Texture Evaluation of Tofu (Soybean Curd) by Viscoelastic Tests*

Yongqiang CHENG*1, Naoto SHIMIZU*2, Toshinori KIMURA*2

Abstract

Viscoelastic tests (stress-strain and stress relaxation tests) were applied to evaluate the texture of tofu. Tofu was made in the laboratory by using different concentrations of soymilk (5%, 6%, 7%, 8% and 9%, w/v) and coagulants, such as glucono-delta-lactone (GDL) and calcium sulfate. The parameters of stress-strain behaviors of GDL-coagulated tofu were higher than that of CaSO4-coagulated tofu at the same soymilk concentration. A 4-element model, composed of 2 Maxwell models, was conformed to fit the stress relaxation curves. The elastic parameters $E_1, E_2$ for the 4-element model did not significantly change while viscous parameters $\eta_1, \eta_2$ and relaxation time $\tau_1, \tau_2$ increased with increasing soymilk concentration. Viscoelastic behaviors of tofu suggested the stronger structures accompanying with the increase of soymilk concentration. It seemed that the stress-strain behavior was involved more with the viscous parameters than the elastic ones. These results showed that viscoelastic tests were effective for texture evaluation of tofu. Using this method, the commercial tofu in a local market of China was analyzed. The results showed that very hard tofu was being distributed in the market of China and it was possible to produce tofu by the production method of kinugoshi tofu (no press tofu) with a texture similar to the commercial tofu in China when using CaSO4 as a coagulant.

[Keywords] soybean curd, tofu, hard tofu, stress relaxation, viscoelastic test, texture, Maxwell model

1 Introduction

Tofu is a traditional soy product very popular in some Asian countries, such as China and Japan. For the traditional food culture, especially the Chinese method of cooking, hard tofu is preferred. Nowadays, in China, most of the commercial hard tofu is produced by family-style small workshops with a short shelf life. There are some industrial lines producing glucono-delta-lactone (GDL) coagulated tofu with a longer shelf life, but the taste of the tofu is a little acidic, which is not preferred by consumers (Cheng et al., 1999). To improve the production of tofu, proper texture evaluation method is always necessary for such kind of hard tofu. Both chemical and physical factors are involved with the taste of foodstuffs. For food like tofu, the physical factors are involved much more with the taste than chemical ones (Matsumoto and Matsumoto, 1977). The rheological properties are significantly related to the quality of tofu. Saio (1979) reported the relationship between texture and fine structure of tofu. To evaluate the texture of tofu, break stress (or hardness) is a very important index used by many researchers (Saio, 1979; Kohyama and Nishinari, 1992; Hou et al., 1997). Both viscous and elastic properties can change the texture of tofu, which is a viscoelastic material. But the elastic indexes (e.g. Young’s modulus) are not always consistent with the break stress (Kohyama and Nishinari, 1992). It means that only break stress could not reflect both the viscous and elastic changes and a more detailed method is necessary. Viscoelastic test (stress-strain, stress relaxation and creep tests) is one of the methods to evaluate the physical properties of viscoelastic food materials and the parameters obtained from this method include both viscous and elastic parts (Mohsenin, 1986; Kawabata, 1989). In stress relaxation tests, a food sample is compressed at a controlled crosshead speed to a desired strain. This strain is maintained as a constant, while the accompanying stress decays with time to provide the characteristic relaxation behavior. Isozaki et al. (1976)
found that the stress relaxation behavior of hydrogels of agar could be fit with a 6-element model. The stress relaxation curves of 20% (w/v) soybean gel were considered to be fit for a 6-element model (Kobayashi et al., 1981). One of the authors examined the stress relaxation characteristics of commercial momen and kinugoshi tofu in Japan by a 7-element model and compared the parameters with results by Peleg's empirical method (Taneya et al., 1993). The concentration of soymilk and type of coagulant greatly influence the hardness of tofu (Saio, 1979). Chinese prefer hard tofu, but there are few reports about the texture of hard tofu being contributed in the local market in China. Viscoelastic tests have not been applied to the texture evaluation of tofu that made from different soymilk concentration with various types of coagulants, such as GDL and CaSO4 for optimizing tofu production of China. The aim of this work was to develop an effective viscoelastic analysis method to evaluate the texture of hard tofu and to get some information on hard tofu production in China. By investigating the stress-strain and stress relaxation behavior, the texture analysis was tried for tofu made in laboratory with different coagulants and concentrations of soymilk, as well as several commercial types of tofu in China.

II Materials and Methods

1. Materials

Both tofu made in the laboratory and commercial tofu in China were used in this study. The materials used are described as following, respectively.

1) For tofu made in the laboratory

The soy protein isolate (SPI, 90%/dry base (84.6%/wet base) protein content, FujiproE) (Fuji Oil Ltd., Osaka) was used to prepare soymilk. Analysis-grade Glucono-delta-lactone (GDL) and food-grade CaSO4·2H2O were purchased from Wako Pure Chemicals Industries Ltd. (Osaka). They were used without further purification.

2) For commercial tofu in China

Three kinds of commercial tofu (not pressed GDL-coagulated (CMGDL-tofu), pressed CaSO4-coagulated (CMCa-tofu) and nigari-coagulated (CMNi-tofu)) were purchased from local market in Beijing, China, and were tested in China.

2. Tofu production in the laboratory

Tofu production method in the laboratory was based on the industrially used kinugoshi (silken) tofu production method in Japan (Watanabe, 1997). SPI was dissolved in distilled water to prepare for 5, 6, 7, 8, and 9% (w/v) protein soymilk, respectively. Soymilk was heated to 100°C and kept for 3 minutes, then was cooled to below 10°C. GDL solution or CaSO4 suspension was added as coagulants. Their final concentrations were adjusted to 30 mM. The soymilk mixture was poured into a steel tank where glass molds (30 mm in height, 36 mm in diameter) were put in advance to shape the columnar tofu samples. The soymilk was then heated to 75°C by a water bath and kept for more than 40 minutes to let the soymilk coagulate. Samples were stored at room temperature for 60 min before viscoelastic tests.

3. Viscoelastic tests for tofu made in the laboratory

Stress-strain and stress relaxation tests of tofu were done by Texture Analyzer (TA-XT2I, Stable Micro Systems, UK) with 5 kg load cell. The samples were 30 mm in height, 36 mm in diameter. A 70 mm in diameter flat plunger was used and the compression speed for the stress-strain test was 1 mm/s. After the linear range was determined by stress-strain profiles, the relaxation test was done. The stress relaxation period was 10 min for all samples.

4. Viscoelastic tests for commercial tofu in China

To understand the texture of commercial tofu in the local market in China, stress-strain and stress relaxation tests of three kinds of commercial tofu (CMGDL-tofu, CMCa-tofu and CMNi-tofu) were done by using a Rheometer (Fudotech Co. Ltd, Japan) in China. Samples were cut into 30 mm-height and 36 mm-diameter ones. A 50-diameter plate plunger and 1 mm/s crosshead speed were used. Stress-strain and stress relaxation curves of both tofu made in the laboratory and commercially produced tofu in China were analyzed by the same way described as the following.

5. Analysis of results of viscoelastic tests

Stress and strain data were recorded by the software with the Texture Analyzer. The apparent elasticity E(t) was calculated as σ(t)/ε(t), where σ(t) is the stress and ε(t) is the strain, which reflects the time-dependent changes of elasticity. The peak point of the stress-strain curve is considered to be break stress. The slope of the stress-strain curve in a linear range is thought to be the Young’s modulus. Stress relaxation tests were done within this range. Stress relaxation curves were tried to fit with different models. Mohsenin (1986) summarized the rheological
evaluation theory of physical properties of plant and animal materials in detail. The Maxwell model (Fig. 1(a)), serialized by a Spring model and a Dashpot model, was used as a primary unit. The generalized Maxwell model (Fig. 1 (b)) can be expressed as equation 1, which consists of a single Spring model and Maxwell model numbered from 1 to n and the detailed derivation was showed by Mohsenin (1986).

\[ E(t) = E_0 + \sum_{k=1}^{n} E_k e^{-\frac{t}{\tau_k}} \]  

Where \( t \) is time(s), \( E(t) \) is apparent elasticity (Pa), \( E_0 \) is stress elasticity of the spring model (Pa), \( E_k \) is stress elasticity of Maxwell model number \( K \) (Pa), \( \eta_k \) is viscosity of Maxwell model number \( K \) (Pa · s), and \( \tau_k = \eta_k / E_k \) is relaxation time of Maxwell model number \( k \) (s).

A 'least squares' non-linear algorithm in Sigmaplot (Jandel Corporation, San Rafael, CA) was used to fit experimental data to Equation 1. The best fit was determined on the basis of the standard error and coefficient of variation of the parameters, the value of the regression coefficient, and by comparison of the residual value between the plots for the experimental and fitted data. The appropriate number of Maxwell elements was determined on the basis of the 'dependence' criterion for the non-linear algorithm in Sigmaplot (Jandel Corporation, 1995). A similar non-linear regression procedure was applied by Ojijo et al. (2000) for the analysis of stress relaxation data of soybean cotyledons.

III Results and Discussion

1. Stress-strain behavior of different concentration tofu

Based on the stress-strain curves, strain below 10% is similarly considered as a linear area and the Young's modulus could be known from the slope of the curve during this range. For both tofu coagulated with GDL (GDL-tofu) and coagulated with CaSO₄ (Ca-tofu), with the increase of soymilk concentration, Young's modulus increased (Fig. 2). For Ca-tofu, a good gel was not obtained for 5% soymilk and the stress-strain behavior was not shown. Except for the 9% soymilk, the break stress also increased for both GDL-tofu and Ca-tofu (Fig. 2);
That is to say, increasing the soymilk concentration can obtain a harder tofu. This result corresponded to the previous report (Saio, 1979). The total amount of protein increased with increasing the soymilk content. For a high protein amount, the density of the network became higher and this resulted in higher break stress. It was noted that the break stress (peak point of the stress-strain curve) value was not always consistent with the elastic modulus (Fig. 2). Break stress of 9% GDL-tofu and Ca-tofu decreased a little while Young’s modulus increased. The contents of GDL and CaSO₄ were constant at 30 mM for all cases and the protein amount increased. The break stress decrease for 9% GDL-tofu and Ca-tofu may be due to the decreasing coagulant/protein ratio. That is to say, it might be that 30 mM GDL or CaSO₄ was not enough for 9% protein. The effect of measurement temperature on the stress-strain properties of tofu has been reported and break stress was not consistent with the elastic modulus (Kohyama and Nishinari, 1992), which is in agreement with the results of this study. It also suggested that only break stress could not reflect the overall profile of the texture and some other complementary method would be necessary.

When at the same soymilk concentration, break stress of GDL-tofu was higher than that of Ca-tofu. This was also reported by other researchers (Saio, 1979). Because of the acidic taste of GDL-tofu, it is not preferred by many consumers (Cheng et al., 1999). But it is suggested that as a coagulant, GDL could provide a higher break stress. Thus, for improving the hardness of tofu, the mixing of GDL coagulant will be an alternative way. These results also indicated that concentration of soymilk and type of coagulant had a great influence on the texture of tofu gel.

2. Stress Relaxation behavior of tofu made in the laboratory

Stress relaxation histories of GDL-tofu made from different concentration soymilks are shown in Fig. 3. With the increase of soymilk concentration, stress relaxation became slower (Fig. 3). It did not reach to equivalent stress for 600 seconds for all cases (even for 1200 seconds, it did not reach to equivalent stress (data not shown)). It was implied that E₀ does not exist for the generalized Maxwell model (Fig. 1 (b)). A similar pattern was obtained for the samples of Ca-tofu (data not shown). So, a model with 2 or 3 Maxwell elements (4 or 6-element model) could be considered. In common cases, about 90% content of tofu is water. When it is subjected to stress relaxation test, water will play an important role, which makes tofu show a viscous behavior at some extent as well as the elastic behavior that mainly influenced by network formed by proteins. After calculating by a ‘least squares’ non-linear algorithm in SigmaPlot®, it was found the 4-element Maxwell model (Fig. 1 (c)) could fit for the stress relaxation behaviors of tofu. The minimum objective function obtained by the algorithm was ensured to be a global convergence by repeating the iterations using different initial model parameters values (Van Boekel, 1996). Data for all the cases could be adequately fitted by the 4-element model. The relationship between apparent elasticity and viscous and elastic parameters can be expressed as following (Equation 2) (Kawabata, 1989):

\[ E(t) = E_1 e^{-t/\tau_1} + E_2 e^{-t/\tau_2} \]  

(2)

Where \( E(t) \) is apparent elasticity, \( t \) is time (s), \( E_1 \) and \( E_2 \) are elasticity of 2 Maxwell models, and \( \tau_i = \eta_i / E_i \) (\( i = 1, 2 \)), is stress relaxation time(s).

After the model was determined, parameters for models were calculated and given by the 'least squares' non-linear algorithm in SigmaPlot® (Jandel Corporation, San Rafael, CA). The best fit was determined on the basis of the standard error and coefficient of variation of the parameters, the value of the regression coefficient, and by comparison of the residual value between the plots for the experimental

<table>
<thead>
<tr>
<th>Soymilk concentration (%)</th>
<th>GDL stress (Pa)</th>
<th>CaSO₄ stress (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6%</td>
<td>6,855</td>
<td>2,802</td>
</tr>
<tr>
<td>7%</td>
<td>7,953</td>
<td>5,837</td>
</tr>
<tr>
<td>8%</td>
<td>8,994</td>
<td>6,956</td>
</tr>
<tr>
<td>9%</td>
<td>7,433</td>
<td>6,534</td>
</tr>
</tbody>
</table>

Fig. 3 Stress relaxation histories of GDL-coagulated tofu with different concentrations of soymilk
and fitted data. Results were showed in Table 2, 3. Both for the GDL-tofu and Ca-tofu, when the soymilk concentration increased, elastic parameters $E_1$ and $E_2$ had a tendency to increase, but did not change very much, while viscous parts $\eta_1$ and $\eta_2$ increased significantly (Table 2, 3). Similarly, relaxation times $\tau_1$, $\tau_2$ also increased with the soymilk concentration (Table 2, 3), which suggested the tendency that the relaxation became slower. It correlated with the stress relaxation histories (Fig. 3). These results indicated that tofu structure became stronger as the soymilk concentration increased. All of these changes of parameters are consistent with the stress-strain behaviors and are more detailed. Furukawa and Ohta (1982) reported that relaxation time of soy protein gel was dependent on the network formation, while the modulus of elasticity was hardly affected. Shimoyamada et al. (1999) also showed that the gel strength of the freeze-gel formed from soymilk was related to the viscosity of the soymilk before freezing. In our study, it also seemed that the viscous parameters were more involved with the hardness of tofu than elastic parameters.

Although break stress of GDL-tofu was much higher than Ca-tofu at the same soymilk concentration, stress relaxation results showed that elastic parameters did not change too much, while the viscous parameters and the relaxation times of GDL-tofu were smaller (Table 2, 3). This might be because GDL-tofu was more fragile and less cohesive than Ca-tofu (Saio, 1979). The network of GDL-tofu consisted of flocculent aggregates, and that of Ca-tofu showed a spongy structure with tight frames (Saio, 1979). It was suggested that the network of tofu gel may be formed via hydrogen bonding, hydrophobic associations, ionic interactions and electrostatic cross-links, and also through some sulphhydryl-disulphide linkages of unfolded polypeptides (Catsimpools et al., 1970; Utsumi and Kinsella, 1985). Compared with Ca-tofu, GDL-tofu was harder to penetrate but had a lower inner hardness and was more fragile and less cohesive than Ca-tofu. The Ca-tofu has a Ca-bridge, which may also have a role. Lee et al. (1983) characterized the stress relaxation of commercial tofu by using an empirical method developed by Peleg (1979) and found the tofu’s deformability mode, like that of sponges, was regulated by both the solid matrix properties and internal hydrostatic pressure. In our study, it was indicated that both large (stress-strain) and small deformation (stress relaxation) behaviors depended greatly on the soymilk property and the type of coagulant.

Stated as above, it was showed the viscoelastic evaluation method was effective for evaluating the texture of tofu and this method could reflect the changes of viscous and elastic parts, respectively. Furthermore, it is more detailed than only measuring the break stress (or hardness). Based on this result, to obtain some information on the hard tofu in China, the viscoelastic tests were tried for the commercial tofu in a local market in Beijing, China.

### 3. Stress-strain behavior of the commercial tofu in China

CaSO₄ and nigari (bitten) have been commonly used as coagulants for tofu production in China. Three kinds of commercial tofu were measured (CMGDL-tofu, CMCa-tofu and CMNi-tofu). Only CMGDL-tofu was an industrially produced tofu without a press. The other two were pressed and made by family-style small factories. The stress-strain curves were recorded by Rheometer (Fudotech Co.Ltd, Japan). Results showed that CMGDL-tofu had the lowest hardness and CMNi-tofu was too hard to be measured for the stress-strain test (over the measurement range) (Table 4). Although GDL-tofu was harder than Ca-tofu with the same soymilk concentration when being made in the laboratory (Table 1), for commercial tofu, CMCa-tofu was a little harder than CMGDL tofu. This is due to the fact that CMCa-tofu was a pressed type while CMGDL-tofu
was made without removing the whey, i.e., for a different processing method, they had different texture compared with tofu made in the laboratory. CMNi-tofu was the hardest one. These data showed that some extremely hard tofu really exists in the local market in China. The processing method had a great influence on the texture of tofu. Even in the same place in China, the texture of different tofu changed greatly due to the processing method and use of different coagulants. Further, the stress relaxation tests of the hard tofu were done.

### 4. Stress relaxation behavior of commercial tofu in China

All three kinds of tofu were subjected to stress relaxation tests. Using the same methodology for tofu made in the laboratory, it was found that these commercial tofu products could also be fit with the same 4-element Maxwell model (Fig. 3, (c)). Parameters were also obtained by a 'least squares' non-linear algorithm in Sigmaplot® as stated. CMNi-tofu showed higher elastic parameters and viscous ones than other two (Table 5). The parameters of CMGDL-tofu and CMCa-tofu did not change much. Although Chinese prefer hard tofu, all the hard tofu do not have similar texture parameters. They are different due to having different processing conditions and coagulants. It has been reported that commercial momen tofu in Japan showed higher viscous and elastic parameters than kinugoshi tofu (Taneya et al., 1993). Because of the process differences, pressed tofu has a close network structure (Taneya et al., 1993) for having the press process, which may also cause the high values of elastic and viscous parameters of CMNi-tofu in our study.

From the point of stress-strain and stress relaxation behaviors, 8% Ca-tofu made in the laboratory had similar parameters with the CMCa-tofu (Table 3 & 5). That is to say, it is possible to produce tofu without removing the whey, which has a similar texture to commercial pressed tofu when CaSO₄ is used as the coagulant.

### IV Conclusions

Stress-strain tests showed that break stress of GDL-tofu was much higher than Ca-tofu at the same soymilk concentration (Table 1). When hard tofu is preferred by consumers, the mixing with GDL for coagulant can be considered to be an alternative way. Increasing the soymilk concentration can also improve the break stress of tofu. But, for the industrial production, too high a concentration of soymilk may cause difficulty of uniform distribution of coagulants in the soymilk.

Stress relaxation behaviors of both type of tofu made in the laboratory and commercially could be fit with the four-element Maxwell model (Fig. 1(c)). Parameters of the four-element model showed both the viscous and elastic changes of tofu. When evaluating the texture of tofu, viscoelastic tests could be effective and useful besides break stress measurement. In this study, viscous parameters seemed to be involved more with the stress-strain behavior than elastic ones. This is to say, factors having influence on the viscous parameters should be taken into account when evaluating the texture of tofu.

The viscoelastic evaluation of commercial tofu in China showed very hard tofu is being distributed in China, which also implies that Chinese prefer hard tofu in another respect. The CMNi-tofu showed the highest value of both elastic and viscous parameters. When taking CaSO₄ as the coagulant, if proper process conditions were obtained, it was possible to produce hard tofu with a similar texture to pressed tofu without removing the whey.

### Acknowledgement

The first author would like to thank Fuji Oil Ltd. (Osaka) for supplying the SPI samples.

### References


(Received: 22 March 2002 - Question time limit: 31 January 2003)

「技術論文」
粘弾性評価方法による豆腐のテクスチャ評価

要 旨
豆腐のテクスチャを評価するために、応力ひずみおよび応力緩和試験を行った。異なる豆乳濃度および凝固剤（グルコンデルタラクトン（GDL）と硫酸カルシウム）で実験室において豆腐を製造した。同じ豆乳濃度の場合、GDLで凝固した豆腐の破断応力は硫酸カルシウムよりも高かった。二つのマックスウェルモデルを含む4-要素模型は応力緩和曲線に合うことが分かった。豆乳濃度の増加に従って，四要素モデルの弾性パラメータが著しく変わらなかったのに対して，粘性パラメータが増加した。豆腐の粘弾性挙動は豆乳の増加に伴う豆腐構造の増強を示した。弾性より粘性パラメータが豆腐の応力-ひずみ挙動における寄与度が大きく見られ，これらの結果は豆腐テクスチャ評価に粘弾性評価方法が有効であることを示した。この方法を用いて，市場の豆腐のテクスチャ評価を試みた。市場市場において非常に硬い豆腐が流通していることが分かり，硫酸カルシウムを凝固剤とする場合，組ごし豆腐の製造方法で中の市場豆腐に近いテクスチャの豆腐を製造できることを示した。

【キーワード】大豆カーディ, 豆腐, 硬い豆腐, 粘弾性試験, テクスチャ, マックスウェル模型

* 一部 2001年4月 第60回農業機械学会(筑波大学)にて講演
* 1 学生会員, 筑波大学農学研究科 (〒305-8572 つくば市天王台1-1-1 TEL 0298-53-4650)
* 2 会員, 筑波大学農林工学系 (同上)
コメント

【閲覧者のコメント】
流動体モデルの4要素Maxwellモデルが適用できるということは、豆腐に含まれる水の挙動が影響していると考えられます。豆腐の含水比の影響はどの程度ありますか。

【コメントに対する著者の見解】
豆腐の水分含量はモデルの種類などに大きく影響します。水分含量があまり高すぎると、材料は液体に近づくので、4要素モデルが適用できないことがあると思われます。逆に、水分含量が低すぎると、固体に近づきますので、固体的挙動が強くなり、別弾性モデルを必要とするでしょう。本研究では、絞ごしご豆腐製造法が使われており、つまり、製造中、圧搾工程がありますので、タンパク質含量が決まります。水分含量も同時に決まります。本研究のタンパク質含量は5%〜9%の間に調整され、それに対して、水分含量は90%〜94.4%の間になっています。実験の結果はこの水分含量条件下において豆腐のモデル解析に4要素MaxwellIIモデルが適用できることを示唆しました。よって、本研究の水分含量の範囲内では、4要素モデル解析の適用範囲内と判断しております。