DEVELOPMENT OF A FINITE ELEMENT MODEL FOR THE SIMULATION OF VISCOELASTIC BEHAVIOR OF FOODS

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ABSTRACT

A finite element analysis model for simulating the compression of bread dough is presented. The prediction of the viscoelastic rheological behavior of dough (pita bread at the cross-rolling stage of production) during compression and under conditions of stress relaxation or elastic behavior, is essential in understanding the phenomena that are responsible for this behavior. Many previous finite element (FE) and computational fluid dynamic (CFD) models of the compression of dough have over-simplified the geometry and the material properties of their elements, yielding results limited generalizability. This study reports on the development of a nonlinear viscoelastic FE model that can quantify the mechanical responses of the compressed material under load. As far as the constitutive viscoelastic law is concerned, the Prony series viscoelastic model is adopted in order to model the viscoelastic behavior of dough with parameters that were either calculated from experimental data or were derived by a trial-and-error process. The simulation results were compared with experimental data in which the force exerted by the dough on the compression plate was measured during the stress relaxation phase and after the immobilization of the plate. The value of the dough Young's modulus was also estimated by simulating the corresponding experiment and comparing the calculated with the experimental results.

KEYWORDS: Finite Element Analysis, viscoelasticity, bread dough, stress relaxation, Young's modulus.

1. Introduction

The behavior of foods during processing and their quality characteristics strongly depend on their rheological properties. Due to their composite structure, many foods (such as bread dough) exhibit complex viscoelastic rheological behavior. Computational tools that can accurately simulate viscoelasticity in foods can be of great help in studying and understanding the phenomena that are responsible for this complex behavior. Nevertheless, only few studies can be found concerning the modeling of the viscoelastic behavior of food systems, and even more specifically, dough during compression tests. As well known, bread dough may exhibit significant viscoelastic deformation during the production process, as it is also subject to stress relaxation phenomena and creep effects under long-term loadings. As a result, during the stress relaxation test, the decrease in stress and force exerted by the dough on the compression plate can be observed.

Several analytical and numerical methods have been proposed to predict the instantaneous behavior of viscoelastic food under compression, nevertheless, these models cannot be easily extended to the case of stress relaxation as most FEA models do not use accurate and complex geometry and CFD models only account for the fluid behavior of the dough. A FEA model that was successfully used to model viscoelastic behavior of food, was that of Ahmadi et al. (2016), that modeled the dynamic behavior of apple under impact loading with regard to its different layers using ANSYS Mechanical APDL.

In addition, some studies can be found where linear viscoelastic constitutive laws are implemented in models, in order to study the rheological properties under loadings. Among them, Myhan et al (2012) proposed a mathematical viscoelastic model that combines the features of an ideal Hookean elastic solid, an ideal St. Venant plastic solid and viscous fluid. However, this model does not apply in cases when the strain is much higher during the initial compression phase compared to the strain during the remaining periods. It has been proven that it can be used in rheological analyses of food materials, however, there has not been a FEA model based on this specific mathematical model in order to get comparative results. Another model that has been successfully applied to describe viscoelastic behavior of polymers, was the Giesekus model approach (Vlassopoulos et al., 1995) which describes the steady-state shear behavior of molten polymers successfully, however it cannot be used in transient, time dependent experiments.

In the present paper, a finite element model for viscoelastic analysis of bread dough compression is developed. The dough is considered to be on a stable base and it is uniaxially pressed from above by a moving plate without any sliding or deformation phenomena on it. The main focus is on the deformation of dough during stress relaxation, so the objective is to obtain the profile of the transient load on the compression plate. Physical experiments conducted on a texture analyzer were used to set-up the geometry of the model and compare the computational with the experimental results. Two sets of experiments were conducted both on the physical and on the simulated system: a compression test to calculate the force exerted during the compression and relaxation phase and a similar test to determine the Young's modulus of the dough.

2. Proposed model

Figure 1 shows (a) the geometry and (b) the computational mesh of the model that was developed in ANSYS Mechanical APDL to simulate an actual texture analyzer apparatus. The geometry shown in Figure 1 consists of 7 solid bodies including the force transducer, the piston, the sample, and the sample plate. The dough sample was designed as a hemispherical solid with a surface of 0,0025m^2, while the plate had a surface area of 0,0035m^2. The mesh also shown in Figure 1 covers only the basic parts of the geometry (dough, probe and sitting plate) that interact during deformation of the dough. The dough is modelled as an elastic part while all other elements of the geometry are considered solid and rigid. In order to increase the accuracy of the results, special (and more detailed) meshing was applied on the dough part in addition to the general computational meshing done by the automated meshing of Ansys Mechanical. More specifically, patch conforming meshing and face sizing were used to refine the dough meshing.

A static structural analysis was chosen to simulate the compression problem. A fixed support in the structure was placed at the point which forms the base of the machine and should remain stable and not slide. Also, it was chosen to apply a displacement load in the X axis from the surface of the probe to the surface of the dough after they come into contact, with the appropriate selection of the contact between them. Specifically, the value of the displacement as a function of time (essentially the velocity of the probe moving towards the dough) was set at 0.01 m/s with a linear increase until the moment it contacts the dough when it stops moving.

The sample was assumed to correspond to pita bread dough at the cross-rolling stage. Regarding the properties of dough itself, the density was set at 1250 kg/m^3, the Young's modulus at 787 Pa and the Poisson's ratio at 0,35 as derived from experimental data. The Prony series viscoelastic model was used to simulate the viscoelastic behavior of the dough. Each term of the series contains two parameters: the relative modulus and the relaxation time. Creep recovery compliance time profiles from creep experiments were fed into the curve fitting utility of ANSYS Mechanical APDL to derive some initial estimates for the Prony series parameters. With these values as starting points, the values that provide the best fit with the stress relaxation experimental results were set through a trial-and-error procedure.

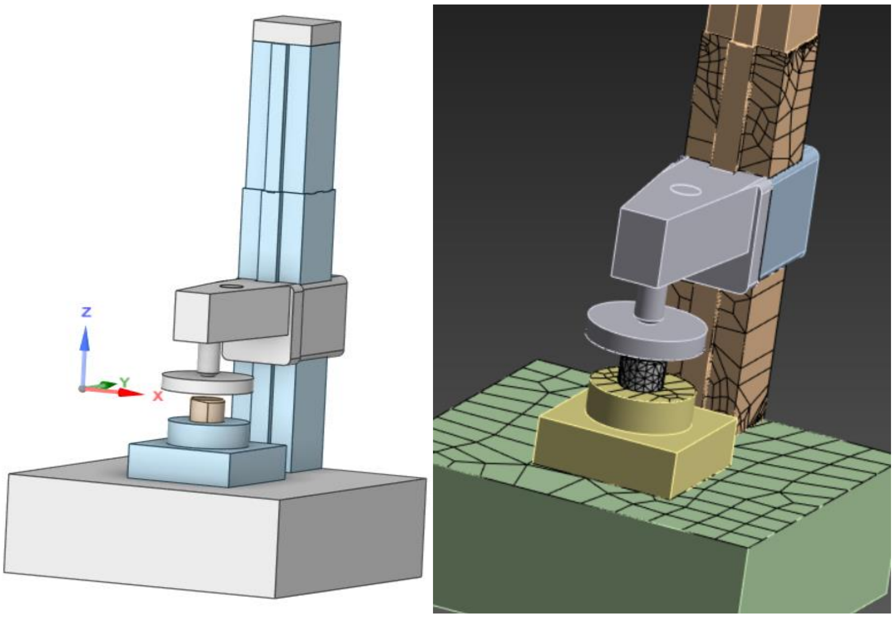

Figure 1. Geometry of the texture analyzer model and computational mesh.

3. Results

The Prony series equation with 10 terms was used to model the viscoelastic behavior of the dough. In the first case, the values of the Prony series parameters (relative moduli and relaxations times) were estimated through curve fitting on experimental data of compliance profiles from creep experiments. Figure 2 shows the experimental values (dots) versus the predicted (solid line) after the fitting. The curve fitting algorithm minimizes the sum of the squares of the differences between the experimental data and the computational results.

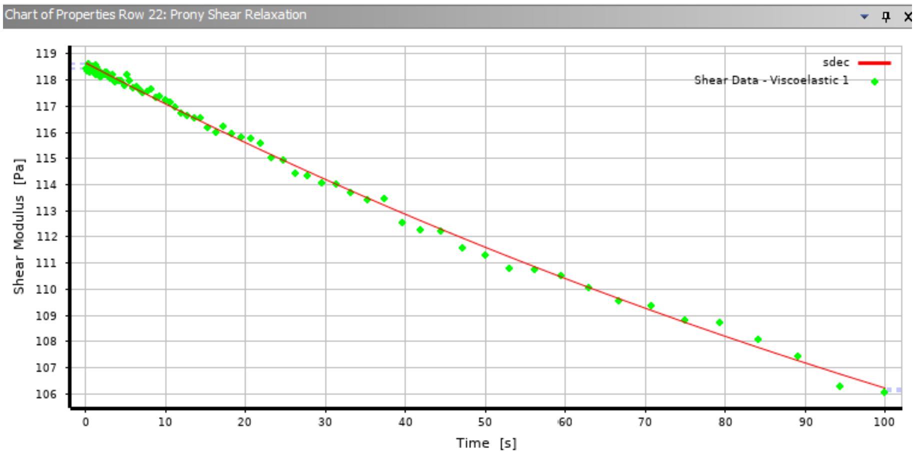

Figure 2. Curve fitting of experimental creep data.

Even though the fit of the creep experimental data was pretty accurate, the Prony series parameter values obtained did not provide a good fit on the stress relaxation experiment results. So, a trial-and-error procedure with different values of the Prony series model parameters was executed until a satisfactory agreement is reached. The resulting parameter values of the Prony series model are listed in Table 1 and the calculated force profile compared to experimental data is shown in Figure 3.

Table 1. Estimated values of the 10-term Prony series model.

Relative moduli	**Relaxation time (s)**
0,11	8
0,11	8
0,11	8
0,11	8
0,09	11
0,09	11
0,09	11
0,09	12
0,09	12
0,09	12

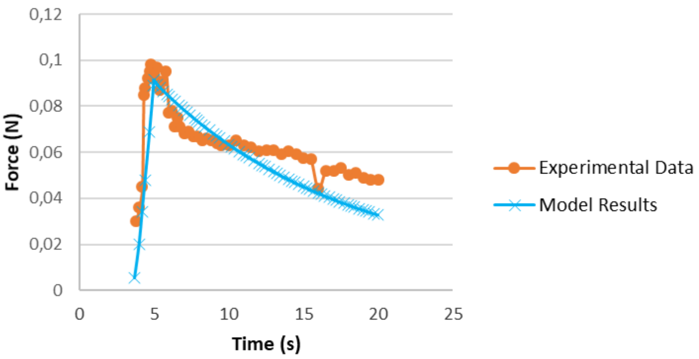

Figure 3. Comparison of the calculated force profile versus the experimental results.

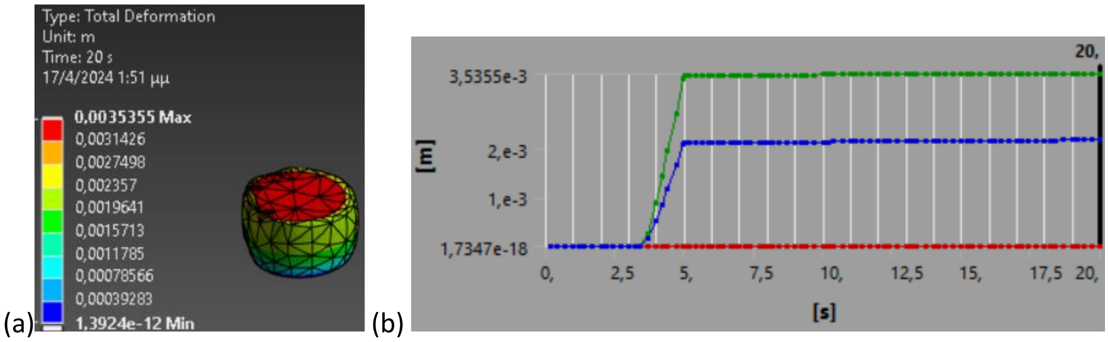

Figure 4. (a) Deformation profile of dough at 20s, (b) Deformation plot versus time.

Figure 4(a) shows the dough deformation contour plot at 20s (at the end of the experiment) and Figure 4(b) shows the minimum (red line), average (blue line) and maximum (green line) deformation as a function of time. The purpose of this illustration is to observe how the compression load affects the mechanical and viscoelastic behavior of the dough sample. Since it is a stress relaxation experiment, the deformation remains constant throughout the compression load.

Figure 5 shows the same information for the maximum shear stress, i.e. the stress parallel to the plane of the cross-section exerted. As expected in a stress relaxation experiment, there is a considerable decrease in stress in response to strain generated by the moving plate after it is immobilized.

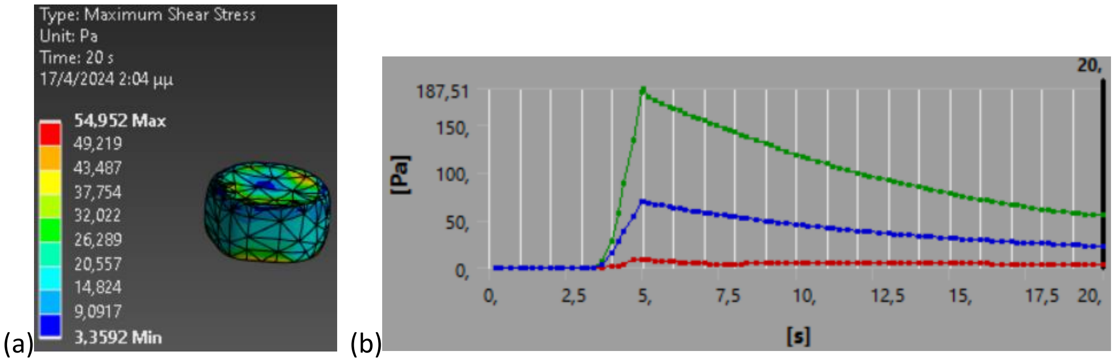

Figure. 5 (a) Maximum shear stress profile of dough, (b) Maximum shear stress versus time.

For the Young's modulus calculation experiment, the compression was simulated for 10 seconds and the compression-induced deformation was set to 10% of the original height of the specimen. To determine the Young's modulus, it is necessary to extract the stress and strain profiles during compression. The calculated stress versus strain diagram is shown in Figure 6(a). From this curve, the elastic region was identified and isolated in Figure 6(b). The slope of the curve in the elastic region corresponds to the value of the Young's modulus and was estimated at 781.33 Pa. This result is very close to the experimentally calculated value (787 Pa) for the same sample.

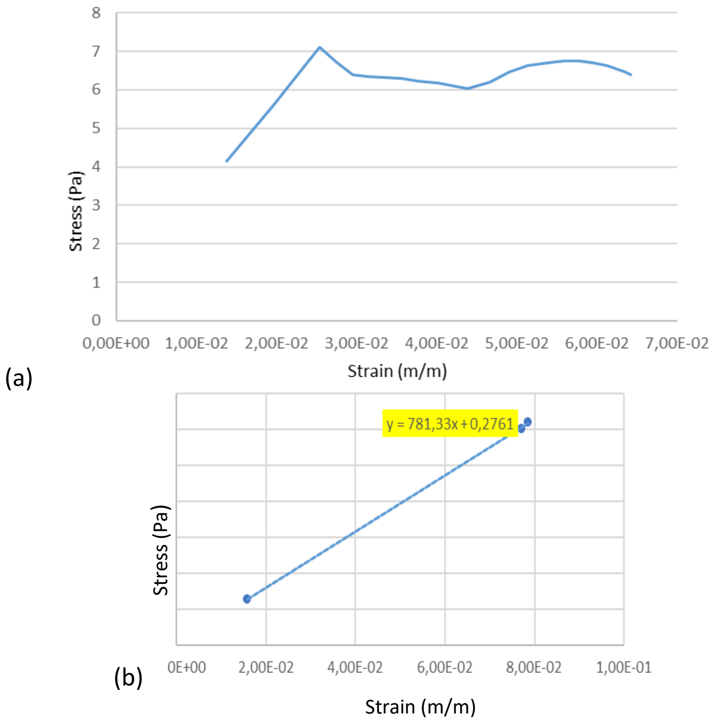

Fig 6. (a) Stress-strain plot for calculating the Young's modulus, and, (b) plot of the elastic region.

4. Conclusions

In this study, computational modeling of dough compression experiments were performed in a simulation model using the finite element method developed within the Ansys Mechanical software. More specifically, two types of compression experiments were performed to simulate stress relaxation and calculate the Young's modulus. To develop the viscoelastic model for the prediction of the rheological behavior of dough, the Prony series model was used with parameters that were either estimated from a trial-and-error procedure. Experimental data concerning the force exerted by the dough on the convergent plate during compression were used to validate the model. In all cases it was demonstrated that the finite element model simulation is able to accurately reproduce the viscoelastic behavior of materials in different deformation experiments.

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