

Rheological properties and maturation of New Zealand Cheddar cheese

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Summary — Trends in the fracture strain, modulus of deformability and chemical properties as a function of storage time were determined for Cheddar cheese made in the New Zealand Dairy Research Institute's pilot plant. The apparent fracture strain of Cheddar cheese increased during the first 14–28 days and thereafter decreased. α_{s1} -Casein levels decreased monotonically and non-protein nitrogen levels increased with storage. Fusion of curd particles probably contributed to the initial increase in fracture strain, and the decrease in strain can be rationalized in terms of increasing proteolysis. The modulus of deformability increased by at least a factor of two over the initial several weeks of storage and then increased slightly or remained constant. However, the moisture content of Cheddar cheese changed very little (the maximum range being 34.6–33.0% with no monotonic change over time). The increase in the modulus over the first 14 days was not associated with a decrease in moisture content. Differential scanning calorimetry indicated there was some crystallization of milkfat from 91 to 210 days of storage, and this (together with small moisture losses) may partly explain the small increase in the modulus of deformability over this period of time.

cheese maturation / rheological property / fracture property / composition / Cheddar cheese

Résumé — **Propriétés rhéologiques et maturation du fromage de Cheddar de Nouvelle-Zélande.**

On a déterminé l'évolution, en fonction du temps d'affinage, de la déformation à la fracture, du module de déformabilité et des propriétés chimiques du fromage de Cheddar, fabriqué à l'usine pilote de l'Institut de recherches laitières de Nouvelle-Zélande. La déformation apparente à la fracture du Cheddar augmentait pendant les 14–28 premiers jours, et diminuait ensuite. La teneur en caséine α_{s1} diminuait régulièrement pendant l'affinage et la teneur en azote non protéique aug-

mentait. La soudure des particules de caillé contribuait vraisemblablement à l'augmentation initiale de la déformation à la fracture, alors que la diminution ultérieure de ce paramètre pouvait être attribuée au développement de la protéolyse. Le module de déformabilité augmentait au moins d'un facteur 2 pendant les premières semaines de maturation, puis diminuait légèrement ou restait constant. Or, la teneur en eau du fromage de Cheddar changeait très peu (la plage de variation maximum étant de 34,6–33,0 %, sans évolution régulière au cours du temps). L'augmentation du module de déformabilité pendant les 14 premiers jours n'était pas associée à la diminution de la teneur en eau. La calorimétrie différentielle à balayage a montré qu'il y avait un peu de cristallisation de la matière grasse entre 91 et 210 jours de stockage et que cela, associé à une légère perte d'eau, peut expliquer partiellement le faible accroissement du module de déformabilité pendant cette période.

maturation du fromage / propriété rhéologique / propriété de rupture / composition / fromage de Cheddar

INTRODUCTION

New Zealand exports most of its cheese. A large proportion of this exported cheese is Cheddar cheese which requires a long storage time before it is suitable for eating. The eating and cutting properties of Cheddar cheese depend not only on conditions of curd formation and handling, but also on storage conditions. A mild New Zealand Cheddar cheese with a high longness (resistant to crumbling) requires a storage time of about 6–12 months at a storage temperature near 13 °C. By comparison, a mature New Zealand Cheddar cheese with relatively high stiffness (hard to dent) and low longness (easily crumbles) requires a storage time greater than 12 months at the same storage temperature. Not only functional properties like eating and cutting but also flavour properties change during storage. Understanding how these changes occur can reduce the variability of the properties of current commercial cheese and can assist in new product development.

The major area of science related to the instrumental measurement of the functional properties like texture, cutting and melting is rheology (and fracture properties). In addition, rheological and chemical measurements in cheese give insights into the physico-chemical changes occurring during ripening. The effect of maturation on rheological and fracture prop-

erties has been reported for various cheeses including American Cheddar cheese (Creamer and Olson, 1982), Colby cheese (Creamer et al, 1988a), New Zealand Cheddar cheese (Creamer et al, 1988b) and Gouda cheese (Luyten, 1988). Creamer and Olson (1982) found that compression at the yield point (longness) was reduced by protein breakdown and that longness and yield force were also influenced by moisture content and pH. Creamer et al (1988b) found that the force to slightly deform the cheese increased until about 3–4 months of storage and then changed little. Calf rennet and rennilase coagulant gave similar curves for this force during cheese storage. Luyten (1988) explored the effect of curd fusion and cheese pH on the rheology of Gouda cheese, finding that fusion occurred within a week in standard Gouda cheese. Fracture strain (longness) decreased when the amount of peptides and amino acids formed from the parent caseins increased, and modulus (stiffness) at a given pH was mainly increased by decreasing the moisture content during maturation (Luyten, 1988).

The main objective of this work was to find trends in a selection of well defined rheological and fracture properties of New Zealand Cheddar cheese as a function of storage time. Another objective was to gain some insight into the physico-chemical changes occurring during ripening by comparing these trends with changes

in chemical composition. In this paper, only the fracture property fracture strain and the rheological property modulus of deformability are discussed.

Because cheese is a non-linear viscoelastic material, rheological and fracture properties are a function of the time scale of the experiment (strain rate, $\dot{\epsilon}$) as well as the strain applied (Walstra and Peleg, 1991). Although the effect of $\dot{\epsilon}$ was not examined in the current study, the initial value of $\dot{\epsilon}$ ($3.3 \times 10^{-2} \text{ s}^{-1}$) was well defined and within the range used by other workers who have examined the effect of $\dot{\epsilon}$ on cheese fracture strain and modulus (Luyten, 1988; Rohm and Lederer, 1991).

Cheddar cheese is eaten when it is at temperatures ranging from refrigerator temperatures to those at ambient conditions. Therefore an indication of textural (eating) properties in this study was found by conducting tests at 5 and 20 °C. Sensory evaluation was not carried out, but indications of the properties of stiffness (rigidity), and longness (resistance to crumbling) were obtained from the modulus of deformability and the fracture strain respectively (Visser, 1991; Zoon, 1991).

Fracture strain not only indicates longness but also influences cutting properties. If it is too small, cheese tends to crumble when cut.

MATERIALS AND METHODS

Experimental design and manufacture of cheese

Two vats of Cheddar cheese were made at the New Zealand Dairy Research Institute (NZDRI) pilot plant. Standardized (protein 3.5%, fat 4.9%) and heat-treated (65 °C, 15 s) milk was held overnight before being pasteurized (72 °C, 15 s) and pumped into 375-L vats. The initial milk pH was 6.61. Then 1.5% starter bacteria (*Lactococcus lactis* subsp *cremoris* strains) and 14 mL calf rennet/100 L (New Zealand Standard Calf Rennet, New Zealand Rennet Co,

Eltham, New Zealand) were added, and the milk was left to set for 40 min before cutting. The setting temperature was 33 °C, the cooking temperature was 39 °C, the draining pH was 6.25, the cheddaring time was 2 h 25 min and the salting pH was 5.35. The cheese was made on the same day to reduce variability from the milk supply, and was made slightly after the middle of the dairy season (in February).

Each vat yielded about 40 kg of curd, which was nominally split into two 20 kg lots of curd. All four lots received an initial light pressing by hand into rectangular moulds. Vat 1 had one block of curd that was subjected to the standard treatment of mechanical pressing (nominally of 0.3 MPa) overnight, and one block that was not pressed. The two blocks from vat 2 received the standard mechanical pressing. The two vats subjected to standard mechanical pressing treatment were regarded as replicates. After pressing, the four nominally 20 kg blocks of cheese were each divided into four equal sub-blocks and were stored in vacuum-sealed polyethylene bags at 13 °C. At each of the storage times (the full range being 1, 14, 28, 50, 124, 209 and 394 days), a new sub-block of cheese was used. A split-split-plot design was used with an unequal number of mainplot experimental units (vats 1 and 2) for each mainplot treatment (pressed/unpressed). The subplot treatment, applied after splitting each of the mainplots into equal units, was storage time. Data were available for all mainplots (vats) for storage times 14, 28 and 209 days only; therefore the data set for the analyses included only these storage times. The sub-sub-plot treatment, applied after splitting each of the subplots into equal units, was test temperature (5 or 20 °C) for the rheological responses. Statistical analyses of the data were carried out using the general linear models procedure in SAS (SAS [1994], Release 6.1. SAS Inc, Cary, NC, USA). An extension of methods described by Milliken and Johnson (1984) was used due to the unbalanced nature of the design.

Linear regression analyses were performed using Minitab (Minitab [1994], Release 10.1, Minitab Inc, State College, PA, USA).

Another two vats of Cheddar cheese were made just before the middle of another dairy season (in November) to allow measurement of differential scanning calorimetry (DSC). The manufacturing procedures were similar to those used during the main manufacturing in February, and measurements were taken at storage times of 28, 91 and 210 days.

Sample preparation for rheological measurements

For uniaxial compression and relaxation experiments, a core borer with an inner diameter of 20.0 mm mounted on a drill press was used. Cores were taken parallel to the direction of pressing of the original block at points half-way between the centre and the edge of the top surface. The core borer was lubricated with paraffin oil (high viscosity type, 340–360 Saybolt universal seconds at 37.8 °C) to make it easier to cut out a sample. The cores were placed in a template and cut into cylinders 25.0 mm in height by a wire-cutting apparatus. The samples were wrapped in polyethylene film and allowed to equilibrate to the test temperature.

Uniaxial compression

Uniaxial compression experiments were performed on a TAHD compression tension test instrument (Stable Micro Systems, Haslemere, UK) with a 50 kg load cell with a resolution of 1 g and an accuracy of 0.025%. The distance measurement had a resolution of 0.001 mm. The TAHD was connected to a personal computer with a data transfer rate of force, displacement and time data triplets of 50 Hz. Temperature was controlled by placement of the instrument and sample in a controlled temperature room. Two parallel Teflon plates were used. Samples were placed between plates that had been lubricated with paraffin oil, and a crosshead speed of 0.83 mm/s was used to compress samples to 80% Cauchy strain. The number of measurements taken for each cheese at each storage time

and test temperature was typically six for uniaxial compression.

The experimental data were initially analysed using XTRAD software (Stable Micro Systems) and the appropriate data were exported into software (Master Work Software, Tawa, New Zealand) written in J, a functional programming language (Iverson Software Inc, Toronto, Canada) (Iverson, 1991; McIntyre, 1991). This software (using J) calculated Hencky strain as suggested by Peleg (1977), and hereafter is abbreviated to strain. The software calculated stress assuming a constant volume during compression. The assumption of a negligible decrease in sample volume upon compression was a reasonable one for Cheddar cheese (Calzada and Peleg, 1978), being on average a 9% volume reduction. The equations were:

$$\dot{\epsilon}_0 = v / h_0 \quad [1]$$

$$\epsilon_c = \Delta h_t / h_0 \quad [2]$$

$$\epsilon_h = -\ln(1 - \epsilon_c) \quad [3]$$

$$\sigma = (1000F_t / \pi r_0^2)(1 - \epsilon_c) \quad [4]$$

v = speed of compression (mm/s);

h_0 = initial sample height (mm);

Δh_t = displacement of crosshead at time t (mm);

F_t = force from lubricated compression at time t (N);

r_0 = initial radius of sample (mm);

$\dot{\epsilon}_0$ = initial strain rate (s^{-1});

ϵ_c = Cauchy strain (-);

ϵ_h = Hencky strain (-);

σ = stress from lubricated compression test (kPa).

The apparent fracture strain was the strain at the local maximum for stress in the stress versus strain curve. The apparent modulus of deformability was the slope of the stress versus strain curve at low strain (typically below 0.03) where

the curve was close to a straight line. Although rheological and fracture properties are dependent on $\dot{\epsilon}$, the term apparent, used to denote this dependence, is omitted for the sake of brevity.

Chemical measurements and proteolysis measurements

The procedures described previously (New Zealand Dairy Board, 1993) were used for measuring fat (Babcock type), moisture (16 h oven dry at 105 °C, gravimetric measurement), salt (Volhard method), pH (measured electrometrically against two reference buffer solutions) and calcium (titration using EDTA and Patton and Reeder's reagents). To measure non-protein nitrogen (NPN) the sample was first dissolved in 1 mol/L NaOH. Trichloroacetic acid (TCA) (15%) was added until the acid strength of the solution was 12% to precipitate the proteins. The filtrate (NPN soluble in 12% TCA, according to the IDF [1993]) was tested for nitrogen content by an automated Kjeldahl procedure with a Kjehl-Foss automatic Kjel200 (A/S N Foss Electric, Hillerod, Denmark). The fraction soluble in 15% TCA contained mainly urea, free amino acids and peptides.

The relative amounts of α_{s1} -casein, α_{s1} -I casein and β -casein were measured using alkaline urea-polyacrylamide gel electrophoresis (PAGE). The Bio-Rad Mini-Protean II system was used with ten slot gels of 0.75 mm thickness and a Bio-Rad model 1000/500 power supply according to previously described methods (Creamer, 1991). Following destaining, the gels were photographed and scanned. Modifications to these methods were as follows. Cheese (0.500 g) was dispersed in 25 mL of sample buffer. The samples were heated to 40 °C and held at that temperature for 1 h, to transform fat into the liquid phase prior to blending with an Ultra-Turrax T25 (Janke and Kunkel, IKA-Labortechnik, supplied by Labsupply Pierce, New Zealand) at approximately 24 000 rev/min

for 20 s. The warm samples were then centrifuged at 10 000 rpm at 4 °C for 10 min to solidify and separate the fat. The aqueous supernatant (2 mL) was treated with 2-mercaptoethanol (20 μ L/mL) and held for 18 h prior to loading 5 μ L of the mixture into the gel slab. A rennet casein standard was prepared by dissolving 12.0 mg of rennet casein in 6 mL of sample buffer. After stirring for 1 h, the standard was diluted to give a final concentration of 1 mg/mL. A trim milk standard was prepared by diluting 0.1 mL of trim milk with 3.9 mL of urea sample buffer. Each standard was treated with 2-mercaptoethanol (20 μ L/mL) as well as bromophenol blue and held for 18 h prior to loading 10 μ L of the mixture into the gel slab.

One chemical and PAGE measurement was taken for each cheese at each storage time. Chemical measurements were made soon after sampling. At each storage time a sample of cheese was also stored below -40 °C until all the samples had been collected. These samples were then analysed at the same time for NPN and by PAGE.

Differential scanning calorimetry

Samples were vacuum-packed and kept at the storage temperature until just prior to the DSC test. A cylinder 2 mm in diameter was taken with a core borer, and cut to about 1 mm in length. It was immediately put into a pre-weighed metal cup, sealed and reweighed. Shortly afterwards the sample and cup were placed in a DSC 7-PC (Perkin-Elmer Corp, Norwalk, USA) and the following temperature time history was used. Samples were cooled from near 20 °C to -40 °C at -10 °C/min. They were held at -40 °C for 5 min, and then heated while measurements were taken of the energy required to heat the sample from -40 °C to 70 °C at 5 °C/min. The onset of melting and the energy per mass of the water and two milkfat fractions were measured.

RESULTS AND DISCUSSION

Chemical composition

The fat and moisture contents of the main experimental cheese made in February (table I) varied little over the storage time. However, from 124 to 394 days for vat 2, the moisture content decreased slightly. Visible exudate from the cheese surface together with the use of samples for moisture measurement that had very little of the original cheese surface probably caused this decrease in moisture content. Polyethylene bags sealed under a partial vacuum provide a watertight container for the maturing cheese. Therefore the moisture content of the Cheddar cheese during maturation did not decrease significantly due to evaporation of cheese moisture. As expected, the pH initially decreased (table I) because of the continued metabolism of the remaining lactose to lactic acid by the starter bacteria. During maturation, the α_{s1} -casein and

β -casein levels decreased and the α_{s1} -I casein levels increased, reached a maximum near 28 days and then decreased (fig 1). The NPN levels increased with time (table I).

The composition of the cheeses made in November was slightly different from that of the cheeses in the main trial in February. In particular, the moisture in the non-fat substance (MNFS) at 1 day for the cheese made in November was higher (52.6–53.2%) than that for the cheese made in February (50.1–51.0%).

Fracture strain

There were two different regions on the fracture strain (ϵ_f , or longness) versus storage time graph (fig 2). The first region showed an initial increase in ϵ_f from 1 to 14 or 28 days, and the second region a decrease in ϵ_f after 28 days. This trend during storage was similar for both test temperatures, but ϵ_f was lower at 5 °C than at 20 °C. Temperature had a significant effect

Table I. Chemical properties and NPN during maturation of Cheddar cheeses made in February.
Propriétés chimiques et NPN déterminés pendant la maturation des fromages de cheddar fabriqués en février.

Cheese vat	Storage time (days)	Fat content (%)	Moisture content (%)	MNFS	pH	NPN (%)
1	14	32.5	34.2	50.7	5.20	0.19
1	28	33.5	33.8	50.8	5.27	0.34
1	124	33.0	33.9	50.6	5.25	0.71
1	209	34.0	33.8	51.2	5.45	0.82
1 (unpressed)	1	32.5	34.4	51.0	5.27	0.20
1 (unpressed)	14	35.0	34.6	53.2	5.17	0.28
1 (unpressed)	28	32.0	34.1	50.1	5.28	0.42
1 (unpressed)	209	35.0	34.3	52.8	5.52	0.78
2	1	33.5	33.3	50.1	5.21	0.24
2	14	33.0	34.5	51.5	5.07	0.32
2	28	33.0	33.8	50.4	5.08	0.36
2	50	32.0	33.9	49.9	5.09	0.43
2	124	34.5	34.0	51.9	5.23	0.74
2	209	34.5	33.7	51.5	5.32	0.88
2	394	35.5	33.0	51.2	5.28	1.15

MNFS: moisture in the non-fat substance; NPN: non-protein nitrogen.

on ϵ_f ($P = 0.0001$). In addition, ϵ_f was slightly lower when unpressed at storage times from 1 to 28 days, but was slightly higher when unpressed at 209 days. Pressing had a significant effect on ϵ_f that depended on storage time ($P = 0.0025$). The graph of ϵ_f over time (fig 2) shows the variability between the two replicates (vat 1 and 2) and the properties of vat 1 unpressed. The coefficient of variation (cov) of ϵ_f for a given storage time, vat and temperature indicates the method variability plus the variability of the material within a replicate. Half of the covs of ϵ_f were below 8.2%. The full range for these covs was 3.3 to 24%.

Luyten (1988) reported a study of the changes in rheological and fracture properties of Gouda during early maturation. During about the first week, curd fusion and diffusion of salt and water increased the viscous-like nature of the cheese, which was partly shown by an increase in ϵ_f . At later storage times, ϵ_f was decreased by increased splitting of caseins into small peptides and amino acids. The breakdown of α_{s1} -casein

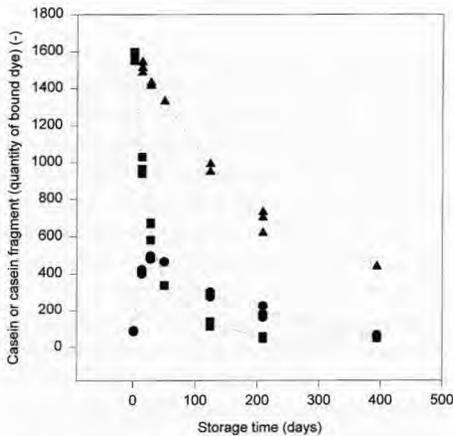


Fig 1. Changes in α_{s1} -casein, α_{s1} -I casein and β -casein during maturation of three Cheddar cheeses; ●: α_{s1} -I casein; ■: α_{s1} -casein; ▲: β -casein; one data point represents one cheese vat.

Évolutions de la caséine α_{s1} , α_{s1} -I et de la caséine β pendant l'affinage de trois fromages de type cheddar.

to large fragments in itself was probably not enough for Gouda cheese to decrease in ϵ_f .

In this study, there was a similar trend in ϵ_f during the maturation of Cheddar cheese. The initial increase in ϵ_f was probably related to curd fusion. Curd fusion starts at the interface of curd particles. Increasing the interfacial area by pressing promotes greater curd fusion. The higher values of ϵ_f for pressed cheese compared with unpressed cheese can be explained by the increased curd fusion induced by greater interfacial area. In addition, the cut surfaces of the 1-day old cheese were not as smooth as those of older cheese, further indicating that curd particles were less fused at 1 day than at later storage times. Curd fusion in this Cheddar cheese probably occurred within the first 14 days, but more experiments during early maturation are needed to accurately characterise this time.

The current work showed an association between ϵ_f and NPN (which includes peptides and amino acids), which is consistent with the hypothesis reported by Luyten (1988) that a

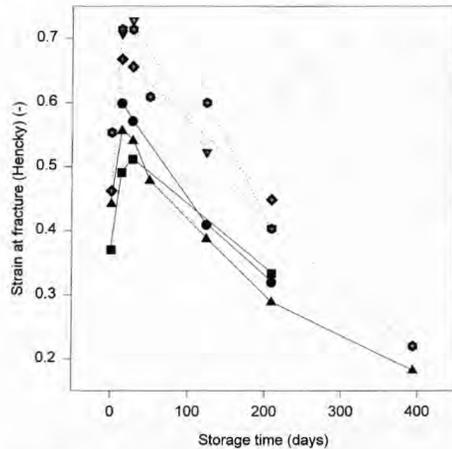


Fig 2. Changes in strain at fracture during maturation of three Cheddar cheeses at two test temperatures; ●: vat 1, 5 °C; ■: vat 1 unpressed, 5 °C; ▲: vat 2, 5 °C; ▼: vat 1, 20 °C; ◆: vat 1 unpressed, 20 °C; ⊙: vat 2, 20 °C.

Évolution de la déformation à la fracture pendant l'affinage de trois fromages de type cheddar à deux températures de test.

decrease in ϵ_f is caused by an increase in small peptides and amino acids. Using the values of ϵ_f that showed a decrease over time (omitting data at 1 day), the current results for ϵ_f and NPN showed a good fit using linear regression equations with a significant negative slope ($P < 0.0005$ for both temperatures, $r^2_{(adj)} = 0.949$ for 5 °C, $r^2_{(adj)} = 0.895$ for 20 °C). If all data were used (fig 3), the fit to the linear regression equations (significant slope, $P < 0.0005$, $r^2_{(adj)} = 0.680$ for 5 °C, $r^2_{(adj)} = 0.589$ for 20 °C) was not as good as the fit with 1 day data excluded. This observation is consistent with the hypothesis that the early maturation period has processes affecting the association between ϵ_f and NPN that are different from those in the later main maturation period.

Although the α_{s1} -casein breakdown to α_{s1} -I casein probably does not in itself cause a decrease in ϵ_f , α_{s1} -casein breakdown influences

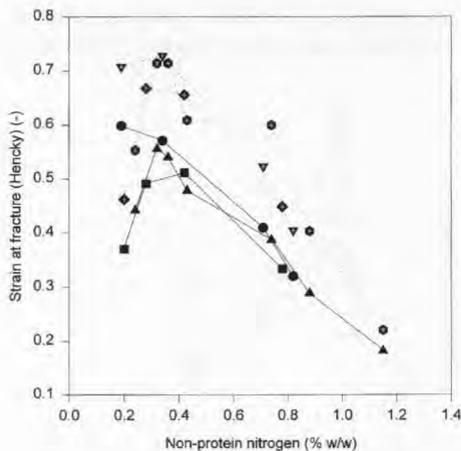


Fig 3. Influence of non-protein nitrogen levels on strain at fracture during maturation of three Cheddar cheeses at two rheological test temperatures. Data points at adjacent storage times are joined. ●: vat 1, 5 °C; ■: vat 1 unpressed, 5 °C; ▲: vat 2, 5 °C; ▼: vat 1, 20 °C; ◆: vat 1 unpressed, 20 °C; ●: vat 2, 20 °C. *Influence des niveaux d'azote non protéinique sur la déformation à la fracture pendant l'affinage de trois fromages de type cheddar dans deux températures de test rhéologique. Les points à des temps de stockage voisins sont reliés.*

the subsequent breakdown to peptides and amino acids. The later breakdown to peptides and amino acids probably does cause a decrease in ϵ_f . Thus there is likely to be an association between α_{s1} -casein levels and ϵ_f . A quadratic regression curve fitted the ϵ_f versus α_{s1} -casein data with a local maximum at 14–28 days, and had an intercept, linear coefficient and quadratic coefficient that were significant ($P < 0.0005$). This quadratic curve had a reasonable fit to the ϵ_f versus α_{s1} -casein data ($r^2_{(adj)} = 0.796$ for 5 °C, $r^2_{(adj)} = 0.722$ for 20 °C). However, a linear regression equation had a poor fit to these data (slope $P < 0.055$, $r^2_{(adj)} = 0.197$ for 5 °C, $r^2_{(adj)} = 0.117$ for 20 °C). Whereas a linear model did not adequately explain the relationship between α_{s1} -casein and ϵ_f , a quadratic regression curve did.

The small increase in ϵ_f in this work as the temperature increased from 5 to 20 °C has been found by others (Luyten, 1988) and can be partly explained by an increase in viscous properties (Roefs, 1986).

Modulus of deformability

The modulus of deformability (E_d , or stiffness) increased markedly (by at least a factor of two) from 1 to 14 days, increased less steeply from 14 to 28 days and thereafter increased slightly or remained about constant (fig 4). There was no general decrease in E_d with time as found for ϵ_f . The trends in E_d during maturation were similar for both test temperatures, but E_d was higher at the lower test temperature of 5 °C. Temperature had a significant effect on E_d that depended on storage time ($P = 0.046$). Pressing did not have a significant effect on E_d ($P = 0.14$) (although unpressed cheese had slightly lower mean values of E_d than pressed cheese [fig 4]).

Half the covs of E_d for a given storage time, vat and temperature were below 9.8%. The full range of these covs was 1.8 to 27%.

Luyten (1988) reported that E_d increased during initial storage and then decreased between two and six days of storage (for standard Gouda,

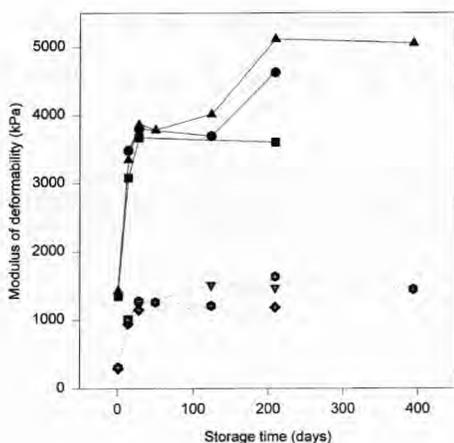


Fig 4. Changes in modulus of deformability during maturation of three Cheddar cheeses at two test temperatures. ●: vat 1, 5 °C; ■: vat 1 unpressed, 5 °C; ▲: vat 2, 5 °C; ▼: vat 1, 20 °C; ◆: vat 1 unpressed, 20 °C; ●: vat 2, 20 °C.

Évolution du module de déformabilité pendant l'affinage de trois fromages de type cheddar à deux températures de test.

but with salt added to the cheese milk instead of by brining). E_d generally increased thereafter for standard Gouda cheese. The decrease in E_d may have been caused by the increase in the spatial homogeneity of the water and the casein in the curd and/or by proteolysis. The general increase in E_d found for standard Gouda cheese after about a week or more was attributed mainly to a decrease in moisture content or MNFS (induced in this case by evaporation of water in the cheese) and also to changes in ionic strength. Later changes in E_d were not significantly influenced by proteolysis.

The trend toward an initial increase in E_d in this study was similar to that in Luyten's work (Luyten, 1988). However, there were insufficient measurements in this study over this early maturation period to determine if E_d decreased after an initial increase, as found by Luyten (1988). The large increase in E_d from one to 14 days in this study was not associated with a

decrease in cheese moisture content (table I) or MNFS. There was little evidence in this study from the effect of pressing to support the idea that curd fusion in itself caused the large initial increase in E_d . It is not clear from this work what did in fact cause this initial large increase in E_d . Further work to investigate the physical and chemical causes of the large initial increase in E_d would provide more insight into the physico-chemical changes occurring in young Cheddar cheese.

The trend toward no large increases in E_d in this study after about 28 days is not the same as that found by Luyten (1988). Increases in E_d cannot be explained by changes in moisture content or the MNFS as in Luyten's study (1988). Unlike Luyten's brine-salted Gouda left to evaporate in the air, the Cheddar cheese made in this study was sealed in polyethylene bags. Consequently, beyond sample and method variability (and one case of exudate), no definite trends in moisture content or MNFS were observed. There was no significant correlation between E_d and moisture content ($r^2_{(adj)} = 0.035$ for 5 °C tests, $r^2_{(adj)} < 0.0005$ for 20 °C tests) and slopes at both temperatures were not significant ($P > 0.05$). However, the data at 1 day were outliers; when these were removed, there was a correlation between E_d and moisture content with a significant ($P < 0.05$) negative slope ($r^2_{(adj)} = 0.678$ for 5 °C tests, $r^2_{(adj)} = 0.525$ for 20 °C tests). There was no significant correlation between E_d and MNFS ($r^2_{(adj)} < 0.05\%$, $P > 0.3$) either for all data or when the outliers at 1 day were removed. This lack of correlation may partly be a reflection of the increased variability introduced by the fat measurement used to calculate MNFS.

The increase in E_d (particularly after the initial maturation period) may have been partly caused by a slight decrease in the amount of water in the casein, induced by proteolysis. Peptide bond cleavage causes more ionic groups, which compete for water in the cheese, to be formed (Creamer and Olson, 1982). Thus there is less water available for solvation of the casein. Less plasticization of casein by water will

Table II. Melting properties during maturation of Cheddar cheeses made in November (from differential scanning calorimetry).

Propriétés de fonte déterminées par calorimétrie différentielle à balayage pendant la maturation des fromages de cheddar fabriqués en novembre.

<i>Cheese vat</i>	<i>Storage time (days)</i>	<i>Onset of melting, low temp milkfat fraction (°C)</i>	<i>Onset of melting, high temp milkfat fraction (°C)</i>	<i>Energy/mass, low temp milkfat fraction (J/g)</i>	<i>Energy/mass, high temp milkfat fraction (J/g)</i>
1	91	7.7	26.7	11.8	6.9
2	91	7.8	26.6	12.3	5.3
1	210	4.8	23.8	6.9	10.2
2	210	4.4	23.9	5.6	11.9

increase E_d . The moisture content of the cheese may not change much during proteolysis in a sealed polyethylene bag, but the water available for solvation of the casein may decrease. These ideas need to be confirmed by measurements of solvation of the casein in cheese. Although peptide cleavage uses up water, the cheese moisture content did not generally decrease with time (with the exception of vat 2 from 124 to 394 days).

The small increases in E_d from 91 to 210 days may be partly explained by an increase in crystallinity of the milkfat in the cheese. Although the casein matrix mainly determines the solid nature of cheese, the amount and modulus (stiffness) of the milkfat influences the modulus of cheese (Visser, 1991). Prentice (1987) reported that some glycerides in cheese slowly crystallized if the processing temperature was higher than the storage temperature. This requirement for crystallization was met for the current cheese processing temperature (near 30 °C) and storage temperature (13 °C).

Table II shows changes in fat melting properties from DSC on the Cheddar cheese made in November. Although these results apply to the cheese made in November and cannot be correlated with the E_d values from the February cheese, the principles probably apply to both cheeses. These results gave an indication that

from 91 to 210 days of storage there was some crystallization of milkfat. Over this period of time, the energy per mass of the low temperature milkfat fraction decreased and the energy per mass of the high temperature milkfat fraction increased by a slightly lower amount. There was therefore a larger proportion of the higher melting temperature milkfat fraction in the cheese at the longer storage time.

From 91 to 210 days of storage, the onset of melting of both the lower melting point milkfat fraction and higher melting point milkfat fraction decreased (table II). These onset of melting temperatures indicated that at a test temperature of 5 °C both milkfat fractions were nominally solid (because both milkfat fractions had an onset of melting near 5 °C or more). Similarly, at a test temperature of 20 °C only the higher melting milkfat fraction was nominally solid (because only the high temperature milkfat fraction had an onset of melting near 20 °C or more). These are guidelines only because the exact melting temperatures of the milkfat in the cheese will depend on the temperature history and rates of change of temperature used for the DSC measurement.

The value of E_d at 5 °C was much higher (by at least a factor of three) than at 20 °C because the reduction in temperature caused an increase in the fraction of milkfat in the solid phase. Anhydrous milkfat has about 60% solid fat at 5 °C

and about 20% solid fat at 20 °C (MacGibbon and McLennan, 1987). Thus the modulus of the milkfat increased with decreasing temperature and in this case caused the E_d of the cheese (which may indicate stiffness) to increase with decreasing temperature. Over the range from 14 to 26 °C, the rheological properties of Gouda cheese were changed mostly by the change in crystallinity of the milkfat (Visser, 1991).

CONCLUSIONS

The trends in ϵ_f during the maturation of Cheddar cheese made at the NZDRI were an increase from 1 to 14 or 28 days and a monotonic decrease thereafter to 209 days. Curd fusion was probably one factor related to the initial increase in ϵ_f . The decrease in ϵ_f after 14–28 days was associated with an increase in NPN which was consistent with the hypothesis that the amount of proteolysis shown by the appearance of peptides and amino acids influenced ϵ_f . The E_d increased markedly (by at least a factor of two) over the first 14–28 days, and thereafter remained constant or increased slightly. The initial increase in E_d over the first 14 days was not associated with a decrease in moisture content. Further investigations of the causes of this initial increase in E_d would give more insights to the physico-chemical changes occurring during the early maturation period of Cheddar cheese. The temperature of the cheese over the range 5 to 20 °C (corresponding to a range of temperatures at which cheese is eaten) has a small influence on ϵ_f (longness) and a large influence on E_d (stiffness). DSC indicated there was some crystallization of milkfat from 91 to 210 days of storage, and this (together with small moisture losses) may partly explain the small increase in E_d over this period of time.

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