manufacture of extruded snack products. The resultant extruded products have the potential to be similar to non-fibre enriched products in terms of the physical and chemical quality of the extrudates. Additionally, inulin and wheat bran can be used to manipulate the potential glycaemic impact of extruded snack foods.

# Chapter 5 Effect of inclusion of soluble and insoluble fibres into extruded breakfast cereal products made with reverse screw configuration

## *5.1 Introduction*

Chapter 4 determined the optimal conditions for the extrusion processes (Table 2.4), whilst in Chapter 3 the selection of a flour base using the optimised extrusion conditions. Previous research has also shown that other dietary fibre components may be used to manipulate the glycaemic impact of extruded snack products (Bourdon *et al.,* 1999; Gaosong and Vasanthan, 2000). However, no systematic evaluation has been conducted on the potential utilisation of a range of commonly used dietary fibres in the extrusion process.

In this Chapter a range of soluble and insoluble fibres were used in a high ratio base, in order to determine whether the solubility of fibres affected the utilisations of the fibres in extruded snack products.

## *5.2 Materials and Methods*

Differing fibres, wheat bran, inulin, guar gum, hi-maize and swede fibre (as detailed in section 2.1), were used at a range of replacement levels to the high ratio base flour mixes (5, 10 and 15% on a w/w flour basis). Extruded breakfast cereals were produced as described in Chapter 2 (Table 2.2) the resulting products were evaluated in terms of moisture content, product density, expansion ratio, texture and *in vitro* digestibility (as detailed in Chapter 2).

## *5.3 Results*

The moisture content of the raw and extruded samples is shown in Figure 5.1. The use of bran at 10 and 15 % reduced the moisture content of the raw (pre-extrusion) samples compared to the control sample. This trend was observed for the extruded samples as well. The use of inulin at all levels showed a reduction of moisture content in the raw samples compared to the control, a pattern also observed in the extruded samples. Both guar gum and swede fibre inclusion into the base recipe yielded similar results, however there was no difference in moisture contents of the hi-maize enriched breakfast cereals compared to the control sample.

Figure 5.2 shows the amount of moisture lost during the extrusion process for all of the fibre samples. Bran, guar gum and swede enriched samples showed elevated moisture loss compared to the control samples, whereas the moisture loss of the inulin samples decreased with increasing inulin levels. No consistent pattern was observed for the hi-maize samples with the 10% inclusion level exhibiting higher moisture loss than both the 5 and 15 % inclusion rates.

Figure 5.1 Moisture content of raw and extruded fibre enriched breakfast cereals

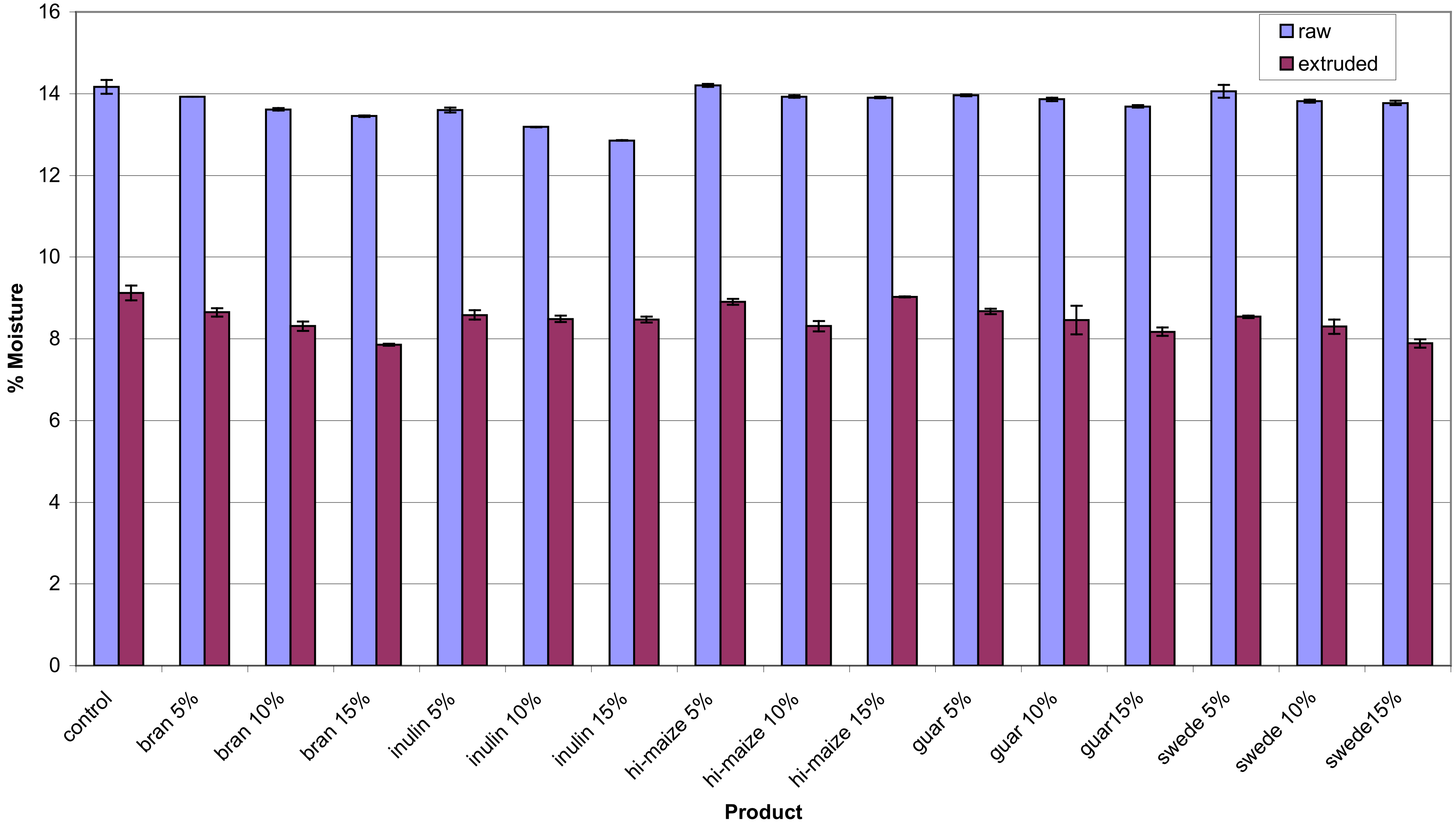


Figure 5.2 Moisture loss (%) of extruded fibre enriched breakfast cereals

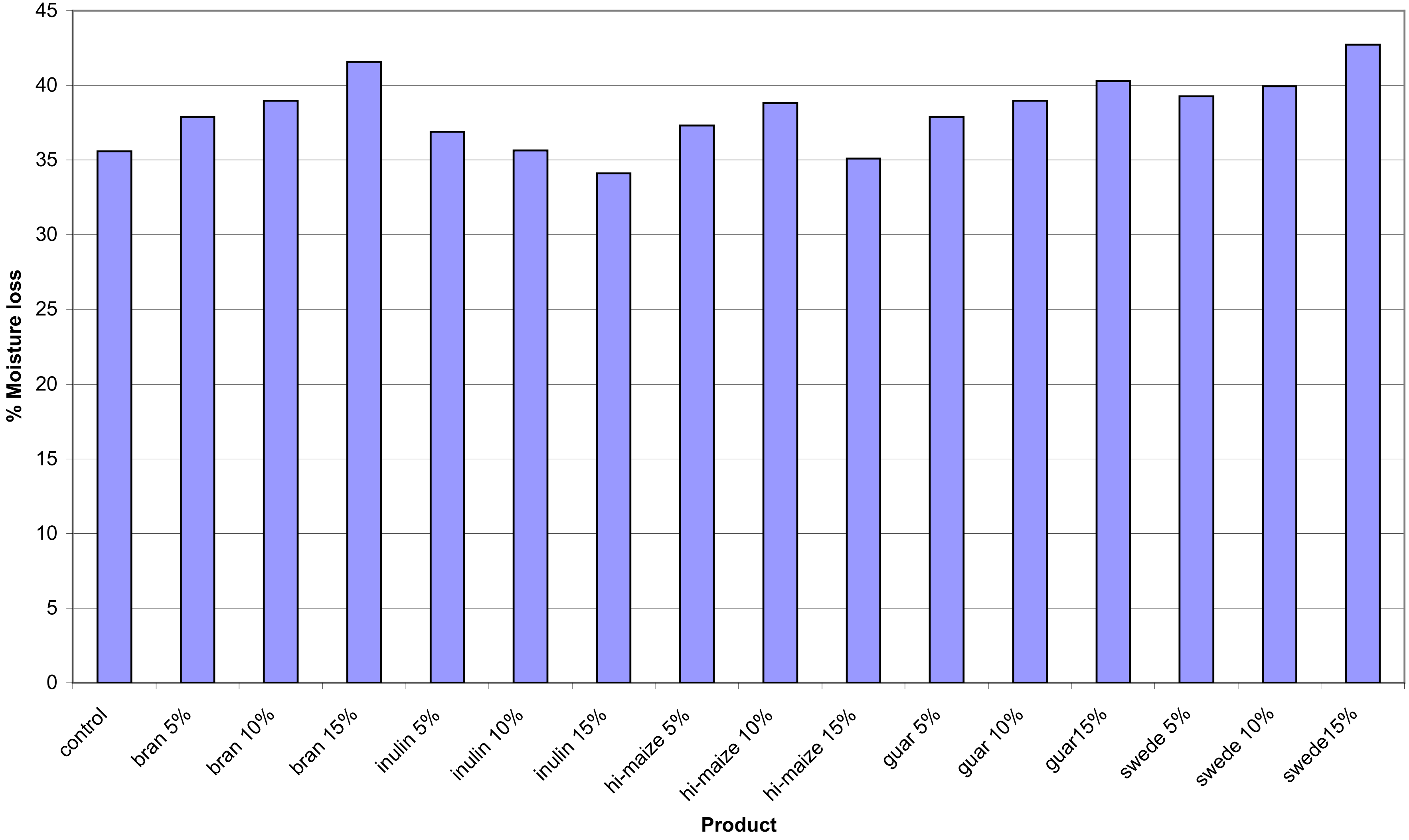


Figure 5.3 shows the expansion ratio of the extruded fibre enriched breakfast cereals. In the case of bran and swede inclusions, the expansion ratios decreased with increasing fibre additions. However, this pattern was not apparent for the other fibre products. The inclusion of bran to the base recipe reduced the degree of product expansion compared to the control sample. The use of inulin and hi-maize resulted in greater expansion ratio compared to the control. A similar pattern was found for guar inclusion, with the exception of 15 % where the values were similar to the control sample.

The extruded products with swede fibre at 5 % and 10 % levels were not different to the control sample but the expansion ratio decreased at 15 % swede fibre use. No differences were observed between samples enriched with inulin, 5 to 15 %, hi-maize , 5 to 15 %, and guar gum, 5 and 10 %.

The product and bulk density values for the extruded fibre enriched samples are shown in Figures 5.4 and 5.5 respectively. Generally product density increased with increasing fibre concentration (Figure 5.4). This trend was also observed for bulk density (Figure 5.5). The inclusion of bran and inulin increased product density compared to the control sample whereas use of hi-maize, guar and swede fibre reduced product density.

Figure 5.3 Expansion ratio of extruded fibre enriched breakfast cereals

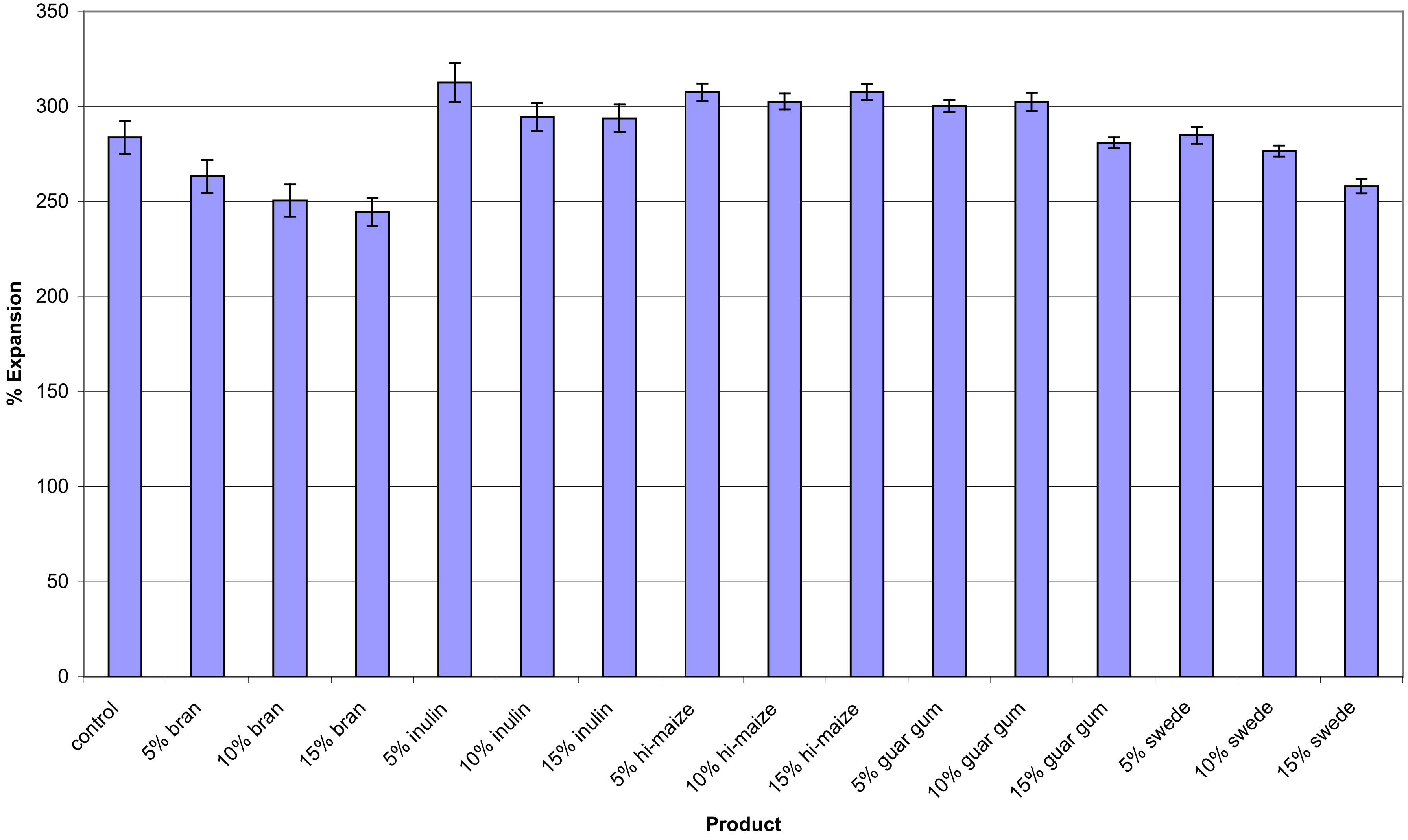


**Figure 5.4 Product density of extruded fibre enriched breakfast cereals**

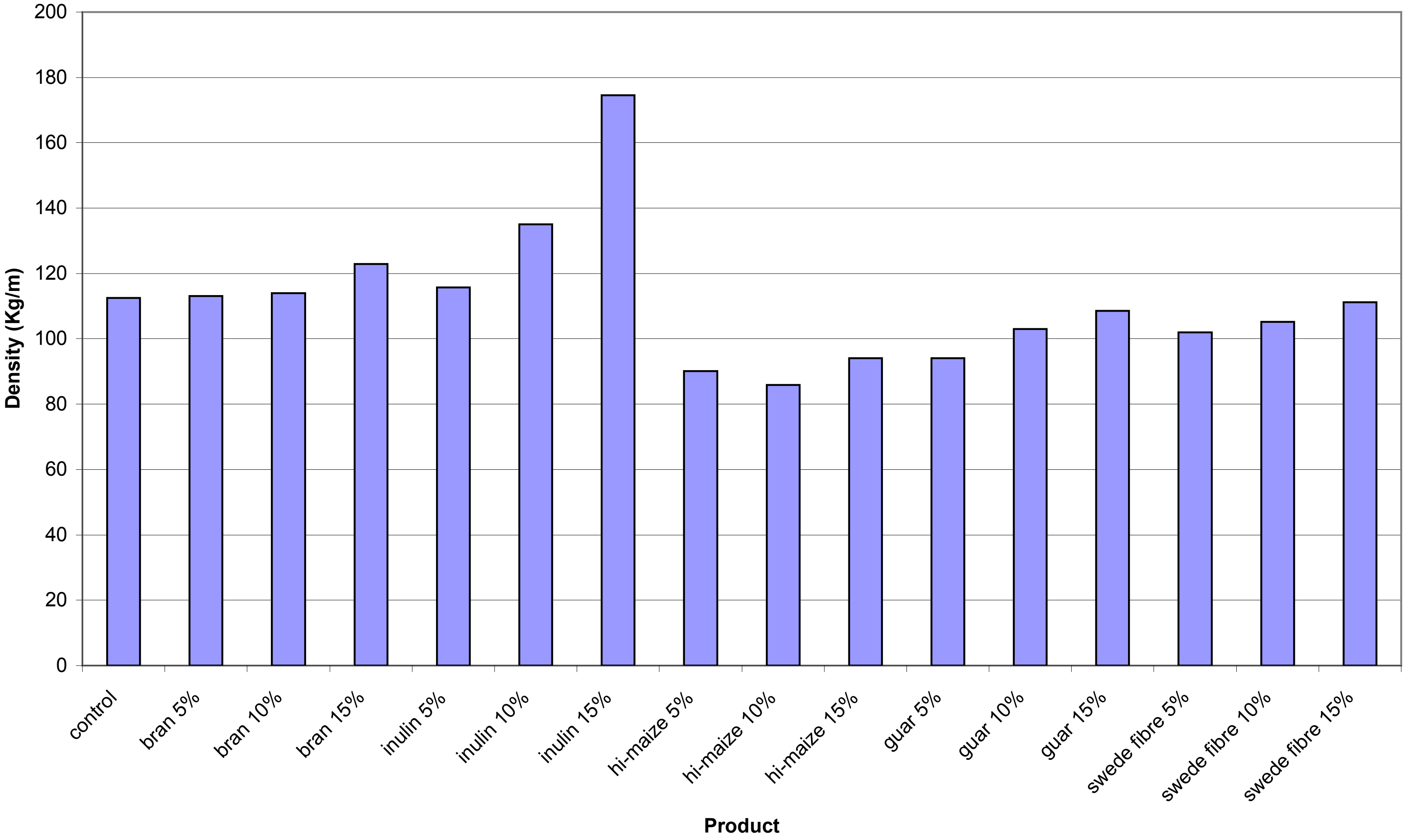
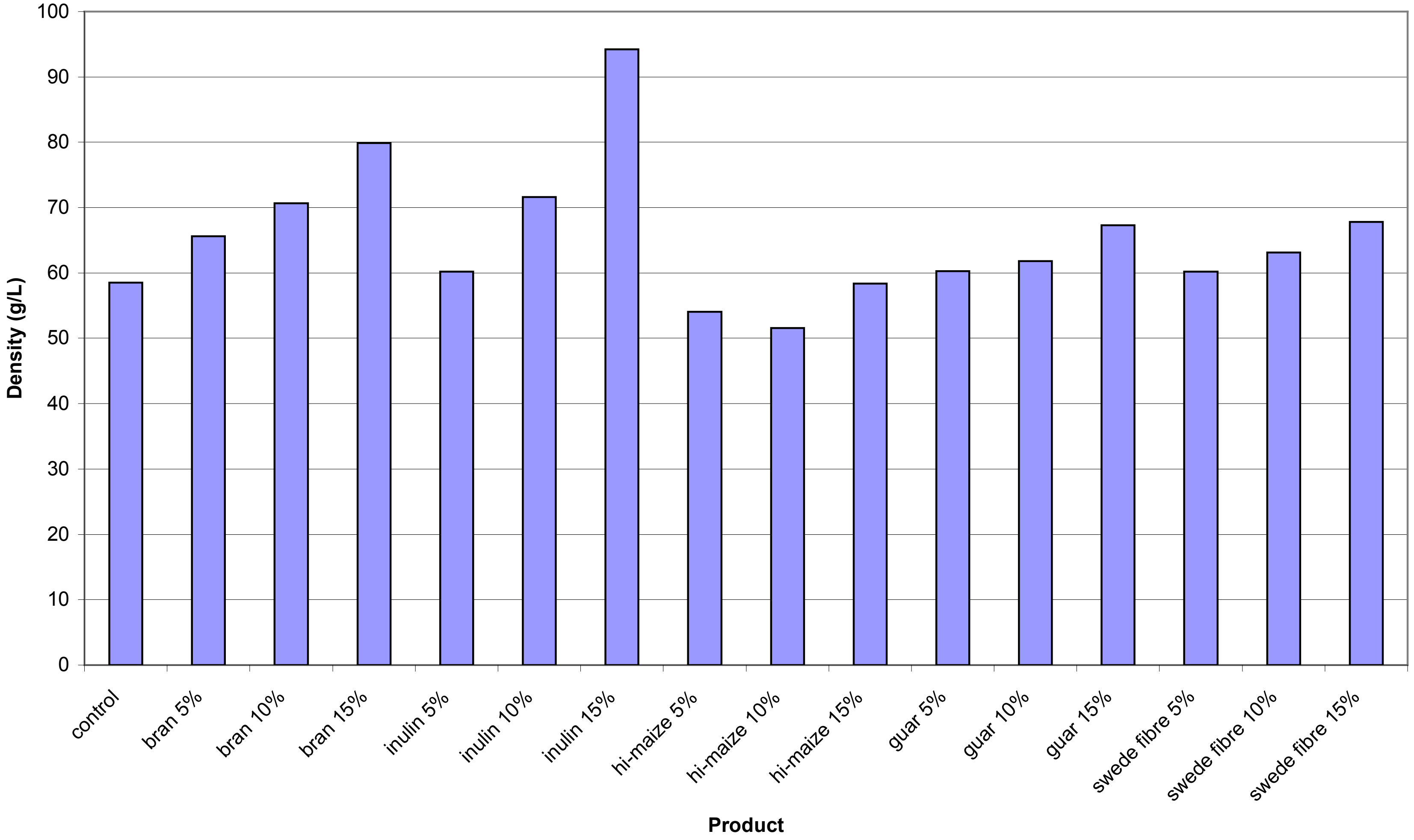


**Figure 5.5 Bulk density of extruded fibre enriched breakfast cereals**



The effect of the different fibres on the pasting properties of the raw and extruded breakfast cereal samples are showed in Table 5.1 and Figure 5.6. The cold peak values for the raw samples of bran enriched breakfast cereal bases increased with increasing bran levels in such a way that at 5 % the bran sample had a lower initial cold peak value whereas the 10 and 15 % enriched samples were similar to the control sample. Inulin enrichment showed a contrasting effect of decreasing cold peak point compared to the control sample compared to the amount of inulin used. The hi-maize enriched samples were higher than the control samples, however, the values decreased with increasing fibre concentration. Inclusion of guar gum raised the cold peak viscosity dramatically (and in proportion to the amount of guar gum used). The cold peak values for swede enriched samples were higher than those of the control samples however, there was no difference with increasing addition rates.  The peak viscosity of the raw samples was affected with the inclusion of fibre components. The bran 5 % sample yielded similar peak viscosity values compared to the control sample. The addition of inulin reduced the peak viscosity of the samples, decreasing in relation to inulin concentration (as did hi-maize enrichment). Use of guar gum increased peak viscosity values compared to the control sample (and increased in relation to increasing guar concentration). The inclusion of swede fibre into the base recipe had no effect on the peak viscosity value of the raw samples.

The final viscosity values of raw bran enriched samples were similar to the control sample at 5 % utilisation but lower at 10 and 15 % rates. Inulin inclusion resulted in a decrease in final viscosity of the raw paste (and decreased in relation to inulin concentration). Hi-maize utilisation showed similar patterns to the inulin samples. Guar inclusion resulted in elevated final viscosity values compared to the control.

## Table 5.1 Pasting properties for raw and extruded fibre enriched breakfast cereals

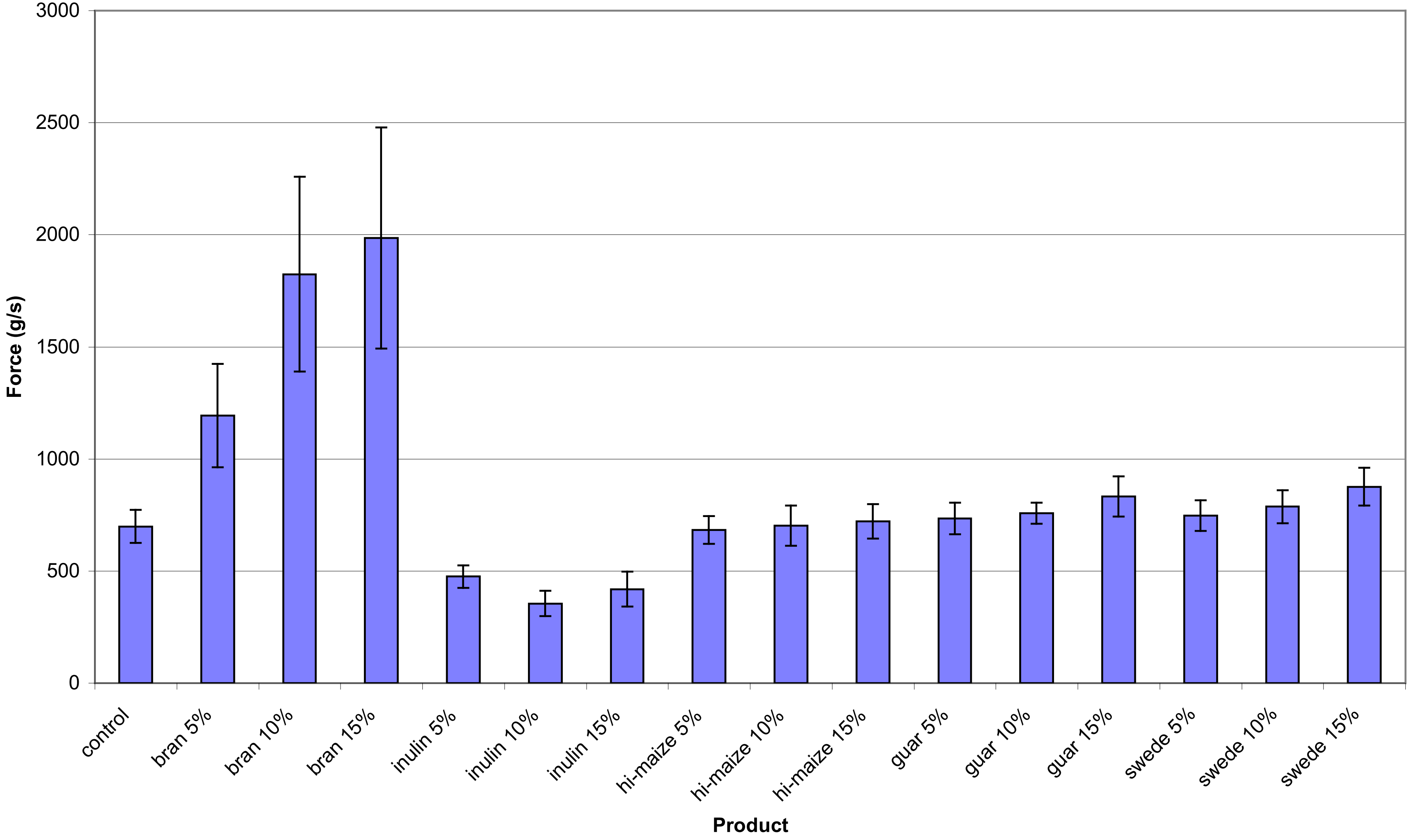
| | Cold Peak | Peak Viscosity | Final Viscosity | Cold Peak Area |
|---|---|---|---|---|
| Raw | (cp) | (cp) | (cp) | (cp) |
| Control | $6.50^{j}$ ±0.71 | $572.00^{d}$ ±26.87 | $905.50^{c,d}$ ±41.72 | $24.33^{j}$ ±2.17 |
| Bran 5% | $5.00^{k}$ ±0.00 | $557.00^{d}$ ±16.97 | $892.00^{d}$ ±28.28 | $21.03^{j}$ ±0.44 |
| Bran 10% | $6.50^{j}$ ±3.54 | $464.00^{e}$ ±5.66 | $743.00^{e}$ ±12.73 | $25.59^{I,j}$ ±7.17 |
| Bran 15% | $7.00^{I,j}$ ±1.41 | $353.00^{g}$ ±1.41 | $564.00^{f}$±24.042 | $22.59^{j}$ ±1.85 |
| Inulin 5% | $3.50^{l}$ ±0.71 | $468.00^{e}$ ±8.49 | $728.50^{e}$ ±4.95 | $18.62^{k}$ ±1.51 |
| Inulin 10% | $2.50^{l,m}$ ±2.12 | $349.07^{g}$ ±24.04 | $543.00^{f}$ ±39.60 | $16.28^{k}$ ±2.00 |
| Inulin 15% | $2.00^{m}$ ±0.00 | $278.00^{I}$ ±31.11 | $420.00^{g}$ ±17.00 | $15.45^{l}$ ±0.63 |
| Hi-maize 5% | $15.52^{h}$ ±2.12 | $497.50^{e}$ ±38.89 | $786.50^{e}$ ±72.83 | $42.19^{h}$ ±3.97 |
| Hi-maize 10% | $10.00^{h}$ ±1.41 | $437.50^{f}$ ±9.19 | $703.50^{e}$ ±33.23 | $31.52^{h}$ ±3.27 |
| Hi-maize 15% | $8.00^{I}$ ±0.00 | $323.50^{h}$ ±2.12 | $513.50^{f}$ ±4.95 | $27.59^{I}$ ±1.46 |
| Guar 5% | $116.50^{d}$ ±16.26 | $1818.00^{c}$ ±73.54 | $2232.00^{b}$ ±36.77 | $152.12^{d}$ ±21.53 |
| Guar 10% | $379.50^{b}$±16.26 | $2402.50^{b}$ ±259.51 | $2726.50^{b}$±120.92 | $479.07^{b,c}$ ±150.69 |
| Guar 15% | $2344.50^{a}$ ±289.21 | $4034.50^{a}$ ±294.86 | $4553.50^{a}$ ±208.60 | $3374.07^{a}$ ±590.41 |
| Swede 5% | $9.50^{h}$ ±0.71 | $591.00^{d}$ ±14.14 | $940.50^{c}$ ±44.55 | $27.26^{i}$ ±0.37 |
| Swede 10% | $9.50^{h}$ ±0.71 | $598.00^{d}$ ±1.41 | $928.50^{c}$ ±3.54 | $30.36^{I}$ ±1.54 |
| Swede 15% | $10.50^{h}$ ±0.71 | $577.09^{d}$ ±14.14 | $880.50^{d}$ ±26.16 | $29.28^{I}$ ±0.00 |
| | | | | |
| Extruded | | | | |
| Control | $101.50^{e}$ ±2.55 | $89.50^{k}$ ±8.60 | $47.17^{k}$ ±0.24 | $174.51^{d}$±20.77 |
| Bran 5% | $53.00^{h}$ ±0.71 | $49.50^{n}$ ±1.06 | $43.00^{l}$ ±0.00 | $123.62^{e}$ ±1.61 |
| Bran 10% | $55.00^{h}$ ±0.71 | $51.00^{n}$ ±0.71 | $44.00^{l}$ ±0.00 | $128.50^{c}$ ±1.38 |
| Bran 15% | $68.00^{g}$ ±2.12 | $63.50^{m}$ ±1.77 | $49.00^{k}$ ±1.41 | $155.16^{d}$±2.40 |
| Inulin 5% | $76.00^{f}$ ±0.71 | $63.00^{m}$ ±2.83 | $43.50^{l}$ ±1.06 | $135.47^{e}$ ±0.91 |
| Inulin 10% | $97.00^{e}$ ±3.54 | $70.00^{l}$ ±4.24 | $48.50^{k}$ ±0.35 | $143.45^{d}$ ±5.61 |
| Inulin 15% | $100.00^{e}$ ±0.00 | $98.50^{k}$ ±3.18 | $53.00^{j}$ ±0.71 | $151.50^{d}$ ±0.86 |
| Hi-maize 5% | $65.00^{g}$±21.21 | $48.00^{n}$ ±8.49 | $38.50^{n}$ ±0.71 | $129.02^{e}$ ±18.02 |
| Hi-maize 10% | $40.50^{g}$ ±2.12 | $36.50^{p}$ ±0.71 | $35.50^{n}$ ±0.71 | $97.52^{g}$ ±1.32 |
| Hi-maize 15% | $67.00^{g}$ ±18.38 | $54.00^{n}$ ±4.24 | $40.50^{m}$ ±0.71 | $120.74^{e}$ ±8.80 |
| Guar 5% | $126.50^{d,e}$ ±19.00 | $83.50^{k}$ ±7.78 | $74.00^{I}$ ±2.83 | $228.43^{d}$ ±4.12 |
| Guar 10% | $215.00^{c}$ ±0.00 | $195.50^{j}$ ±3.53 | $171.00^{h}$ ±31.11 | $401.63^{c}$ ±41.09 |
| Guar 15% | $294.50^{c}$ ±7.78 | $270.50^{I}$ ±6.36 | $244.50^{g}$ ±3.54 | $563.00^{b}$ ±48.67 |
| Swede 5% | $56.50^{f}$ ±2.12 | $51.00^{n}$ ±1.41 | $43.00^{m}$ ±1.41 | $128.98^{e}$ ±2.85 |
| Swede 10% | $45.50^{g}$ ±3.54 | $40.50^{o}$ ±3.54 | $36.00^{n}$ ±1.41 | $110.48^{f}$ ±6.68 |
| Swede 15% | $45.00^{g}$ ±8.49 | $34.50^{p}$±0.71 | $32.00^{o}$ ±1.41 | $96.43^{g}$ ±0.71 |

Within columns each attribute means different letter are significant different ($P \leq 0.05$).

The pasting properties of the extruded breakfast products were also affected by the inclusion of fibre within the base recipe. The cold peak values of the bran samples were lower than the control sample, however the cold peak values increased with increasing fibre concentration. Similarly, inulin enriched samples had lower cold peak values at the 5 and 10 % rate (compared to the control sample) but was similar to the control sample at 15 %. Extruded samples with hi-maize fibre had lower cold peak values compared to the control as did the swede extruded samples. However samples with guar gum were higher than the control sample and increased with increasing values. The addition of most fibres resulted in lower peak viscosity values than the control sample, with the exception of the guar gum enriched samples which showed increased peak viscosity values compared to the control and other fibre samples. Final viscosity values of the extruded hi-maize, swede, bran (5 and 10 %) and inulin (5 %) were lower than the control sample. Guar gum final viscosity values were higher than the control and other fibre samples.

The amount of force required to fracture an individual cereal bubble (the hardness of the cereal product) is showed in Figure 5.6. The use of bran in the base recipe significantly increased product hardness compared to the control sample (increasing in relation to fibre concentration). In contrast, the use of inulin reduced the hardness of the extruded product compared to the control sample. Interestingly, hi-maize, guar and swede utilisation did not affect product texture compared to the control.

**Figure 5.6 Hardness of individual extruded fibre enriched breakfast cereal products**

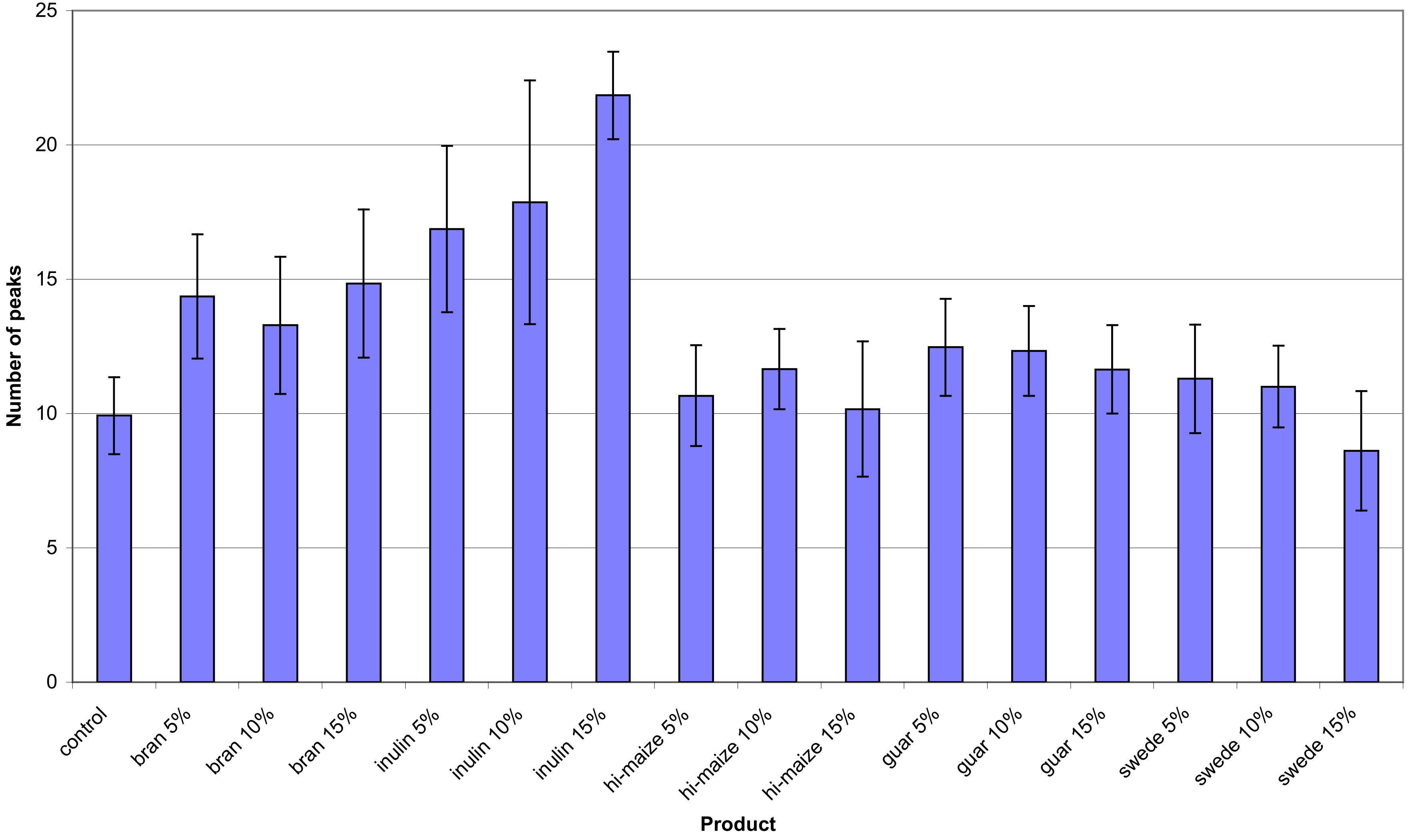


The crispiness of the extruded breakfast cereal products (measured as the number of peaks recorded during the compression of a product) is shown in Figure 5.7. The addition of bran increased the number of peaks observed during compression compared to the control sample. Inulin addition also increased the number of peaks visible (crispiness of the product) with the 15 % inulin enriched sample having the highest number of peaks of all samples. The addition of all other fibers did not affect the number of peaks visible during the compression of the samples.

The amount of starch within the raw and extruded samples was determined to evaluate the effect of the extrusion process on the amount of apparent starch within the samples. All the fibre samples had lower apparent starch contents than the control sample in the raw bases. Bran, inulin, guar and swede enriched raw bases showed decreasing starch contents with increasing fibre contents.

The inclusion of inulin or guar at 5 % level yielded an apparent 15 % and a 10 % reduction in starch concentration respectively, whereas the addition of inulin and guar at 15 % resulted in an apparent decrease of 23 %. The use of hi-maize in the raw bases was lower than the control sample but showed an increase in apparent starch content with increased fibre content, so that 5 % hi-maize addition resulted in a reduction of 10 %, whilst the addition of 15 % hi-maize resulted in an apparent starch reduction of 5 % compared to the control sample.

Figure 5.7 Crispness of individual extruded fibre enriched breakfast cereal products



Compared to the raw base, the extruded breakfast cereal products showed an increase in apparent starch content (Figure 5.8). The starch contents of the extruded fibre samples were lower in apparent starch content with increasing fibre inclusion (hi-maize excluded). Thus at the 5 % level bran, inulin, guar gum and swede breakfast cereals showed a reduction in apparent starch content compared to the control sample of; 11, 17, 12 and 7 % respectively. This increased at 15 % addition rates to a reduction of; 20, 23, 19 and 21 % (bran, inulin, guar and swede respectively). However the reduction of apparent starch content within the 5 and 10% hi-maize samples was 8 and 5 % less than the control sample respectively, with the 15 % hi-maize sample showing similar apparent starch content to the control sample.

Figures 5.9 and 5.10 show the available carbohydrate for digestion. In the raw bases, the amount of available carbohydrate at time zero (amount of free sugars) was relatively low and did not differ between the control and fibre enriched samples. However, the amount of carbohydrate digested at 20 minutes was reduced with the addition of fibre, excluding the bases containing swede fibre. A similar reduction was observed for the bran, inulin and guar gum samples, except for: bran at 5 %, inulin at 5 %, and guar gum at 5 % and 10 %. Generally, the digestibility of samples at 120 minutes were similar to the control sample, with the exception of the guar gum 5 % and 10 % samples and also the swede samples which were higher than the control sample.

**Figure 5.8 Apparent starch content of raw and extruded fibre enriched breakfast cereal products**

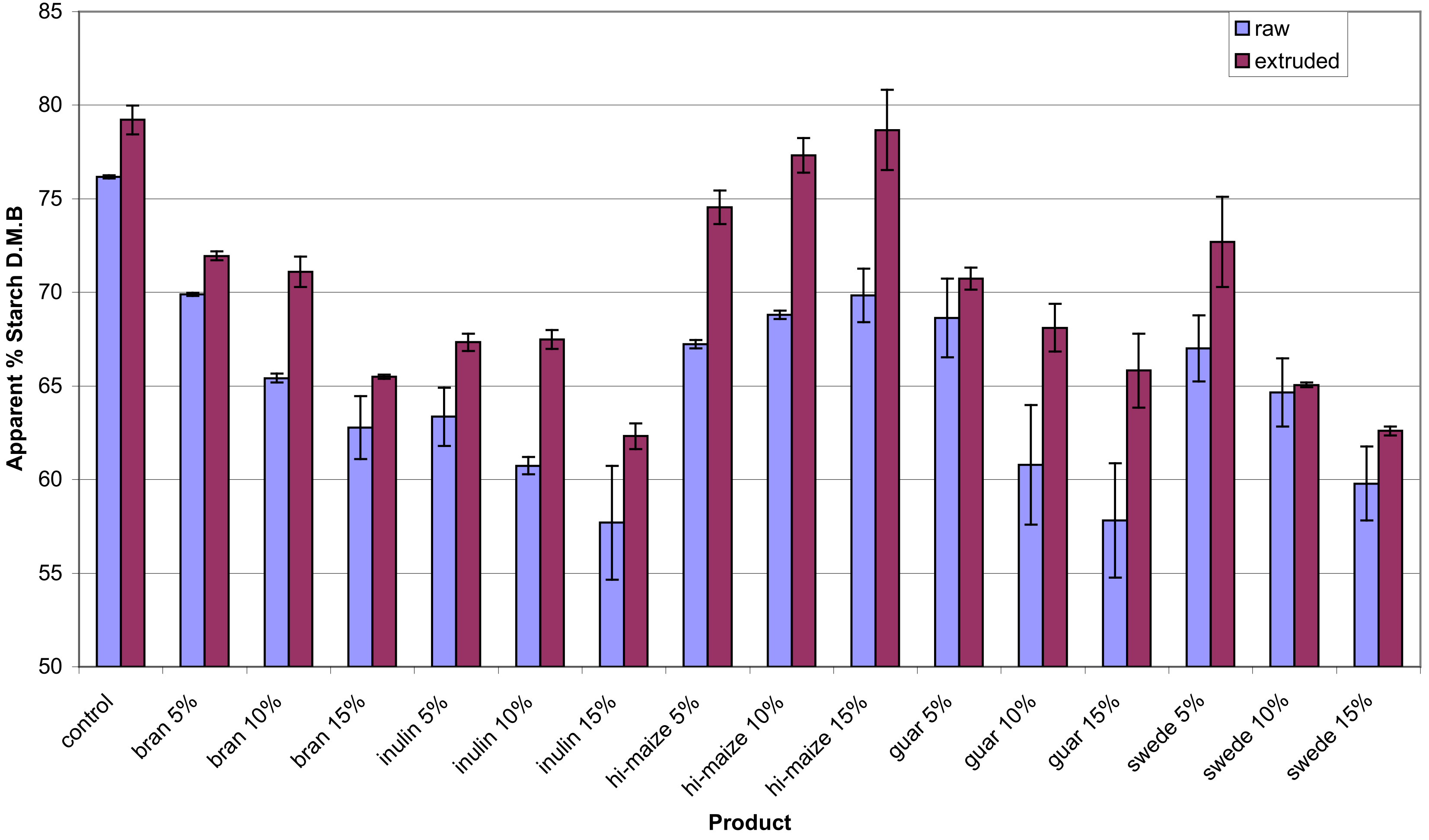


Figure 5.9: Carbohydrate digestibility of raw fibre enriched breakfast cereal products

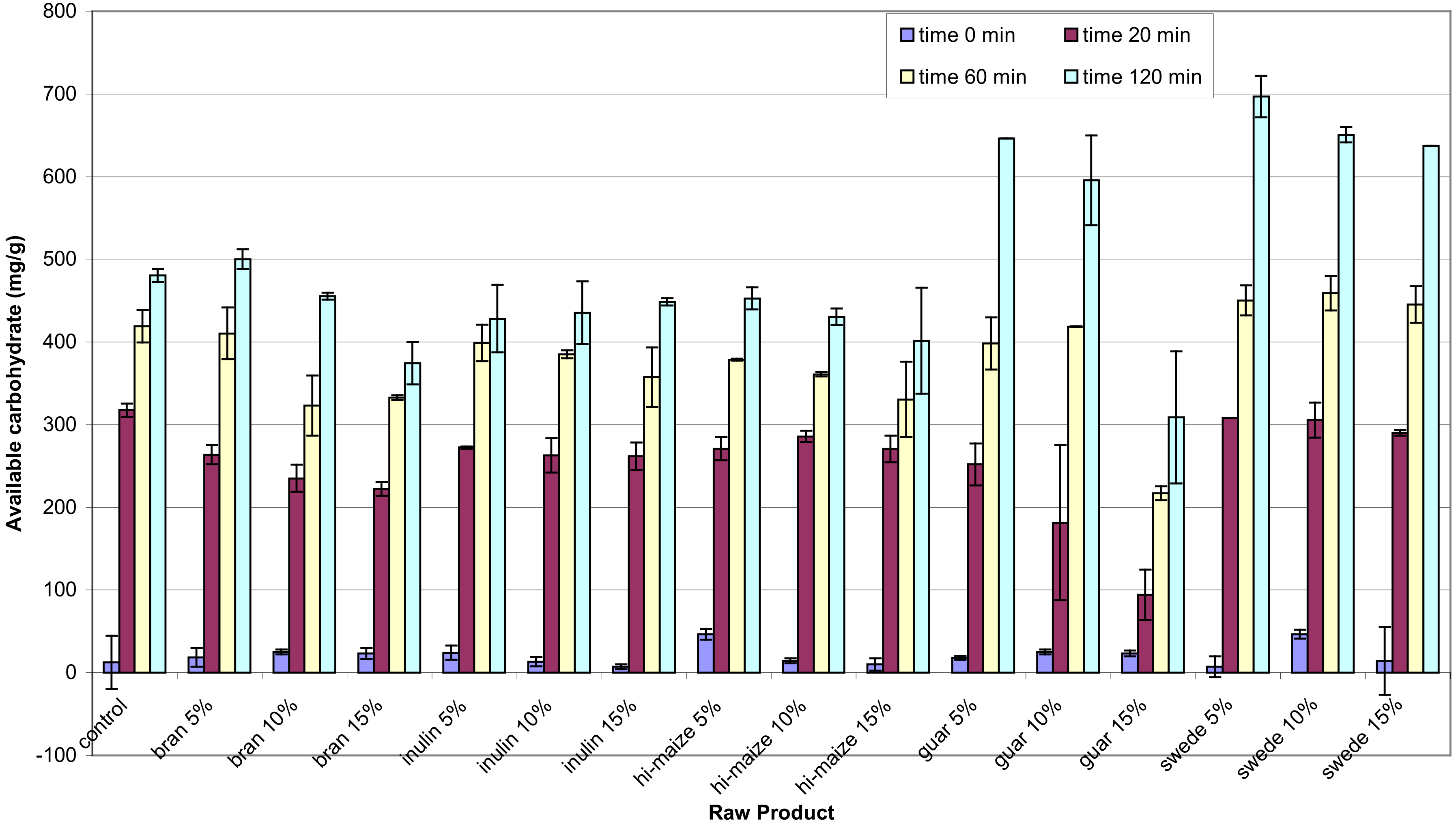
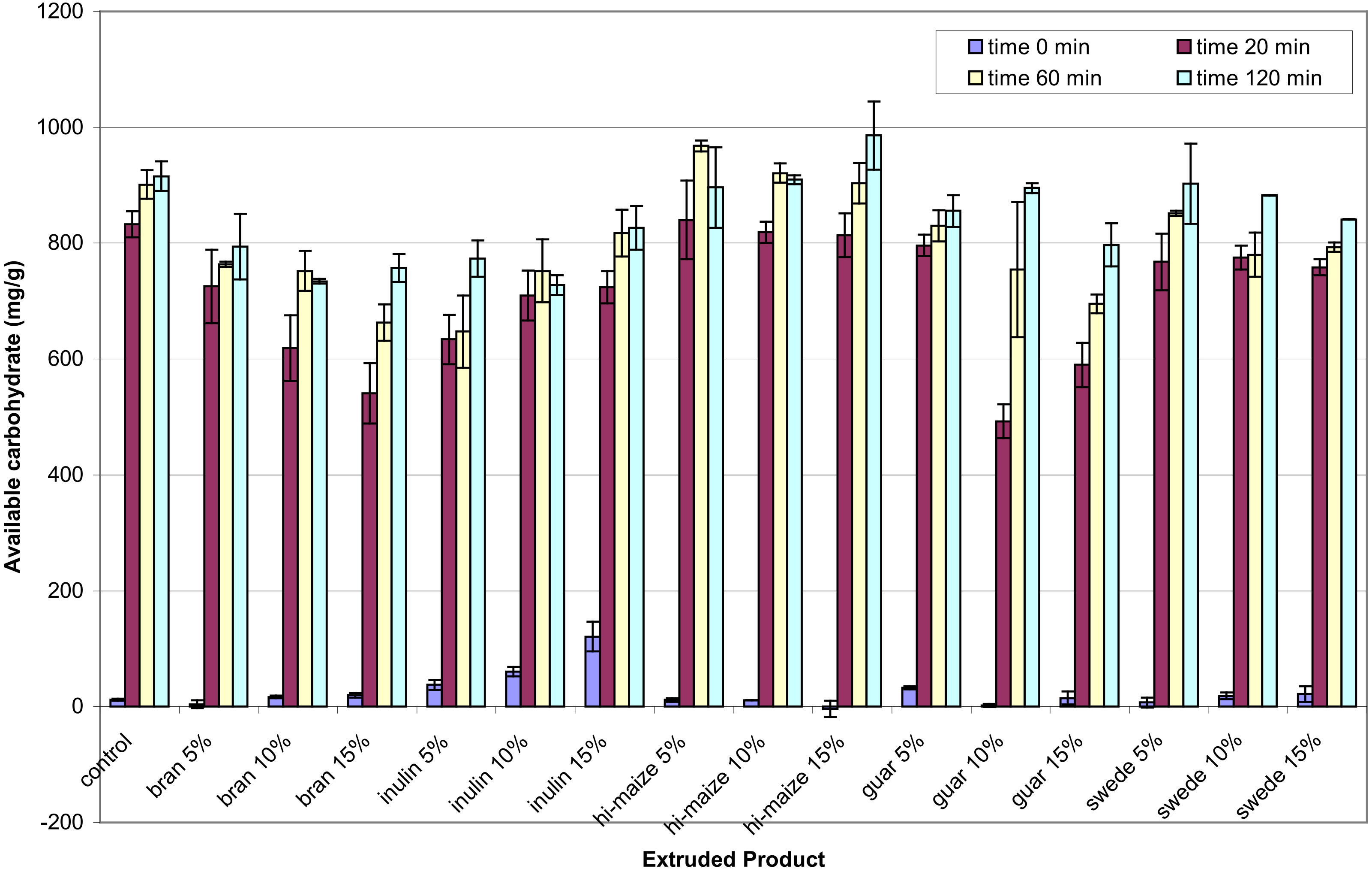


**Figure 5.10: Carbohydrate digestibility of extruded fibre enriched breakfast cereal products**



The carbohydrate digestibility of extruded cereal products is shown in Figure 5.10. The addition of bran to the extruded cereal product significantly reduced the amount of carbohydrate digestibility recorded at 20, 60 and 120 minutes compared to the control sample. The greatest reduction (27 %) was shown at 15 % addition level at 20 minutes, whereas at 120 minutes the reduction was only 17 %. The addition of inulin to the breakfast cereal products reduced carbohydrate digestibility by an average of 12 %; 5 % enrichment yielding a 23 % reduction, whilst a 15 % enrichment yielded a 6 % reduction.

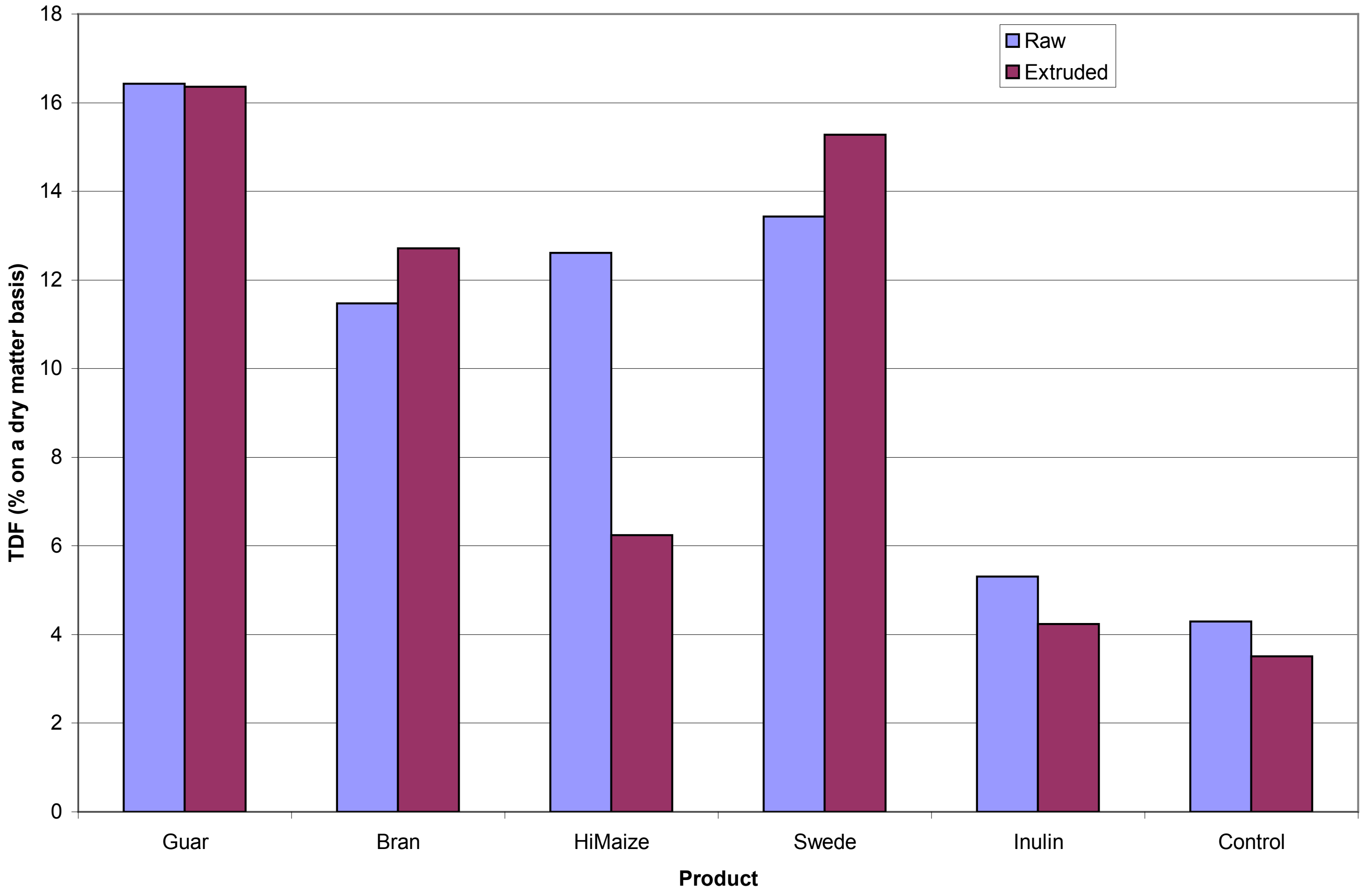
A similar pattern was observed at all time intervals. The addition of hi-maize to the extruded samples did not reduce carbohydrate digestibility of the samples, but had similar or increased carbohydrate digestibility levels; 5, 10 and 15 % addition having similar digestibilities at 20, 60 and 120 minutes, except for 5 % enrichment at 60 minutes which had a 8 % increase, and 15 % enrichment at 120 minutes which corresponded to a 6 % increase.

Utilisation of guar reduced the amount of carbohydrate digestibility at all levels, notably a 47 % reduction at 20 minutes when using 10 % enrichment. The swede fibre enriched products had generally similar digestibility values to the control sample at 20 minutes, but lower digestibility values at 60 and 120 minutes, except for the product with 5 % swede fibre addition. However, these reductions were generally less than what would have been expected when taking into account the swede fibre replacing the flour component of the base recipe.

The amount of apparent dietary fibre in the raw and extruded samples (15%) was also estimated to determine whether the extrusion process had an effect on fibre levels within the breakfast cereals (Figure 5.11). Although the results are taken from a single determination as no replications were done due to time constraints of the project, the results show a general trend. In the control sample the extrusion process showed a slight reduction in fibre components after extrusion, showing a similar pattern to the inulin containing sample. The dietary fibre content of the 15 % inulin enriched raw sample was estimated at 5.7 %, representing a 1.5 % increase compared to the control, suggesting inaccuracies associated with the analytical method in determining the dietary fibre content of fructo-oligosaccharides.

The addition of guar gum to the base recipe increased the apparent dietary fibre content to above 16 % which was the highest content in all samples, whereas a 15 % addition of bran, hi-maize and swede increased the dietary fibre content of the recipe by 10-11 %. Extrusion had no effect on the amount of dietary fibre within the 15 % guar gum product. However, the amount of dietary fibre appeared to increase with the addition of 15 % of bran and swede. Interestingly, the extrusion process reduced the apparent dietary fibre content of the 15 % hi-maize sample (a reduction of 50 %), indicating that the hi-maize may be susceptible to degradation during the extrusion process.

Figure 5.11: Total dietary fibre content of selected fibre enriched (15%) breakfast cereal products



## *5.4 Discussion*

As discussed in the previous chapter, the addition of fibre affected moisture loss during the extrusion process. No clear pattern was observed in that moisture loss increased with addition for bran, guar, and swede samples, but decreased with inulin. Similarly, expansion ratio was affected differentially by the fibres used in that bran and swede inclusion resulted in reduced expansion ratios, whereas inulin, hi-maize and guar gum inclusion resulted in increased expansion ratios compared to control. Thus expansion properties of extruded products were not related to moisture loss of the products during the extrusion process.

It is possible that expansion characteristics could be related to viscosity properties of the raw materials. For instance, in the raw samples, cold peak increased with increasing bran, hi-maize, guar gum and swede levels, but decreased with inulin levels. Hi-maize inclusion increased the cold peak above the control but increasing fibre concentration decreased the cold peak values. Guar gum inclusion greatly raises the cold peak viscosity. Swede fibre enrichment raised the cold peak values.

In the extruded product, samples enriched with bran and inulin showed a decreased cold peak viscosity compared to the control, while the viscosity increasing with increasing fibre inclusion. Hi-maize and swede enriched product had a decreased cold peak viscosity compared to the control. Guar gum inclusion increased cold peak viscosity compared to the control and increased with increasing fibre inclusion.

Previous research has indicated that RVA patterns of foods typically show large differences in pasting properties between the raw and extruded products, so that in most cases the peak viscosity and final viscosity values are significantly lower in extruded products than raw (Bouvier, 2001). This has been associated with the gelatinisation and disruption of the starch granule during the high shear and high temperature of extrusion. Peak viscosity for starch / polysaccharide systems have been shown to be significantly higher than control starch systems, possibly due to the thickening effect of polysaccharides and interactions between the polysacchairdes and swollen starch granules (Tester and Morison, 1990; Rojas *et al.,* 1999).

Generally more expanded extruded products have larger cells and thinner cell walls. However, Jin *et al.* (1995) showed that by increasing the fibre content of the extruded snack product the breaking strength of the products could be increased (breaking strength in this case being negatively correlated with radial expansion). Similar results have been described by Lue *et al.* (1991) who showed that fibre in the feed material results in formation and low retention of expanded air pockets. These observations support the early research by Guy (2001) which indicated that bran interfered with bubble expansion.

Several studies have investigated the relationship between the structure and texture of extruded products (Barrett and Palag, 1991; Van Hecke *et al.,* 1995). All of these suggest that the rheology of the dough within the extruder has a significant effect on the final product.

In the current study, the use of bran in the base recipe increased product hardness compared to the control sample (increasing in relation to fibre concentration). In contrast, the use of inulin reduced the hardness of the extruded product compared to the control sample. Interestingly, hi-maize, guar gum and swede utilisation did not affect product texture compared to the control, illustrating their potential utilisation in extruded snack products without affecting product quality.

Crispiness of the extruded breakfast cereal products (measured as the number of peaks recorded during the compression of a product) was also affected. The addition of bran increased the number of peaks observed during compression compared to the control sample. Inulin addition also increased the number of peaks visible (crispiness of the product) with the 15 % inulin enriched sample having the highest number of peaks of all samples. The addition of all other fibers did not affect the number of peaks visible during the compression of the samples. This observation appears to be linked to the behaviour of the fibres in product expansion and density.

*In vitro* digestibility of the raw bases demonstrated that the amount of available carbohydrate at time zero (amount of free sugars) was relatively low and did not differ between the control and fibre enriched samples. However, the amount of carbohydrate digested at 20 minutes was reduced with the addition of fibre (excluding the bases containing swede fibre). Generally, the digestibility of samples at 120 minutes were similar to the control sample, with the exception of the guar gum 5 % and 10 % samples and also the swede samples which were higher than the control sample.

Added dietary fibre have been shown to affect the digestibility of carbohydrates in food, for instance cellulose when added to maize starch decreased solubility of the starch and hence digestibility (Brennan *et al.,* 1996). Similarly, Fairchild *et al*., (1996) showed that the inclusion of guar gum into a wheat based product improved human glucose tolerance by reducing the serum glucose postprandially compared to low-fibre cereal products. This reduction in blood glucose level in guar gum enriched breakfast cereal products was proposed to be related to the added viscosity that guar gum provides during digestion, and also an interaction of starch-guar which was later demonstrated more clearly by similar research on guar gum enriched wheat breads (Brennan *et al*., 1996). More recently Hardacre *et al*. (2006) showed that the addition of peas and lentils into maize based extruded snack products could reduce the glycaemic impact of those foods and Börjck and Elmståhl (2003) reported a similar occurrence in fibre enriched breakfast cereals.

The carbohydrate digestibility values of extruded cereal products derived from this experiment showed that the addition of bran to the extruded cereal product reduced the amount of carbohydrate digestibility recorded at 20, 60 and 120 minutes compared to the control sample. The greatest reduction being shown at 15 % addition level at 20 minutes, showing a 27 % reduction, whereas at 120 minutes the reduction was only 17 %. Addition of inulin to the breakfast cereal products reduced carbohydrate digestibility by an average of 12 %; for instance a5 % enrichment yielding a 23 % reduction, whilst a 15 % enrichment yielded a 6 % reduction.

Use of guar gum reduced the amount of carbohydrate digestibility at all levels, notably a 47 % reduction at 20 minutes when using 10 % enrichment. Addition of hi-maize to the extruded samples did not reduce carbohydrate digestibility of the samples, with the samples recording similar, or increased, carbohydrate digestibility levels compared with the control. Thus a 5, 10 and 15 % addition had similar digestibilities at 20, 60 and 120 minutes, excepting 5 % enrichment at 60 minutes which corresponded to a 8 % increase, and 15 % enrichment at 120 minutes which corresponded to a 6 % increase. Swede fibre enriched products had generally similar digestibility values to the control sample at 20 minutes, but lower digestibility values at 60 and 120 minutes, excepting the product with 5 % swede fibre addition.

## *5.5 Conclusion*

The suitability of dietary fibre components for extruded snack products depends upon the origin of the dietary fibre. In particular the physical characteristics of extruded products varied depending upon the selection of either soluble or insoluble dietary fibres. Inclusion of inulin in the extruded products increased expansion ratio and reduced bulk density, hence potentially increasing consumer suitability, compared to bran and swede fibres. In terms of suitability based on the ability to lower the glycaemic impact of extruded cereals, the inclusion of bran and guar gum show great potential.

# Chapter 6 The potential synergistic effect of combining dietary fibres on the product characteristics of extruded break fast cereal

## *6.1 Introduction*

Chapter 5 described the potential effects of individual dietary fibre ingredients on the physico-chemical and nutritional characteristics of extruded breakfast cereal products when added singularly. However, dietary fibre is often included in food products in combined forms rather than singularly, thus it was decided to explore the potential of using the dietary fibres in combinations with the combinations adding up to 15 % total enrichments level, 7.5 % from two separate dietary fibres. The physico-chemical and nutritional quality of these extruded cereal products was evaluated.

## *6.2 Materials and Methods*

Combinations of dietary fibre ingredients were used in fibre enriched extruded products. The level of fibre enrichment was set at 15 % (based upon the observations of Chapters 4 and 5). In order to achieve this two fibres were included at 7.5 % level. The dietary fibres used in this part of the research were wheat bran, hi-maize and guar gum (as detailed in section 2.1). Extruded breakfast cereals were produced as described in Chapter 2 (Table 2.2) the resulting products were evaluated in terms of moisture content, product density, expansion ratio, texture and *in vitro* digestibility (as detailed in Chapter 2).

## *6.3 Results*

Figures 6.1 and 6.2 show the moisture content of the raw and extruded samples, and the amount of moisture loss during extrusion processing. The inclusion of the dietary fibres into the raw sample base reduced the moisture content of the products. The extruded cereal products showed a similar reduction compared to the control sample. However, there was no consistent pattern in terms of moisture loss and dietary fibre inclusion.

The effect of fibre inclusion on product expansion rate is shown in Figure 6.3. The combination of hi-maize + guar gum, inulin + guar gum, and inulin + hi-maize resulted in increased expansion of the breakfast cereal compared to the control sample. However the bran + hi-maize, bran + inulin, and bran + guar gum products were not different from the control sample.

The extruded samples with added bran showed an increase in product density and bulk density (Figures 6.4 and 6.5, respectively), whereas the combination of guar gum, inulin and hi-maize resulted in products with lower product and bulk densities compared to the control samples.

**Figure 6.1 Moisture content of raw breakfast cereal bases with combinations of dietary fibres**

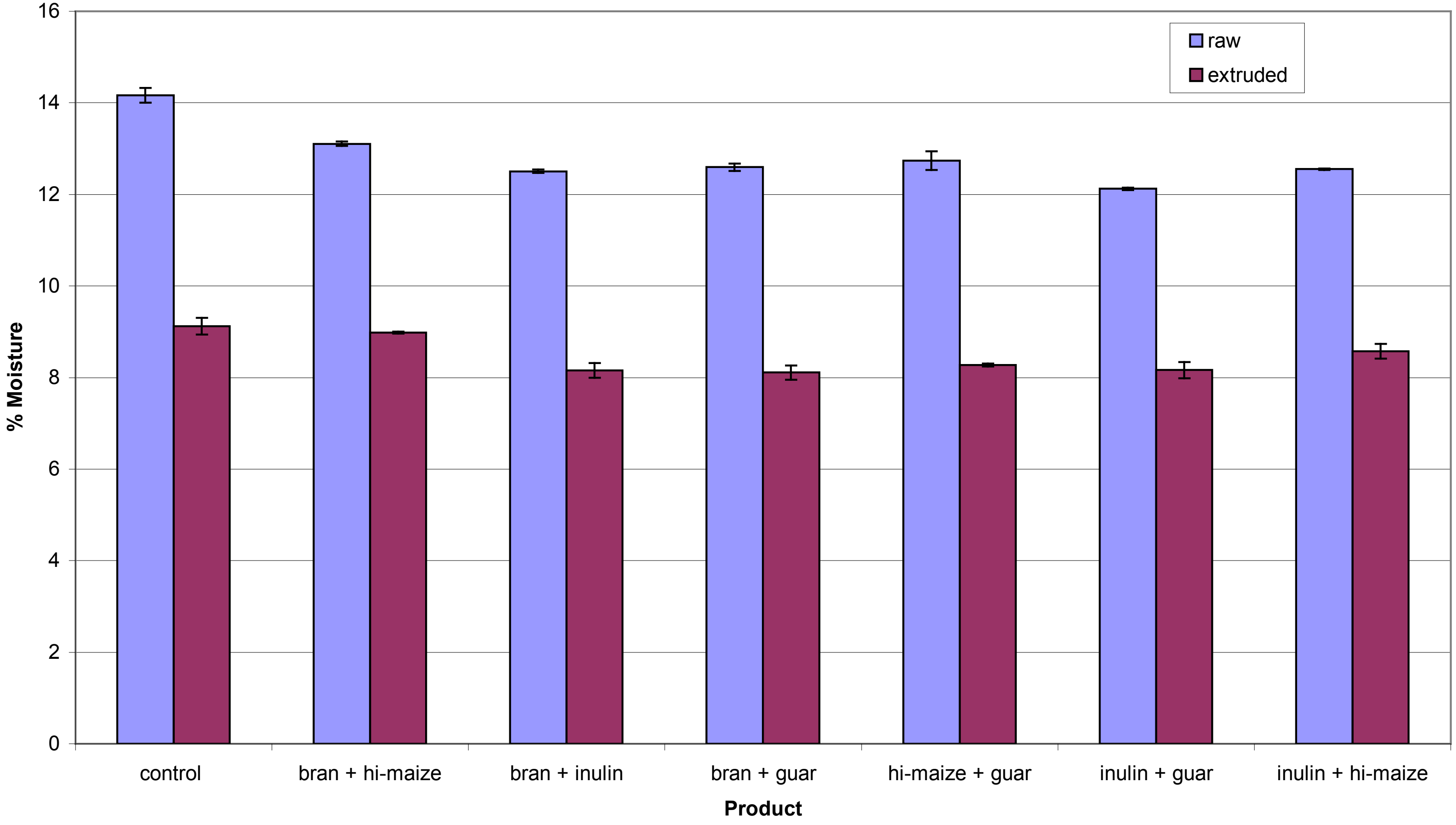


Figure 6.2 Moisture loss (%) of extruded breakfast cereals with combinations of dietary fibres

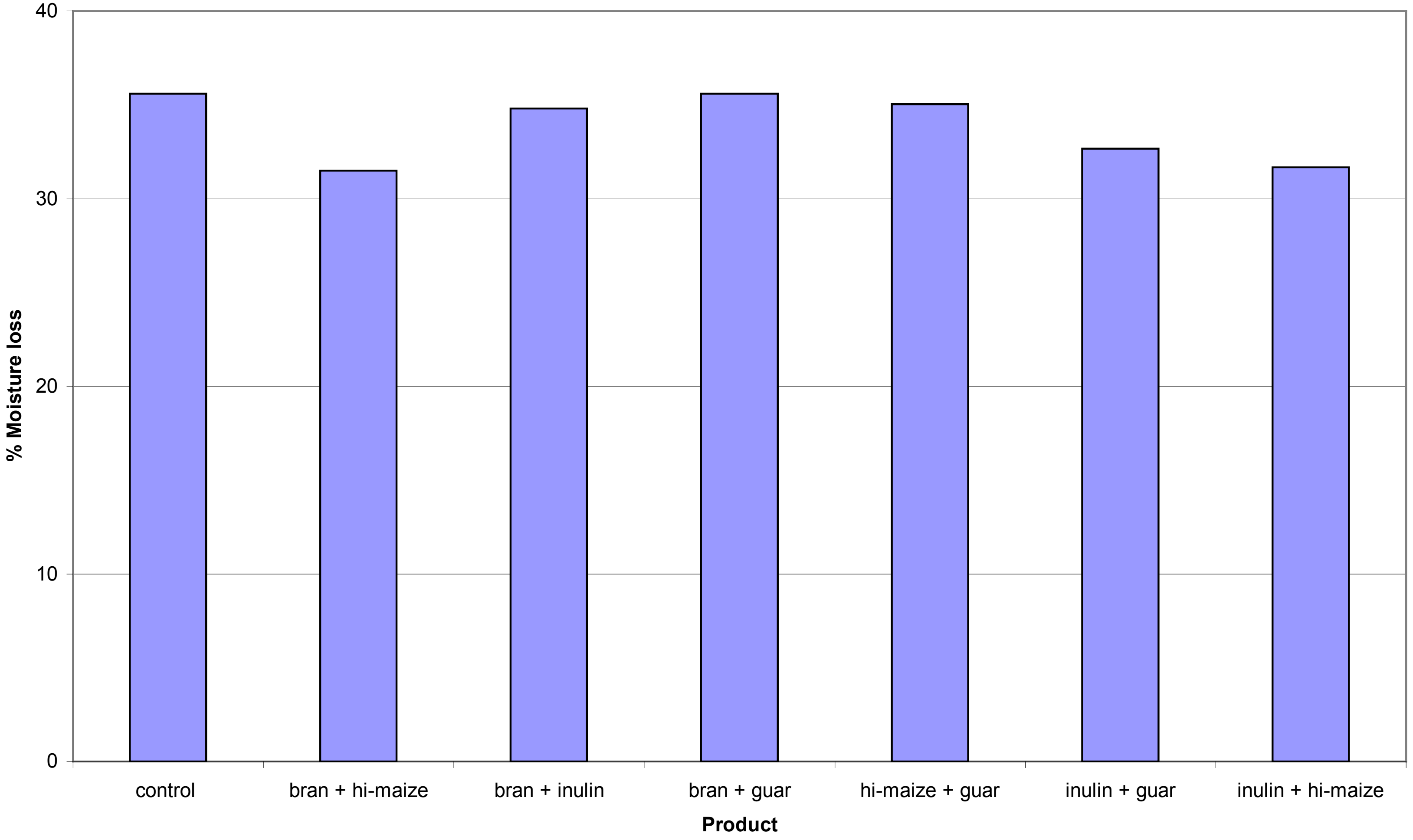


Figure 6.3 Expansion ratio of extruded breakfast cereal products

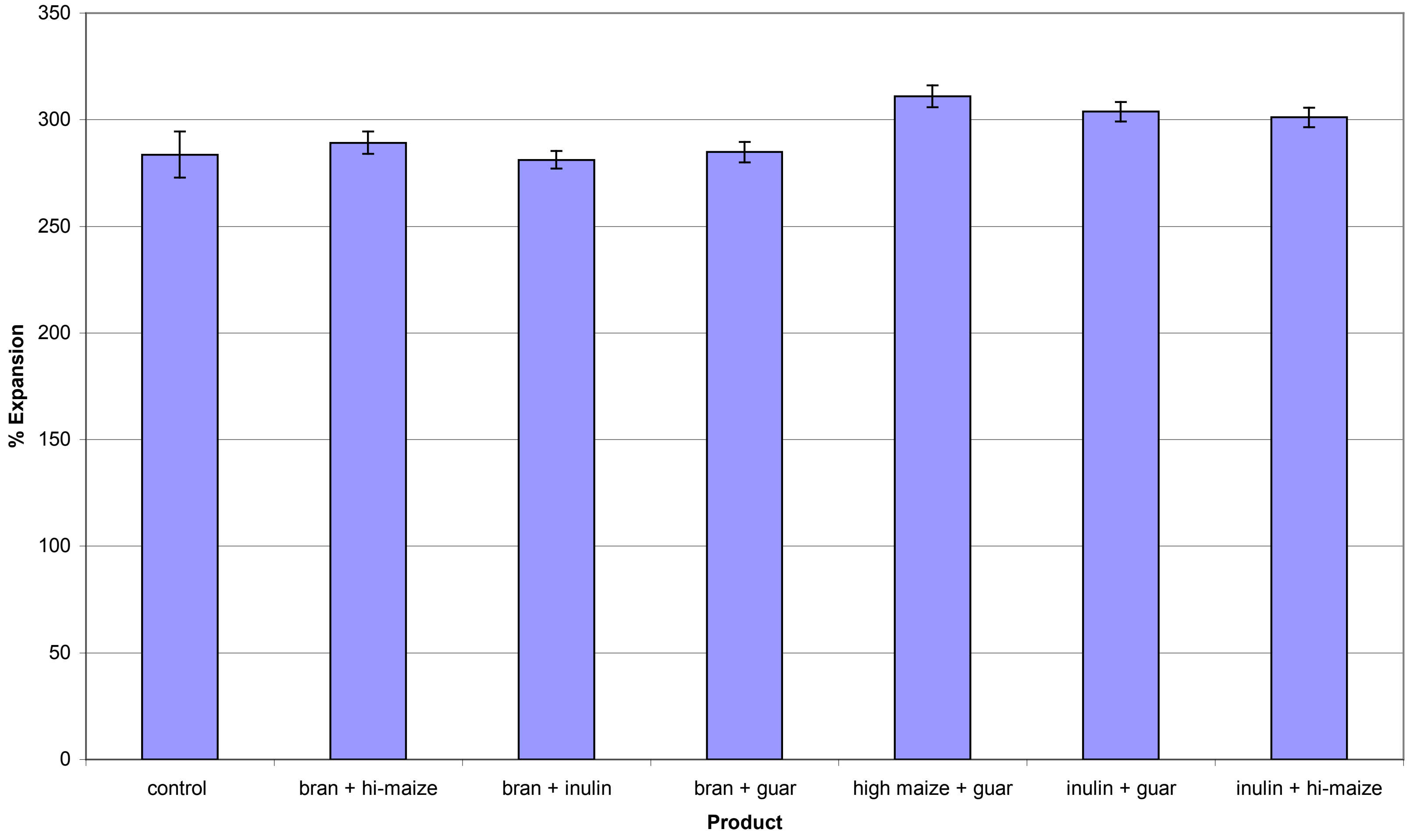


**Figure 6.4 Product density of extruded breakfast cereals with combinations of dietary fibres**

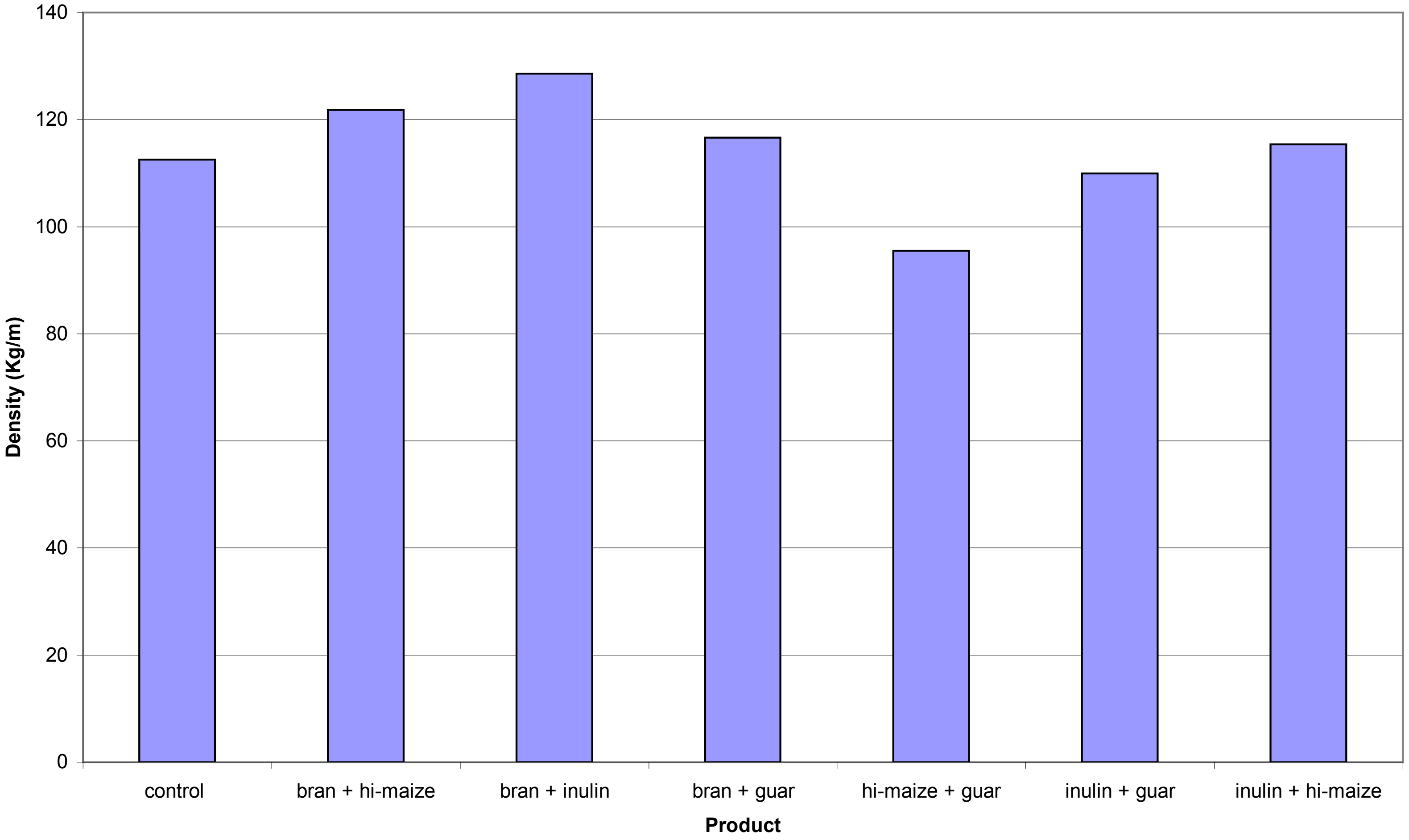
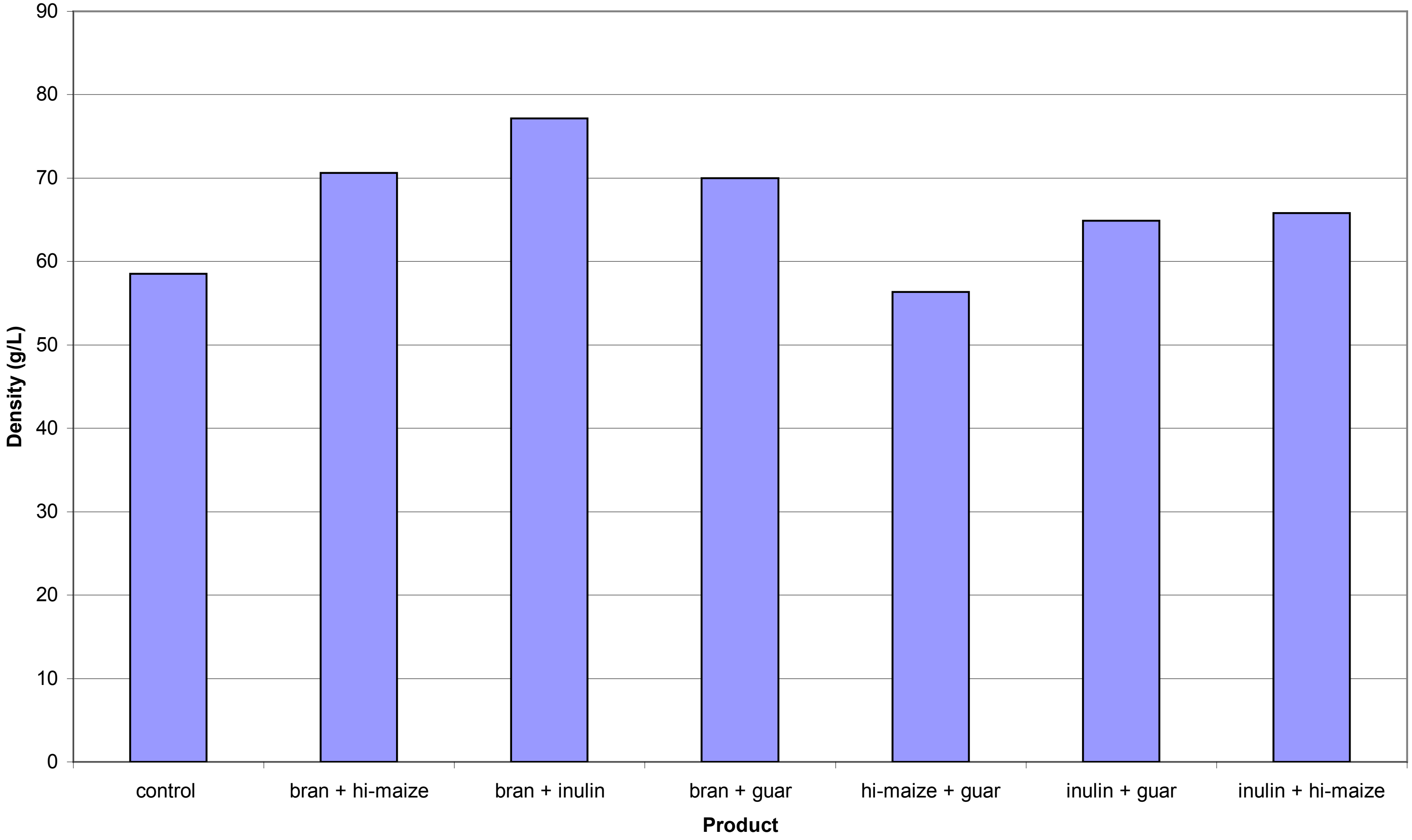


**Figure 6.5 Bulk density of extruded breakfast cereals with combinations of dietary fibres**



The addition of dietary fibres to the base recipe increased the cold peak values of the raw samples compared to the control sample. Addition of guar gum to the recipes resulted in an increase in cold peak viscosity compared to the addition of the other dietary fibres. Peak and final viscosity of the raw samples decreased with the addition of all the dietary fibre combinations, except for those with guar gum inclusion. The pasting properties of extruded samples (Table 6.1) showed similar characteristics with the dietary fibre enriched samples possessing lower cold peak, peak and final viscosity values compared to the control sample. The exception being for those samples with guar gum addition which showed higher cold peak, peak and final viscosity than the control sample.

Figure 6.6 shows the hardness values of extruded breakfast cereal products with a combination of dietary fibres included into the base recipe. The combinations of bran + hi-maize, bran + guar gum and hi-maize + guar gum resulted in higher force required to fracture the breakfast cereal products. Inulin + hi-maize combination resulted in a softer product compared to the control, whereas inulin + guar gum, and bran + inulin products were similar to the control sample.

**Table 6.1 Pasting properties of raw and extruded breakfast cereals with combinations of dietary fibres**

| | **Cold Peak** | **Peak Viscosity** | **Final Viscosity** | **Cold Peak Area** |
|---|---|---|---|---|
| Raw | (cp) | (cp) | (cp) | (cp) |
| Control | 6.50$^{l}$ ±0.71 | 572.00$^{d}$ ±26.87 | 905.50$^{d}$ ±41.72 | 24.33$^{k}$ ±2.17 |
| Bran + hi-maize | 13.00$^{j}$ ±0.00 | 348.00$^{f}$ ±5.66 | 573.50$^{e}$ ±12.02 | 34.97$^{i}$ ±1.41 |
| Bran + inulin | 9.50$^{k}$ ±0.70 | 377.00$^{e}$ ±28.28 | 595.00$^{e}$ ±45.25 | 28.21$^{k}$ ±0.29 |
| Bran + guar | 240.00$^{a}$ ±4.24 | 2179.00$^{a}$ ±5.66 | 2496.00$^{a}$ ±1.41 | 259.86$^{d}$ ±0.49 |
| Hi-maize + guar | 257.50$^{a}$ ±10.61 | 2120.00$^{b}$ ±28.28 | 2298.00$^{b}$ ±8.49 | 276.50$^{c}$ ±9.68 |
| Inulin + guar | 110.00$^{e}$ ±4.24 | 1533.00$^{c}$ ±33.94 | 2010.50$^{c}$ ±9.19 | 136.86$^{f}$ ±4.34 |
| Inulin + hi-maize | 10.00$^{j}$ ±0.00 | 346.00$^{g}$ ±0.00 | 546.00$^{f}$ ±0.00 | 32.55$^{j}$ ±0.00 |
| Extruded | | | | |
| Control | 101.50$^{f}$ ±2.55 | 89.50$^{k}$ ±8.60 | 47.17$^{i}$ ±0.24 | 174.51$^{e}$±20.77 |
| Bran + hi-maize | 62.00$^{h}$ ±4.24 | 57.50$^{m}$ ±2.12 | 43.50$^{j}$ ±0.71 | 132.24$^{f}$ ±5.07 |
| Bran + inulin | 55.00$^{i}$ ±0.00 | 51.00$^{n}$ ±0.00 | 43.00$^{j}$ ±0.00 | 122.31$^{g}$ ±0.88 |
| Bran + guar | 212.50$^{b}$ ±9.19 | 199.00$^{h}$ ±8.49 | 132.50$^{g}$ ±7.78 | 405.36$^{a}$ ±37.87 |
| Hi-maize + guar | 147.00$^{d}$ ±0.00 | 134.50$^{j}$ ±0.71 | 111.00$^{h}$ ±1.41 | 285.67$^{b}$ ±3.00 |
| Inulin + guar | 159.00$^{c}$ ±2.83 | 147.00$^{i}$ ±0.00 | 116.50$^{h}$ ±7.78 | 291.48$^{b}$±12.44 |
| Inulin + hi-maize | 72.50$^{g}$ ±3.54 | 67.50$^{l}$ ±0.71 | 34.50$^{k}$ ±0.71 | 116.55$^{h}$ ±2.49 |

Within columns each attribute means different letter are significant different ($P \leq 0.05$).

With regards to crispiness of the products (Figure 6.7), only inulin + guar gum, and inulin + hi-maize combinations produced crispier products compared to the control product. The other combinations produced final breakfast cereal products which were similar in crispiness characteristics (the number of fracture peaks recorded during compression) to the control sample.

As with the addition of the single dietary fractions to the base recipe, the addition of dietary fibres reduced the apparent starch content of the recipes (only the bran + guar gum, inulin + guar gum  and bran + inulin being greater than 15 %). In all the samples, the extrusion process appeared to increase the amount of available starch content.

Unlike  the samples with single addition of dietary fibres, the addition of dietary fibres in combination with each other to the raw base mixtures did not reduce overall carbohydrate digestibility (Figure 6.9). The combinations of bran + guar gum, inulin + guar gum and bran + hi-maize were similar to the control in starch digestibility at 60 and 120 minutes. However, the readily digestible starch fraction (the value at 20 minutes) was reduced by the addition of all the fibre fractions.

**Figure 6.6 Hardness of extruded breakfast cereals with combinations of dietary fibres**

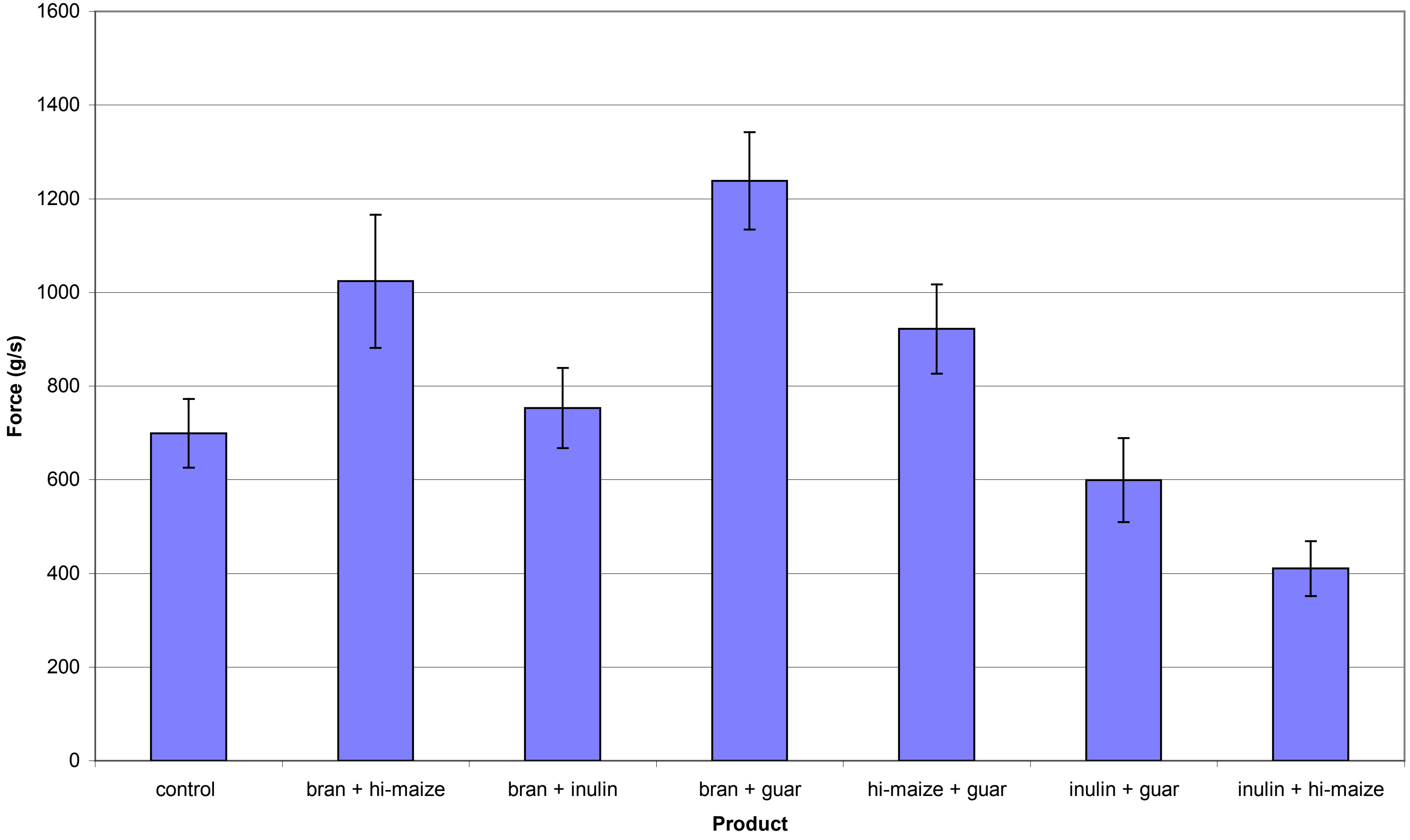


Figure 6.7 Crispiness of extruded breakfast cereals with combinations of dietary fibres

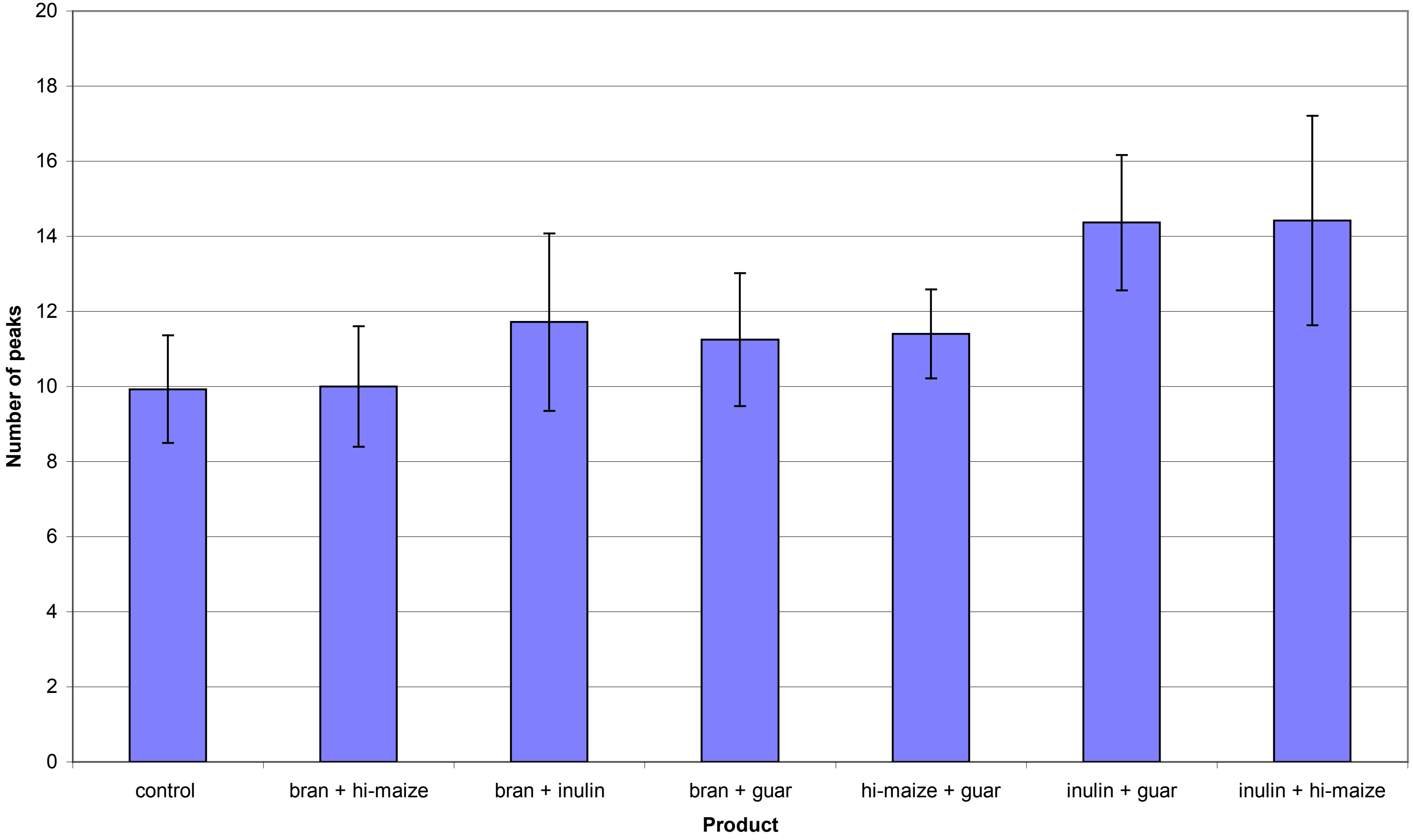


**Figure 6.8 Starch content of raw and extruded breakfast cereals with combinations of dietary fibres**

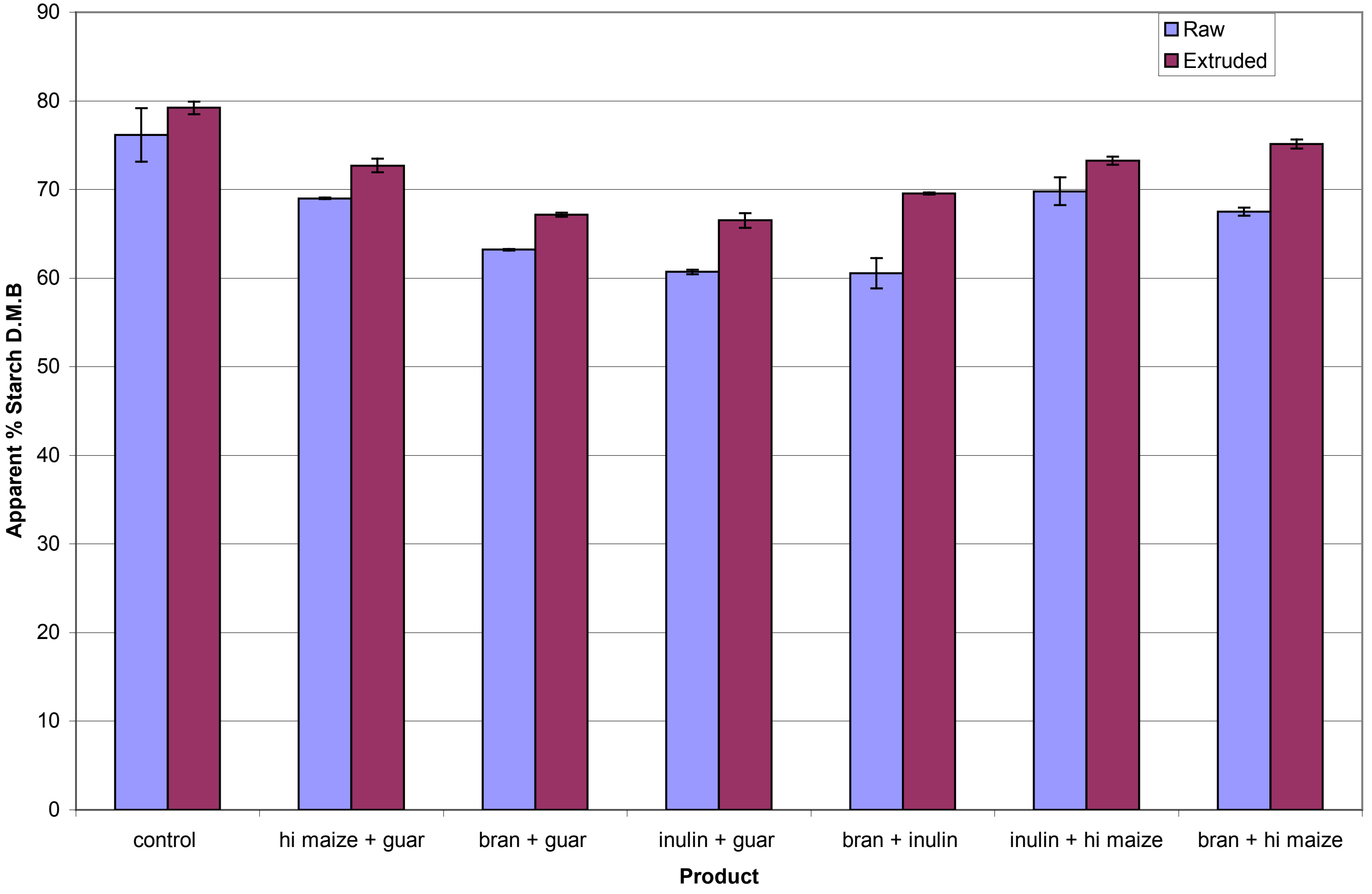


**Figure 6.9 Carbohydrate digestibility of raw breakfast cereal bases with combinations of dietary fibres**

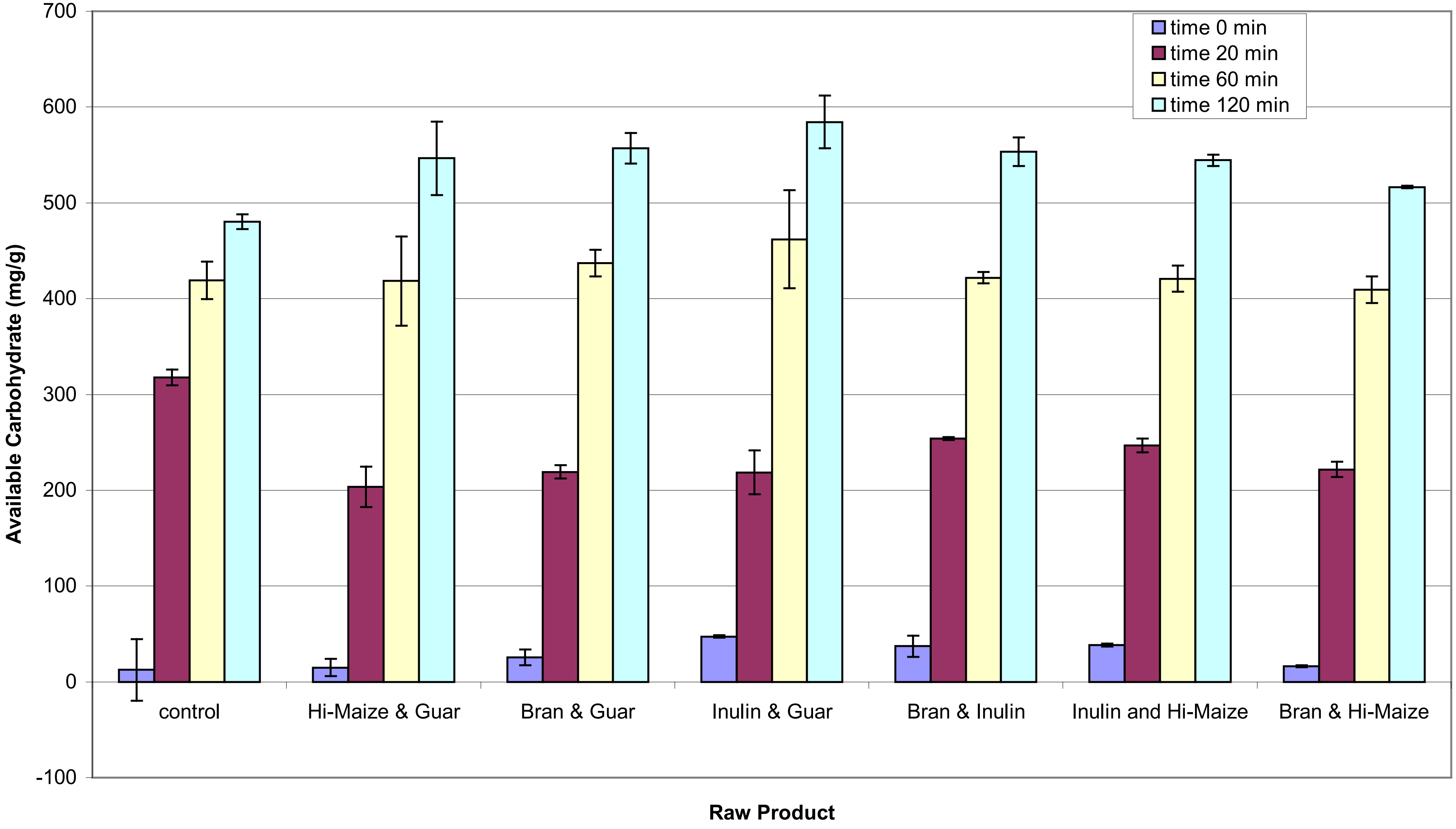
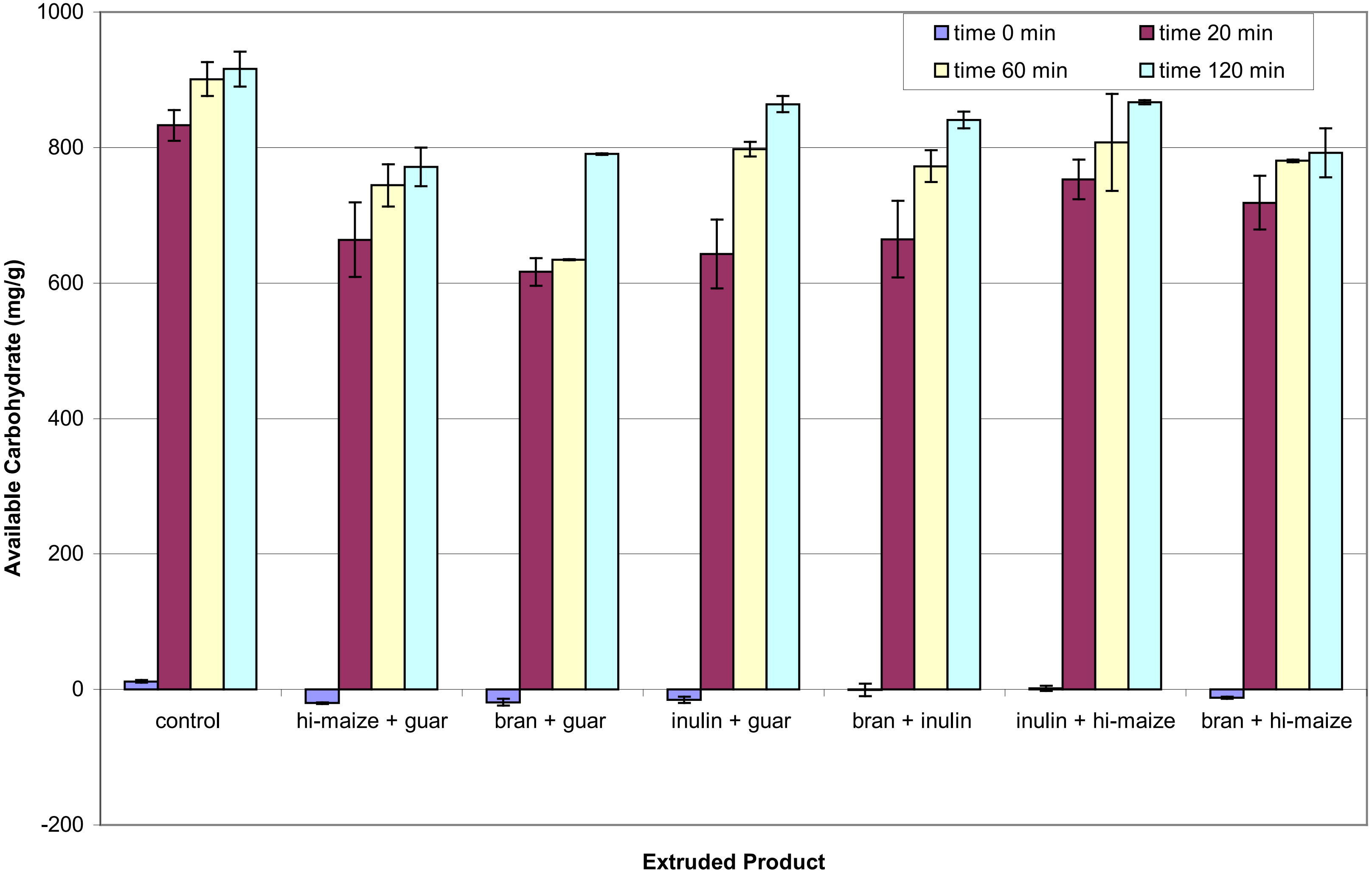


**Figure 6.10 Carbohydrate digestibility of extruded breakfast cereals with combinations of dietary fibres**



The extruded samples showed a greater effect of the fibres reducing the glycaemic effect of the breakfast cereal products. At each of the time digestion intervals all of the fibre fractions reduced the amount of starch digestibility significantly compared to the control extruded cereal product, except for the samples at 60 minutes of the inulin + hi-maize. The inclusion of guar gum appeared to have the highest effect in reducing the readily digestible carbohydrate fraction. Thus the 20 minute sample showed a 27 % reduction in readily digestible carbohydrates.

The combination of bran and guar gum produced the lowest digestibility values at 20 and 60 minutes. The combination of inulin and hi-maize was the least effective in reducing carbohydrate digestibility values, for instance at 20 minutes a 6 % reduction, at 60 minutes a 10 % reduction and at 120 minutes a 9.5 % reduction. These results being less than one would expect from a 15 % replacement of flour as one would expect a 9.5 % reduction based on a starch content of the base being 70 %. Thus when a combination of fibres exert a digestibility reduction of less than 9.5 % the fibres can be regarded as having no significant effect on carbohydrate digestibility

### *6.4 Discussion*

Although the inclusion of individual DFs in extruded snack food recipes has been studied by a number of researchers (Chinnaswamy and Hanna, 1991; Fairchild *et al.,*1996; Bourdon *et al.,* 1999; Brennan and Tudorica, 2007), no research had been conducted on the use of combinations of DFs on manipulating the functionality of extruded products. The uniqueness of the research in this chapter is therefore evident.

Results indicate that selecting the combinations of fibres to be included in the base recipe of breakfast cereal products could have both positive and negative effects on product characteristics and nutritional quality. The combination of guar in the base recipes showed a greater effect in terms of reduction of starch digestibility than either bran or inulin. Work conducted by Tudorica *et al.* (2002) and Brennan and Tudorica, (2007) have shown that guar can reduce starch digestibility greater than the incorporation of other soluble or insoluble fibres. This effect has been associated with the thermodynamic incompatibility of fibre and starch (Tolstoguzov, 2003 a,b) and the effect guar gum has in encapsulating starch granules (Brennan *et al.,* 1996).

Although the addition of inulin can lower the potential glycaemic effect of food products and hence reduce blood glucose levels (Yamashita *et al.,* 1984), it is clear that the effect of inulin in reducing the glycaemic index of foods is minimal (Schneeman, 1999; Tudorica *et al.,* 2002). However, the addition of inulin to the extruded base recipes resulted in an increase in product expansion compared to bran samples. The inclusion of bran into extruded snack products resulted in a denser, harder, breakfast cereal product, probably due to the ability of bran to absorb high levels of water (Robertson *et al*., 2000). It is of paramount concern to the food manufacture that products which have high fibre composition are accepted by the consumer, hence these products require a high amount of expansion and a low overall product density.

### *6.5 Conclusion*

Currently no research has been conducted on the effect of combining different dietary fibres in extruded food products. The current research showed that no combination of fibres significantly affected moisture loss during extrusion. Hi-maize and guar, inulin and guar, and inulin and hi-maize significantly increased the expansion characteristics compared with the control. This result is similar to that observed in Chapter 5.

In relation to the viscosity altering properties of fibre systems, all raw samples and extruded product enriched with guar showed increased cold peak viscosity, and final viscosity compared with the controls. Readily digestible carbohydrate was significantly reduced in all raw samples at 20 minutes. The extruded product showed reduced available carbohydrate at all times for all combinations. The significance of these results is discussed in the following chapter.

# Chapter 7 General Discussion and Conclusion

In order to establish a clarity to this final chapter, it is divided into three distinct sections. A summary of the results obtained for each of the experiments is stated at the start, this is then followed by a general discussion as to the relationships between different components and the product characteristics, and lastly recommendations for future research are made.

## *7.1 Conclusions from the first experiment.*

Extrusion had no effect on protein content when moisture content of the products was accounted for. When the different dietary fibres were used, inclusion of bran resulted in a lower pasting viscosity, increased product density, reduced product expansion, and there was no significant effect on readily digestible carbohydrate. Inclusion of guar gum increased pasting viscosity and product density, but no significant effect on expansion. Inclusion of guar gum reduced the readily digestible carbohydrate. In all cases, the use of high ratio wheat flour bases showed higher expansion ratio on extrusion than wholemeal bases as well as higher carbohydrate digestibilities.

## *7.2 Conclusions from the screw configuration experiment*

The reverse screw configuration gave a greater moisture loss, a reduced density, more readily digestible carbohydrate, and reduced viscosities compared to the straight screw configuration. The hardness of control samples was similar for both screw configurations. The hardness of fibre enriched samples was reduced and the crispness increased in the reverse screw configuration compared to the straight screw configuration.

## *7.3 The role of wheat bran as an ingredient in extruded breakfast products*

The current research shows clearly that the amount of moisture loss during extrusion (amount of moisture driven off during the extrusion process) increases with increasing bran content. In conjunction with this, increasing bran concentrations increases product density, reduces expansion, increases hardness and increases crispness.

From a starch structure point of view, as determined by the pasting properties assessed by the rapid visco analyser, when bran is added, the extruded product gives a decreased cold peak viscosity and peak viscosity compared with the control. Final viscosity was not affected in such a way, thus the extruded products were similar to the control especially at 15 % inclusion.

It is noteworthy that bran inclusion gives a larger than expected decrease in starch compared to the control for instance a 5 % replacement gave an 11 % reduction whereas a 15 % replacement gave a 20 % reduction. This reduction in apparent starch could be related to variations in the digestibility of starch. In this case, *in vitro* analysis showed that the comparing the bran enriched extruded products to the control samples, the carbohydrate digestibility was reduced with increasing amounts of bran. The effect was most noticeable at 20 minutes where 15 % bran gave 27 % reduction in digested carbohydrate, although after 120 minutes the reduction was only 17 %. This may be associated with the fact that a 15 % inclusion of bran increases TDF to approximately 10 %.

### *7.4 The role of guar gum as an ingredient in extruded breakfast products*

As with bran, the amount of moisture loss during extrusion increased with increasing content of guar gum. Guar gum addition also resulted in increased product density and expansion (except at 15 % inclusion). Although the hardness of the product was not different to the control crispiness of the product increased. With regards to the pasting characteristics, addition of guar increased all viscosity profiles at all levels of inclusion raw and extruded compared to the control, probably due to the hydrating capacity of guar gum. Guar gum inclusion was shown to decrease carbohydrate digestibility at all times and at all levels of inclusion when compared to the control samples. Guar gum addition gave a larger than expected decrease in starch compared to the control, 5 % replacement giving a 12 % starch reduction, 15 % replacement giving a 19 % starch reduction, and a 15 % inclusion of guar gum appeared to increase TDF to 16 %.

### *7.5 The role of inulin as an ingredient in extruded breakfast products*

In the case of inulin, the amount of moisture loss during extrusion decreased with increasing inulin levels. Inulin addition also resulted in increased product density and expansion at 5 %, but not significant from control at 10 % and 15 %. Interestingly hardness of the extruded product was reduced with inulin inclusion whereas crispiness increased. The pasting properties of extruded and raw products slightly increased with

15 % inulin addition, however cold peak and final viscosities at 10 % were similar to the control and at 5 % all viscosities were lower than those observed with the control samples. A larger than expected decrease in starch content was observed compared to the control sample, thus a 5 % replacement gave a 17 % reduction in apparent starch content and a 15 % replacement gave a 23 % reduction. The extruded product with 5 % inulin addition gave a carbohydrate digestibility that was reduced compared to the control. However, increasing inulin content equated to similar product digestibility to the control. There was no increase in TDF when inulin was incorporated, however this may be due to the fact that the assay kit was not designed to recognise oligosaccharide fractions.

### *7.6 The role of hi-maize as an ingredient in extruded breakfast products*

Hi-maize addition resulted in a decrease in amount of moisture loss with increasing hi-maize inclusion. Product density also decreased but product expansion was observed to increase. Both hardness and crispness were not different to control. The pasting viscosities of the extruded product decreased compared with control, although there were no trends with increasing inclusion. Pasting properties of the raw product decreased with increasing inclusion. Percentage starch increased more in the hi-maize enriched product than in the control on extrusion. Even though carbohydrate digestibility of the raw sample was lower than the control at 60 minutes and 120 minutes, hi-maize addition did not affect the carbohydrate digestibility of the extruded product (being similar to the control samples). Addition of 15 % hi-maize increased TDF in the raw bases to 10 %, but after extrusion this dropped to only 6 %. This was the highest drop in TDF of all fibres after extrusion suggesting that the extrusion process had an effect on starch composition.

## *7.7 The role of swede as an ingredient in extruded breakfast products*

As with the majority of the other dietary fibres, increasing the amount of swede fibre in the extruded product resulted in an increase in the amount of moisture loss during extrusion. However, addition of swede fibre fraction reduced the density of the product compared to the control. Expansion of the products was also reduced and this was related to an increase in product hardness and a reduction in product crispness. The pasting viscosities of the extruded product were significantly lower than the control, and this further decreased with increased additions of fibres. Viscosity of the raw samples slightly increased compared to the control, with the final viscosity decreased as fibre content increased. A higher than expected reduction of total starch was observed so that a 5 % replacement gave a 7 % reduction, and a 15 % replacement gave a 21 % reduction. In the raw samples there was no clear pattern of carbohydrate digestibility although there was significantly more carbohydrate available at 120 minutes at all levels of inclusion. The carbohydrate digestibility in the extruded product was similar to the control at 5 % inclusion at all times, whereas the 10 % and 15 % addition showed a reduction in digestibility at all times compared to the control. The amount of TDF increased in the raw sample with including 15 % swede fibre, and increased more in the raw. This was similar to the observation with wheat bran.

## *7.8 Discussion of results*

A direct expansion extruding-cooking process cooks cereal flours at low moisture contents (usually below 20 %). The shear stress and mechanical work can be adjusted by control of the screw speed (between 200 to 450 rpm) in combination with the screw profile. Under these conditions, the extruder cooks the material more mechanically than thermally. The process makes it possible to use various raw materials and recipes and thus alters product characteristics widely (Bouvier, 1996). The results suggest that the inclusion of dietary fibre in the breakfast cereals affects the moisture contents of the extruded products, e.g. in some instances decreases moisture loss, whereas in others increasing moisture loss apparently dependant upon fibre solubility.

Increasing screw speed can damage starch granules and create more expanded products (Della Valle *et al.,* 1987). Generally more expanded extruded products would have larger cells and thinner cell walls. However, Jin *et al.* (1995) reported that altering the screw speed did not effect the expansion properties of fiber enriched products. Hence the structure of extruder snack foods could be altered by a combination of adding fibre and altering processing parameters. Thus by increasing fibre concentration and increasing screw speed reduced the expansion ratio of the snack products, creating smaller air cell size and thicker walls. Jin *et al.* (1995) further showed that by increasing fibre content the breaking strength of the products increased (breaking strength in this case being negatively correlated with radial expansion). Similar results have been described by Lue *et al.* (1991) who reported that fibre in the feed material results in formation and low retention of expanded air pockets. Early research by Guy (1985) indicated that bran interferes with bubble expansion and reduces the extensibility of extruded snack product walls. Moore *et al*. (1990) developed this idea further and reported that increased bran in extruded products increased the cell number per unit area but decreased average cell size.

These examples demonstrate that food structure is a result of microstructural changes which are influenced by physical forces exerted on the chemical components during processing of foods (Stanley, 1986). Thus, the texture of extruded food products can be greatly influenced by the composition of the feed being extruded.

After a direct expansion extrusion cooking process, puffed breakfast cereals can be regarded as low density foamed structures. With a die size ranging from 0.1 to 3 to4 mm the bulk density of the products ranges from 50 to 200 g/L (Guy, 2001). The bulk density is a very important product quality attribute for the commercial production of extruded products because most extruded products are filled by weight and not by volume. Therefore, if the bulk density varies during production, either the pack will not be full or it will overflow. As both these scenarios have serious production implications, bulk density is a quality attribute that is measured regularly for quality assurance purposes. For this reason product structure and texture are of great importance in terms of production efficiency and product quality.

In addition to controlling the correct volume of product in the pack, the bulk density is important in terms of consumer perception of product texture. This is because there is a relationship between the bulk density and the texture because both these parameters are controlled by the degree of expansion (Chessari and Sellahewa, 2001).

Results from this study suggest that the inclusion of dietary fibre components generally leads to an increase in bulk density associated with a general trend of decreasing expansion ratio. Such an observation is important with regards to the commercial usefulness of the product. Products with lower bulk density and higher expansion ratio will be more aerated and hence more final product could be made from the same raw material content. Differences do exist between the types of dietary fibres used, these differences appear to be based on the solubility of the fibre components.

Several studies have been carried out to understand the relationship between the structure and texture of extruded products (Barrett and Palag 1992; Van Hecke *et al.,* 1995; Alverez-Martinez *et al*., 1998). Reports from these studies suggest that the rheology of the dough within the extruder has a significant effect on the final product. For instance, in the formulation of the product, the interaction between carbohydrates, protein and fat alter the rheology of the dough and hence the texture of the final products (Moore *et al*., 1990).

Added dietary fibre affects the digestibility of carbohydrates in food, for instance cellulose when added to maize starch decreased solubility of the starch and hence digestibilty (Chinnaswamy and Hanna, 1991). The adverse nutritional consequences of easily-digested starch include increased dental caries and a rapid rise in blood sugar levels after ingestion. The reduction of polymer size associated with extrusion shear can increase the stickiness of the product to teeth and hence toothpack (Björck *et al.,* 1984).

Fairchild *et al.* (1996) reported that the inclusion of guar gum into a wheat based product improved human glucose tolerance by reducing the serum glucose postprandially compared to low-fibre cereal products. This reduction in blood glucose level in guar gum enriched breakfast cereal products was proposed to be related to the added viscosity that guar gum provides during digestion. This interaction of starch-guar gum in food products was demonstrated more clearly by similar research on guar gum enriched wheat breads (Brennan *et al.,* 1996). More recently Hardacre *et al.* (2006) reported that the addition of peas and lentils into maize based extruded snack products could reduce the glycaemic impact of those foods and Börjck and Elmståhl (2003) reported a similar occurrence in fibre enriched breakfast cereals.

The presence of non-starch polysaccharides in a meal may reduce postprandial sugar and lipid levels, the bio-availability of micronutrients, assist weight reduction and increase stool output. These effects may be explained by the physiological action of non-starch polysaccharides. But not all of them have the same properties. For example guar gum reduces postprandial glycaemia, but has little effect on stool bulking. By contrast, wheat bran and cellulose are better as laxative agents. A possible reason for the differences are the physical and chemical characteristics of the individual non-starch polysaccharides (Read and Eastwood, 1992).

Moisture content being equal, a rise in extrusion temperature will increase the degree of starch gelatinisation and decrease product density and hardness (Sacchetti *et al.,* 2005). The effect of product puffing has been characterised by other researchers (Mercier and Feillet, 1975; Case *et al.,* 1992). Thus, moisture content and the flashing off of moisture could be regarded as a limiting factor in expansion properties and hence the texture of the extruded food product (Lund, 1984).

Previous research by Gourgue *et al.* (1994) has indicated that the extrusion process alters the composition of dietary fibre within the final product. The authors research demonstrated that the extrusion process may not necessarily increase or reduce the level of dietary fibre in the final extruded product, but does appear to reduce the level of insoluble fibre whilst increasing the level of soluble fibre in the food products.

This altering of the composition of the fibre in extruded products could be related to changes in molecular structure. For instance, Ralet *et al.* (1991) showed that the extrusion process significantly reduced the molecular weight of sugar beet pectin and hemicellulose and increased its solubility by up to 40 %. Gaosong and Vasanthan (2000) have found similar observations in the functionality of beta-glucans after extrusion.

RVA patterns of extruded products typically show large differences in pasting properties between the raw and extruded products. In most cases the peak viscosity and final viscosity values are significantly lower in extruded products than raw products (Bouvier, 2001). This has been associated with the gelatinisation and disruption of the starch granule during the high shear and high temperature of extrusion. Peak viscosity for starch / polysaccharide systems have been shown to be significantly higher than control starch systems, possibly due to the thickening effect of polysaccharides and interactions between the polysacchairdes and swollen starch granules (Rojas *et al.,* 1999, Tester and Morrison, 1990).

The branched structure of amylopectin makes it more susceptible to shear stress than amylose (Jin *et al.,* 1994) thus high amylose starches will be less prone to degradation. Panlasigui *et al.* (1992) suggested that high amylose rice extruded into noodles had a lower starch digestibility and reduced glycaemic index than normal rice flour.

Foster *et al*. (1998) have proved that eating breakfast associates with an improved memory in the morning. Children between 11-13 years who have a breakfast tended to remember more words after 30 minutes, than children without. The effect has also been confirmed for adults but has disappeared for both 90-120 minutes after the meal. The rapid rise in blood glucose after breakfast provides these high mental functions. After two hours the memory still correlates with the glucose level (Foster *et al.*, 1998).

### 7.9 Future research

The research in this thesis has shown that the inclusion of a wide range of dietary fibres into breakfast cereal products is possible without necessarily negatively affecting the physical and nutritional properties of the product. However careful selection of the fibres is important in ensuring the optimal quality of the products in terms of consumer acceptance.

One of the areas which could be explored in more detail is the consumer acceptance of such products. No sensory analysis was conducted in this study. Future research should investigate the use of sensory panels in the determination of product characteristics.

This would help to evaluate the level of fibre inclusion that can be used in breakfast cereals to determine consumer acceptance and preference.

The research also indicated that significant differences in glucose release can be achieved by including fibre ingredients into breakfast cereal products. This was evaluated using standardised *in vitro* analysis. Further research could investigate this observation further by conducting *in vivo* glucose determinations in order to illustrate clear relationships between fibre use and control of glycaemic response.

Finally, the fibres used in this study were relatively uncharacterised in relation to molecular weight, polymer length and viscosity altering properties. Previous research has suggested that the viscosity altering attributes of fibres play a significant role in the manipulation of the glycaemic impact of foods. A further piece of research could focus on the inclusion of fibres with well characterised and defined molecular weight and viscosity properties. Inclusion of these fibres and the determination of the physical and nutritional characteristics of the resultant extruded products would illustrate any relationship between raw material viscosity profile and the nutritional impact of such products.

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