Journal of Cereal Science 77 (2017) 84–89

Contents lists available at ScienceDirect

Journal of Cereal Science

journal homepage: www.elsevier.com/locate/jcs

Stress relaxation behavior of oat flakes

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ARTICLE INFO

Article history:
Received 25 January 2017
Received in revised form
21 July 2017
Accepted 1 August 2017
Available online 4 August 2017

Keywords:
Stress relaxation
Oat flakes
Generalized Maxwell model

ABSTRACT

It is important to understand the viscoelastic properties of cereals as they affect product texture. Therefore, the stress relaxation behavior of oat flakes was studied using static testing. The oat flakes exhibited linear viscoelastic behavior at strain levels under 2%. The relaxation modulus was directly influenced by the moisture content of the samples; it was low at higher moisture levels. A two-element generalized Maxwell model fitted well to describe the viscoelastic behavior of oat flakes with its high R^2 and low RMSE. The first and second stress coefficients (G_1 *and* G_2) and the second relaxation time component (τ_2) of the model generally decreased as the moisture content of the samples increased, which implied that samples showed lower resistance against applied force and relaxed faster with the increase in moisture content. The viscoelastic behavior of oat flakes was a function of both moisture content and temperature. The viscoelastic properties obtained in this study can be used to improve the textural attributes of oat-based products and further utilized in mathematical models describing drying or sorption processes.

1. Introduction

Oat grain (*Avena sativa* L.) is one of the most important cereals, and is used for purposes such as animal feed, human diet, and health care (Zheng et al., 2015). The tolerance of oat grain to wet weather and acidic soils, its resistance to disease, and its low need for fertilizers and chemicals during cultivation are the reasons behind its popularity in agriculture (Biel et al., 2014). Many consumers consider oats to be superior to most other cereals due to their high nutritional value, which makes them one of the most important cereals in the human diet (Liu et al., 2010). Studies on oat-based products (Londono et al., 2015; Wood, 2007) have shown that oats impact human health positively by lowering blood cholesterol levels, reducing glucose uptake, reducing the risk of cancer, decreasing plasma insulin response, and providing satiety. These effects generally result from β-glucans, which also cause high viscosity in the gastrointestinal system (Liu et al., 2010). In addition to these reasons, the high amount of soluble fibers in their structure and the increased awareness of population to consume more fibers in their diet lead to an enormous increase in the consumption of oat grains (Autio and Eliasson, 2009). This stimulation effect has led to the creation of new oat-based products in the food industry such as breakfast cereals, fermented oat products, oat flour products, and oat milk-based beverages (Hu et al., 2014).

Several studies have reported that moisture, temperature, and time are the most significant parameters that affect the mechanical properties of cereals (Bargale and Irudayaraj, 1995; Figueroa et al., 2011; Gates et al., 2004, 2008b). Therefore, various studies have focused on these variables to determine changes in the mechanical properties of cereals during processing and storage. Cereal grains are subjected to many types of static and dynamic loads during harvesting, processing, and storage and such loadings case significant damage to grains. Therefore, understanding the mechanical properties of cereals can elicit new harvesting methods, improve the design of unit operations for efficient processing, and preserve the quality of products (Bargale and Irudayaraj, 1995; Hernandez et al., 2012). Understanding the mechanical properties of cereals is necessary not only for processing operations, but also for human consumption as they are related to consumers' mastication and swallowing.

Since most foods including cereal grains and their processed derivatives exhibit both fluid- and solid-like behavior, their mechanical properties need to be investigated by treating them as viscoelastic (Gates and Dobraszczyk, 2004). Several researchers have utilized both static and dynamic methods such as steady ones like stress relaxation test (Liu et al., 1989; Figueroa et al., 2011; Hernandez et al., 2012) and creep test (Bonnand-Ducasse et al.,

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http://dx.doi.org/10.1016/j.jcs.2017.08.005
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2010), and oscillatory ones like force-deformation test (Gates et al., 2004, 2008a) to analyze the mechanical properties of food material.

During the stress relaxation test, the relaxation modulus of a viscoelastic material is measured as a function of time at a constant strain. In this manner, the relaxation behavior and dissipation of stress can be observed as a function of time (Hernandez et al., 2012). There are different behaviors that can be observed by performing stress relaxation test, such as ideal elastic, ideal viscous and viscoelastic. Studies on soybeans (Liu et al., 1990), wheat kernels (Figueroa et al., 2011), barley kernels (Bargale and Irudayaraj, 1995; Lopez-Perea et al., 2012), cowpeas (Pappas et al., 1988), wheat starch/dietary fiber systems (Yildiz et al., 2013), dough matrices (Rodriguez-Sandoval et al., 2009), and various types of spaghetti (Sozer and Dalgic, 2007) have shown that the viscoelastic behavior of food samples can be analyzed using stress relaxation tests and represented using a generalized Maxwell model. These foods have a high starch content. Interaction of starch and water makes the water transport in these foods to depend upon the glass-transition phenomenon. Glass transition has a strong impact on possible configuration of molecules toward equilibrium with its contribution to relaxation behavior since it affects molecular mobility of the molecules in polymer segments. Systems above glass transition (in rubbery or viscous states) are able to reach equilibrium at shorter time scales (Liu et al., 2006). Sandoval et al. (2009) measured the glass transition temperature of oat flour and showed that oat flour is in the rubbery state around 100 °C when the moisture content is higher than 5% on dry basis. Therefore, the pan cooking process of oats is expected to occur in the rubbery state as oat flakes are added to the boiling water.

Although a considerable amount of research has been conducted in the past to understand the rheological and mechanical behavior of different cereals, there is very limited information on mechanical and viscoelastic properties of oats. Gates et al. (2004, 2008b) used the pin deformation method to test the strength of oat flakes. Their results indicated the difference between thick and thin oat flakes and the effect of moisture content on rupture force. Also, Gates et al. (2008a) and Gates and Talja (2004) provided additional information on the mechanical properties of oat groats and flakes by using dynamic mechanical testing at short time scales. Gates et al. (2008a) conducted mechanical testing for 5 s after maximum force was attained. However, there is no published data on the stress relaxation behavior of oats at long time scales, which is needed for modeling of non-Fickian transport (Singh et al., 2003) during applications such as drying, sorption, and cooking. The specific objectives of this study were to characterize the stress relaxation behavior of oat flakes in the cooking moisture content range using static testing and to determine the generalized Maxwell model parameters representing the viscoelastic behavior for oat flakes. The static testing allowed collecting data at longer time scales. The cooking moisture content range will allow processors to predict mechanical textural changes in oat meal as a function of pan heating parameters.

2. Materials and methods

2.1. Fitted model

Stress relaxation data can be interpreted through the Maxwell model, which includes a Newtonian dashpot to describe the viscous behavior of fluids and a Hookean spring to represent the elastic behavior of ideal solids in series as illustrated in Fig. 1. However, since this model does not include an equilibrium stress, it is not suitable for viscoelastic solids. This problem can be overcome by the addition of an individual Hookean spring to a Maxwell element in parallel. The generalized Maxwell model, which consists of several Maxwell elements in parallel with a spring as described in Fig. 1, can better explain the viscoelastic behavior of food materials. The sum of the stress in each element generates the total stress in this system when constant strain is applied (Steffe, 1996).

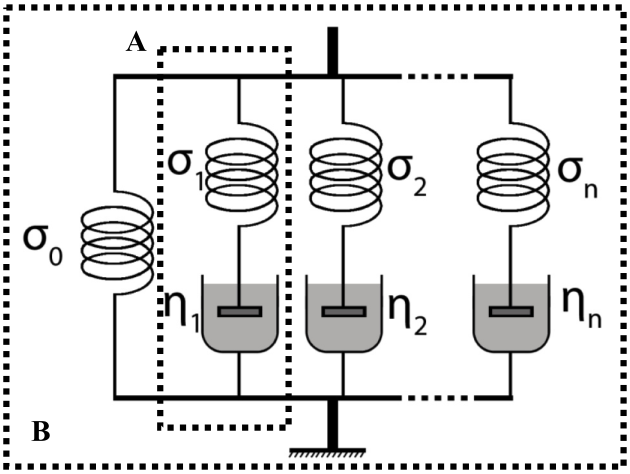

Fig. 1. Representation of **A)** Maxwell element and **B)** generalized Maxwell model.

A generalized Maxwell model describing the viscoelastic behavior of a solid food material can be written using the Prony series as:

$$G(t) = G_0 + \sum_{i=1}^{N} G_i e^{-t/\tau_i} \tag{1}$$

where N denotes the number of Maxwell elements and G_0, G_i and τ_i are coefficients of the generalized Maxwell model. G_0 is the equilibrium stress or stress at the infinite time, G_i is the stress coefficient of the ith element of the Maxwell model, and τ_i is the relaxation time of the Maxwell element that is also expressed as the time required for stress in an element to decay to 1/e (36.8%) of its original value. $G(t)$ describes the decaying parameter of relaxation modulus at any time and can be calculated as:

$$G(t) = \frac{\sigma(t)}{\varepsilon_0} \tag{2}$$

where $\sigma(t)$ is stress as a function of time and ε_0 is the applied constant strain during the stress relaxation test.

2.2. Materials and sample preparation

The oat flakes were obtained from a local market. Based upon information listed on the package label, it was calculated that they were composed of 8% fats, 73% carbohydrates, and 13.5% proteins on dry basis. They were stored at room conditions in original packages before their use in experiments. Cylindrical shapes of oat flake pastes with dimensions of 5 cm diameter and 13 mm height were prepared by heating them in boiling water for 1 min and molding. The specific weight of oat flakes before and after cooking was found to be 0.372 ± 0.016 and 0.987 ± 0.033 g/ml, respectively. Next, samples were frozen at −20 °C for one day prior to the freeze-drying process. Then, the samples were freeze-dried for 48 h. To modify the moisture content of the samples, they were conditioned