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RATE AND TEMPERATURE DEPENDENCE OF THE MECHANICAL PROPERTIES OF CHEDDAR CHEESE.

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ABSTRACT

In this study, the mechanical properties of mature cheddar cheese (Young's modulus, E; yield strength, σ_Y and "fracture toughness", R) were investigated at different rates and different temperatures. Most biological materials are viscoelastic and therefore their mechanical properties will depend on testing conditions. The ultimate aim is to incorporate the measured properties into a model for food cutting. The properties were obtained from uniaxial compression tests and three point bending tests over a range of strain rates and temperatures. Traditional fracture mechanics methods are not always applicable, given the viscoelasticity of cheese, but graphical methods are still appropriate. As expected, the resistance to cracking and yielding of cheddar cheese is both rate and temperature dependent.

KEYWORDS

Mechanical properties, toughness, cheese, viscoelasticity, cutting, rate-temperature dependence

INTRODUCTION

There is a crucial need to understand, model and explain the current 'rules-of-thumb' used for decision making in the food industry. Studies to date have related the mechanical properties of foods to sensory texture, ripening quality etc. but not to industrial processing operations. A thorough knowledge of the fracture behaviour of food materials is necessary to evaluate the relationship between their mechanical properties and industrial processing operations, such as cutting, slicing, flaking etc. 1. Cutting of brittle materials, polymers and biological materials has highlighted the need to consider crack resistance in addition to plastic shearing and friction. Reluctance to incorporate toughness in cutting models of ductile material arises, even now, because free-standing cracks running ahead of the tool are not seen. However it has been argued that the whole cut surface is, in fact, one side of a crack and that, during cutting, the crack moves precisely with the tool tip 8. In order to provide the basis for a more scientific approach to industrial cutting and food processing, data on mechanical properties will be collected. A model will then be constructed to predict the overall cutting force required under different conditions and identify the 'minimum' criteria (maximum rate of propagation with minimal applied force).

Characterisation of food materials is complex because of their heterogeneity and their viscoelastic nature: the mechanical properties are rate and temperature dependent. It is therefore clear that the properties collected for future modelling must be determined under conditions (such as strain rate, temperature) comparable with those found in commercial cutting machines.

Resistance to crack growth in a given material is defined by the fracture toughness, R, which is the amount of work required to propagate a crack by unit area.

The fracture toughness can be evaluated graphically from the area under a load-displacement diagram up to fracture. Most biological materials are viscoelastic i.e. highly extensible, non-linear and ductile, and plastic flow or other dissipative mechanisms might occur. In this case the strain (potential) energy change is not entirely absorbed by the fracture process and the total area under a load-displacement diagram will contain the combined contribution of flow and fracture work1. In this paper we are going to refer to **R** as the ‘fracture toughness’, however this value (area under the load-displacement curve divided by the area of fracture) may contain the sum of several energy dissipating mechanisms and is more correctly termed ‘Work to Fracture’.

EXPERIMENTAL PROCEDURES

Mature cheddar cheese was chosen for the experiments, and it was always purchased from the same manufacturer and tested soon after to avoid ageing effects on the mechanical properties 2.

Different tests (uniaxial compression, three point bending) and different geometries were used. These tests were performed at equivalent strain rate rather than equal crosshead speeds: cylinders, beams and cracked beams have different strain rates at the same crosshead velocity. The specimens were loaded to failure at a given rate and temperature and the load-displacement diagram recorded. Mechanical properties obtained from different tests were therefore plotted as a function of strain rates and temperatures. Note that all tests were repeated: each point on the material properties graph represents an average of 4 results.

In a first set of tests the crosshead speeds and therefore the strain rates were varied; cheese was taken out of the fridge (-2°C) and then immediately tested.

As previously stated, tests should be performed at strain rates comparable to those currently used in industrial cutting. Such strain rates though cannot be obtained in the common testing machines. Cheese is a viscoelastic material and its behaviour is not expected to differ from some polymeric materials (i.e. PMMA): time-temperature superposition is believed to hold true for cheese also.

The second set of tests was therefore performed at decreasing temperatures ranging from -5 to –35 ^{o}C in a temperature controlled cabinet mounted on the Instron machine (fig.1). The temperature of the samples was also checked with a thermocouple during and after the tests.

Strain rates were also varied (~0.25, 1.00, 4.00 s^{-1}).

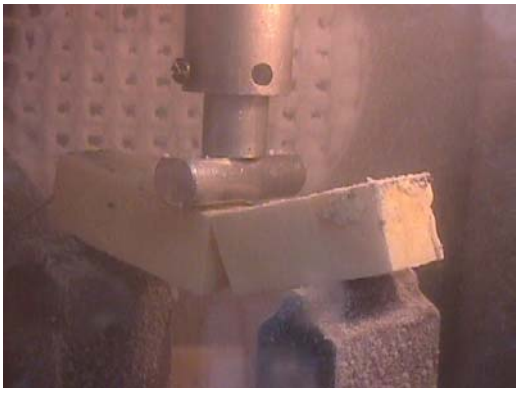

Figure 1: 3 point bending, low temperature test

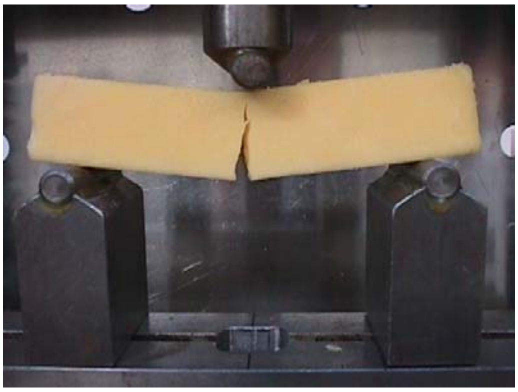

Figure 2: cheese beam loaded in 3 point bending

Compression tests (E, σ_y)

Uniaxial compression tests were performed on cylindrical samples (25x25mm): PTFE film was placed between the loading plates so that the deformation was homogeneous and no 'barrelling' due to friction occurred 345. The strain rate was given by crosshead velocity/H.

Three point bending tests (E, σ_y)

Un-notched cheese samples (25x25x130 mm) were loaded on an Instron testing machine with a 1000N load cell (fig xxx, loaded beam). The span, s is 100 mm.

The modulus for this geometry, according to beam theory, was given by E = load x span^3 / 48 x I x l_y (deflection). The yield strength was given by σ_y = 6 load (from plot) x span /h. The strain rate is given by 6v (crosshead velocity) x h (width) / s^2.

Three point bending tests (R)

Single edge notched (by means of a razor blade, length of notch, a_o was 8mm) cheese samples (25x25x130 mm) were loaded on an Instron testing machine with a 1000N load cell.

"Fracture toughness", R, was measured as the area under the force-displacement curve divided by the area of fracture ($R= \eta U/Bb_o$, η=2 for beams, B is the thickness of the beam, b_o is the difference between the height of the beam and the notch length). The strain rate was given by [ε_y(from compression)xcrosshead velocity]/l_{crack}(from plot).

RESULTS AND DISCUSSION

The mechanical properties of cheese vary with strain rate and with temperature.

Cheese also possesses directional properties (fig. 3). The long bars of rectangular section purchased for the testing are cut across the diameter of whole rounds of cheese. Pre-existing cracks run parallel to the round base of the cheese: this structure is due to the production process. Care was used so that specimens would always be tested in a given direction.

Figure 3: fractured surfaces showing directional properties

Constant T (2-3 ^oC), different strain rates (E, σ_y,R), compression and bending

E and σ_y increase with strain rate. Figure 4 shows R (fracture toughness or total work to fracture) plotted against strain rate. In three point bending on notched samples, although crack initiation was not always easily detected it was observed that it occurred in proximity of maximum load. R slightly increases with decreasing strain rates.

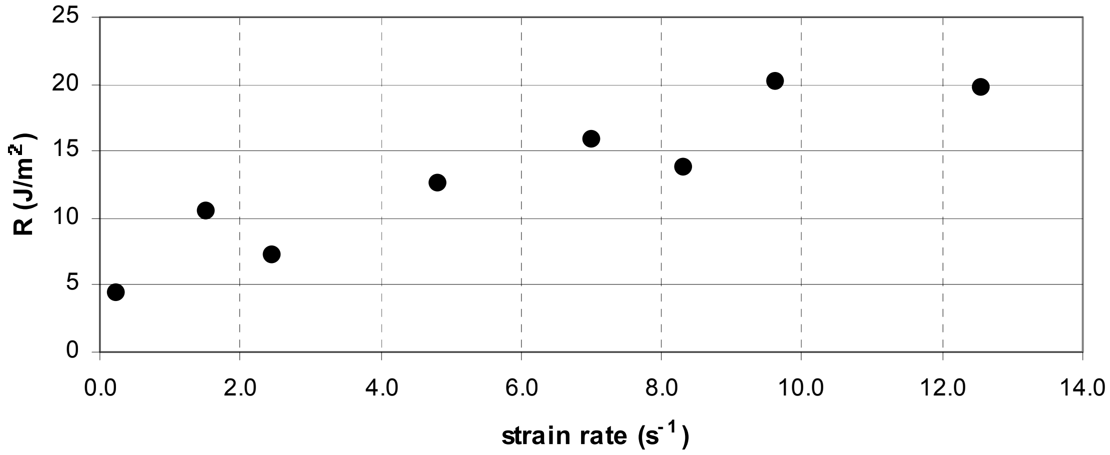

Figure 4: R (fracture toughness or total work to fracture) plotted against strain rate

Different T, different strain rates, compression (E, σ_y)

During the tests cracks at 45° (plane of maximum shear stress) appeared.

Both E and σ_y increase with increasing strain rate and decreasing temperature There seems to be a transition between –15÷20°C, confirmed by the change in shape of the load-displacement curves.

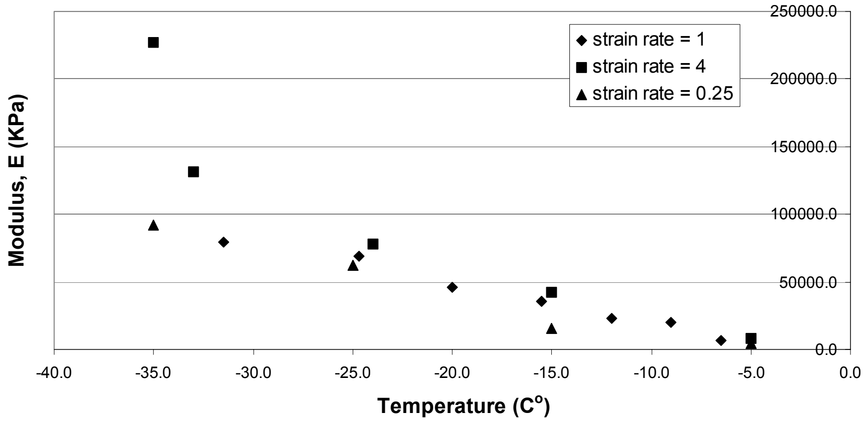

Figure 6: Mature cheddar cheese, Young's modulus (E), vs temperature (-5 to -35 oC) at different strain rates, compression test

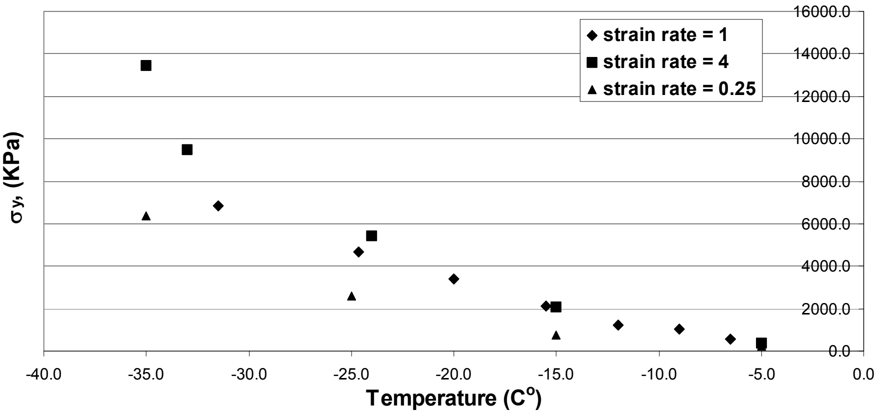

Figure 7: Mature cheddar cheese, yield strength, σy vs temperature (-5 to -35 oC) at different strain rates, compression test

Different T, different strain rates, bending (E, σ_y)

As in the compression test, both E and σ_y increase with increasing strain rate and decreasing temperature.

Different T, different strain rates, bending (R)

Figure 8 shows R against temperature at three different strain rates. Specimens tested at the two higher strain rates (~4, 1 s^{-1}) seem to display a similar behaviour, with two 'peaks' occurring between –10 and –15°C. A second, smaller peak seems to occur at around –30°C (fig.10).

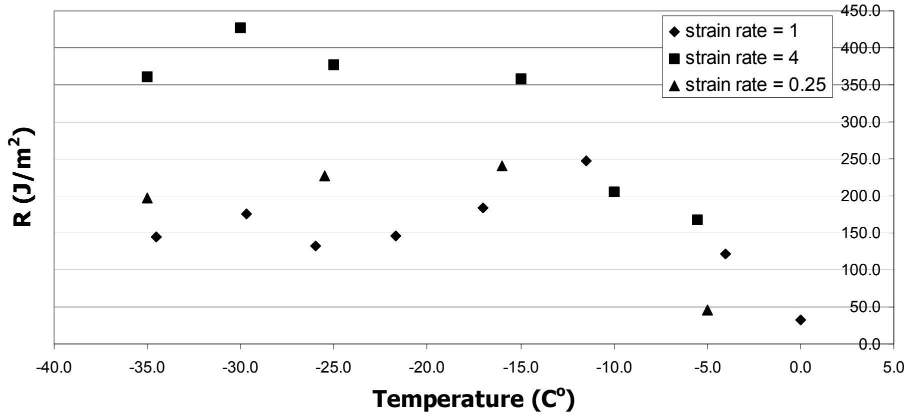

Figure 7: Mature cheddar cheese, work to fracture, R (J/m^2) vs temperature (-5 to -35 ^{o}C) at different strain rates, three point bending test (8 mm notch)

Compression and bending load-displacement curves at different temperature show the nature of deformation occurring in the material 1 (fig 9 showing different shapes of load-displacement curves at different T, similar to the one in 1). At –35 to –30°C the area under the curve is small and the work to fracture is therefore low even though the peak load is high ('brittle' fracture). The area under a 'ductile' type curve (T=-10 to –15°C) is larger despite a lower failure load. It was observed that, after testing, the two halves of the specimen fitted together perfectly: the 'non linearity' was probably not due to permanent deformation but to viscoelasticity 2.

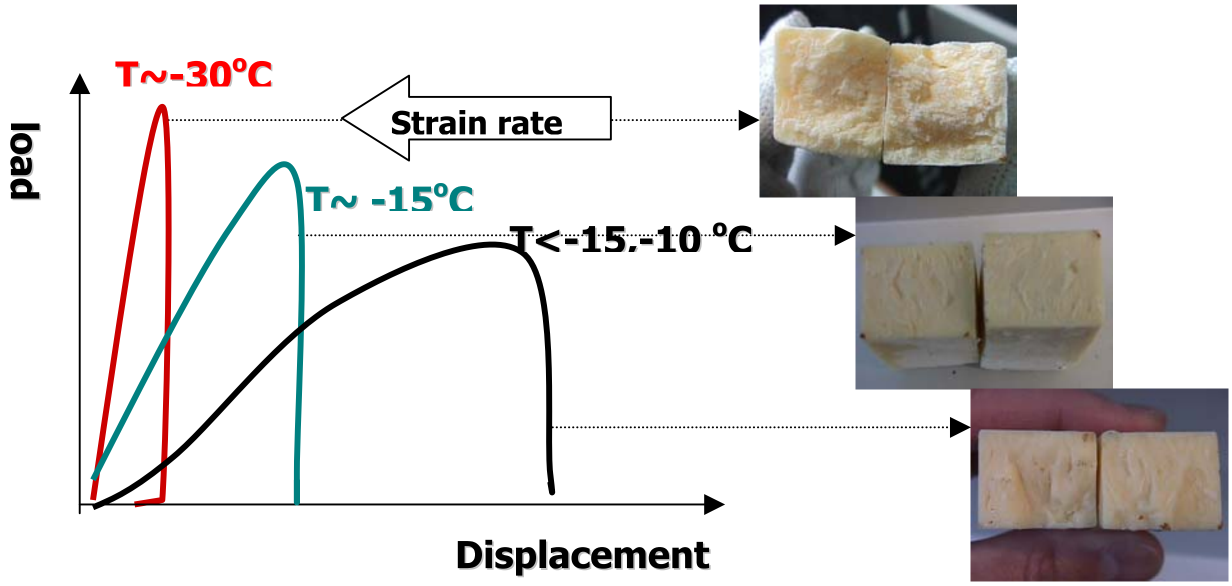

Figure 9: schematic diagram of different shapes of load-displacement curves at different T

CONCLUSIONS

The mechanical properties of mature cheddar cheese are strain rate and temperature dependent as expected. Cheese appears stiffer at increasing rates and decreasing temperature, due to its viscoelasticity. As in the case of polymers, such as PMMA 6 the resistance to cracking increases as the crack velocity (strain rate) increases and the temperature decreases.
The results can be interpreted in terms of a 'viscoelastic' type of behaviour at high temperatures and low strain rates, and a 'brittle fracture' type of behaviour at low temperatures and high strain rates7. Work is in progress to collect data on forces involved in the cutting process so that the model based on the mechanical properties can be applied.

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