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Measuring ring tensile stress and strain of surimi gels using a novel ring tensile test with image analysis

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ABSTRACT

A ring tensile test with image analysis to measure failure properties, such as failure ring tensile stress (σ_f) and strain (ε_f), of surimi (*Itoyori* A grade) gels with varying moisture content (76–80%) was developed using Laplace's law. The novel approach was validated for different inside diameters and thicknesses. Digital image correlation (DIC) was used to identify the validity of Laplace's law. For normalization, Laplace's law was applied to eliminate the dependence of the width and inside diameter. The values of σ_f by thickness, including the zero point, was accurately described using linear regression analysis ($r^2 > 0.99$). This shows that σ_f can estimate the reference σ_f regardless of thickness. The values of σ_f of the ring specimen were best fit with a linear function to moisture content ($r^2 > 0.94$). The results of ε_f for differing moisture content and thickness showed no significant differences ($p < 0.05$).

1. Introduction

Surimi is a refined and stabilized fish myofibrillar protein (Park and Lin, 2005) and is a major ingredient for surimi seafood, including steamed or fried fish cakes, fish sausage, and crab sticks (Park, 2013). The elastic and/or viscoelastic properties of fish myofibrillar protein gels are considered as the most important parameter in determining the textural properties of surimi seafood (Park, 2000). Several mechanical tests are used to characterize the textural properties of surimi seafood. Although the failure tensile properties of surimi gels are highly related to sensory results ($r^2 = 0.82$) and consumer preference (Hamann and McDonald, 1992), compressive and/or the punch test have been widely used in the surimi and surimi seafood related industries and research institutes due to the simplicity of the measuring process (Hamann et al., 2006; Lee and Chung, 1989; Shi et al., 2014; Tabilo-Munizaga and Barbosa-Cánovas, 2004). For elastomers, the compression method fundamentally generates the same information as the tensile test does. However, because the magnitude of the displacement or the strain in the compressive test is limited by the height of specimen, the compression test does not fully support the force or stress data at the high value of displacement or strain, especially as the strain becomes close to unity. Indeed, the maximum strain during compressive testing cannot be higher than 1. For many food gels, the strain values exceeds unity. Torsion test using a Hamann Torsion Gelometer (Gel Consultant, Raleigh, NC, USA) has been recognized as an excellent method for providing failure tensile properties of surimi gels by twisting their unique dumbbell shapes (Park, 2013). However, the preparation of the dumbbell (or hourglass) shape of the samples is time consuming, and the variation of the diameter at the center of the specimen highly influences the resulting measurements (Park, 2013).

The ring tensile test is widely used in the metal and tissue industries to measure tensile properties (Bae et al., 2008; Berglund et al., 2004; Konig et al., 2009; Laterreur et al., 2014; Nieponice et al., 2008; Wang et al., 2012; Yoshitake et al., 2004). The ring tensile test method is conducted by inserting a ring specimen into the outside of two pins. However, the stress concentration and slip at the holding parts are observed in many food materials. The ring shape of the specimen may minimize such stress concentrations and slip during the tensile measurement. Applications of the ring tensile test in measuring the failure tensile properties with Laplace's law have been discussed in many studies (Berglund et al., 2004; Konig et al., 2009; Laterreur et al., 2014; Nieponice et al., 2008). However, there has been no report on the use of the ring tensile test to measure the failure tensile properties of food. Application of the ring tensile test may be useful for measuring the failure tensile properties of surimi gels, because it is easy to prepare the ring shape of a specimen by perforation of a board shape of surimi gel. Because the surimi gel is highly flexible, changes in the shape of the specimen during measurement could cause an error during stretching the specimen. Therefore, changes in shape during measurement must be accurately monitored, and

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Nomenclature

A_{view}	front view area of the ring specimen obtained by the number of pixels in the image (pixel)
C_i	instantaneous inside circumference of the ring specimen during ring tensile testing (mm)
C_0	initial inside circumference (mm)
D_i	instantaneous inside diameter of the ring sample (mm)
d_{pin}	diameter of the pins (mm)
H_{view}	front view height of ring specimen (pixel)
R_t	dimensionless thickness ratio
S_c	wall circumferential stress (Pa)
Δs	the distance between the pins
T	wall tension by unit width (Pa mm)
T_r	thickness of the ring specimen (mm)
T_{ref}	reference thickness (mm)
$T_{r,i}$	initial thickness of ring specimen (mm)
w	initial width of ring specimen (mm)
w_i	instantaneous width of the ring specimen (mm)

Greek symbols

ε_f	failure ring tensile strain
σ	internal stress (Pa)
σ_f	failure ring tensile stress (Pa)
$\sigma_{f,\text{ref}}$	reference failure ring tensile stress (Pa)
σ_s	failure stress (Pa)

Subscripts

DIC	digital image correlation

the data related to changes in shape have to be used to calculate mechanical properties such as true strain. Image analysis can continuously measure the changes in the shape of specimen without contacting the specimen (Du and Sun, 2006; Huang et al., 2014; Lee and Yoon, 2015; Shei and Lin, 2012; Yu et al., 2014). Additionally, the adaptability of this technique can be demonstrated by digital image correlation (DIC) to quantify the local displacement and strains.

The objectives of this study were to (1) develop novel equipment to measure the tensile properties of surimi gels, (2) normalize the ring tensile test for dimensions, such as width, diameter, and thickness of ring specimens, and (3) develop mathematical models to estimate the tensile properties of surimi gels using Laplace's law and regression models.

2. Materials and methods

2.1. Surimi gel preparation

According to Yoon et al. (1997), the surimi paste and gel were prepared. Frozen *Itoyori* (threadfin bream) surimi (A grade) was kindly provided by Pulmuone Co. (Seoul, S. Korea) and partially thawed at room temperature for 1 h before being cut into approximately 3 cm cubes. Surimi cubes were chopped for 10 s using a mixer (HMF-260S, Hanil electric, Seoul, Korea). Chopping continued for 10 s with addition of sodium chloride (2 g/100 surimi paste) to extract myofibrillar proteins. Moisture content was adjusted to 76%, 78% and 80% (*w*/*w*) using ice water (0 °C) before chopping for another 30 s. During chopping, cold temperature (<5 °C) was maintained continuously using ice packs. The paste was stuffed into stainless steel cylinders (diameter, 50 mm; length, 45 mm). The cylinders were heated in a water bath at 90 °C for 30 min. Cooked gels were chilled quickly in ice water (0 °C). The gels were kept refrigerated (5 °C) overnight.

2.2. Preparation of rings and conduction of ring tensile tests

The cylinder gels were cut to be disk shaped (diameter, 50 mm; length, 10 mm). The ring shaped specimens were prepared by perforation of gels using a ring cutter (Fig. 1). The ring specimen dimensions had a width = 10 mm, inside diameter = 31 mm and varying thickness = 3, 6 and 9 mm. Cold gels (5 °C) were placed at room temperature for 1 h before the perforation.

The ring tensile measurement system was developed as shown in Fig. 2. Top pin of equipment moved upward at constant speed (2 mm/s) to increase the distance from bottom pin of equipment until the sample failed. The pin displacement and the load required for rupture were measured by a CT3 texture analyzer (Brookfield Inc., Middleboro, USA) with a 50 kg load cell. The diameter of the pins was 19 mm. As shown in Fig. 3, the origin of the displacement of the pins ($\Delta s = 0$) was defined as the position where the pins come into contact. By combining the diameter and the displacement of the pins (Δs), it is possible to evaluate the instantaneous inside circumference and instantaneous inside diameter using Eqs. (1) and (2),

$$C_i = d_{\text{pin}}(\pi + 2) + 2\Delta s \tag{1}$$

$$D_i = \frac{d_{\text{pin}}(\pi + 2) + 2\Delta s}{\pi} \tag{2}$$

where C_i is the instantaneous inside circumference of the ring specimen during ring tensile testing, D_i is the instantaneous inside diameter of the ring sample during ring tensile testing, d_{pin} is the diameter of the pins and Δs is the distance between the pins (Fig. 3). All experiments were conducted 5 times.

2.3. Image analysis

2.3.1. Measurement of instantaneous widths of ring specimens

To estimate instantaneous widths of ring specimens, an image processing technique was used. The image processing steps for this study were (1) image acquisition, (2) image segmentation, and (3) image analysis. A digital single-lens reflex camera (DSLR-500D, Canon Inc., Tokyo, Japan) with a lens (EF-S 18–55 mm *f*/3.5–5.6, Canon Inc., Tokyo, Japan) was located horizontally over the sample at a distance of 13.5 cm. The camera recorded the front view of the ring specimen at frame rates of up to 20 fps and with a resolution of 2.07 million pixels during the tensile test. All images were saved in JPEG format from selected frames of the video. The image processing tool in MATLAB (Mathworks® Inc., Natick, MA, USA) was used for analysis of the instantaneous deformation of the ring specimen. Threshold-based segmentation was a particularly effective technique for scenes containing solid objects placed on a contrasting background. After image segmentation, the Canny edge operator in MATLAB was used for edge detection, the shape of the object was extracted with white color in a black background and then lines of the pictures less than reference value (200 pixel) were cropped (Fig. 4).

The average width of ring specimens during ring tensile testing was calculated using Eq. (3)

$$w_i = \frac{A_{\text{view}}}{H_{\text{view}}} \tag{3}$$