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Adhesion Testing of Dysphagia Diets for the Quantitative Evaluation of Swallowing

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Abstract

Swallowability is an essential characteristic of foods, particularly for dysphagia patients, but it is still difficult to quantitatively evaluate. Although fluid-mechanics-based rheological methods have been developed for evaluating liquid foods in recent years, they are not suited to highly viscous or near-

solid foods. In addition to shear flow, the detachment of the food bolus from the pharyngeal mucosa should also be considered. To address this, we conceptualized swallowing as an adhesion phenomenon between the food bolus and pharyngeal mucosa, and applied testing methods designed for industrial adhesive tapes. Scallop mousse and whole rice porridge, representative dysphagia diets that are too heterogeneous to evaluate using conventional fluid mechanics, were used as the test samples. The shear and detachment stresses of the food samples on simulated pharyngeal mucosa were measured considering the addition of thickeners and interaction with saliva. For the scallop mousse, the addition of thickeners and simulated saliva resulted in similar trends in both the rheological and adhesion tests. Conversely, the rice porridge exhibited inconsistency between the test results, indicating that the rheological data alone were insufficient for predicting swallowability. Moreover, the amount of residue adhering to the model mucosa after detachment in the adhesion tests was affected by the addition of the thickener and simulated saliva. As this study represented a preliminary attempt to assess the applicability of methodologies from the field of mechanical engineering to the field of food evaluation, a tentative saliva substitute without digestive enzymes was used. Nevertheless, these findings highlight the value of adhesion testing in capturing the cohesiveness of dysphagia diets, offering complementary insights to conventional evaluation methods.

Keywords: Dysphagia, Swallowing, Rheology, Thickener, Extensibility, Adhesion

1. Introduction

In today's aging society, there is an urgent need for easily swallowable diets and nutritional supplements because many elderly people and patients with diseases suffer from dysphagia—that is, they have difficulty in swallowing—which is directly related to deterioration in their nutritional status and quality of life (Logemann, 2007; Ueda & Nohara, 2024; Yoshimatsu *et al.*, 2022). Highly liquid foods can be modified with thickening agents to produce swallowable foods, which play an important role in facilitating the eating behavior of people with dysphagia and ensuring the safe intake of nutrients (Nakauma *et al*., 2011; Nishinari *et al*., 2019).

The International Dysphagia Diet Standardization Initiative (IDDSI) is an international standard for evaluating the physical properties of foods for people with dysphagia (Cichero *et al.*, 2013). This framework was designed to provide appropriate meal forms for patients based on their swallowing ability by classifying food and beverage textures into eight categories (Cichero *et al.*, 2017; Su *et a*l., 2018). However, optimizing the amount of added thickening agents can be challenging as it tends to rely on the experience of dietitians (Jun Kayashita, Ichiro Fujishima, Junko Fujitani, Shouji Hironaka, Akiko Kojo, Miki Mizukami, Naoyuki, Senda, 2021). To correlate the sensory indicators of “ease of swallowing” with quantifiable metrics, the effects of thickener addition during the development of swallowing aids have been evaluated by correlating the rheological properties of food—such as the shear-rate-dependent viscosity—with swallowing safety (Cultler *et al*., 1983; Houska *et al*., 1998; Hutchings & Lillford, 1988; Ohie *et al*., 2022; Shama & Sherman, 1973; Wood, 1968). These methods

have shown some value but are limited to liquid foods.

The swallowability of solid foods is strongly related to the chewing process to form a food bolus, which is a heterogeneous medium consisting of solid ingredients with a viscous liquid matrix (Nishinarl, 2003). The food bolus is generally characterized by its extensibility (Ben Tobin *et al*., 2020; Hadde & Chen, 2019; Nishinari *et al*., 2019; Ross *et al*., 2019), which originates from its cohesiveness and adhesion to the pharyngeal mucosa. Consequently, swallowability should be related to the mastication process and detachment of the food bolus from the pharyngeal mucosa (Iwasaki *et al.*, 2009). However, the IDDSI framework does not adequately account for physical interaction along the interface between a food bolus and the pharyngeal mucosa. Several devices and assessment tools have been proposed to imitate the real swallowing process, considering not only the velocity profile and shear rate but also the physiological geometry of the throat with pressure (Qazi & Stading, 2017; Stading *et al.*, 2019). They are useful in linking the process parameters—such as the swallowing time and thickener concentration—with extensional behaviors from a swallowing safety point of view. Demonstrations using these *in-vitro* models are indispensable for clinical purposes, but simple testing methods based on a fundamental understanding of the swallowing process are also necessary for quantitative and practical evaluation. Notably, testing methods have not yet been established for the adhesion of the food bolus to the pharyngeal mucosa and its subsequent detachment during swallowing, whereas the rheological and extensional properties of the food bolus itself have been extensively characterized.

Consequently, by focusing on the similarity to other adhesion–detachment systems, we proposed applying the widely used testing methods designed for industrial adhesive tapes (Sun *et al*., 2013) to quantitatively evaluate the sensory indicators of swallowing ease. In the development of novel dysphagia diets leveraging knowledge of food hydrocolloids, the establishment of such measurement techniques could enable a shift in functional evaluation from conventional qualitative assessments to a more scientific and quantitative approach.

The adhesion performance of industrial adhesive tapes is generally evaluated in terms of three metrics (**Figure 1**)—that is, the peel force (**Figure 1(a)**) indicates how strongly an adhesive tape adheres to an object (adherend) and is measured by removing the adhesive tape from it; the holding power (**Figure 1(b)**) indicates how long the adhesive tape maintains its adhesion over time under a certain applied load; and the tack (**Figure 1(c)**) indicates how quickly the adhesive tape adheres to an object upon contact and is determined by measuring the force required to detach a probe from the adhesive surface after a few seconds of contact. Our group has applied these testing methods extensively to clarify the mechanisms of adhesion and establish general strategies for designing industrial adhesive tapes (Takahashi *et al.*, 2016, 2020, 2021). Interestingly, our proposed index for evaluating the adhesion performance of industrial adhesive tapes is similar to that of liquid foods as it focuses on their rheological properties (Ohie *et al.*, 2022; Yamada *et al.*, 2022).

Accordingly, this study developed novel methods for characterizing semi-solid dysphagia diets by focusing on the adhesion of food to the pharyngeal mucosa and its subsequent detachment during the

swallowing process. We selected two kinds of food samples—that is, scallop mousse as a highly viscous and homogeneous sample and rice porridge as a heterogeneous semi-solid sample. First, their viscoelastic properties were investigated with the addition of thickeners and a polymer solution (simulated saliva). Subsequently, the shear and detachment stresses along the interface between the food samples and silicone rubber sheets (simulated pharyngeal mucosa) were measured by testing methods modified from those used for industrial adhesive tapes. The adhesion of the model dysphagia diets along the simulated pharyngeal mucosa was then related to their viscoelastic properties.

To closely approximate real human saliva, it is essential to consider both chemical aspects—such as digestive enzymes—and physical properties—including its shear-rate-dependence viscosity and extensibility. Although several model saliva formulations have been proposed (Nishinari *et al*., 2024; Vissink *et al*., 1984), the properties of natural saliva vary among individuals. To perform measurements using a simplified system as a stepping stone, artificial saliva was employed in the present study. We selected PEO-27—a nonionic water-soluble thermoplastic polymer solution—because a recent report described a simple recipe for preparing a solution whose extensional properties closely resembled those of real human saliva (Shimokasa & Obara 2020). Because the process of decomposition of food by digestive enzymes is complex (Zhang et al., 2022), it was thereby neglected for simplicity to focus on the relationship between their viscoelastic properties and adhesion to the silicone rubber sheets. It was a preliminary attempt to assess the applicability of the methodologies from the field of mechanical engineering to the field of food evaluation. It should be emphasized that the measurement techniques

proposed here are not limited to the PEO-based solution and could be applied to a wide range of saliva models, which should be the next phase of future work. This study offers complementary insights to conventional rheology-based evaluations, which could benefit the effective development of safer dysphagia diets.

2. Experimental Methods

2.1 Sample preparation

Scallop mousse and rice porridge—provided by the Department of Nutrition and Dietetics, Hokkaido University Hospital, Japan—were used as representative examples of highly viscous liquid food and semi-solid food samples, respectively. Scallops are low in fat, high in protein, and rich in vitamins and minerals, rendering them an ideal food for maintaining the health of the elderly. The mousse-like scallops melt in the mouth and are an ideal food for swallowing. Scallop mousse was prepared by processing scallops in a blender for approximately 40 s until they formed a paste, followed by the addition of cream, milk, salt, paprika, and other ingredients, before being further blended for approximately 3 min. The blended mousse was then heated at 130 °C for at least 20 min.

Rice porridge has high water content and can help prevent dehydration in people with dysphagia. It was prepared by soaking raw rice in seven times its weight of water, followed by cooking for 20 min. A xanthan-gum-based thickener (Softia S, Newtree Co., Ltd.) was used as a thickening agent, which also contains a pH adjuster according to the product information provided by the company. The

porridge also contains a total of 24.9 g of dietary fiber per 100 g and can help increase a patients' intake of dietary fiber.

Simulated saliva solution was prepared in the laboratory using 0.05% polyethylene oxide (PEO) with an average molecular weight of 7,000,000 (PEO-27, Sumitomo Seika Chemicals Co., Ltd.). PEO-27 is a non-Newtonian, nonionic, water-soluble thermoplastic polymer used mainly for controlling the viscosity, texture, and other rheological properties of foods. In this study, the prepared PEO-27 solution exhibited rheological properties similar to those of saliva and was mixed with the food samples to simulate the food entering the throat after chewing (Shimokasa & Obara, 2022). The scallop mousse and rice porridge samples were mixed with 0.02 g/mL of thickener and a range of PEO-27 content (0, 9, or 16.7 wt%, to simulate the differences between individuals). Four types of samples were prepared using the scallop mousse and rice porridge (**Table 1**).

A 1.0-mm-thick silicone rubber sheet (Tokawa Rubber Co., Ltd.) was prepared to simulate the pharyngeal mucosa in the evaluation of the interaction between the food bolus and the surface of the throat lining (Vieira *et al*., 2020). The silicone rubber sheet was cut into appropriate lengths, and the resistance to shear flow and detachment of the food samples from its surface were measured using testing methods for industrial adhesive tapes with appropriate modifications.

2.2 Dynamic mechanical analysis (DMA)

The viscoelastic properties of the prepared food samples were measured using a dynamic mechanical analyzer (MCR 702e MultiDrive, Anton Paar GmbH). The temperature was set to 25 °C, and a circular

flat fixture of diameter 50 mm was used. First, the linear viscoelastic range of the food sample was determined at a frequency of 1 Hz over a strain sweep range of 0.01–100%. It is evident that the lower strain amplitudes would yield torque values that approached the rheometer's resolution limit. Consequently, it was preferable to employ the highest strain amplitude, provided that the linear regime was guaranteed. Accordingly, the upper limit of the strain amplitude was set to 0.3%, 0.3%, 0.5%, and 0.4% for sample conditions (i)–(iv), respectively, for angular frequency sweeps over the 0.01–100 rad/s range.

2.3 Shear-resistance tests

The shear characteristics of adhesive tapes are usually measured using holding-power tests, in which a fixed load is applied vertically to a tape attached to the substrate (**Figure 1(b)**). However, food samples cannot be placed vertically owing to their high fluidity. Therefore, based on the peel test shown in **Figure 1(a)**—which is a common method of measuring the peel force of an adhesive tape—we performed shear-resistance tests using the setup shown in **Figure 2**. In a typical peel test, the substrate needs to slide as the adhesive tape is pulled off the substrate to maintain the peeling angle. However, in our test setup, the food sample was intentionally fixed to generate shear flow along the food sample. A silicone rubber sheet was cut into strips (250 mm long and 25 mm wide), and half of the entire length was placed on a food sample in a plastic container. One end of the silicone rubber sheet was gripped using a small tabletop testing machine (EZ-LX HS, Shimazu Corporation), and the force was measured as the sheet was pulled vertically through a pulley. A preliminary calibration test was conducted using

a silicone film floated on a water surface under conditions of negligible shear force to obtain the weight of the film itself during the pulling process. Subtracting this force measured for water, the shear force along the silicone rubber sheet in contact with the food samples was obtained. The shear force was then divided by the remaining contact area with the food sample to consider the decrease in contact area with the food during lifting to obtain the shear stress.

As the adhesion test is typically conducted at a constant velocity over an extensive range, this study applied three distinct pulling velocities of 3, 180, and 1800 mm/min, considering typical swallowing conditions (Kumagai *et al.*, 2009). During the process of eating and swallowing, a food bolus undergoes unsteady deformation as well as kinematic behavior. In principle, both the shear-resistance and probe-tack tests can measure the force response to unsteady deformation, though whether the results are meaningful is debatable. As a general approach, however, it is common to begin by understanding the underlying physics through measurements conducted in simplified and confined systems. Following this rationale, the present study first conducted measurements at three different constant velocities.

2.4 Probe-tack tests

The detachment force between the food and silicone rubber was measured using probe-tack tests as the contact time during the swallowing process is short. An acrylic cylinder was attached to a small tabletop tester (EZ-LX HS, Shimadzu Corporation), and a piece of a silicone rubber sheet of diameter 30 mm was attached to the bottom of the cylinder (**Figure 3**). This cylindrical probe approached the

surface of the food samples and was raised at speeds of 3, 180, and 1800 mm/min after confirmation of complete contact with the sample surface. The separation between the silicone sheet on the tip of the probe and the food sample was recorded from the side using a single-lens reflex camera (EOS 6D, Canon Inc.).

3. Results and Discussion

3.1 Dynamic viscoelasticity

Figure 4 shows the DMA results for the storage and loss moduli, respectively, obtained for the scallop-mousse samples with various amounts of added thickener and PEO-27 (as defined in **Table 1**). The DMA tests were repeated twice for each sample to ensure reproducibility. Under very-low frequency conditions—specifically, < 0.1 Hz for the storage modulus G' and < 0.01 Hz for the loss modulus G''—the moduli decreased with the addition of the thickener; by contrast, at higher frequencies, the moduli increased with the addition of the thickener. Moreover, the addition of PEO-27 (samples (iii) and (iv)) reduced the thickening effect of the thickener, observed as reductions in the storage and loss moduli curves toward those for (i)—that is, the control sample (pure scallop mousse).

Figure 5 shows the DMA results for the storage and loss moduli, respectively, obtained for the rice porridge samples. As demonstrated in a comparison of samples (i) and (ii), the storage and loss moduli both decreased with the addition of the thickener, indicating that the thickening agents could soften heterogeneous semi-solid foods such as rice porridge. Both moduli decreased further upon the addition

of PEO-27, as was observed with the scallop mousse. The addition of simulated saliva generally reduced the storage and loss moduli, irrespective of the type of food.

3.2 Shear resistance

Figure 6(a) shows the shear-stress–displacement curves obtained for the scallop-mousse samples from the shear-resistance tests, conducted at 1800 mm/min. The tests were repeated three times for each condition, and the average values for displacements above 20 mm are summarized in **Figure 6(b)** for the various test velocities. The shear stress increased with the addition of the thickener but decreased with the addition of PEO-27. This result was consistent with the general trends in the storage and loss moduli curves (**Figure 4**), indicating the effectiveness of dynamic viscoelasticity measurements for evaluating the shear resistance of the simulated pharyngeal mucosa.

Figure 7(a) shows the shear-stress−displacement curves obtained for rice porridge using shear-resistance tests conducted at 1800 mm/min. The shear resistance did not change appreciably upon the addition of the thickening agent but decreased slightly with the addition of PEO-27. The average shear stresses measured at all testing velocities are shown in **Figure 7(b)**. The general trends of increasing shear stress with the addition of the thickener and decreasing shear stress with the addition of PEO-27 were consistent with those for the scallop mousse (measured at 180 mm/min). At the lowest velocity of 3 mm/min, the shear stress remained unchanged even with the added thickener, whereas the addition of 9 wt% PEO-27 increased the shear stress. However, at the highest velocity of 1800 mm/min, the shear stress decreased with the added thickener and further decreased with the addition of PEO-27

(**Figure 7(a)**). This trend was consistent with that of the dynamic viscoelasticity results shown in **Figure 5**. Although the DMA results showed that the effects of adding a thickener and PEO-27 were similar over a wide range of frequencies, they did not always correspond to the shear resistance on the simulated pharyngeal mucosa but were strongly dependent on the shearing velocity.

3.3 Delamination resistance

Figure 8(a) shows the displacement–load curves for the scallop-mousse samples obtained from the probe-tack tests, conducted at a velocity of 1800 mm/min. The control sample (i) exhibited a decrease in load after approximately 2 mm of displacement, whereas the samples with only the thickener (ii) and the thickener and PEO-27 (iii and iv) exhibited a decrease in load after approximately 5 mm of displacement. The maximum load increased considerably with the added thickener and decreased with the further addition of PEO-27. Consequently, the presence of the thickener determined the displacement at which the maximum load was reached, and the addition of PEO-27 systematically decreased the load without changing the elongation. **Figure 8(b)** shows the results of converting the maximum load to maximum stress by dividing the measured force by the contact area. The maximum stress increased considerably with the addition of the thickener and decreased with the addition of PEO-27, regardless of the velocity.

Figures 9(i)–(9(iv) show photographs of the scallop-mousse samples (i)－(iv), respectively, captured at four equally spaced displacements between the maximum stress and the point at which the sample detached or broke—that is, as indicated by the arrows in **Figure 8(a)**. The control sample

detached from the silicone film with almost no elongation and little food remained on the probe (**Figure 9(a)**). The elongation profiles of sample (ii) with the added thickener and samples (iii) and (iv) with the thickener and PEO-27 exhibited similar shapes at each point; the amount of food remaining on the probe was similar in all cases. Comparing the photographs for these samples with those of the control sample shows that more food remained on the probe after the addition of the thickener. This implies that adding a thickener to swallowing diets made it more difficult to detach the food from the pharyngeal mucosa.

Figure 10(a) shows the displacement–load curves for the rice porridge samples obtained using probe-tack tests, conducted at a velocity of 1800 mm/min. Unlike the scallop mousse, the load–displacement curves did not change notably with the addition of the thickener. The tendency of the maximum load to decrease with the addition of PEO-27 to rice porridge was consistent with that observed for the scallop-mousse samples, with a similar maximum displacement of approximately 5 mm for all samples. The maximum load values were converted to maximum stress values by dividing the measured values by the contact areas; these data were plotted as a function of the test velocity, as shown in **Figure 10(b)**. Here, the maximum stress increased with increasing velocity. The maximum stress did not change notably or slightly increased with the addition of the thickener; however, it decreased with the addition of PEO-27 in the same manner at all velocities.

Like **Figure 9** for the scallop-mousse samples, **Figures 11(i)–11(iv)** show photographs captured at four displacement steps during the detachment of the rice porridge samples from the test probe. The

detachment profiles were similar for samples (i) and (ii), with and without the thickener, respectively; however, the addition of PEO-27 enhanced the elongation of the samples considerably, with less food remaining on the probe after separation. Consequently, the thickener had minimal effect, whereas the simulated saliva promoted the detachment of a semi-solid food sample from the simulated pharyngeal mucosa.

3.4 Relationship between shear and detachment stresses

To examine the effects of the thickener and PEO-27 on the interaction between the shear and detachment stresses, we plotted the data for the scallop-mousse samples in **Figures 6(b)** and **8(b)** together, as shown in **Figure 12(a)**, where the x-axis shows the shear stress from the shear-resistance tests, and the y-axis shows the maximum detachment stress from the probe-tack tests. Similarly, the data for the rice-porridge samples in **Figures 7(b)** and **10(b)** are summarized in **Figure 12(b)**. At the highest velocity of 1800 mm/min, the arrows indicate the change from the control sample (i) to those with the thickener (ii), and thickener and PEO-27 (iii and iv). The detachment stress was higher than the shear stress for both the scallop-mousse and rice-porridge samples, indicating the importance of evaluating the detachment stresses to understand the swallowing efficiency.

Both the shear and detachment stresses of the scallop mousse increased with the addition of the thickener (**Figure 12(a)**), but the increase in the detachment stress was particularly pronounced. As the amount of PEO-27 increased, the shear and detachment stresses approached those of the control sample. This trend was similar at the moderate measurement velocity of 180 mm/min. However, the

photographs captured during the probe-tack tests for the scallop mousse (**Figure 9**) show that the control sample detached cleanly from the silicone sheet, whereas all the samples with both the thickener and PEO-27 remained on the silicone sheet after extensive elongation. This implies that the addition of the thickener increased the risk of pasty food residue adhering to the pharyngeal mucosa. Moreover, evaluating the properties of the food sample itself—for example, by DMA—is not sufficient; its adhesion with the pharyngeal mucosa must also be studied to comprehensively understand the swallowing process.

Similarly, the detachment–shear stress relationship for the rice-porridge samples (**Figure 12(b)**) showed that the addition of the thickener did not change the detachment stress noticeably. Thickener addition only increased the shear stress appreciably at a test velocity of 180 mm/min, whereas the decrease in the detachment stress with the addition of PEO-27 was more pronounced at the same velocity. Additionally, the photographs from the probe-tack tests with the rice-porridge samples (**Figure 11**) show no change with the addition of the thickener. However, PEO-27 addition increased the elongation during the detachment process, and the food sample was less likely to remain on the probe surface. Unlike the DMA results showing that the storage and loss moduli decreased with the addition of the thickener, no direct correlation between the shear-resistance and detachment from the silicone sheet was observed upon the addition of the thickener.

3.5 Interpretation and limitations of this study

The thickener used in this study (Softia S), is composed primarily of xanthan gum, which is a

polysaccharide composed of repeating units consisting of a main chain of two glucose residues and a side chain containing two mannose residues and one glucuronic acid residue. This binds with water molecules, restricting their movement, thereby increasing the liquid's viscosity. Owing to its high stability, low temperature dependence of viscosity, and resistance to degradation by α-amylase, it is widely used as a thickening agent in fluid foods. This thickening effect was confirmed by the increase in both the storage and loss moduli of the scallop-mousse samples. However, this was not the case for rice porridge samples, which could be because of its rice-grain heterogeneity surrounded by a liquid matrix.

As shown in **Figure 11**, the swollen rice grains were dispersed within the starch matrix at almost the maximum packing limit. Because the individual rice grain is highly sticky, the cohesiveness originates from direct contact between the rice grains. Even though the addition of the thickener increased both moduli of the liquid matrix, increasing the total volume of the liquid matrix widens the distance between individual rice grains, reduces their contact, and decreases the cohesion of the food bolus.

Generally, PEO-27 has a thickening effect, but its aqueous solution has a lower viscosity than that of the scallop mousse or rice porridge; consequently, the solution exhibited a viscosity reduction effect in this study. It is noteworthy that the rice porridge showed no residue after detachment (**Figure 11**) but plenty of the scallop mousse remained on the silicone rubber sheet although both moduli diminished to the same extent after the addition of PEO-27. PEO-27 diluted the rice porridge and

widened the gaps between individual rice grains, preventing their adhesion to the silicone rubber sheet. By contrast, the addition of the thickener to the scallop mousse promoted its compatibility to the silicone rubber sheet considerably, as well as the viscosity, but the dilution effect of the added PEO-27 decreased the cohesion of the scallop mousse itself relative to the strong adhesion to the silicone rubber sheet. Consequently, the adhesion property of the food bolus did not always correlate to the viscoelastic property and should be evaluated separately with the consideration of heterogeneity of the food bolus and compatibility with the pharyngeal mucosa. The effect of the combination of the fluid phase and dispersed phase—specifically their size distribution and morphology—on rheological properties and texture has been recognized as important in previous studies (Ben Tobin *et al*., 2020). We believe that the method proposed in this study could serve as a quantitative tool for evaluating the safety and texture of novel, highly functional food products developed through the application of food hydrocolloids.

It is important to note that the present study concentrated on the relationship between the viscoelastic and adhesion properties of the food bolus to validate the effectiveness of the new testing methods. The experiment was intentionally designed with simple systems using the simulated saliva (PEO-27) and pharyngeal mucosa (silicone rubber sheet) to interpret the results without unknown factors. Quantitative evaluation using the proposed testing methods was established as the first step; consequently the next step should be examination with the addition of digestive enzymes under a more realistic pharyngeal-mucosa model. Various studies have examined the interaction between rice and α-

amylase in relation to the size of rice grains, moisture content, chewing strength, and stickiness (Chen et al., 2022; Yang et al., 2023; Zhang et al., 2022). The proposed testing methodology of this study could quantify these effects individually and relate them to observations from *in-vitro* models. This in turn will facilitate a comprehensive understanding of the fundamental factors of viscoelasticity, extensibility, cohesiveness, and adhesion of the food bolus to underpin the design of ideal dysphagia diets.

4. Conclusions

This study investigated the adhesion between semi-solid foods and a pharyngeal-mucosa model by measuring the shear and detachment forces. Scallop mousse and rice porridge were prepared, and the effects of adding a thickener and polymer-based simulated saliva solution on swallowing were examined. The food samples were first measured by DMA to obtain the viscoelastic properties, before being examined using shear-resistance and probe-tack adhesion tests to quantify their interaction with a silicone rubber sheet to simulate the pharyngeal mucosa. The relationship between the DMA results and the shear and detachment stresses was consistent for the scallop mousse samples in terms of the effect induced by the thickener and saliva model, but was not consistent for the rice porridge samples. This indicates that the viscoelastic properties of the food samples measured by DMA were not sufficient to evaluate the swallowing process. Consequently, it is essential to evaluate the adhesion of the food bolus to the pharyngeal mucosa separately because the extensibility of dysphagia diets is

strongly related to their adhesion and cohesion properties.

Moreover, by evaluating the relationship between the shear and detachment stresses, we could quantitatively evaluate the effect of the addition of the thickener and simulated saliva on the swallowing process. Although the interaction between the food samples and pharyngeal mucosa was characterized, it is necessary to consider the differences among individual patients by performing sensory tests in future studies. Based on measurement of the shear and detachment stresses proposed in this study, we aim to contribute to the development of swallowing aids with optimal textures by comprehensively considering such sensory and physiological factors in future studies.

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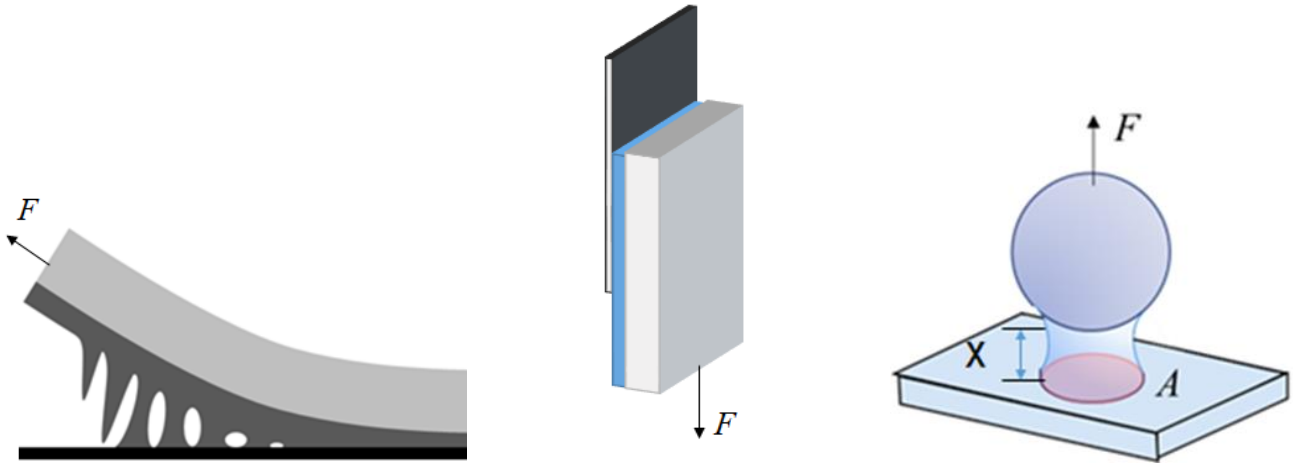
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Table 1 Sample compositions

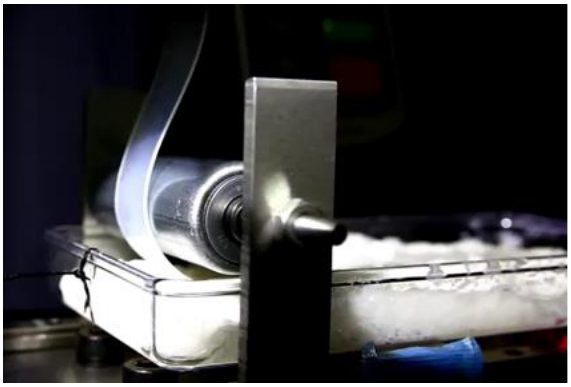
Sample name	Thickener [g/mL]	PEO-27 [wt%]
(i)	-	-
(ii)	0.02	0
(iii)	0.02	9
(iv)	0.02	16.7

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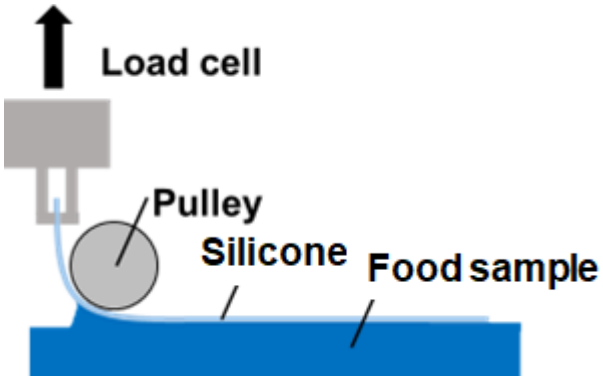


(a) (b) (c)

Figure 1

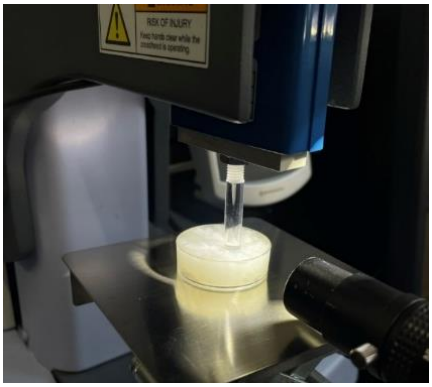


(a)

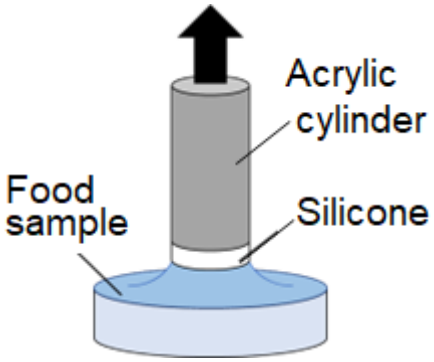


(b)

Figure 2



(a)



(b)

Figure 3

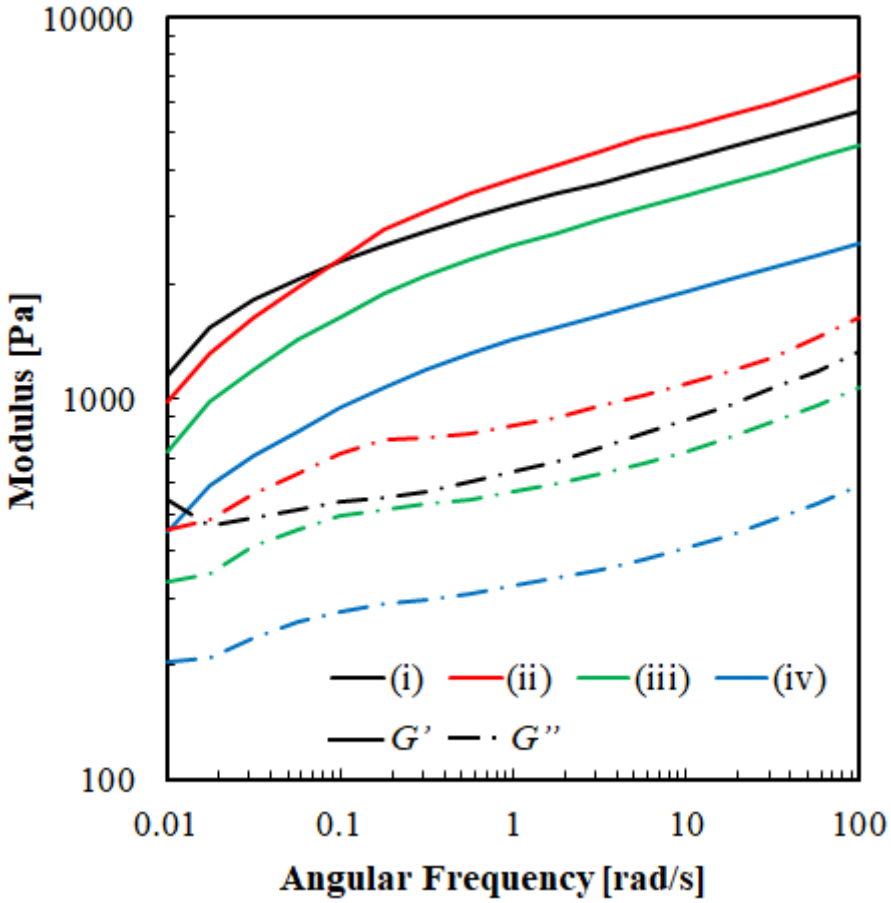

10000
1000
100
Modulus [Pa]
0.01
0.1
1
10
100
Angular Frequency [rad/s]
(i)
(ii)
(iii)
(iv)
G'
G''

Figure 4

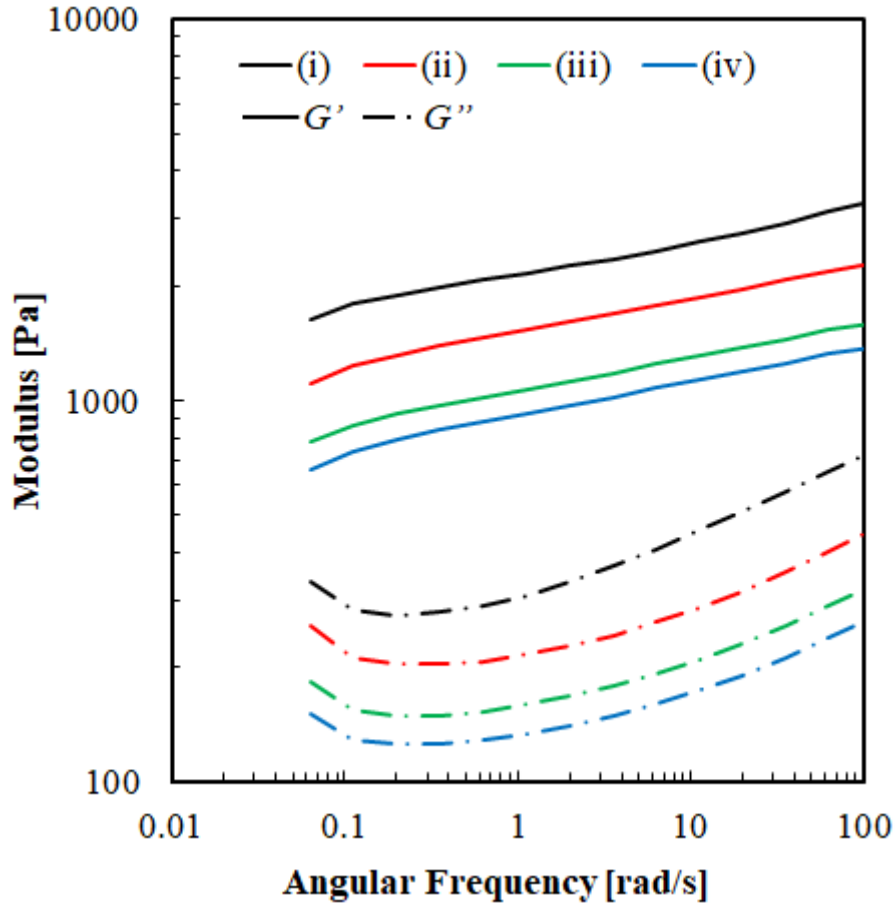
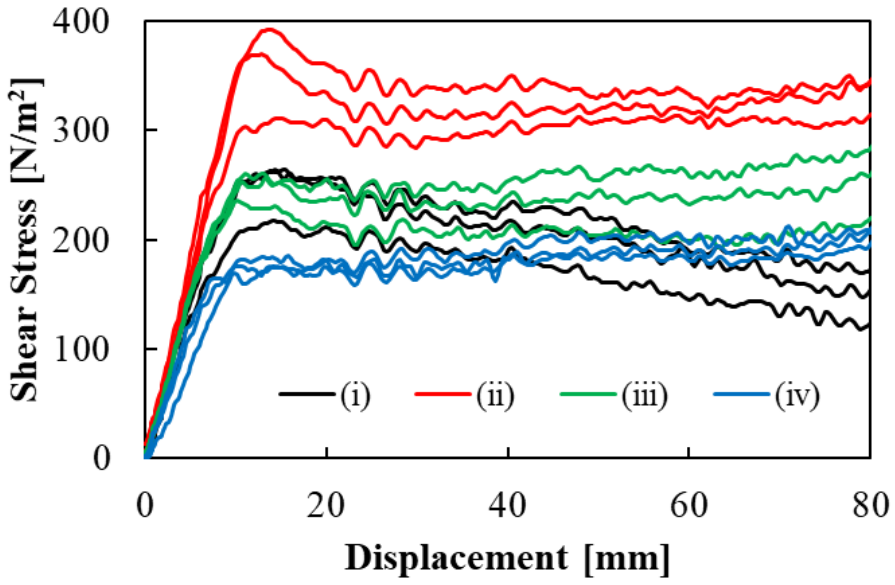
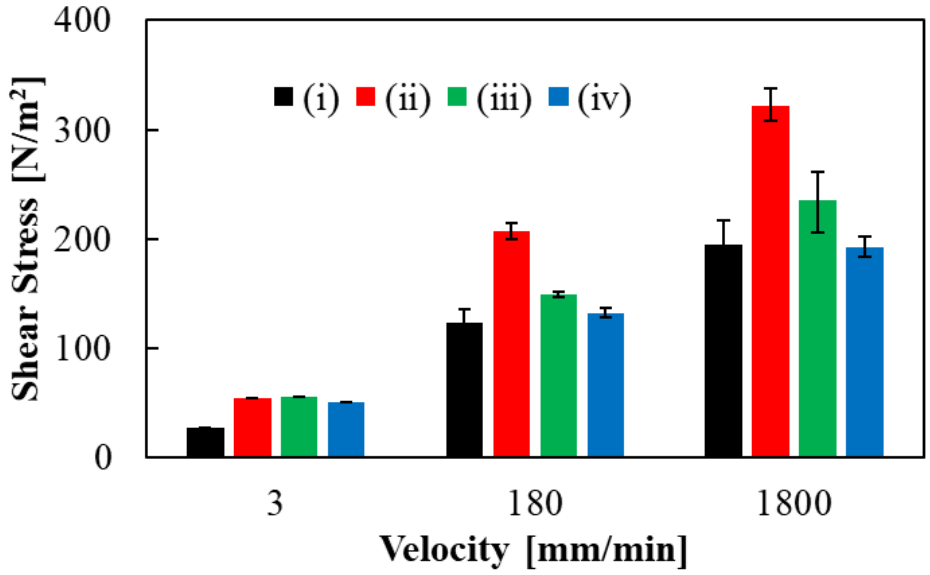

10000
1000
100
Modulus [Pa]
(i)
(ii)
(iii)
(iv)
G'
G''
0.01
0.1
1
10
100
Angular Frequency [rad/s]

Figure 5

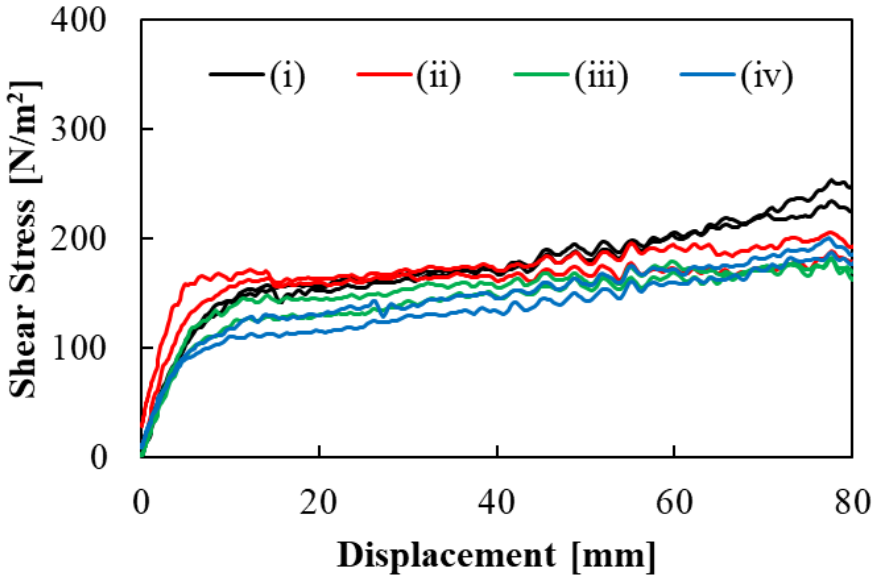

400
300
200
100
0
Shear Stress [N/m²]
(i)
(ii)
(iii)
(iv)
0
20
40
60
80
Displacement [mm]

(a)

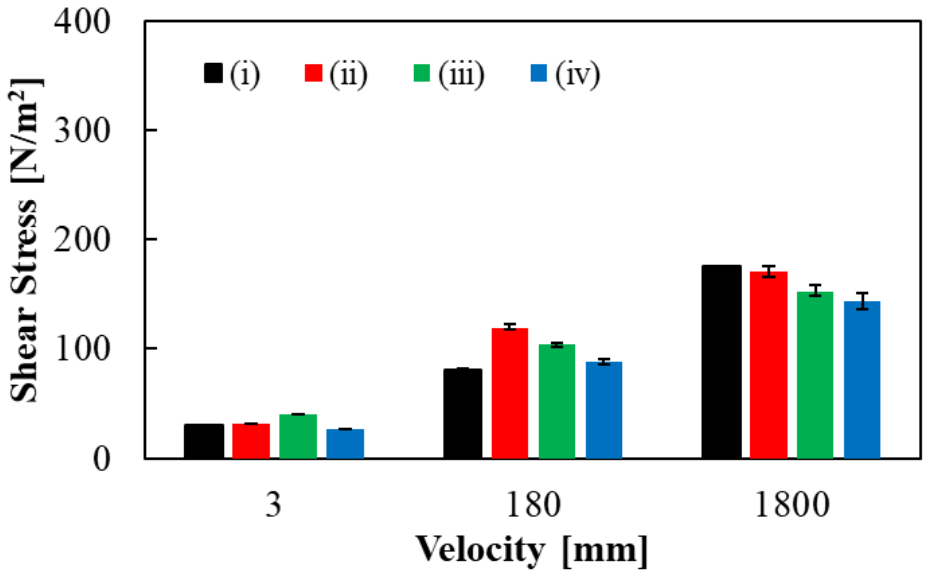

400
300
200
100
0
Shear Stress [N/m²]
(i)
(ii)
(iii)
(iv)
3
180
1800
Velocity [mm/min]

(b)

Figure 6

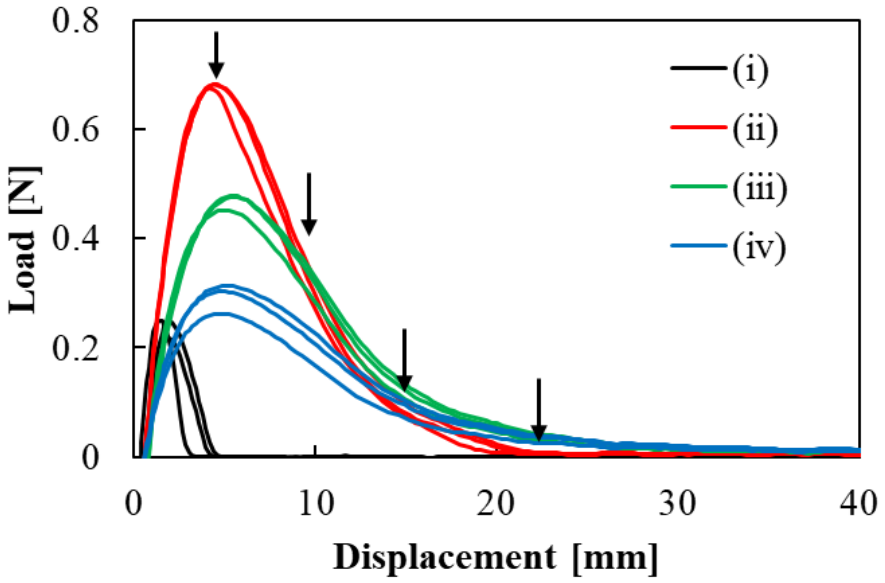

400
300
200
100
0
Shear Stress [N/m²]
(i)
(ii)
(iii)
(iv)
0
20
40
60
80
Displacement [mm]

(a)

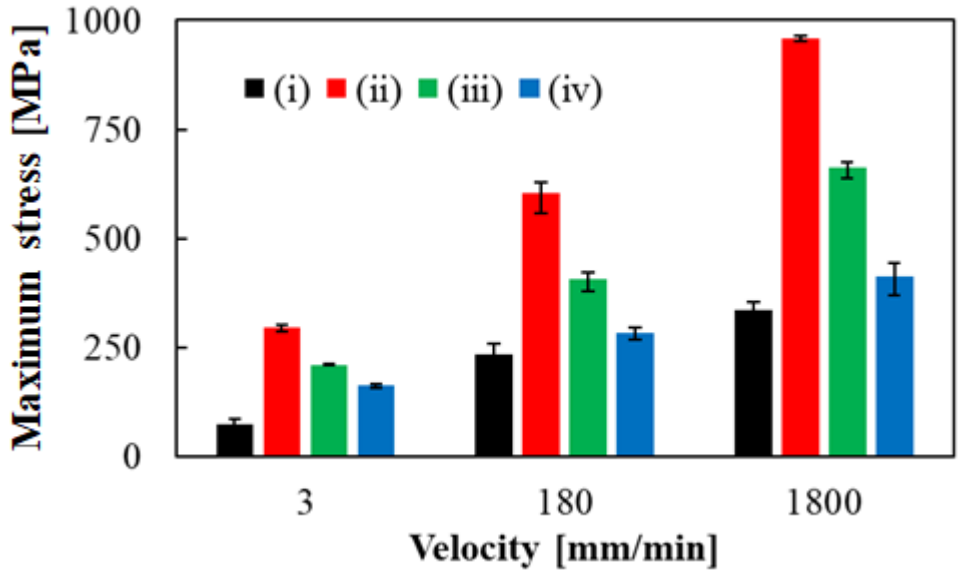

400
300
200
100
0
Shear Stress [N/m²]
(i)
(ii)
(iii)
(iv)
3
180
1800
Velocity [mm]

(b)

Figure 7

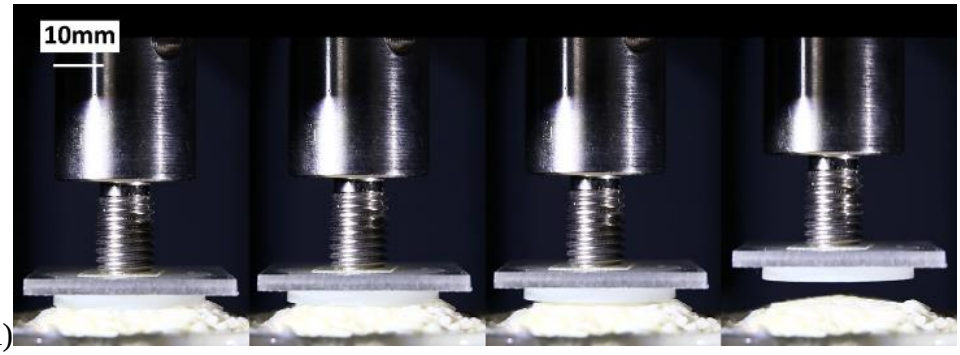

0.8
0.6
0.4
0.2
0
Load [N]
0
10
20
30
40
Displacement [mm]
(i)
(ii)
(iii)
(iv)

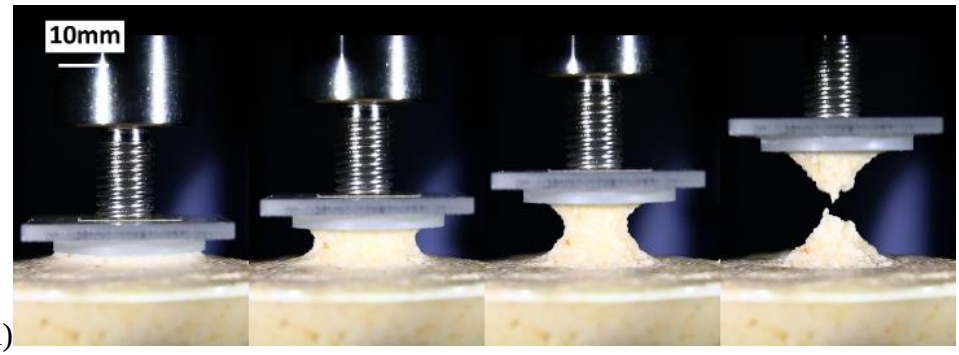
(a)

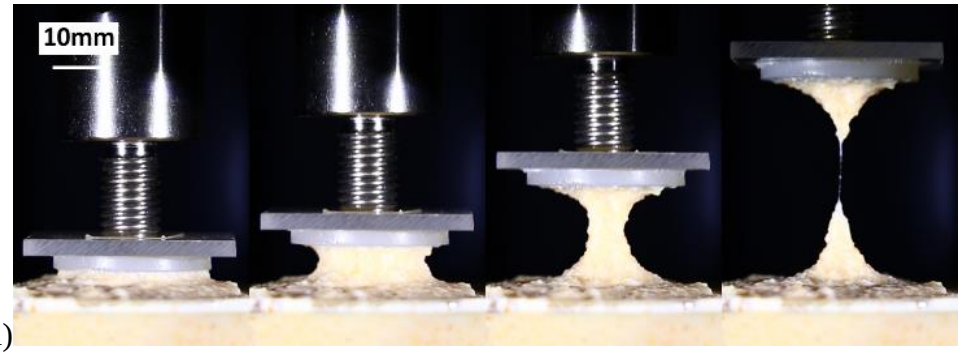

1000
750
500
250
0
Maximum stress [MPa]
(i) (ii) (iii) (iv)
3
180
1800
Velocity [mm/min]

(b)

Figure 8

(i) 

(ii) 

(iii) 

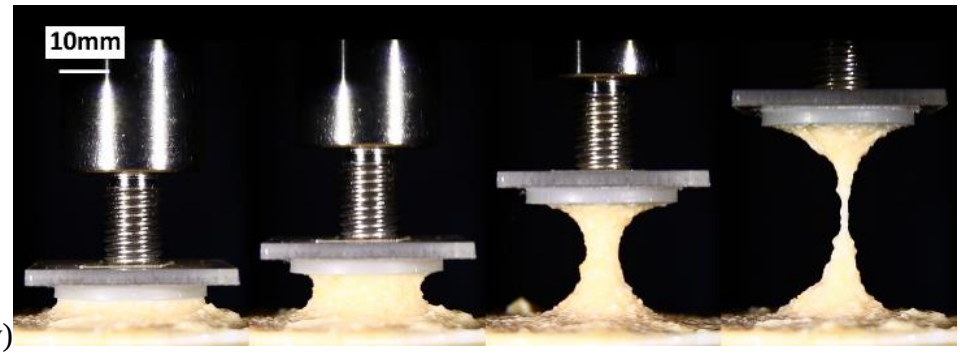
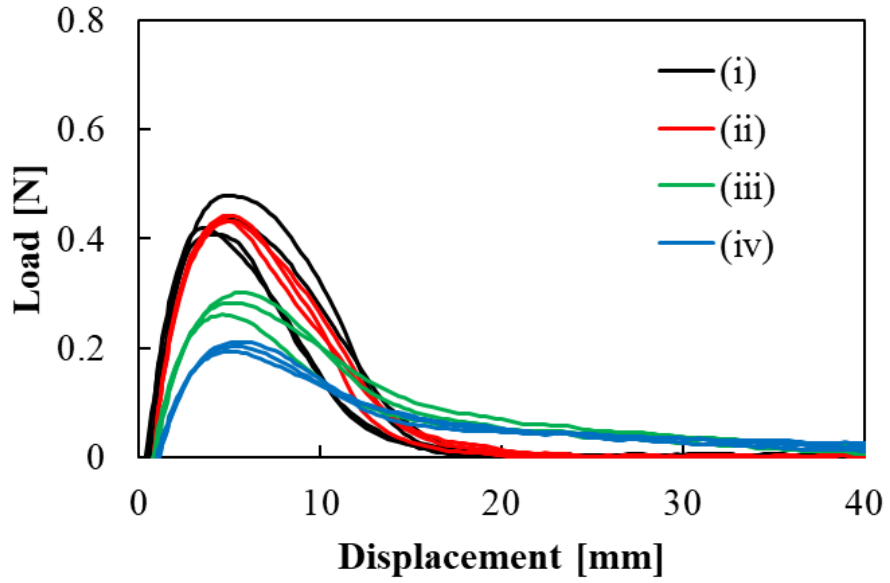
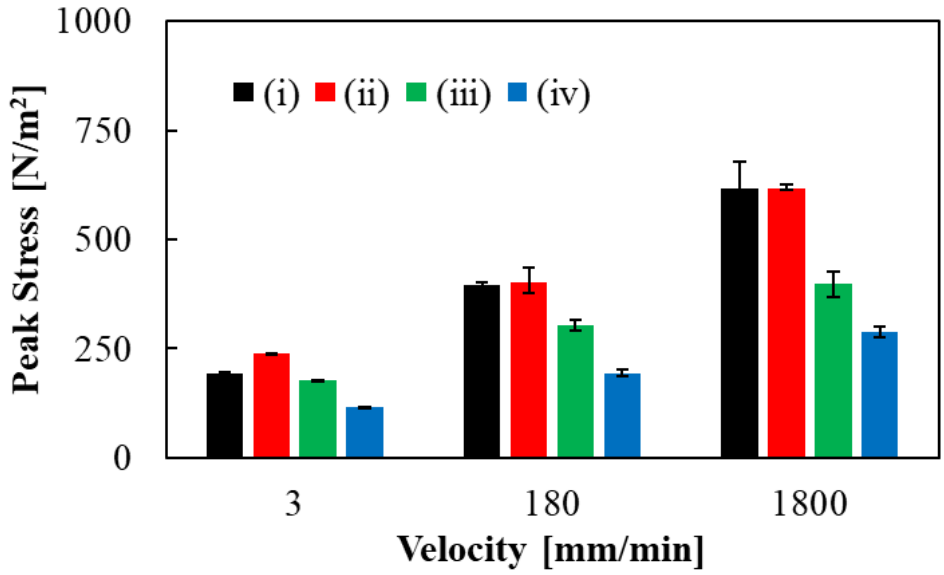
(iv) 

Figure 9


0.8
0.6
0.4
0.2
0
Load [N]
0
10
20
30
40
Displacement [mm]
(i)
(ii)
(iii)
(iv)

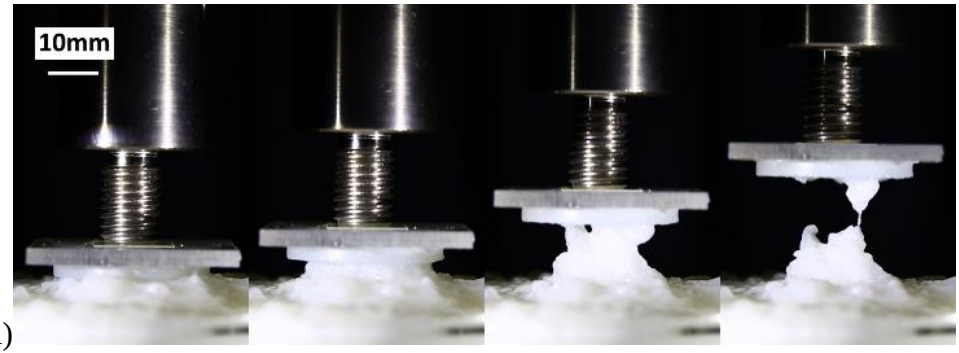
(a)


1000
750
500
250
0
Peak Stress [N/m²]
(i)
(ii)
(iii)
(iv)
3
180
1800
Velocity [mm/min]

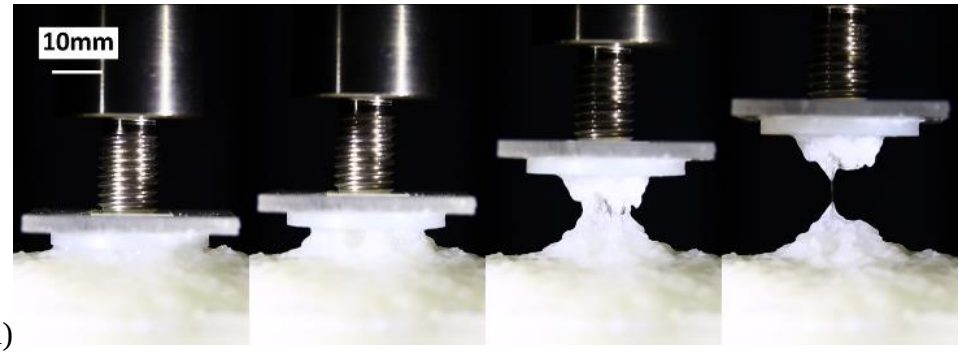
(b)

Figure 10

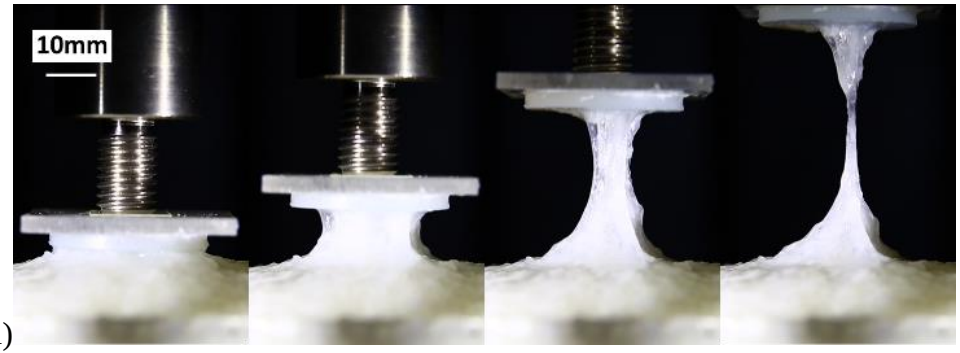
(i)



(ii)



(iii)



(iv)

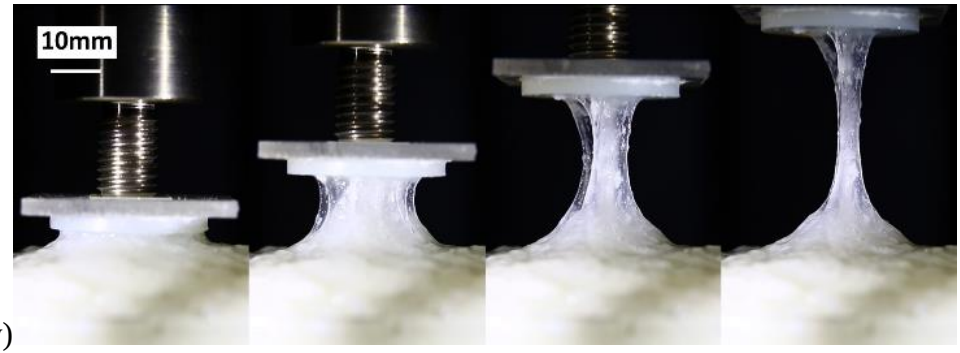
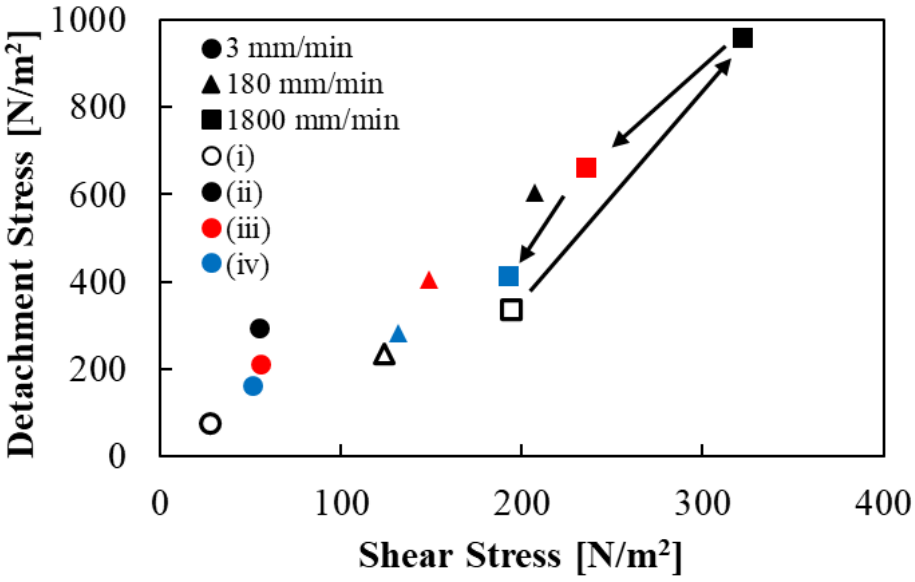
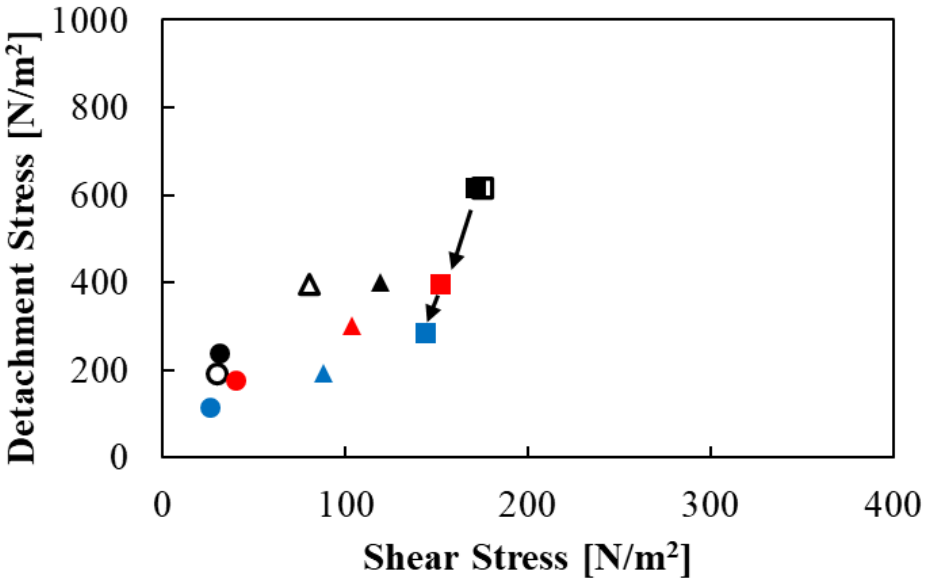


Figure 11


Detachment Stress [N/m²]
Shear Stress [N/m²]
3 mm/min
180 mm/min
1800 mm/min
(i)
(ii)
(iii)
(iv)
0
200
400
600
800
1000
0
100
200
300
400

(a)


Detachment Stress [N/m²]
Shear Stress [N/m²]
0
200
400
600
800
1000
0
100
200
300
400

(b)

Figure 12

Figure Click here to access/download;Figure;Figure_Captions.docx

Figure 1. Typical testing methods for evaluating industrial adhesion tapes: (a) peel test, (b) holding-power test, and (c) probe-tack test.

Figure 2. (a) Photograph and (b) schematic of the shear-resistance test setup.

Figure 3. (a) Photograph and (b) schematic of the probe-tack test setup.

Figure 4. Storage modulus and loss modulus curves for scallop mousse samples measured using DMA.

Figure 5. Storage modulus and loss modulus curves for rice porridge samples measured using DMA.

Figure 6. (a) Shear stress versus displacement curves of scallop mousse samples obtained from shear-resistance tests at a shearing velocity of 1800 mm/min. (b) Average plateau stresses obtained at velocities of 3, 180, and 1800 mm/min.

Figure 7. (a) Shear stress versus displacement curves of rice porridge samples obtained from shear-resistance tests at a shearing velocity of 1800 mm/min. (b) Average plateau stresses obtained at velocities of 3, 180, and 1800 mm/min.

Figure 8. (a) Relationships between load and displacement of scallop mousse samples obtained by probe-tack tests at a shearing velocity of 1800 mm/min. (b) Average maximum stresses obtained at velocities of 3, 180, and 1800 mm/min.

Figure 9. Photographs of scallop mousses of samples (i)‑(iv) during the detachment process indicated by arrows in Fig. 8(a).

Figure 10. (a) Load–displacement curves of rice porridge samples obtained by probe-tack tests at 1800 mm/min. (b) Average maximum stresses obtained at velocities of 3, 180, and 1800 mm/min.

Figure 11. Photographs of rice porridge of samples (i) to (iv) during the detachment process indicated by arrows in Fig. 10(a).

Figure 12. Relationships between shear and detachment stresses of the various (a) scallop mousse and (b) rice porridge samples measured at various test velocities.