Cheddar Cheese: Its texture, chemical composition and rheological properties.

Joanne Hort

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Abstract

Procedures associated with Quantitative Descriptive Analysis were used to identify and subsequently train a panel to quantify the perceived textural attributes of Cheddar cheese. Seventeen types of Cheddar were assessed by the panel for creaminess, crumbliness (fingers), crumbliness (chewing), firmness, graininess, hardness (first bite), hardness (cutting), and springiness. Cluster and Principal Component analyses of the sensory data revealed that the cheese samples could be subdivided into young, mature and extra mature Cheddars in terms of the textural attributes measured. The panel was also able to distinguish between the low fat and genuine Cheddars.

The percentage fat, moisture and salt contents and the pH level of the seventeen Cheddar samples were established. An inverse correlation between fat and moisture content and a positive correlation between pH level and salt content were observed. The rheological properties were measured using three tests performed on an Instron Universal Testing Machine - a compression test, a cutting test and a stress relaxation test - and, where appropriate, were reported in terms of true stress and true (Hencky) strain curves. The viscoelastic properties of Cheddar observed during stress relaxation tests were modeled using a Generalised Maxwellian model consisting of two exponential elements and a residual term. Considerable variation in all the rheological properties was observed amongst the Cheddar samples. The rheological parameters did not distinguish between the samples to the same extent as the sensory assessment. However, Cluster Analysis of the rheological data did differentiate between the rheological profiles of the young (mild & medium) and the remaining mature/extra mature samples.

The relationships between the textural attributes and the chemical and rheological parameters were investigated. No relationship between chemical composition and texture was identified, but correlations between the rheological parameters and the textural attributes were not uncommon. Multiple regression techniques were employed to construct mathematical models to predict the textural attributes from the rheological data. Successful models were constructed utilising parameters from the compression and cutting tests for all the attributes apart from creaminess. More precise models were constructed for firmness, springiness and crumbliness (fingers) where the action of the instrumental test from which the rheological parameters were obtained resembled the test method used by the panel.

The chemical, textural and rheological properties of an English Cheddar were determined at various stages during its ripening period to investigate any changes that occurred. A slight increase in pH was the only chemical change recorded. Progressive changes in the majority of the textural attributes were observed. The most dramatic changes included a decrease in springiness and an increase in creaminess. A changing rheological profile was also observed during maturation, a decreasing strain at fracture being the most notable development. The sequence of changes in both the textural and rheological properties was divided into three fairly distinct phases, the initial stage reflecting the developments necessary before the cheese would be suitable for retail sale and the final stage including the development of the necessary textural attributes characteristic of a Mature English Cheddar. It was evident that the timing of the maturation period was pertinent to the development of textural attributes characteristic of particular maturities of Cheddar cheese. The textural attributes of the maturing Cheddar were also predicted at each stage of maturation using the mathematical models constructed in the initial study. Accurate predictions were made for all the attributes except crumbliness (chewing) and graininess.

Publications

Hort, J. (1996) The relationships between the texture, physical and chemical properties of Cheddar cheese - developing a methodology. *Food Science and Technology Today* **10,** 94-99.

Hort, J., Le Grys, G. & Woodman, J. (1996) Objective sensory measurement of consumer perceptions of the textural properties of Cheddar cheese - an aid to classification and marketing. *'Consumer Research Science' in The Home Economist* **15**, 11-14.

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1.1 Cheese

Although the precise origins of cheesemaking may never be known, evidence from ancient writings and archeological sites suggests that some form of cheese has been consumed since at least 8000 BC (Davis, 1965). Rennet curd cheeses, a group to which Cheddar belongs, are believed to have been discovered by accident by nomadic tribesman using the stomachs of dead animals to transport their milk supplies (Ogilvy, 1976).

Cheddar cheese manufacture originated in the United Kingdom (UK) during the nineteenth century and took its name from the village of Cheddar (Somerset, England) where the process of piling cheese curds, thereafter known as cheddaring, was first thought to have been carried out (Fox, 1987). Cheddar rapidly established itself as an important cheese in the UK, not least due to its ease of manufacture, ease of transport and keeping qualities. The cheddaring technique was quickly embraced by cheesemakers in the United States of America (USA) and Canada; in fact the first factories built for the mass production of Cheddar were founded in North America in the latter half of the nineteenth century (Lawrence & Gilles, 1987). In the past thirty years the introduction of more reliable starters, continuous mechanised manufacturing systems and close monitoring of the chemical composition of the cheese has enabled dramatic improvements to be made in the large scale production of Cheddar of a consistent quality (Lawrence & Gilles, 1987). Currently Cheddar is the top selling cheese in the UK, USA, Asia and Australia (Anon., 1997).

The market for cheese in the UK is continuing to increase and, although the volume of Cheddar sold has decreased slightly during the nineties, it still accounts for half of the total market value (MINTEL, 1996). Maturer Cheddars are capturing the consumers attention and a growth in the number of premium cheeses has further increased the range of Cheddars available to the public, although mild Cheddars still account for one third of the market due to their popularity with children (MINTEL, 1996).

1.1.1 Cheese texture

Szczesniak (1971) highlighted the significance of texture to the consumer proving it to be a discernible characteristic in a wide variety of foods. This is particularly true for cheese where its texture is widely recognised as one of the most important parameters in determining both its quality and identity (Creamer & Olson, 1982). Indeed, McKewan et al. (1989) reported that the textural attributes of Cheddar were important in determining the acceptability of this cheese to the consumer. Reliable methods enabling the measurement of cheese texture are therefore a pertinent requirement for the cheese industry.

1.2 The manufacture of Cheddar cheese and its effect on texture

The major constituents of cheese - casein, fat and water - all contribute to the final structure of the cheese. Cheddar cheese is composed of an open, mesh-like casein matrix which is interspersed with fat globules and a complex solution of small molecules in water, some of which is bound to the protein molecules (Jack & Paterson, 1992). The relative amounts of fat, moisture and protein present affects the textural properties of the cheese as the extent to which the protein matrix can be deformed is restricted by the amount of fat and, to a lesser extent, moisture present (Prentice, 1987).

Although ultimately the texture of Cheddar cheese depends on the extent of the proteolysis of the protein network during ripening, the final structure of the cheese is strongly influenced by the nature of the raw ingredients and the various stages involved during its manufacture (Figure 1-1). The curd structure developed during manufacture is a direct precursor of the final cheese structure and thus forms the basis of its textural properties (Green & Grandison, 1987).

Coagulation of the Milk

As the composition of raw milk affects the composition of the final cheese, milk is usually bulked and standardised before production to achieve a casein to fat ratio between 0.67 and 0.72 (Lawrence & Gilles, 1987). If the proportion of fat is too high then inadequate whey removal occurs, resulting in a cheese with a too high moisture content. In addition, prior treatment of the milk by homogenization or ultra filtration has been shown to affect the final texture of the cheese; ultra filtration, for example, produces a coarser protein network (Green et al., 1981).

In the first stage of Cheddar production a coagulant and lactic starter culture are added to cooled pasteurised milk to produce a firm coagulum. The main role of the starter culture is the production of lactic acid. The rennet coagulant, usually chymosin, is responsible for the proteolysis of spherical casein micelles in the milk which subsequently aggregate to form the coagulum. The casein micelles consist of αs_1-, αs_2-, β- and κ-casein, insoluble calcium phosphate and water (Walstra et al., 1987). The primary stage of curd formation involves the proteolysis of the κ-casein causing the destabilization of the casein micelles (Fox, 1989) which ultimately rebond to form a network. As the micelles contract they begin to fuse together. The aggregation of the casein micelles continues throughout all the stages of Cheddar production (Green & Grandison, 1987).

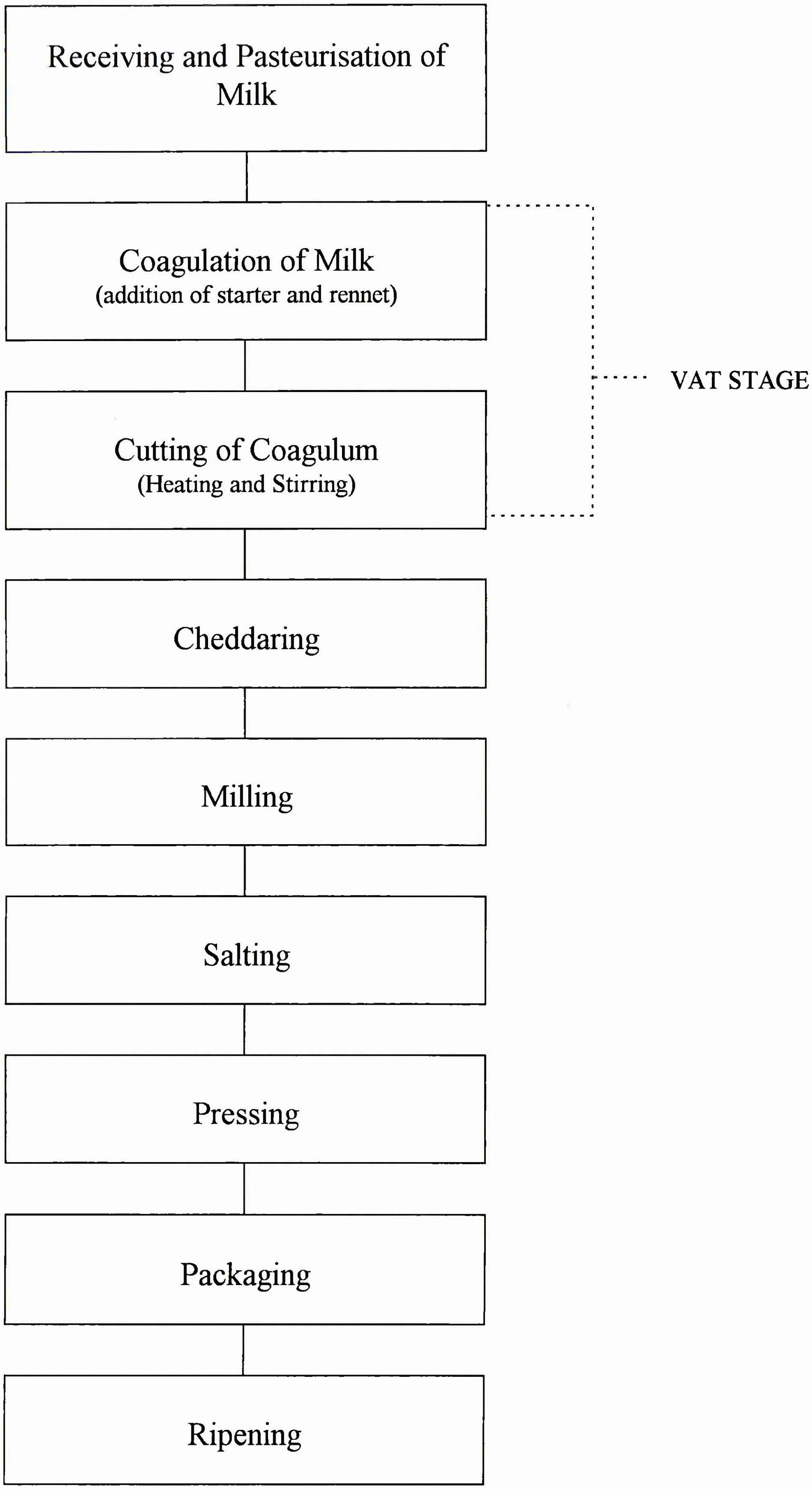


Figure 1-1. Stages in the manufacture of Cheddar cheese

Cutting of the coagulum

The second stage of Cheddar production involves the cutting of the rennet coagulum to produce the curds and whey. The cutting initiates the process of syneresis during which the curd contracts causing expulsion of the whey. The curds and whey are stirred and heated to approximately 39°C (Lawrence & Gilles, 1987) which, together with the decrease in pH that occurs as a result of starter activity, contributes to the shrinkage of the casein micelles and consequent whey expulsion.

The level of acid production during the vat stage is cited as the "single most important factor in the control of Cheddar cheese quality" (Lawrence & Gilles, 1987 p7) since the pH level determines the extent of the whey expulsion and consequently controls the level of lactose, chymosin, plasmin and calcium phosphate in the curd. The amount of lactose remaining in the curd will affect the extent of further acid production. The level of residual enzymes is important in terms of the extent of proteolysis that can occur during ripening. As more acid is produced dissolution of calcium phosphate increases. The colloidal calcium phosphate is believed to play a role in the aggregation of the casein micelles (Walstra et al., 1987). If mineral loss is high then the aggregates tend to be small which results in a weak and pasty texture such as that observed in Cheshire cheese.

The pH of the curd must have become 5.8 or less to enable the development of the fibrous texture that occurs during the cheddaring stage (Lawrence & Gilles, 1987). Once this level is attained, the whey is drained.

Cheddaring

Traditionally, cheddaring involved the piling and turning of the curd - a process that was viewed as essential for the development of the typical close fibrous texture associated with Cheddar cheese. Although presently the curd is held in cheddaring towers during manufacture, this stage of the process is believed to be more important in terms of further acid development and to allow the curd to mat together (Lawrence and Gilles, 1987). During this stage, at a pH of 5.8 or less, calcium phosphate and some moisture are lost from the spherical casein micelles causing changes in the conformation of the casein structure. The micelles become more fibrous in nature and begin to fuse under gravity and the pressure of the weight of the curd. The resultant texture of the cheddared curd is often described as 'chicken breast'.

Milling and Salting

The curd is milled into small pieces to ensure even distribution of the salt and allow further whey drainage. If the particles are too large uneven salt distribution will occur which results in a seamy textured cheese. The amount of salt added is important in order to obtain the required salt in moisture level (S/M) (Gilles, 1976). The S/M level controls the pH and the rate of proteolysis. If too much salt is added extensive moisture loss causes incomplete binding of the curd particles resulting in a crumbly texture known as seaminess (Lawrence & Gilles, 1987)

Schroeder et al. (1988) reported that a reduction in salt content resulted in an increase in cohesiveness and decrease in firmness but concluded that reducing the salt content to 1.12% would not affect the acceptability of the cheese texture (or flavour). Additionally, time is given to allow the absorption of the salt into the milled curd particles prior to pressing.

Pressing

In most modern Cheddar plants the curd particles are fed into a tower under vacuum and are subjected to a short period of mechanical pressure (approx. 33 kPa pressure). The vacuum prevents air being trapped in the cheese which could otherwise cause the development of defects in the cheese. The pressed Cheddar blocks are then packaged ready for a period of ripening.

1.3 The influence of the maturation period on Cheddar texture

In order to achieve the desired texture a newly manufactured Cheddar must undertake a period of maturation. The length of the ripening period varies depending on the type of Cheddar; typically, in the UK, the length of maturation can vary from three to twelve months but can be as long as twenty four months. Maturation temperatures range between 5-12°C and the relative humidity can vary between 87 and 95% (Davis, 1965). When Cheddar blocks are enclosed in a moisture proof barrier controlling the humidity level is less important (Derbyshire, 1994, personal communication).

Lawrence et al. (1987) identified two distinct phases in the development of cheese texture. Initially, that is within the first 7 to 14 days, residual coagulant enzymes are responsible for the relatively rapid hydrolysis of the α_{s1}- casein to the soluble α_{s1}-I casein fraction, which reduces the rubbery texture of the cheese. Indeed the cleavage of one individual bond in 20% of the α_{s1}- casein has been reported to have a marked effect on the strength of the protein matrix (Creamer & Olson, 1982).

The second stage of maturation, which covers the remainder of the ripening period, involves further, but distinctly slower, proteolysis of the protein by coagulant enzymes; native milk proteases, such as plasmin; and enzymes released by starter bacteria and secondary microflora, such as lactobacilli and pediococci (Fox, 1989). However, the majority of β-casein and other serum proteins remain intact providing bulk to the cheese (Adda et al., 1982).

Several factors, in addition to the duration and temperature of maturation, are known to determine the rate of proteolysis. The concentration of the various proteolytic agents present is influential. The amount of residual coagulant in the cheese is particularly important and this is controlled by the pH at draining during the manufacture of the cheese (Lawrence et al., 1987). Additionally, the pH level during maturation affects the size and shape of the casein sub-micelles. At higher pH levels, pH > 5.5, a springy cheese is produced, whereas at pH levels of around 4.9 the production of smaller micelles results in a shorter textured cheese (Lawrence et al., 1987)

Considerable variation in the rheological properties of a single cheese may develop during the maturation process. Cheddars ripened in contact with the air lose moisture more rapidly from the outside layers and thus the rate of proteolysis may be different in different areas of the cheese. Additionally, as large cheeses such as Cheddar are turned during maturation the top and bottom layers are subjected to both low and high compressive stresses in comparison to the centre of the block. Consequently the outer layers are firmer than the centre portion of the cheese (Prentice, 1987).

Research considering changes in the perceived textural properties of Cheddar during ripening is limited and much of that published is in review format, for example Lawrence et al. (1987). Piggott and Mowat (1991), Roberts and Vickers (1994) and Muir et al. (1996) have recently published research which included investigating the relationship between Cheddar texture and aging; all concluded that texture did not appear to be correlated with age. Muir et al. (1996) reported no systematic changes in the textural attributes measured, apart from 'mouth coating', when the results of 16 different Cheddar types were combined. Roberts and Vickers (1994) had expected to observe differences in texture at different stages of maturation and suggested that changes may have been detected had they extended the ripening period beyond nine months.

1.4 Sensory measurement of texture

The human senses instinctively guide consumers in their choice of food. Appearance can give some indication as to a food's textural properties, as can the noise made when it is consumed (Abbott, 1973). However, most of the information utilised by the brain in its perception of textural attributes is obtained via the sense of touch, including mouthfeel. Reflecting this the food industry uses sensory panels to indicate which textural attributes are important and how they should be measured.

Early research concerning food texture treated it as a single entity as opposed to a combination of different attributes (Szczesniak, 1973). Much of the early work was also related to specific foods - for example the tenderness of peas and the toughness of meat - and thus the textural attributes considered and the terminology used were defined in relation to the particular foodstuffs (Bourne, 1982). Szczesniak (1963) cited this, together with problems in applying theoretical rheology, as reasons for the fact that texture was the "least well described" attribute of a food. At the same time she highlighted the need for a "rational system and nomenclature for describing and translating textural qualities into precisely defined, measurable properties" (Szczesniak, 1963).

1.4.1 General Foods Sensory Texture Profile Analysis

The limited availability of research in this area led to what is regarded as a major development in the area of food texture measurement. In 1963 workers at the General Foods Corporation, USA, published a method of texture profiling designed to meet those requirements stated above (Brandt et al., 1963). The General Foods Texture Profile Analysis (GFTPA) involved the evaluation of the mechanical, geometrical, fat and moisture properties of a food perceived at the three different stages of ingestion - initial, mastication and residual (Abbott, 1973). The terminology and associated definitions used to describe the mechanical and geometrical attributes perceived in foods were predefined in a manner it was expected the assessor could relate to. They were based on Szczesniak's (1963) classification of textural attributes, for example 'adhesiveness', detected during mastication, was defined as 'the force required to remove the material that adheres to the mouth during the normal eating process' (Abbott, 1973). It was quickly established that a panel, carefully selected to carry out texture profiling, required comprehensive training. The adoption of this technique by many food laboratories led to the publication of detailed guidelines on how to train a panel (Civille & Szczesniak, 1973). GFTPA panels are trained to reach a consensus on the use of the specially designed Standard Rating Scales (Szczesniak, 1963). These scales exist for each of the mechanical and geometrical characteristics and consist of specific food samples which represent increasing increments of the particular textural characteristic. For example, Philadelphia cheese represents one and Rock candy represents nine at either end of the Hardness Standard Rating Scale. Once these scales have been mastered the assessors are instructed in how to produce the texture profile of the particular food under investigation (Bourne, 1982).

The GFTPA technique has and is still used to measure the textural properties of a wide range of foods and can be modified to investigate the range of properties in a specific food. Civille and Liska (1975) published recommendations for modifying and applying the General Foods Sensory Texture Profile technique for specific food products. Modifications included the development of a specific evaluation technique and terminology appropriate for the food in question. Lee et al. (1978) modified the technique to measure the initial mechanical characteristics of relevance to cheese (hardness, adhesiveness, cohesiveness and chewiness) and compared them to results obtained using various instrumental tests. More recently Lakhani et al. (1991) used the technique to produce a sensory texture profile of Cheddar made from ultra filtered milk and Bryant et al. (1995) used it to quantify the effects of varying fat content on Cheddar texture.

1.4.2 Quantitative Descriptive Analysis

The development of the GFTPA technique led to an increased interest in descriptive methods of sensory analysis, especially those that would alleviate problems in the food industry. In the food industry judgments concerning food quality are often made by a single expert; a role performed by the cheese grader in the cheese industry. The assessment of quality by an expert, although valuable, is subjective and not necessarily a firm basis for the types of market decisions made by a food company (Stone et al., 1974).

In 1974 Stone et al. published a technique, which they called Quantitative Descriptive Analysis (QDA), to be used as an alternative to other descriptive analysis procedures and in those areas unsuitable for assessment by a single expert, for example, product development. The technique involved the description and quantification of all the sensory properties associated with a food, - appearance, taste, aroma, flavour and texture. Unlike previous descriptive methods, which collected data on what could only be treated as ordinal scales, this approach generated interval data which could then be subjected to statistical analysis (Stone & Sidel, 1985). The QDA procedure has since been modified and adapted by sensory analysts to meet their own particular needs and is now regarded as the preferred method of texture measurement (Jack & Paterson, 1992).

The group of methods developed from QDA, sometimes referred to as Conventional Profiling techniques, all follow the same basic stages (Lyon et al., 1992). Panelists, screened for their sensory abilities, are presented with a wide range of samples of the product in question in order to individually produce a list of all the terms they would use to describe the sensory properties they perceive. Following this, the panel discuss, agree upon and define the descriptors that should be used to describe the sensory properties of that product. Unlike the GFTPA technique which predefines the textural attributes, QDA allows all the textural attributes perceived in that product to be considered. The properties are quantified by the positioning of marks on continuous line scales which can then be converted to numerical values. Consequently panel training involves practice at using these scales until assessors can repeatedly quantify the different attributes. After the training is complete the testing begins with replicate judgments made in order to establish the reliability of the procedure (Stone & Sidel, 1985).

Quantitative Descriptive Analysis procedures have been used extensively over the past decade to define and measure the texture properties of cheese (Colwill, 1989; McEwan et al., 1989; Piggott & Mowat, 1991; Muir & Hunter, 1992; & Muir et al., 1995). Colwill (1989) used Conventional Profiling to determine the ideal sensory properties for Cheddar cheese. The textural properties identified by the panel consisted of 'graininess', 'mouth coating', 'rubbery' and 'soft-firm'. Muir et al. (1995) set out to identify the key sensory attributes of hard cheeses concluding that the important textural attributes were 'firmness', 'rubbery character', 'pasty character', 'grainy character' and 'mouth coating character'. The texture attributes identified by the different researchers are similar even though the approach, such as the size, background and time spent training the panel, varies. Other perceived texture properties identified during descriptive analyses of Cheddar cheese include 'smoothness', 'crumbliness' and 'tongue tingling'.

1.4.3 Free Choice Profiling

Sensory techniques are both time consuming and expensive. The use of a technique called Free Choice Profiling (FCP) was first published in 1984 (Williams & Langron, 1984) and has since been increasingly employed in the UK. Unlike other techniques it does not require a highly trained panel and, as a result, the cost advantage appeals to the food industry. Free Choice Profiling assumes that all the panel members perceive the same sensory attributes but use different words to describe them and measure them on different scales (Jack & Paterson, 1992). Assessors generate their own individual list of descriptive terms to describe the sensory properties of a product and then rate the intensity of their own attributes on their own chosen type of scale. The results are subjected to sophisticated statistical analysis, namely General Procrustes Analysis, to identify which descriptors describe and discriminate between the particular food product (Lyon et al., 1992). The technique has been applied, using a small trained panel, to Cheddar cheese with some success (McKewan et al., 1989). More recently Jack et al. (1993) used the technique with a consumer panel concluding it to be a useful procedure for gaining information concerning the range of textural properties of Cheddar cheese.

1.4.4 COST/902 FLAIR programme of the European Community

As part of the FLAIR COST programme a group was established to "harmonise the training of the tasting panel and to develop a common method for characterizing hard and semi-hard cheeses" (Lavanchy et al., 1993). They believed that Szczesniak's classification of the textural attributes of food was not specific enough for cheese. Consequently guidelines for the sensory evaluation of the texture of such cheeses were published in 1993 (Lavanchy et al., 1993). The guidelines identified textural characteristics specifically related to semi-hard and hard cheeses providing both sensory and, where appropriate, rheological definitions of the attributes. Specific methods and scales were presented for measuring the attributes. Ordinal category scales were presented for measuring some characteristics, mainly the geometric attributes, whilst interval scales were supplied for mechanical properties. Reference samples were indicated for training the panel in the interpretation and use of the scales.

1.4.5 The cheese grader

A discussion of the methods employed to evaluate the textural properties of cheese would not be complete without mention of the highly respected and successful role of the Cheese grader. In the cheese industry the textural quality of Cheddar is determined primarily through sensory assessment, a task which is traditionally the responsibility of a single expert cheese grader. Following a considerable number of years experience and training the grader can accurately assess, and predict, the textural quality of a cheese based on a few simple sensory measures. By observing, bending, manipulating and finally tasting a cylinder of Cheddar cut from a maturing block the grader assigns a range of scores to various textural attributes listed on a scorecard (Bodyfelt et al., 1988). Within the industry his/her assessments are used not only to assess the suitability of a given batch for a final end description, but also to define a likely maturation time.

Unfortunately textural attributes are communicated by a vocabulary of terms which appear ambiguous (Prentice, 1987). This ambiguity becomes increasingly problematic when the terms used by sensory panels and consumers are also interpreted differently again.

1.5 Instrumental measurement of texture

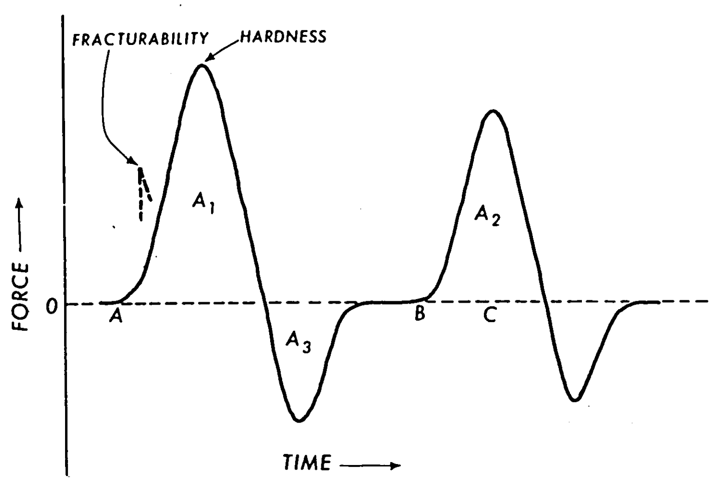
Rheology is a branch of physics concerned with the deformation and flow properties of matter. The rheological properties of cheese are very important to both the consumer and the cheese industry as it is these properties that manifest themselves as the textural attributes perceived by the consumer; dictate the ease of cutting, grating etc. and influence ease of handling and packaging (Walstra & Peleg, 1991).

The rheological properties of a food are measured by instruments that deform a food sample in some manner whilst recording the forces applied and resulting deformation. The use of instruments to measure the textural properties of food dates back to the 1600's (Bourne, 1982). However, it was in the late 1800's and early 1900's that research into the development of testing instruments to evaluate the texture of specific foodstuffs, including cheese, began to increase. For example, the Ball Compressor was designed to mimic the pressing of a cheese graders thumb on the cheese surface - the depth of the indentation made by the ball and recovery time were indicative of the level of firmness and elasticity (Konstance & Holsinger, 1992).

Brennan et al. (1970) described the three categories of instruments available at that time: those which attempted to simulate mastication, those which acted upon specific food stuffs and finally those which measured a particular physical property by the application of a simple mechanical action to the food. Indeed all such categories of instruments are still used routinely in the food industry today.

1.5.1 General Foods Objective Texture Profile Analysis

In 1963 the General Foods Corporation made a major development in the area of instrumental texture measurement using a imitative device, thereafter known as the Texturometer, which could perform objective assessments of several textural attributes. Food specimens were compressed twice by a descending plunger. The textural properties were calculated from various elements on a force-time curve that was produced simultaneously on a chart recorder, an example of which can be seen in Figure 1-2. The measures were based on the classification of textural characteristics drawn up by Szczesniak (1963) which were also used for the General Foods Sensory texture profile.



Hardness	*height of first peak*
Fracturability	*force at the significant break in the first curve*
Cohesiveness	*ratio of areas beneath the two curves (A_2/A_1)*
Adhesiveness	*the area of the negative curve after the first compression (A_3)*
Springiness	*the time taken between the end of the first bite and the start of the second (BC)*
Gumminess	*hardness x cohesiveness*
Chewiness	*gumminess x springiness*

Figure 1-2. GFTPA force-time curve (Bourne, 1982)

The technique was adapted for use with the Instron Universal Testing Machine and was applied with some success during the 1960s and 70s. In comparison to the Texturometer the Instron was a more effective 'tool' to use as it allowed the use of a constant crosshead speed and the production of a force-time curve that was effectively a force-displacement curve (Breene, 1975).

Instrumental measurements of Cheddar's textural properties using the General Foods TPA technique are widespread. Chen et al. (1979) employed the technique to compare instrumental texture measurements of a variety of cheeses with those made by a sensory panel. More recently the technique was used to examine the texture profile of Cheddar made from buffalo's milk (Patel et al., 1993). Jack et al. (1993) used several of the General Foods parameters when comparing instrumental measures from a double bite test with textural characteristics perceived by a consumer panel.

1.5.2 Empirical methods

Various instruments have been developed to measure the texture of specific foodstuffs such as the aforementioned Ball Compressor, the Warner-Bratzler Shear (Bourne, 1982) and the Ottowa Pea Tenderometer (Timbers & Voisey, 1987). Many such empirical tests are based on puncturing or shearing a food sample and have been shown to correlate significantly with sensory data (Bourne, 1982). However, such empirical methods are subject to criticism as the parameters measured often represent a combination of several aspects of the structure of the food sample and are therefore poorly defined. As Bagley and Christianson (1987) pointed out "erroneous conclusions can only too readily be drawn from data obtained by methods not fully understood".

1.5.3 Fundamental methods

Fundamental methods entail the measurement of a food material's precise rheological properties. These can be described mathematically and the results of tests are returned in standard units of measurement. As a consequence the properties measured are well defined and are not, theoretically, restricted to the test instrument, test method or test laboratory (Muller, 1973).

An inventory of test methods was published recently (van Vliet et al., 1991), which, although not exhaustive, critically reviewed those most often used to measure the rheological properties of cheese. The methods were classified into two groups static, where a constant stress, strain, or strain rate is applied to a specimen, and dynamic, where stress, strain or strain rates vary sinusoidally with time. Dynamic tests provide effective information concerning viscoelastic materials but, as van Vliet highlighted, they involve relatively small deformations of the product and may not be as useful in terms of quality control investigations.

1.5.3.1 Compression testing

Zoon (1991) reported that the majority of deformation tests performed on cheese involved the compression of a specimen by a plate attached to a crosshead which descends at a constant speed.

A significant number of researchers (for example Green et al., 1985; Emmons et al., 1980; Jack et al., 1993) have described the rheological properties of cheese in terms of the force displacement curve, a typical example of which is illustrated in Figure 1-3. Zoon (1991) reported that the properties most frequently measured were the force at a given compression, force at first maximum in the curve, initial slope (Modulus), compression at first maximum, work done until a given compression, height recovered after deformation and adhesive force during ascending motion.

However, it is the stress-strain relationship during these tests which characterises the materials rheological properties and so force-deformation curves must ultimately be converted to stress-strain curves (Konstance & Holsinger, 1992). Integrated computer software can perform such conversions automatically once specimen dimensions are entered. Additionally, if other test parameters are also standardised, meaningful comparisons can be made between similar work in this field (Zoon, 1991).

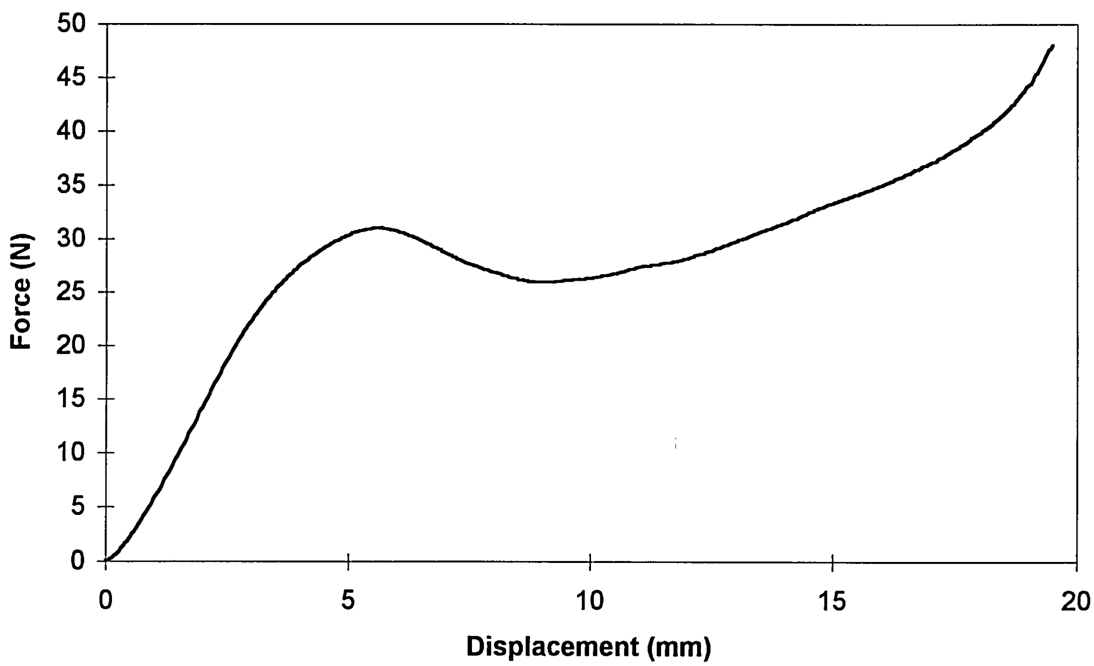


Figure 1-3. Typical force-displacement curve for Cheddar cheese

Compressive tests carried out on food materials involve large deformations and so the theory related to tests involving small deformations can no longer be applied. The relative, or engineering, strain is widely used in instrumental measurement of food texture. However, this does not account for the changing specimen dimensions and consequently the engineering strain and stress levels measured are significantly different to the true strain and true stress levels imposed (Calzada & Peleg, 1978).

Better definitions of true strain and true stress used within this work are

a) True strain (ε) (also known as Hencky Strain) calculated according to Equation 1-1 (Calzada & Peleg, 1978):

$$\varepsilon = \ln (H_0 / (H_0 - \Delta H))$$ **Equation 1-1**

where:

H_0 = original height

ΔH = change in height

b) True stress (σ) calculated by dividing the force (F_t) applied by the surface area (A_t) of the specimen at time (t) as shown in Equation 1-2 (Calzada & Peleg, 1978):

$$\sigma_{(t)} = F_{(t)} / A_{(t)}$$ **Equation 1-2**

1.5.3.2 Stress relaxation

Cheese falls into the category of substances known as viscoelastic materials (Prentice, 1987) and, although there are numerous methods for measuring the viscoelastic properties of such materials, stress relaxation tests are frequently used (Peleg & Normand, 1983). A sample is compressed until a defined stress level is detected and the strain level is then maintained for a predetermined period of time. In simple viscoelastic solids the subsequent stress is 'composed' of two elements: the elastic stress and the time dependent stress. The elastic stress is that which would be released once the strain was removed allowing partial recovery of the sample to its original shape. The time dependent stress is dissipated as a result of the breaking and reconformation of the protein structure to a less stressed state, and other complex phenomena (Peleg, 1987).

The relaxation properties of a simple viscoelastic material can be described using a relaxation time - the time at which the stress level reaches 1/*e* of the original stress level (Peleg, 1987). However, for Cheddar cheese a plot of a typical log stress - time relaxation curve (Figure 1-4) reveals that the stress time relationship is not simple and consequently a single relaxation time is not an appropriate representation of the behaviour of the material.

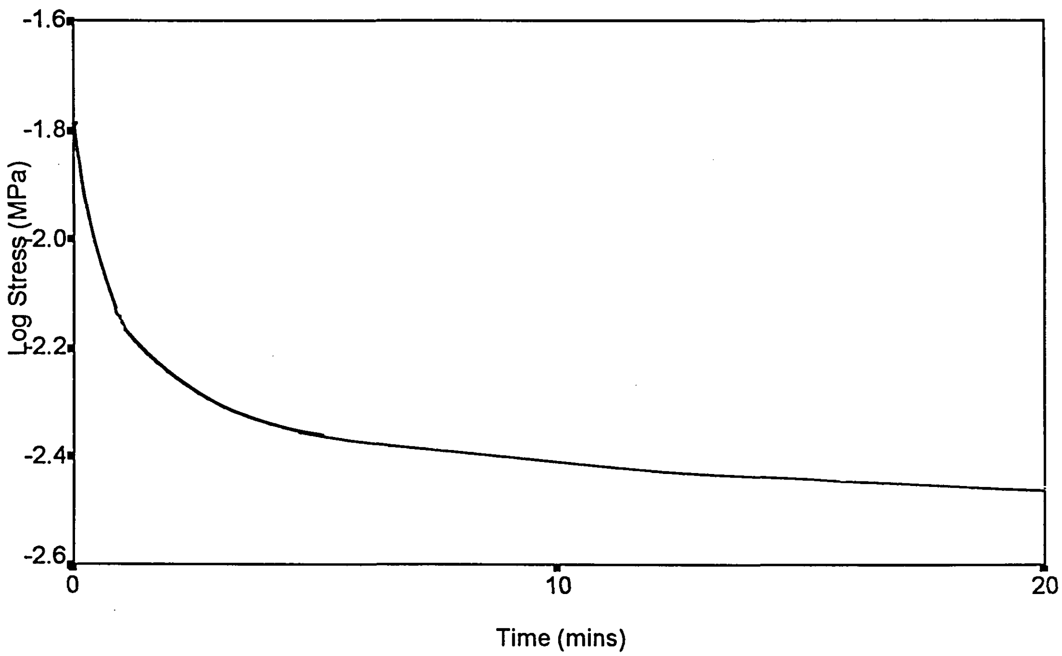


Figure 1-4. Log stress-time relaxation curve for an Irish Mild Cheddar cheese

Typically the stress relaxation behaviour of a complex viscoelastic solid, which shows a spectrum of relaxation processes, is described by the following equation based on the Maxwellian model of viscoelastic behaviour (Peleg & Normand, 1983):

$$P_{(t)} = P_o + \sum_{i=1}^{n} P_i \exp\left(-\frac{t}{\tau_i}\right)$$ **Equation 1-3**

where

$P_{(t)}$ = stress at time t (MPa)

P_o = predicted residual stress (MPa)

P_i = constant (MPa)

τ_i = constant (minutes)

Two or three Maxwellian elements are usually suitable for describing food materials (Peleg, 1987). The elastic modulus (G_i) of each element is calculated using the following equation (Equation 1-4):

$$G_i = P_i/\gamma_0$$ **Equation 1-4**

where γ_0 = initial strain

In addition the viscosity coefficient (η_i) of each element can then be derived as follows (Bertola et al., 1995):

$$\eta_i = G_i\tau_i$$ **Equation 1-5**

1.5.3.3 Test parameters

Although fundamental measures are theoretically independent of the test method, extensive research has shown that the physical properties of a material may change according to the test conditions and previous research has been criticised for not stating test parameters (Breene, 1975). Theoretically, if the testing of materials is restricted to the linear region, the physical parameters should be independent of the test geometry and conditions. Given, however, that any technique that attempts to mimic larger deformations used in sensory analysis would move to the non-linear region, test conditions, geometry, etc. would then be critical and would influence the data.

Sample shape

Cylindrical specimens, although more difficult to prepare, are the preferred shape for compression tests as they allow a more symmetrical dispersion of the stress. Specimen dimensions directly affect the magnitude of the stress and strain values and ideally specimen sizes should be standardised to allow data from separate research to be compared. A low height to diameter aspect ratio increases the likelihood of bulging during compression (van Vliet & Peleg, 1991), although this can be alleviated by lubricating the compression surfaces. Specimens that are too tall are likely to buckle (Masi, 1987).

Compression surface

Several studies using cheese samples (Casiraghi et al., 1985; Goh & Sherman, 1987; Masi, 1987) have revealed that the friction that occurs between the compression surface and sample interface affects the magnitude of the rheological properties measured. However, it has also been noted that frictional effects are reduced to some extent due to the self-lubricating action of the cheese itself (Luyten, 1988). Brennan and Bourne (1994) investigated the influence of the frictional effects of molars and compression plates on the deformation behaviour of cheese samples. They concluded that the use of non lubricated compression plates was more representative of deformation patterns that occurred in the mouth.

Environmental conditions

As the rheological properties of food materials are temperature dependent, it is important that both the temperature and temperature history of different specimens are standardised in order to allow valid comparisons to be made (van Vliet & Peleg, 1991).

In stress relaxation experiments samples should ideally be left until a constant stress level is observed. Technically this is very difficult as food materials are prone to enzymic activity and interact with the environment causing, for example, dehydration of the sample (Peleg & Pollak, 1982). Consequently the residual stress cannot often be obtained experimentally and mathematical models of the stress relaxation behaviour as discussed in section 1.1.4.2 have to be used to predict residual stress levels.

Strain history

The rheological behaviour of viscoelastic materials depends on its strain history and therefore the rate at which it is compressed (Scott Blair, 1969). Work by Culioli and Sherman (1976) reported this to be the case for hard cheeses thus confirming the need for the crosshead speed used in any research to be carefully determined and clearly stated.

The relaxation properties of cheese have also been revealed to be dependent on the level of strain and, to a greater extent the time taken to produce the deformation (Masi, 1989). If deformation is too slow then the structure will relax during the compression stage. It is therefore pertinent that the deformation should be carried out as quickly as possible in order to obtain the most accurate picture of the relaxation properties of the material (van Vliet & Peleg, 1991).

1.6 Relationships between the textural, rheological and chemical properties of cheese

Szczesniak (1987) cited four main incentives for attempting to find correlations between sensory and instrumental measures of texture: the need for instruments for use in quality control; the need to predict consumer response; the quest to understand what is actually perceived during sensory evaluation; and the further development of instrumental tests which will duplicate the sensory assessment of texture.

Similar comments can be made concerning the identification of correlations between chemical parameters and sensory attributes.

Zoon (1991) presented a review of published work concerning the relationships between instrumental and sensory measures of the rheological properties of cheese. There is an inconsistent pattern of correlations between sensory and instrumental Texture Profile Analysis measures. Brennan et al. (1970) only found a correlation for firmness when working with Cheddar, although Chen et al. (1979) found more apparent relationships when working with a wider variety of cheeses.

Researchers (Emmons et al., 1980; Green et al., 1985) comparing more fundamental measures have reported a limited number of correlations with sensory measures of texture. In a review of recent studies Zoon (1991) summarised those parameters which appeared to be the better predictors of sensory attributes (Table 1-1). However, Zoon also emphasised that measurements should be reported in terms of the stress-strain curve in order to make results between studies comparable.

Table 1-1. Instrumental predictors of textural attributes (Zoon, 1991)

Sensory attribute	Instrumental Parameter
Firmness	Force at fracture
Springiness	Recovery after large deformation
Cohesiveness	Relative compression at fracture
Graininess	Inverse of compression at fracture.

Szczesniak (1987) commented that studies relating instrumental and sensory results appear to report different, often conflicting results. However, the fact that researchers have used a variety of different approaches and test conditions when investigating cheese could partly account for this.

Relationships between the compositional parameters of Cheddar and its textural attributes have been identified by researchers who have investigated samples of Cheddar, or cheese analogues, which fall outside the range associated with commercially available Cheddar. Schroeder et al. (1988) and Stampanoni and Noble, (1991) reported that decreasing salt content increased cohesiveness and decreased firmness. Stampanoni and Noble (1991) also found that increasing fat content produced a softer, less springy and more cohesive cheese. However, Jack et al. (1993) found no correlations between the composition of a range of commercially available Cheddars and sensory data obtained using Free Choice Profiling.

1.7 Research aims

In the dairy industry the textural quality of Cheddar cheese is assessed by the cheese grader and is described by a vocabulary of terms often misunderstood amongst graders themselves (Prentice, 1987). The procedures involved are subjective and, considering the training and experience required, can be costly. The aim of this research was to identify and define the perceived textural attributes of Cheddar and investigate the possibility of predicting these characteristics from the rheological and chemical properties of the cheese. Existing research in this area is limited to two way correlations between sensory measures and what are often poorly defined physical parameters. Consequently one of the important objectives of this study was to measure the precise rheological parameters of Cheddar and construct mathematical models using a combination of its rheological and chemical properties which could predict the textural attributes of the cheese.

Although it is well established that a period of ripening is necessary to develop the required textural characteristics of Cheddar, few studies have investigated the development of texture in a single cheese during maturation. Hence the development of both the textural and rheological properties of Cheddar during a period of ripening, and the relationship between the two, warranted further investigation. What is more, in addition to predicting the textural attributes of ripe Cheddar a further objective of this study was to investigate the ability of mathematical models constructed to predict the textural attributes of a cheese at any point during the maturation period.

As has been presented in this chapter numerous methods are available for the measurement of both the sensory and rheological properties of cheese. The approaches adopted for the purposes of this research are justified below.

Textural attributes

Quantitative Descriptive Analysis procedures were chosen to investigate the perceived textural attributes of Cheddar cheese. The GFTPA approach was rejected on the basis that it identifies and predefines many of the textural attributes to be measured. Such attributes and definitions may not be appropriate as has been suggested by Lavanchy et al. (1993) who claim that Szczesniak's classification of textural attributes (Szczesniak, 1963) is not specific enough for cheese. The approach suggested by Lavenchy et al. (1993) was also rejected for various reasons. They also pre-identified the textural attributes to be measured which, although defined specifically in relation to cheese, were represented by a vocabulary which could be ambiguous. The terms, such as friability, deformability, and squeaky are more representative of a graders vocabulary (Bodyfelt et al., 1988) than of the type of terms generated by recent 'consumer' panels (Jack et al., 1993; McKewan et al., 1989; Muir et al., 1995; Piggott & Mowat, 1991). Additionally many of the attributes are measured on ordinal scales, some of which only have three categories, and as such may not discriminate sufficiently between samples and do not lend themselves as readily to statistical analysis.

Free Choice Profiling was rejected as the attributes identified would not be sufficiently defined and the data obtained would not offer the level of objectivity and reliability obtained using QDA. Descriptive Analysis presented several advantages. The textural attributes identified would not only be specific to Cheddar cheese but would also be described by a familiar, unambiguous and well-defined vocabulary. As the terms are defined by the panel, one obtains a reliable indication of what is actually being measured. Such definitions together with the prescribed methods of measurement, can be useful when comparing the relationships between sensory and instrumental measures. Furthermore, the quantitative nature and reliability of the data obtained from QDA enables the use of a variety of statistical techniques to analyse and interpret the information obtained.

Rheological properties

Instrumental Texture Profile Analysis and other empirical methods of measuring rheological behaviour were rejected on the basis that the parameters measured are not well defined and are innately dependent on the test conditions (Walstra & Peleg, 1991). Additionally, the terminology and parameters used in TPA have different meanings compared to the same terms used by rheologists and as such can be misleading in that they do not necessarily relate to the equivalent sensory terms (van Vliet, 1991).

For this study a series of well defined fundamental tests were to be developed which enabled the rheological properties of Cheddar to be calculated under both small and large compressions and when penetrated by a cutting blade, and to be expressed in terms of the stresses and strains imposed. Indeed, as emphasised by Zoon (1991) the properties measured were to be reported in terms of the true stress and Hencky strain when appropriate.

As it was not the aim of this investigation to present a detailed chemical study of Cheddar cheese the chemical analyses performed were limited. However, as Visser (1991) recommended when comparing the rheological properties of cheese, in addition to knowing the age of test samples, the pH level and the fat, salt and moisture content of cheese samples were to be ascertained.

2. The perceived textural properties of Cheddar cheese

2.1 Introduction

The determination of the perceived textural attributes of Cheddar cheese was central to the aims of this investigation. This chapter documents the identification of these attributes by a chosen panel and their subsequent training. The range of textural attributes observed in the Cheddar samples tested is discussed and the use of these attributes to identify sub groups of cheese within the Cheddar classification is investigated.

2.2 Materials and methods

2.2.1 Cheese samples

An extensive range of Cheddar cheeses was purchased for use during panel training sessions.

Seventeen Cheddars, which exhibited a range of both maturity and place of origin, were selected for inclusion in this part of the study (Table 2-1); two of which were low fat Cheddar-like cheeses. The majority of the cheeses were provided by St. Ivel Ltd., Carmarthen, and the remainder by a specialist cheese shop in Sheffield - Silverhill Dairy. Comprehensive histories of the Cheddars were provided by St. Ivel, which included place and date of manufacture. Similar, but less accurate, information was available for most of the cheeses purchased from Silverhill Dairy. The majority of the Cheddar blocks were delivered using refrigerated transport and were placed on arrival in a refrigerator held at 2 °C ± 2 °C.

Table 2-1. Variety, supplier, type and age (on receipt) of Cheddar samples

Cheddar Variety	Supplier	Type	Age (Months)
Mousetrap	Silverhill	block	3
English Mild	St. Ivel	block	4
Irish Mild	St. Ivel	block	6
Irish Medium	St. Ivel	block	8
English Medium	St. Ivel	block	9
Scottish Medium	St. Ivel	block	9
Sturminster Newton	Silverhill	farmhouse	9
Cricketers Low Fat	Silverhill	block	9
Shape Mature (low fat)	St. Ivel	block	9
Somerset Mature	Silverhill	block	8
Quickes Farmhouse	Silverhill	farmhouse	9
Irish Mature	St. Ivel	block	10
Tasty	St. Ivel	block	11
English Mature	St. Ivel	block	14
Quickes Extra Mature	Silverhill	farmhouse	17
Canadian	St. Ivel	block	21
Vintage Wexford	St. Ivel	block	22

It has been established that all properties of Cheddar vary significantly from block to block, and within block (Prentice, 1987). As within block variation is less than block to block variation, all specimens were taken from one 22 kg block of each type of cheese. The outer 30 mm of the block was discarded due to the water loss that can occur at this position, especially in farmhouse cheeses, and the remainder was cut into smaller pieces. Regular turning during the ripening period results in the outer layer of the block being subjected to more compressive stress than the centre and thus the firmness of the cheese is not uniformly distributed (Prentice, 1987). Consequently specimens were cut, in the same direction, from random pieces of the cheese. Cylinders of cheese, 19 mm diameter by 26 mm were obtained, using a cork borer and parallel blade cutter, at 4 °C to prevent barreling

Cheddar samples obtained from retail outlets during the early stages of panel training were placed in the refrigerator within 30 minutes of purchase. Where identifiable, the outer edge of the block was also removed and cylindrical specimens cut when required from the sample as described above.

All Cheddar specimens were wrapped in coded polythene bags and equilibrated at 20 °C for one hour prior to testing.

2.2.2 Panel training

The first stage in the collection of sensory data using the descriptive analysis approach was the selection of a panel to a) identify and b) be trained to measure the textural properties of Cheddar cheese. Training was required to ensure that the definition of each attribute was clear to each assessor and that the methods that were used were consistently reproduced by each individual.

The role of panel leader, performed by the author, was restricted to providing a framework around which sessions were conducted, directing the discussion, giving feedback, keeping records and analysing the data.

2.2.2.1 Stage 1 - Panel selection

A group of eleven assessors, who were regular consumers of Cheddar cheese, were selected from technical and research staff at Sheffield Hallam University on the basis of interest and availability.

The training consisted of twelve weekly one hour training sessions which are outlined below. Two panelists resigned during the initial stages due to increased commitments elsewhere, leaving a group of nine who completed the full training programme.

2.2.2.2 Stage 2 - Generation and definition of descriptors

During the first session the assessors were introduced to the research project and were instructed in the conventions of sensory testing including the use of palate cleansers, the importance of testing samples in the order prescribed and the necessity of adhering to attribute definitions and agreed methods of measurement.

Procedures suggested by Lyon et al. (1992) and Marie (1994) were followed throughout the training sessions:

- Each session was conducted in the same quiet, naturally lit room.
- Identical white apparatus was used for each assessor.
- Samples were coded using random two letter codes.
- Partial Latin-square tables were used to counter balance order of presentation effects.
- A palate cleanser was used between samples.

During the first session the assessors were presented with eight Cheddar samples. Each assessor was instructed to test the first sample using any methods they wished and to record all the descriptors they felt described the textural attributes they perceived. They were also advised to make notes concerning how the attribute had been perceived and, where possible, to define their chosen descriptors. The assessors continued to test the different samples recording further descriptors as new attributes were perceived. A further 12 samples were tested over the next two sessions and any new descriptors were recorded.

Over twenty descriptors were generated although it was evident from the discussion that some assessors had used different words to mean the same thing or the same word to mean different things.

Each of the textural characteristics were discussed by the panel in order to agree upon the most suitable descriptor, at what point in testing the attribute was perceived and also to decide upon standard methods for measuring the attribute. Cheddar samples were available during the discussion to help assessors demonstrate and witness particular attributes.

After some discussion the panel agreed that hardness was related to the force required to penetrate the cheese sample whereas firmness was associated with the force required to compress the sample. It was also concluded that soft was the opposite of firm rather than the opposite of hard. The descriptors 'tough' and 'rubbery' were both found to hold several different meanings amongst panel members and so were deemed inappropriate descriptors. The panel agreed that hardness could be measured both when biting into a cheese sample and when cutting into it with a knife, whereas firmness was detected when squeezing a cylinder between the fingers. Although firmness could be sensed in the mouth the panel found that it was comparatively difficult to distinguish between the different levels of firmness. A summary of the discussion concerning each of the remaining attributes can found in Appendix I.

Three attributes, graininess, dryness and gumminess, were also recorded as characteristics detected after the sample had been swallowed. After swallowing, the particles remaining are very different from the original sample. Although important textural characteristics, they were deemed beyond the focus of this investigation.

Table 2-2 lists the agreed attribute descriptors, their definitions and the point at which they were detected by this stage. The nine descriptors, several of which were detected (and were therefore potentially measurable) by more than one technique, were considered too many for the purpose of this study. However, it was decided to edit the list after the next stage when further information had been obtained.

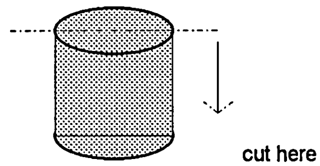
Table 2-2. Prospective list of descriptors

Descriptor	Definition	Detectable when:
Hardness	Force required to penetrate cheese	Cutting, First Bite
Firmness	Force required to compress the cheese with the fingers	Fingers
Springiness	Extent to which cheese springs back when compressed	Fingers
Crumbliness	Extent to which the cheese breaks up into pieces	Cutting, Fingers, First Bite, Chewing
Graininess	The extent to which the cheese is bitty	Chewing
Creaminess	Extent to which cheese has a velvety mouthfeel	Chewing
Chewiness	How tedious it is to chew, remains in the mouth- doesn't melt away	Chewing
Gumminess	Extent to which the cheese sticks to the gums	Chewing
Dryness	Extent to which the cheese feels dry	Chewing

From panel discussions it was obvious that the assessors were using similar but not identical techniques for testing the cheese. The techniques shown in Figure 2-1 illustrate the methods for testing agreed upon by the panel.

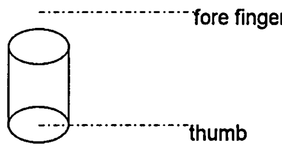
Cutting

Stand cylinder on flat end and cut across the diameter of the sample



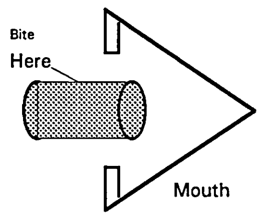
Fingers

Place the cylinder between the forefinger and thumb as indicated and squeeze



First Bite

Place the cylinder lengthways between the teeth and bite through the middle



Chewing

Chew half a cylinder as bitten off during first bite

Figure 2-1. Methods for sensory measurement of textural attributes

2.2.2.3 Stage 3 - Recognising the varying intensities of textural attributes

The next stage of the training involved developing the panel's ability to recognise the varying intensities of the textural attributes. Four sessions were devoted to this stage, with each meeting concentrating on two to three attributes.

For each attribute the assessors were provided with a set of Cheddar samples (different sets of samples were chosen for each attribute in order to present the assessors with a range of the particular attribute being measured). During the first of these sessions varying numbers of samples were presented in order to determine how many samples they felt they could measure in one session without effecting their judgment. The consensus of opinion was four, which was also the number recommended and used by Muir and Hunter (1992) and Wolters and Allchurch (1994) when researching the performance of descriptive panels.

The assessors were asked to rank the samples in increasing order of intensity of the attribute being tested. The panel then compared results and retested specimens when necessary until they agreed, or almost agreed. As a step in developing the assessors ability to quantify the attributes, the group discussed how they would rate the samples on a scale of one to ten. Finally the assessors were given a further sample to test and were asked where it would fit in relation to the other samples. Samples were retested when the panel did not agree to within one unit of each other.

The ensuing discussions enabled the list of attributes to be reduced and definitions clarified. For example, some assessors had ranked cheeses that cracked as soon pressure was applied as not very hard as the knife or teeth penetrated the sample quite easily. Other assessors had ranked such cheeses as hard because of the initial effort required to penetrate the sample. It was decided that hardness should be measured as the amount of force required to initially penetrate the specimen.
A summary of the pertinent points raised during the discussion for other particular attributes is given in Appendix II.

The final definitive list of textural attributes that were to be included in this study is presented in Table 2-3. It was decided that hardness was to be measured by cutting and on first bite, and that crumbliness was to be measured both by compressing between the fingers and whilst chewing.

Table 2-3. Agreed textural descriptors and their definitions

Descriptor	Definition
Firmness	The force required to compress the cheese with the fingers
Springiness	The extent to which the cheese springs back when compressed
Crumbliness	The extent to which the sample breaks when chewed or compressed
Hardness	The force required to penetrate the cheese with a knife or the teeth
Chewiness	How tedious it is to chew; remains in the mouth rather than melting away
Graininess	The extent to which the cheese is bitty towards the end of chewing
Creaminess	The extent to which the cheese has a velvety mouthfeel

2.2.2.4 Stage 4 - Developing the ability to repeatedly quantify textural attributes

The final stage of training entailed developing the panel's ability to repeatedly quantify the different attributes on continuous line scales. The panel were involved in the development of the scales to be used and at their request the scales were numbered from zero to nine, although assessors were aware that scores could be placed on any part of the scale. The scales were nine centimeters in length to enable quantification of the data and increased in intensity of the attributes from left to right. Allowing the panel to contribute to the design of the scale meant that they were more comfortable with using it. Word anchors were also discussed and agreed upon by the panel and are illustrated in Figure 2-2 .

Assessors were presented with sets of Cheddar samples for each textural attribute in turn. Judgments were recorded on acetate sheets which were then overlaid on an overhead projector. Individuals were able see almost immediately when their judgments did not compare with the rest of the panel and so make the necessary adjustments. Outliers were present for some of the attributes but most of the attribute

Firmness

0	1	2	3	4	5	6	7	8	9
soft									firm

Springiness

0	1	2	3	4	5	6	7	8	9
not springy									very springy

Hardness (cutting)

0	1	2	3	4	5	6	7	8	9
not very hard									very hard

Crumbliness (fingers)

0	1	2	3	4	5	6	7	8	9
not crumbly									very crumbly

Hardness (first bite)

0	1	2	3	4	5	6	7	8	9
not very hard									very hard

Crumbliness (chewing)

0	1	2	3	4	5	6	7	8	9
not crumbly									very crumbly

Chewiness

0	1	2	3	4	5	6	7	8	9
not chewy									very chewy

Graininess

0	1	2	3	4	5	6	7	8	9
not grainy									very grainy

Creaminess

0	1	2	3	4	5	6	7	8	9
not very creamy									very creamy

Figure 2-2. Scales and word anchors for textural attributes

assessments matched to within three points of the scale. Panel results from these sessions were examined after the session. Those assessors whose scoring consistently fell more than two standard deviations from the mean were informed so that they could adjust their scoring to the panel norms.

The final three sessions involved the assessors measuring a set of six Cheddars in duplicate for all the textural attributes (four samples per session). This was to introduce the panel to the format that would be used for the actual collection of sensory data as well as enable further analysis of the panels progress.

The results from these sessions were analysed statistically to determine the level of consistency obtained by the panel. Boxplots were produced for each attribute which revealed that only a limited number of the judgments were statistical outliers. Figure 2-3 shows the boxplot for springiness which identifies one outlier as case number 16. Observations of the raw data set showed that the replicate judgments associated with the outliers were in line with the remainder of the judgments, except in the case of the hardness by first bite variable. The natural inhomogeneities found in Cheddar may account for the outlying results.

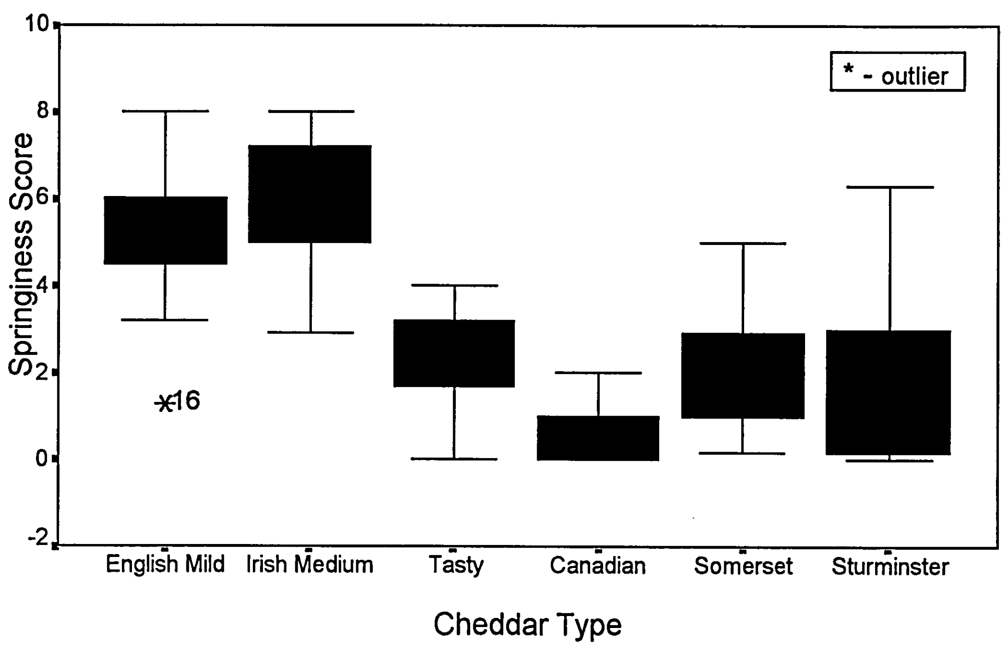


Figure 2-3. Boxplot identifying one outlier in springiness scores

The outliers were removed from the data set and a one-way analysis of variance was performed, followed by a Least Significance Difference (LSD) test to determine if there were significant differences amongst the panel in their use of the scales.

Significant differences were observed ($p \leq 0.01$) for graininess and creaminess but the LSD tests revealed that the significant differences only existed between one assessor, a different one in each case, and the rest of the panel. The two assessors were informed of the need to adjust their scoring. The remaining significant differences identified by the analysis of variance involved the two hardness variables. The least significant difference tests indicated that assessors were in disagreement with several other members of the panel. Subsequent discussions revealed that several panel members had not remembered that a decision had been taken to measure hardness on initial penetration of the sample which may have accounted for the difference identified.

The scores from the two assessors scoring inconsistently for creaminess and graininess were removed and a two way analysis of variance performed on the remaining data to identify whether or not significant differences occurred between the Cheddars and the assessors when both these factors were taken into account (Table 2-4).

Table 2-4. Significance levels obtained from two way analysis of variance of each attribute by Assessor and Cheddar.

Descriptor	Cheddar Significance Level	Assessor Significance Level
Firmness	≤0.01	0.23
Springiness	≤0.01	0.27
Crumbliness (fingers)	≤0.01	0.04
Crumbliness (chewing)	≤0.01	0.27
Hardness (first bite)	0.01	0.00
Hardness (cutting)	≤0.01	0.00
Chewiness	0.01	0.04
Graininess	≤0.01	0.05
Creaminess	0.15	0.03

The analysis of variance revealed that significant differences were observed between the different Cheddars for all the attributes except for creaminess ($p \leq 0.01$). It is worth noting that the panel expressed difficulties in measuring the creaminess of those samples with a particularly strong flavour. The analysis also revealed a consistent performance by the panel in that no significant differences occurred ($p \leq 0.01$) in terms of their measurement of the attributes except for the two hardness variables - an inconsistency that had been observed earlier. This problem was addressed by allowing the assessors to practice measuring these variables, concentrating on measuring the level of hardness as the cheese sample was initially penetrated.

The analysis of the final training sessions enabled problems with methods for measuring specific attributes to be highlighted and addressed. The statistical analysis revealed that the majority of the panel were working consistently and that significant differences could be perceived between different varieties of Cheddars for the majority of the textural attributes measured.

2.2.2.5 Panel monitoring and maintenance

The performance of the panel was monitored throughout the testing of the Cheddar samples. The testing period was divided into three manageable blocks, each lasting approximately two weeks, with six Cheddar samples evaluated during each block. At the end of the first block the two way analysis of variance, which also included a two-way interaction term (O'Mahony, 1986), revealed that in addition to significant differences being identified between the samples, some assessors were also scoring inconsistently for both the hardness variables ($p \leq 0.01$). Subsequent LSD tests revealed that two assessors were responsible for the majority of these inconsistencies and, as they were the same two who had been identified towards the end of training, a decision was taken to remove them from the panel.

The analysis also revealed significant interactions between assessors when measuring chewiness ($p \leq 0.001$). These differences could not be eliminated during a refresher session and so the attribute was removed from the investigation. Brown et al. (1994) discovered that considerable variation exists in individual chewing patterns, particularly chewing time and muscle work rate. It is therefore possible that inconsistencies in the measurement of chewiness could be attributed to individual differences in chewing patterns. No significant interaction was identified for the remainder of the attributes.

Similar analyses of the data from the subsequent sets of Cheddars revealed no significant differences between assessors for the majority of the attributes. Where significant differences did occur, LSD tests revealed that no one assessor was responsible for the inconsistencies which could have been attributable to inhomogeneities in the cheese itself. It should be noted that one assessor was scoring inconsistently for the graininess variable.

2.2.3 Sensory testing

Testing took place in the same naturally lit room that was used for training. During each testing session each assessor evaluated four samples of Cheddar for all the textural attributes previously identified. Five cylindrical specimens of each cheese were presented in white polystyrene cups marked with random two letter codes. Assessors were also provided with identical butter knifes for cutting, a copy of the attribute definitions, a palate cleanser, a set of response sheets and a pen. A partial

Latin square design was used to balance order of presentation of the samples to the panel.

The assessors were invited to score each Cheddar for all the textural attributes by placing a mark on the appropriate line scale. Sensory assessments were quantified by measuring the distance in centimeters from the left of the line scale to the mark made by the assessor. Sessions were arranged so that each assessor tested each sample in duplicate within a 12 day period.

2.2.4 Statistical analysis

All the following statistical procedures were carried out using SPSS for Windows version 6.1 (SPSS Inc., Chicago.)

In order to determine whether the attributes discriminated between the Cheddar samples tested, the sensory data were initially subjected to a two-way analysis of variance for each attribute, which included a two way interaction term (O'Mahony, 1986). Where no significant assessor-sample interaction was identified the analysis of variance was recalculated without the interaction term. (The two-way analysis of variance also enabled any inconsistencies in panel performance to be identified). LSD tests were performed, at the appropriate significance level, to reveal between which samples and/or assessors differences occurred.

Pearson's correlation coefficients were calculated between the mean scores of the individual characteristics in order to identify any possible interrelationships between the textural attributes. Significant correlations were investigated further using X-Y scatterplots.

Mean attribute scores were subjected to cluster analysis (Jacobsen & Gunderson, 1986) to determine whether distinct subgroups of cheeses could be identified within the Cheddar variety based on textural measures. The Euclidean distance was used to calculate the distances between cases and the average linkage between groups method was utilised for combining clusters.

Principal Components Analysis (Norušis, 1993) was applied to the data to determine primarily whether combinations of textural attributes could be identified that would explain a considerable proportion of the variance in the data set and thus provide a more meaningful description of the data. As suggested by Piggott and Sharman (1986), the number of principal components was chosen on the basis of the number of components with an eigenvalue greater than one. Varimax rotation was applied to aid interpretation of the components. Component scores were also calculated for each Cheddar to enable the relationships between the different samples to be explored in terms of the components identified.

2.3 Results

2.3.1 Textural attribute scores

The mean attribute scores and associated standard deviations for each Cheddar sample are listed in Table 2-5. The intensities of each attribute varied considerably across the Cheddar samples, although the ranges identified at the bottom of table indicates that for some attributes, for example springiness and hardness, the full extent of the scale was not utilised by the panel.

Table 2-5. Mean attribute scores and associated standard deviations for each Cheddar sample

Cheddar	Creaminess	Crumbliness (chewing)	Crumbliness (fingers)	Firmness	Graininess	Hardness (cutting)	Hardness (first bite)	Springiness
Mousetrap	2.51	5.22	1.98	3.49	4.51	3.12	3.77	6.27
sd	1.67	1.13	1.54	0.85	2.73	0.61	1.88	0.89
English Mild	4.69	2.49	2.34	4.41	2.50	4.63	3.54	4.61
sd	2.32	1.17	0.75	1.53	1.77	1.62	1.68	2.10
Irish mild	4.50	1.69	1.10	1.63	1.15	1.98	1.24	6.26
sd	2.62	1.64	0.87	0.82	0.75	1.14	0.86	2.00
Irish Medium	4.71	2.33	1.49	3.30	2.47	3.04	2.49	6.25
sd	2.09	1.42	0.83	1.83	2.26	1.73	1.09	0.73
English Medium	5.20	1.09	1.44	1.66	1.81	2.45	1.23	6.63
sd	1.99	0.63	1.12	0.85	1.37	1.17	0.67	1.72
Scottish Medium	5.14	3.20	3.95	6.21	4.32	4.50	4.23	3.06
sd	1.54	1.49	2.05	1.82	2.21	1.67	1.38	1.86
Sturminster Newton	3.41	7.43	8.25	7.69	7.13	5.06	4.69	0.57
sd	2.16	0.85	0.41	0.90	0.91	2.11	2.79	0.54
Cricketers Low Fat	2.13	7.02	7.16	6.90	5.93	6.35	5.58	2.59
sd	1.20	1.00	1.21	1.57	1.98	1.04	2.53	2.51
Shape Low Fat	1.63	5.41	6.10	5.15	5.71	6.25	5.25	4.13
sd	0.87	1.46	1.99	1.96	2.06	1.06	1.38	1.86
Somerset	5.32	2.81	4.54	6.24	3.22	5.47	5.21	2.29
sd	1.12	1.47	2.12	1.44	1.93	1.73	1.41	1.48
Quickes Farmhouse Mature	6.43	3.01	4.79	5.71	4.76	4.93	3.31	2.45
sd	1.41	1.44	2.09	1.91	2.12	1.47	1.87	1.70
Irish Mature	4.99	2.87	3.95	5.72	3.51	5.47	5.10	3.50
sd	1.88	1.64	1.86	1.76	2.00	1.77	2.32	1.81
Tasty	5.16	3.20	3.15	5.40	2.79	5.24	5.45	2.75
sd	1.72	1.72	1.43	1.82	1.72	1.82	1.64	1.17
English Mature	6.31	2.06	3.01	5.07	2.65	4.18	3.19	3.74
sd	1.94	1.07	1.39	1.85	1.96	0.83	1.32	2.25
Quickes Extra Mature	4.06	6.48	7.05	8.39	7.15	6.32	6.42	0.32
sd	2.74	1.36	.70	0.61	1.52	1.47	2.24	0.38
Canadian	4.24	6.82	7.44	7.74	5.77	5.36	4.89	0.77
sd	2.16	1.39	1.08	0.81	2.14	1.64	2.59	0.61
Wexford	5.45	4.10	4.50	5.98	3.92	5.16	4.72	3.67
sd	1.87	1.47	1.44	1.95	1.49	1.64	1.63	2.54
Range	1.63-6.43	1.09-7.43	1.1-8.25	1.63-8.39	1.15-7.15	1.98-6.35	1.23-6.42	0.32-6.63

2.3.2 Analysis of variance

The initial two-way analysis of variance showed that no significant assessor-sample interaction had occurred except in the case of the hardness (first bite) variable ($p = 0.01$). Nevertheless, hardness (first bite) was still shown to discriminate between the Cheddars. The subsequent analysis of variance for the remaining attributes, with the interaction term removed, showed that significant differences were evident between the Cheddar samples in terms of all the other attributes ($p < 0.0005$) (Table 2-6).

LSD tests revealed that, for the majority of attributes, each Cheddar was significantly different to at least six other samples, but more often eight or nine. Hardness (cutting) and, more noticeably, creaminess were less discriminating. In the case of creaminess the LSD test illustrated that differences between only four Cheddar samples were responsible for the significant difference revealed in the analysis of variance: Shape, Cricketers, Mousetrap and Quickes Farmhouse Mature.

Table 2-6 also highlights that the results of the analysis of variance indicated that significant differences between the assessors were also evident for all the attributes except crumbliness (fingers) ($p \leq 0.005$). Such differences had not been observed during panel maintenance where statistical analysis was carried out on smaller data sets. However, subsequent LSD tests showed that in the majority of cases the inconsistencies were not between all panel members, but were confined to between two or three assessors. It is worth noting that the inconsistency was more noticeable for graininess, where three of the assessors were scoring significantly different to over half of the panel.

Table 2-6. Significance level (p) associated with assessor and Cheddar sample terms calculated during two-way analysis of variance

Attribute	Assessor	Cheddar Sample
Creaminess	<0.001	<0.001
Crumbliness (chewing)	0.002	<0.001
Crumbliness (fingers)	0.086	<0.001
Firmness	<0.001	<0.001
Graininess	<0.001	<0.001
Hardness (cutting)	0.003	<0.001
Hardness (first bite)*	0.005	<0.001
Springiness	<0.001	<0.001

* analysis of variance included significant assessor-sample interaction term

2.3.3 Pearson's correlation coefficients

The correlation coefficients listed in Table 2-7 reveal that significant correlations were observed amongst the majority of the textural attributes. Creaminess was the exception and did not correlate with any other characteristic apart from crumbliness (chewing). Nevertheless, subsequent scatterplots illustrated that although many of the correlations were statistically significant, the relationships were not quite as strong as initially indicated. For example, the correlation coefficient between firmness and crumbliness (chewing) ($r = 0.73$) was highly significant ($p = 0.001$) but the corresponding scatterplot (Figure 2-4) suggested a relatively weaker association when the distribution of data points was observed.

Observations of the remaining scatterplots indicated that strong relationships between variables existed where the coefficient was 0.87 or greater, as exemplified by the scatterplot of firmness by springiness ($r = 0.96$) shown in Figure 2-5.

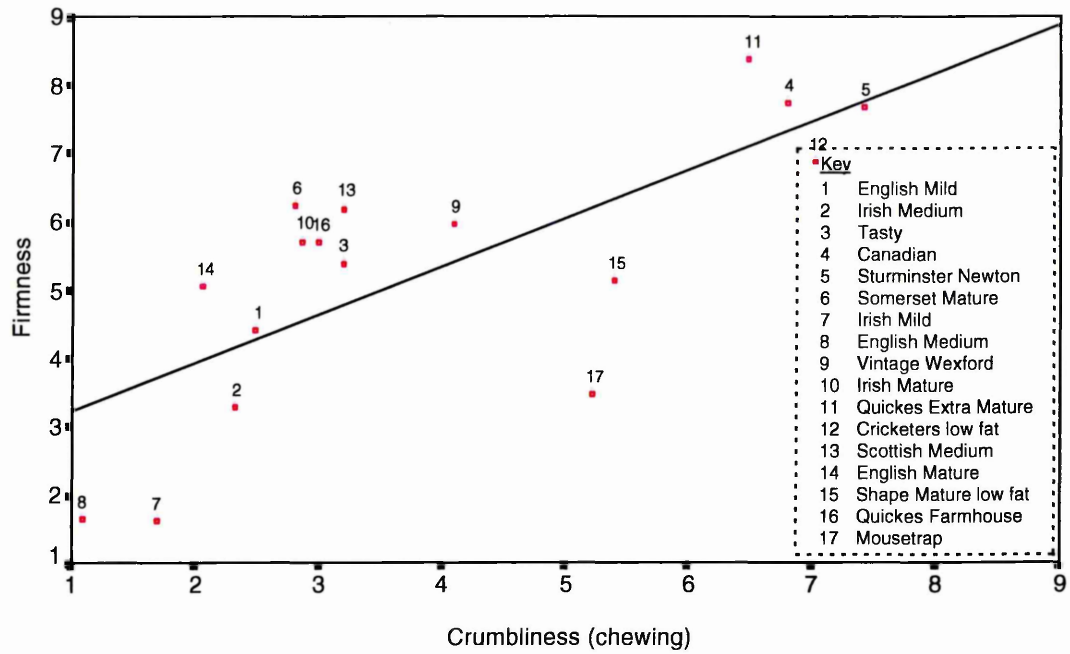


Figure 2-4. X-Y Scatterplot of crumbliness (chewing) against firmness score

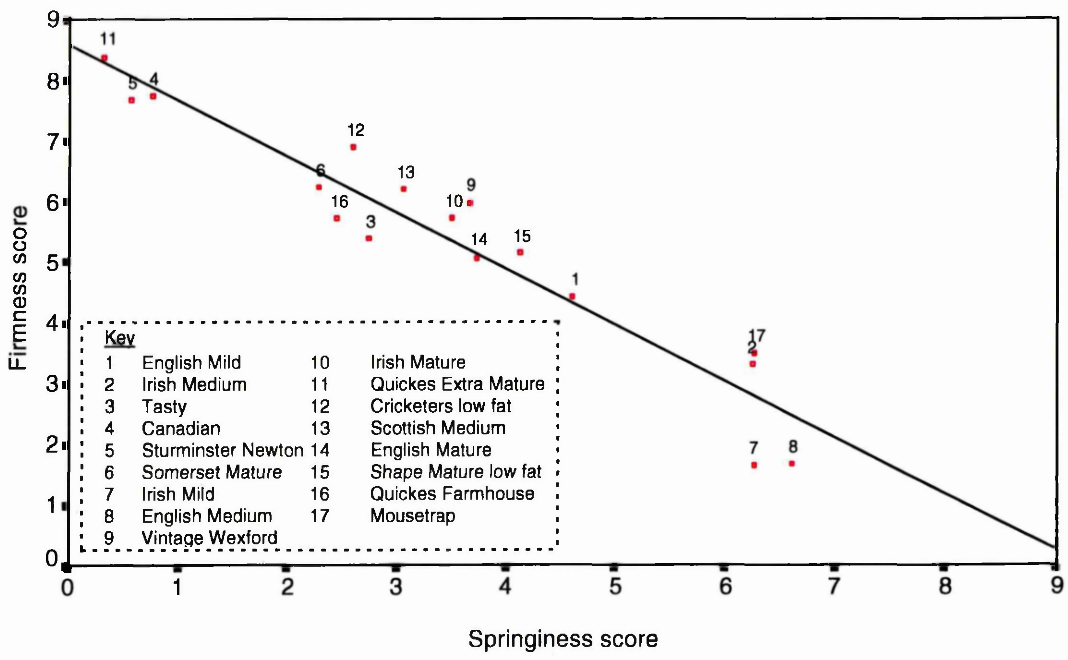


Figure 2-5. X-Y Scatter plot of firmness against springiness

Table 2-7. Pearson's correlation coefficients between textural attributes and associated levels of significance

	Creaminess	Crumbliness (chewing)	Crumbliness (fingers)	Firmness	Graininess	Hardness (cutting)	Hardness (first bite)
Crumbliness (chewing)	-0.66*						
Crumbliness (fingers)	-0.4^{ns}	0.87***					
Firmness	-0.11^{ns}	0.73**	0.88***				
Graininess	-0.52^{ns}	0.91***	0.91***	0.82***			
Hardness (cutting)	-0.25^{ns}	0.62*	0.81***	0.86***	0.7*		
Hardness (first bite)	-0.33^{ns}	0.69**	0.75**	0.86***	0.71**	0.93***	
Springiness	-0.002^{ns}	-0.66*	-0.87***	-0.96***	-0.75**	-0.79***	-0.76***

^{ns} = not significant *p = 0.01 **p = 0.001 ***p< 0.0005

The strong correlation between firmness and springiness strongly suggests that they are in fact measure of the same attribute. Ideally identifying those attributes which are not correlated is more informative. For example, the fact that creaminess is not correlated with any of the other attributes implies it is a manifestation of a different aspect of Cheddar 's physical structure.

It is also noteworthy that the scatterplot between firmness and crumbliness (fingers) revealed a curvilinear relationship between the two attributes. The correlation coefficient between the two variables increased to 0.94 when the log of crumbliness (fingers) was used.

2.3.4 Cluster analysis

Figure 2-6 represents the dendrogram output from the cluster analysis. Four clusters of Cheddar samples were easily interpretable in that they occurred before the distances at which the clusters combined became too large (Norušis, 1993). Mousetrap was placed in a group by itself.

Due to intercorrelations amongst the textural characteristics two additional cluster analyses were performed using reduced subsets of the attributes. The analysis was repeated with the two hardness variables removed as they correlated with firmness. One of the crumbliness variables was also removed as the two were strongly related. The analysis was then repeated using the other crumbliness variable. The resulting dendrograms were similar for both analyses. The dendrogram produced as a result of the latter analysis (Figure 2-7) was similar to the original except that the English Mild cheese was located in cluster B.

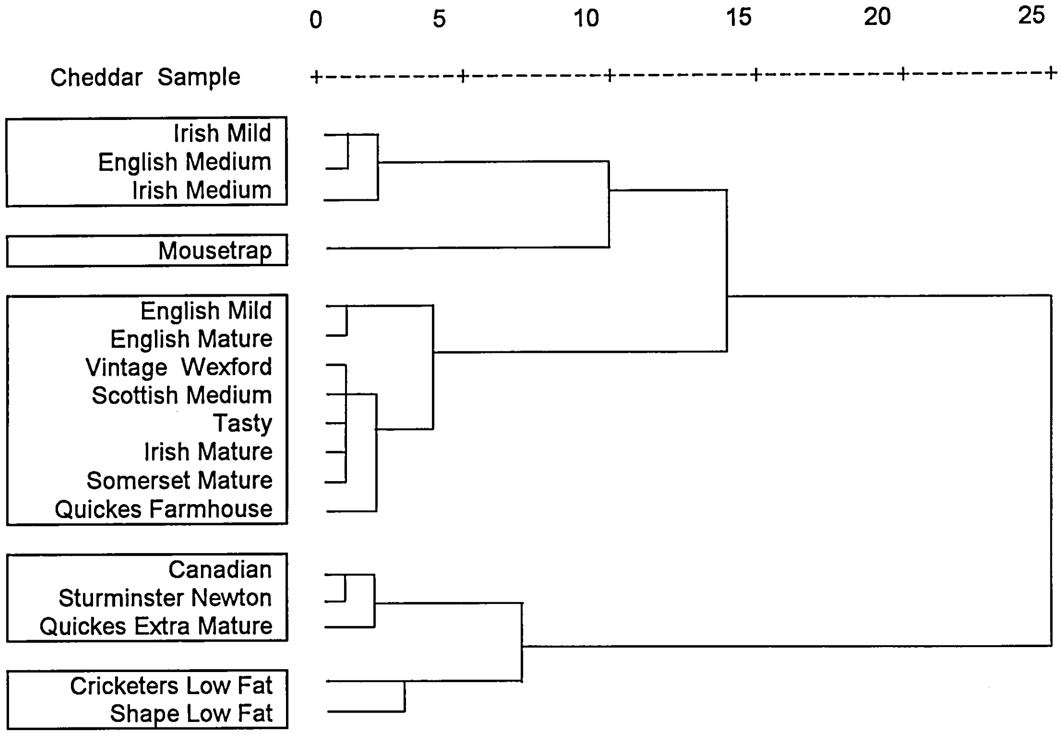


Figure 2-6. Dendrogram output from cluster analysis using all textural attributes

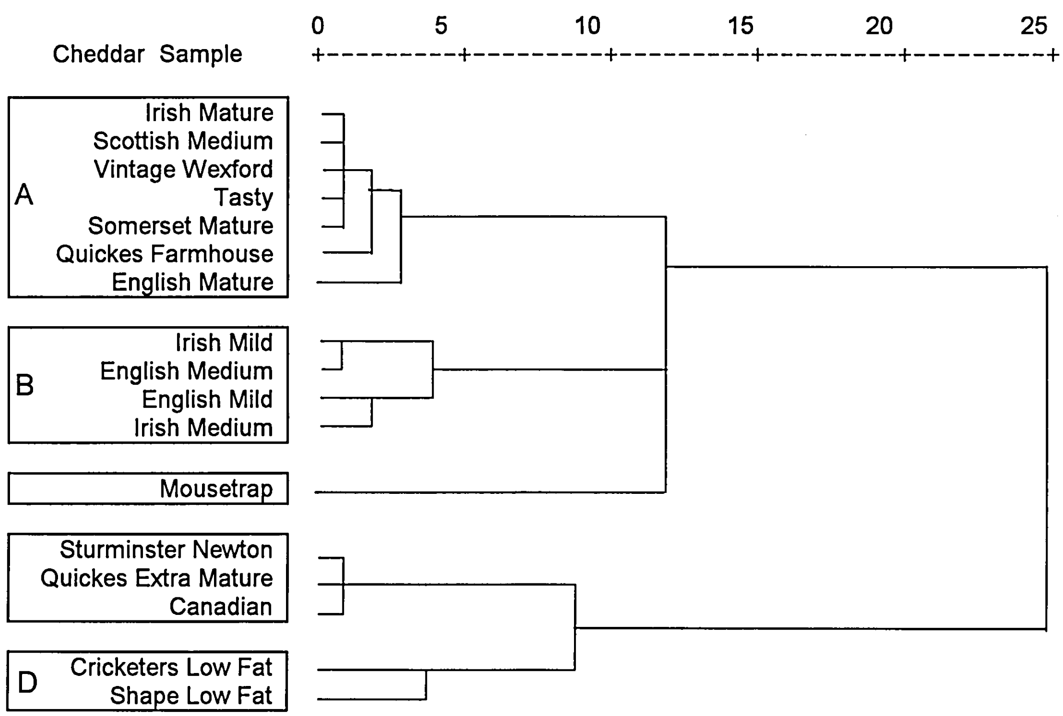


Figure 2-7. Dendrogram output from cluster analysis using a subset of the textural attributes

The members of the clusters identified in Figure 2-7 indicated meaningful classifications of the Cheddar samples. Cluster A, the largest group, contained those Cheddars that were relatively old and were commercially marketed as mature - Scottish Medium was the exception. Cluster B consisted of the younger mild and medium types.

The Quickes Extra Mature and Canadian Cheddar, which is also matured for an extensive period, were grouped together with Sturminster Newton - a comparably younger, but farmhouse Cheddar. It should noted that these three Cheddars were regarded as the highest quality cheeses by the suppliers.

The Mousetrap sample remained on its own and the final cluster consisted of the two low fat Cheddar like cheeses.

2.3.5 Principal Components Analysis

Two components were identified which accounted for 90.8% of the variance in the data. Observations of the factor loading plot after Varimax rotation (Figure 2-8), indicated that the first component was associated with the majority of the textural attributes with positive loadings for firmness, hardness, crumbliness and graininess characteristics and a negative loading for springiness.

The second component was dominated by the creaminess attribute but, as indicated by the rotated factor matrix (Table 2-8), was also associated with crumbliness (chewing) to a certain extent. It should be noted that this variable also correlated with the first component to only a slightly lesser extent.

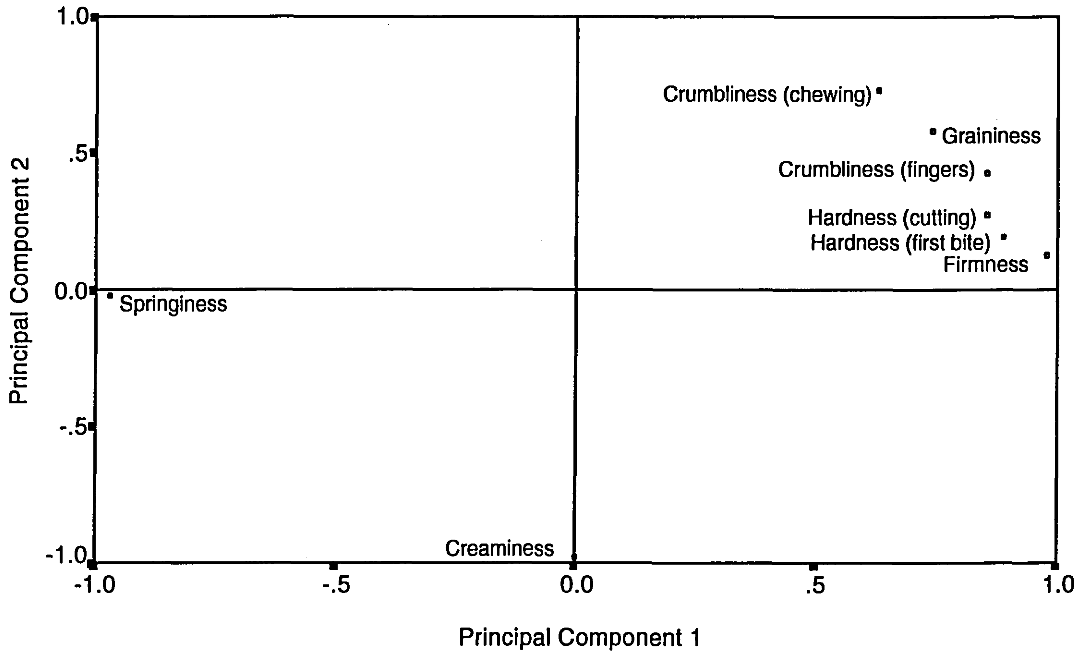


Figure2-8. Loadings for textural attributes on first and second principal components

Table 2-8. Rotated factor correlation matrix

	Principal Component 1	**Principal Component 2**
Firmness	0.9799	0.1313
Springiness	-0.9678	-0.0177
Hardness (cutting)	0.8909	0.196
Hardness (first bite)	0.8552	0.2765
Crumbliness (fingers)	0.8541	0.4331
Graininess	0.7425	0.5886
Creaminess	0.0036	-0.9783
Crumbliness (chewing)	0.6309	0.7341

The sample scores plotted on the two principal components are shown in Figure 2-9. Not surprisingly the groupings of the samples suggested on this plot mirror those suggested by the Cluster Analysis.

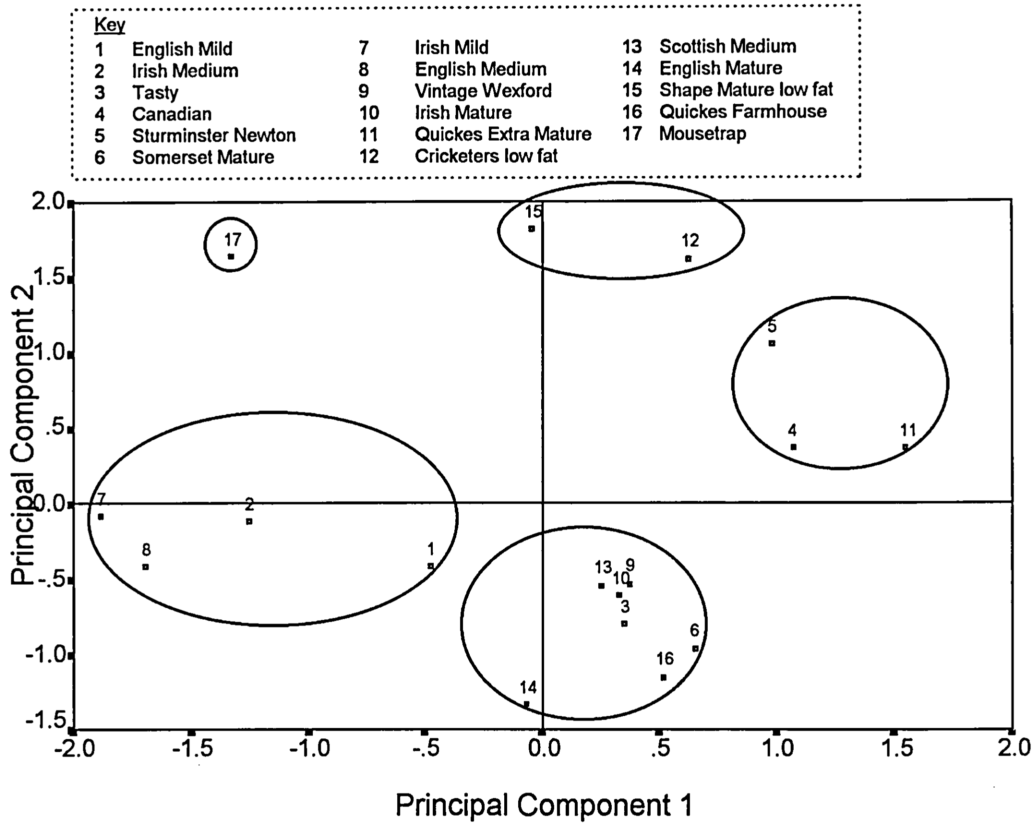


Figure 2-9. Sample scores on first and second principal components

2.4 Discussion

2.4.1 Perceived textural attributes

The vocabulary developed by the panel bears little resemblance to that used in the General Foods texture profile technique (Brandt et al., 1963) supporting Lavanchy et al. (1993) in their observation that the GFTPA technique is not specific enough for cheese texture measurement.

The terms identified by the panel compare favourably with those generated recently by consumers during free choice profiling (Jack et al., 1993) (although obviously not as numerous) and by other trained descriptive panels (Piggott & Mowat, 1991; Muir et al., 1995). It is interesting to note that in all the studies mentioned above the term rubbery was used to describe the attribute referred to by the panel in this investigation as springy. As the definitions of the terms used by other researchers are not published or, as in the case of free choice profiling, not obtained, it is not possible to confirm whether the terms used actually referred to the same attribute.

Previous studies of Cheddar (Emmons et al., 1980; Jack et al., 1993b; Muir et al., 1995) have consistently reported that textural attributes can be used to discriminate between the different types of cheese within this variety. The results of this investigation support these findings as significant differences also existed between the Cheddar samples evaluated in terms of all the textural attributes measured.

The extent of the discrimination obtained using the textural attributes was revealed by the LSD tests. Although the majority of the attributes could discriminate between a large proportion of the Cheddars this was not the case for creaminess. Of the four Cheddars identified as significantly different, two were the low fat samples which scored low for creaminess. The further two samples, Mousetrap and Quickes Farmhouse Mature represented the minimum and maximum scores for creaminess amongst the remaining fifteen samples. Thus no significant differences in creaminess were perceived between the majority of genuine Cheddars tested.

2.4.2 Panel performance

During the sensory evaluation of the Cheddar samples panel performance was monitored with analysis of variance techniques revealing very little inconsistency amongst the panel, once two assessors had been removed early on, although some concern was noted concerning graininess. When the performance of the panel was investigated using the whole data set, although differences were identified, LSD tests made it apparent that they were minimal except for where graininess was involved.

As three of the assessors were scoring differently the mean scores may not be an accurate representation, but as no significant assessor sample interaction was identified, it can be assumed that the panel were in agreement in terms of the comparable intensities of the graininess of the samples. The disagreements observed for this attribute could be attributed to differences in individuals chewing patterns particularly as this attribute was defined to be measured towards the end of chewing. In their investigation into the effects of chewing efficiency on texture perception, Brown et al. (1996) discovered that individual differences in efficiency of food breakdown resulted in different temporal perceptions of texture. Hence the extent to which a sample was perceived to be bitty towards the end of chewing could have been effected by the extent to which the individuals disrupted the structure of the cheese sample prior to swallowing.

Limited inconsistency is accepted during sensory testing due to the inherent variability that can exist in human performance despite training (Stone & Sidel, 1985). Additionally, avoiding the natural inhomogeneities that occur in Cheddar is unavoidable when preparing test specimens (van Vliet & Peleg, 1991), and so some differences in the perception of the textural attributes within the same sample is expected. It was therefore concluded that the panel were performing to an acceptable level of consistency during the testing.

2.4.3 Relationships between the textural attributes

Szczesniak (1987) highlighted the need to identify intercorrelations between groups of variables in an attempt to avoid erroneous conclusions as to cause and effect.

Few researchers have reported observations of the interrelationships between textural attributes. Emmons et al. (1980) noted highly significant correlation coefficients between the textural attributes measured when investigating low fat cheddar type cheeses. However, he suggested that the correlations may have been caused by the inclusion of one traditional Cheddar which increased the range of the data considerably.

Bourne (1982) cautions against drawing hasty conclusions from significance levels associated with correlation coefficients. As was suggested, a more informed understanding of the relationships between the individual textural attributes was obtained through scatterplots which illustrated where reliable relationships existed.

The two hardness variables were, not unexpectedly, closely related and were both positively correlated with firmness which indicated that as the force required to compress the cheese sample increased so did the force required to penetrate it. The negative correlation between firmness and springiness was even stronger which suggested that those samples that were easier to compress were also springier. Alternatively it is quite conceivable that softer samples were consequently subjected to more deformation - the extent of sample deformation may then have affected the panels perception of the extent to which the sample sprung back. The strong relationship between the two variables suggests that the two are potentially opposites of the same attribute.

Quite logically, the two crumbliness variables were strongly related. Both also showed a strong positive correlation with graininess. One suggestion could be that where the sample had been broken into a considerable number of pieces, more 'bits' were likely to be perceived towards the end of mastication.

2.4.4 Classification of types of Cheddar by textural attributes

Cluster analysis revealed that within this one variety of cheese the different types could be classified into different subsets as a consequence of their textural properties. Apart from the cluster of low fat cheeses the remaining subsets represented, to a large extent, Cheddars of different levels of maturity. The positioning of the Mousetrap sample also conforms to this theory to a certain extent as it is at least a month younger than any of the Cheddars in the mild/medium cluster and suits a group of its own. Not surprisingly, when the Cheddar samples were plotted on the two principal components, these groupings were also identifiable (Figure 2-9). The group of young cheeses was not as discernible as the samples were not positioned very close together. Nevertheless they were clearly distinct from the other groups of Cheddar samples.

An analysis of the attribute scores for each of the clusters (Table 2-9) revealed that the younger Cheddars were less crumbly, less firm, less grainy and more springy than the mature Cheddars in Cluster A. These observations concur with Jack et al. (1993) who also reported that mild and medium Cheddars displayed soft and rubbery characteristics. The mature Cheddars in Cluster A were much firmer, less springy, slightly crumblier and possibly slightly creamier; and the Cheddars in Cluster C were even firmer, crumblier and less springy. The general increase in crumbliness with age concurs with Lawrence et al. (1987) who reported a decrease in cohesiveness as cheese matures.

Table 2-9 Mean attribute scores for Cheddars listed according to cluster groups

Cluster	Cheddar	Creaminess	Crumbliness (chewing)	Firmness	Graininess	Springiness
	Irish Mature	4.99	2.87	5.72	3.51	3.50
	Scottish Medium	5.14	3.20	6.21	4.32	3.06
	Vintage Wexford	5.45	4.10	5.98	3.92	3.67
A	Tasty	5.16	3.20	5.40	2.79	2.75
	Somerset	5.32	2.81	6.24	3.22	2.29
	Quickes Farmhouse	6.43	3.01	5.71	4.76	2.45
	English Mature	6.31	2.06	5.07	2.65	3.74
	Irish Mild	4.50	1.69	1.63	1.15	6.26
B	English Medium	5.20	1.09	1.66	1.81	6.63
	English Mild	4.69	2.49	4.41	2.50	4.61
	Irish Medium	4.71	2.33	3.30	2.47	6.25
	Mousetrap	2.51	5.22	3.49	4.51	6.27
	Sturminster Newton	3.41	7.43	7.69	7.13	0.57
C	Quickes Extra Mature	4.06	6.48	8.39	7.15	0.32
	Canadian	4.24	6.82	7.74	5.77	0.77
D	Cricketers low fat	2.13	7.02	6.90	5.93	2.59
	Shape low fat	1.63	5.41	5.15	5.71	4.13

Notably, the PCA revealed that more variation occurred in the group of younger Cheddars when compared to other groups. Although this group of cheeses were united by similar scores on the second principal component, there was considerable variation on the first principal component. As the latter component correlated with the majority of the textural attributes measured this would suggest that although the younger Cheddars have been identified as an homogenous group some variation in textural properties does exist.

The cluster analysis provided strong evidence that particular textural attributes were associated with the extent of maturity. An inspection of the Cheddars' scores for the first principal component also revealed a potential relationship with the age of the sample. The younger Cheddars had low, negative scores, the mature samples scored around zero and the older cheeses had the higher positive scores. However, in support of Piggott and Mowat (1991), the positioning of a minority of the samples indicated that perhaps raw materials and production processes were also influential. The Scottish Medium Cheddar ought to have been in Cluster B with the other medium matured varieties. However its textural attributes were more representative of a mature cheese and hence it was grouped with the mature Cheddars. This was not unexpected as previously Jack et al. (1993) has described Scottish Cheddars as harder than varieties of equivalent maturation times and McKewan et al. (1989) also reported that the Scottish Medium variety of Cheddar exhibited similar textural characteristics to mature Cheddar samples.

The Wexford and Sturminster Cheddars were the only other two samples that did not conform to the clustering as a result of the length of maturation. The Sturminster ought to have been grouped with the mature Cheddars and the Wexford (22 months old) positioned in its place with the extra mature types. The Wexford sample was a block formed Cheddar as were the majority of the samples in its cluster. The Sturminster was marketed as a farmhouse Cheddar and was regarded as a high quality, specialty Cheddar - a profile held by the other two Cheddars in its cluster. Such factors suggested that production processes were also influential in terms of texture development. However, as such detailed information was not available it was not possible to investigate this further.

The positioning of the Mousetrap Cheddar is noteworthy. Discussions with the distributors of this type of cheese revealed that it is sourced on the basis of price and is not purchased from one particular creamery (Lacey, 1997, personal communication). The particular block used for this had undergone comparatively little ripening (12 weeks) which could account for its uncreamy and very springy character.

2.4.4.1 Low fat Cheddar like samples

The cluster analysis revealed that the panel were able to distinguish between the genuine Cheddar and low fat Cheddar like samples on the basis of their textural attributes.

Previous researchers (Emmons et al., 1980; McKewan et al., 1989) have reported that low fat Cheddar like cheeses are firmer than genuine Cheddars. Emmons et al. (1980) concluded that more effort was required to deform the sample due to the increase in protein mass thus accounting for the increase in firmness. The results of this study revealed that the two low fat samples were considerably firmer than the mild/medium Cheddars but were as firm as the mature samples. However the panel did perceive the low fat samples as being harder to penetrate than the other samples which is probably a result of the denser protein matrix. The low fat samples were also perceived to be as springy as the mature samples and considerably less springy than the younger samples.

The results of this investigation suggest that it is the creaminess, crumbliness graininess, and to a lesser extent, firmness attributes which enabled the assessors to distinguish between the low fat and remaining Cheddar samples. As was also reported by Piggott and Mowat (1991) and McKewan et al. (1989) the low fat samples were substantially crumblier and grainier. Emmons et al.'s (1980) study of the macro structure of reduced fat Cheddar revealed that the fusion between the milled curd particles was incomplete in the low fat samples causing holes to occur - a condition referred to as mechanical openness. Both Emmons et al. (1980) and Bryant et al.'s (1995) investigations of the microstructure of Cheddar cheese using Scanning Electron Microscopy revealed a more compact protein matrix with much smaller fat globules in the reduced fat samples. The increase in perceived crumbliness and graininess of the two low fat samples could therefore be attributed to the poor fusion between curd particles and the slight increase in firmness to the denser protein matrix (Bryant et al., 1995).

3. The chemical and rheological properties of Cheddar cheese.

3.1 Introduction

This chapter outlines the methods employed to determine the chemical composition and the fundamental approach adopted to measure the rheological properties of the Cheddar samples selected for this investigation. The ability of the chemical and rheological parameters to discriminate amongst the different types of Cheddar is discussed and the relationships between all the variables are investigated.

3.2 Materials and methods

3.2.1 Samples

Chemical and instrumental analyses were performed on random pieces of cheese taken from the same seventeen Cheddar samples selected for sensory testing (see section 2.2.1). Cylindrical specimens were prepared according to the procedures outlined in section 2.2.1 for the instrumental testing and samples were finely grated for the chemical analysis as and when required.

3.2.2 Chemical composition

3.2.2.1 Moisture determination

The percentage moisture content was determined using a distillation procedure based on the American Association of Analytical Chemists (AOAC) Method 969.1 (AOAC, 1990). A weighed grated Cheddar sample (10-12 g), together with a distillation solvent made up of 2 parts xylene and 1 part pental-1-ol, were added to a 250 ml round bottomed flask containing fine sand and was placed on a heating mantel for a minimum of 60 minutes. The distillate was collected in the volumetric tube of a Dean and Stark receiver. When no more droplets of moisture were observed to occur the amount of water distilled was read off from the volumetric tube, from which the percentage moisture content of the sample was calculated. Prior to moisture determinations being performed a standardization procedure was carried out using just the chemical reagents and a known volume of water (approx. 4 ml). For all intents and purposes, given the accuracy of the visual accuracy of the volume of moisture distilled, the distillation factor was found to be 1 ±0.01.

3.2.2.2 Fat determination

The percentage fat content of the Cheddar samples was determined using the Gerber process as described in British Standard 696 (British Standards Institution, 1989). A 3±0.001 g finely grated sample of cheese was added, together with 10 ml 90% sulphuric acid and 1 ml amyl alcohol, to a butryometer. The butryometer was subsequently filled with distilled water, stoppered and shaken to dissolve the cheese sample. Once the particles of cheese had dissolved the butryometers were centrifuged at 1100 rpm for 6 minutes. The fat meniscus and fat/acid interface levels were recorded. Centrifuging was repeated until two consecutive readings were the same.

3.2.2.3 pH level

Several attempts were made to obtain a suitable sample preparation from which to take the pH reading. Methods using slurries of Cheddar sample produced inaccurate results and simply inserting a spearheaded pH probe into a Cheddar block gave inconsistent data. Difficulties measuring the pH of cheese are recognised throughout the dairy industry (Lawrence & Gilles, 1982). The chosen method was developed in consultation with the technical centre at St. Ivel Ltd., Swindon. A Unicam combination spearheaded electrode and temperature probe attached to a Jenway pH meter was calibrated using pH 4 and pH 7 buffers. A finely grated sample of cheese was packed firmly into a 10 ml beaker into which the electrode and probe were inserted. The pH level was recorded once the reading had stabilised. The probe was cleaned after every 5 measurements with a neutral detergent to avoid fat build up on the probe.

3.2.2.4 Salt determination

The percentage salt content of the Cheddar samples was determined using a Corning 926 Chloride analyser. Distilled water was added to a 1 g grated sample of cheese to make 100 ml. This was macerated and then centrifuged at 2000 rpm for 1 minute to remove the debris that could have otherwise interfered with the probe (Mettler-Toledo, 1995, personal communication). The analyser was calibrated using standard 200 mg/l salt solution before performing an electronic titration of the chloride ions present in 0.05 ml of the prepared sample. The resulting figure was multiplied by a dilution factor of one hundred and the percentage salt content of the sample calculated. The silver electrodes were polished after every five titrations to remove any debris.

3.2.3 Rheological test parameters

The test parameters established for the rheological testing are outlined below.

3.2.3.1 Sample size and preparation

Cylindrical specimens 19 mm in diameter and 26 mm in height, an aspect ratio of 1.4, were used for the instrumental testing. Masi (1987) recommended the use of samples with an aspect ratio greater than one. Samples that were also an adequate size for the sensory testing were required in order to provide consistency between the tests. Preliminary tests revealed that buckling did not occur with this size sample.

During preparation of the cylinders particular care was taken to cut as slowly as possible to avoid distorting the shape of the cylinder (van Vliet & Peleg, 1991). Great care was also taken to ensure that the cylinder ends were parallel to ensure that an uneven application of stress was avoided, especially in the case of stress relaxation tests (Masi, 1989).

3.2.3.2 Instrumentation and software

An Instron Universal Testing Machine, model 1140, integrated with Instron Series IX Automated Materials Testing Software (Instron Ltd., High Wycombe, UK) was used to measure the rheological properties of the cheese samples. The series IX software digitally recorded the force deformation (or time) data registered by the Instron Universal Testing Machine at a maximum of 18.2 data points per second and utilised the information to produce preprogrammed reports of each samples' rheological properties. The digital record of the data also allowed for reanalysis of the data and enabled data to be imported into SPSS for Windows (version 6) and Microsoft Excel for Windows (version 5) for further examination.

Despite the 'automated' nature of the software, considerable user input was required. The parameters used by the software to identify key points on the force-deformation curve were not able to account for noise in the transmission of the data. The on-screen force-deformation curves revealed that incorrect yield and fracture points were often used in the calculations performed by the software. It was therefore necessary to use the crosshair facility to identify the correct points on the curve manually.

The software was preprogrammed to calculate Young's Modulus from the steepest linear region of the curve. However, on screen calculation lines revealed that inappropriate parts of the curve were used for a large proportion of the cheese samples. The software provided the option of setting deformation limits for identifying the initial linear region but, as these varied considerably from sample to sample, the calculation of the Young's Modulus was performed off-line after the data was downloaded and analysed further using facilities available in Excel 5.0.

3.2.3.3 Instron test parameters

Initial tests on a selection of Cheddars revealed that the use of a standard 5-50 kg load cell calibrated to 5 kg would be suitable for obtaining the force-deformation data for all the proposed tests.

One of the principal aims of this study was to investigate the relationships that exist between sensory and physical measurements of cheese texture. As non lubricated compression plates have been shown to be more representative of the deformation behaviour that occurs in the mouth, the compression plates were not lubricated during testing (Brennan & Bourne, 1994).

To determine a suitable crosshead speed for this investigation replicates of a Medium English Cheddar were subjected to identical compression tests carried out at crosshead speeds of 5, 10, 20, 50, 100, 200 and 500 mm/min. In each case the Young's Modulus and the stress and strain at fracture were recorded. One way analysis of variance, together with a LSD test, revealed that results obtained at speeds above 100 mm/min for stress at fracture were significantly different to those obtained at lower speeds as is illustrated in Figure 3-1 ($p = 0.01$). For the Young's Modulus those results taken between 5 to 20 mm/min were significantly lower than those taken at the remaining higher speeds (Figure 3-2). Only the results at 500

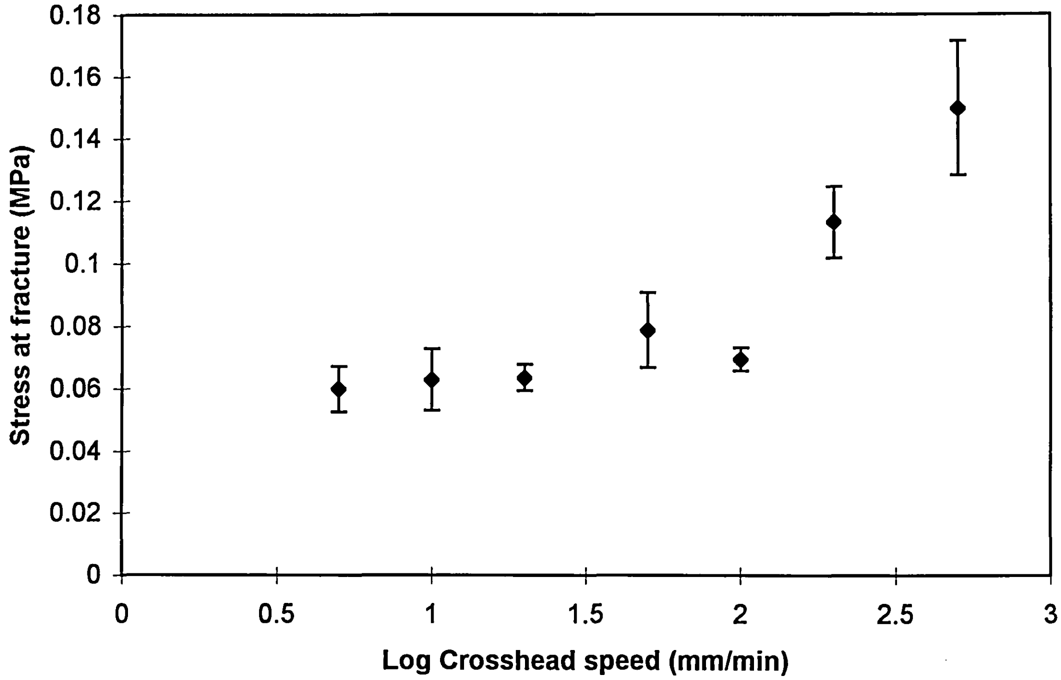


Figure 3-1. Stress at fracture at different crosshead speeds for an English Medium Cheddar

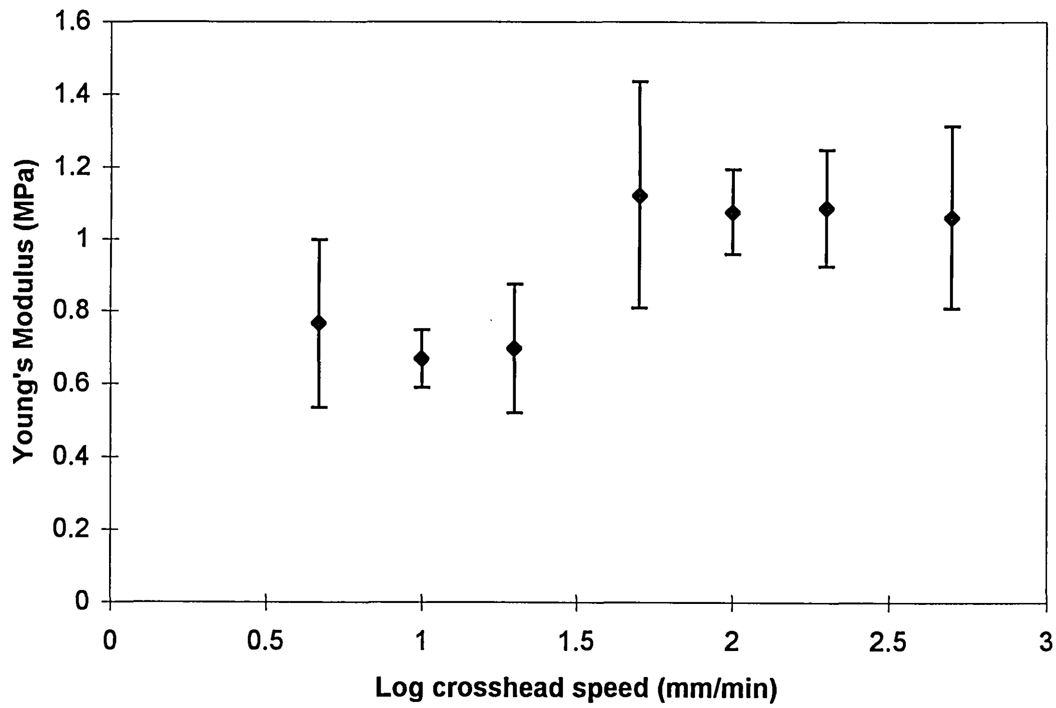


Figure 3-2. Young's Modulus at different crosshead speeds for an English Medium Cheddar

mm/min were significantly different for the strain at fracture variable. Significant correlations ($p = 0.01$) between crosshead speed and both Young's Modulus ($r = -0.61$) and stress at fracture ($r = 0.82$) confirmed that the speed at which the test was carried out affected the values of some physical properties.

3.2.4 Rheological testing methods

3.2.4.1 Compression test

Uniaxial compression tests were used to measure the rheological properties listed in Table 3-1 for each Cheddar sample:

Table 3-1. Rheological properties determined using compression test

Rheological Parameter	Abbreviation
Young's Modulus (MPa)	(YM)
(true) Stress at yield (MPa)	(Ss_y)
(true) Strain at yield	(Sn_y)
Energy to yield (J/M^3)	(E_y)
(true) Stress at fracture (MPa)	(Ss_f)
(true) Strain at fracture	(Sn_f)
Energy to fracture (J/M^3)	(E_f)

Five cylindrical specimens of each Cheddar sample were subjected to a seventy per cent deformation using a 45 mm diameter compression anvil at a crosshead speed of 50mm/min. Preliminary tests revealed that deformation to this level was required for fracture to occur across the range of Cheddars. Figure 3-3 illustrates a typical force-deformation curve displayed by the Series IX software during compression testing, annotated with the relevant points from which measurements were taken.

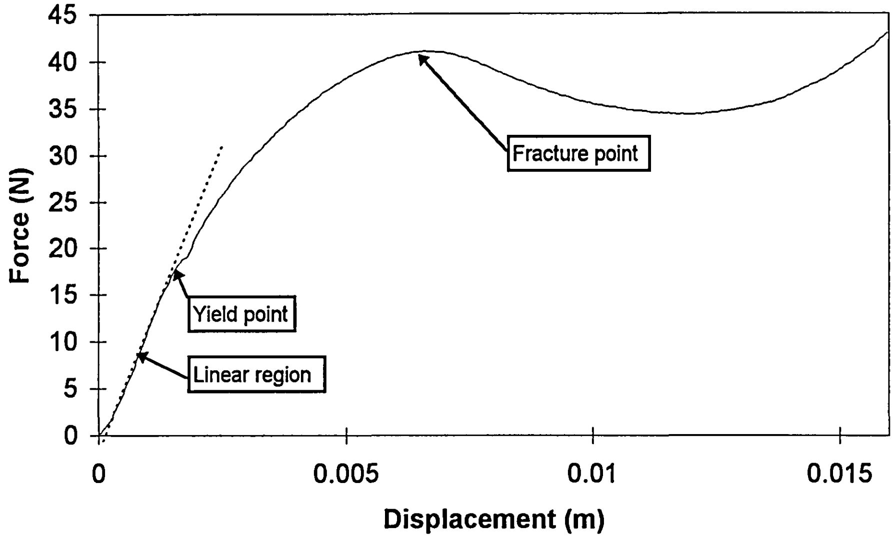


Figure 3-3. Typical force-displacement curve for Cheddar cheese

The force-deformation data was downloaded into Excel 5.0 in order to calculate the Young's Modulus as a result of the difficulties with the software (see section 3.3.1). The data were converted to the true stress-true strain equivalents and the initial linear region identified from scatter charts. The Young's Modulus was then determined by calculating the slope of this particular area of the curve.

The Instron Model 1140 only records force and deformation. To obtain measures of the true rheological properties the force deformation data was converted to true stress-true strain measures using the equations described in section 1.5.3.1. Changes in specimen width could not be recorded by the Instron model 1140 and so the changing specimen dimensions were determined mathematically. On the assumption that Poisson's ratio for Cheddar cheese is equal to 0.5 (Muller, 1973; van Vliet et al., 1991) little or no change in volume would occur during compression and therefore at any point

Equation 3-1

$$\pi r_0^2 H_0 = \pi r_1^2 H_1$$

where r_0 = radius of original specimen

r_1 = radius of deformed specimen

H_o = height of original specimen

H_1 = height of deformed specimen

Consequently the radius of the deformed specimen could be determined and used to calculate the true stress at any one point during compression (Equation 3-2).

$$r_1 = r_0\sqrt{H_0 / H_1}$$ **Equation 3-2**

The equations required to determine true stress and true strain at both yield and fracture were substituted in the appropriate algorithms in the Series IX software. (Appendix III)

3.2.4.2 Cutting test

The second Instron test allowed the fracture behaviour of Cheddar to be observed when being penetrated with a cutting blade. A blade, much wider than the specimen diameter, 1 mm thick with an angled cutting edge of ≈ 66°, was attached to the crosshead fitted with a load cell calibrated to 5 kg full scale load. A crosshead speed of 50 mm/min was used as with the previous test. Specimens were accurately placed on the Instron using a guide to ensure that the blade cut into the sample across its diameter. The blade was allowed to cut through the sample before returning to its original position.

Initial investigations revealed that the behaviour of Cheddar specimens during this test was quite variable. Figure 3-4 shows the force-distance curves from three specimens

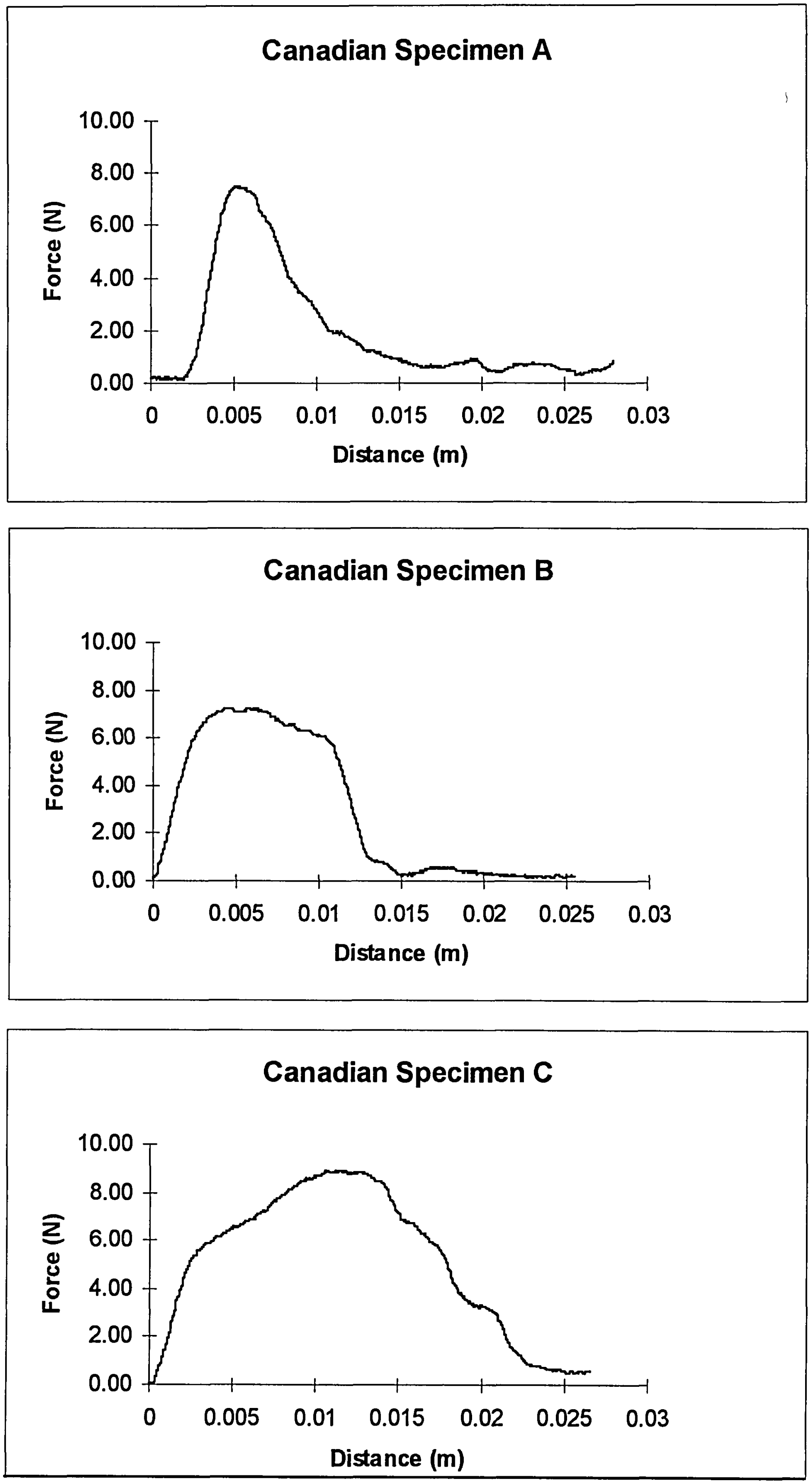


Figure 3-4. Force-distance curves for Canadian Cheddar specimens during cutting test

of a Canadian Cheddar and illustrates the erratic behaviour of specimens from the same Cheddar sample. Observations during these tests indicated that the pattern of the force-distance curve depended upon the nature of any crack propagation once the sample had been penetrated and also the frictional effects that arose depending upon the amount of contact between the blade and cut edges of the cheese. With Specimen A the specimen split in half almost immediately after penetration. In Specimen B the blade continued to cut through the specimen for a few millimeters, maintaining limited contact with the cut specimen edges. In specimen C the blade maintained close contact with the edges of the sample during its descent such that the force required to cut through the sample continued to increase. Finally a large crack formed and the blade was no longer actually cutting through the cheese. Despite this variability the tests revealed that the shape of the initial part of the curve remained consistent across all the specimens from one type of Cheddar and also across the different Cheddar samples tested. An initial linear relationship leading to a shoulder or plateau where the force leveled for a short instance can be seen in the curves for all the Canadian specimens and also in the curve for an English Mild Cheddar specimen presented in Figure 3-5. Visual observations revealed that the shoulder corresponded to the point at which the blade penetrated the surface of the sample.

As a result of the preliminary findings the test method was modified. The blade was allowed to cut into the cheese specimen to a depth of 5 mm thus providing ample data from which to calculate the force to cut (N/m) and energy to cut (J/m).

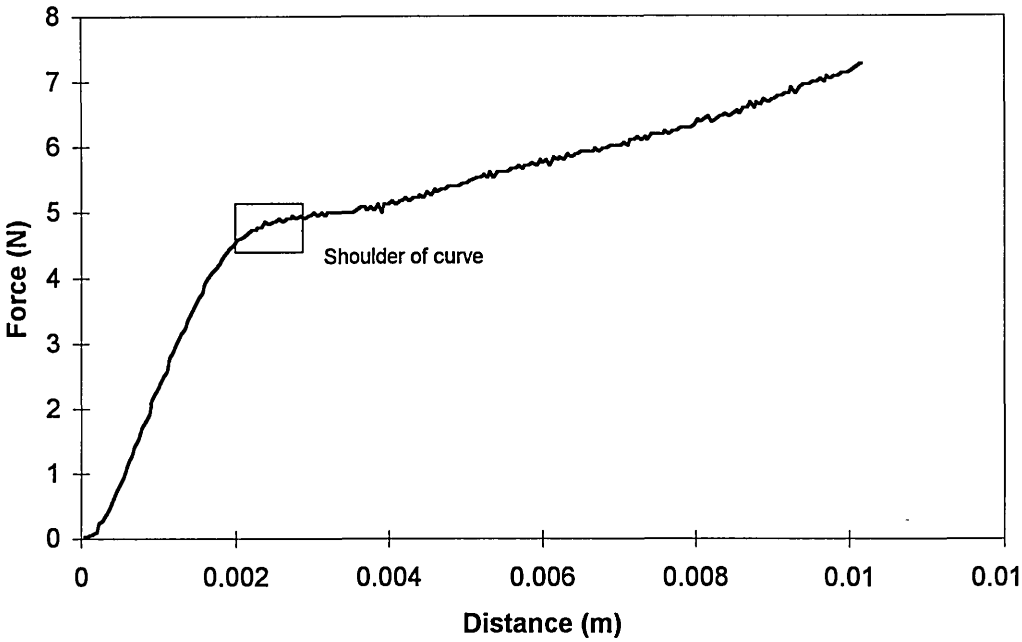


Figure 3-5. Typical force-distance curve for English Mild Cheddar (cutting test)

Stress relaxation test

Cylindrical specimens of Cheddar were compressed until a force of 5 N (equivalent to a stress of 0.0176 MPa) was detected by the Instron. This level of stress was chosen as a result of information gained from preliminary stress relaxation and compression tests. The raw data from the preliminary stress relaxation tests revealed that the stress at time zero was always above that of the preset stress limit, often nearer 0.02 MPa - a consequence of the digital nature of the data acquisition process. As compression tests revealed that some varieties of Cheddar began to yield around 0.04 MPa, imposing a stress of approximately 0.02 MPa avoided initiating fracture within the specimen. During testing the mean stress level imposed was 0.0192 MPa (sd 0.0012). The motion of the crosshead was checked at the preset stress level and the compression anvil held in place for twenty minutes to maintain a constant strain. Specimens were not left until a constant stress level was observed as initial tests revealed that after twenty minutes the cheese began to dry out and/or sweat. The subsequent decay of stress over the first minute was recorded at 9.1 data points per second and at 4.55 points per second for the remainder of the test. The rate of data acquisition was limited by the software and length of the experiment, but it was possible to employ a faster rate during the initial part of the test in order to obtain a more accurate representation of the stress decay that occurred rapidly during the initial part of the experiment.

The mean strain imposed to achieve the preset stress level was 0.04 (sd = 0.01) but varied between 0.01 and 0.07. Consequently the time taken to reach the stress level was relatively quick with a mean of 1.16 seconds and was considerably less than the time allowed for relaxation once the crosshead was stopped. The variation in time taken to reach the required stress level was observed across specimens of the same cheese and was not restricted to particular Cheddar types. It is possible that this could be a result of the cylinder ends not being parallel despite all efforts to the avoid the contrary during sample preparation.

The force-time data recorded by the Series IX software was exported to Excel 5.0, converted to stress-time data and then copied to SPSS for Windows. Non linear regression analysis of data from preliminary tests enabled a suitable model to be chosen to describe the stress relaxation behaviour of Cheddar. Figure 3-6 illustrates the predicted stress relaxation curves obtained using three different equations based on the Generalised Maxwellian viscoelastic model presented in section 1.5.3.2. Predictions made using a model containing a residual component and two exponential elements provided the best fit (Equation 3-3).

$$P_{(t)} = P_0 + P_1 \exp\left(\frac{-t}{\tau_1}\right) + P_2 \exp\left(\frac{-t}{\tau_2}\right)$$

Equation 3-3

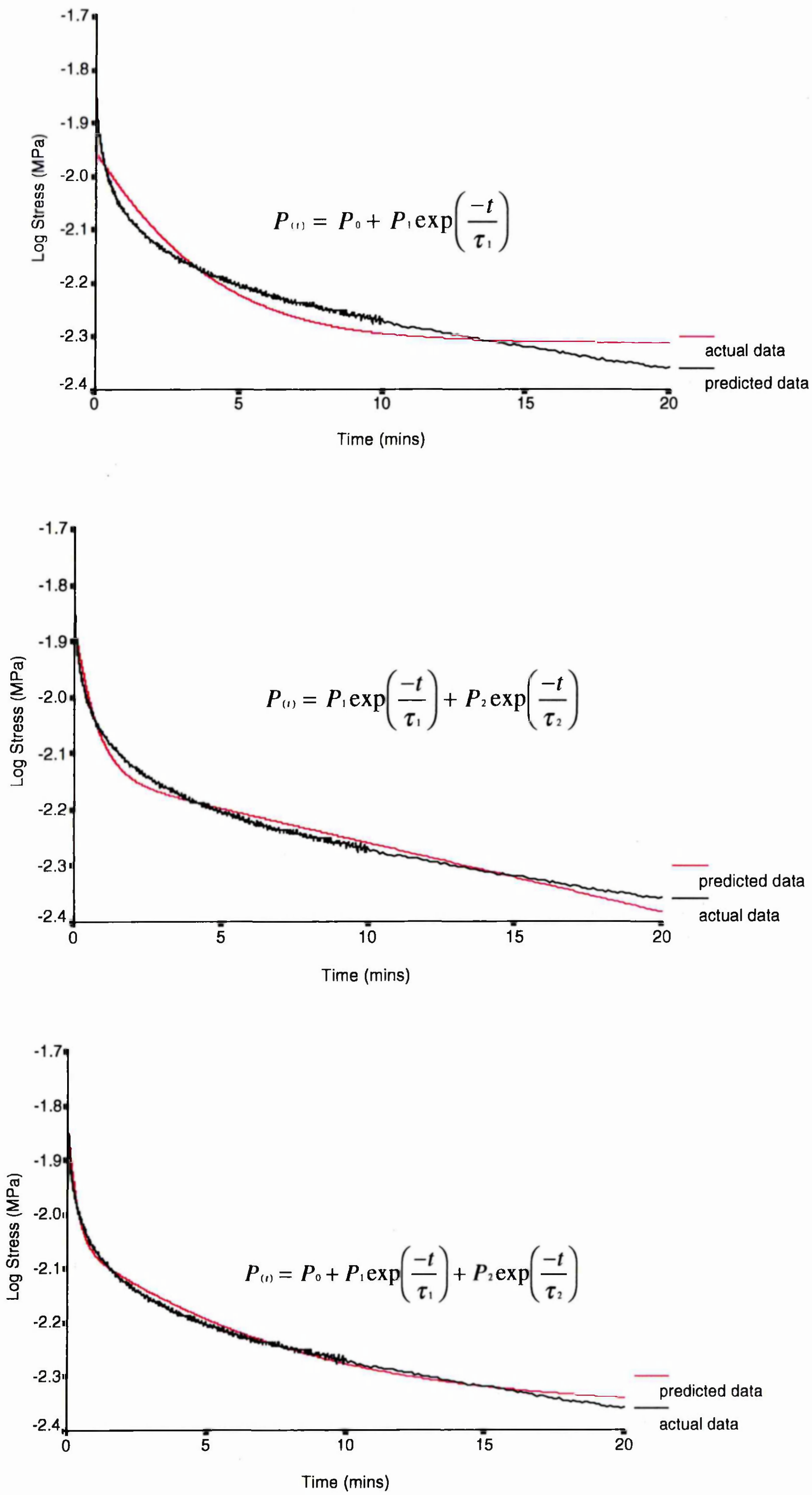


Figure 3-6. Log stress-time and predicted log stress-time curves for 'Tasty' English Cheddar using three different mathematical models.

Hence predictions for the parameters P_o, P_1, P_2, τ_1 and τ_2 were obtained using non-linear regression analysis for each Cheddar specimen. As the strain levels imposed varied for each Cheddar sample, values for P_0, P_1 and P_2 were standardised by dividing by the appropriate initial strain level (γ_0) and consequently represented the respective elastic moduli G_0, G_1 and G_2 (Equation 1.4). Thus, expressed in terms of the elastic modulus (G), the model chosen to represent the viscoelastic behaviour of Cheddar became:

$$G_{(t)} = G_0 + G_1 \exp\left(\frac{-t}{\tau_1}\right) + G_2 \exp\left(\frac{-t}{\tau_2}\right)$$ **Equation 3-4**

where:

$G_i = P_i/\gamma_0$

The corresponding viscosity coefficients η_1 and η_2 were calculated by multiplying the appropriate elastic moduli and relaxation time for each Maxwellian element (Equation 1.5).

3.2.5 Statistical analysis

The chemical and rheological data were subjected to one way analysis of variance, followed by LSD tests, to determine which parameters could be used to distinguish between the different types of cheese within the Cheddar variety.

Pearson's correlation coefficients, and associated significance levels, between all the rheological and chemical parameters were calculated and investigated further using scatterplots.

A cluster analysis was performed using the majority of the rheological parameters to ascertain if meaningful subsets of cheeses could be identified based on their rheological properties (yield parameters were omitted as they were not observed to discriminate between samples). In addition, PCA was applied using the same set of variables to determine whether combinations of the rheological parameters could explain the variance in the data set and provide further insight into the data. Both analyses were performed as described in section 2.2.4 except that the rheological parameters were standardised to Z scores prior to the cluster analysis.

Both these analyses were repeated with the stress relaxation variables omitted in order to establish the contribution made by these parameters in discriminating between different Cheddar samples.

3.3 Results

3.3.1 Chemical composition

The mean chemical composition and associated standard deviations for each Cheddar sample are listed Figure 3-2.

The composition varied significantly across the different Cheddar samples in terms of all the chemical attributes measured ($p < 0.001$). Subsequent LSD tests revealed that differences existed between the majority of samples for all the attributes, but less so in the case of percentage salt content. It is notable that the two low fat Cheddars had markedly higher percentage moisture contents.

Table 3-2. Chemical composition of Cheddar samples

Cheddar	% Moisture Content	% Fat Content	pH	% Salt Content
Mousetrap	34.69	36.80	5.48	2.37
sd	0.51	0.27	0.01	0.04
English Mild	38.53	34.20	5.05	1.92
sd	1.18	0.45	0.02	0.05
Irish Mild	37.77	31.33	5.38	2.26
sd	0.36	0.40	0.03	0.05
Irish Medium	36.67	32.52	5.16	1.92
sd	0.62	0.38	0.01	0.06
English Medium	38.19	31.84	5.26	1.89
sd	0.34	0.42	0.02	0.09
Scottish Medium	35.97	35.22	5.02	1.89
sd	0.73	0.35	0.01	0.05
Sturminster Newton	36.92	34.22	5.21	1.88
sd	0.19	0.30	0.01	0.06
Cricketers Low fat	44.46	22.38	5.21	2.05
sd	0.64	0.57	0.01	0.06
Shape Low Fat	45.94	16.52	5.30	2.23
sd	0.66	0.48	0.01	0.05
Somerset	34.32	35.70	5.15	1.99
sd	0.34	0.27	0.01	0.06
Quickes Farmhouse	35.65	36.90	5.4	2.33
sd	0.46	0.17	0.01	0.09
Irish Mature	37.3	31.16	5.11	1.94
sd	0.93	0.53	0.01	0.06
Tasty	35.93	35.10	5.25	1.87
sd	0.25	0.22	0.01	0.03
English Mature	37.99	33.52	5.12	1.89
sd	0.45	0.60	0.02	0.07
Quickes Extra Mature	31.06	38.40	5.65	2.43
sd	0.11	0.65	0.02	0.06
Canadian	34.8	36.24	4.91	1.77
sd	0.40	0.39	0.02	0.05
Wexford Vintage	37.68	32.96	5.16	2.10
sd	0.74	0.60	0.02	0.09

Figures are means and standard deviations of five replicates

Highly significant correlations ($p < 0.001$) were revealed between the percentage fat content and percentage moisture content ($r = -0.95$), and the percentage salt content and pH level ($r = 0.87$).

3.3.2 Fracture properties

The rheological data obtained from the compression and cutting tests are listed in Table 3-3. The mild and medium (younger) Cheddars (the Scottish sample being an exception) required lower levels of stress to bring about yield and fracture than the remaining maturer samples. The Young's Modulus was lower for the younger samples and both the strain and energy at fracture were higher, indicating that the younger samples deformed, elastically, more easily and needed to be deformed to a greater extent before fracture occurred.

The younger samples also required less force to be penetrated by the cutting blade although some of the maturer Cheddars, namely the Vintage Wexford and English Mature, required comparable levels.

In comparison to the mature samples the two low fat Cheddar-like samples had slightly lower Young's Moduli and fractured at larger strain levels.

Significant differences were identified between the Cheddar samples in terms of all the rheological attributes that were measured ($p = < 0.0005$). LSD tests revealed that Young's Modulus, stress and strain at fracture and force to cut discriminated between a large proportion of the samples.

3.3.3 Stress relaxation properties

The accuracy of the equation chosen to model the relaxation behaviour of the Cheddar samples is illustrated in Figure 3-7. A similar fit was observed for all Cheddar samples.

Table 3-3. Rheological properties of Cheddar samples

Cheddar	Stress at Yield (MPa)	Strain at Yield	Energy at Yield (J/M³)	Stress at Fracture (MPa)	Strain at Fracture	Energy at Fracture (J/M³)	Young's Modulus (MPa)	Force to Cut (N/M)	Energy to Cut (J/M)
Mousetrap	0.0466	0.1237	2992.51	0.0667	0.8474	58675.26	0.6766	0.24	0.30
sd	*0.0032*	*0.0131*	*585.4*	*0.0125*	*0.2830*	*23710.93*	*0.1067*	*0.04*	*0.06*
English Mild	0.0440	0.0735	1876.53	0.0782	0.3700	31414.53	0.8132	0.27	0.39
sd	*0.0029*	*0.0075*	*146.31*	*0.0016*	*0.0699*	*8331.54*	*0.1281*	*0.02*	*0.06*
Irish Mild	0.0468	0.1437	3733.85	0.0690	0.6220	38013.38	0.5008	0.17	0.28
sd	*0.0050*	*0.0201*	*777.48*	*0.0019*	*0.1002*	*10108.10*	*0.1541*	*0.02*	*0.09*
Irish Medium	0.0460	0.1132	2732.05	0.0793	0.5427	36102.70	0.6636	0.23	0.35
sd	*0.0026*	*0.0211*	*383.64*	*0.0099*	*0.0162*	*4588.42*	*0.582*	*0.01*	*0.07*
English Medium	0.0412	0.1265	3025.06	0.0653	0.4889	26069.12	0.4774	0.16	0.24
sd	*0.0027*	*0.0193*	*431.11*	*0.0065*	*0.0157*	*3856.56*	*0.0966*	*0.01*	*0.05*
Scottish Medium	0.0644	0.0675	2190.80	0.0970	0.2009	15081.91	0.9876	0.28	0.29
sd	*0.0047*	*0.0187*	*487.91*	*0.0056*	*0.0172*	*2377.67*	*0.1185*	*0.05*	*0.06*
Sturminster Newton	0.0527	0.0563	1771.63	0.0672	0.1056	5070.03	1.0012	0.42	0.73
sd	*0.0135*	*0.0083*	*545.79*	*0.0208*	*0.0333*	*2691.12*	*0.1231*	*0.03*	*0.15*
Cricketers Low fat	0.0647	0.0853	3098.32	0.1020	0.2261	19572.02	0.8223	0.29	0.36
sd	*0.0069*	*0.0024*	*431.18*	*0.0069*	*0.0231*	*5818.05*	*0.0916*	*0.02*	*0.09*
Shape Low Fat	0.0476	0.1008	2713.06	0.0842	0.2961	17396.15	0.6226	0.29	0.41
sd	*0.0011*	*0.0079*	*241.71*	*0.0046*	*0.0429*	*3722.15*	*0.029*	*0.04*	*0.07*
Somerset	0.0640	0.0976	3621.94	0.0822	0.2500	16213.25	0.6642	0.32	0.51
sd	*0.0094*	*0.0152*	*952.91*	*0.0076*	*0.0437*	*2938.01*	*0.1196*	*0.05*	*0.16*
Quickes Farmhouse	0.0657	0.0641	2444.47	0.0958	0.1780	13062.60	1.2000	0.27	0.34
sd	*0.0112*	*0.0124*	*614.75*	*0.0192*	*0.0228*	*3092.19*	*0.0000*	*0.06*	*0.11*
Irish Mature	0.0650	0.0584	2257.27	0.1079	0.2198	18424.40	1.1619	0.31	0.41
sd	*0.0042*	*0.0069*	*234.29*	*0.0106*	*0.0070*	*2352.82*	*0.1485*	*0.01*	*0.06*
Tasty	0.0509	0.0532	1568.15	0.0946	0.2620	19943.71	0.9658	0.32	0.41
sd	*0.0051*	*0.0027*	*157.50*	*0.0117*	*0.0178*	*2986.44*	*0.1242*	*0.02*	*0.06*
English Mature	0.0509	0.0518	1503.39	0.0921	0.2887	23470.69	1.1204	0.25	0.32
sd	*0.0042*	*0.0078*	*351.04*	*0.0160*	*0.0188*	*2150.55*	*0.1188*	*0.03*	*0.04*
Quickes Extra Mature	0.0988	0.0604	3518.84	0.1201	0.1112	9343.78	1.7421	0.33	0.60
sd	*0.258*	*0.0096*	*1277.76*	*0.0229*	*0.0122*	*1431.88*	*0.3144*	*0.07*	*0.25*
Canadian	0.0632	0.0646	2284.40	0.0895	0.1438	9360.06	1.0782	0.34	0.50
sd	*0.0067*	*0.0109*	*343.39*	*00164*	*0.0123*	*2459.68*	*0.1971*	*0.05*	*0.1*
Wexford Vintage	0.0606	0.0596	2118.90	0.0964	0.2162	16028.76	0.9904	0.22	0.32
sd	*0.0086*	*0.0113*	*689.79*	*0.0067*	*0.0231*	*1887.96*	*0.1609*	*0.03*	*0.1*

Figures are means and standard deviations of five replicates

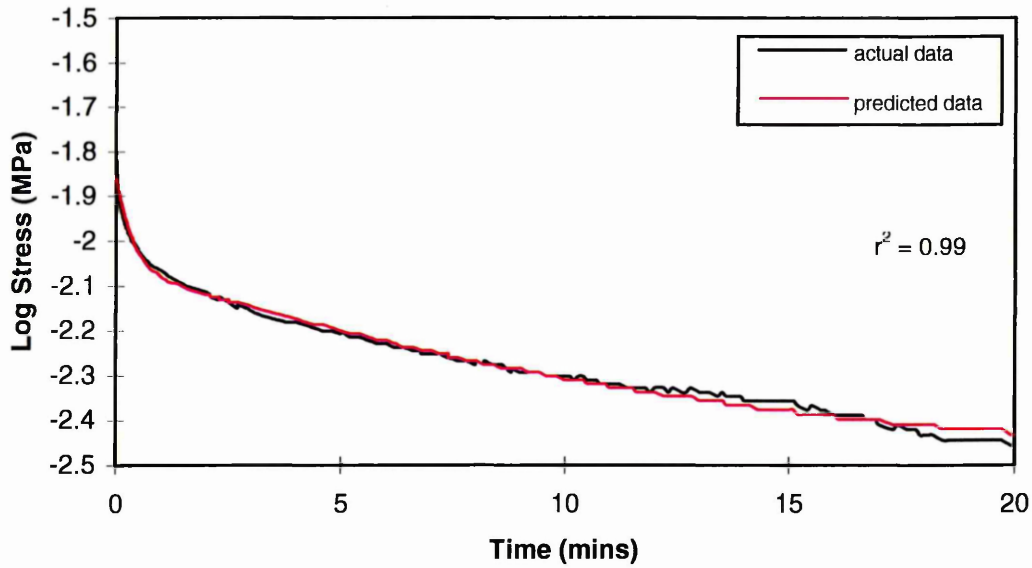


Figure 3-7. Stress - time and predicted stress - time curve for an Irish Medium Cheddar

The parameters G_0, G_1, G_2, τ_1 and τ_2 , in addition to the viscosity coefficients η_1 and η_2 are listed for each Cheddar sample in Table 3-4.

The younger Cheddars appeared to have lower values for G_1 and G_2, and notably higher values for τ_1 , than the remainder of the samples. However, the Vintage Wexford and English Mature cheese demonstrated similar results to the mild and medium samples for τ_1. Inspections of the viscosity coefficients η_1 and η_2 indicated that the younger samples were less viscous than the older samples, although the English Mild sample demonstrated a similar level of viscosity to some of the mature samples.

One way analysis of variance revealed that significant differences existed between the Cheddar samples in terms of all the stress relaxation variables ($p < 0.0005$). The LSD tests ($p = 0.05$) highlighted that G_o and τ_1 discriminated between a considerable

Table 3-4. Stress relaxation parameters of Cheddar samples

Cheddar	G_o (MPa)	G_1 (MPa)	G_2 (MPa)	τ_1 (min)	τ_2 (min)	η_1 (MPa.min)	η_2 (MPa.min)
Mousetrap	0.0351	0.1523	0.1626	0.336	7.7076	0.050	1.14
sd	*0.0070*	*0.0253*	*0.0264*	*0.013*	*0.762*	*0.004*	*0.14*
English Mild	0.0653	0.1229	0.1062	0.312	6.838	0.056	1.02
sd	*0.0057*	*0.0209*	*0.0187*	*0.007*	*0.295*	*0.002*	*0.08*
Irish Mild	0.0534	0.1263	0.1213	0.321	7.905	0.038	0.9
sd	*0.0100*	*0.0440*	*0.0456*	*0.029*	*0.980*	*0.04*	*0.15*
Irish Medium	0.0834	0.1190	0.0966	0.299	6.982	0.035	0.66
sd	*0.0170*	*0.0293*	*0.0307*	*0.015*	*0.306*	*0.002*	*0.09*
English Medium	0.0653	0.1229	0.1062	0.314	7.729	0.038	0.81
sd	*0.0057*	*0.0209*	*0.0187*	*0.012*	*0.806*	*0.001*	*0.09*
Scottish Medium	0.1051	0.2727	0.2524	0.303	6.635	0.077	1.55
sd	*0.0350*	*0.0926*	*0.0937*	*0.008*	*0.155*	*0.004*	*0.13*
Sturminster Newton	0.1636	0.2914	0.2420	0.299	6.460	0.084	1.51
sd	*0.0330*	*0.0459*	*0.0342*	*0.006*	*0.335*	*0.004*	*0.12*
Cricketers Low fat	0.1145	0.2018	0.1687	0.307	6.881	0.058	1.11
sd	*0.0342*	*0.0481*	*0.0319*	*0.019*	*0.357*	*0.004*	*0.12*
Shape Low Fat	0.0910	0.1984	0.1951	0.277	7.060	0.051	1.29
sd	*0.0248*	*0.0567*	*0.0524*	*0.003*	*0.153*	*0.003*	*0.06*
Somerset	0.0823	0.1823	0.1557	0.302	6.691	0.051	0.95
sd	*0.0309*	*0.0575*	*0.0544*	*0.008*	*0.277*	*0.004*	*0.11*
Quickes Farmhouse	0.2189	0.3332	0.2855	0.257	6.340	0.08	1.69
sd	*0.0408*	*0.0937*	*0.0838*	*0.007*	*0.374*	*0.003*	*0.13*
Irish Mature	0.0546	0.2054	0.1685	0.321	6.932	0.063	1.12
sd	*0.0147*	*0.0524*	*0.0406*	*0.014*	*0.614*	*0.005*	*0.1*
Tasty	0.1417	02053	0.1589	0.287	6.435	0.043	0.77
sd	*0.0267*	*0.0429*	*0.0412*	*0.004*	*0.229*	*0.003*	*0.1*
English Mature	0.0056	0.2044	0.1887	0.333	5.281	0.063	0.92
sd	*0.0046*	*0.0741*	*0.0669*	*0.010*	*0.356*	*0.005*	*0.08*
Quickes Extra Mature	0.0000	0.5309	0.5142	0.290	6.353	0.119	2.59
sd	*0.0000*	*0.2751*	*0.2824*	*0.017*	*0.297*	*0.01*	*0.31*
Canadian	0.0787	0.2226	0.1950	0.278	5.981	0.051	0.97
sd	*0.0347*	*0.0977*	*0.0883*	*0.01*	*0.558*	*0.003*	*0.09*
Wexford Vintage	0.0000	0.3341	0.3435	0.349	6.652	0.106	2.09
sd	*0.0000*	*0.0937*	*0.0859*	*0.024*	*0.747*	*0.013*	*0.24*

Figures are means and standard deviations of five replicates

number of samples, whereas G_1 and G_2 distinguished between the samples to a much lesser extent. The latter two parameters identified similar differences, most notably between the two Quickes and Wexford samples and the majority of the remaining samples. Although differences existed between the Cheddars in terms of τ_2 the LSD test revealed that these were limited to four Cheddar samples, two at either end of the value range. Hence the majority of cheese samples formed a homogenous group in terms of τ_2, the second relaxation time.

3.3.4 Correlations between rheological parameters

It is clear from Table 3-5, which lists the correlation coefficients between a selection of the rheological parameters, that interrelationships between these parameters were widespread.

A strong relationship between Young's Modulus and strain at yield was apparent from the scatterplot (Figure 3-8). Indeed the correlation coefficient increased from -0.78 to -0.91 when an outlying data point from the Quickes Extra Mature was removed. In fact, a curvilinear relationship between the two variables, as illustrated in Figure 3-8, is more appropriate. Although Young's Modulus correlated significantly with the stress at yield the scatter plot revealed that this relationship was distorted by one data point.

Strain at fracture correlated with several other parameters, especially energy to fracture. Strain at fracture was also the only parameter to show a strong correlation with the force to cut variable (r = -0.68). The correlation between these two parameters also increased considerably when two outlying data points, Mousetrap and Sturminster, were removed.

Table 3-5. Selected correlation coefficients between rheological parameters

	Young's Modulus	Stress at Yield	Strain at Yield	Strain at Fracture	G_1
Stress at Yield	0.83				
Strain at Yield	-0.78**	-0.48			
Stress at Fracture	0.79**	0.81**	-0.65*		
Strain at Fracture	-0.66*	-0.61*	0.82**		
Energy to Fracture	-0.56	-0.56	0.69*	0.97**	
Force to Cut	0.52	0.45	-0.65*	-068*	
G_0	-0.08	-0.14	-0.15	-0.27	-0.06
G_1	0.87**	0.85**	-0.62*	-0.65*	
G_2	0.82**	0.82**	-0.53	0.55	0.98**
τ_2	-0.67*	-036	0.8**	0.47	-0.44

* p = 0.01 ** p < 0.001

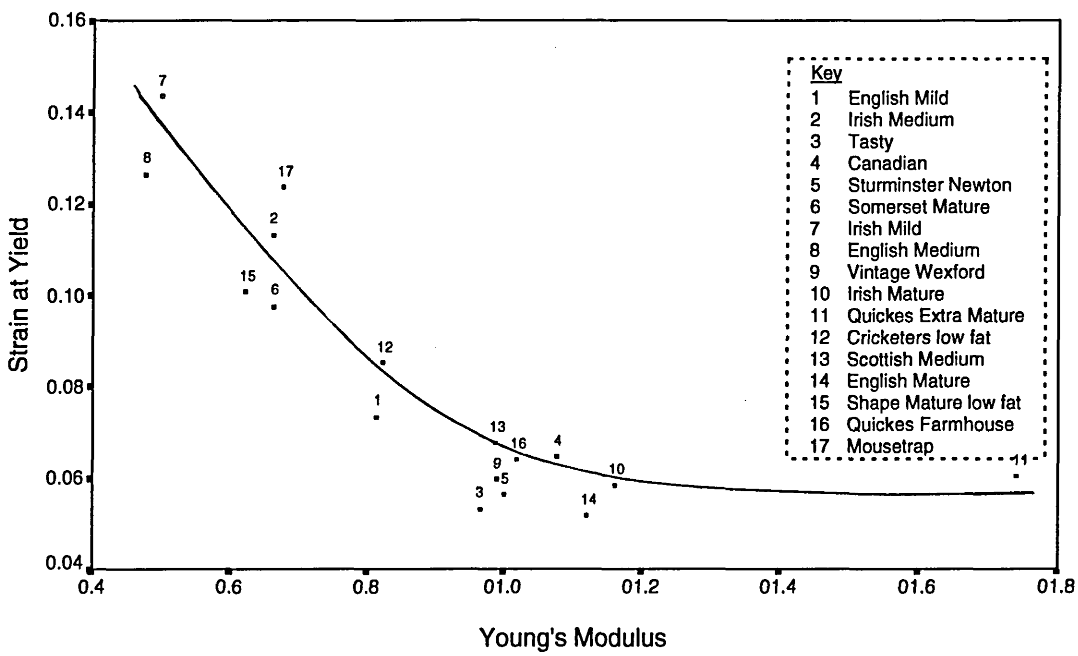


Figure 3-8. X-Y scatter of Young's Modulus v strain at yield

The relationship between the stress relaxation parameters G_1 and G_2 was strong as illustrated in Figure 3-9. G_1, and by association G_2, correlated with several of the compression test variables as well, particularly Young's Modulus (Figure 3-10).

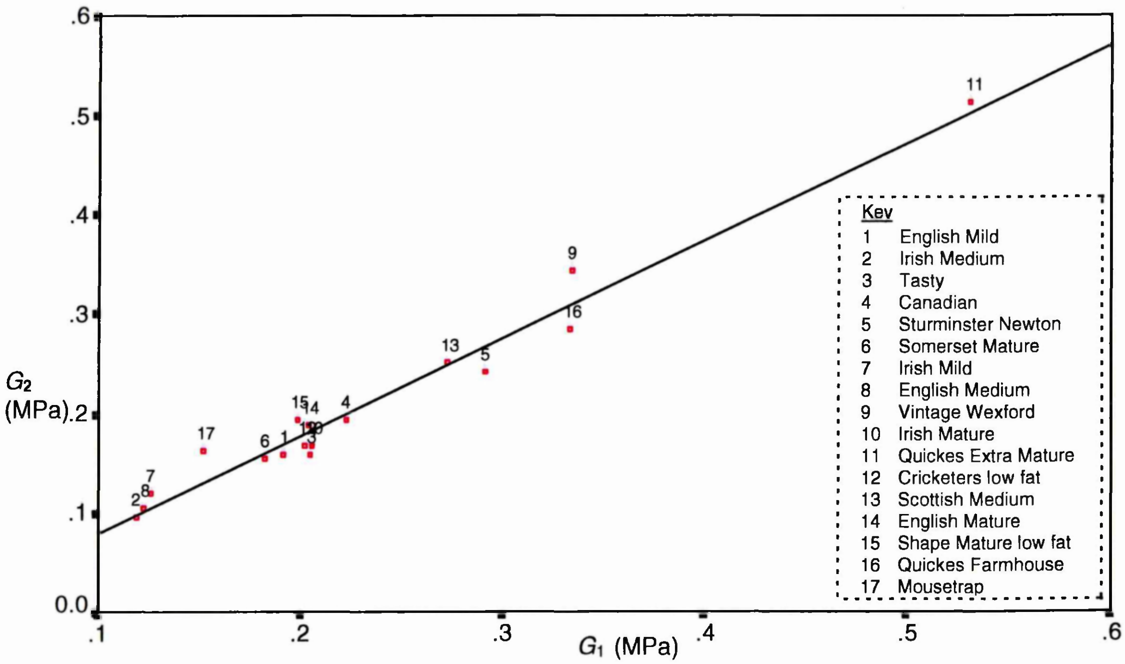


Figure 3-9 X-Y Scatter of G_1 against G_2

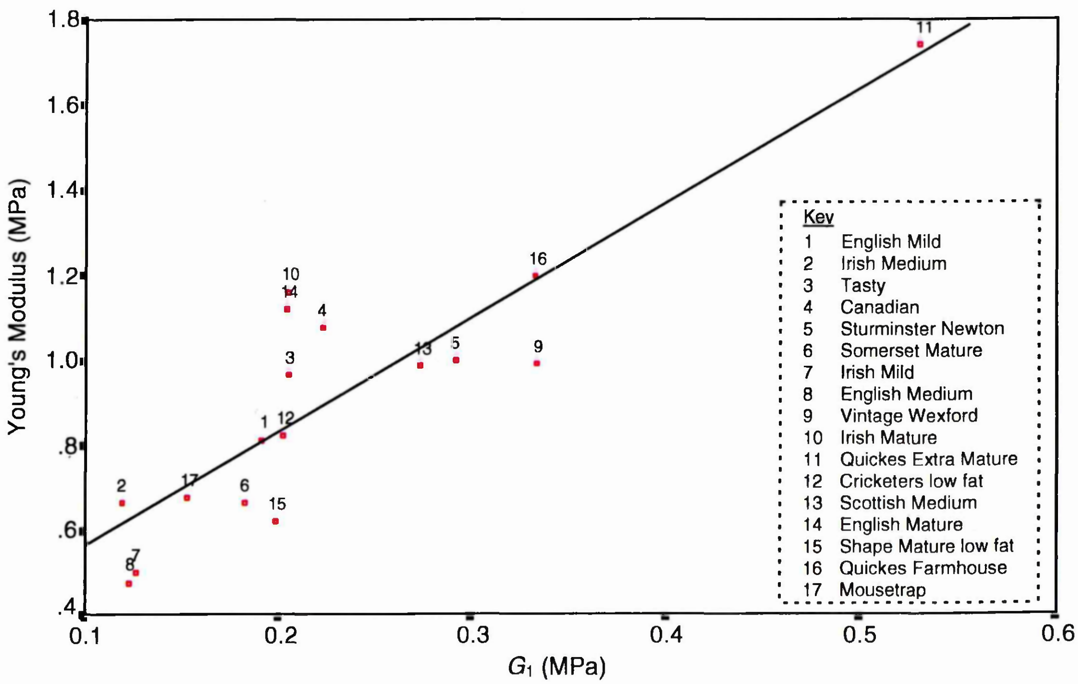


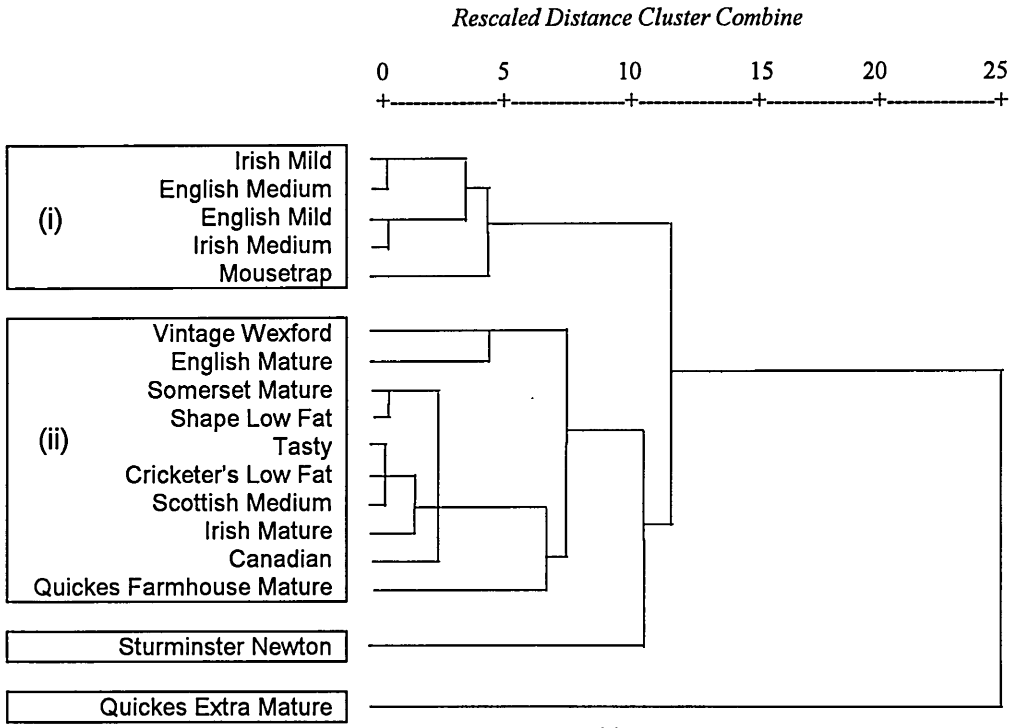
Figure 3-10. X-Y scatter of G_1 against Young's Modulus

3.3.5 Cluster and Principal Component Analysis

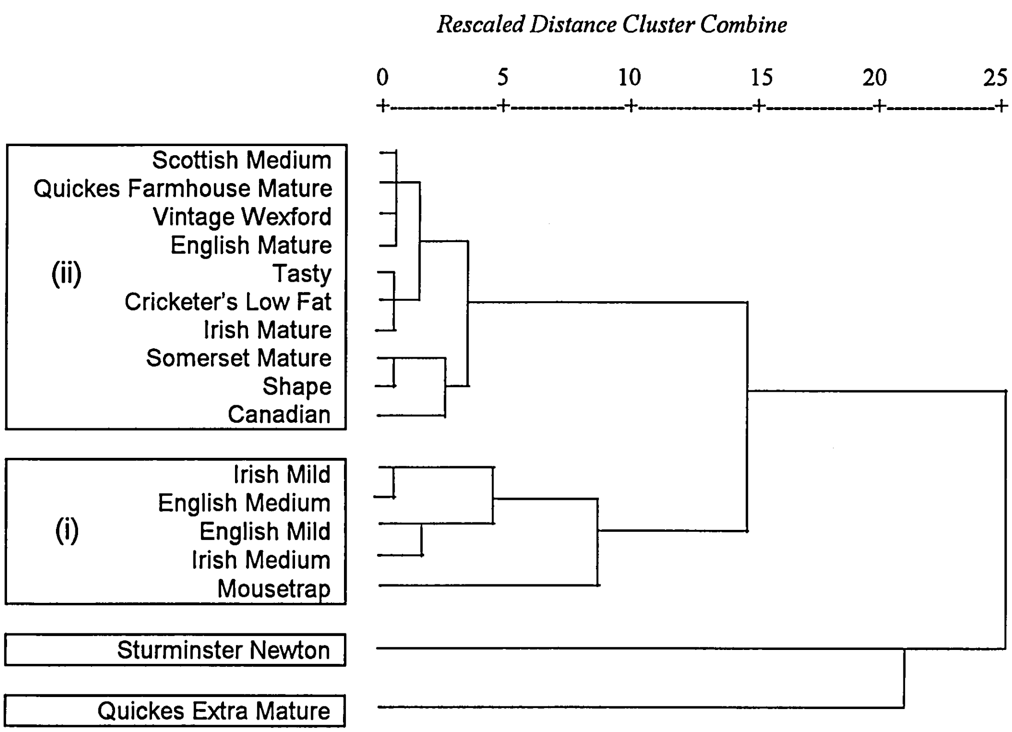
The dendrograms produced from the cluster analyses are presented in Figure 3-11. Both charts suggested that the Cheddar samples could be divided into two main groups: a group of younger Cheddars (i) and a group of more mature Cheddars (ii), with two samples, Sturminster Newton and Quickes Extra Mature, being placed in groups of their own.

The PCA identified two components which explained 72.9% of the variance within the data. The factor correlation matrix, shown in Table 3-6, identified which of the components each parameter was more closely related to. The first principal component was associated with measures of elasticity (Young's Modulus and the two elastic components from the stress relaxation model, G_1 and G_2) - and the second relaxation time, τ_2. The second component was related to those parameters from the cutting test in addition to energy to fracture from the compression test and two stress relaxation parameters, G_0 and τ_1. Strain and energy to fracture were correlated with both components. The samples scores plotted on these two components are shown in Figure 3-12.

The younger Cheddars had negative scores on the first component with the majority of the remaining samples scattered around zero. Figure 3-12 clearly reveals the extreme position of Quickes Extra Mature which has a notably high score on this component. Although less distinct for the second component, the younger samples scored on the negative part of the scale and the older samples scored positively. English Mature and Vintage Wexford were the exception as they scored negatively on this component. The relatively high score of the Sturminster sample on this component should also be noted.



(a)



(b)

Figure 3-11. Dendrogram outputs from cluster analysis including all rheological variables (a) and with stress relaxation parameters omitted (b).

Table 3-6. Rotated Factor Correlation Matrix

Rheological Parameter	Principal Component 1	Principal Component 2
Young's Modulus	0.93027	
G_1	0.91018	
G_2	0.90281	
Stress at Fracture	0.82120	
Strain at Fracture	-0.68980	-0.59350
τ_2	-0.62059	
G_0		0.82409
τ_1		-0.80778
Force to cut		0.73650
Energy to fracture	-0.60352	-0.63023
Energy to cut		0.62242

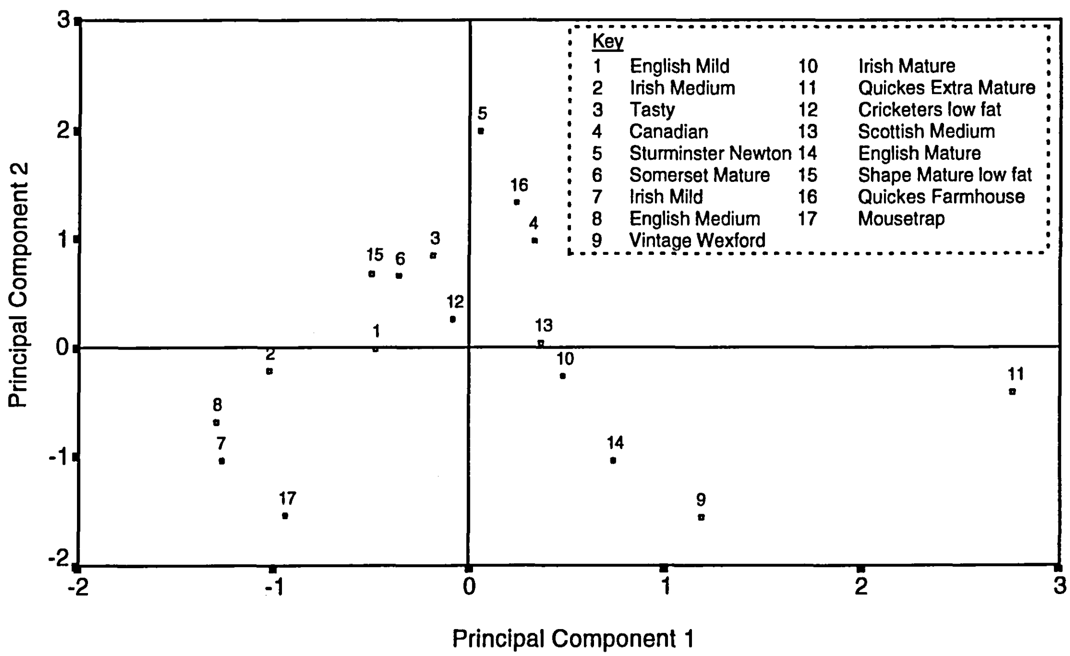


Figure 3-12. Sample scores on first and second rheological principal components

When the PCA was repeated with the stress relaxation parameters omitted, two components, accounting for 86% of the variance in the data, were also suggested (Appendix IV). The relationships between the rheological parameters and the two components were very similar to the initial analysis, apart from the obvious absence of the stress relaxation parameters. Inspections of the sample scores on each of the components also mirrored the findings of the initial PCA, although the distinction between the Cheddars on the second component was not as apparent. It is therefore possible that the presence of G_0 and τ_1 in this component in the initial analysis was responsible for the previous wider discrimination between the samples.

3.3.6 Correlations between chemical and rheological properties

There were few convincing relationships observed between the chemical and rheological variables. A weak relationship ($p = 0.05$) was suggested between Young's Modulus and percentage moisture content ($r = -0.48$) which, on closer inspection, appeared to be exaggerated by three Cheddars at the extreme ends of the range of moisture contents measured (Figure 3-13). However, the scatterplot did suggest the possibility that the two parameters grouped the Cheddars to a certain degree. The younger Cheddars were grouped below the regression line and the mature samples in a cluster above it. The two low fat samples were grouped on their own to the right of the chart.

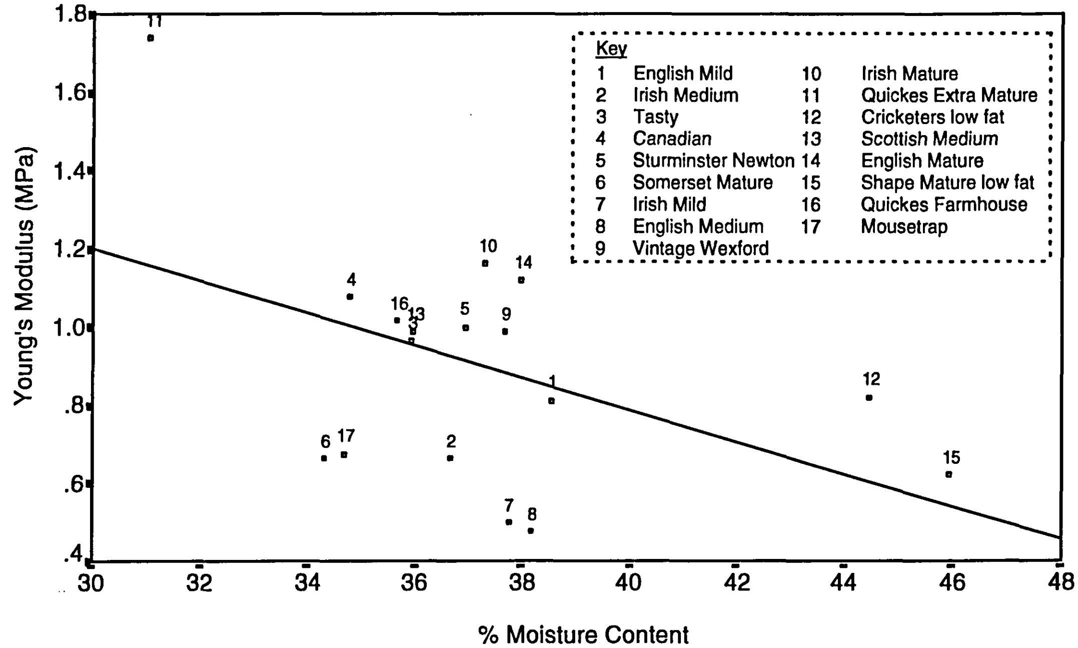


Figure 3-13. Relationship between moisture content and Young's Modulus

Discussion

Chemical composition

The results of the chemical analysis agree with other data published concerning the composition of commercially available Cheddar cheese (Kirk & Sawyer, 1991; Jack et al., 1993). This study also confirms the findings of previous research (Lawrence & Gilles, 1987) that, as the fat content decreases, moisture content increases and small increases in salt content is linked to increases in the pH level of the cheese. An increase in salt concentration reduces the activity of acid producing bacteria which results in an increase in pH.

3.4.2 Rheological properties

The fracture properties reported in this study correspond in several instances to the data published by recent researchers measuring rheological properties in terms of the stress strain curves (Kaluntec et al., 1991; Ak and Gunasekaren, 1992). The energy, stress and strain at fracture for the younger Cheddars in this study, agree with those reported by the above researchers who also used less mature types of cheese. No reports concerning samples of a similar age to the maturer Cheddars investigated in this study could be found.

Kaluntec et al. (1991) and Ak and Gunasekaren (1992) also reported that Cheddar had a Young's Modulus of approximately 300 kPa. The results of this investigation indicated a higher figure, ranging from 400 kPa, for the younger samples, to 1200 kPa. The difference observed could be attributed to the different techniques that are used amongst researchers to calculate the Modulus or to the use of different Cheddar samples and/or test parameters. Kaluntec et al. (1991), for example, used a slower crosshead speed. Charalambides et al. (1995) reported the Modulus of Cheddar to be approximately 1150 kPa but further inspection of the test method revealed that tests were carried out at 4 °C, as opposed to room temperature, which was the temperature used in this study and those cited above.

Prentice (1987), in his review of published results concerning the rheological properties of cheese, pointed out that a wide variation in the reported physical properties of cheese existed. This review focused on Cheddar. Given that this work demonstrated variation in the Young's Modulus by a factor of 3 for different cheeses within the variety Cheddar, it is not surprising to find differences between this work and other published data.

Bertola et al. (1995) reported that two exponential components and a residual term were sufficient to model the stress relaxation behaviour of Reggianito Argentino cheese and Masi (1989) reported a similar model for Pasta Filata cheese. The results of this investigation revealed that a two component model, with an additional residual term, was also successful in modeling the relaxation behaviour of Cheddar cheese.

As Prentice (1992) remarked, studies reporting the stress relaxation properties of cheese are limited. Even so comparisons with other work would be difficult due to the use of dissimilar test conditions and different approaches adopted to model stress relaxation behaviour. For example, Bertola et al. (1995) only allowed the sample to relax for five minutes during testing; Luyten (1991) used only one relaxation time when investigating Gouda; and Mohensin and Morrow (1967) did not include the residual term in their double Maxwellian model. It should therefore be noted that the stress relaxation properties reported in this study are in terms of the test parameters and time limit stated and only serve to compare the cheese samples investigated in this study. The results of this study revealed that the stress relaxation parameters were of value as they discriminated amongst the samples tested. Additionally, although obvious trends in the data were not apparent, the group of younger Cheddars was isolated to a certain extent by G_1, G_2, τ_1 and the two viscosity coefficients and as such further research into the stress relaxation behaviour of cheese is warranted.

In a comparison of a young and mature Cheddar, Creamer and Olson (1982) reported that young cheese had a lower Modulus of elasticity and fractured at a greater force and compression level. During early stages of ripening considerably more of the casein network is intact thus it retains its elasticity and strength. The results of this study agree with these findings in that two broad groups of samples emerged from the analysis of the fracture properties. In general, the mild and medium Cheddars had a lower Young's Modulus and fractured at a greater level of strain than the maturer samples. However, in contrast to Creamer and Olson's (1982) findings, the majority of the mature samples in this study fractured at a higher stress level than the young samples. The maturer samples also required more force to be penetrated by the cutting blade. It is probable that as the maturer samples were less elastic a greater force was required to bring about the deformation or penetration of the samples and so although fracture occurred at a lower deformation the force required to achieve it was greater. The mature sample used by Creamer and Olson (1982) was considerably older and it is likely that the degradation of the casein network was such that only the smallest force was required to fracture any remaining bonding between the matrix. It should also be noted that there are additional factors that could contribute to the fracture stress not least the manufacturing process, ripening conditions and varying chemical composition - factors that could not be controlled in this study.

The analysis of the individual rheological parameters suggested that some discrimination between types of Cheddar may exist in terms of maturity. The results obtained from the cluster and Principal Components analyses revealed that the Cheddars studied in this investigation could be subdivided in terms of their rheological parameters but this was limited to two groups, young and old. Individual sample component scores indicated that there was still considerable variation in the rheological properties of the groups suggested, particularly the older samples. The positioning of the Quickes Extra Mature and Sturminster Newton samples on the extreme ends of the first and second principal components respectively confirms the different rheological profile of these two cheeses from the remaining samples and verifies the interpretation of the cluster analysis in which they were placed in clusters of their own.

It had been noted earlier (section 3.3.2 & 3.3.3) that the English Mature and Vintage Wexford samples had demonstrated rheological properties resembling those of the younger Cheddars. The comparable scores observed for these two samples and the younger Cheddars on the second principle component confirmed this similarity.

3.4.3 Relationships between chemical and rheological data

Chemical indices have consistently been reported to correlate with physical properties (Chen et al., 1979; Casiraghi et al. , 1989; Marshall 1990). Creamer and Olson (1982) reported correlations between the percentage moisture content and force at fracture. Luyten (1988) reported that, in the case of Gouda cheese, as moisture content increased the stress at fracture and Modulus decreased. A higher moisture content reduces the concentration of bonds holding together the casein network (Visser, 1991) and also reduces the resistance of the protein matrix to deformation (Jack & Paterson, 1992). Such relationships were not evident in the results of this study although a weak correlation was identified between the Young's Modulus and moisture content. Additionally, a comparison of the fracture properties of those Cheddars with particularly low and high moisture contents (Quickes Extra and the two low fat samples) did agree with the results published in the studies cited above.

Bryant et al. (1995) discovered that reducing the fat content of Cheddar increased the level of force and deformation at fracture. (It should be noted that the range of fat content in the samples studied by Bryant et al. (1995) was much larger than the range studied here.) Although no relationships were identified between the fat content and rheological properties of the samples measured in this study, a relatively high level of stress was required to effect the fracture of the two low fat cheeses. As Bryant suggests, the increased protein content probably accounts for this occurrence. In contrast similar levels of strain at fracture were recorded for the low fat samples in comparison to the other mature Cheddars in this investigation.

It is widely accepted that variations in pH level affect the rheological properties of cheese (Lawrence et al., 1987). Creamer and Olson (1982) reported that higher pH Cheddars exhibited higher levels of force and compression at fracture than those with a low pH. However, no relationships between the pH and any of the rheological properties were evident from the results of this study.

Unlike several previous researchers, no relationships between the chemical and rheological properties of cheese were revealed in this study. However, Jack et al. (1993) also reported no relationships between Instron parameters and compositional data in a study of 19 Cheddar samples. In most studies either a wider range of varieties of cheese have been investigated (Chen et al. 1979; Casiraghi, 1989), or the range of the chemical constituents being investigated has been extended beyond the normal range associated with Cheddar. The relatively narrow range of chemical composition observed in this study, as was also the case in the study by Jack et al. (1993), could therefore account for the lack of observed relationships.

4. The relationships between the perceived textural attributes and the chemical/rheological properties of Cheddar cheese.

4.1 Introduction

The representation of a food's textural characteristics by mathematical models may, via their use of rheological and chemical parameters, provide a greater understanding of the sensory attributes in question. Furthermore, the potential for using these models to predict textural attributes on the basis of instrumental tests provides an economical and reliable alternative to sensory panels for the food industry.

A key aim of this research was to investigate the possibility of constructing models that could predict the textural attributes of Cheddar cheese from its rheological and/or chemical properties. Consequently the relationships between the textural and the chemical and rheological parameters of the Cheddar samples were investigated using the data presented in the two preceding chapters (the sensory, rheological and chemical data for each of the seventeen Cheddar samples were collected from the same block within a nine day period). This analysis, including the construction and testing of various models to predict the textural attributes of Cheddar cheese is outlined in this chapter.

To test the reliability of the models additional data were collected from six further Cheddar samples; a Mousetrap, an English Mature, a Quickes Extra Mature and three separate blocks of English Mild. The types of the selected samples were similar to those tested earlier. However, given the differences that occur from batch to batch it was not anticipated that the properties of the cheese would be precisely the same. The sensory, rheological and chemical properties were determined following the procedures outlined in sections 2.2.3, 3.2.2 and 3.2.4 respectively. Samples for sensory analysis were tested at the same time as other Cheddar samples being tested for further parts of this study, during which time panel performance was monitored for consistency.

4.2 Data analysis

The following sequential series of investigative methods were used to seek possible relationships between the data.

- Calculation of Pearson's correlation coefficients between the textural attributes and the chemical/rheological parameters.

- Investigation of individual relationships using scatterplots.

- Logarithmic transformation of curvilinear relationships where appropriate.

- Construction of mathematical models to predict textural attributes using multiple regression analysis (SPSS for Windows 6.0.1, 1993). Initially a 'Stepwise' option (Norušis, 1993) was chosen as the method for deciding which variables were to be included in the regression equations. However, rather than relying totally on the algorithm used by SPSS to select variables, other rheological parameters were forced into the equation to see if the relationship could be improved. Such variables were only left in the equation if there was a marked improvement of at least 0.1 units to the regression coefficient. The standard error and 95% confidence intervals for the predicted individual and mean responses were also determined for each model.

In an industrial context carrying out one, as opposed to three, separate instrumental tests would allow greater control and time efficiencies. Therefore models were initially constructed with only those parameters obtained from the compression test available for inclusion in the regression equation. Subsequent models were then obtained with all the rheological parameters measured available.

The predicted values for the textural attributes for each of the original Cheddar samples were calculated using the relevant models suggested by the regression analysis and compared against the panel results.

Finally, the textural attributes of the six additional Cheddars were predicted using the regression equations to validate the models and to determine which were the most precise in the case of each attribute.

4.3 Results

4.3.1 Relationships between chemical composition and textural attributes

The only significant correlation between the chemical and sensory variables was between fat content and creaminess ($r = 0.61$, $p = 0.05$). The scatterplot revealed that much of the apparent correlation was due to the effects of two extreme data points from the two low fat cheeses (Figure 4-1).

When the correlation coefficients were recalculated with the two low fat Cheddars removed the relationship between fat content and creaminess no longer existed. Conversely, a number of significant correlations between fat content and other textural parameters appeared to emerge. However, a closer inspection of the relevant scatterplots revealed that in all cases the data points were dispersed some distance from the associated regression lines. Similarly relationships between moisture content and the textural attributes were also poor. However, a closer inspection of the

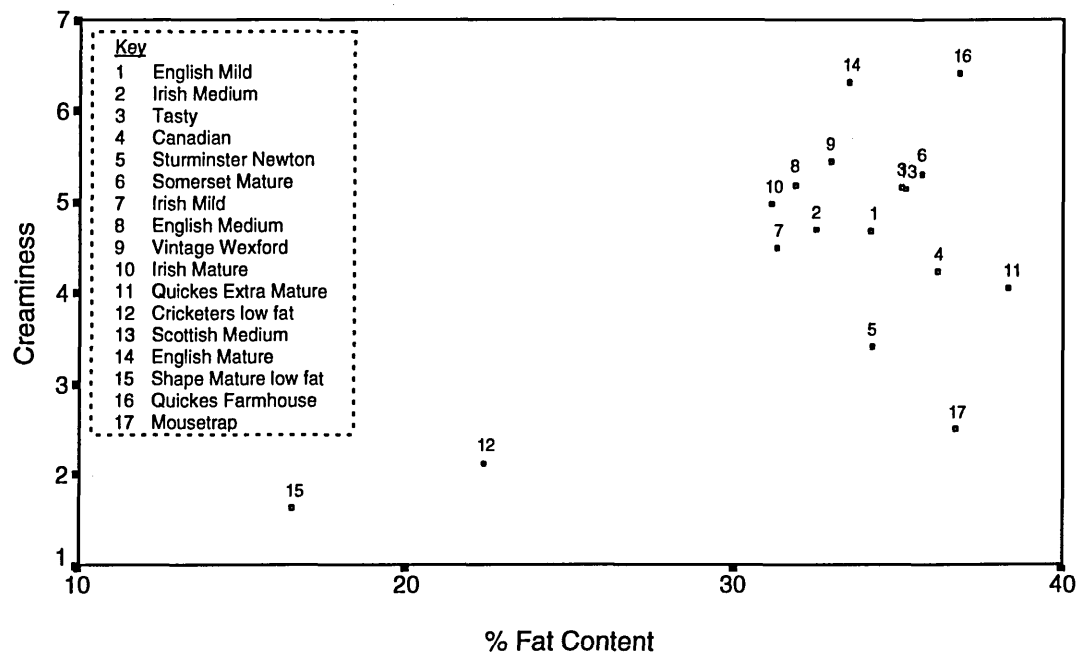


Figure 4-1. Scatter plot of % fat content against creaminess score

scatterplot between moisture content and springiness revealed that although a group of 'young' Cheddars were dispersed some distance from the regression line, the majority of the remaining Cheddars which, apart from the English mild were marketed as mature, displayed a very close relationship in terms of moisture and springiness. This would indicate that within the subset of mature samples springiness was related to moisture content.

No relationships between the pH level or percentage salt content and the textural attributes were apparent.

Relationships between the rheological and textural attributes

Numerous correlations were evident between the rheological and textural parameters (Table 4-2). Correlations existed between all the rheological properties measured during the compression test (except Work to Yield) and the majority of the textural attributes. It is noteworthy that the removal of an outlying data point (Mousetrap) identified from scatter plots, improved the correlations significantly in many cases. For example, the coefficient between crumbliness (chewing) and energy to fracture increased to -0.71 from -0.37.

Force to cut correlated with all the textural attributes (except creaminess) and in each case, apart from springiness, displayed a higher correlation coefficient than the compression test parameters. Significant correlations also existed between the textural attributes and energy to cut but, since this parameter was closely related to force to cut, this was not surprising.

The stress relaxation parameter G_1 appeared to be related to several of the textural attributes. Scatterplots confirmed strong relationships between firmness and G_1 but the dispersion of data points around the regression line for the remaining attributes suggested a weaker relationship than originally indicated. Similar observations were made for G_2, which, as a strong correlation occurred between this parameter and G_1, was anticipated.

Although the correlation coefficients suggested a weak relationship between τ_2 and both firmness and springiness, the removal of an outlier (English Mature), revealed by the scatter plot, improved the correlation coefficients to -0.86 and 0.84, from -0.66 and 0.65 respectively.

Table 4-1. Pearson's correlation coefficients between selected parameters

	Crumbliness (fingers)	Crumbliness (chewing)	Firmness	Graininess	Hardness (cutting)	Hardness (first bite)	Springiness
Strain at Yield	ns -0.53	ns -0.31	***-0.77	ns -0.43	**-0.68	.**-0.62	***0.76
Stress at Yield	**0.59	ns 0.44	***0.74	**0.60	**0.62	**0.65	***-0.72
Strain at Fracture	***-0.76	ns -0.39	***-0.84	*-0.55	***-0.78	**-0.63	***0.87
Stress at Fracture	ns 0.43	ns 0.24	**0.64	ns 0.38	**0.70	**0.66	*-0.57
Energy to Fracture	***-0.75	ns -0.37	***-0.76	*-0.53	**-0.69	*-0.54	***0.83
Young's Modulus	*0.50	ns 0.38	***0.74	*0.55	*0.57	**0.60	***-0.73
Force to Cut	***0.79	**0.69	***0.86	**0.73	**0.74	***0.77	***-0.86
G_0	*0.58	*0.59	***0.72	**0.67	*0.58	*0.57	***-0.70
τ_2	ns -0.43	ns 0.46	**-0.66	ns -0.37	*-0.49	ns -0.45	**0.65

ns = not significant *$p \leq 0.05$ **$p \leq 0.01$ ***$p \leq 0.001$

4.3.3 Regression models

Compression test parameters:

The initial regression equations, determined by the multiple regression analysis with the rheological parameters from the compression test available, are listed in Table 4-2, together with the associated regression coefficients and the standard errors for the mean predicted values. Models for predicting springiness, firmness and crumbliness (fingers) demonstrated particularly good fits.

A comparison of the predicted values suggested by the models with the actual panel results revealed small standard errors for the majority of the attributes. For example Figure 4-2 illustrates the relationship between the actual and predicted values for firmness. The plots also revealed that predictions for the Mousetrap type of Cheddar were poor in most instances. As inconsistencies between this and the remaining Cheddars had been identified previously, the regression coefficients were recalculated with this Cheddar removed. Considerable improvements were seen in the case of firmness ($r^2 = 0.86$), crumbliness (chewing) ($r^2 = 0.6$) and graininess ($r^2 = 0.72$) suggesting that the models were more accurate for the majority of Cheddars than initially revealed.

The scatter plots also highlighted that poor predictions were made concerning the crumbliness and graininess of the low fat Cheddar-like samples. Additional models were constructed omitting the data from the low fat samples (Table 4-3). Improved regression coefficients suggested that the latter equations may have been more successful in predicting crumbliness and graininess.

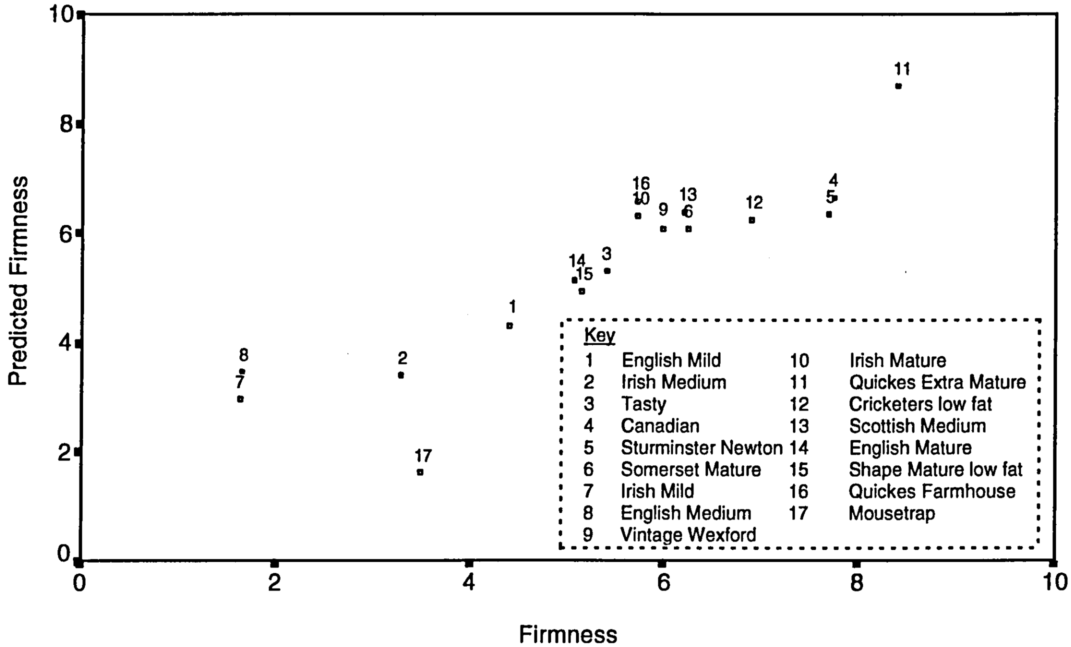


Figure 4-2. X-Y scatter plot of firmness against predicted firmness

All rheological parameters:

Including all the rheological parameters in the regression equation resulted in different models for all but the springiness and crumbliness (fingers) attributes (Table 4-4). All of these models included the force to cut variable. The regression coefficients associated with these models were higher than or at least similar to those obtained for the compression models, but it should also be noted that the 95% confidence intervals were larger.

Scatter plots of the predicted values against the panel scores revealed that, as with the previous models, poor predictions were made for Mousetrap and the two low fat samples in terms of crumbliness, graininess and, additionally, hardness (cutting).

An acceptable model for predicting creaminess could not be constructed using any combination of the chemical or rheological parameters measured.

Table 4-2. Variables included in regression equations, r^2 and standard errors for each textural attribute when limited to compression test parameters

Sensory Attribute	Springiness	Firmness	Log Crumbliness (fingers)	Hardness (cutting)	Hardness (first bite)	Graininess	Crumbliness (chewing)
Variables included in Equation	Log Strain at Fracture	Strain at Fracture Stress at Yield	Log Strain at Fracture [a]Log Strain at Yield	Strain at Fracture [a]Energy to Fracture	Log Stress at Yield [a]Stress at Fracture [a]Strain at Yield	Log Strain at Fracture [a]Stress at Yield	Log Energy to Fracture
Regression Equation	$7.85+(7.57 \times LgSn_f)$	$4.24+(-5.96 \times Sn_f) + (51.99 \times Ss_y)$	$0.26+(-1.08 \times LgSn_f) +(0.29 \times LgSn_y)$	$6.1+(-12.33 \times Sn_f) + (0.000113 \times E_f)$	$13.61+(7.03 \times Ss_f) + (6.93 \times LgSs_y) + (-17.08 \times Sn_y)$	$0.265+(-4.1 \times Lg\ Sn_f) + (25.91 \times Ss_y)$	$23.36 + (-4.54 \times LgE_f)$
r^2	0.9	0.78	0.77	0.69	0.56	0.53	0.33
Standard Error of mean predicted value	0.21	0.37	0.06	0.32	0.51	0.52	0.56

[a] Variable forced into regression equation

Table 4-3. Regression Equations and coefficients when Mousetrap and Low fat Cheddar-like samples were removed

Sensory Attribute	Log Crumbliness (fingers)	Graininess	Crumbliness (chewing)
Regression Equation	$-0.17+(-1.09 \times LgSn_f)$ $+(-0.04 \times LgSn_y)$	$-0.9+(-6.96 \times LgSn_f)$ $+(8.37 \times Ss_y)$	$33.74+(-7.12 \times LgE_f)$
r^2	0.96	0.9	0.79
Standard Error of mean predicted value	0.03	0.27	0.34

Table 4-4. Variables included in regression equations, r^2 and standard errors for each textural attribute with all rheological parameters available

Sensory Attribute	Firmness	Hardness (cutting)	Hardness (first bite)	Graininess	Crumbliness (chewing)
Variables included in Equation	Force to cut [a]Stress at yield [a]Strain at yield	Force to cut [a]Stress at Fracture	Force to cut [a]Stress at Fracture	Force to cut [a]Stress at yield	Force to cut
Regression Equation	$-0.897+(F_c \times 16.14)$ $+(Ss_y \times 54.55)$ $+(Sn_y \times -16.72)$	$-2.49+(F_c \times 12.04)$ $+(Ss_f \times 43.61)$	$-3.79+(F_c \times 14.89)$ $+(Ss_f \times 43.89)$	$-3.09+(F_c \times 16.75)$ $+(Ss_y \times 43.84)$	-2.26 $+(F_c \times 22.34)$
r^2	0.92	0.78	0.79	0.63	0.48
Standard Error of mean predicted value	0.23	0.34	0.34	0.46	0.5

[a] *Variable forced into regression equation*

4.3.3.1 Selecting reliable models

In order to test the reliability of the proposed models, the panel scores for the six additional Cheddar samples were compared with those predicted using the appropriate regression equations (sensory, chemical and rheological data for the six additional Cheddars can be found in Appendix V). These comparisons revealed that models constructed using the compression test parameters, without exception, were more accurate. It had been anticipated that the force to cut parameter would be better correlated with the hardness measures as the cutting test resembled the action used by the panel to a certain extent when assessing this attribute. Therefore the hardness scores for the additional Cheddars were also predicted using models containing just the force to cut parameter. These scores were considerably more precise than any of the previous models for either hardness attribute, despite the associated models having lower regression coefficients. Predicted textural attribute scores for each Cheddar, calculated using the most accurate models, are given in Table 4-5, together with the associated regression equation. The predicted scores were very precise for five of the six Cheddars, usually to within 1 or 1.5 units of the actual score, which, in the majority of cases, fell within the 95% confidence interval bands associated with the model. (Predictions for the English Mild IV sample were consistently inaccurate). For example, the accuracy of the predictions made for firmness is illustrated in Figure 4-3, the 45° dotted line indicating where precise predictions should lie.

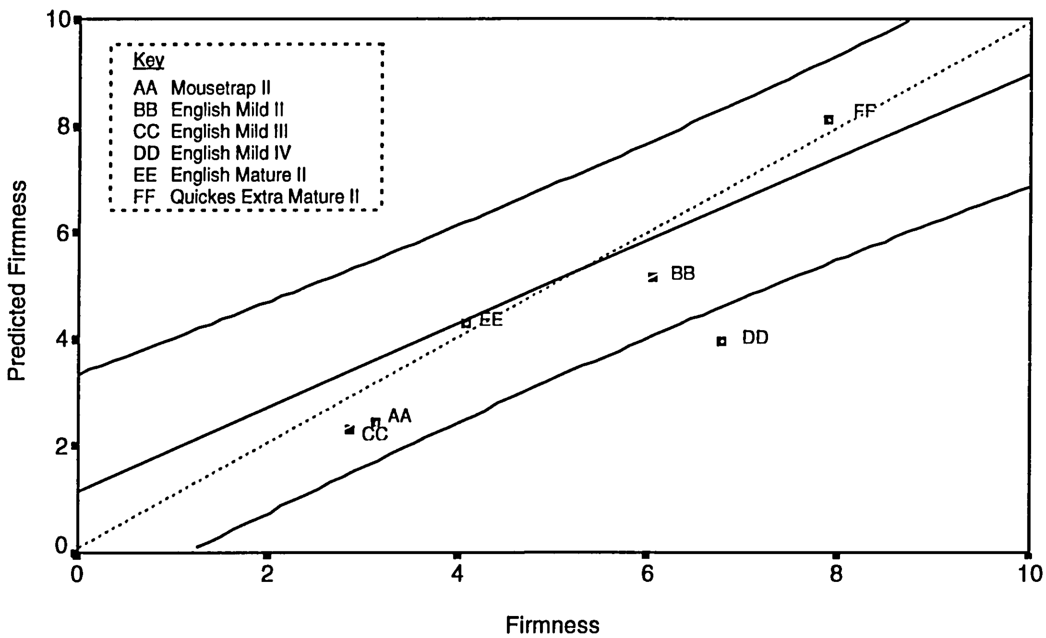


Figure 4-3. Scatter plot of actual against predicted firmness scores for six additional Cheddars.(—— regression line and upper and lower 95% confidence intervals for firmness model)

Table 4-5. Difference in panel and predicted scores for six additional Cheddars

	Springiness			Firmness			Hardness (first bite)			Hardness (cutting)			Crumbliness (fingers)			Crumbliness (chewing)			Graininess		
Regression Model	7.85+(7.57 x Lg Sn_f)			4.24+ (-5.96 x Sn_f) + (51.99 x Ss_y)			-0.93 + (F_c x 18.22)			0.35 + (F_c x 15.55)			10**(0.26+ (-1.08 x LgSn_f) + (0.29 x LgSn_y))			23.36+(-4.54 x LgE_f)			0.265+(-4.1 x LgSn_f) + (25.91 x Ss_y)		
r^2	**0.9**			**0.86***			**0.6**			**0.45**			**0.96**			**0.79**			**0.72***		
	Pan	Pred	*Diff.*	Pan	Pred	*Diff.*	Pan	Pred	*Diff.*	Pan	Pred	*Diff.*	Pan	Pred	*Diff.*	Pan	Pred	*Diff.*	Pan	Pred	*Diff.*
Mousetrap II	**5.29**	5.81	*-0.52*	**3.15**	2.44	*0.71*	**2.40**	n/a		**3.63**	n/a		**2.83**	1.81	*1.02*	**2.49**	3.47	*- -0.98*	**2.25**	2.06	0.19
English Mild II	**3.18**	4.29	*-1.11*	**6.05**	5.16	*0.89*	**5.84**	4.04	*1.8*	**4.75**	4.59	*0.16*	**3.01**	2.08	*0.93*	**4.75**	2.99	*1.76*	**3.67**	3.65	0.02
English Mild III	**4.50**	6.02	*-1.52*	**2.86**	2.29	*0.57*	**2.95**	2.14	*0.81*	**4.07**	2.97	*1.1*	**2.70**	1.77	*0.93*	**3.12**	3.41	*-0.29*	**2.95**	1.98	0.97
English Mild IV	**3.38**	4.88	*-1.50*	**6.77**	3.94	*2.83*	**5.84**	2.41	*3.43*	**5.58**	3.2	*2.38*	**3.77**	2.27	*1.5*	**5.71**	3.42	*2.29*	**4.25**	2.92	1.33
English Mature II	**3.67**	3.98	*-0.31*	**4.08**	4.28	*-0.20*	**2.85**	2.41	*0.44*	**3.26**	3.2	*0.06*	**3.14**	2.99	*0.15*	**2.79**	2.85	*-0.06*	**2.86**	3.29	-0.43
Quickes Extra Mature II	**1.61**	2.86	*-1.25*	**7.89**	8.09	*-0.20*	**5.26**	5.51	*-0.25*	**5.87**	5.85	*0.02*	**5.26**	3.21	*2.05*	**4.26**	4.24	*0.02*	**5.18**	5.53	-0.35

Pan - Panel score Pred - predicted score ** = to the power * calculated with Mousetrap data point omitted

4.3.4 A note concerning panel performance

Some findings from the ongoing monitoring of the panel's performance during sensory testing are of note at this point. Two way analysis of variance of sensory data, which included the scores from the six further Cheddar samples referred to in this chapter, indicated that the panel were only measuring firmness, hardness (first bite) and crumbliness (fingers) consistently ($p < 0.01$) (Appendix VI). Subsequent LSD tests revealed that in most cases only two panelists - different panelists for different attributes - were using the scales differently, although in the case of crumbliness (chewing) there was considerable disagreement amongst the panel. Finally, although some inconsistency with graininess had been noted during the initial study of seventeen Cheddars, the current analysis revealed that the panel were now split into two groups one using a significantly lower part of the scale to the other. Consequently it should be noted that measures for crumbliness (chewing) and graininess may not be as accurate as in previous tests due to some deterioration in the panel.

4.4 Discussion

4.4.1 Relationships between sensory and chemical/rheological parameters

The results revealed that the chemical indices measured had very limited value in predicting the texture attributes perceived by the panel. Although it is widely accepted that the chemical composition of cheese affects its texture, the data showed no correlations between compositional data and sensory parameters; similar results have been reported by Jack et al. (1993). It must be remembered that for a single classification of cheese such as Cheddar, the range of chemical composition in terms of the commercial samples investigated in this study is comparatively small. Chen et al. (1979) found relationships between the textural attributes of a range of cheeses and their chemical composition but this was obviously over a much larger compositional range. Other researchers have found relationships between the composition and textural attributes of Cheddar (Marshall, 1990) but the samples investigated were outside the range of composition found in Cheddar available for retail sale. In addition it should be noted that changes in one chemical parameter have significant effects on others. The range of samples used for this investigation meant that no chemical parameter could be investigated in isolation which, as highlighted by Visser (1991), makes it difficult to isolate the relationship of any one chemical parameter with the textural attributes.

Conversely, many correlations were identified between the rheological properties and textural attributes. When establishing relationships between rheological and sensory parameters researchers have often commented on a logarithmic, as opposed to linear, relationship (Peleg, 1980). Indeed significant correlations were identified when logarithmic transformations were applied to parameters when investigating crumbliness, springiness and graininess. Szczesniak et al. (1963) noted that, when a large range in a textural attribute was identified, relationships with instrumental measures were often non-linear. Interestingly larger ranges of panel scores were ascribed to crumbliness, springiness and graininess, although the difference was minimal. (Table 2.5)

4.4.2 Mathematical models

It was evident that, although regression coefficients are an indication of the accuracy of a model, they were not particularly reliable in this investigation and that testing models on further samples gave a better insight into the predictability of a model. Initially several models utilising the force to cut appeared more accurate in terms of the regression coefficient (r^2). Nevertheless, for the majority of attributes, the more successful models - identified from predictions made on the six further Cheddar samples - were those using parameters from the compression tests. However, for both measures of hardness the force to cut parameter from the cutting test was more successful. It is apparent that parameters taken from tests which resembled the method employed during the sensory assessment of an attribute were more reliable predictors.

The rationale behind the success of the models suggested for hardness, reflected the need for mathematical models to be a sound physical representation of the textural attributes themselves (Pike, 1986). With this in mind, it would be logical to expect a model of springiness to include Young's Modulus. However, although a significant correlation did exist between the two ($r = -0.73$; $p = 0.05$), a stronger correlation was identified with strain at fracture - an observation also made by Green et al. (1985). This may suggest that the manner in which the panel perceived springiness was related to how much they were able to squeeze the sample in addition to the extent to which it sprung back.

Green et al. (1985) also reported significant correlations between the 'compression at fracture' of Cheddar samples and panel measures of crumbliness and graininess. The equivalent strain at fracture variable also occurred in the models suggested for crumbliness (fingers) and graininess in this study, in addition to the firmness and hardness (cutting) models. The success of a model containing the two strain variables for crumbliness (fingers) is not surprising. By definition a cohesive material would be expected to withstand considerable deformation before fracturing - the strain levels at which yield and fracture occur provide reference points for the break down of the structure. Interestingly, it was the energy to fracture variable which was a better predictor of crumbliness when assessed in the mouth. The use of this variable can be considered sound in that it is quite acceptable to assume that during chewing the effort to break down the sample is being assessed and is potentially easier to assess than, for example, the amount of deformation applied.

The inclusion of the stress at yield parameter in the model to predict firmness is logical considering the fact that the panel were measuring the force required to compress the sample and were therefore probably only measuring firmness up to the point when the sample began to fail.

The same parameters were included in the model to predict graininess as in the firmness model. The logic behind this model is less obvious and may be a result of the significant correlation between these two textural attributes. Graininess was concerned with the 'bittiness' of the samples and hence is probably related to the number of particles the sample breaks down into. Thus, as the strain at fracture variable is related to the cohesiveness of the sample, this may offer some explanation. The model was only able to explain 70% of the variation in the data. Mastication involves considerable breakdown of the cheese structure plus the addition of saliva and changes in temperature. It was not possible to account for such factors in the instrumental tests but these could account for some of the unexplained variance in the data.

The inability to construct a model to predict creaminess suggests that other mechanisms contribute to the characterization of this attribute.

The models for crumbliness and graininess and, possibly, hardness appeared inadequate for the prediction of these attributes for the low fat Cheddar-like samples.

A reduction in fat content, achieved by manipulating the fat to casein ratio of the cheese milk, has a marked effect on the structure of the cheese. As data from a majority of genuine Cheddars was used to construct the models, it is justifiable that the models would not be as accurate on samples of considerably different composition and structure.

The proposed models did not make accurate predictions of the textural characteristics of the original Mousetrap Cheddar. The fact that this Cheddar is of a particularly low grade, and in this instance, was very young, could account for this. Interestingly, predictions were quite accurate for the second Mousetrap Cheddar. This particular block was a month older and, although the precise information was not obtained at the time, it is probable that it was sourced from a different creamery (Lacey, 1997, personal communication).

5. The chemical, textural and rheological properties of maturing Cheddar.

5.1 Introduction

It is well established that a relatively long period of ripening is essential for the development of the required flavour and texture in Cheddar cheese. However, very few studies have investigated the relationship between the rheological properties of Cheddar and maturation time, and only a limited number of researchers have investigated the difference in textural properties of Cheddars of different maturities. Muir et al. (1996), Piggott & Mowat (1991) and Roberts & Vickers (1994) investigated the relationship between Cheddar texture and aging, all concluding that texture did not appear to be correlated with age. However, Piggott & Mowat (1991) assessed the texture of a range of Cheddars of different ages rather than that of an individual cheese during maturation. Data reported in the previous chapters indicated that textural attributes were linked to level of maturity, although it was acknowledged that other contributory factors may exist. Roberts and Vickers (1994) had expected to observe differences in texture at different stages of maturation and suggested that changes may have been detected had they extended the ripening period beyond nine months. No work was found in the literature concerning relationships in the progressive development of the textural and rheological properties of maturing Cheddar.

Consequently the objective of this particular part of this research was to investigate the changes in the chemical, textural and rheological properties of one particular type of Cheddar during and beyond its recommended maturation time.

As it was possible that the mathematical models constructed in the previous chapter could provide mechanisms to determine the textural attributes of the cheese block during ripening, an important objective of this investigation was also to assess the reliability of the models in predicting the textural attributes of the maturing Cheddar block.

5.2 Materials and method

The textural, chemical and rheological properties of an English Cheddar were measured at various stages during its maturation using the methods outlined in sections 2.2.3, 3.2.2 and 3.2.4 respectively.

An English Cheddar was chosen for the purpose of this investigation as this type is regarded as more consistent in quality and its performance during maturation can be predicted more accurately (Derbyshire, 1994, personal communication).

A 22 kg block of Cheddar, identified by graders as prospective Mature English Cheddar, was obtained from St. Ivel's Cheddar plant in Carmarthen. As grading does not take place until two months after manufacture the Cheddar block was already just under eight weeks old when received. The graders predicted that a further nine months ripening would be required before the Cheddar would be ready for retail sale. A Cheddar block that had undergone an identical production process was also obtained the day after its manufacture in order to provide a profile of the textural properties of a 'green' Cheddar.

The Cheddar blocks were each cut into eight smaller blocks before being resealed and placed in a maturation cabinet set at 8 ± 1 °C, the temperature recommended by the manufacturer. The blocks were vacuum sealed in SUDPACK A RE 120 tubular bags which allow very little gas movement in or out of the sleeve; therefore it was not necessary to control the humidity of the maturation cabinet. The blocks were also packaged in cardboard which provided some insulation against minor changes in temperature and helped guard against physical damage.

The Cheddar was evaluated by the trained panel at the following stages during the maturation period.

- 8 weeks old
- 18 weeks old
- 28 weeks old
- 34 weeks old
- 50 weeks old
- 64 weeks old

The recommended ripening times for mild and medium classifications of this particular type of Cheddar were approximately 18 and 34 weeks respectively. The Cheddar was predicted to be ready for retail sale as a Mature Cheddar at 50 weeks old and so the final assessment at 64 weeks was made to obtain data after the recommended maturation time.

At each stage of maturation a random block of the cheese was removed from the maturation cabinet and placed in a refrigerator (2 ± 2°C) the day before testing began. Cylindrical samples of the cheese, 19 mm diameter and 26mm high, were cut whilst still chilled and were equilibrated at 20°C for one hour before testing. At each stage of maturation cheese samples were presented to the panel together with two to three additional Cheddar samples which were being evaluated for another part of this investigation. Assessments of the 'green' Cheddar were also included. Replicate judgments were made by all assessors within a five day period.

5.2.1 Statistical analysis

The chemical, sensory and rheological data were subjected to one-way analysis of variance in order to establish whether significant differences occurred in each of the variables during maturation. As the block of 'green' cheese was manufactured from a different production run its data were not included in the analysis of variance procedure. LSD tests were performed to identify between which stages the differences occurred.

Pearson's correlation coefficients were also calculated between all the variables to identify any relationships that may exist.

The textural attributes of the Cheddar were predicted at each stage of ripening using the mathematical models constructed in the previous chapter (Table 4-5) and were compared to the actual scores awarded by the panel. Additionally, the predicted scores were inspected to determine if they mirrored the developments in texture observed by the panel as the block matured.

5.3 Results

5.3.1 Chemical composition

The compositional data collected during ripening are listed in Table 5-1. There was no significant change in moisture content and no systematic changes in the fat and salt content. It is possible that the small differences that did exist in terms of fat and salt content at some stages of maturation were attributable to within block variation.

Table 5-1. Chemical composition and standard deviation of Cheddar block at different stages of maturation

Age (weeks)	% Fat		% Moisture		% Salt		pH level	
+Green Cheddar	32.32	*0.41*	a36.80	*0.70*	1.51	*0.09*	5.43	*0.01*
8	a33.16	*0.43*	a37.40	*0.25*	a1.88	*0.04*	5.19	*0.02*
18	a32.86	*0.36*	a36.97	*0.57*	a1.87	*0.05*	a5.25	*0.03*
28	a33.24	*0.73*	a37.60	*0.33*	b1.97	*0.08*	a5.25	*0.01*
34	b32.38	*0.43*	a37.70	*0.41*	b1.95	*0.06*	a5.27	*0.01*
50	b32.90	*0.20*	a36.38	*0.30*	b1.89	*0.10*	5.32	*0.02*
64	b32.06	*0.13*	a37.76	*0.32*	2.28	*0.02*	5.35	*0.01*

Adjacent figures marked with the same letter code (a or b) in any one column are not significantly different (p = 0.05)
+ data from green Cheddar not included in ANOVA

The pH of a typical Cheddar at the end of production is in the region of 5.4. The pH readings taken at week 8 therefore suggested that a decrease in pH had occurred in the initial period of maturation (Figure 5-1). Following this a slight, but significant increase in the pH level was identified during ripening (p=0.05), although the level remained fairly constant during the mid maturation period.

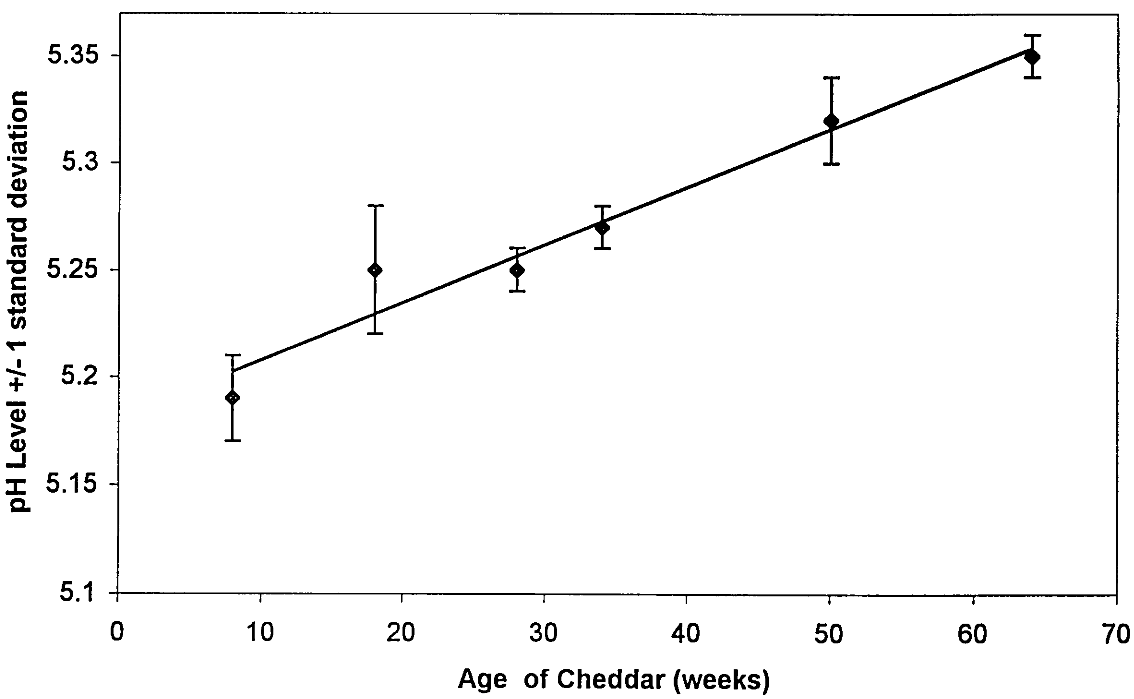


Figure 5-1. Changes in pH level during maturation

As expected the 'green' Cheddar had a higher pH level, but it should also be noted that, although it was produced from an identical production run to the maturing block, it had a significantly lower salt content and possibly a lower fat content.

5.3.2 Textural attributes

The textural attributes determined at each stage of maturation are listed in Table 5-2. Significant changes occurred in each of the attributes, except crumbliness (chewing), although not at every stage of ripening ($p \leq 0.01$). Samples that were not significantly different are identified in Table 5-2 by the same letter code. (As detailed in section 4.3.4, panel judgments for graininess and crumbliness (chewing) were known to have deteriorated at this point in the investigation.)

In comparison with the maturing block at 8 weeks, the 'green' Cheddar was not at all creamy and was also notably firmer and harder, suggesting that considerable changes do occur in the texture of Cheddar during the initial weeks of ripening, if the 'green' Cheddar was representative of an English Cheddar at the end of manufacture.

The most dramatic changes in texture observed during ripening were in springiness and creaminess. Figure 5-2 illustrates the significant decrease in springiness during maturation from a mean score of 7.5 down to 2.3, but also shows that the level remained notably constant for several months in the middle of the ripening period.

Figure 5-3 charts the development of the creamy character of the maturing Cheddar. A higher intensity of creaminess was detected in the maturing block at eight weeks than in the 'green' Cheddar and by the end of the maturation the level of creaminess had increased to a mean score of 7.04. The change in creaminess with time exhibited a non-linear relationship.

Table 5-2. Textural attribute scores and standard deviation of Cheddar block at different stages of maturation

Age (weeks)	Creaminess		Crumbliness (chewing)		Crumbliness (fingers)		Firmness		Hardness (cutting)		Hardness (first bite)		Springiness		Graininess	
$^{+}$Green Cheddar	0.65	*0.65*	4.02	*2.99*	1.19	*0.79*	3.76	*1.47*	3.37	*1.14*	4.91	*2.09*	6.53	*0.98*	2.75	*3.24*
8	2.55	*1.83*	^{a}2.14	*1.39*	^{a}1.78	*1.05*	^{a}1.95	*1.39*	^{a}2.04	*2.04*	^{a}1.78	*1.11*	7.53	*0.64*	2.17	*1.99*
18	^{a}4.59	*0.93*	^{a}2.43	*0.89*	^{ab}2.47	*1.62*	^{a}1.73	*1.14*	^{a}2.42	*1.37*	^{ab}1.95	*0.98*	^{a}5.10	*1.23*	2.5	*1.05*
28	^{ab}5.05	*1.33*	^{a}2.34	*1.16*	^{ab}2.14	*0.75*	^{b}3.54	*1.07*	3.61	*1.24*	^{ab}2.40	*0.66*	^{a}5.10	*1.1*	1.98	*1.61*
34	^{ab}5.42	*1.44*	^{a}1.84	*1.03*	^{ab}2.13	*0.84*	^{b}2.99	*0.92*	3.16	*0.63*	^{ab}2.28	*1.24*	^{a}5.30	*1.34*	2.36	*1.94*
50	^{b}5.93	*0.86*	^{a}2.79	*1.56*	^{b}3.14	*1.65*	4.08	*1.96*	3.26	*1.37*	^{b}2.85	*0.99*	3.67	*1.59*	2.86	*2.24*
64	7.04	*0.89*	^{a}2.79	*1.83*	4.22	*2.39*	2.37	*1.27*	3.53	*1.32*	1.42	*1.15*	2.30	*2.06*	3.35	*2.02*

Adjacent scores marked with the same letter code (^{a} or ^{b}) in any one column are not significantly different ($p = 0.05$)
$^{+}$ data from green Cheddar not included in ANOVA

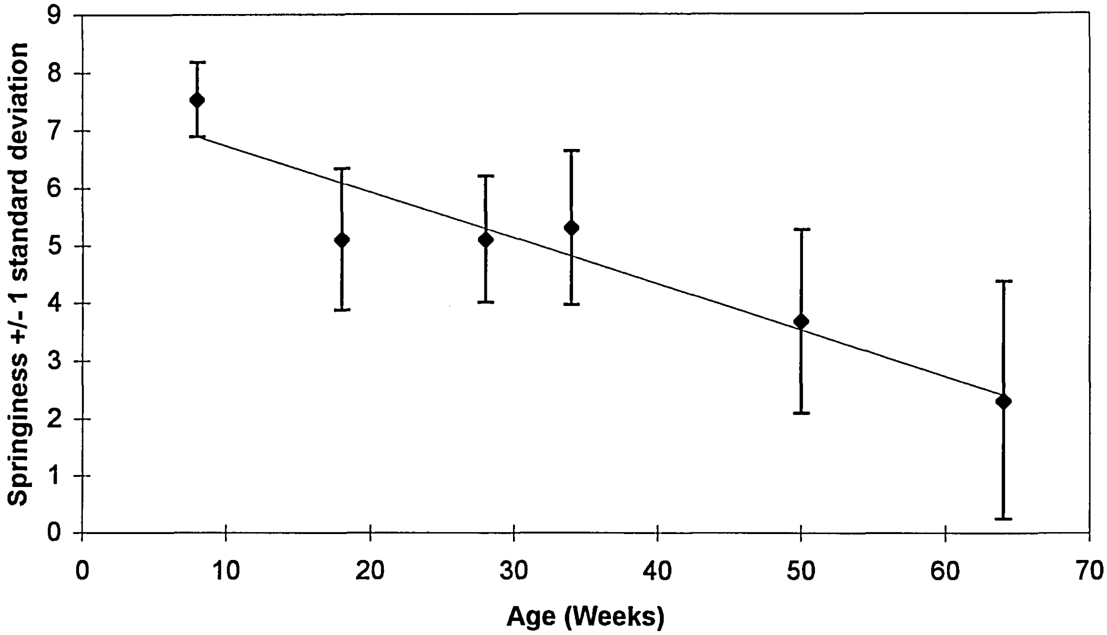


Figure 5-2. Change in springiness level at different stages during maturation

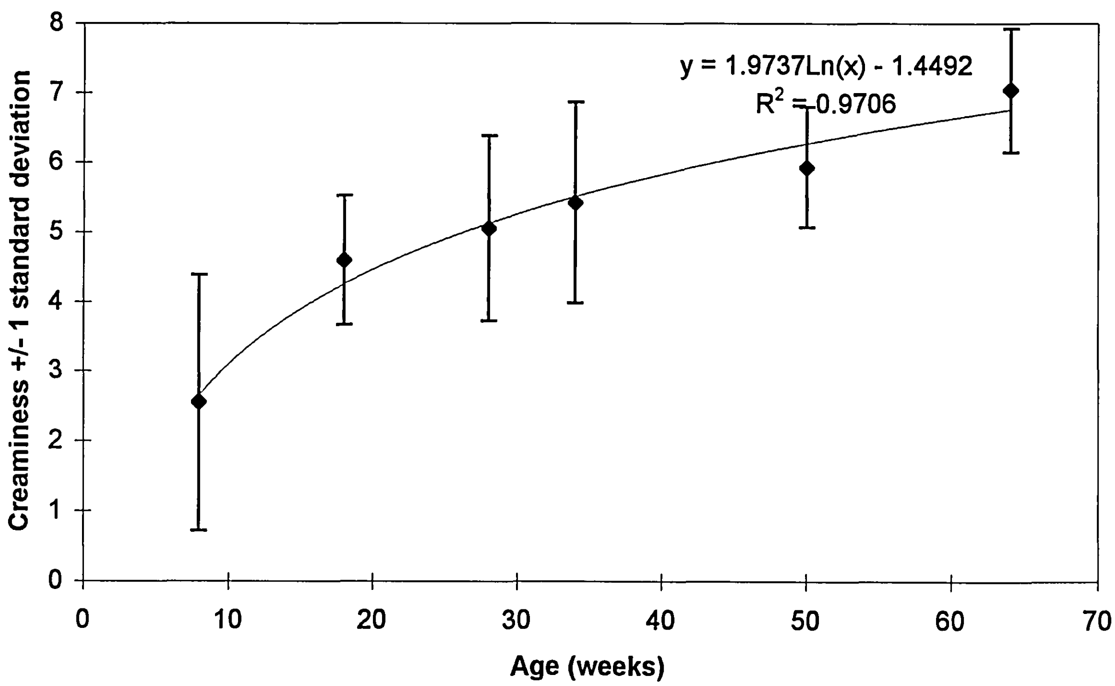


Figure 5-3. Change in creaminess level at different stages during maturation

In addition systematic increases in both crumbliness (fingers) and firmness were observed, although the cheese was not perceived as a particularly crumbly or firm

Cheddar as the mean scores did not reach above the mid point of the scale. Nevertheless, significant changes in these attributes did occur during the ripening period albeit within a smaller range.

Little change was observed in terms of graininess, crumbliness (chewing) and both hardness attributes. The only changes of note were a slight increase in graininess after week 34 and a decrease in hardness (first bite) after week 50. (It is possible that measures of graininess and crumbliness were affected by panel inconsistency.)

The assessments made at week 18, 34 and 50 corresponded with the suggested approximate ripening times for the mild, medium and mature classes of this particular type of Cheddar (Derbyshire, 1994, personal communication). The textural properties of the mild cheese were still very similar to those perceived some 10 weeks earlier apart from a significant decrease in springiness. Comparisons of the assessments made at the mild and medium maturity stages revealed that the textural properties remained very similar apart from a slight, but significant, increase in firmness.

At full maturity (50 weeks) the textural attributes had changed to a much larger extent. The mature Cheddar was considerably firmer, harder, slightly grainier and less springy than at a medium level of maturity, suggesting that changes that occurred during the latter sixteen weeks of maturation were more perceivable than during the middle sixteen.

Assessments made beyond the recommended maturation period revealed that further significant changes had occurred for all the textural attributes, except crumbliness (chewing). The level of creaminess and crumbliness had continued to increase and the level of springiness decrease, but the cheese was perceived to be significantly less hard and less firm than at week 50.

5.3.3 Rheological properties

The rheological properties of the Cheddar block determined at each stage of maturation are listed in Table 5-3.

An inspection of the stress-strain (Figure 5-4) for the 'green' Cheddar and the Cheddar block at selected stages during its maturation, illustrates the changing behaviour of the cheese under compression.

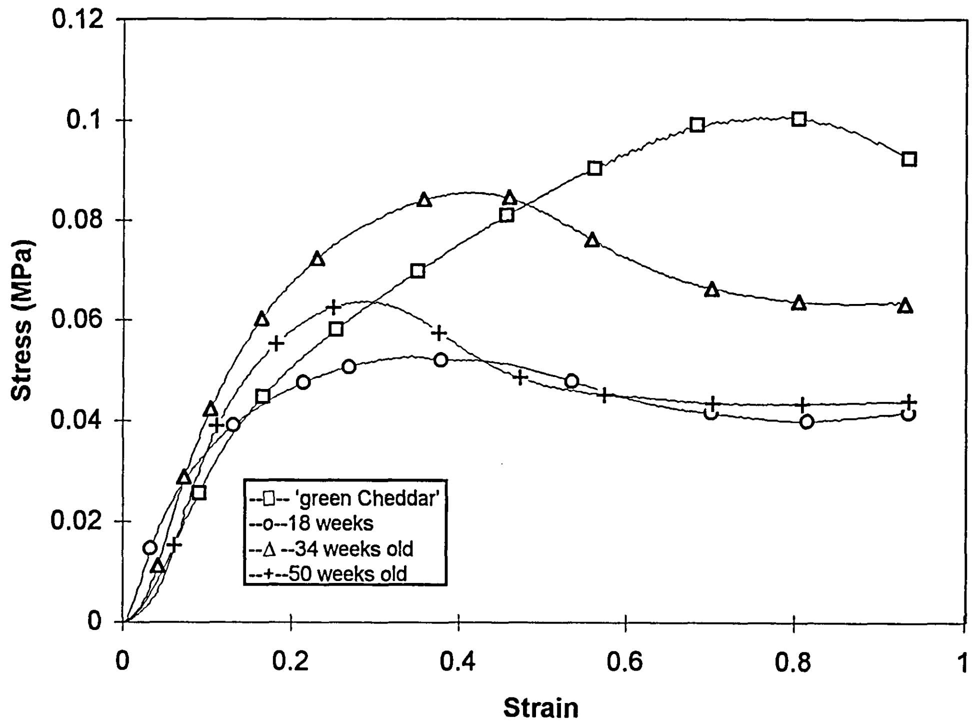


Figure 5-4. Stress strain curves of Cheddar cheese at different stages of maturation

Although the samples behaved comparably during the initial linear stage of the test, each demonstrating similar levels of strain at yield, considerable differences occurred after this point in terms of the stress and strain at fracture. Indeed, as illustrated in

Table 5-3. Rheological properties and standard deviation of Cheddar block at different stages of maturation

	Compression Test																Cutting Test			
Age (weeks)	Stress at Yield (MPa)		Strain at Yield		Energy to Yield (J/M^3)		Stress at Fracture (MPa)		Strain at Fracture		Energy to Fracture (J/M^3)		Young's Modulus (MPa)				Force to cut N/M		Energy to cut J/M	
$^{+}$Green Cheddar	0.038	*0.001*	0.122	*0.02*	2235.4	*318*	0.09	*0.012*	0.802	*0.08*	61401.0	*9519*	0.460	*0.07*			0.29	*0.04*	0.40	*0.20*
8	^{a}0.032	*0.005*	^{a}0.089	*0.01*	^{a}1419.3	*358*	^{a}0.06	*0.006*	0.731	*0.25*	42325.6	*16628*	0.643	*0.08*			0.21	*0.03*	0.32	*0.08*
18	^{ab}0.027	*0.005*	^{a}0.088	*0.01*	^{a}1244.9	*560*	^{ab}0.051	*0.002*	^{a}0.449	*0.13*	^{a}19121.4	*560*	^{a}0.456	*0.12*			0.13	*0.01*	0.21	*0.02*
28	^{b}0.022	*0.006*	^{a}0.097	*0.02*	^{a}1013.1	*119*	^{b}0.048	*0.008*	^{ab}0.595	*0.10*	^{a}23763.9	*6407*	^{a}0.426	*0.08*			^{a}0.18	*0.01*	^{a}0.29	*0.04*
34	0.042	*0.002*	^{b}0.073	*0.01*	^{b}1717.8	*331*	0.080	*0.003*	^{bc}0.350	*0.03*	^{ab}22713.7	*1429*	0.734	*0.09*			n/a	n/a	n/a	n/a
50	0.036	*0.003*	^{b}0.069	*0.01*	^{cb}1318.9	*286*	0.065	*0.004*	^{c}0.309	*0.02*	^{bc}16301.2	*1274*	0.604	*0.11*			^{a}0.18	*0.01*	^{a}0.26	*0.06*
64	0.022	*0.004*	^{c}0.094	*0.02*	^{c}1164.2	*198*	0.034	*0.009*	^{c}0.270	*0.07*	^{c}7006.8	*2760*	0.289	*0.09*			0.13	*0.02*	^{a}0.22	*0.04*

					Stress Relaxation Test									
Age (weeks)	G_o		G_1		G_2		τ_1		τ_2		η_1		η_2	
Green Cheddar	0.0490	*0.0013*	0.0767	*0.0032*	0.0625	*0.0034*	0.3025	*0.0106*	6.4698	*0.0767*	0.023	*0.001*	0.40	*0.03*
8	^{a}0.0139	*0.0042*	0.1650	*0.0031*	0.1798	*0.0060*	^{a}0.3314	*0.0095*	^{a}6.6120	*0.3923*	0.055	*0.003*	1.19	*0.07*
18	^{a}0.0130	*0.0036*	0.0849	*0.0232*	0.0942	*0.0059*	^{a}0.3203	*0.0191*	^{a}6.2111	*0.3330*	0.027	*0.008*	0.58	*0.02*
28	^{b}0.0754	*0.0078*	^{a}0.1284	*0.0048*	0.1056	*0.0082*	^{b}0.2885	*0.0338*	^{a}7.1229	*0.9983*	0.037	*0.004*	0.75	*0.11*
34	^{b}0.0787	*0.0046*	^{a}0.0965	*0.0021*	^{a}0.0680	*0.0022*	^{b}0.2675	*0.0148*	^{b}6.0304	*0.7325*	0.026	*0.001*	0.41	*0.04*
50	0.0291	*0.0052*	0.0879	*0.0027*	^{a}0.0692	*0.0060*	^{b}0.2873	*0.0160*	^{b}6.9449	*1.1774*	0.025	*0.002*	0.48	*0.11*
64	0.0371	*0.0024*	0.0412	*0.0182*	0.0267	*0.0150*	^{b}0.2768	*0.0150*	^{b}5.7848	*0.2352*	0.011	*0.005*	0.16	*0.09*

Adjacent figures marked with the same letter code ($^{a, b}$ or ^{c}) in any one column are not significantly different ($p = 0.05$)
$^{+}$ data from green Cheddar not included in ANOVA

Figure 5-5, the most notable change in the rheological properties with age was the decrease in strain at fracture, which proceeded at a slower rate during the latter period of ripening. A similar observation was made for energy to fracture.

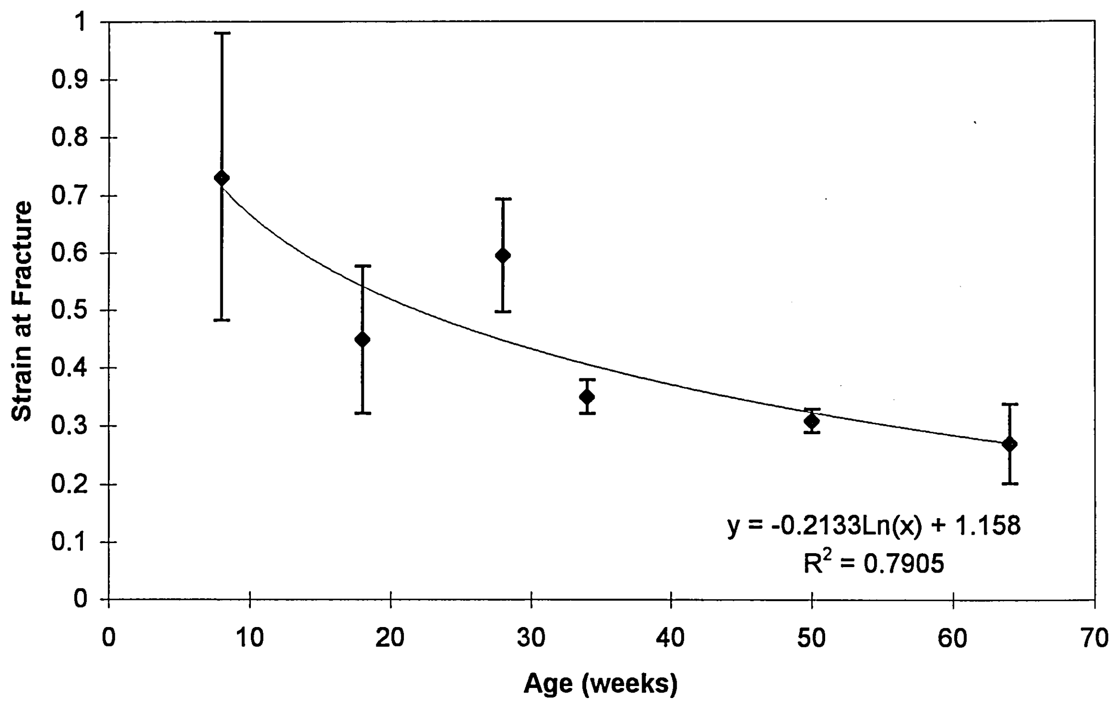


Figure 5-5. Strain at fracture at different stages during maturation

Initially, it appeared as though stress at yield, stress at fracture and the Young's Modulus decreased with age. However, all these properties showed a significant increase at week 34 ($p = 0.05$) and then continued to decrease in value over the remaining maturation period reaching their lowest levels at week 64.

Little change was observed during the maturation period in the force and energy required to cut the samples.

Changes in the stress relaxation behaviour were also apparent as maturation progressed. Indeed, it should first be noted that the strain applied to obtain the required stress level for the stress relaxation test increased with age.

Figure 5-6 illustrates the standardized stress relaxation curves of the Cheddar sample at different stages during the ripening period. It is evident that changes in the stress relaxation behaviour of the cheese occurred systematically, as three pairs of samples from consecutive stages of the maturation period (8 and 18 weeks, 28 and 34 weeks, 50 and 64 weeks), could be identified from Figure 5-6, each pair demonstrating similar stress relaxation curves.

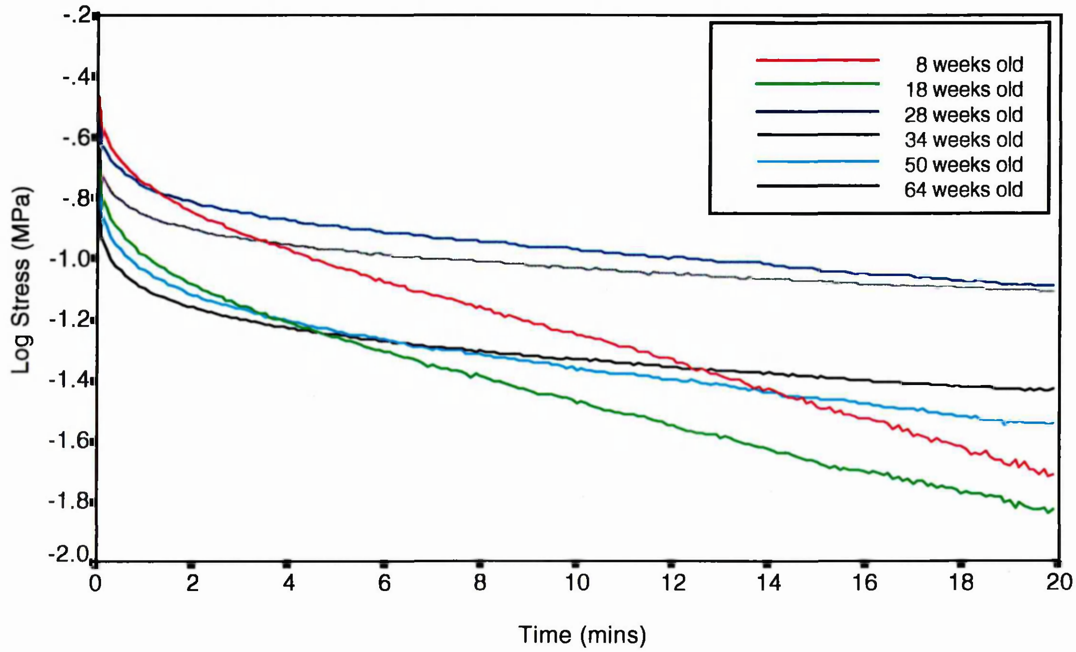
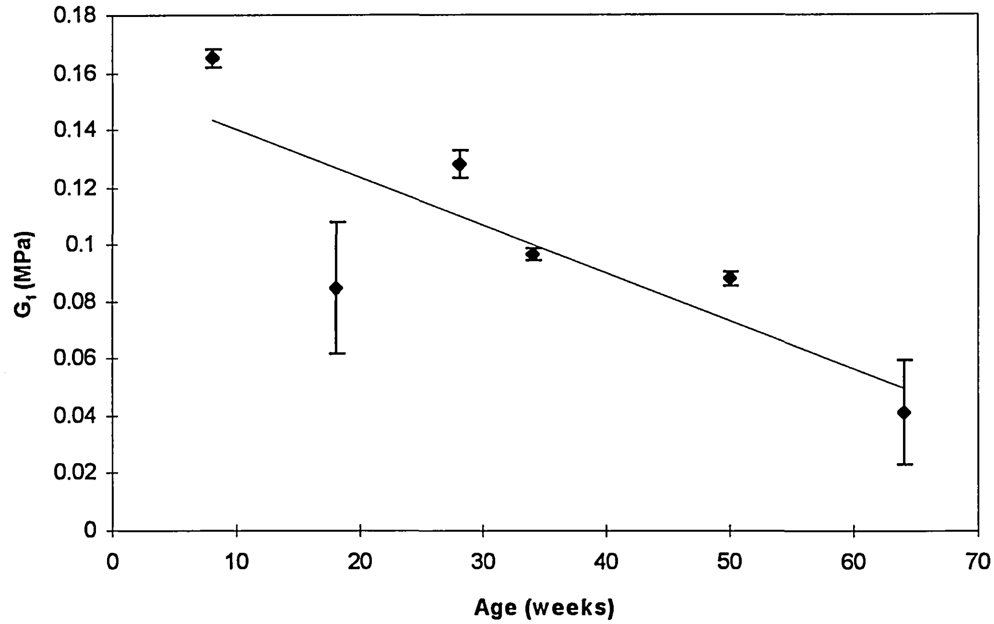


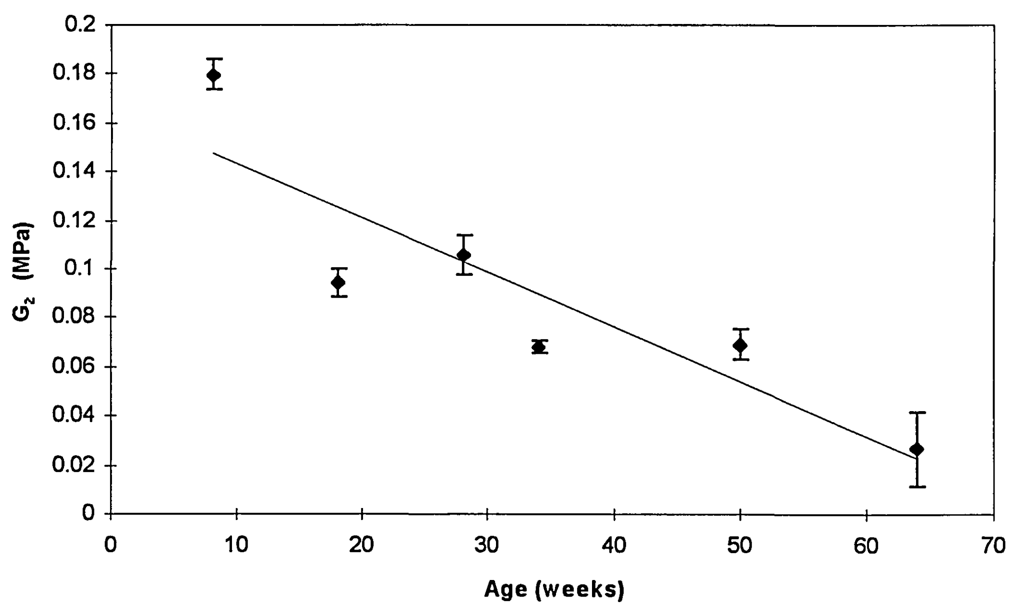
Figure 5-6. Log stress relaxation curves for Cheddar at different stages during maturation

The most noticeable change in the stress relaxation parameters derived using equation 3-4 was a concomitant decrease in both G_1 and G_2 as shown in Figure 5-7. Distinctly different residual stress levels, G_0, were also evident for each of the pairs of samples identified from Figure 5-6. In contrast no change in either relaxation time was observed, apart from a slight decrease in the first relaxation time, τ_1, after week

18. As the relaxation times stayed fairly constant and the values for the elastic moduli decreased, the viscosity of the maturing Cheddar also decreased.



(a)



(b)

Figure 5-7. Changes in G_1 (a) and G_2 (b) during maturation

5.3.4 Correlation coefficients between maturation variables

A considerable number of correlations occurred amongst the rheological properties, particularly between variables obtained from the same test. Significant correlations were also identified between some of the sensory attributes. The majority of the correlations observed between the rheological and sensory properties involved the strain and energy to fracture variables and the springiness, creaminess and crumbliness (fingers) attributes. The coefficients associated with a selection of pairs of variables are listed in Table 5.4.

Table 5-4. Pearson's correlation coefficients between maturation variables ($p \leq 0.05$)

Variables	r
springiness - crumbliness (fingers)	-0.93
springiness - creaminess	-0.97
graininess - crumbliness (fingers)	0.95
firmness - hardness (first bite)	0.83
pH - springiness	-0.99
pH - crumbliness (fingers)	0.92
pH - creaminess	0.97
pH - strain at fracture	-0.91
springiness - energy to fracture	0.97
springiness - strain at fracture	0.87
crumbliness (fingers) - energy to fracture	-0.85
creaminess - energy to fracture	-0.96
creaminess - strain at fracture	-0.90

5.3.5 Predicted textural attributes of maturing Cheddar block

As no model was constructed for creaminess it was not possible to make predictions for this attribute during maturation. With the exception of the 'green' Cheddar, predicted attribute scores determined at each stage of maturation fell within the 95% individual confidence intervals associated with each model. The differences between the panel and predicted scores are shown in Table 5-5. Predictions for crumbliness (fingers) and springiness were particularly precise, falling within 0.5 and 1 unit respectively of the actual scores given. The majority of the remaining predicted scores were within 1.5 units of the panel judgments.

Predicted scores for springiness, crumbliness, hardness and graininess mirrored the pattern of development of these attributes observed by the panel during maturation. A comparison of the patterns for the predicted and panel scores for crumbliness (fingers) is shown in Figure 5-8. It should be noted that although the general trends in firmness were mirrored by the model predictions, the stages at which the changes occurred were not quite synchronized.

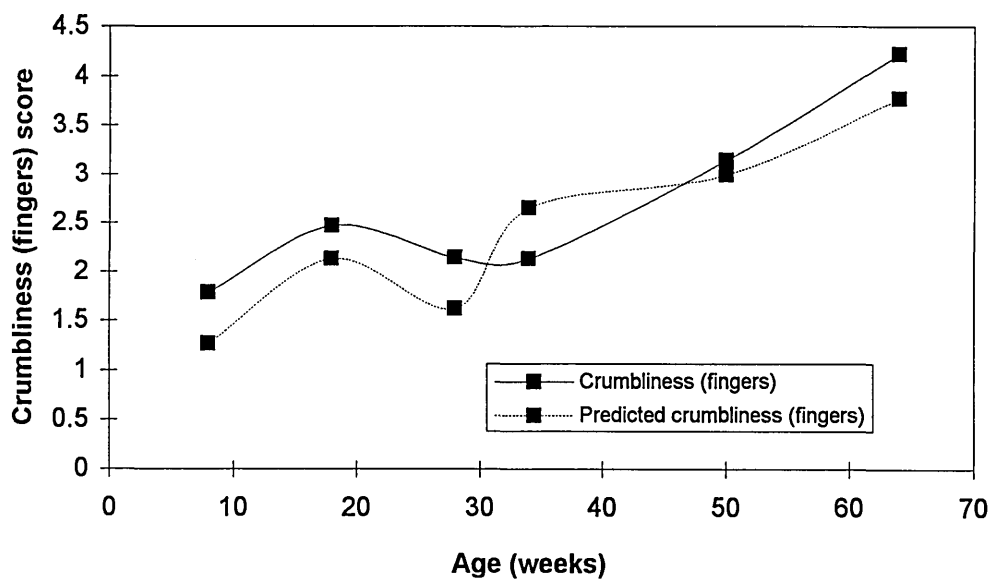


Figure 5-8. Predicted and panel scores for crumbliness (fingers) during maturation

Table 5-5. Differences between panel and predicted score for maturing English Cheddar

	Springiness			Firmness			Hardness (first bite)			Hardness (cutting)			Crumbliness (fingers)			Crumbliness (chewing)			Graininess		
Regression Model	7.85+(7.57 x $LgSn_f$)			4.24+ (-5.96 x Sn_f) + (51.99 x Ss_y)			-0.93+(F_c x 18.22)			0.35+(F_c x 15.55)			10 ** (0.26 + (-1.08 x $LgSn_f$) + (0.29 x $LgSn_y$)			23.36+(-4.54 x LgE_f)			0.265+(-4.1 x $LgSn_f$) + (25.91 x Ss_y)		
Age of Cheddar	**Pan**	**Pred**	***Diff.***	**Pan**	**Pred**	***Diff.***	**Pan**	**Pred**	***Diff.***	**Pan**	**Pred**	***Diff.***	**Pan**	**Pred**	***Diff.***	**Pan**	**Pred**	***Diff.***	**Pan**	**Pred**	***Diff.***
'Green'	**6.53**	7.12	*-0.59*	**4.02**	1.42	*2.60*	**4.91**	4.34	*0.57*	**3.37**	4.85	*-1.48*	**1.19**	1.25	*-0.06*	**4.02**	1.62	*2.40*	**2.75**	1.62	1.13
8 wks	**7.53**	6.82	*0.71*	**1.95**	1.57	*0.38*	**1.78**	2.85	*-1.07*	**2.04**	3.57	*-1.53*	**1.78**	1.27	*0.51*	**2.14**	2.36	*-0.22*	**2.17**	1.66	0.51
18 wks	**5.10**	5.22	*-0.12*	**1.73**	2.98	*-1.25*	**1.95**	1.37	*0.58*	**2.42**	2.31	*0.11*	**2.47**	2.13	*0.34*	**2.43**	3.92	*-1.49*	**2.50**	2.39	0.11
28 wks	**5.10**	6.14	*-1.04*	**3.54**	1.84	*1.70*	**2.40**	2.35	*0.05*	**3.61**	3.15	*0.46*	**2.14**	1.62	*0.52*	**2.34**	3.49	*-1.15*	**1.98**	1.75	0.23
34 wks	**5.30**	4.40	*0.9*	**2.99**	4.35	*-1.36*	**2.28**	n/a		**3.16**	n/a		**2.13**	2.65	*-0.52*	**1.84**	3.58	*-1.74*	**2.36**	3.22	-0.86
50 wks	**3.67**	3.98	*-0.31*	**4.08**	4.28	*-0.20*	**2.85**	2.41	*0.44*	**3.26**	3.20	*0.06*	**3.14**	2.99	*0.15*	**2.79**	4.24	*-1.45*	**2.86**	3.29	-0.43
64 wks	**2.30**	3.55	*-1.25*	**2.37**	3.76	*-1.39*	**1.42**	1.47	*-0.05*	**3.53**	2.4	*1.13*	**4.22**	3.77	*0.45*	**2.79**	5.90	*-3.11*	**3.35**	3.15	0.20

** to the power

5.4 Discussion

The results of this study agree with previous work (Creamer & Olson, 1982; Charalambides et al., 1995) and revealed that modifications to the rheological properties of the cheese occurred as it matured. However, in contrast to research reporting no correlation between age and textural attributes (Piggott and Mowat, 1991), this study revealed systematic developments in the majority of the textural attributes measured. It is reasonable to presume that this disparity was due to the fact that previous researchers have focused on testing different Cheddars, of different ages, selected at the end of ripening, as opposed to investigating one particular type throughout the maturation period. In the former approach no control is implemented for other factors such as the raw materials and processing conditions which introduce considerable variability.

Any interpretation of physical changes occurring during the ripening period of Cheddar will ultimately be based on proteolysis of the casein network which reduces its elasticity (Lawrence & Gilles, 1987). Indeed Charalambides et al. (1995) reported an increase in the Young's Modulus of maturing Cheddar following an initial decrease during the first three months. The results of this investigation concurred with these findings, although a decrease in the Young's Modulus was observed after 34 weeks - a period not covered by Charalambides and his co-workers.

Not unexpectedly an inverse relationship existed between springiness and Young's Modulus. However, the decrease in the Young's Modulus after week 34 was not accompanied by an increase in perceived springiness (it continued to decrease) and as such was not detected by the panel. It is conceivable that the extent of proteolysis within the protein matrix after this time was such that compression of the cheese sample by the assessors resulted in extensive fracture of many of the bonds that remained and so the sample was not observed to 'spring back' and hence was not perceived as springy. Indeed a significant positive correlation existed between strain at fracture and springiness (Table 5-4).

The breakdown of the bonds connecting the casein network means that cheese is fractured more readily (Law, 1987) and becomes less cohesive with time (Lawrence et al., 1987). The weakening of the casein structure accounts for the continued decrease in both energy and strain at fracture with age and the observed increase in crumbliness during maturation. The disintegration of the casein network is also reported to produce a smoother more homogenous structure (Green & Grandison, 1987) which could explain the increase in creaminess character.

Lawrence et al. (1987) suggested that the texture of a cheese at any stage of ripening was determined by the ratio of intact casein to moisture and by its pH. The pH of the maturing block increased slightly during the maturation period but more specifically during the latter weeks of ripening. During the middle period of maturation little change in the textural attributes or the pH level of the cheese was observed, whereas during the latter stages of maturation systematic changes in several of the textural attributes and a rise in pH were detected.

As anticipated, no significant moisture loss was recorded (Table 5-1) and so the slight increases in firmness and hardness could not be attributed the loss of moisture but could, perhaps, be attributed to crystallization of glycerides which occurs over time (Prentice, 1987). Additionally, as proteolysis continues less water is available for the solution of the protein matrix which results in a less easily deformable, harder cheese (Creamer & Olson, 1982). Extensive proteolysis of the casein network may account for the decrease in both firmness and hardness beyond the recommended maturation period.

The close relationship between the (decrease in) strain at fracture and age reported by Creamer and Olson (1982) was also evident from the results of this investigation; even to the point that a more rapid decrease was observed during the initial weeks of maturation than towards the end.

Creamer and Olson (1982) also reported a decrease in force at fracture with age. However, in this investigation the changes in stress at fracture with age were more erratic. A small decrease was followed by an increase at week 34 and further decreases towards the end of the experiment. However, an increase in stress at fracture with age followed by a decrease towards the end of the maturation period was also reported by Charalambides et al. (1995).

A decrease in the viscosity of Cheddar during ripening, as was observed from the stress relaxation data in this study, has been reported by previous researchers performing dynamic rheological tests (Tunick et al., 1990; Ustunol et al., 1995); it has been attributed to proteolysis of the protein network during ripening (Creamer and Olson, 1982). At the same time the breakdown of the protein network should also give rise to a decrease in elasticity of the cheese as was observed by those researchers cited above. Initially it appeared as though the elasticity of the maturing sample decreased during ripening. However, a closer examination of the data revealed that during weeks 18 to 50 the level of elasticity remained fairly constant with the major decreases in G_1 and G_2 taking place in the initial stage of ripening and in the period beyond the recommended maturation time. Inspections of the sample's Young's Modulus during ripening also indicated an apparent increase in elasticity.

Between weeks 18 and 50 weeks an increase in the Young's Modulus was observed. However, as with the elastic moduli measures from the stress relaxation experiment, the lower values of the Young's Modulus were observed at the initial and during the last stages of maturation. Indeed Charalambides et al. (1995) also recorded a decrease in the Young's Modulus of Cheddar during the initial stages of ripening. As previous researchers have not continued to measure the rheological properties of Cheddar beyond the recommended maturation time it is not possible to indicate if the apparent changes in the rheological properties observed in this investigation are representative of all Cheddars.

No studies were found in the literature that investigated the concurrent developments in the rheological and textural properties of a maturing block of Cheddar cheese and hence the emerging results of this part of this investigation warrant further discussion. Further consideration of the relationships between the developments in the rheological and textural properties of maturing Cheddar can be found in the main discussion together with an analysis of the value of the mathematical models constructed to predict the textural attributes of Cheddar when applied during the ripening period.

The textural attributes of cheese have been reported to be of primary importance to the consumer (Jack, 1994) and consequently the ability to measure these properties is important to the cheese industry.

Texture has been regarded as the "least well described" attribute of food (Szczesniak, 1963) and difficulties in applying theoretical rheology were cited as one reason for this. However, as the textural attributes are a manifestation of the rheological (and chemical) properties of a food, an understanding of the rheological behaviour of a foodstuff is pertinent to any investigation of its texture.

6.1 Describing the textural attributes of Cheddar cheese

The varied and ambiguous terminology used by the dairy industry to describe cheese texture has been criticised (Prentice, 1972). As textural attributes are important it follows that the nomenclature chosen to describe such characteristics should be clearly understandable. The vocabulary developed to describe the textural attributes of Cheddar cheese in this study was consistent with that reported by other researchers using both consumer and trained panels (McKewan et al., 1989; Muir et al., 1995) but did not compare with that used by graders (Bodyfelt et al., 1988). It is apparent that those terms employed by the experts are not suitable for the wider audience. Recently Jack et al. (1994) reported that the term pasty, used regularly by graders had to be removed from a list of descriptors as the panel had difficulty in defining the attribute.

It is still possible that even the more obvious terms could be interpreted differently amongst individuals. Defining the textural attributes was, in this study, invaluable to ensure consistent use of the vocabulary between assessors, particularly in the case of firmness and hardness. These characteristics have received extensive attention in the literature and in some cases have been regarded as the same attribute. In GFTPA hard represents the extreme end of a scale running from soft, through firm, to hard. When used as representations of instrumental measures the two terms have appeared interchangeable and the rheological parameters that they have represented have varied considerably. For instance, the indentation made by a Ball Compressor was reported as a representation of firmness (Bourne, 1982); Baron (1949), using the same technique, referred to the same measure as hardness. As Prentice (1992) points out, the lay person would understand hardness to be associated with the effort required to breakdown a material and firmness with the resistance of a material to deformation. Indeed this was reflected in the decision taken by the panel in this study to measure firmness as the force required to compress the sample and hardness as the force required to penetrate its surface. Van Vliet (1991) also recommends distinct use of these terms suggesting that, for viscoelastic materials, hardness relates to resistance to permanent deformation of the sample surface and firmness relates to recoverable deformation. What is clear is that definitions of terms used to describe textural characteristics are pertinent as an aid to the understanding of cheese texture. Additionally, as collaborative research increases between different cheese producing countries the definition of sensory terms is of importance in alleviating problems which may occur as a result of cultural and language differences.

Although the textural attributes perceived by the assessors were perceived as distinct characteristics, the majority of the attributes were closely correlated; all except creaminess, and perhaps crumbliness by chewing, were associated with the first sensory principal component. Consequently it is probable that crumbliness, graininess, hardness, firmness and springiness represented different measures of similar structural components of the Cheddar cheese structure. The data certainly suggested that springiness and firmness represented opposite extremes of the same attribute. The close inverse relationship between these two attributes revealed in the initial study was also observed during the maturation experiment where, up to week 50, the decreasing springiness of the sample was accompanied by a concomitant increase in firmness. Both firmness and springiness decreased considerably after this time and the cheese structure displayed little resemblance to that associated with Cheddar cheese.

Textural attributes which are not correlated are pertinent to the characterization of a product's sensory characteristics as they represent measures of a different aspect of a food's structure. Textural creaminess, which was not related to any other attribute, was therefore identified as a potentially important attribute in terms of Cheddar cheese texture. Sensory data from the maturing block revealed that a considerable increase in this attribute took place during ripening and as such it could be an important quality indicator.

6.2 Discriminating between different types of Cheddar Cheese

All cheeses have a common physical structure composing of a protein matrix interspersed with water and fat globules. It is the variation in this structure, caused by differing raw materials and processing parameters, that accounts for the wide range of textural characteristics observed between different varieties of cheese (Prentice, 1987). An inspection of the sensory, rheological and chemical data collected in this study demonstrated that these properties also vary considerably within the single variety Cheddar, and that significant changes take place during the ripening period. These results were not surprising for Cheddar considering the wide range of textural characteristics that are tolerated in this cheese by the consumer (Lawrence and Gilles, 1987).

Differences between the majority of the samples were identified using all the textural attributes apart from creaminess and, despite the narrow compositional range of the samples, all the chemical parameters. The ability of the rheological parameters to discriminate between the samples was more varied. Young's Modulus and those parameters relating to the gross failure of the sample (Ss_f, Sn_f, F_c) discriminated between a much larger proportion of the samples in comparison to yield parameters. In addition the variables G_o and τ_1 differentiated between more of the samples than the remaining stress relaxation parameters.

Although many of the individual parameters were able to discriminate between the different types of Cheddar, the identification of subsets of samples within the Cheddar variety, from their textural and rheological properties, was of greater significance. Cluster and Principal Component analyses of the sensory data revealed that with few exceptions the groups into which Cheddars were classified also represented the different commercial levels of maturity. The mild and medium Cheddars were grouped together indicating, that in terms of texture, little distinction occurs between these types of cheese. Nevertheless, it was evident from Figure 2.9 that although this group was distinct from other types of cheese, the measures for the textural attributes within this group were quite wide. Piggott and Mowat (1991) observed that considerable variation existed in the textural characteristics of the group of mature Cheddars they studied and suggested that raw materials and production techniques had more influence on textural properties than maturation time. However, the cluster analysis placed all the mature samples in this study into one group (Figure 2.7) thus indicating that the panel perceived them to have similar textural properties. The similarity amongst the mature samples was further substantiated by the PCA where the plot of sample scores on the two principal components showed the mature samples all bunched closely together (Figure 2.9). The disagreement between the results of this study and that of Piggott and Mowat (1991) may be partly explained because in this study the extra mature samples had been separated from those classified as mature and placed in a cluster of their own.

The subgroups of Cheddars revealed by the cluster and Principal Components analyses of the rheological data were less distinct. Nevertheless, as was observed from the sensory data the younger Cheddars, including the Mousetrap sample, were identified as one cluster. The majority of the remaining samples formed a large second group. Unlike the sensory parameters the rheological parameters were unable to discriminate between the low fat and genuine Cheddars. Furthermore, although the Sturminster and Quickes Extra samples were separated from the mature samples in both the rheological and sensory cluster analyses, the sensory data had clustered the extra mature and Sturminster samples together in a distinct group. The rheological analysis identified them as having different rheological profiles, as their scores on the two rheological principal components later confirmed.

It is apparent that the sensory data were better at discriminating between different groups of Cheddars than the rheological properties measured. When measuring textural attributes not only are the panel measuring the combined effects of the rheological properties, but they may also process additional information gained, for example, from visual and flavour perceptions. This additional information may account for the increased discrimination between samples that occurs when the sensory data is observed. It is also possible that assessors may adjust the rate at which they apply a force or cut through the sample as a result of how easy or difficult the task feels - feedback that the Instron is not programmed to imitate.

6.3 The textural and rheological properties of Cheddar cheese during maturation

Evidently the results of the initial study revealed that the textural character of the Cheddar samples investigated was, to a certain extent, related to degree of maturation. It is believed that raw material and processing parameters also affect the final texture of a cheese (Piggott & Mowat, 1991) and therefore, unless these variables are controlled, it is difficult to investigate the true relationship between the textural attributes of Cheddar and age. The study of a single maturing block of English Cheddar enabled changes in the properties of Cheddar cheese in relation to age to be studied without this added variation.

The inspection of the sensory data from the maturing block confirmed the findings of the initial study which concluded that particular textural characteristics of Cheddar were associated with different levels of maturity. At stages of ripening equivalent to mild and medium maturation times the Cheddar sample exhibited similar textural attributes thus supporting the findings that mild and medium types of Cheddar have comparable textural profiles. At this early stage of development the cheese was springy, quite cohesive and not particularly creamy - all characteristics observed in the mild and medium Cheddars in the initial study. At the end of the proposed ripening time the 'mature' Cheddar was considerably creamier, crumblier, firmer and less springy - again all attributes exhibited by the group of mature samples identified in the sensory cluster analysis. Indeed, apart from a lower score for firmness and hardness (first bite), the scores given to the matured sample closely matched those attributed to the English Mature sample in the initial study (Table 6-1).

Table 6-1. Comparison of textural attribute scores for an English Mature Cheddar sample and maturing Cheddar block aged 50 weeks.

Textural Attribute	English Mature Sample	Maturing Sample at week 50
Creaminess	6.31	5.93
Crumbliness (chewing)	2.06	2.79
Crumbliness (fingers)	3.01	3.14
Firmness	5.07	4.08
Hardness (cutting)	2.65	3.26
Hardness (first bite)	4.18	2.85
Graininess	3.19	2.86
Springiness	3.74	3.67

The rheological Cluster Analysis of the initial set of Cheddars revealed that two sub groups of cheese could be identified, both of which encompassed a considerable range of the rheological parameters. The analysis suggested that, as one group consisted of the younger samples and the second contained the remaining maturer samples, particular rheological characteristics could be associated with different levels of maturity. However, the data obtained from the maturing block of Cheddar indicated that changes in the rheological properties of the cheese as it aged were quite complex. Comparisons of the rheological parameters of the maturing English Cheddar with those of the English samples in the initial study revealed that the rheological properties of the maturing block were considerably lower in the majority of cases. For instance, the Young's Modulus of the English Cheddars in the initial study ranged from 0.48 to 1.12 MPa (Table 3-3) whereas the Young's Modulus of the maturing sample only increased from 0.456 MPa at week 18 to 0.604 MPa at week 50 (Table 5-3). The overall rheological profile of the maturing block at its proposed ripening time was more typical of the Cheddars placed in the cluster of younger samples in the initial study. However, the strain at yield and strain at fracture values for the maturing block were more characteristic of the cluster of mature samples. The fact that the majority of the models constructed to predict the textural attributes of Cheddar contained these two variables provides an explanation for the comparable textural scores observed between the English Mature sample in the initial study and the matured block, despite their different overall rheological profiles. These observations also suggest that the strain at yield and fracture variables have a significant role in determining the perceived textural character of Cheddar cheese.

It should also be noted that, although the rheological properties of the maturing block were lower than comparable samples in the initial study, the differences observed between the two clusters of 'young' and 'maturer' Cheddars were mirrored in the maturing block. Comparisons of the maturing Cheddar at 18 (mild) and 50 weeks (mature) revealed that the mature cheese exhibited increased levels of stress at fracture, Young's Modulus, τ_1 and viscosity (η_1 and η_2), and lower levels of strain at fracture.

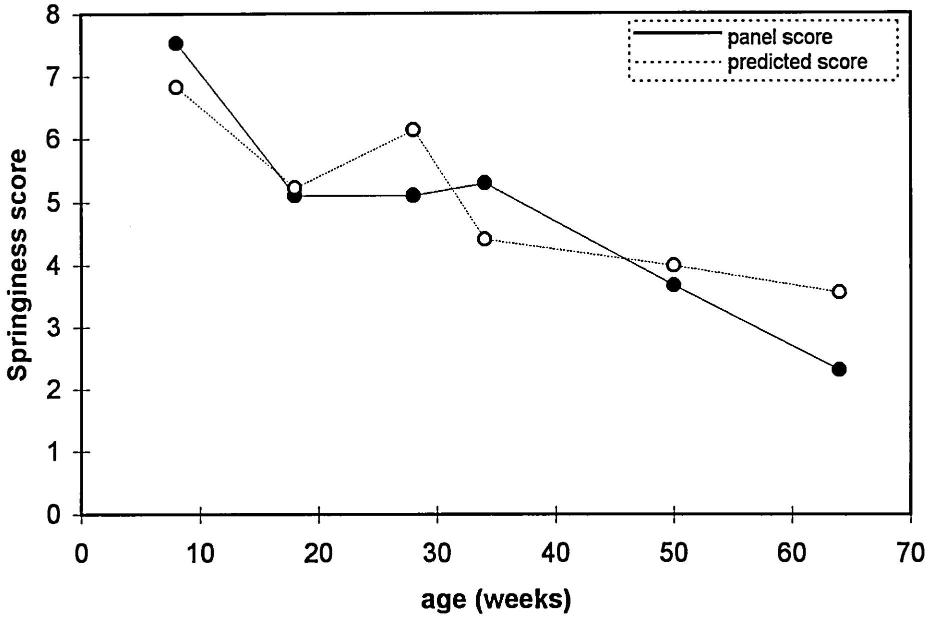
Uncharacteristically the maturing sample did not show a considerable increase in the force to cut parameter with age. However, the English Mature sample in the initial study had been shown to exhibit similar force to cut levels as the younger samples which compares with the observation made in the maturing block.

Close analysis of the sensory and rheological data obtained from the maturing block revealed that the ripening period could be divided into three distinct stages. The initial stage covered the period up to the point where the cheese was expected to be developed to be of sufficient quality for retail sale as a mild cheese (18 weeks).

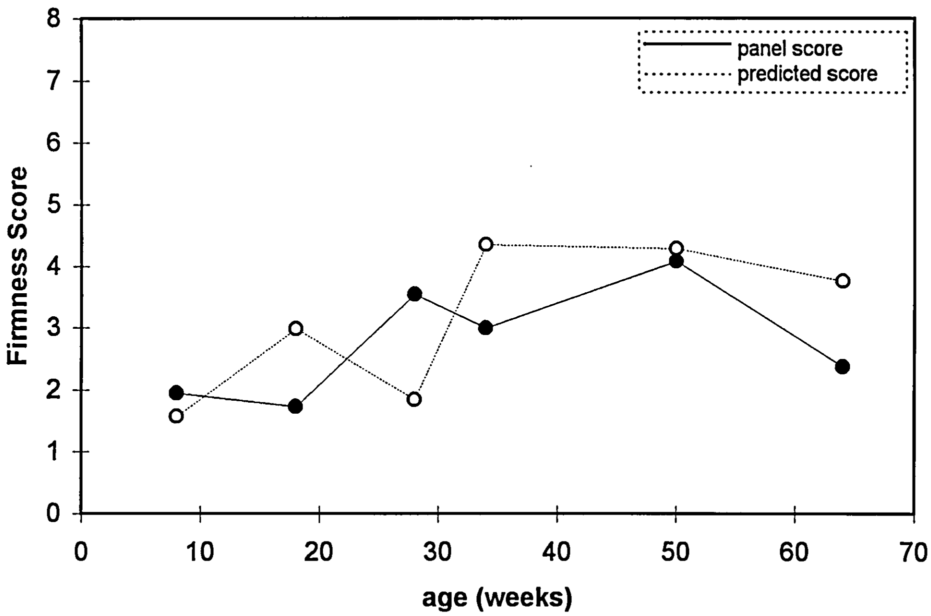
Important changes that occurred during this stage included a considerable reduction in springiness, an increase in crumbliness and a decrease in stress at fracture, Young's Modulus and strain at fracture.

Interestingly the second stage, up to week 34, saw very little change in the textural attributes of the cheese but considerable variation in the rheological properties. Most of the parameters measured by the compression test decreased initially and then increased, apart from the strain at yield and fracture where the opposite pattern was observed. Similarly the stress relaxation parameters showed an initial increase followed by a decrease during the middle stage. Evidently the combined effects of these rheological changes were not perceived as changes in the textural attributes of the cheese by the panel. As a consequence the predicted textural scores suggested slightly larger changes in the textural attributes of the Cheddar during this stage than were recorded by the panel (Figure 6-1). In the case of Firmness, as is illustrated in Figure 6-1b, it appears that although the general pattern of changes in this attribute is evident in the predicted scores the changes are not synchronous with the panel's judgments.

The final stage of maturation saw considerable developments in the texture of the cheese which included a further decrease in springiness and increase in crumbliness and creaminess. A slight increase in firmness was observed although this then decreased after week 50. Consequently this stage can be regarded as an important phase for the development of the textural character observed in a mature Cheddar. The textural changes were accompanied by considerable changes in the rheological properties although more dramatic changes occurred in the latter part of this stage, after the proposed length of ripening. At 64 weeks old the sample was very soft and



(a)



(b)

Figure 6-1. Comparison of panel and predicted attribute scores for springiness (a) and firmness (b) during maturation

had lost its structural integrity - very little energy was required to cause fracture - probably as a result of extensive proteolysis of the protein network. The low figures associated with this sample at this stage for the Young's and Elastic Moduli implied that the sample would deform elastically very easily. However, as the majority of the matrix responsible for the elastic properties associated with Cheddar cheese would no longer be intact, it is probable that these figures were a result of the dramatically low levels of stress required to deform the sample and the small amount of strain imposed at fracture. At this stage the cheese sample would not have been suitable for retail sale and did not resemble the textural character associated with any type of Cheddar cheese.

Seventy per cent of the Cheddar sold in the UK is prepackaged (MINTEL, 1997) and consequently labels provide a valuable means of communication to the consumer. Currently Cheddar cheese for retail sale is often assigned a number to denote its flavour strength so that the consumer can make more informed choices. Previous research (Jack, 1994) has indicated that the textural attributes of cheese have significant implications for its end use. The results of this investigation suggest that a similar labeling policy could be assigned to the different maturities of Cheddar to highlight the particular textural attributes associated with different levels of maturity.

6.4 Modeling the textural attributes of Cheddar cheese

An important component of this study was the construction of mathematical models to predict the textural character of Cheddar from its chemical and rheological properties. Instrumental tests, that can be routinely administered, offer considerable advantages in comparison to a single expert or sensory panel in terms of objectivity, reliability and cost effectiveness.

All the major constituents of cheese contribute to its rheological properties (Jack and Paterson, 1992) and numerous researchers have continued to report correlations between both textural and rheological parameters and cheese composition. Recently Bryant et al. (1995) reported that reducing the fat content of Cheddar modified its textural characteristics and Marshall (1990) provided evidence that increasing the fat and protein content of processed cheese analogues caused systematic increases in Young's Modulus. It should be noted that as the levels of the chemical constituents of cheese are interdependent on each other, unambiguous conclusions concerning the relationships between chemical and textural parameters can only really be made when varying one compositional parameter at a time (Visser, 1991). In practice this is difficult to accomplish, especially within the compositional range of Cheddars available for retail sale.

The results from this study suggested no convincing relationships between the chemical constituents and the textural or rheological parameters. The disagreement between the results of this study and those of other studies can be accounted for by the small range of composition observed in this investigation. Previous researchers have investigated a wider variety of cheeses or have manipulated the composition of the cheese outside the normal range associated with Cheddar; it is easier to obtain correlations when the compositional variation between samples is greater (Qvist, 1987). When studies have been limited to commercially available samples (Hill & Ferrier, 1989; Jack et al., 1993) no apparent relationships have been observed between chemical composition and textural and rheological parameters. Consequently it would seem that the value of chemical indices as measures of the textural quality of Cheddar cheese is questionable. As previous research suggests (Lawrence & Gilles, 1987), it is probable that close monitoring of the chemical composition of the Cheddar during manufacture, particularly at the draining stage, has more relevance in producing a cheese of the required textural quality.

As no relationships between the chemical composition and textural attributes of the Cheddar samples were evident, the modeling of the textural attributes was restricted to the rheological parameters.

Szczesniak (1987) has previously commented that more accurate models of the textural attributes of foods have been produced using instrumental variables where the test method used had a similar action to that employed by the human assessor. An inspection of the source of the parameters constituting the final models in this investigation confirms this to be the case for Cheddar cheese (Table 6-2).

Table 6-2. Rheological parameters included in mathematical models and instrumental test from which they were obtained.

Attribute	Rheological Parameters	Instrumental Test
Crumbliness (chewing)	Energy to fracture	Compression test
Crumbliness (fingers)	Strain at yield & strain at fracture	Compression test
Firmness	Strain at fracture & stress at yield	Compression test
Graininess	Strain at fracture & stress at yield	Compression test
Hardness (cutting)	Force to cut	Cutting test
Hardness (first bite	Force to cut	Cutting test
Springiness	Strain at fracture	Compression test

Those attributes measured under compression were best represented by models using parameters from the compression test, whereas the models most accurately predicting hardness used the force to cut parameter. However, not all the variation observed in the textural attributes was accounted for by the models which would suggest that the assessors were utilising additional information not measured during this investigation. For example, it was considered that the elasticity of the sample could affect the rate at which an assessor cut into to a sample of cheese. However, models including both Young's Modulus and force to cut, which were not closely correlated, were less precise.

Pike (1986) emphasised the need to ensure the validity of mathematical models when applied to biological systems. Accepting a model because it fits the data is not sufficient. Indeed several of the models that had high regression coefficients in this research were not the most reliable when used to predict the textural attributes of further Cheddar samples (see section 4.4.2); the choice of models for both measures of hardness were clear examples of this. As Pike (1986) reiterates, mathematical models should be a rational physical representation of the relationships under investigation and, to a large extent, the final models suggested in this investigation to predict the textural attributes of Cheddar (Table 4.5) met this criterion (see section 4.4.2).

The most successful models were those that predicted springiness, firmness and crumbliness - attributes which were also measured using the fingers. Springiness is considered to be concerned with the 'recovery of height' made after deformation (Prentice, 1992), indeed such a definition was given by the panel in this study (Table 2.3). Instrumental measures of springiness have been made based on this definition (Lee et al., 1978) and correlations with sensory measurements of this attribute established; other researchers have reported better correlations with compression at fracture (Green et al., 1985). The results of this investigation concur with Green et al.'s findings in that a simple regression model containing the log of strain at fracture produced accurate predictions of springiness.

Investigations of the firmness of cheese are extensive in the literature; all studies concerned with identifying instrumental measures of texture have attempted to measure it (Zoon, 1991). In the past, the level of force recorded at a given deformation was used as a representation of this attribute but several researchers have reported that force at fracture correlates well with sensory measures of firmness (Vernon Carter & Sherman, 1978; Green et al., 1985; Qvist et al., 1987). Although a significant correlation between stress at fracture and firmness was reported in this study (r = 0.64: p = 0.05), a model taking into account strain at fracture and stress at yield was more successful in predicting this attribute. The majority of previous researchers have not reported the use of multiple parameters to predict textural attributes but when one considers that assessors make their textural evaluation on the basis of several simultaneous rheological phenomena it is not surprising that a multivariate approach can be successful. The suggestion that the level of firmness detected by the assessor is related to both the stress required to compress the sample before it begins to yield and the strain imposed is quite rational.

Successful predictions for crumbliness (fingers) were also made using a combination of strain at yield and fracture. Compression at fracture has consistently been reported to relate to the cohesiveness of hard cheese and 'relative deformation at fracture' is the parameter recommended by the International Dairy Federation group specializing in this field (Zoon, 1991). Crumbliness (chewing) was more precisely predicted by a model using energy to fracture , although it should be noted that a strong correlation between this variable and strain at fracture was observed (Table 3.5).

The model suggested for graininess resembled that suggested for firmness in that it included both strain at fracture and stress at yield parameters (Equation 6-1 & Equation 6-2).

Firmness = $4.24 + (-5.96 \times Sn_f) + (51.99 \times Ss_y)$ $r^2 = 0.78$ **Equation 6-1**

Graininess = $0.265 + (-4.1 \times LgSn_f) + (25.91 \times Ss_y)$ $r^2 = 0.53$ **Equation 6-2**

The close correlation observed between graininess and firmness ($r = 0.82$: $p < 0.0005$) probably accounts for this and as such the model may not be a sound rheological representation of graininess. Nevertheless, Qvist et al. (1987) and Green et al. (1985) reported that compression at fracture was related to graininess in Danbo and Cheddar cheese respectively and so the inclusion of the strain at fracture variable was expected.

It was not possible to construct a model to predict creaminess. As this characteristic was also not correlated with any other attribute, it can be concluded that the panel was measuring something quite different in comparison to the remaining attributes which could not be explained by the rheological or chemical parameters measured. Creaminess was judged after considerable mastication of the sample and it is possible that the interaction between the sample and saliva and changes in temperature, which will particularly affect the fat, may have a role in determining this characteristic. Hence, as such factors were not accounted for in this study, the difficulty in constructing a model for creaminess was understandable. Additionally, as the panel mentioned the difficulty in scoring this attribute in strong flavoured samples (section 2.2.4) it is possible that the strength of flavour had some impact on the assessors' judgment of this characteristic. It was clear that the panel were able to perceive systematic developments in the creaminess of the maturing sample but, as considerable flavour development is also known to occur during ripening (Lawrence & Gilles, 1987), it is not possible to say whether flavour developments contributed to the panel's assessment of creaminess.

6.5 Predicting the textural attributes of maturing Cheddar

When the models constructed to predict the textural attributes of Cheddar cheese were applied to the maturing block of English Cheddar the predictions made were fairly precise (Table 5.5) and in many cases were more accurate than those made on the additional Cheddars used to test the validity of the models. The most successful model was for crumbliness (fingers) where predictions were consistently within 0.55 units of the panel's assessment. In contrast, the model to predict crumbliness (chewing) was the least accurate with almost all the predictions being out by over one unit. The most likely explanation for this can be attributed to the fact that, whilst changes in the rheological properties of the cheese did occur, the panel did not perceive any significant increase in crumbliness when assessing this attribute orally. It is possible that the visual clues obtained when compressing a sample between the fingers enabled the panel to make more precise judgments of this attribute. Interestingly, crumbliness scores assigned to the seventeen Cheddars in the initial study were consistently higher when measured manually in comparison to those made whilst chewing.

Predictions made concerning the springiness, hardness (first bite) and graininess of the sample throughout maturation were also precise. Predictions made for hardness (cutting) were fair but not particularly accurate at the initial and final stage of ripening.

Predictions made for firmness were less precise although the majority were within 1.5 units of the panel assessments. In actual fact, the prediction made at 50 weeks (the point the Cheddar was predicted to be ready for retail sale) was very precise. Indeed, except for crumbliness (chewing), all the predictions made concerning the textural character of the matured cheese were within 0.45 units of the panel's assessments (Table 5-5).

Less accurate predictions were made when the sample was young or beyond the recommended maturation time and the fact that the models were constructed from samples that had completed their period of maturation may account for this. However, as was revealed when the models were tested on the additional Cheddars, the majority of the predictions were within 1.5 units of the panel's judgments and as such can be regarded as fairly successful predictors of the textural attributes of Cheddar cheese during maturation.

6.6 Low fat Cheddar Cheese

An increased awareness of the health risks associated with a high fat diet has meant that demands for low fat alternatives to everyday products, which also offer the same level of quality, are in high demand by today's consumer (O'Donnell, 1993). As many dairy products are high in fat this has particular relevance to the dairy industry. Low fat cheeses, many of which are marketed as 'Cheddar like', account for 15% of the cheese market in the UK in 1996, but are not regarded as being as successful as other low fat alternative products (MINTEL, 1997).

Cluster analysis using the sensory parameters from this investigation, revealed that the panel could distinguish between the two low fat samples and the remaining Cheddar samples on the basis of texture. As has also been reported by Piggott and Mowat (1991) and McKewan et al. (1989), the low fat cheeses were considerably harder, grainier and crumblier than the cluster of mature samples that they were intended to emulate.

Furthermore the results of this investigation revealed that the low fat Cheddars were considerably less creamy. The two low fat samples had similar scores on the first principal component to the mature samples but extremely different scores on the second component (Figure 2.9). It is therefore probable that it was this component, which highly correlated with creaminess, that the assessors used to discriminate between the low fat and genuine Cheddars. Interestingly this attribute could not be utilised successfully to discriminate amongst the genuine Cheddars. McKewan et al. (1989) revealed that low fat Cheddar like samples were the least acceptable by consumer testing; Adda et al. (1982) remarked that the poor textural quality of low fat cheeses could be attributed to a lack of smoothness, which could be interpreted as a similar attribute to creaminess. As low fat Cheddars appear to be less creamy than their genuine counterparts the role of textural creaminess in terms of Cheddar acceptability warrants further investigation. Textural creaminess has not been measured under this descriptor in the other studies referred to in this section and as definitions of the attributes measured have not been given in papers cited it is difficult to compare this finding with that of other researchers in this field.

It is interesting to note that, although slight differences in the rheological properties of the low fat samples were identified, the cluster analysis performed using the rheological data did not position the low fat samples in a cluster of their own. Indeed they were grouped together with the mature samples.

Predictions of the textural character of the low fat samples were not very precise in comparison to those made for the genuine Cheddar samples. It was suggested that the models' poor representation of the textural attributes of low fat samples was due to considerable differences in the basic structure of the cheeses. In Cheddar, a reduction in fat content causes a concomitant 30% increase in the protein mass (Lawrence and Gilles, 1987), producing a more compact matrix where the casein-casein interactions are not as substantially disrupted by fat globules (Bryant et al., 1995). Indeed a closer inspection of the data revealed some inconsistencies concerning the rheological behaviour of the low fat samples in comparison to the remaining Cheddars. Increasing strain at fracture was highly correlated to sensory crumbliness. Consequently the relatively high strain at fracture associated with the two low fat samples would suggest a somewhat cohesive cheese. However, sensory measures indicated that both samples were perceived as being considerably crumbly. Bryant et al. (1995) reported the same apparently conflicting data.

7. Conclusions and suggestions for further work

7.1 Conclusions

The findings of this study have confirmed the wide variety of textural and rheological properties that exist for different types of cheese marketed as Cheddar, even though they lie within a narrow compositional range. Although the trained sensory panel identified many textural attributes the majority of these were closely correlated and were concluded to be manifestations of similar structural features of Cheddar cheese. In contrast, creaminess was not related to any other attribute and thus provided additional information concerning the textural profile of the cheese. Although the list of textural attributes measured in this study compared favourably to other researchers, additional textural attributes were identified by the panel during preliminary training, several of which were perceived during mastication and may warrant further investigation.

In terms of the samples investigated in this study, it appears that cheeses within the Cheddar variety can be subdivided with respect to their rheological and textural properties into groups which also reflect their maturity. The rheological profile of the mild/medium samples was distinct from the maturer samples. The sensory measures were more discriminatory identifying two further subgroups - one of extra mature samples and one of low fat samples. Not all samples fitted neatly into these groups indicating that raw material and processing parameters also affected the textural profile of some types of Cheddar. Chemical analyses demonstrated no systematic variation between samples except for the fat and moisture content of the low fat and the extra mature samples.

The relationship between maturity and the textural profile of Cheddar was also apparent from the maturation study where progressive changes in the textural attributes of the English Cheddar were observed as ripening proceeded. The ripening period of the Cheddar studied could be split into three phases representing the stage up to when the cheese was first ready for retail sale, the period where it would be regarded as mild/medium matured and the period up to the point it would be considered fully mature. The same three phases were observed for the rheological properties although the changes taking place in each phase were more complex. Considerable changes in the texture of the sample, which were described as deterioration, were noted beyond the recommended maturation period. It was evident that, in addition to the development of flavour, the timing of the maturation period was pertinent to the development of the textural characteristics associated with the different maturities of Cheddar cheese.

An important aim of this study was to construct mathematical models of the textural attributes of Cheddar based on its chemical and rheological properties. The chemical indices measured in this investigation proved unsuccessful predictors of any textural attribute and also showed limited correlations with the rheological parameters. Models were constructed for all the attributes, apart from creaminess, using rheological variables from the compression and cutting tests. The models reflected rational representations of the attributes in question and made fairly good predictions of the textural profiles of additional Cheddar samples and of the maturing English Cheddar at various stages during its ripening. Those models constructed from tests that imposed a similar action on the cheese as that used by the panel, namely springiness, crumbliness (fingers) and firmness, were more precise. The value of the strain at fracture variable was highlighted by its presence in several of the mathematical models. It was also this variable which clearly differentiated between the different rheological profiles of the maturing Cheddar at different stages of ripening.

Although fairly accurate predictions were made by models for hardness, graininess, crumbliness (chewing) not all the variance in the sensory data was fully explained by the models constructed. Evidently additional factors were involved in the perception of the attributes perceived during mastication which were not included in this investigation. This is not surprising given the nature of mastication compared to the testing methods used in this study.

Parameters obtained from the stress relaxation test were not used to model the textural attributes of Cheddar cheese. However, significant correlations between some of the parameters, for example between springiness and the predicted residual stress level, indicated that they could contribute to investigations of Cheddar cheese texture. Furthermore, stress relaxation data from the maturation experiment also revealed that, as ripening progressed, both the viscosity and the elastic modulus of the cheese increased. Such parameters could prove useful as maturation indices.

7.2 Suggestions for further work

Ultimately the textural quality of Cheddar is assessed by the consumer. Consequently, if the results of this study are to be meaningful to the Cheddar industry, further research is needed to identify which textural attributes are important to the consumer. Indeed several of the attributes identified by the panel in preliminary training sessions, which were subsequently eliminated from this study, may merit further investigation if they are pertinent to the consumer's perception of quality Cheddar.

Creaminess provided important information concerning the textural profile of Cheddar and was one of the attributes that showed considerable development during the maturation period. It was also identified as one of the major attributes that discriminated between the genuine and low fat Cheddar-like samples. Additional research is needed to develop a further understanding of creaminess, particularly as no model could be constructed to predict this attribute in this investigation. As manufacturers continue to try to produce a high quality low fat Cheddar alternative a deeper understanding of creaminess could aid developments in this area.

The investigation of the chemical composition of Cheddar was limited and did not include the determination of protein content or any measure of the breakdown products of casein hydrolysis. However, developments in the rheological, and particularly the textural attributes, of the maturing Cheddar block were attributed to continued proteolysis of the casein network. Research by Creamer and Olson (1982) and Charalambides et al. (1995) revealed that the rheological properties of Cheddar showed some relationship with α-casein, and to a certain extent, β-casein concentrations. Consequently, further research concerning the relationships between the various breakdown products of casein proteolysis and the perceived textural attributes of Cheddar cheese could provide additional insight into the contribution the integrity of the casein network makes to texture perception.

The results of the maturation experiment yielded important information concerning the development of texture during the ripening period. However, the results should be regarded with some caution as they were only obtained from a single block. More research is required to replicate the investigation on additional blocks and on different types of Cheddar. Furthermore, more frequent testing during the maturation period is required to enable a more complete picture of the developments taking place within each of the three stages identified in this investigation.

The instrumental methods developed and the parameters determined from them were not adequate to enable the full textural profile of Cheddar cheese to be accurately predicted. Those attributes measured during mastication and, in particular, creaminess were not predicted to the same degree of accuracy of the remaining attributes. In order to accurately predict all the textural characteristics of Cheddar cheese research is still needed to develop further methods that provide reliable fundamental data and that are capable of analysing all the parameters that contribute to the sensory perception of Cheddar cheese texture.

Appendix I Summary of initial panel discussions

Table I-I. Tabulated summary of initial panel discussion concerning the perceived textural attributes of Cheddar cheese, their definition and descriptors used to describe them.

Favoured Descriptor	Springiness
Attribute description	springs back when compressed
Descriptors generated	springy, rubbery, elastic
Notes	the term rubbery was ambiguous, elastic was acceptable but springy was more user friendly in that it formed part of definition

Favoured Descriptor	Crumbliness
Attribute description	breaks up into pieces when force is applied
Descriptors generated	snappy, brittle, crumbly
Notes	majority of panel had difficulty defining and understanding the term snappy. Disagreement over term brittle. Some assessors felt that brittle meant it shattered immediately when force was applied. Crumbly was the preferred term. Panel felt that it was difficult to quantify the level of crumbliness when biting or cutting into the cheese.

Favoured Descriptor	Graininess
Attribute description	bitty mouthfeel perceived whilst chewing
Descriptors generated	grainy, lumpy, coarse
Notes	lumpy felt to be associated with size of grains. Coarse not fully understood by several assessors. Initially thought to be opposite of creamy. Further tasting of samples proved this to be untrue.

Favoured Descriptor	Creaminess
Attribute description	smooth mouthfeel
Descriptors generated	creamy, smooth
Notes	smooth caused difficulty with some of panel as they felt it was opposite of grainy. Assessors were measuring this attribute at different stages of chewing. Resolved to measure towards end of chewing. Suggestion of using term velvety mouthfeel to define attribute

Favoured Descriptor	Chewiness
Attribute description	effort required to chew sample. Very chewy sample does not melt in the mouth
Descriptors generated	chewy, leathery
Notes	only two assessors preferred term leathery. Others felt this referred more to springiness.

Favoured Descriptor	Gumminess
Attribute description	adheres to mouth during chewing
Descriptors generated	sticky
Notes	use of term gummy in attempt to define attribute was seen as favourable to the term sticky

Favoured Descriptor	Dryness
Attribute description	dry mouthfeel
Descriptors generated	dry
Notes	only evident in some Cheddar samples

Appendix II Summary of panel discussion during training

Table II-I. Summary of discussions concerning particular attributes following initial training sessions to recognise varying intensities of textural characteristics

Attribute	Comments
Graininess	assessor disagreement due to variation in stage at which graininess was measured. A decision to measure graininess towards the end of chewing enabled the rank order of Cheddar samples to be agreed.
Creaminess	panel commented that interference from strong flavours inhibited their ability to determine creaminess.
Gumminess and Dryness	despite several attempts at retesting samples continued inconsistencies amongst the panel led to the elimination of both these attributes from further investigation. Some assessors were unable to detect dryness in any of the samples.
Crumbliness	erratic results confirmed the assessors' difficulty in distinguishing varying levels of crumbliness on first bite and when cutting. Measuring crumbliness using these methods was eliminated from further investigation.
Chewiness	considerable disagreement amongst concerning chewiness of samples, although it was agreed that it was not related to number of chews. Compromised rank order reached but some assessors were still underconfident in measuring attribute.

Appendix III Algorithms substituted in Instron Series IX Materials Testing Software

True strain at fracture and true strain at yield

True strain = ln H_0 / (H_0 - ΔH). As H = 26mm the following algorithm was programmed into the Series IX software custom calculations facility.

ALOG (26/(26 - [D]))

where D = displacement (mm) recorded at crosshair position

True stress at fracture and true stress at yield

True stress = $F_{(t)}$ / $A_{(t)}$. The radius, and hence the surface area of the sample at any point during compression could be determined by Equation 3-2. Consequently these calculations were included in the algorithm used to determine the true stress at both yield and fracture:

([F] / (π x (9.5 x (SQRT(26/26-[D])))**2) x 100

where F = force (kN) recorded at crosshair position

** to the power

Appendix IV Principal Component Analysis using a limited number of rheological parameters

Table IV-I. Factor Correlation Matrix for Principal Components Analysis of rheological parameters of seventeen Cheddar samples (no stress relaxation parameters)

	Principal Component 1	Principal Component 2
Stress at Fracture	0.95841	
Young's Modulus	0.83020	
Strain at Fracture	-0.70977	-0.61191
Energy to cut		0.95066
Force to Cut		0.91154
Energy to Fracture	0.61190	0.63733

Appendix V Textural, chemical and rheological properties of additional Cheddar samples

Table V-I. Textural attributes of additional Cheddar samples

Cheddar	Creaminess	Crumbliness by Chewing	Crumbliness by Fingers	Firmness	Graininess	Hardness on first bite	Hardness by cutting	Springiness
Mousetrap II	4.79	2.49	2.83	3.15	2.25	2.40	3.63	5.29
sd	2.03	1.26	1.66	1.36	1.78	1.40	1.55	1.38
English Mild II	4.03	4.75	3.01	6.05	3.67	5.84	4.75	3.18
sd	2.15	1.27	1.26	1.62	2.02	0.64	0.79	1.51
English Mild III	4.55	3.12	2.7	2.86	2.95	2.95	4.07	4.5
sd	1.61	1.75	1.05	1.15	1.93	1.78	1.83	1.99 1
English Mild IV	3.82	5.71	3.77	6.77	4.25	5.84	5.58	3.38
sd	1.44	0.52	1.78	1.14	2.76	1.22	1.13	1.68
English Mature II	5.93	2.79	3.14	4.08	2.86	2.85	3.26	3.67
sd	0.86	1.56	1.65	1.96	2.24	0.99	1.37	1.59
Quickes Extra Mature II	4.83	4.26	5.26	7.89	5.18	5.26	5.87	1.61
sd	2.61	1.27	1.75	0.77	1.68	1.75	1.31	1.24

Table V-II. Chemical composition of cheddar samples

Cheddar	% Moisture Content	% Fat Content	pH	% Salt Content
Mousetrap II	38.13	31.90	5.14	1.98
sd	0.5	0.37	0.01	0.01
English Mild II	38.84	32.22	n/a	1.72
sd	0.21	0.43		0.07
English Mild III	36.73	33.24	5.41	2.16
sd	0.59	0.25	0.02	0.06
English Mild IV	35.89	35.32	5.01	2.1
sd	0.39	0.41	0.01	0.1
English Mature II	36.38	32.9	5.32	1.89
sd	0.3	0.2	0.02	0.1
Quickes Extra Mature II	30.46	39.06	5.53	1.94
sd	0.46	0.93	0.01	0.08

Figures are means and standard deviations of five replicates

Table V-III. Rheological Properties of Cheddar samples

Cheddar	Compression Test							Cutting Test	
	True Stress at Yield (MPa)	True Strain at Yield	Energy at Yield (kJ/M^3)	True Stress at Fracture (MPa)	True Strain at Fracture	Energy at Fracture (kJ/M^3)	True Young's Modulus (MPa)	Force to Cut (N/M)	Energy to Cut (J/M)
Mousetrap II	0.0270	0.977	1427.41	0.457	0.5370	24067.84	0.4075	n/a	n/a
sd	*0.0026*	*0.0058*	*190.54*	*0.0228*	*0.355*	*2242.41*	*0.0812*		
English Mild II	0.0565	0.0671	1877.88	0.1087	0.3383	30648.58	11797	0.27	0.39
sd	*0.0062*	*0.0197*	*518.06*	*0.0104*	*0.0663*	*6864.02*	*0.1813*	*0.02*	*0.06*
English Mild III	0.283	0.1141	1624.83	0.0516	0.5713	24830.39	0.4299	0.17	0.26
sd	*0.0102*	*0.0275*	*1071.73*	*0.0061*	*0.0597*	*347533*	*0.0857*	*0.01*	*0.05*
English Mild IV	0.0406	0.0743	17310.34	0.0728	0.4051	24618.72	0.7027	0.18	0.29
sd	*0.0034*	*0.0102*	*220.17*	*0.0048*	*0.0686*	*4720.14*	*0.857*	*0.01*	*0.03*
English Mature II	0.0361	0.0691	1318.86	0.0648	0.3085	16301.22	0.6041	0.18	0.26
sd	*0.0027*	*0.0051*	*285.65*	*0.0035*	*0.0199*	*1273.80*	*0.1142*	*0.01*	*0.06*
Quickes Extra Mature II	0.0992	0.0250	2347.35	0.1731	0.2195	32912.71	1.7839	0.35	0.43
sd	*0.0146*	*0.0159*	*564.69*	*0.0342*	*0.0298*	*9942.74*	*01713*	*0.05*	*0.09*

Figures are means and standard deviations of five replicates

Table V-IV. Stress relaxation parameters of additional Cheddar samples

Cheddar	P_o/γ_0 (MPa)	P_1/γ_0 (MPa)	P_2/γ_0 (MPa)	t_1	t_2
Mousetrap II	0.0772	0.0854	0.0699	0.315	6859
sd	*0.166*	*0.0197*	*0.0119*	*0.06*	*0494*
English Mild II	0.1122	0.1294	0.1010	0.266	6396
sd	*0.0094*	*0.008*	*0.0069*	*0.025*	*0.677*
English Mild III	0.0516	0.1254	0.1357	0.303	6359
sd	*0.001*	*0.0011*	*0.0056*	*0.027*	*0.886*
English Mild IV	0.0251	0.0852	0.0768	0343	8.696
sd	*0.0039*	*0.0092*	*0.0057*	*0.053*	*1.537*
English Mature II	0.0291	0.0879	0.0692	0.287	6945
sd	*0.0052*	*0.0027*	*0.0060*	*0.016*	*1.177*
Quickes Extra Mature II	0.0776	0.1676	0.1213	0.257	4.345
sd	*0..0128*	*0.0208*	*0.0140*	*0.024*	*2.848*

Figures are means and standard deviations of five replicates

Appendix VI Two way analysis of variance of sensory data from maturing sample and six additional Cheddar samples

Table VI-I Significance level (p) associated with cheese sample and assessors in two way analysis of variance of sensory data

Attribute	Assessor	Cheese sample
Creaminess	<0.0005	<0.0005
Crumbliness (chewing)	<0.0005	<0.0005
Crumbliness (fingers)	0.025	<0.0005
Hardness (cutting)	<0.0005	<0.0005
Hardness (first bite)	0.116	<0.0005
Graininess	<0.0005	<0.0005
Firmness	0.655	<0.0005
Springiness	<0.0005	<0.0005

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Nomenclature

A	surface area	m^2
F	force	N
G	elastic modulus	MPa
H	height	m
H_1	height of deformed specimen	m
H_o	height of original specimen	m
P_i	constants in equation 1-3	
P_o	predicted residual stress	MPa
exp	exponential constant	
p	probability, significance level	
r	correlation coefficient	
r_1	radius of deformed specimen	m
r^2	regression coefficient	
r_o	radius of original specimen	m
sd	standard deviation	
t	time	minutes
Δ	change in	
ε	true strain (Hencky strain)	
γ_o	initial strain	
η_i	viscosity coefficient	MPa.min
σ	true stress	MPa
τ_i	relaxation time	minutes

E_c	Energy to cut	Jm
E_f	Energy at Fracture	Jm^2
F_c	Force to cut	Nm
Sn_f	Strain at fracture	
Sn_y	Strain at yield	
Ss_f	Stress at fracture	MPa
Ss_y	Stress at yield	MPa
YM	Young's Modulus	MPa

ANOVA	Analysis of Variance
AOAC	American Association of Analytical Chemists
IDF	International Dairy Federation
FCP	Free Choice Profiling
GFTPA	General Foods Texture Profile Analysis
LSD	Least Significant Difference
PCA	Principal Component Analysis
QDA	Quantitative Descriptive Analysis
TPA	Texture Profile Analysis