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A study of the influence of ageing on the mechanical properties of Cheddar cheese

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The aim of this study was to characterize Cheddar cheese in terms of mechanical properties and to relate these with maturing time. Three different types of cheese were studied: sharp Cheddar, mild Cheddar and Monterey Jack. The mechanical behaviour was described in terms of (a) stress–strain curves as obtained from uniaxial compression tests and (b) the fracture toughness values obtained from bending tests on single-edge notched specimens. For each test, the moisture, fat and protein content of the samples were also measured. In order to study the effect of friction between the sample and the loading plates on the measured stress–strain curve, samples of various heights were tested. However, the different sample height led to different applied strain rates. The data from the fracture tests were analysed using the European Structural Integrity Society testing protocol for plastics. A discussion is given on the effect of ageing on the mechanical properties.

1. Introduction

Cheese is a solid derivative of milk, produced by the process of coagulation of the protein component (casein) and the draining of the liquid (whey). Structurally, cheese is a complex protein matrix stabilized by several types of chemical and physical bonds, including disulphide, hydrophobic and hydrogen bonds. Fat globules, enzyme molecules, salts and bacterial cells are entrapped in this matrix. The continued action of bacteria and enzymes throughout the curing phase and the shelf life of the product lead to breakdown in the protein matrix. Such biochemical changes result in the development of unique flavours, aromas and texture. These basic phenomena are true for natural cheeses including that of Cheddar cheese, which is the subject of this study. Cheddar cheese is a living system.

Although modern Cheddar cheese manufacturing has been largely standardized, the quality of Cheddar cheeses is still judged by the experienced cheese graders. A "feel" for how well a piece of cheese bends or crushes and tastes is used by the cheese graders to assess the ripening quality and maturation of cheeses.

There have been no studies in which the mechanical properties of Cheddar cheeses were determined and the effect of the protein breakdown on the mechanical properties of the cheeses reported. We have carried out such a study, the results of which are presented below.

2. Previous work

2.1. Stress–strain properties

Uniaxial compression tests on cylindrical samples of cheese and other solid food products have been widely used in the past in order to relate the stress–strain properties to sensory texture. The compression test is simple to perform; for soft food products, it is preferred over the tensile test because it avoids the need to grip the specimen. However, the compression test has the disadvantage that the results are affected by the friction between the loading plates and the sample.

Culioli and Sherman [1] reported a change in the stress–strain behaviour of Gouda cheese when plates where lubricated with oil as opposed to when they were covered with emery paper. They also noted that as the height of the sample increased, the force required to achieve a certain compression decreased. Carter and Sherman [2] reported the same effect for Leicester cheese. They found that when emery paper was used or no lubricant oil was used, the sample attained a primarily barrel shape. This was due to the top and bottom surfaces being frictionally constrained, whereas the middle section was free to deform. Similar observations were also made by Chu and Peleg [3] for potato flesh and processed American cheese, Casiraghi *et al.* [4] for Mozzarella, Cheddar and processed cheese, Christianson *et al.* [5] for starch gels, and Bagley *et al.* [6] for gelatin gels. On the other hand, Ak and Gunasekaran [7] reported no significant change on the mechanical properties of Cheddar cheese when lubrication was used; no barrelling of

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samples in non-lubricated conditions was observed either. They explained this phenomenon by the release of fat during compression which eliminated differences between non-lubricated and lubricated cases. Similar observations were made by Luyten [8] for Gouda cheese.

Cook and Larke [9] studied the compressive behaviour of copper and copper alloys and the effect of friction between the sample and the loading plates on the measured stress–strain curves. They also observed that when a sample is compressed between non-lubricated plates, the deformation is not homogeneous, i.e. the specimen attains a "barrelled" shape. If compression is carried out under conditions where there is no friction, the deformation is homogeneous and the sample remains a straight-sided cylinder. When the end faces of the cylinder are restricted from spreading because of friction, the material adjacent to the pressing plates resists deformation, as opposed to the central portion of the cylinder. The effect of these partially deformed zones, is more pronounced in shorter specimens because of the overall smaller specimen volume. This explains why, to achieve the same compression in two specimens of different heights, a larger stress is required for the shorter specimen. Based on this last statement, the authors suggested an experimental technique, enabling the determination of the stress–strain curve that would be obtained under "frictionless" conditions. They proposed testing cylinders of various heights, calculating the stresses and strains in the usual way and then plotting the results in the form of a family of curves of stress versus the reciprocal of the sample height. Each curve corresponds to a constant strain value. Extrapolating the results to an infinite height, i.e. $1/H = 0$, gives the value of stress that would be obtained in ideal frictionless conditions. Cook and Larke's method was used to calculate the stress–strain curves of the cheeses in this study.

2.2. Fracture toughness

Green *et al.* [10] tried to relate the compressive properties with the sensory texture assessments of Cheddar and Cheshire cheeses and came to the conclusion that the compression test alone, "does not provide a useful guide to the mouthfeel. Methods of texture assessment of cheese may be more meaningful if they involve fracture". Several researchers carried out fracture tests on cheese and other food products.

A test that has been extensively used is the instrumented microtome test [11]. The cutting work is calculated from the area under the force/blade-displacement curve, which simplifies to cutting force divided by sample width. In such a test, the total work involved in cutting is considered to be the sum of three components: friction, flow and fracture. The friction is assumed to be comparatively small, at angles of cut around the "optimum" value. The plastic component is expressed as section curling; extrapolation to zero slice thickness provides a value for the work of fracture. Dobraszczyk *et al.* [12] used this test to calculate the fracture toughness of frozen meat. A variation of the microtome test is the wire cutting test. In this test, the fracture energy is estimated from the forces necessary to cut a sample of cheese with wires of different diameters by linear extrapolation to a zero wire diameter. This test was used by Luyten *et al.* [13] to measure fracture toughness of Gouda cheese which was found to be in the range of $1\text{–}10\,\mathrm{J\,m^{-2}}$. The fracture toughness of potato starch gels was also found to be in the same range [14]. Another popular fracture test in the food industry is the wedge fracture test [15]. A sharp wedge is forced into the sample such that a crack propagates in a stable manner in the material ahead of the tip of the wedge. The fracture toughness is obtained by dividing the area under the force–displacement diagram by the nominal surface area of the crack formed. The authors used this technique to calculate the work to fracture of apples and Gouda cheese. The same method was used by Lucas *et al.* [16] and Oates *et al.* [17] in a study of fracture toughness of mung bean gels and gels of various polysaccharide concentrations. They suggested subtracting hysteretic energy losses due to viscoelasticity from the total work done, via a graphical method first suggested by Hol and Schoorl [18]. The samples were loaded until stable crack propagation was achieved. The load was then reversed so that a loading–unloading loop was obtained. The area in this loop was the energy due to fracture and hysteretic losses. The load at which crack initiation occurred was noted and in a second test with an identical cubic sample, the gel was loaded between 70% and 90% of that cracking force. The crosshead was then reversed producing a hysteresis loop; the area in this loop was then subtracted from the original loading–unloading area of the cracked sample to estimate "work to fracture" corrected for hysteresis. Additionally, a similar method was suggested, compensating for frictional effects between the sample and the wedge, as well as viscoelastic energy losses.

An alternative fracture specimen geometry is the single-edge notched bend shown in Fig. 1. This is the geometry used in this study. Before testing, the sample is notched with a razor blade at a depth a. It is then loaded in a three-point bending configuration. This geometry is widely used to determine fracture toughness of plastics and a relevant testing protocol was drafted by the European Structural Integrity Society (ESIS). The analysis for this test is based on a linear elastic material behaviour [19]. Langley *et al.* [20] used this fracture test in a study of a model food composite. The main advantage of this test is that it is very simple to perform and does not require complicated specimen geometry or gripping arrangements. Additionally, it does not suffer from frictional effects as in the microtome and wedge fracture tests described above. The analysis is also straight forward, assuming, of course, that the material behaves in a linear elastic manner. This assumption will be discussed in a later section.

3. Experimental procedure

The cheeses tested were mild Cheddar (MC), sharp Cheddar (SC) and Monterey Jack (MJ) cheeses.

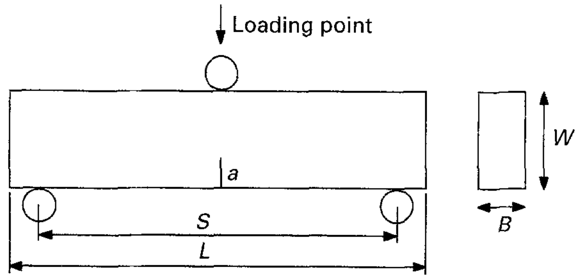


Figure 1 SENB geometry.

Cheddar cheeses were manufactured in 640 lb (~290 kg) blocks. At the end of the curing period, which varied depending on the type of cheese, 8 oz (~227 g) bricks were cut from the original block, packaged and marketed. Measurement of the mechanical properties for MC and MJ cheeses was performed on such 8 oz bricks randomly sampled from the same 640 lb block. Consequently, the data reported in this study for MC and MJ reflect shelf-life changes.

For SC, the changes in the mechanical properties were monitored during the curing phase. However, 640 lb blocks of cheeses are heterogeneous and often a moisture gradient is obtained throughout the block, causing textural changes. To ensure testing homogeneous samples, one 640 lb block of SC was cut into several 40 lb (~ 18 kg) blocks, each of which was then cured individually. A new 40 lb block was cut each month to produce 8 oz bricks. A number of these bricks were randomly selected for testing.

Tests were performed at various dates to characterize the above-mentioned cheeses in terms of stress–strain and fracture toughness properties and to establish the effect of the maturing time. All cheeses were stored in a refrigerator at a temperature of approximately 4 °C, in the factory-sealed wrappers until the day of testing.

The moisture content was determined in every brick undergoing mechanical testing. Fat and protein were also determined on bricks from the same batch as those tested.

Details for each test/measurement are given separately in the following subsections.

3.1. Moisture-content measurement

A small sample (2–3 g) of cheese was cut and weighed before inserting in a vacuum oven, at 100 °C for 5 h. During drying, a slow current of air was admitted into the oven, the air being dried by passing through concentrated H_2SO_4. Care was taken to keep the pressure in the oven below 100 mm Hg. The sample was reweighed and the loss in weight expressed as percentage moisture content.

3.2. Protein-breakdown measurements

The total protein was measured using the Kjeldahl Nitrogen determination method and the alpha- and beta-casein concentrations were determined using the SDS gel electrophoresis technique.

3.3. Compression tests

Cylindrical specimens were cut using a 0.4 mm diameter wire cutter and a cylindrical borer based on the design given by Luyten [8].

The diameter of all the cylinders was 20 mm. In order to study the effect of friction, four heights were tested; 7, 10, 13 and 20 mm. For each height, four specimens were tested, bringing the total number of cylinders compressed at any time to sixteen. The experiments were carried out on a Instron testing machine at a constant displacement crosshead rate of 10 mm min^{-1}. A 1 kN load cell was used. An environmental chamber was used to keep the test temperature at 4 °C.

Stress, σ, and strain, ε, were calculated using the usual relations

$$\sigma = \frac{Ph}{\pi R^2 H} \tag{1}$$

$$\varepsilon = -\ln\frac{h}{H} \tag{2}$$

where P is the load, H the original height, R the original radius and h the current height ($= H - \Delta h$). Note that Equation 1 essentially assumes a constant volume deformation. This is a reasonable assumption for cheese as shown by Luyten [8] and makes computations simpler. The strain as defined in Equation 2 is the true or Hencky strain and for high deformations is a better estimate of the real strain in the sample than engineering strain. Equations 1 and 2 are the most commonly used relations in compression test data analyses.

The results were plotted in the form of a family of plots of σ versus $(1/H)$ for various strain values. Straight lines were fitted through the experimental data corresponding to each strain. The intercept of each line with the stress axes corresponds to the stress that would be measured if an "infinitely" high cylinder was tested and hence was not affected by frictional effects. In this way, the "correct" stress–strain curve was estimated.

3.4. Fracture tests

The single-edge notched bend (SENB) geometry was used for the fracture tests (see Fig. 1). The sample was loaded in three-point bending on an Instron testing machine with a 10 N load cell. The test temperature was also 4 °C and the crosshead displacement rate was 10 mm min^{-1}. The length, L, span, S, width, W, and breadth, B, of the samples were 88, 74, 18.5 and 9.3 mm, respectively. A sharp razor blade was pushed into the sample, creating the necessary prenotch, whose length was 5–6 mm.

Assuming linear elastic behaviour, the critical energy release rate, G, can be evaluated from

$$G = \frac{U}{BW\phi} \tag{3}$$

where ϕ is a calibration factor and is a function of (a/W), a being the prenotch length [19]. U is the energy represented by the area under the load versus load-point displacement diagram between zero and crack initiation load. Because the specimen was enclosed in the environmental chamber during the test, it was rather difficult visually to detect crack initiation accurately. Even so, it was noticed that crack initiation occurred reasonably close to the maximum load point. Therefore, for consistency purposes, the crack initiation load was always taken to be the maximum load. Corrections to the energy for sample indentation effects were also taken into account as described in the ESIS testing protocol.

The number of specimens tested at each time was limited by the number of cheese bricks available. Up to five specimens could be cut from each brick. Either five or ten specimens were tested at each time.

4. Results

Test results and measurements for MC and MJ will be quoted with the corresponding ageing time, i.e. the number of days that elapsed from the date the cheese bricks were packaged at the factory to the date the test was performed. This will enable correlation of mechanical properties with ageing. For SC, ageing time will be indicated by the month it was tested.

The typical fat, protein and moisture content measured for the three cheeses is shown in Table I.

The effect of different lubricants on the measured stress–strain curve was studied using paraffin oil and Vaseline on MC cheese. Samples of various heights were used. It was found that the σ versus $1/H$ plots showed the anticipated trend when paraffin oil was used, i.e. the stress increased with decreasing sample height. On the contrary, when Vaseline was used, the lines had a negative slope: the stress increased with increasing sample height. During the tests, the shape of the deformed samples was also distinctively different when a different lubricant was used (see Fig. 2). Numbers 1 and 2 distinguish between deformed samples when paraffin oil and Vaseline were used, respectively. Number 1 shows the classic "barrel" shape, whereas number 2 shows a rather irregular shape. Also evident from the photographs is that Vaseline allowed a greater movement between the sample and the loading plate, i.e. it reduced friction. During the tests, it was actually observed that specimen number 2 showed the opposite effect to number 1. The cylinder started cracking at one of the loaded edges and eventually became almost concave, as shown schematically in Fig. 3.

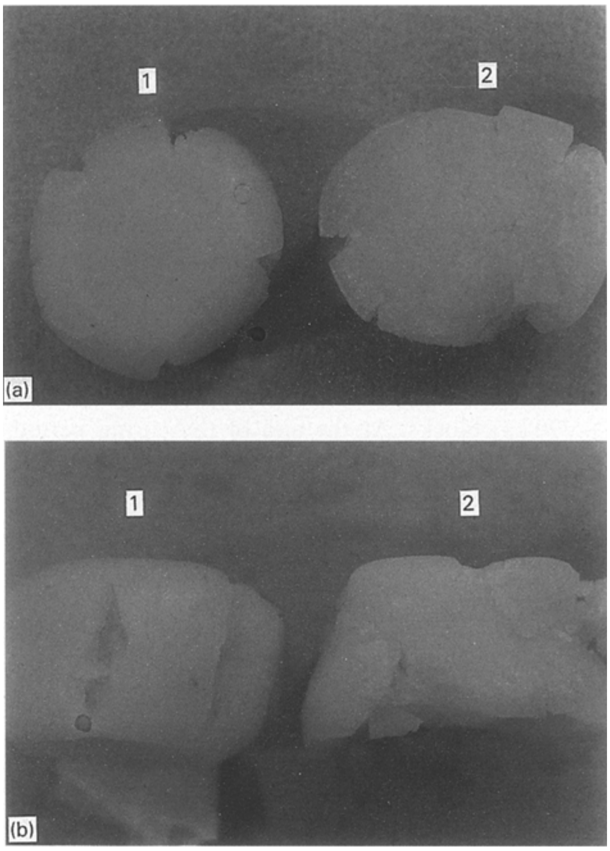
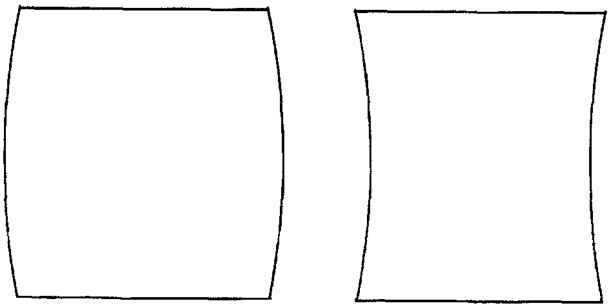


Figure 2 Deformed shape of MC: (1) when paraffin oil is used, (2) when Vaseline is used.



Paraffin oil,
specimen number 1

Vaseline,
specimen number 2

Figure 3 Effect of lubricant on sample deformation shape.

Similar observations were made by Culioli and Sherman [1] in a study of compression properties of Gouda cheese. They noticed that when the loading plates were covered with emery paper, the cheese developed a barrel deformation. However, when the plates were lubricated with a thin film of oil, the sample did not show a barrel shape. Instead, the deformation was concave so that the increase in the diameter at the sample's top and bottom surfaces exceeded the increase in the diameter in the sample's middle region, i.e. the sample assumed an hourglass shape. This led to cracks appearing first near the ends and then spreading towards the middle. This was in contrast to the case when emery paper was used where cracks appeared initially about halfway between the two ends of the sample and then spread towards the middle. Similar findings were reported in another study of Leicester cheese by Carter and Sherman [2].

TABLE I Typical fat, protein and moisture content of the cheeses tested

Cheese variety	Fat content (%)	Protein content (%)	Moisture content (%)
Mild Cheddar	32	24	36
Monterey Jack	33	24	39
Sharp Cheddar	35	24	35

In conclusion, from the results of this study as well as previous ones, it was found that when there is sufficient lubrication between the loading plates and the cheese sample, the sample could develop a concave or hourglass shape. This is in contrast to the classic barrel shape which indicates that frictional effects are taking place. Cook and Larke [9] actually concluded that larger frictional effects make extrapolation of the results more accurate because the curves resulting from different height cylinders show a much greater spread. Following the above observations and Cook and Larke's suggestions, it was decided that paraffin oil should be used for all subsequent tests. As stated above, paraffin oil was found to lead to the anticipated behaviour trends.

Fig. 4 shows the extrapolated stress–strain curves of MC for the four maturing dates. The data obtained for the other two cheeses are presented in Figs 5 and 6 for MJ and SC, respectively. Sample plots of stress versus $(1/H)$ are shown in Fig. 7. The stress–strain curves that are obtained are highly non-linear (Figs 4–6). For this reason, the Young's modulus, E, is expressed as the 5% strain secant modulus. This also avoids the scatter produced by the end sides of the cylinders being not always exactly flat and parallel. The maximum stress value in the figures is also noted and is referred to as yield stress, σ_y. Note that in most cases, small cracks were observed before the maximum point on the load–displacement diagram was reached. The Young's moduli and the yield stresses, as measured from Figs 4–6, are tabulated in Tables II–IV for MC, MJ and SC, respectively. The corresponding moisture content and alpha- and beta-casein concentrations are also presented in Tables II–IV.

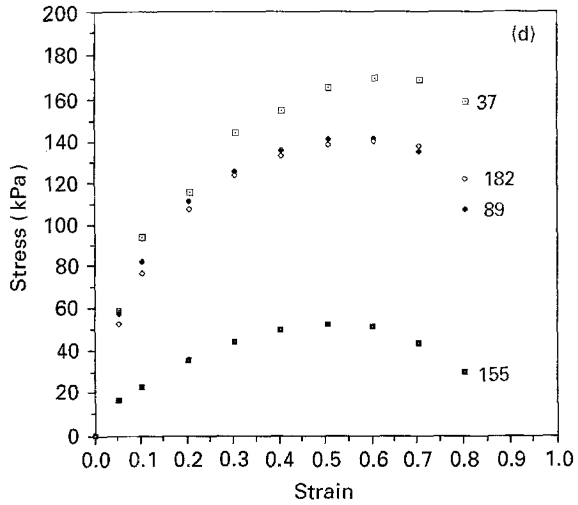


Figure 4 Effect of maturing time on extrapolated stress–strain curves for MC after (⊡) 37 d, (◆) 89 d, (■) 155 d, (◇) 182 d.

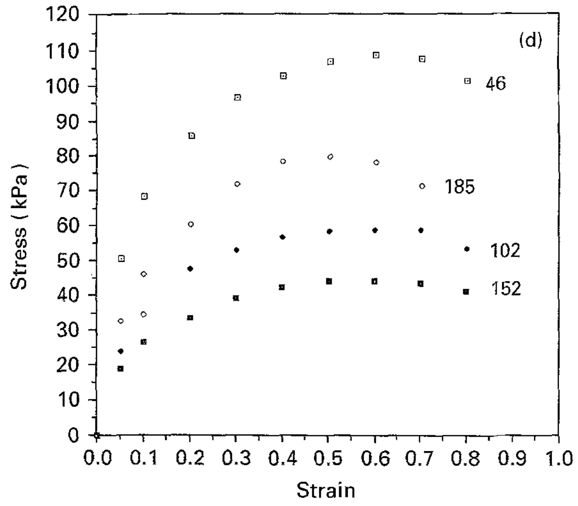


Figure 5 Effect of maturing time on extrapolated stress–strain curves for MJ after (⊡) 46 d, (◆) 102 d, (■) 152 d, (◇) 185 d.

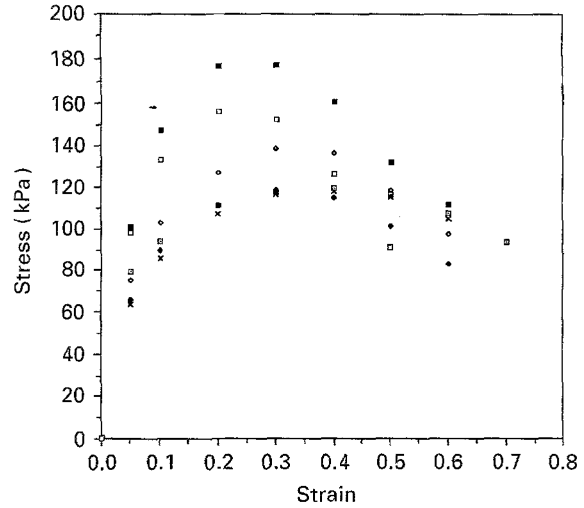


Figure 6 Effect of maturing time on extrapolated stress–strain curves for SC after (⊡) month 1, (◆) month 2, (×) month 3, (◇) month 4, (■) month 5, (□) month 6.

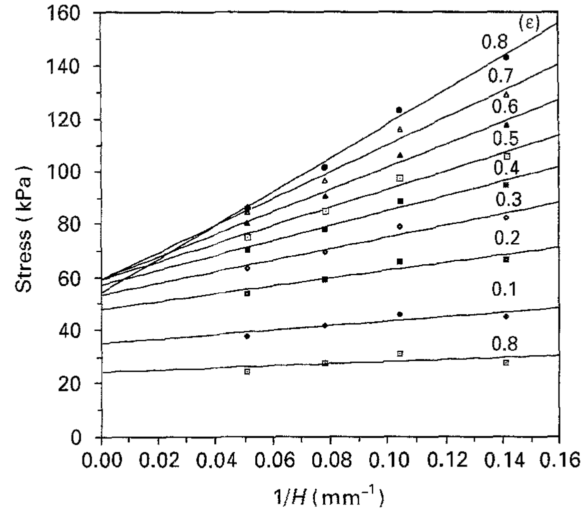


Figure 7 σ versus $(1/H)$ for MJ (152 days) at ε: (⊡) 0.05, (◆) 0.1, ( ) 0.2, (◇) 0.3, (■) 0.4, (□) 0.5, (▲) 0.6, (△) 0.7, (●) 0.8.

Finally, the fracture toughness of the cheeses is calculated using Equation 3. U is calculated from the area under the load–displacement diagram between the origin and the maximum load points. The fracture toughness values are shown in Tables II–IV. All data, except those marked with an asterisk, are the average of results from five samples, all cut from the same brick. The ones marked with an asterisk are the average of results from ten samples, i.e. specimens cut from two different bricks. Where two values are quoted, they correspond to the fracture toughness for each

TABLE II Experimental results for mild Cheddar (MC)

Ageing time (days)	Alpha-casein (%)	Beta-casein (%)	Moisture content (%)	E at $\varepsilon = 0.05$ (kPa)	σ_y (kPa)	G_c $(\mathrm{J\,m^{-2}})$
37	19	39	36.5	1176	170	41 ± 7
89	17	36	36.5	1150	140	29.3 ± 7.7
155	9	33	41.2	330	53	17.9 ± 4.2/36.9 ± 11.9*
182	8	31	40	1050	140	30.6 ± 3.6/37.4 ± 6.8*

* Average of ten samples from two different bricks.

TABLE III Experimental results for Monterey Jack (MJ)

Ageing time (days)	Alpha-casein (%)	Beta-casein (%)	Moisture content (%)	E at $\varepsilon = 0.05$ (kPa)	σ_y (kPa)	G_c $(\mathrm{J\,m^{-2}})$
46	13	39	39.6	1008	110	26.5 ± 7.5
102	13	42	40	474	59	24.6 ± 4.6
152	8	35	41	378	44	20.4 ± 4*
185	7	32	38.9	652	80	17.5 ± 3.5*

* Average of ten samples from two different bricks.

TABLE IV Experimental results for sharp Cheddar (SC)

Ageing time (month)	Alpha-casein (%)	Beta-casein (%)	Moisture content(%)	E at $\varepsilon = 0.05$ (kPa)	σ_y (kPa)	G_c $(\mathrm{J\,m^{-2}})$
1	20	42	34.2	1580	120	31.2 ± 12
2	16	45	35.9	1306	120	23.6 ± 6
3	14	43	35.3	1268	123	21.5 ± 7.6
4	14	33	35.3	1490	137	19.8 ± 3.2*
5	10	32	35.9	1990	176	15.7 ± 4.7*
6	8	11	35.5	1938	155	16.5 ± 1.4/13.2 ± 3.4*

* Average of ten samples from two different bricks.

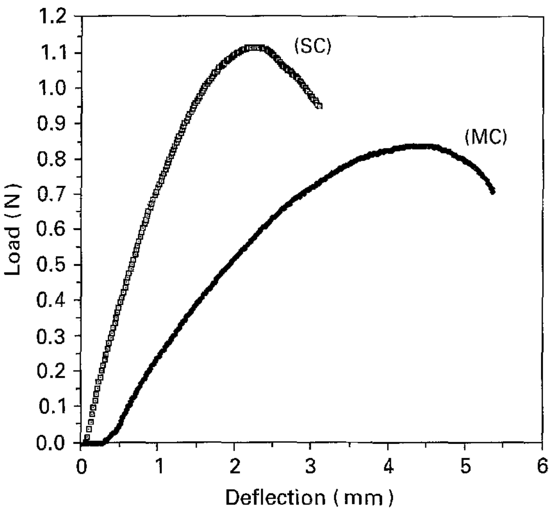


Figure 8 Load–deflection diagrams from fracture tests on SENB specimens: (□) SC, (◆) MC.

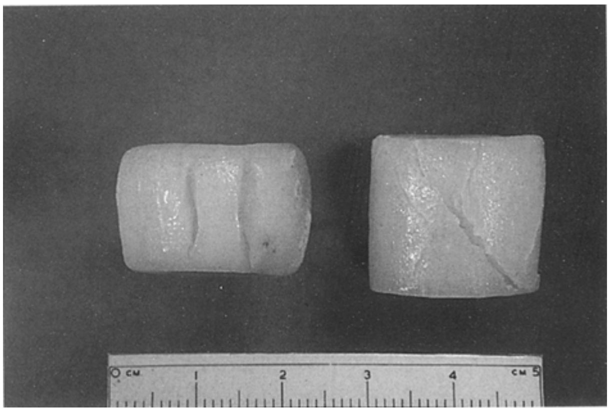


Figure 9 Deformed shapes of specimens tested in compression; MJ (left) and SC (right).

brick; when only one value is quoted, the calculated fracture toughness was the same for both bricks. Typical load–deflection diagrams obtained from the fracture tests are shown in Fig. 8. Because, after testing, the two halves of the specimen fitted each other perfectly, the non-linearity was not due to permanent deformation. The main cause for the observed non-linearity was viscoelasticity. Strictly speaking, the ESIS test standards are valid only for linear elastic deformations. However, because the energy release rate is calculated from the actual area under the load–displacement diagram, it is thought that the errors that would be introduced would not be large.

5. Discussion

5.1. Compression tests

Fig. 9 shows two deformed specimens tested in compression. The one on the left is MJ and the one on the right is SC. MC showed a similar deformed shape to MJ. This is the classic barrel shape due to frictional effects between the loading plates and the specimen's top and bottom edges, as discussed in Section 1. Cracks parallel to the direction of the applied load occurred in these cheeses, a direct consequence of the frictional effects. SC, on the other hand, remained a straight-sided cylinder; cracks at 45° to the direction of the applied load were observed, at the plane of maximum shear stress. It seems that frictional effects were negligible during testing of this type of cheese and the deformation was indeed uniform. However, short specimens still appeared to be stiffer than long specimens.

An added complication that appears in this study and not in Cook and Larke's work, is the fact that cheese is a highly viscoelastic material; its properties are extremely rate dependent. When a constant displacement crosshead rate is used to test cylinders of different heights, the applied strain rate is higher for the shorter specimens. At higher strain rates, a viscoelastic material tends to appear stiffer than when tested at a lower strain rate. Hence, the differences observed in the stress–strain curves of specimens of varying height, will be due to the different applied strain rates, *as well as* the consequences of frictional effects between the loading plates and the samples [3, 8, 21].

One could argue that the displacement crosshead rate could be changed so as to account for the difference in specimen heights and hence applied strain rates. For example, the samples that were chosen in this study, were such that the effective applied strain rates are different by approximately a factor of three. Hence, the displacement crosshead rate for the shortest specimens should be almost three times smaller than that used for the tallest specimens. However, by changing the displacement crosshead rate, the friction between the specimen and the loading plate is affected. This is simply due to the different rate at which the lubricant is squeezed out of the specimen and loading plate interface.

It is obvious from the above discussion that quantifying frictional effects in compression tests of cheese is a complicated matter. Additional information is needed regarding the strain-rate dependence of cheese. From the above arguments, it is concluded that the extrapolations made on the σ versus $(1/H)$ plots results in values that would be obtained under "infinitesimally small strain rates" as well as under "frictionless conditions".

5.2. Ageing effect on stress–strain curves and fracture toughness

The effect of maturing time on the stress–strain curves is different for the three cheeses that were studied. As stated earlier, the ageing data for the MC and MJ reflect ageing after packaging, whereas for SC, the ageing data truly reflect curing.

For SC, during the first three months, there is practically no change in the stress–strain curve, apart from a small decrease in the initial modulus after the first month. From then onwards, the modulus and yield stress both rise significantly with maturing time. During the last month, the modulus remains constant whereas the yield stress decreases. The moisture content of this cheese did not change, as shown in Table IV. Figs 10 and 11 are plots of beta-casein and E versus time and beta-casein and σ_y versus time, respectively. It is observed that there is roughly an inverse relationship between E and the beta-casein and between σ_y and the beta-casein: when one increases the other decreases.

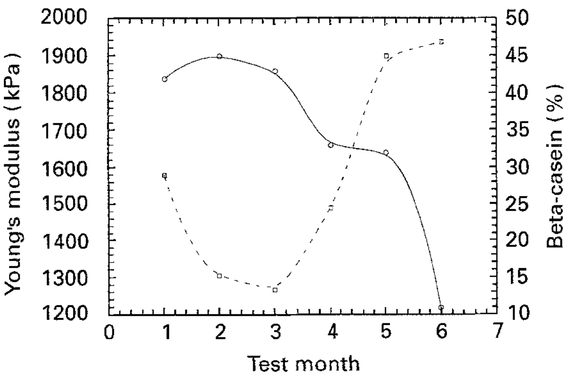


Figure 10 (○) Beta-casein and (□) E versus time of testing for SC.

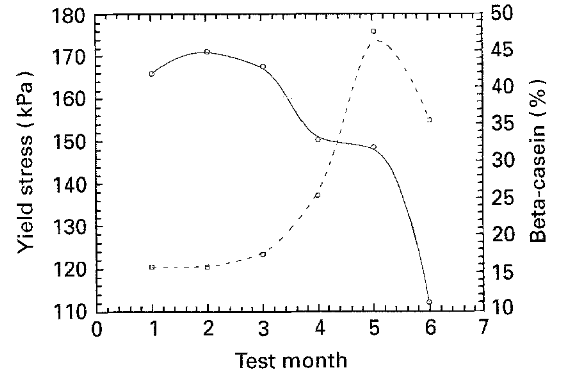


Figure 11 (○) Beta-casein and (□) σ_y versus time of testing for SC.

For MJ and MC, the effect of the ageing time on the stress–strain curves is not as obvious as for the SC. In addition there seems to be no correlation between the changes in E and σ_y and the changes in the beta-casein. Moisture fluctuations were also observed for these cheeses. This could be a direct consequence of the way the samples were produced. As mentioned earlier, these were cut from a large 640 lb block where a moisture gradient is very likely to occur. It has generally been recognized in the cheese industry that moisture influences cheese texture. Further studies are necessary to confirm this major effect of moisture on E and σ_y. The stress–strain data corresponding to MC aged for 155 days deviate substantially from the observed trend, hence they should be ignored.

From the fracture toughness data shown in Tables II–IV, the general conclusion can be made that the cheeses tend to become more brittle with maturing time, i.e. the fracture toughness decreases. This is in agreement with observations made by cheese grading experts. In Table II, the fracture toughness of 155 and 182 days old MC was found to vary between different cheese bricks. This makes the correlation of fracture toughness with maturing time difficult and also throws some doubt on the validity of the stress–strain data as well. All cylindrical specimens that were compressed at any time were all cut from a single brick. If there is a variation between bricks, the observed

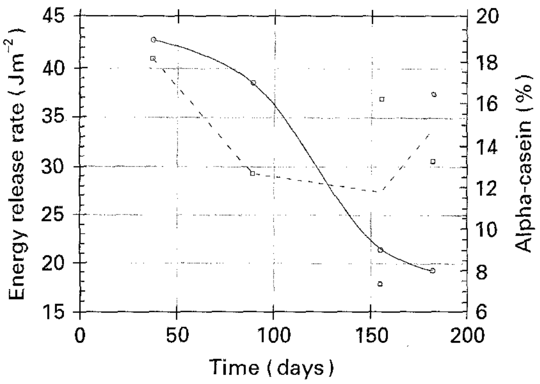


Figure 12 (○) Alpha-casein and (□) G_c versus time of testing for MC.

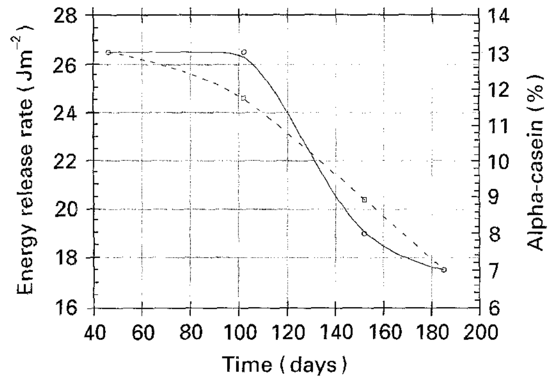


Figure 13 (○) Alpha-casein and (□) G_c versus time of testing for MJ.

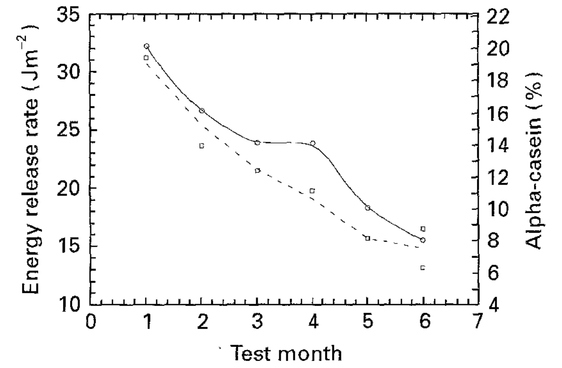


Figure 14 (○) Alpha-casein and (□) G_c versus time of testing for SC.

changes in the stress–strain curves as shown in Fig. 4, are not solely due to increasing maturing time. A variation between bricks was also noted for the last batch of SC (Table IV).

Figs 12–14 show plots of G_c and alpha-casein versus time for MC, MJ and SC, respectively. It is obvious that for all cheeses, G_c as well as the alpha-casein decreased with ageing time. This suggests that the drop in G_c could be a consequence of the drop in the alpha-casein concentration.

6. Conclusion

Compression testing was performed to measure the stress–strain curves of cheeses. The specimen height was varied in order to examine the frictional effects. The results were extrapolated to infinite height, simulating "friction-free conditions" and "infinitesimally small strain rates".

The modulus of SC was found to increase with increasing maturing period. A sharp increase was noted after the end of the third month. There seems to be a correlation between the changes in E and σ_y and the change in the beta-casein concentration. For the rest of the cheeses the trend was not as clear.

Fracture tests were performed on SENB specimens. The fracture toughness was calculated according to the ESIS testing protocol for plastics. The fracture toughness as well as the alpha-casein decreased with time for all cheeses.

Cheese chemistry is very complex and not well understood. The precise location of the beta- or the alpha-casein in the protein matrix with respect to each other or with respect to the location of the fat droplets, is unknown. Conceptually, cheese structure can be thought of as a collection of mazes, each maze being a collection of some number of protein agglomerates with entrapped fat droplets (curd). Owing to the continuous bacterial and enzymatic activity, the mazes become smaller in size, but probably larger in number. There is no easy explanation as to why the breakdown of the alpha-casein should lead to lower G_c, why the breakdown of the beta-casein gives a higher E and σ_y, or why moisture has such an influence on E and σ_y. However, these observations could be refined through controlled experimentation using different cultures or enzymes that give different rates of alpha- and beta-casein breakdown. Such studies will lead to a better understanding of factors that control cheese quality. From this work, it is concluded that the studies investigating cheese quality should include the determination of stress–strain relationship (E and σ_y) and fracture toughness (G_c). The techniques for measuring the above have been discussed in this study.

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