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<RUNNING TITLE> Water and gelatinized starch improve the texture of pizza crust

<Full Title> Effects of water and gelatinized starch on the viscoelasticity of pizza dough and the texture of pizza crust

<Full Names and Affiliations of the Authors>

Akane Matsumoto¹, Kanae Nakai², and Kiyoshi Kawai¹,²,*

¹ Graduate School of Integrated Sciences for Life, Hiroshima University, 1-4-4 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8528, Japan
² School of Applied Biological Science, Hiroshima University, 1-4-4 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8528, Japan

<The Phone Number, Fax Number, E-mail Address, and ORCID ID of the Corresponding Author>

Tel. & Fax. +81-82-424-4344, e-mail: kawai@hiroshima-u.ac.jp, ORCID ID: https://orcid.org/0000-0001-9828-9030

<List of Abbreviations>

DM, dry matter, $G'$, Storage modulus, $G''$, Loss modulus, $\sigma_{yield}$, yield stress

<Any Necessary Footnotes>

Not applicable
<Abstract>
The soft texture of the pizza crust rim is generated by baking at a high temperature for a short period in a stone oven. In the case of baking in an electric oven, the pizza dough is baked at a much lower temperature and for a longer period, resulting in a harder texture. To improve the texture of electric oven-baked pizza crust, the effects of water and gelatinized starch on the viscoelasticity of pizza dough and the texture of pizza crust was investigated. Rheological properties (storage modulus, loss modulus, and yield stress) of pizza dough decreased with an increase in water content. When wheat flour in the dough was partially replaced with pre-gelatinized wheat starch, the rheological properties of the dough were maintained even at a high-water content. These results indicate that water-enriched dough can be prepared with gelatinized starch and baked using an electric oven. There was no significant difference in apparent density between the conventional and modified pizza crusts. Water content of the crumb part of the modified crust was significantly higher than that of the conventional crust. Texture analysis revealed that the modified pizza crust showed significantly lower stress at high strain than the conventional crust. In addition, sensory evaluation showed that the modified pizza crust exhibited greater firmness and stickiness than the conventional crust, which was attributed to the increased water content with gelatinized starch of the dough.

<Keywords>
gelatinized starch, pizza, dough, texture, viscoelasticity
INTRODUCTION

Pizza is a widely favored meal served at traditional pizzerias, exclusive and fast-food restaurants, and at home. The cooking process of pizza is simple. First, pizza dough is prepared similarly to bread dough, in which wheat flour, water, and other ingredients (e.g., NaCl, sucrose, oil, and yeast) are combined, kneaded, and fermented. Next, the pizza dough is spread onto a round sheet with a small rim, and topped with sauce and various other food ingredients. Finally, the raw pizza is baked at a high temperature for a short period of time. To achieve such high temperature baking, a stone oven is used, especially at traditional pizzerias and exclusive restaurants. For more convenient serving at fast-food restaurants and at home, frozen dough or semi-baked pizza is used, which is baked in an electric oven.

The rim of the pizza crust, the so-called “cornicione”, is particularly favored in Naples, Italy. The soft texture of the rim of the pizza crust (hereafter pizza crust) is generated by baking at a high temperature for a short duration in a stone oven. When baked using an electric oven, the raw pizza is baked at a much lower temperature and for a longer period compared to baking with a stone oven, resulting in a harder texture. The difference in baking condition is thought to be the reason for the large texture difference of the pizza crust. However, it is practically difficult to use stone ovens at fast-food restaurants and at home. Modification of the physical properties of pizza dough may be an effective way to improve the texture of pizza crust baked in an electric oven.
Water is the most effective plasticizer for foods. Thus, it is expected that the higher the water content of the pizza dough, the softer the texture of the crust. However, the rheological properties of pizza dough are obviously affected by the addition of water, and thus the kneading and forming properties of the dough are negatively affected. In fact, the viscoelastic parameters such as storage modulus ($G'$) and loss modulus ($G''$) of dough samples (wheat flour, water, and dry yeast) decrease as the water content increases. To maintain optimum rheological properties of pizza dough, hydrophilic polymers are proposed to be effective as physical modifiers. For example, Sciarini et al. (2012) reported that the viscoelasticity of bread dough containing hydrophilic colloids such as xanthan gum did not significantly change, even when the water content of the dough exceeded that of conventional (non-additive) dough.

Since pizza dough is comprised of only a few components (mainly wheat flour and water), it is possible that physical modifiers could result in an unnatural pizza crust taste. Wheat starch is the main component of pizza crust, and thus provides a natural taste even if it is added as a physical modifier to pizza dough. When starch is heated with water, the double-helix of amylopectin unfolds, and the amorphous amylopectin hydrates a larger amount of water molecules than its original form. This process is known as starch gelatinization. Starch gelatinization occurs in pizza crust during the baking process. Thus, if wheat flour in pizza dough is partially replaced by pre-gelatinized wheat starch, the pizza dough is expected to maintain its viscoelastic properties even at a higher water content compared to conventional dough. As a result, it is possible that pizza crust baked using
an electric oven could be modified to produce a softer texture. Similar approach has been employed for the texture modification of bread\(^6\)\(^7\) and rice bread\(^8\)\(^9\)\(^10\).

The purpose of this study is to clarify the effects of water and gelatinized starch on the viscoelasticity of pizza dough. In addition, the water-enriched pizza dough with gelatinized starch was baked using a household electric oven, and the texture of the modified pizza crust was compared mechanically and sensorially with that of conventional pizza crust.

**MATERIALS AND METHODS**

**Materials.** High gluten wheat flour (Nissin Seifun Group Inc., Tokyo, Japan), sucrose (Pearl Ace Co., Ltd., Tokyo, Japan), NaCl (Hakata Salt Co., Ltd., Ehime, Japan), olive oil (Nisshin OilliO Group, Ltd., Tokyo, Japan), and dry yeast (Nissin Seifun Group Inc., Tokyo, Japan) were purchased at a local market. Wheat starch was purchased from Wako Pure Chemical Industries, Ltd. (Osaka, Japan). The water content of the wheat flour and wheat starch was determined preliminarily to be 14.0 ± 0.3 g/100 g-DM (dry matter) and 11.9 ± 0.2 g/100 g-DM, respectively, by oven-drying at 105 °C for 24 h. For sensory analysis of pizza crust, commercially available wheat starch (Pioneer Planning Co., Kanagawa, Japan) was used as a food stuff. The water content of the commercially available wheat starch was 11.8 ± 0.1 g/100 g-DM.

**Preparation of pizza dough models and samples.** The experimental procedure is shown in Figure 1. The ingredients of pizza dough models
and samples (mixture of wheat flour, water, sucrose, NaCl, and dry yeast with and without pre-gelatinized starch) are shown in Table 1. For the preparation of pizza dough models and samples without pre-gelatinized starch, the ingredients were placed into the container of the bread maker (Home Bakery SD-BMS106; Panasonic Corp., Osaka, Japan). For the preparation of pizza dough models and samples with pre-gelatinized starch, gelatinized wheat starch was prepared in advance; water was added to the starch in a glass beaker containing a magnetic stir bar according to Table 1, and covered with plastic film. The beaker was placed in a water bath (98-100 °C) and heated for 10 min with stirring to prevent sedimentation of the starch granules. The gelatinized starch paste was cooled to room temperature and mixed with the other ingredients in the container of the bread maker. For the preparation of pizza dough samples with and without pre-gelatinized starch, the dry yeast was set in a separate compartment of the bread maker.

The pizza dough models and samples were prepared using the bread maker on ‘pizza dough mode’. The ingredients in the container of the bread maker were kneaded over a 45 min period. It was previously confirmed that the dough temperature was increased up to 25 °C within 5 min. Then the temperature was maintained for 10 min, increased up to 34 °C within 10 min, and maintained for 20 min during processing\(^1\)). The pizza dough models and samples were used within the same day.

**Viscoelasticity of pizza dough models and samples.** The $G'$, $G''$, and yield
stress ($\sigma_{\text{yield}}$) of the pizza dough models and samples were evaluated using a
dynamic mechanical thermal analyzer (Haake Mars III system; Thermo
Fisher Scientific K. K., Tokyo, Japan). The dough was set on the sample
stage, and a parallel plate (diameter 20 mm and gap 1.0 mm) was used\(^\text{12}\).
The $G'$, $G''$, and $\sigma_{\text{yield}}$ were evaluated at 1 Hz in the shear stress range
between 1 Pa and 10,000 Pa at 25 °C (see detailed explanation below). The
measurements were performed in triplicate and the results were averaged.

**Preparation of pizza crust samples.** For the preparation of pizza crust
samples, conventional and water-enriched pizza dough samples were used as
listed in Table 1. Pizzas were formed according to our previous study\(^\text{11}\)
with a minor modification. In brief, the dough (50 g) was rolled out in a
circular mold and pressed manually using a circular stamp. Then, a circular
recess (diameter 65 ± 2 mm and depth 10 ± 1 mm) in the center of the pizza
dough (diameter 99 ± 1 mm and height 13 ± 1 mm) was formed (Figure 1).
To prevent expansion in the center of the crust sample during baking, pin
holes were randomly made in the dough. The dough samples were
immediately baked using a household electric oven (NB-DT50; Panasonic
Co., Osaka, Japan) according to the manufacturer’s instructions. The dough
sample was placed on an aluminum plate and baked at 220 °C (set
temperature) for 6 min in the electric oven. As a reference, the time courses
of air, plate, and sample temperatures during the baking are shown in Figure
S1 (supplemental file).

**Water content at each part of pizza crust samples.** The pizza crust was
removed from the oven, and immediately the rim of the pizza crust was cut out with a circular mold (diameter of 30 mm) on a cutting board. In addition, the rim was divided into three parts with a knife; top and bottom layers and crumb (Figure 1). To prevent water evaporation during analysis, the samples were enclosed into a plastic bag immediately after sampling and cooled down to ambient temperature. Water content of the samples was evaluated gravimetrically by oven-drying 105 °C for 24 h. The measurements were performed in triplicate and the results were averaged.

*Apparent density of pizza crust samples.* The pizza crust was cooled to ambient temperature, divided into half using an electric knife, weighed, and the volume was determined using a 3D-scanner (MFS1V2 3D SCANNER; Matter and Form, Inc., Toronto, ON, Canada). The measurements were performed in triplicate and the results were averaged.

*Texture of the crumb part of pizza crust samples.* Immediately after baking, the pizza crust sample was held at 60 °C for 8–11 min in an incubator before using for the texture measurement. It had been preliminarily confirmed that there was no significant change in the water content of pizza crust crumb samples during the holding period. The rim of the pizza crust was cut with a knife, and the crumb part formed a cube (10–15 mm) in the incubator. The size of samples was measured using a caliper. The sample was set on the sample stage surrounded by a heating system and compressed with a plate plunger (diameter 30 mm) at 100 mm/min at 60 °C (Figure 1) using a rheometer of which digital force recorder (ZTA-100N,
Imada Corp., Aichi, Japan) was equipped with a cylinder system (Nissin
Seiki Co., Ltd., Hiroshima, Japan). From the stress-strain curve,
compressive stress at strains 0.25 and 0.70 was evaluated. The
measurements were performed in triplicate and the results were averaged.

**Sensory analysis.** Sensory analysis of the conventional and modified
samples was carried out by ten panelists consisting of 4 men and 6 women
between the ages of 22 and 29 years (mean age, 23.1 ± 2.4 years). The
samples were served to the panelists within 5 min after preparation, and the
firmness and crumb stickiness of the samples were evaluated using a scale
from -2 (firm or not sticky) to +2 (soft or sticky). The evaluation index was
in accordance with the literature on the sensory evaluation of bread\(^{13}\).

**Statistical analysis.** Statistical analysis was performed with a t-test and
the Tukey-Kramer test \((p < 0.05)\) using Microsoft Excel and R 4.0.2 for
Windows.

**RESULTS AND DISCUSSION**

**Rheological properties of pizza dough models.** As a typical result of
dynamic mechanical thermal analysis, the effect of shear stress on the \(G'\)
and \(G''\) of a pizza dough model (wheat flour-water mixture without
pre-gelatinized starch, water content of 0.82 g/g-dry wheat flour) is shown
in Figure 2-a. The \(G'\) and \(G''\) indicate elastic and viscous properties of the
sample, respectively. With an increase in the shear stress, the \(G'\) and \(G''\)
showed a constant value up to approximately 100 Pa (linear stress region),
and then largely decreased (non-linear stress region). The $G'$ was slightly higher than the $G''$ in the linear stress region, but they showed crossover at a certain stress in the non-linear stress region. From the rheological behavior, $G'$ and $G''$ values at around 10 Pa (linear stress region for every sample) were determined. In addition, shear stress at the crossover-point between $G'$ and $G''$ was determined as $\sigma_{\text{yield}}$. The $\sigma_{\text{yield}}$, which is the minimum shear stress required for flow (irreversible deformation) of the sample, corresponds to the kneading property of dough\textsuperscript{14}). It should be noted that the $\sigma_{\text{yield}}$ evaluated by this approach is slightly higher than that determined from the shear stress-strain curve\textsuperscript{15}). The $\sigma_{\text{yield}}$ for a portion of the samples could not be determined because the crossover-point was not in the measured stress range.

The effect of water content on the $G'$, $G''$, and $\sigma_{\text{yield}}$ of pizza dough models is shown in Figure 2-b, -c, and -d, respectively. The values with the results of statistical analysis are also listed in Table S1 (supplemental file). The water content in the figures was described as the total amount of water per total amount of dry wheat flour and wheat starch. The water content of the conventional pizza dough model (WS0) was 0.82 g/g-dry wheat flour. The $G'$, $G''$, and $\sigma_{\text{yield}}$ for the conventional pizza dough model were 21,020 Pa, 8,514 Pa, and 4,167 Pa, respectively. These reference values are indicated as horizontal dotted lines in the figures. The $G'$ was approximately 1.8–3.0 times higher than $G''$ for all models, and the tangent loss ($G''/G'$) values ranged between 0.3 and 0.6. The parameter tan $\delta$ characterizes the viscoelasticity of the sample between solid-like ($\tan \delta < 1$) and liquid-like ($\tan \delta > 1$). Gelatinized starch tended to reduce slightly the
\( \tan \delta \) of the dough models. Water content, on the other hand, did not affect \( \tan \delta \). The \( G' \), \( G'' \), and \( \sigma_{\text{yield}} \) decreased logarithmically with an increase in water content because of water plasticization\(^{2,16}\). When wheat flour was partially replaced with gelatinized starch, the \( G' \), \( G'' \), and \( \sigma_{\text{yield}} \) of the pizza dough models increased with the increase in replaced content at each water content. In other words, the rheological properties could be maintained by the addition of gelatinized starch even at a higher water content. The water content of the pizza dough model could be elevated up to 1.04 g/g-dry wheat flour-starch when wheat flour was replaced with 20% gelatinized starch. Gelatinized starch is an amorphous polymer; thus, much greater intermolecular hydrogen bonding with water molecules is expected compared to non-gelatinized starch\(^{16,17,18}\). Since wheat flour was replaced with wheat starch, wheat protein (mainly gliadin and glutenin) content decreased. Effect of wheat protein on the rheological properties of pizza dough is discussed below.

**Rheological properties of pizza dough samples.** According to the rheological properties of the pizza dough models, the conventional and modified pizza dough samples (Table 1) were used in the subsequent experiments. The rheological properties (\( G' \), \( G'' \), and \( \sigma_{\text{yield}} \)) are shown in Figure 3. For comparison, pizza dough models having the same contents of water and replaced gelatinized starch (WS0 and WS20) are also shown. There was no significant difference in the rheological properties between WS0 and the conventional pizza dough sample (water content = 0.82 g/g-dry wheat flour).
wheat flour) (Table S2). This suggests that the minor ingredients (sucrose, NaCl, oil, and dry yeast) had a negligible effect on the rheological properties of the wheat flour-water mixture.

In a comparison between WS20 and the modified pizza dough (water content = 1.04 g/g-dry wheat flour-starch), the modified pizza dough exhibited slightly lower rheological properties. This suggests that the rheological properties of gelatinized starch are more sensitive to the minor ingredients. It is known that the structure of gas cells generated by yeast affects the viscoelasticity of dough. For example, Upadhyay et al (2012) reported that $G'$ increased with increasing yeast concentration and resulted in smaller gas cells. When wheat flour was replaced with 20% wheat starch, 2.16% wheat protein content (per pizza dough) is lost. As is well known, gliadin and glutenin form the gluten network during dough making, and gas generated by yeast is trapped in this network. Since the reduction of gluten content will have resulted in an increase in the size of gas cells because of the loose gluten network, the rheological properties of modified pizza dough were lower than those of the model dough.

**Apparent density and water content of pizza crust samples.** Conventional and modified pizza dough samples were baked at 220 °C for 6 min in the electric oven, and conventional and modified pizza dough crust samples were obtained. The apparent density of the conventional and modified pizza dough crust samples was 0.44 ± 0.22 g/cm$^3$ and 0.43 ± 0.2 g/cm$^3$, respectively, and the values were not significantly different.

Water content at each part of the pizza crust samples is shown in Figure 4.
For comparison, the water content of the dough samples is also shown. There was no significant difference in the top and bottom water content between conventional and modified pizza crust samples. The top and bottom areas are exposed to the high-temperature condition during baking; thus, the water content in these parts will have been obviously diminished, irrespective of the initial water content\textsuperscript{17,20).} The crumb water content of the modified pizza crust, on the other hand, was much higher than that of the conventional crust. Notably, the crumb water content of the pizza crust samples was equivalent to the water content of each dough. Since the surface layer is formed at the early stage of baking, water evaporation from the crumb part will have been prevented\textsuperscript{20).} Thus, the water content was completely maintained in the crumb part after baking.

\textit{Texture of pizza crust samples.} A typical stress-strain curve for the pizza crust sample is shown in Figure 5-a. The stress gradually increased at the low-strain region, and largely increased at the high-strain region. As texture parameters, compressive stress at strains 0.25 and 0.70 was evaluated. The measurement was carried out according to the texture analysis of bread\textsuperscript{19,22) with minor modifications.} Since bread is commonly served at room temperature\textsuperscript{21,24)}, the texture of bread has been investigated at 25 °C. Pizza, on the other hand, is served piping hot, and thus the texture was investigated at 60 °C. In the case of texture analysis for bread, compressive force at strain 0.25 is evaluated for the classification of bread as being hard or soft. On the other hand, it has been reported that compressive force at strain 0.70 is evaluated as a parameter for the gumminess of rice noodles\textsuperscript{25).}
Compressive stress at strains 0.25 and 0.70 for conventional and modified pizza crust samples is shown in Figure 5-b. There was no significant difference in the stress at strain 0.25 between conventional and modified pizza crusts. Similar to bread\textsuperscript{22)}, pizza crust has a gas cell structure. Samples are compressed reversibly at low strain because of the low elasticity originating from the gas cell structure. When wheat flour was replaced with 20% wheat starch, 2.32% wheat protein content (per pizza crust) is lost. The reduction of protein (gluten) content will have resulted in an increase in the size of gas cells because of the loose gluten network. However, there was no significant difference in the apparent density between conventional and modified pizza crusts. This suggests that the gas cell structure is developed in the modified pizza crust similar to the conventional crust. It was demonstrated that the stress at strain 0.70 for the modified pizza crust was significantly lower than that for the conventional crust. A value of 0.70 for strain is useful to characterize differences in the texture of pizza crusts\textsuperscript{11}).

The results of sensory analysis are shown in Figure 6. The modified pizza crust exhibited higher firmness and crumb stickiness compared to the conventional crust. As mentioned above, the higher the water content, the softer the bread texture\textsuperscript{26}). Compressive stress at low and high strain is expected to correspond to firmness and stickiness, respectively. Although there was no significant difference in compressive stress at low strain, the firmness was perceived to be significantly different between the samples. This is considered to originate from the sensitivity of this method, as the compressive stress at low strain was much lower than that at high strain. To
physically characterize the sensory firmness, other rheological techniques
such as creep measurement will be effective\textsuperscript{27}).

**CONCLUSION**

The $G'$, $G''$, and $\sigma_{\text{yield}}$ of the pizza dough decreased as the water content increased. However, the rheological properties of the pizza dough with added gelatinized starch were maintained even at a high-water content. In addition, it was demonstrated that the water-enriched pizza crust with gelatinized starch was softer and stickier than the conventional crust. When pizza is baked in an electric oven, the texture of the pizza crust is harder than when baked in a stone oven. The results of this study suggest that the texture of electric oven-baked pizza crust can be improved to a more favorable texture. These findings are of practical importance, especially for the convenient serving of pizza such as by fast-food restaurants and at home.

<Conflicts of interest>

The authors declare no conflicts of interest associated with this manuscript.

<Acknowledgement>

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*Figure Legends*

Fig. 1. Experimental procedure.

Fig. 2. Rheological properties of pizza dough models. (a) Typical viscoelastic measurement result, and the effect of water content on the (b) storage modulus ($G'$), (c) loss modulus ($G''$), and (d) yield stress ($\sigma_{\text{yield}}$) of pizza doughs. The values are expressed as the mean ± SD ($n = 3$).
Fig. 3. Rheological properties of conventional and modified pizza sample doughs and pizza model doughs. The model doughs (WS0 and WS20) have the same water and gelatinized wheat starch contents as the sample doughs. (a) Storage modulus ($G'$), (b) loss modulus ($G''$), and (c) yield stress ($\sigma_{\text{yield}}$) of doughs. The values are expressed as the mean ± SD ($n = 3$). Values with different letters are significantly different at $p < 0.05$.

Fig. 4. Water content of conventional and modified pizza dough and crust samples. The pizza crust samples were divided into top and bottom layers, and crumb. The values are expressed as the mean ± SD ($n = 3$). An asterisk indicates a significant difference at $p < 0.05$.

Fig. 5. Texture analysis of conventional and modified pizza crust samples. (a) Typical stress-strain curve for the conventional pizza crust. (b) Compressive stress at strains 0.25 and 0.70. The values are expressed as the mean ± SD ($n = 3$). An asterisk indicates a significant difference at $p < 0.05$.

Fig. 6. Sensory evaluation score. The values are in the range between -2 (firm or not sticky) and +2 (soft or sticky). The values are expressed as the mean ± SD ($n = 10$). An asterisk indicates a significant difference at $p < 0.05$.

Table 1. The recipe for pizza dough models and samples.
<table>
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<th>wheat flour</th>
<th>wheat starch</th>
<th>water</th>
<th>oil</th>
<th>sucrose</th>
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Unit is gram.

Table 1.
For Peer Review

Pizza dough model  Conventional and modified pizza dough samples

Rheological analysis
- storage modulus ($G'$)
- loss modulus ($G''$)
- yield stress ($\sigma_{\text{yield}}$)

Conventional and modified pizza crust samples

Baking 220 °C 6 min

Apparent density

Water content at each part
top layer  bottom layer  crumb

Texture analysis
- compressive stress at strain 0.25
- compressive stress at strain 0.70

Sensory analysis
- firmness
- crumb stickiness

Fig. 1.
Fig. 2.

(a) Shear stress (Pa)

(b) Water content (g/g-dry wheat flour-starch)

(c) G' (Pa)

(d) G" (Pa)

σ_{yield}
Fig. 3.
Fig. 4. Water content (g/g-DM) for dough, top, bottom, and crumb for Conventional and Modified conditions. The bars with an asterisk (*) indicate significant differences, while n.s. indicates no significant difference.
Fig. 5.

(a) Stress vs. Strain graph showing the comparison between conventional and modified materials. The graph illustrates a nonlinear relationship between stress and strain, with the modified material demonstrating a higher stress capacity at the same strain.

(b) Bar graph showing the stress values at two different strain levels (0.25 and 0.7). The graph indicates that the modified material has a significantly higher stress value at these strain levels, as marked by an asterisk (*) indicating statistical significance. The conventional material shows a non-significant difference (n.s.) compared to the modified material.
Fig. 6. Firmness: firm

-3 -2 -1 0 +1 +2 +3

Firmness: firm

Crumb stickiness: not sticky

-3 -2 -1 0 +1 +2 +3

Crumb stickiness: not sticky

* : Conventional, ○ : Modified

not sticky

sticky
Figure S1. Temperature change at each part during baking. The sample temperature increased and reached an equilibrium temperature (approximately 100 °C) for approximately 150 s. There was no large difference in the temperature change between conventional and modified pizza dough samples.
Table S1. Comparison of $G'$, $G''$, and $\sigma_{\text{yield}}$ of the pizza dough models

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<tr>
<th>Water (g)</th>
<th>$G'$ (Pa)</th>
<th>$G''$ (Pa)</th>
<th>$\sigma_{\text{yield}}$ (Pa)</th>
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<td>60</td>
<td>21020.0</td>
<td>48236.7</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>$\pm$ 3776.9$^c$</td>
<td>$\pm$ 4385.5$^b$</td>
<td>-</td>
</tr>
<tr>
<td>70</td>
<td>8785.7</td>
<td>22276.7</td>
<td>40886.7</td>
</tr>
<tr>
<td></td>
<td>$\pm$ 671.5$^d$</td>
<td>$\pm$ 1969.8$^e$</td>
<td>$\pm$ 3119.1$^b$</td>
</tr>
<tr>
<td>80</td>
<td>3419.7</td>
<td>8910.3</td>
<td>24496.7</td>
</tr>
<tr>
<td></td>
<td>$\pm$ 712.4$^d$</td>
<td>$\pm$ 433.2$^d$</td>
<td>$\pm$ 436.6$^c$</td>
</tr>
</tbody>
</table>

The values are expressed as mean ± SD ($n = 10$).

Values with different letters are significantly different at $p < 0.05$. 
Table S2. Comparison of $G'$, $G''$, and $\sigma_{\text{yield}}$ of the pizza dough models and samples

<table>
<thead>
<tr>
<th>Pizza dough</th>
<th>$G'$ (Pa)</th>
<th>$G''$ (Pa)</th>
<th>$\sigma_{\text{yield}}$ (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>model</td>
<td>21020.0 ± 3776.9$^a$</td>
<td>8514.0 ± 2229$^a$</td>
<td>4167.1 ± 227.8$^a$</td>
</tr>
<tr>
<td>sample</td>
<td>19976.7 ± 1907.1$^{a,b}$</td>
<td>7899.3 ± 756.5$^a$</td>
<td>3660.7 ± 389.8$^{a,b}$</td>
</tr>
<tr>
<td>Modified</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>model</td>
<td>24496.7 ± 436.6$^a$</td>
<td>8065.0 ± 1503.6$^a$</td>
<td>4559.6 ± 416.0$^a$</td>
</tr>
<tr>
<td>sample</td>
<td>15313.3 ± 257.7$^b$</td>
<td>5269.3 ± 302.3$^a$</td>
<td>3166.3 ± 396.2$^b$</td>
</tr>
</tbody>
</table>

The values are expressed as mean ± SD ($n = 10$).

Values with different letters are significantly different at $p < 0.05$. 