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Non-linear stress relaxation model as a tool for evaluating the viscoelastic properties of meat products

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ABSTRACT

A non-linear rheological model was developed for processed pork and poultry meats. The modeled parameters were identified based on the results of compression stress relaxation tests at a constant strain rate in initial (compression) and final (expansion) phases of the test and at constant deformation values in the principal stage of the test (stress relaxation). The analyzed material comprised processed pork and poultry meats which are supplied by renowned manufacturers and are available in retail throughout Poland. The proposed rheological model of the analyzed processed meats was logically and empirically validated, and it adequately described changes in stress in all three phases of the relaxation test. Significant differences were observed in the rheological properties of processed meats that belonged to the same processing groups, but were made of different meat (pork or poultry). Significant correlations were noted between the proximate chemical composition and rheological properties of the analyzed products. The proposed rheological model can be used to optimize the production of processed meats.

1. Introduction

Processed meats, in particular sausages, have a large share of the meat and processed meat market in many countries. Manufacturers introduce diverse meat products in response to the consumers' varied requirements and expectations concerning product quality. Predictions of product quality based on instrumental measurements of rheological properties play an important role from the technological point of view. A knowledge of a product's rheological properties, the correlations between a product's rheological properties and proximate chemical composition, and the correlations between a product's rheological and sensory characteristics facilitates an evaluation of its technological and eating quality (Ma and Boye, 2013; Stokes et al., 2013; Zhiguo et al., 2013; Ahmed and Ramaswamy, 2007; Bayarri et al., 2007; Funami et al., 1998; Torley and Young, 1995).

Modeling is an efficient approach for predicting the rheological behavior of foods. The behavior of biological materials during rheological analyses differs considerably from that of ideal solids, which is why various models are applied to describe the rheological properties of the analyzed materials (Chen and Opara, 2013). The choice of a model is determined by various factors, including the range and type of the applied loads (Pietsch, 2002). In most cases, generalized multi-element mechanical models of viscoelastic solids are used. The models based on the Boltzman superposition principle combine simple models describing ideally elastic solids (Hookean solids), ideal fluids (Newtonian fluids) and ideally plastic solids (Saint–Venant bodies) (Mohsenin and Mittal, 1977; Mitchell and Blanshard, 1976). A model and its parameters are generally selected based on their fit to experimental data (Tscharnuter et al., 2011; Sorvari and Malinen, 2007). The resulting solutions are mostly semi-empirical equations whose parameters generally may not be directly interpreted based on the laws of physics applicable to solid bodies.

The viscoelastic properties of meat products have been studied extensively with the involvement of stress relaxation tests (Campus et al., 2010), creep tests (Dolz et al., 2008) and transient and dynamic measurements (Chattong and Apichartsrangkoon, 2009). The viscoelastic behavior of meat products in stress relaxation tests is generally described with the use of the generalized Maxwell model (Campus et al., 2010; Andrés et al., 2008), whereas Burger's model supports the description of viscoelastic properties in creep tests (Yilmaz et al., 2012; Dolz et al., 2008). Del Nobile et al. (2007) used the generalized Maxwell model to describe stress relaxation behavior of solid-like foods, including meat products, when deformation remained unchanged, but compression stress decreased during the test. Yilmaz et al. (2012), Dolz et al. (2008)

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Nomenclature

E	elastic modulus (Young's modulus) (Pa)
k_1	coefficient in Eq. (7) (s)
k_2	coefficient in Eq. (7), hypothetical asymptotic value of normalized stress (–)
k_3	coefficient in Eq. (20) (Pa)
k_c	coefficient in Eq. (12) (Pa)
m_c	exponent in Eq. (12) (–)
m_e	exponent in Eq. (22) (–)
n	exponent in Eq. (10) (–)
t	time (s)
T_{rel}	relaxation time (time after which stress decreases e-fold) (s)

Greek symbols

ε	relative strain (–)
$\dot{\gamma}$	shear displacement rate (s^{-1})
κ	consistency index in Eq. (26) (Pa s^n)
η	coefficient of dynamic viscosity (Pa s)
σ	stress (Pa)

Subscripts

1	beginning of compression phase
2	transition from compression phase to stress relaxation phase
3	transition from stress relaxation phase to expansion phase
4	end of expansion phase
c	compression phase
e	expansion phase
H	elastic properties of material
N	viscous properties of material
r	stress relaxation phase
V	plastic properties of material

and Kuo et al. (2000) investigated the rheological properties of meat products in creep and recovery tests where constant load was applied to the sample and deformation was measured over time. Karaman et al. (2011) and Bruno and Moresi (2004) relied on dynamic oscillatory tests to study the rheological behavior of meat products. In most studies investigating the viscoelastic properties of meat products, shear stress was applied during torsional loading of meat specimens. The above approach is commonly applied in tests of emulsion-type meat products such as cooked sausages and frankfurters. To date, the viscoelastic properties of emulsion-type meat products have not been investigated based on a mechanical approach involving compression testing and creep analysis. Classical linear rheological models of solids in relaxation and creep-recovery tests (Maxwell model, Saint–Venant model and Burger's model) are based on several assumptions. It is assumed that a rheological model of a solid body contains a finite number of Hookean elastic elements and Newtonian viscous elements with constant coefficients. The increase and decrease in deformation in initial and final stages of stress relaxation tests, respectively, do not affect the modeled rheological parameters of a solid body. It is also assumed that the increase and decrease in load in initial and final phases of creep tests, respectively, do not influence the estimated parameters in a rheological model. Rheological models of meat products developed in line with the above assumptions generate results that significantly diverge from measured data. For this reason, generalized multi-component Maxwell and Burger's models, whose parameters may not be interpreted based on the laws of physics, are applied in practice (Yilmaz et al.,2012; Dolz et al., 2008). This implies that linear rheological models do not always produce reliable results for meat products. The above is particularly true of the present experiment which investigated not only emulsion-type products (*Vienna sausages*), but also coarsely-ground dry sausage (*Krakowska*) and meat blocks (*canned ham*).

The objective of this study was to propose a rheological model of processed pork and poultry products based on the results of compression stress relaxation tests. The model and its parameters were evaluated in view of the results of a stress relaxation test with a constant strain rate in initial and final (expansion) phases of the test and at constant deformation values in the principal stage of the test (stress relaxation). The experiment was performed on the assumption that a rheological model of a solid body does not have to be a linear combination of Maxwell and Newtonian model elements and that it can comprise non-linear elements.

2. Materials and methods

2.1. Materials

The experimental material comprised two brands of processed pork and poultry products which are supplied by renowned Polish manufacturers are popular among consumers and available in stores across Poland. The evaluated products represented the following processing groups (PN-A-82007:1996/Az1:1998): emulsion-type products (finely-ground sausages – *Vienna sausages*), semi-coarse ground semi-dry sausage (*Żywiecka*), dry sausage (*Krakowska*) and meat blocks (*canned pork ham, canned poultry ham*, *turkey breast ham*). The analyzed meats were manufactured by standard production processes in industrial plants. Each product was randomly selected and purchased at monthly intervals over a period of two years ($n = 24$). The number of canned poultry ham samples was smaller ($n = 9$) because the product was discontinued during the study. The products were transported to the laboratory and stored at 4 °C for 24 h. Every product batch was divided into two groups. The products from the first group were analyzed to determine their proximate chemical composition, and the products from the second group were subjected to stress relaxation tests. Rheological properties were analyzed in cylindrical samples with the diameter of 19 ± 1 mm and the height of 15 ± 1 mm. They were punched with the use of a special cylindrical knife that ensured parallel scratching.

2.2. Chemical composition

The dry matter content, total protein content (Kjeldahl method, the nitrogen content of meat was converted to total protein content using a conversion factor of 6.25), fat content (Soxhlet method, diethyl ether solvent) and ash content (AOAC, 1990) of the evaluated products were determined. Hydroxyproline content (ISO 3496:1994) was converted to collagen content through multiplication by 8.

2.3. Stress relaxation testing

Compression stress relaxation tests were performed with the TA.HD Plus Texture Analyzer (Stable Micro Systems, UK) and Exponent5.1.2.0 software. An AACC 36 mm cylinder probe with radius (P/36R) was used in all tests. The speed of the measuring head in