1 **Tensile testing to quantitate the anisotropy and strain hardening of mozzarella**
2 **cheese**

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10 **ABSTRACT**

11 We explored anisotropy of mozzarella cheese because some studies reported anisotropy whereas
12 others looked for anisotropy and failed to find it. Tensile testing proved to be a good method
13 because the location and mode of failure were clear. Mozzarella cheese cut direct from the block
14 showed no significant anisotropy though confocal microscopy showed good structure alignment at a
15 microscale. Deliberately elongated mozzarella cheese showed strong anisotropy with tensile
16 strength in the elongation or fibre direction about 3.5 times that perpendicular to the fibres.
17 Temperature of elongation had a marked impact on anisotropy with maximum anisotropy after
18 elongation at 70°C. We suggest the disagreement on anisotropy in the literature is related to the
19 method of packing the mozzarella cheese into a block after the stretching stage of manufacture.
20 Tensile stress/strain curves in the fibre direction showed marked strain hardening with modulus just
21 before fracture about 2.1 times that of the initial sample, but no strain hardening was found
22 perpendicular to the fibre direction.

23 1. Introduction

24 A hot-water stretching and working step forms part of the production of mozzarella cheese. In this
25 step the proteins in the cheese curds coalesce into larger protein strands oriented in the direction of
26 stretching, resulting in a typical fibrous microstructure based on protein networks (McMahon, Fife
27 & Oberg, 1999). This fibrous structure is also visible on a macroscopic level, for instance by tearing
28 the cheese manually along its fibres. This fibrous structure suggests the likelihood of anisotropy, i.e.
29 physical and mechanical properties dependent on the direction of examination. However, the
30 literature on mozzarella cheese anisotropy is conflicting. Cervantes, Lund and Olson (1983) used
31 compression tests and reported anisotropy in some samples but not in others. Ak and Gunasekaran
32 (1997) found anisotropy using tensile testing whereas others specifically looked for anisotropy and
33 did not find it (Muliawan & Hatzikiriakos, 2007, using an extensional rig similar to tensile testing;
34 Olivares, Zorrilla & Rubiolo, 2009, using creep/recovery tests). No attempt was made in these later
35 papers to explore or discuss the reasons for the differences with earlier work.

36 Rheological properties are closely related to the functional characteristics of melted mozzarella
37 cheese such as meltability, stretchability, elasticity, oiling-off and browning. The orientation of
38 protein fibres is expected to impact in particular the melting and stretching properties of mozzarella
39 cheese (Kindstedt & Fox, 1993) suggesting a correlation between the extent of anisotropy and the
40 functional characteristics of mozzarella cheese. Olivares et al. (2009) also suggest that the extent of
41 anisotropy is related to the functionality of mozzarella cheese.

42 Anecdotal experience suggests that mozzarella cheese shows work thickening or strain
43 hardening behaviour or both. For example the stretching or working step in the manufacture process
44 makes the cheese mechanically stronger. Strain hardening is defined as the phenomenon in which
45 the stress required to deform a material increases more than proportionally to the strain – at constant
46 strain rate and increasing strain (Kokelaar, van Vliet & Prins, 1996; Van Vliet, 2008). Work
47 thickening is a broader term and we use it for an increase in mechanical strength when a material is
48 worked. To the best of our knowledge no work thickening or strain hardening behaviour has been

49 reported for mozzarella cheese or for any other cheese. Strain hardening has, however, been
50 reported for fine stranded whey protein isolate gels (Lowe, Foegeding & Daubert, 2003), for weak
51 β -lactoglobulin gels (Pouzot, Nicolai, Benyahia & Durand, 2006) and for gels formed by acidifying
52 transglutaminase cross-linked casein (Rohm, Ullrich, Schmidt, Lobner & Jaros, 2114). For some
53 texturizing proteins, such as gluten in wheat dough, strain hardening is well explored. In wheat
54 dough strain hardening plays an important role in the gas holding capacity, the gas cell stability and
55 the extension behaviour during fermentation and baking. The strain hardening behaviour of wheat
56 dough is also related to breadmaking performance (Kokelaar et al., 1996; Van Vliet, Janssen,
57 Bloksma & Walstra, 1992). Mozzarella cheese has some similarities in mechanical behaviour to
58 bread dough suggesting that it could exhibit strain hardening.

59 We began our study with three hypotheses that if true might help to explain the conflict in the
60 literature: 1. Extent of anisotropy depends on the degree of alignment of the fibrous cheese
61 structure; 2. Melting the cheese would remove alignment of protein fibres and so remove
62 anisotropy; 3. Holding the cheese at an elevated temperature (but below melting temperature) would
63 reduce alignment and decrease anisotropy. The studies referred to above all evaluated mechanical
64 properties of mozzarella cheese slices cut directly from the block. In addition to this methodology
65 we decided to use deliberate elongation of the mozzarella cheese to induce fibre formation in the
66 direction of elongation. If hypothesis 1 is true this fibre formation should lead to anisotropy. We
67 considered various methods of elongation and decided on manual rolling because of its simplicity
68 and because Muliawan and Hatzikiriakos (2008) had used rolling. Tensile tests were chosen for
69 three reasons – they are easier to interpret because fracture location is clear, there are no
70 complicating factors such as friction or change in sample orientation under load, and analysis of
71 tensile stress-strain curves should indicate strain hardening if it is present. Tensile fracture in the
72 cheese fibre direction is assumed to fracture the fibres themselves. Tensile fracture perpendicular to
73 the protein fibre direction is more likely to cause fracture between the protein fibres.

74 2. Materials and methods

75 2.1. Materials

76 Mozzarella cheese directly from a Fonterra cheese plant in New Zealand (named “factory cheese”)
77 was obtained as two 10 kg blocks frozen at -20 °C. The cheese had been frozen at the age where its
78 functionality was optimal for application as pizza cheese. The 10 kg blocks were thawed for 3 d at
79 4 °C, cut into smaller blocks of ~ 300 g, vacuum-packed into plastic bags and stored at -30 °C.
80 These blocks were tempered to 4 °C for 2 to 7 d before use. Perfect Italiano Semi Soft mozzarella
81 cheese (Fonterra Brands Pty. Ltd., Melbourne, Australia) (named “supermarket cheese”), string
82 cheese (Bega Original Stringers®, Bega Cheese Ltd., Bega, Australia) and butter (Fonterra Brands,
83 Auckland, New Zealand) were obtained from a local supermarket and stored at 4 °C. The
84 compositions of the cheese samples (g/100g) were determined by Fonterra Research and
85 Development Centre – factory cheese, 48.9 moisture, 22.1 fat, 24.5 protein, 1.26 salt and 3.06 ash;
86 supermarket cheese, 47.8 moisture, 22.6 fat, 24.8 protein, 1.57 salt and 3.44 ash; string cheese, 46.5
87 moisture, 21.8 fat, 27.4 protein, 1.53 salt and 3.20 ash.

88 2.2. Sample preparation for tensile testing

89 2.2.1. Elongated factory and supermarket cheese - standard procedure

90 First ~ 300 g cheese were heated to 60 °C using a water bath and a leak proof stainless steel
91 container. Excess liquid (always < 2 g) was then decanted quickly. The melted cheese was placed
92 near one end of a large aluminium metal plate (750 mm x 250 mm x 20 mm) with aluminium strips
93 (600 mm x 40 mm x 3 mm) fixed on both sides as rails (to ensure minimum thickness of 3 mm) and
94 rolled manually towards the other end with a granite rolling pin. The thickness of the elongated
95 cheese mass was uniform and ~ 3 - 4 mm. The metal plate, strips and rolling pin had been stored at
96 4°C for at least 14 h. The cheese was rolled in one direction for a total elongation time of 120 s at a
97 frequency of 10 rolls min⁻¹. One roll means steady movement of the roller from one end of the
98 cheese sheet to the other; each roll lasted for 6 s. The rationale for elongating the cheese on a

99 cooled, highly heat conductive surface with large thermal mass was to cool the cheese quickly in
100 order to lock in any structure generated by elongation. The elongated cheese was covered with
101 plastic wrap, stored for 2 h at 4 °C and cut with a scalpel into tensile samples using a template
102 (Fig. 1) following the pattern shown in Fig. 2. This resulted in 16 longitudinal samples and 12
103 perpendicular samples per trial. The samples were individually wrapped in plastic and kept at
104 21 °C for at least 1 h before tensile testing. Variations from this standard procedure were made to
105 explore the effects of experimental variables as explained in the results section.

106 2.2.2. *String cheese and original factory and supermarket cheese*

107 Slices 3-4 mm thick were cut longitudinally from the string cheese sticks. Samples were cut
108 from these slices in longitudinal and perpendicular orientation to the stick axis. The string cheese
109 sticks were only ~ 15 mm diameter but the same template was still used for longitudinal samples.
110 The perpendicular string cheese samples were short and were cut into a dumbbell shape without a
111 template. A 300 g factory cheese block was cut into slices ~ 3-4 mm thick. One of the slices was
112 used to define the preferred orientation of the cheese fibres by tearing along these fibres. In this way
113 the orientation of the template for cutting was determined. Two tensile samples were cut from each
114 slice, one in each orientation. The procedure for obtaining supermarket cheese samples was exactly
115 as for factory cheese. Samples were kept at 21 °C for at least 1 h before tensile testing.

116 2.3. *Tensile testing*

117 Tensile tests were carried out with a TA.XTplus Texture Analyser (Stable Micro Systems Ltd.,
118 Godalming, UK) in a laboratory controlled at 21 °C. Crosshead speed was 2 mm s⁻¹ and trigger
119 force was 0.05 N. Serrated jaws were used and were tightened enough to prevent slippage. The
120 initial dimensions of the smallest cross-section of each sample were measured with vernier calipers
121 accurate to 0.01 mm. The initial gap between the tensile jaws was 23 mm and the final gap 63 mm
122 (except for the string cheese samples with perpendicular orientation). As expected the cheese
123 samples all fractured in the narrow area of the dumbbell where stress would be greatest.

124 2.4. Data analysis and image acquisition

125 Force-displacement data from tensile tests were converted into a true stress (σ)-Hencky strain
126 (ε) format using the following equations:

$$127 \quad \sigma = \frac{F(t)}{A(t)} \quad (1)$$

$$128 \quad \varepsilon = \ln \frac{L(t)}{L_o} \quad (2)$$

129 where $F(t)$ was force, $A(t)$ minimum cross sectional area, and $L(t)$ the length of the narrow mid part
130 of the sample all at time t and L_o was the initial length of the narrow mid part of the sample
131 (20 mm). $A(t)$ was estimated as follows:

$$132 \quad A(t) = \frac{V}{L(t)} = \frac{V}{L_o + \Delta L} = \frac{L_o W_o T_o}{L_o + \Delta L} \quad (3)$$

133 where V was the volume of the narrow mid part of the cheese sample, calculated from the initial
134 width and thickness W_o and T_o of the narrowest part of the cheese samples and L_o . ΔL is the
135 displacement recorded. Charalambides, Williams and Chakrabarti (1995) similarly assumed
136 constant volume during cheddar cheese testing and stated that this assumption was fairly accurate
137 for cheese. Rohm, Jaros and deHaan (1997) experimentally demonstrated volume constancy during
138 compression testing of Gouda cheese. The maximum modulus was the maximum slope before
139 fracture in the σ - ε diagram. The extent of anisotropy R was calculated as
140 $\sigma(\text{longitudinal})/\sigma(\text{perpendicular})$ and similarly for other parameters.

141 To check the assumptions made in calculation of $A(t)$ (equation 3) 3 different tensile tests were
142 filmed. A camera was fixed on a tripod with the front of the lens parallel to the front side of the
143 cheese. A mirror at a 45° angle and a small ruler were placed next to the sample. For each of the
144 three tests images were analysed at 3 times – beginning, mid-test and immediately before fracture.
145 Width and thickness were estimated for all images using the freeware image analysis tool
146 ImageJ 1.47t (<http://rsbweb.nih.gov>).

147 2.5. Confocal scanning laser microscopy (CSLM)

148 Confocal microscopy was used to determine the microstructure of cheese samples after various
149 treatments including fracture. Cheese samples were cut and frozen (-20 °C) before being sectioned
150 into 50 µm slices on a microtome. Slices were immediately stained with 0.4% Nile red and 0.2%
151 fast green (made in citifluor to minimise photobleaching) and covered with a coverslip. The
152 sectioned samples were then stored at 4 °C for a minimum of 24 h before imaging. Images were
153 taken using a confocal microscope (Leica DM6000B, Heidelberg, Germany) with excitation
154 wavelengths of 488 nm and 633 nm.

155 2.6. Statistical analysis

156 Significant differences ($P < 0.05$) in the results were analysed by SPSS 12.0 software using
157 single factor ANOVA and the Duncan post hoc test to compare means. All experiments with
158 elongated supermarket and factory cheese were performed at least twice and sub-sampled, resulting
159 in $n \geq 32$ longitudinal replicates and $n \geq 24$ perpendicular replicates, unless otherwise stated. For
160 string cheese and original factory cheese at least 6 slices were cut from the cheese stick/block
161 resulting in $n \geq 6$ longitudinal and perpendicular samples.

162 3. Results

163 3.1. Tensile test basics

164 Tensile force versus displacement curves for both longitudinal and perpendicular samples
165 decreased in slope with stretching as the area of the sample decreased. $\sigma - \epsilon$ curves (Fig. 3) showed
166 a slope (tensile modulus) that slightly decreased with strain for perpendicular samples. For
167 longitudinal samples the maximum modulus just before fracture was about 2.5 times the initial
168 modulus. Longitudinal samples strain hardened during the tensile test.

169 σ values calculated using $A(t)$ from image acquisition were in reasonable agreement with the
170 corresponding σ values calculated from equations 1 and 3. Image acquisition plus direct visual

171 observation of fracture indicated that longitudinal samples usually fractured at roughly a 45° angle
172 to the stretching direction. Mohr's circle analysis for pure tension indicates shear failure. In most
173 cases the fractured surface was rather stringy and in many cases it was shaped randomly. In
174 contrast, perpendicular samples fractured mainly at a 90° angle to the stretching direction. Mohr's
175 circle analysis for pure tension indicates that this means tensile failure. Ak and Gunasekaran (1997)
176 similarly noted 45° fracture angles for longitudinal samples and 90° fracture angles for
177 perpendicular samples during tensile testing of mozzarella cheese.

178 3.2. *Reproducibility of the overall method*

179 Four trials were carried out at standard conditions using elongated factory cheese to check
180 reproducibility (Table 1). The standard deviations were rather high. One reason for this is variability
181 in manual elongation, particularly variation in the first roll to produce a cheese sheet. Another
182 reason is the inherent variability in tensile fracture, because failure is related to the random
183 occurrence of structural weaknesses or imperfections where cracks may initiate and propagate.
184 Manski, van der Zalm, van der Goot and Boom (2008) and Grabowska, van der Goot and Boom
185 (2012) produced fibrous materials from dense calcium caseinate-fat dispersions cross-linked by
186 transglutaminase and similarly reported variability in their tensile measurements and attributed this
187 to the fibrous nature of the samples with some samples breaking all at once and others in multiple
188 stages. Fracture stress (σ_f) and fracture strain (ϵ_f) showed no significant differences between the
189 four trials, but some differences in modulus were observed at a 5% significance level. These
190 differences were not significant at a 10% level. In spite of the variability in the method significant
191 differences were found between longitudinal and perpendicular samples and between sample
192 treatments.

193 3.3. *Comparison of cheese types*

194 Table 2 shows tensile fracture behaviour for the five cheese types. String cheese had the highest
195 extent of anisotropy with an R value of 6.0 for σ_f and 5.7 for ϵ_f . Original factory cheese and original

196 supermarket cheese showed no significant anisotropy. Elongated supermarket cheese indicated
197 significant anisotropy for ε_f but not for σ_f or maximum modulus. Elongated factory cheese showed
198 pronounced anisotropic characteristics with large differences between longitudinal and
199 perpendicular samples. All subsequent experiments were therefore carried out with elongated
200 factory cheese.

201 3.4. Effect of elongation conditions

202 Fig. 4 shows σ_f versus sample location along the rolled cheese sheet. σ_f for longitudinal samples
203 showed a maximum at 140 mm. σ_f at 140 mm was significantly different from σ_f at 45 mm and 330
204 mm but not from σ_f at 235 mm. The higher variability towards the ends of the rolled sheets
205 suggested less uniformity in sample preparation. For the remaining experiments only the data for
206 140 mm and 235 mm for longitudinal samples ($n = 8$ per trial) and 90, 185 and 280 mm for
207 perpendicular samples ($n = 9$ per trial) were used. This removed the end locations that had higher
208 standard deviations and gave enough replicates for good statistical significance.

209 Anisotropic characteristics of elongated factory cheese were investigated for 5 different
210 elongation temperatures (Fig. 5, Table 3). Elongation temperature was the cheese equilibration
211 temperature before placing on the 4°C plate and elongating. For longitudinal samples σ_f increased
212 with elongation temperature to a maximum at 70 °C. Further increase of elongation temperature to
213 80°C resulted in a decrease of σ_f . There was no statistical difference between the means for σ_f at 40,
214 50 and 80°C. σ_f at 60°C was significantly higher than these but at the same time significantly lower
215 than σ_f at 70°C. No significant differences were found between σ_f values for perpendicular samples.

216 For longitudinal samples σ_f decreased significantly with longer elongation times (Table 4).
217 However, perpendicular samples showed no significant differences for σ_f with elongation time. It
218 appeared that the alignment of cheese fibres depended mainly on the first roll, which produced a flat
219 cheese sheet. Further rolls generated only small changes in the length and thickness of the sheet.
220 Consequently, the orientation of fibres and thus the degree of anisotropy are likely to be mainly

221 influenced by the procedure when cheese is converted from a molten mass into a flat sheet. This
222 largely took place during the first roll.

223 An elongation frequency of 3 min⁻¹ produced a significantly lower σ_f and modulus than 10 min⁻¹
224 for longitudinal samples (Table 5). An elongation frequency of 10 min⁻¹ is close to the practical
225 limit for manual rolling. The impact of elongation frequency might also be explained by the first
226 roll. A faster first roll produces a significantly higher σ_f . If the molten cheese was rolled too slowly
227 a thick and poorly elongated cheese sheet resulted from the first roll. With further rolls the sheet did
228 not change much as the deformability of the cheese decreased quickly with temperature reduction.
229 Cracks would sometimes appear in the cheese sheet when trying to adjust after a slow first roll. It
230 appears that there is an interplay between the rate of deformation and the rate of solidification. It is
231 important to complete the first roll before the cheese has solidified too much.

232 3.5. *Effect of plate and storage temperature*

233 The metal plate and granite rolling pin were preconditioned to the experimental temperature for at
234 least 14 h before rolling, and the elongated cheese sheet was then stored at the same temperature for
235 2 h. To minimize moisture loss during storage at 21°C and 37°C the elongated cheese was covered
236 with plastic film and also placed in a sealed snaplock plastic bag. σ_f of both longitudinal and
237 perpendicular samples decreased with increasing plate and storage temperature, although the
238 differences between σ_f at 21°C and 37°C were not statistically significant (Table 6). Hypothesis 3
239 suggested that anisotropy would decrease on holding at an elevated temperature. However,
240 although σ_f reduced with storage temperature, longitudinal and perpendicular σ_f decreased by
241 different amounts and anisotropy increased with increasing storage temperature. This experiment
242 has not confirmed hypothesis 3.

243 3.6. *Effect of remelting elongated cheese*

244 This experiment was designed to test hypothesis 2. The standard procedure was followed, but after
245 storing the elongated cheese at 4 °C for 2 h the elongated sheet was wrapped in plastic film, placed

in a sealed snaplock bag to reduce moisture loss and stored at 60°C in an oven for 2 h. The remelted sheet was then stored at 4°C for another 2 h before sample cutting and tensile testing. While remelting caused a large decrease in R values to 1.2 for σ_f and modulus and 1.1 for ε_f , significant differences in means were observed between longitudinal and perpendicular samples for σ_f , ε_f and modulus (Table 7). This shows that anisotropy is greatly reduced by remelting at 60°C, but not completely removed. Longitudinal σ_f was reduced by around 50%, but perpendicular σ_f increased by around 30% (Fig. 4). An impact of moisture loss on the results is possible, but would not be directionally selective. Some condensation build up was observed inside the snaplock bag and this moisture had not completely reabsorbed after 2 h further storage at 4°C. The moisture contents of the cheese before and after the 2 h storage at 60°C were not significantly different. After 2 h storage at 60°C the sheet length in the elongation direction had reduced by 15%. This is an indicator that locked in strain was being relaxed. The longitudinal samples after remelting showed very little strain hardening.

3.7. Confocal scanning laser microscopy

Confocal micrographs of the original factory cheese showed clear structural anisotropy at this scale with longitudinal samples showing aligned fat phase between the protein strands (Fig. 6a) and perpendicular samples showing little alignment as we are looking end on at the aligned structure (Fig. 6b). The melted and elongated cheese similarly showed alignment for the longitudinal sample (Fig. 6c) but no alignment for the perpendicular sample (Fig. 6d). The fat phase in the elongated cheese showed more coalescence and less individual fat globules than the original factory cheese. The melted, elongated and remelted cheese showed no alignment for either the longitudinal (Fig. 6e) or perpendicular (Fig. 6f) samples. Confocal micrographs that show the fracture surface after tensile testing (Fig. 6g, h) indicate a high concentration of fat near or at the fracture surface suggesting that weak fat planes in the cheese may be the location of fracture initiation.

3.8. Tensile testing of butter

Tensile testing of butter was attempted to determine whether the milkfat component of mozzarella cheese contributes any tensile strength. The same method of sample preparation was used as for original factory cheese but without choosing direction of cutting. Sample cutting and tensile testing proved to be impossible at 21°C because the butter was too soft. The butter was therefore stored at 4°C before cutting. The dumbbell samples were also stored at 4°C for at least 2 h before tensile testing. They were then tested as quickly as possible in the 21°C laboratory. Of the 8 samples prepared, 5 samples broke before testing or slipped out of the tensile grips. The remaining 3 samples had σ_f of 5.73 ± 1.49 kPa, ε_f of 0.082 ± 0.025 and modulus of 49.6 ± 15.1 kPa. The samples were not isothermal during tensile testing with measured temperatures of 14°C to 20°C. Nevertheless these results showed that the tensile strength of milkfat at 21°C is very small.

4. Discussion

As milkfat has very low tensile strength at 21°C, we conclude that the tensile properties of mozzarella cheese are largely due to the strength of the protein network. Tensile testing is therefore a good method to determine protein network strength and the effect of any processing changes. String cheese exhibited the highest degree of anisotropy with an R value for σ_f of 6.0. String cheese is produced by extrusion into the shape of sticks (Chen et al., 2009) and shows a very fibrous character at a macroscopic level. The highly anisotropic character is therefore not surprising. Manski et al. (2008) reported R values for σ_f up to 14.2 for their fibrous calcium caseinate materials formed by simultaneous shear and transglutaminase action showing that casein molecules are capable of producing highly anisotropic structures. The elongated supermarket cheese showed statistically significant anisotropy only for ε_f whereas elongated factory cheese was strongly anisotropic for all fracture properties. This might be because the supermarket cheese was described as semi-soft, indicating a high level of proteolysis (Chen et al., 2009). The effect of proteolysis on mozzarella functionality is well reported (e.g. Kindstedt & Fox, 1993). It is likely that the extent of

295 anisotropy depends on the degree of proteolysis and therefore is affected by the ripening time of
296 mozzarella cheese.

297 The variation of σ_f with distance along the plate (Fig. 4) suggests that anisotropy increased with
298 the force applied and the amount of flow induced while elongating. During the first roll at lower
299 distances the amount of cheese in front of the roller was higher, requiring higher forces and more
300 flow induction. At higher distances the thickness of the cheese sheet decreased continuously so that
301 the required force and amount of flow decreased. Perhaps the higher rolling force and higher flow
302 near the beginning of the plate resulted in better alignment of the samples at these distances.

303 Elongation temperature had a bigger impact on the degree of anisotropy than any other
304 parameter. It is clear that elongation builds up or strengthens a network structure in the cheese.
305 Presumably this strengthening is caused by increasing protein-protein interactions. Bryant and
306 McClements (1998) note that hydrophobic protein-protein interactions increase in strength as
307 temperature rises up to a maximum at about 60 to 70 °C, above which hydrophobic interactions
308 begin to reduce again as the temperature is further increased. Hence, the increase in σ_f from 40 to
309 70 °C and the decrease in σ_f to 80 °C are probably linked to changes in hydrophobic protein-protein
310 interactions. An alternative explanation for the temperature effect is changes to the milk mineral
311 system at high temperatures and various possibilities are discussed by Udyarajan, Horne and Lucey
312 (2007). Calcium has higher affinity for α_{s1} -casein as the temperature increases. In addition calcium
313 and phosphate in the serum phase of the cheese may form new insoluble calcium phosphate at
314 higher temperature that could interact with the caseins. Commercially mozzarella cheese is usually
315 stretched in hot water circulating at a temperature of approximately 72 °C (Chen et al., 2009), near
316 the temperature where we found the greatest effect of elongation on σ_f .

317 There are several indications of both strain hardening and work thickening of mozzarella
318 cheese. The shapes of the longitudinal σ - ϵ curves (Fig 3) show a more than doubling of tensile
319 modulus between the start of the test and fracture, i.e. significant strain hardening. Perpendicular σ -
320 ϵ curves did not show strain hardening. Similar behaviour was reported by Manski, van der Goot

321 and Boom (2007) for their tensile testing of fibrous materials produced by shearing fat-free calcium
322 caseinate dispersions. Strain hardening was found in the fibre direction but not perpendicular to the
323 fibre direction. Three trials under standard conditions were analysed to quantitate strain hardening.
324 The ratio of maximum tensile modulus to initial modulus was 2.12 ± 0.38 ($n=24$). Curve fitting
325 showed two distinct regions on the σ - ϵ curves. A linear model accurately fitted σ - ϵ data up to a
326 strain of about 0.4. From 0.4 to a point near fracture, σ - ϵ data was best modelled by an exponential
327 curve. Clearly all the strain hardening is in the exponential part of the curve. Van Vliet (2008) notes
328 that for bread dough there is often an exponential relationship between σ and ϵ , though for bread
329 dough this fits the whole σ - ϵ curve rather than just the portion at high strain.

330 The reason for two distinct regions on the longitudinal σ - ϵ curve is not clear. One possible
331 explanation is that in the linear region, curves or bends in the fibre network are merely straightened.
332 The concept of the straightening of curved strands was used by Lakemond and van Vliet (2008) to
333 explain the fracture behaviour of acid skim milk gels. At higher strains where all the strands are
334 now straight, the protein fibres must either stretch or move past one another, increasing the
335 interactions between fibres. This may cause an increase in the strength of the protein network. The
336 protein fibres in the longitudinal orientation also become progressively closer together because of
337 the reducing cross-sectional area thus increasing interactions. In perpendicular samples, fibres
338 would be pulled further apart, resulting in no strain hardening. Many biopolymers have been shown
339 to strain harden both as single molecules, e.g. collagen, and also as network structures resulting in a
340 significant body of biophysics literature on the topic, e.g. pectin (Vincent, Mansel, Kramer, Kroy &
341 Williams, 2013), rubber (Horgan & Saccomandi, 2006). At the molecular level the strain hardening
342 arises from limits to chain extensibility and to the “stickiness” of adjacent polymer chains. There
343 are many reports of strain hardening of flour dough (e.g. Kokelaar et al., 1995; van Vliet et al.,
344 1992; van Vliet, 2008).

345 Work thickening is also evident. The original factory cheese had σ_f of 36 kPa parallel to the
346 fibres and 33 kPa perpendicular to the fibres (Table 2). After elongation the longitudinal σ_f had

347 increased by 5.7 times to 204 kPa and the perpendicular σ_f had increased by 2.1 times to 68 kPa.
348 Presumably the elongation operation at 60°C has increased the strength of the casein network, i.e.
349 increased protein-protein interactions. This stronger protein structure is aligned because of the
350 elongation. σ_f of the remelted perpendicular samples is 84 kPa, about 30% higher than σ_f before
351 remelting (Table 7), whereas σ_f of the remelted longitudinal samples is 105 kPa, about 50% lower
352 than the 223 kPa σ_f before remelting (Table 7). One possible explanation is that the increased
353 protein-protein interactions formed during elongation at 60°C are not destroyed by remelting, but
354 the alignment is relaxed. Some of the increased protein-protein interactions thus increase σ_f in the
355 remelted perpendicular samples. During mechanical flour dough development there are similarly
356 significant increases in mechanical strength, or work thickening (e.g. Zheng, Morgenstern,
357 Campanella & Larsen, 2000).

358 Do these results help to explain the disagreement in the literature about anisotropy of mozzarella
359 cheese? No significant anisotropy was found for original factory cheese when slices were cut from
360 the block, but when this cheese was elongated strong anisotropy was observed (Table 2). Today, the
361 final stages of continuous mozzarella cheese manufacture generally involve a stretching machine
362 followed by a moulding step to form a block (Chen et al., 2009). We expect that the original cheese
363 from stretching would be highly aligned and therefore anisotropic as it is transferred through a pipe
364 to moulding. However, during moulding into blocks it is expected that this aligned structure will
365 pack randomly with different orientations in different parts of the block. An aligned microstructure
366 is retained in the confocal micrographs (Fig. 6a) but when a slice is cut and a large enough sample
367 taken for tensile testing isotropic behaviour is observed. The length scale of anisotropy in the
368 formed cheese block will vary between packing operations and might be expected to depend on the
369 diameter of the cheese pipe feeding the block, any motion of the pipe around the space of the block,
370 the presence of vibration to aid packing (eliminate air) and the packing rate. All previous studies
371 that tested anisotropy of mozzarella cheese used samples cut from original cheese blocks. In the
372 recent papers no anisotropy was observed as for our results with original factory cheese (Muliawan

373 & Hatzikiriakos, 2007; Olivares et al., 2009). However, in older papers anisotropy was clearly
374 demonstrated, e.g. Ak and Gunasekaran (1997). One possibility is that their cheese samples were
375 from smaller scale batch operations where large masses of cheese were placed into the moulds at
376 once leading to anisotropy on a macroscale. Part of our thinking was that if the cheese was packed
377 hot then relaxation of the structure could lead to the disappearance of anisotropy. However, the
378 confocal micrographs show clear alignment at the microscale so that is not the correct explanation.

379 **4. Conclusions**

380 Original factory mozzarella cheese showed no anisotropy on tensile testing but confocal
381 micrographs indicated clear alignment in the structure at the microscale. The structure produced by
382 melting and elongating the factory cheese was shown to be highly anisotropic both by tensile testing
383 and by confocal microscopy. Elongation temperature had a significant impact on the extent of
384 anisotropy. Remelting the mozzarella cheese after elongation gave a non-aligned structure that
385 showed very little anisotropy. We suggest the disagreement on anisotropy in the literature is related
386 to the method of packing the cheese into a block after the stretching stage of manufacture. During
387 tensile testing elongated factory cheese showed strain hardening behaviour in the longitudinal
388 direction but not in the perpendicular direction. Tensile testing was a good method to demonstrate
389 and quantitate anisotropy and strain hardening in mozzarella cheese.

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396 **References**

- 397 Ak, M.M., & Gunasekaran, S. (1997). Anisotropy in tensile properties of mozzarella cheese.
398 *Journal of Food Science*, 62, 1031-1033.
- 399 Bryant, C.M., & McClements, D.J. (1998). Molecular basis of protein functionality with special
400 consideration of cold-set gels derived from heat-denatured whey. *Trends in Food Science and*
401 *Technology*, 9, 143-151.
- 402 Cervantes, M.A., Lund, D.B., & Olson, N.F. (1983). Effects of salt concentration and freezing on
403 Mozzarella cheese texture. *Journal of Dairy Science*, 66, 204-213.
- 404 Charalambides, M.N., Williams, J.G. & Chakrabarti, S. (1995). A study of the influence of ageing
405 on the mechanical properties of cheddar cheese. *Journal of Materials Science*, 30, 3959-3967.
- 406 Chen, C., Wolle, D., & Sommer, D. (2009). Mozzarella. In S. Clark & F.W. Bodyfelt (Eds.), *The*
407 *sensory evaluation of dairy products* (pp. 459-487). New York, NY, USA:Springer.
- 408 Grabowska, K.J., van der Goot, A.J. & Boom, R.M. (2012). Salt-modulated structure formation in a
409 dense calcium caseinate system. *Food Hydrocolloids*, 29, 42-47.
- 410 Horgan, C.O. & Saccomandi, G. (2006). Phenomenological hyperelastic strain-hardening
411 constitutive models for rubber. *Rubber chemistry and technology*, 79, 152-169.
- 412 Kindstedt, P.S. & Fox, P.F. (1993). Effect of manufacturing factors, composition, and proteolysis
413 on the functional characteristics of mozzarella cheese. *Critical Reviews in Food Science and*
414 *Nutrition*, 33, 167-187.
- 415 Kokelaar, J.J., van Vliet, T. & Prins, A. (1996). Strain hardening properties and extensibility of
416 flour and gluten doughs in relation to breadmaking performance. *Journal of Cereal Science*, 24,
417 199-214.
- 418 Lakemond, C.M.M. & van Vliet, T. (2008). Rheological properties of acid skim milk gels as
419 affected by the spatial distribution of the structural elements and the interaction forces between
420 them. *International Dairy Journal*, 18, 585-593.

421 Lowe, L.L., Foegeding, A.E. & Daubert, C.R. (2003). Rheological properties of fine-stranded whey
422 protein isolate gels. *Food Hydrocolloids*, 17, 515-522.

423 Manski, J.M., van der Goot, A.J. & Boom, R.M. (2007). Formation of fibrous materials from dense
424 calcium caseinate dispersions. *Biomacromolecules*, 8, 1271-1279.

425 Manski, J.M., van der Zalm, E.E.J., van der Goot, A.J. & Boom, R.M. (2008). Influence of process
426 parameters on formation of fibrous materials from dense calcium caseinate dispersions and fat.
427 *Food Hydrocolloids*, 22, 587-600.

428 McMahon, D.J., Fife, R.L. & Oberg, C.J. (1999). Water partitioning in Mozzarella cheese and its
429 relationship to cheese meltability. *Journal of Dairy Science*, 82, 1361-1369.

430 Muliawan, E.B., & Hatzikiriakos, S.G. (2007). Rheology of mozzarella cheese. *International Dairy*
431 *Journal*, 17, 1063-1072.

432 Muliawan, E.B., & Hatzikiriakos, S.G. (2008). Rheology of mozzarella cheese: extrusion and
433 rolling. *International Dairy Journal*, 18, 615-623.

434 Olivares, M.L., Zorrilla, S.E. & Rubiolo, A.C. (2009). Rheological properties of mozzarella cheese
435 determined by creep/recovery tests: effect of sampling direction, test temperature and ripening time.
436 *Journal of Texture Studies*, 40, 300-318.

437 Pouzot, M., Nicolai, T., Benyahia, L. & Durand, D. (2006). Strain hardening and fracture of heat-set
438 fractal globular protein gels. *Journal of Colloid and Interface Science*, 293, 376-383.

439 Rohm, H., Jaros, D. & deHaan, M. (1997). A video-based method for determination of average
440 stress-strain relations in uniaxial compression of selected foods. *Journal of Texture Studies*, 28,
441 245-255.

442 Rohm, H., Ullrich, F., Schmidt, C., Lobner, J. & Jaros, D. (2014). Gelation of cross-linked casein
443 under small and large shear strain. *Journal of Texture Studies*, 45, 130-137.

444 Udyarajan, C.T., Horne, D.S. & Lucey, J.A. (2007). Use of time-temperature superposition to study
445 the rheological properties of cheese during heating and cooling. *International Journal of Food*
446 *Science and Technology*, 42, 686-698.

447 Van Vliet, T. (2008). Strain hardening as an indicator of bread-making performance: A review with
448 discussion. *Journal of Cereal Science*, 48, 1-9.

449 Van Vliet, T., Janssen, A.M., Bloksma, A.H. & Walstra, P. (1992). Strain hardening of dough as a
450 requirement for gas retention. *Journal of Texture Studies*, 23, 439-460.

451 Vincent, R.R.R., Mansel, B.W., Kramer, A., Kroy, K. & Williams, M.A.K. (2013). Micro-
452 rheological behaviour and nonlinear rheology of networks assembled from polysaccharides from
453 the plant cell wall. *New Journal of Physics*, 15, Article number 035002.

454 Zheng, H., Morgenstern, M.P., Campanella, O.H. & Larsen, N.G. (2000). Rheological properties of
455 dough during mechanical dough development. *Journal of Cereal Science*, 32, 293-306.

456

457 Figure Legends

458 **Fig. 1.** Dumbbell-shaped template used for cutting cheese samples. Dimensions are in mm.

459 **Fig.2.** Sample cutting in longitudinal and perpendicular orientations.

460 **Fig. 3.** True stress versus Hencky strain for tensile testing of one longitudinal (—) and one
461 perpendicular (---) sample of factory mozzarella cheese prepared under standard conditions.

462 **Fig. 4.** True fracture stress versus distance along the rolled sheet for factory
463 mozzarella cheese prepared under standard conditions in the longitudinal (— $\rightarrow$) and perpendicular (— $\leftarrow$) orientations, and where standard conditions
464 were altered by holding the elongated cheese at 60 °C for 2 h before cooling
465 to 4 °C for 2 h then cutting dumbbell samples in longitudinal ($\times$) and
466 perpendicular orientations ($\blacksquare$). Error bars represent one standard deviation
467 from the mean.

469 **Fig. 5.** True fracture stress as a function of elongation temperature in the longitudinal (— $\rightarrow$) and
470 perpendicular (— $\leftarrow$) orientations and the corresponding ratio R (— $\rightarrow$). Error bars represent one
471 standard deviation from the mean.

472 **Fig. 6.** CSLM images of factory mozzarella cheese samples. Original cheese in the longitudinal (a)
473 and perpendicular (b) direction; elongated cheese in the longitudinal (c) and perpendicular (d)
474 direction; elongated and remelted cheese in the longitudinal (e) and perpendicular (f) direction; and
475 fractured edges of elongated cheese in the longitudinal (g) and perpendicular (h) direction.
476 Longitudinal samples were always viewed across the fibre direction whereas perpendicular samples
477 were viewed end on to the fibre direction. Red – fat; green – protein.

Table 1

Reproducibility of the method – 4 independent experimental trials under standard conditions

Experimental trial	Fracture stress (kPa)			Fracture strain (-)			Maximum modulus (kPa)		
	Longitudinal	Perpendicular	<i>R</i>	Longitudinal	Perpendicular	<i>R</i>	Longitudinal	Perpendicular	<i>R</i>
1	197 ± 64 ^A	58 ± 21 ^B	3.4	0.78 ± 0.11 ^A	0.38 ± 0.08 ^B	2.1	337 ± 114 ^A	146 ± 27 ^C	2.3
2	215 ± 31 ^A	72 ± 18 ^B	3.0	0.75 ± 0.05 ^A	0.41 ± 0.08 ^B	1.8	418 ± 72 ^B	170 ± 21 ^C	2.5
3	209 ± 39 ^A	71 ± 17 ^B	2.9	0.74 ± 0.08 ^A	0.40 ± 0.08 ^B	1.9	393 ± 80 ^{A,B}	170 ± 19 ^C	2.3
4	199 ± 54 ^A	63 ± 19 ^B	3.2	0.81 ± 0.09 ^A	0.45 ± 0.11 ^B	1.8	340 ± 91 ^A	143 ± 27 ^C	2.4

Values are means with standard deviations from n = 16 longitudinal samples and n = 12 perpendicular samples for each trial. Means for the same parameter, e.g. fracture stress, with different superscript letters are significantly different ($P < 0.05$).

Table 2

Effect of cheese type and cheese treatment

Cheese type	Fracture stress (kPa)			Fracture strain (-)			Maximum modulus (kPa)		
	Longitudinal	Perpendicular	<i>R</i>	Longitudinal	Perpendicular	<i>R</i>	Longitudinal	Perpendicular	<i>R</i>
String cheese	204 ± 21 ^A	34 ± 6 ^{B,C}	6.0	0.65 ± 0.04 ^A	0.11 ± 0.01 ^D	5.7	450 ± 36 ^A	387 ± 55 ^C	1.2
Orig. supermarket cheese	34 ± 8 ^{B,C}	24 ± 8 ^B	1.4	0.39 ± 0.04 ^B	0.34 ± 0.15 ^B	1.0	76 ± 17 ^B	71 ± 9 ^B	1.1
Elong. supermarket cheese	60 ± 12 ^{C,D}	40 ± 8 ^{B,C}	1.5	0.76 ± 0.07 ^C	0.60 ± 0.06 ^A	1.3	88 ± 21 ^B	65 ± 13 ^B	1.4
Orig. factory cheese	36 ± 11 ^{B,C}	33 ± 12 ^{B,C}	1.1	0.34 ± 0.12 ^B	0.33 ± 0.08 ^B	1.0	101 ± 19 ^B	97 ± 11 ^B	1.0
Elong. factory cheese	204 ± 47 ^A	68 ± 18 ^D	3.0	0.76 ± 0.09 ^C	0.41 ± 0.08 ^B	1.9	383 ± 95 ^C	162 ± 24 ^D	2.4

Values are means with standard deviations from the following: $n \geq 6$ longitudinal and perpendicular samples for both string cheese and original factory cheese, $n = 3$ longitudinal and $n = 4$ perpendicular samples for original supermarket cheese; $n = 48$ longitudinal and $n = 36$ perpendicular samples for both elongated supermarket and factory cheese, from 3 trials. Means for the same parameter, e.g. fracture stress, with different superscript letters are significantly different ($P < 0.05$).

Table 3

Effect of elongation temperature on tensile properties

Elongation temperature (°C)	Fracture stress (kPa)			Fracture strain (-)			Maximum modulus (kPa)		
	Longitudinal	Perpendicular	<i>R</i>	Longitudinal	Perpendicular	<i>R</i>	Longitudinal	Perpendicular	<i>R</i>
40	161 ± 27 ^A	70 ± 26 ^D	2.3	0.78 ± 0.06 ^{A,B}	0.43 ± 0.12 ^{D,E}	1.8	322 ± 56 ^A	127 ± 19 ^D	2.5
50	174 ± 23 ^A	57 ± 14 ^D	3.0	0.79 ± 0.05 ^{A,B}	0.45 ± 0.08 ^D	1.8	355 ± 47 ^A	131 ± 20 ^D	2.7
60	223 ± 31 ^B	64 ± 18 ^D	3.5	0.80 ± 0.07 ^A	0.38 ± 0.07 ^E	2.1	421 ± 69 ^B	161 ± 23 ^{D,E}	2.6
70	259 ± 60 ^C	64 ± 19 ^D	4.0	0.73 ± 0.08 ^B	0.32 ± 0.07 ^F	2.3	494 ± 114 ^C	216 ± 42 ^F	2.3
80	177 ± 56 ^A	62 ± 27 ^D	2.8	0.63 ± 0.13 ^C	0.32 ± 0.07 ^F	1.9	359 ± 93 ^{A,B}	192 ± 41 ^{E,F}	1.9

Values are means with standard deviations from n = 16 longitudinal and n = 18 perpendicular samples for elongation temperatures of 40, 50, 70 and 80 °C, plus n = 24 longitudinal and n = 27 perpendicular samples for an elongation temperature of 60 °C. Means for the same parameter, e.g. fracture stress, with different superscript letters are significantly different ($P < 0.05$).

Table 4

Effect of elongation time on tensile properties

Elongation time (s)	Fracture stress (kPa)			Fracture strain (-)			Maximum modulus (kPa)		
	Longitudinal	Perpendicular	<i>R</i>	Longitudinal	Perpendicular	<i>R</i>	Longitudinal	Perpendicular	<i>R</i>
18	242 ± 21 ^A	66 ± 17 ^D	3.7	0.80 ± 0.05 ^A	0.39 ± 0.08 ^B	2.0	467 ± 52 ^A	180 ± 32 ^C	2.6
120	223 ± 31 ^B	64 ± 18 ^D	3.5	0.80 ± 0.07 ^A	0.38 ± 0.07 ^B	2.1	421 ± 69 ^B	161 ± 23 ^C	2.6
180	204 ± 33 ^C	72 ± 16 ^D	2.8	0.78 ± 0.06 ^A	0.42 ± 0.07 ^B	1.8	398 ± 60 ^B	174 ± 24 ^C	2.3

Values are means with standard deviations from n = 16 longitudinal and n = 18 perpendicular samples for elongation times of 18 and 180 s, plus n = 24 longitudinal and n = 27 perpendicular samples for an elongation time of 120 s. Means for the same parameter, e.g. fracture stress, with different superscript letters are significantly different ($P < 0.05$).

Table 5

Effect of elongation frequency on tensile properties

Elongation frequency (min ⁻¹)	Fracture stress (kPa)			Fracture strain (-)			Maximum modulus (kPa)		
	Longitudinal	Perpendicular	<i>R</i>	Longitudinal	Perpendicular	<i>R</i>	Longitudinal	Perpendicular	<i>R</i>
3	197 ± 45 ^A	65 ± 22 ^C	3.0	0.77 ± 0.07 ^A	0.39 ± 0.10 ^B	2.0	370 ± 88 ^A	166 ± 32 ^C	2.2
10	223 ± 31 ^B	64 ± 18 ^C	3.5	0.80 ± 0.07 ^A	0.38 ± 0.07 ^B	2.1	421 ± 69 ^B	161 ± 23 ^C	2.6

Values are means with standard deviations from n = 16 longitudinal and n = 18 perpendicular samples for an elongation frequency of 3 min⁻¹, plus n = 24 longitudinal and n = 27 perpendicular samples for an elongation frequency of 10 min⁻¹. Means for the same parameter, e.g. fracture stress, with different superscript letters are significantly different ($P < 0.05$).

Table 6

Effect of plate and storage temperature on tensile properties

Plate temperature (°C)	Fracture stress (kPa)			Fracture strain (-)			Maximum modulus (kPa)		
	Longitudinal	Perpendicular	<i>R</i>	Longitudinal	Perpendicular	<i>R</i>	Longitudinal	Perpendicular	<i>R</i>
4	223 ± 31 ^A	64 ± 18 ^C	3.5	0.80 ± 0.07 ^A	0.38 ± 0.07 ^B	2.1	421 ± 69 ^A	161 ± 23 ^C	2.6
21	192 ± 35 ^B	46 ± 12 ^D	4.2	0.79 ± 0.07 ^A	0.40 ± 0.06 ^B	2.0	372 ± 69 ^B	120 ± 22 ^D	3.1
37	179 ± 39 ^B	41 ± 18 ^D	4.4	0.77 ± 0.09 ^A	0.38 ± 0.07 ^B	2.0	353 ± 67 ^B	112 ± 43 ^D	3.2

Values are means with standard deviations from n = 16 longitudinal and n = 18 perpendicular samples for plate and storage temperatures of 21 and 37 °C, plus n = 24 longitudinal and n = 27 perpendicular samples for a plate and storage temperature of 4 °C. Means for the same parameter, e.g. fracture stress, with different superscript letters are significantly different ($P < 0.05$).

Table 7

Effect of remelting MC after elongation on tensile properties

Treatment	Fracture stress (kPa)			Fracture strain (-)			Maximum modulus (kPa)		
	Longitudinal	Perpendicular	<i>R</i>	Longitudinal	Perpendicular	<i>R</i>	Longitudinal	Perpendicular	<i>R</i>
Remelted MC	105 ± 23 ^A	84 ± 16 ^C	1.2	0.52 ± 0.06 ^A	0.47 ± 0.07 ^C	1.1	232 ± 48 ^A	199 ± 36 ^C	1.2
Elongated MC	223 ± 31 ^B	64 ± 18 ^D	3.5	0.80 ± 0.07 ^B	0.38 ± 0.07 ^D	2.1	421 ± 69 ^B	161 ± 23 ^D	2.6

Values are means with standard deviations from n = 16 longitudinal and n = 18 perpendicular samples for remelted elongated MC, plus n = 24 longitudinal and n = 27 perpendicular samples for MC elongated under standard experimental conditions. Means for the same parameter, e.g. fracture stress, with different superscript letters are significantly different ($P < 0.05$).

Fig. 1. Dumbbell-shaped template used for cutting cheese samples. Dimensions are in mm.

Fig. 2. Sample cutting in longitudinal and perpendicular orientations.

Fig. 3. True stress versus Hencky strain for tensile testing of one longitudinal (—) and one perpendicular (---) sample of factory mozzarella cheese prepared under standard conditions.

Fig. 4. True fracture stress versus distance along the rolled sheet for factory mozzarella prepared under standard conditions in the longitudinal (—◆—) and perpendicular (---▲---) orientations, and where standard conditions were altered by holding the elongated cheese at 60 °C for 2 h before cooling to 4 °C for 2 h then cutting dumbbell samples in longitudinal (✱) and perpendicular orientations (■). Error bars represent one standard deviation from the mean.

Fig. 5. True fracture stress as a function of elongation temperature in the longitudinal ($\bullet$) and perpendicular ($\blacktriangle$) orientations and the corresponding ratio R ($\blacklozenge$). Error bars represent one standard deviation from the mean.

a

c

e

b

d

f