Food Hydrocolloids 36 (2014) 301–307

Contents lists available at ScienceDirect

Food Hydrocolloids

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

Deformation behavior of agar gel on a soft substrate during instrumental compression and its computer simulation

Makoto Nakauma [a,*], Sayaka Ishihara [a], Takahiro Funami [a], Takeshi Yamamoto [b], Mitsuru Higashimori [b]

[a] San-Ei Gen F.F.I., Inc., 1-1-11, Sanwa-cho, Toyonaka, Osaka 561-8588, Japan
[b] Osaka University, 1-1 Yamadaoka, Suita, Osaka 565-0871, Japan

ARTICLE INFO

Article history:
Received 18 May 2013
Accepted 27 September 2013

Keywords:
Deformation
Agar gel
Soft substrate
Compression
Computer simulation
Fracture

ABSTRACT

Deformation behavior of agar gel on a hard or soft substrate was investigated during instrumental compression at a crosshead speed of 10 mm/s, and its computer simulation was performed. Silicone rubbers of different consistencies were used as a soft substrate, and linear stress–strain response upon instrumental compression was confirmed in a range of 10%–30% nominal strain for each silicone rubber at the same crosshead speed. All agar gels of different consistencies tested fractured upon instrumental compression on hard aluminum stage at a nominal strain of av. 58.4% and showed high linearity in a range of 15%–30% nominal strain. Some agar gels fractured upon instrumental compression on the soft substrate at a smaller nominal strain of av. 41.9%, depending on the combination of both entities. Computer simulation based on a finite element model used the linear isotropic elastic moduli of both agar gel and silicone rubber as parameters for the linear static analysis. The simulation recreated well the reality of instrumental compression tests of agar gel on each substrate. The maximum equivalent strain for an element of agar gel was approx. 75% at the fracture point regardless of the substrate, where local strain-concentration occurred at the middle to lower part of the gel, working as a trigger of fracture.

1. Introduction

Texture is important not only for food palatability but also for the safety of eating (Nishinari, 2009), particularly in recent aged society, where the number of people with mastication and swallowing difficulties is increasing. For mastication and swallowing ease, food texture should be optimized from rheological, colloidal, and tribological aspects so that foods can be masticated and swallowed easily even by these patients or elderly people. For example, dysphagia is commonly managed using texture-controlled foods, including thickened liquids and puddings, designed to moderate the flow speed of bolus through the pharyngeal phase (Quinchia et al., 2011). To meet the requirements from the society, texture design of food products is now one of the most important tasks in the industry.

Food texture is associated with the mechanical properties of foods under large deformation conditions rather than under small deformation conditions. This is reasonable when the mode of mastication is considered. In relation to this, food texture is often evaluated instrumentally by fracture stain and fracture stress obtained through compression. In this case, geometries (plunger and sample stage) used are generally made of metal; much stiffer than foods and completely dissimilar from human tissues like the tongue, which is highly deformable and mechanically flexible. This is believed to be one of the main causes for the deviation in results between instrumental measurement and sensory evaluation (Peleg, 2006). This may be particularly for foods of soft texture, which is preferred by people with oral deficiency due to easy consumption with less effort of eating, not requiring teeth mastication but palatal reduction (i.e. compression between the tongue and the hard palate).

In the previous study (Ishihara et al., 2013), an *in vitro* evaluation system of food texture has been developed using soft material instead of hard stage to deduce human oral strategy for size reduction; teeth mastication or palatal reduction. In this evaluation system, agar gel (as a model food) placed onto deformable soft silicone rubber was compressed with a non-deformable hard plunger to mimic human palatal reduction. It has been elucidated that the facture of agar gels on the evaluation system corresponds to the selection of palatal reduction by panel as an oral strategy for size reduction when the elastic modulus of the silicone rubber is close to that of human tongue encountered during eating.

In the present study, differences in the deformation behavior of agar gels either on a hard or soft substrate were confirmed by

* Corresponding author. Tel.: +81 6 6333 0521; fax: +81 6 6333 2076.
E-mail address: m-nakauma@saneigenffi.co.jp (M. Nakauma).

0268-005X/$ – see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.foodhyd.2013.09.022

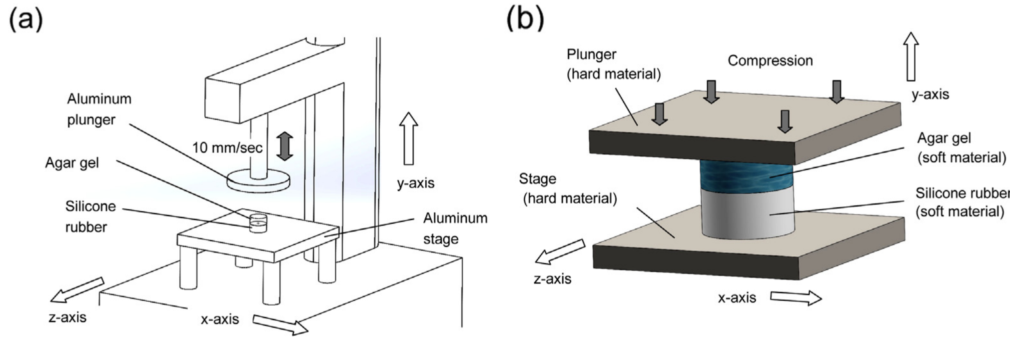

Fig. 1. Schematic drawing of the evaluation system used for instrumental compression tests (a) and of the configuration for computer simulation (b). In instrumental compression tests, each sample was compressed vertically (uniaxially along the *y*-axis into minus direction) at a crosshead speed of 10 or 1 mm/s using aluminum plunger of 50 mm in diameter and 15 mm in thickness on aluminum stage (hard substrate) (*W*: 150 mm × *L*: 150 mm × *H*: 10 mm) or silicone rubber (ϕ 20 mm × *H*: 10 mm). For computer simulation, shape of agar gel or silicone rubber was cylindrical, regarded as a circle of 20 mm in diameter on the *zx*-plane thickened in 10 mm into the *y*-axis. Shape of the stage or the plunger was rectangular, regarded as a square of 150 mm on the *zx*-plane thickened in 10 mm into the *y*-axis. Ager gel was sandwiched between the stage and the plunger with or without silicone rubber between agar gel and the stage.

instrumental compression tests. For the consistency with the previous study (Ishihara et al., 2013), the same gel samples and the same silicone rubbers were used. Fracture profile of the gel on soft substrate from silicone rubber can mimic the size reduction of soft foods during consumption by human and also relates to textural attributes that human perceives. Conditions for computer simulation were optimized based on a finite element model using the linear isotropic elastic moduli of both agar gel and silicone rubber as parameters for the linear static analysis. To the authors' knowledge, few literatures have been reported regarding computer simulation of the deformation behavior for food gels but mostly for synthesized non-edible polymer gels using expanded non-linear model (Duan, Zhang, & Jiang, 2012; Matsuda, Otori, Yabana, & Hirata, 1999; Rzepiela, van Opheusden, & van Vliet, 2002; Sengers, Oomens, & Baaijens, 2004).

The goal of the present study is to recreate the reality of the deformation behavior of ager gels as a model food using computer simulation and to clarify the mechanism of gel fracture. To gain the knowledge on computer simulation is another research interest as a measure for food texture design, particularly food products for the patients or elderly people, importance of which should increase globally for the industry in this aged society.

2. Materials and methods

2.1. Soft substrate from silicone rubber

As a soft substrate, silicone rubbers of different consistencies were prepared according to the previous report (Ishihara et al., 2013). Silicone rubbers were molded into a cylindrical shape of 20 mm in diameter and 10 mm in height. Silicone rubbers obtained were termed as S40, S50, and S60 in the increasing order of consistency.

2.2. Agar gels

Agar gels of different consistencies were prepared according to the previous report (Ishihara et al., 2013). Shape and size of the gels were identical to those of silicone rubbers. Agar gels obtained were termed as A4, A5, and A6 in the increasing order of consistency.

2.3. Instrumental compression tests and image analyses

Stress–strain response of silicone rubbers, agar gels, and the combinations of agar gel and silicone rubber was investigated at 20 °C using a TA XT-2i texture analyzer (Stable Micro Systems, Surrey, UK). Evaluation system used for instrumental compression tests was drawn schematically (Fig. 1(a)). Each measurement sample was compressed vertically (uniaxially along the *y*-axis into minus direction) at a crosshead speed of 10 mm/s using aluminum plunger of 50 mm in diameter and 15 mm in thickness on aluminum stage (hard substrate) (*W*: 150 mm × *L*: 150 mm × *H*: 10 mm) till 45% nominal strain for silicone rubbers, till 50% nominal strain for the combinations of agar gel and silicone rubber, and till fracture for agar gels. The crosshead speed was based on the finding (Hiimeae & Palmer, 2003) that average speed of tongue surface movement is 10.34 mm/s with a range from 2.10 to 32.43 mm/s although this paper deals with liquid swallowing. To confirm the effect of the crosshead speed on the fracture profile of agar gels, tests were also carried out at a lower crosshead speed of 1.0 mm/s due to the limitation of instrument used, which cannot produce the crosshead speeds higher than 10 mm/s. To prevent slippage between agar gel and the plunger, water proof sand paper was adhered onto the surface of the plunger.

Strain–stress curves were identified during instrumental compression. The initial local maximum in the curve was regarded as the yield point. When the fracture of agar gel was detected visually at the yield point, the yield point corresponds to the fracture point. In this case, strain and stress at that point were equal to

Table 1
Fracture profile of agar gels during instrumental compression on aluminum stage or on silicone rubber at a crosshead speed of 10 mm/s.

		On aluminum stage	On silicone rubber		
			S40	S50	S60
A4	Fracture or not	F	F	F	F
	Fracture strain (%)	57.3	39.9	41.4	40.2
	Fracture stress (kPa)	12.8	7.1	9.9	12.2
A5	Fracture or not	F	N	F	F
	Fracture strain (%)	58.5	na	43.9	42.5
	Fracture stress (kPa)	37.8	na	21.3	21.9
A6	Fracture or not	F	N	N	F
	Fracture strain (%)	59.4	na	na	43.2
	Fracture stress (kPa)	60.3	na	na	37.6

F and N represent that agar gels did and did not fracture upon instrumental compression, respectively. Fracture strain and stress were listed when the gel fractured. Crosshead speed was 10 mm/s during compression. In using silicone rubber as a substrate, the maximum nominal strain was 50% of the combination of agar gel and silicone rubber, and the fracture strain of agar gel itself was determined by the image analyses. Data on the fracture strain and stress were means of triplicate. na: Not applicable.