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The effects of ingredients and water content on the rheological properties of batters and physical properties of crusts in fried foods

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Abstract

This study investigated the effect of ingredients and flour/water ratio on the rheological properties of batter. Replacing part of the wheat flour present in a weak composition (W-pattern) batter with gluten yielded a higher protein concentration that renders a strong composition (S-pattern) batter. This study also tested the effects of adding HPMC to S-pattern (SH-pattern) batter and crisping agents to W-pattern (WC-pattern) batter. The S- and SH-pattern batter exhibited Bingham-pseudoplastic fluid properties in a temperature range of 5–35 °C. W-pattern batters with a flour/water ratio of 1/1.5 and WC-pattern batters with flour/water ratio of 1/1 exhibited pseudoplastic fluid properties. Adding HPMC increased the fluid consistency index (b) of batter, revealing a higher viscosity and diminished fluidity. This batter showed a higher thermal solidification temperature and increased shear modulus (G', G''), complex viscosity and further raised the batter pick-up. The addition of crisping agents to W-pattern batter shifted solidification temperature to a lower range. In fried mackerel nuggets, the S- and SH-pattern crusts exhibited a texture that was firm and brittle, while W- and WC-pattern crusts exhibited a texture that was significantly more crisp.

Keywords: HPMC; Rheological properties; Viscosity; Crispness; Batter; Crust

1. Introduction

Typically a simple mixture of flour and water, batter can be defined as liquid dough into which a product is dipped prior to cooking, normally by frying (Fiszman and Salvador, 2003). Crust brittleness or crispness is a critical element in a consumer's evaluation of a particular fried battered food product. To achieve the desirable texture of crust in fried battered products, design of appropriate ingredients with wide-ranging functionalities is available.

The proteins in batter provide structure and increase the coating pick-up values and final yield in the fried products (Fiszman and Salvador, 2003). Gluten is a tough, elastic substance. Like a net, gluten traps and holds air bubbles in batter. The addition of gluten is traditionally associated with greater adhesion and crispness in final products (Breuil, 2001). Llorca et al. (2005) found that starch granules, small granules (average area = $28 \pm 5\ \mu m^2$) and bigger granules (average area = $228 \pm 45\ \mu m^2$) in a wheat gluten matrix (conventional batter) or in a gluten and hydrocolloid matrix (batter with MC), can be observed in batter. However, depending on the quantity and quality of gluten and the available water, the resultant structure can be as firm as bread dough or as flowing as batter, thus determine the products texture (Loewe, 1993).

Most food gums have a significant effect on available free water and liquid batter system rheology. By helping to retain moisture, form films, improve freeze-thaw stability and infuse with mild surfactant properties, gums can enhance the quality of fried food products (Duxbury,

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1989). The addition of carbohydrates, gums in particular, can also improve batter adhesion. Film formers such as methylcellulose (MC), hydroxypropylmethylcellulose (HPMC) and carboxymethylcellulose (CMC) have previously been used for this purpose. Adding CMC to batter has been found to increase product consistency (Hsia et al., 1992) and effectively reduce oil content in French-fries (Pinthus et al., 1993; Sahin et al., 2005). MC and HPMC exhibit thermal gelation and form a structure upon heating (Kuntz, 1997; Naruenartwongsakul et al., 2004). These two additives were also found to serve as an appropriate barrier to water and oil (Dziezak, 1991) and were successful applied in microwave reheated battered nuggets (Chen et al., 2008). Furthermore, porous crust is separated from the underlying food product in battered and fried foods systems that use HPMC in combination with starch. This is apparently accomplished by the superimposition of the HPMC–starch mixture onto cell structures (Meyers, 1990).

Crisping agents are substances, which reduce the tendency of individual particles of a foodstuff to adhere to one another, and used as an ingredient that improves crispness in foods. Materials with water insolubility, high glass transition temperature and good stability can act as a crisping agent. Dextrin, cellulose fiber and even leavening agent may act as crisping agents in batter (Fitchett et al., 2002). Calcium carbonate can also provide expanded fried snack structure during frying (Villagran et al., 1995).

Viscosity, solids suspension, set-up character, leavening stability, browning rate and flavor represent important batter selection criteria, with batter viscosity typically the most important criterion of batter-coated food product success (Suderman, 1993). Research on battered products in the past few decades has focused on researching a formula to control the quality of fried products, particularly studying ways to reduce the amount of fat absorbed during frying. Few research studies have investigated the rheological properties of batter systems containing HPMC (Sanz et al., 2005). Rheological properties are among the most important physical properties defining batter behavior. Flow properties directly influence key final batter-coating characteristics (e.g., appearance, crispness, color, pick-up and pumping) and thus have a key role in industrial batter-coated food manufacturing processes (Loewe, 1993; Sanz et al., 2005). Rheological tests run using dynamic methods, as long as they are obtained within the linear viscoelastic domain, may be considered a sort of material structure fingerprint (Sanz et al., 2004).

Many studies have addressed the viscoelastic properties of flour dough (Watanabe et al., 2002) and individual dough ingredients (Singh et al., 2003) using a small amplitude oscillatory test (SAOT). The thermorheological behavior of cellulose derivative solutions has also been previously studied (Li, 2002). Nevertheless, there is currently no comprehensive rheological properties information available on more complex systems such as batters containing HPMC or crisping agents. The main aim of this study was to evaluate the influence of temperature and ingredient composition on the rheology and flow properties of batters with varying flour/water ratios. Further understanding the functionality and rheological properties of HPMC and crisping agents in batter systems can enhance manufacturers' control of battering operations and battered nugget crust quality. Therefore, we used high and low protein concentration pattern to achieve strong and weak composition of batter, respectively. HPMC and crisping agents were applied to strong and weak composition of batter, respectively, to evaluate the rheological properties of batter and crispness of crust.

2. Materials and methods

2.1. Horse mackerel mince

Frozen horse mackerel (*Trachurus japonicus*) was purchased from Cheer-Foods Enterprise Co. LTD. (Ilan, Taiwan). The fish block used for this study (10 kg) had been previously frozen for two months at −20 °C, and was thawed at 25 °C for 12 h. The fish mince, prepared from ordinary muscles, was collected from the thawed fish and then chopped in a Stephan vertical vacuum cutter (Model UM 5 Universal, Stephan Machinery Co., Hameln, Germany) for 1 min at 1600 rpm.

2.2. Ingredients for battering and breading

HPMC (HPMC300, Taian Ruitai Cellulose Co., LTD., Feicheng, PRC.) was purchased from Toong Yeuan Enterprise Co., LTD. (Taipei, Taiwan). Wheat flour (all purpose flour) and cornstarch (30% amylose) were purchased from Gi Chan Food Co., LTD. (Hsin Chu, Taiwan). Leavening ($Na_2H_2P_2O_7/NaHCO_3$) was purchased from Chien Yuan Food Chemicals Co., LTD. (Taipei, Taiwan). Crisping agent ($CaCO_3$ content >95%), breadcrumbs and salt were purchased from SCI-MISTRY Co., LTD. (Ilan, Taiwan).

2.3. Battered and breaded mackerel nuggets

The batter formulation consisted of wheat flour, cornstarch, leavening and salt with different additives and ingredients (Table 1). As lower temperatures cause higher batter viscosity, a flour/water ratio of either 1/1 or 1/1.5 was provided, respectively, for batter applied immediately after being prepared or applied following a period of time in cold storage. The thoroughly pre-blended powders were mixed with cold water in ratios of 1/1 and 1/1.5 (w/w) in a stirring apparatus (K5SS, KitchenAid, St. Joseph, Michigan, USA) for 10 min. These batters were designated, as strong (S and SH-patterns) and weak (W and WC-patterns) composition batters. Strong and weak composition batters were defined as such based on, respectively, the addition or absence of gluten. S-pattern and W-pattern batters were designed, respectively, to provide brittle and crispy textures. HPMC was not added to W-type batter

Table 1
Ingredients in mackerel nugget batter

Ingredients (%)[a]	S-pattern[b]	SH – pattern[c]	W-pattern[d]	WC – pattern[e]
Wheat flour	55	53	65	64
Corn starch (30% amylose content)	30	30	30	30
Gluten	10	10	–	–
Leavening ($Na_2H_2P_2O_7$/ $NaHCO_3$)	2	2	2	2
HPMC	–	2	–	–
Crisping agent ($CaCO_3$)	–	–	–	1
Salt	3	3	3	3

[a] All ingredient percentages are given on a weight basis.
[b] S-pattern: strong structure pattern with gluten addition.
[c] SH-pattern: HPMC added S-pattern.
[d] W-pattern: weak structure pattern without gluten addition.
[e] WC-pattern: crisping agent added W-pattern.

in order to prevent a toughening of the crust. Crisping agents were not added to S-type batter in order to prevent crusts from becoming overly fragile.

Mackerel minces (20 g) were used as the food matrix, predusted with wheat flour, immersed in the SH-, S-, W- or WC-pattern batters for 10 s and then breaded with breadcrumbs (<20 mesh). Mackerel nugget batter pick-up was calculated as

$$\text{pick-up } (\%) = [(\text{battered minces–minces}) / (\text{battered mince})] \cdot 100\% \tag{1}$$

Battered and breaded nuggets were fried at 180 °C for 2.5 min in a commercial deep-fat fryer (Chin Ying Fa Mechanical Ind. Co., LTD., Chang-Hua, Taiwan) containing 2.5 L of hydrogenate oil.

2.4. Rheological properties

Rheological properties of the HPMC and batter were determined in a dynamic rheometer (Rheometer AR-550, TA Instruments, New Castle, Delaware, USA) with a small amplitude oscillatory test (SAOT). The dynamic rheometer was equipped with cone geometry (60 mm diameter with 2° angle). Gap and strain were set at 52 μm. Prior to the temperature ramp test, frequency and strain sweeps were conducted to obtain the linear viscoelastic region, after which the frequency and strain were fixed at 1 Hz and 1%, respectively. Temperature sweeps involved heating at 2 °C/min from 5 °C to 80 °C. The frequency was fixed at 1 Hz. For viscosity measurements, the shear rate was scanned from 0.1 to 100 1/s at 5, 15, 25 and 35 °C. Batter and 2% HPMC samples, respectively, were set on the rheometer peltier for 3 min of relaxation before each measuring. Grease was applied to the exposed surface of samples and a cover split was fixed to prevent sample dehydration. Three replicate scans were made, with the storage modulus (G'), loss modulus (G''), $\tan\delta$, magnitude of the complex viscosity (η^*) and flow property indexes recorded. A non-Newtonian fluid model was utilized to estimate sample's flow properties:

$$T = b\gamma'^{n} + c \tag{2}$$

where T, b, γ', n and c represent shear stress, fluid consistency index, shear rate, flow behavior index and yield stress, respectively.

2.5. Texture analysis

The crust crispness of six replicates was evaluated with a Sun Rheometer (R-150, Sun Scientific Co., LTD., Tokyo, Japan). Crusts were then separated from mackerel nuggets, cut into rectangular (20 × 10 mm) portions, and subjected to a compression test using a knife adaptor (No. 8). Compression speed was 60 mm/min, with maximum peak force representing cutting force (in kg) and compression distance representing deformation (in mm). Results were used to evaluate the degree of crust crispness.

2.6. Statistical analysis

Statistical analysis on data was performed using a system developed by SAS Institute Inc. (1993). When analysis of variance (ANOVA) revealed a significant effect ($P < 0.05$), data means were compared using a least significant difference (LSD) test.

3. Results and discussion

3.1. Flow properties of batter

SH-pattern batter flow properties were evaluated by testing shear stress vs. shear rate in flour/water ratios of 1/1 and 1/1.5 at various temperatures (Fig. 1). The parameters, including S-, SH-, W- and WC-pattern batters in a non-Newtonian fluid model are listed in Table 2. The strong composition batters (S and SH-patterns) prepared with flour/water ratios of 1/1 and 1/1.5 exhibited Bingham-pseudoplastic fluids in a temperature range of 5 to 35°C (Table 2). Both higher temperatures and lower ingredient concentrations (flour/water = 1/1.5) produced a higher flow behavior index (n) and lower fluid consistency index (b) and lower yield stress (c). This reflected lower batter viscosity, resulting in easier coating performance. On the contrary, higher b values corresponded with higher viscosity, which produced enhanced adherence and batter pick-up. The batter with Bingham-pseudoplastic properties corresponded to a thick solution with suspended irregularly shaped particles (Bourne, 1982). Sanz et al. (2005) also found that the addition of gluten resulted in more marked shear thinning properties (lower flow index values), likely the result of a more robust protein-base structure at low shear rates. The b value of batter with a flour/water ratio of 1/1.5 at 5 °C approached that of batter with a flour/water ratio of 1/1 at 15–25 °C.

Batter viscosity influences batter pick-up quantity and quality, the potential of producing voids, ease of handling, breading pick-up, and final coating texture. Viscosity, in

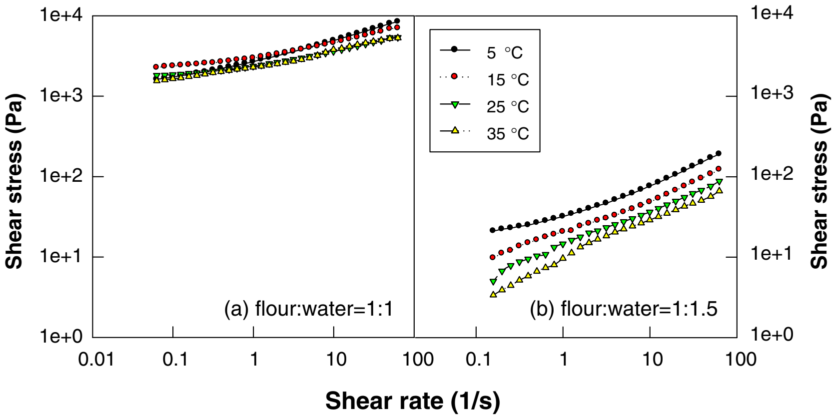

Fig. 1. Flow behavior properties of SH-pattern batter at 5 °C, 15 °C, 25 °C and 35 °C.

Table 2
Batter flow properties under various temperatures

Flour/water	Fluid properties		Flow behavior index, *n*		Fluid consistency index, *b* (Pa s)		Yield stress, *c* (Pa)s	
	1/1	1/1.5	1/1	1/1.5	1/1	1/1.5	1/1	1/1.5
S-pattern								
5 °C	BP[i]	BP	$0.16 \pm 0.03\text{e}^{e,y}$	$0.17 \pm 0.01^{f,y}$	$472.6 \pm 50.5^{d,y}$	$365.1 \pm 44.3^{c,z}$	$430.7 \pm 33.1^{d,y}$	$223.5 \pm 12.8^{a,z}$
15 °C	BP	BP	$0.18 \pm 0.02^{e,z}$	$0.29 \pm 0.03^{e,y}$	$384.8 \pm 20.6^{d,e,y}$	$252.0 \pm 31.7^{d,z}$	$293.8 \pm 30.2^{d,e,y}$	$183.0 \pm 10.6^{a,b,z}$
25 °C	BP	BP	$0.41 \pm 0.6^{c,d,z}$	$0.59 \pm 0.05^{c,y}$	$268.1 \pm 26.4^{e,y}$	$98.9 \pm 10.2^{e,f,z}$	$254.3 \pm 19.7^{e,y}$	$89.7 \pm 7.7^{c,z}$
35 °C	BP	P[j]	$0.70 \pm 0.08^{b,z}$	$0.84 \pm 0.19^{a,b,y}$	$188.7 \pm 11.7^{e,f,y}$	$25.7 \pm 3.1^{g,z}$	$138.8 \pm 9.6^{f,y}$	$0.0 \pm 0.0^{f,z}$
SH-pattern								
5 °C	BP	BP	$0.34 \pm 0.07^{d,y}$	$0.26 \pm 0.04^{e,y}$	$1807.3 \pm 98.1^{a,y}$	$1366.1 \pm 95.5^{a,z}$	$901.9 \pm 88.3^{a,y}$	$152.9 \pm 13.4^{b,z}$
15 °C	BP	BP	$0.35 \pm 0.07^{d,z}$	$0.47 \pm 0.02^{d,y}$	$1229.5 \pm 120.3^{b,y}$	$608.5 \pm 72.1^{b,z}$	$791.1 \pm 70.6^{a,b,y}$	$85.4 \pm 6.5^{c,z}$
25 °C	BP	BP	$0.43 \pm 0.04^{c,z}$	$0.55 \pm 0.07^{c,y}$	$1007.8 \pm 96.4^{b,c,y}$	$160.4 \pm 10.3^{e,z}$	$613.7 \pm 38.8^{c,y}$	$54.0 \pm 5.9^{c,d,z}$
35 °C	BP	BP	$0.67 \pm 0.09^{b,y}$	$0.75 \pm 0.06^{b,y}$	$847.7 \pm 75.1^{c,y}$	$120.9 \pm 9.9^{e,z}$	$407.6 \pm 35.5^{d,y}$	$14.8 \pm 1.3^{e,z}$
W-pattern								
5 °C	BP	P	$0.45 \pm 0.03^{c,y}$	$0.52 \pm 0.04^{c,d,y}$	$101.1 \pm 14.2^{f,y}$	$25.9 \pm 3.1^{g,z}$	$111.0 \pm 8.7^{f,y}$	$0.0 \pm 0.0^{f,z}$
15 °C	BP	P	$0.49 \pm 0.08^{c,z}$	$0.60 \pm 0.06^{c,y}$	$73.8 \pm 6.6^{f,g,y}$	$22.9 \pm 1.6^{g,z}$	$102.3 \pm 7.6^{f,y}$	$0.0 \pm 0.0^{f,z}$
25 °C	BP	P	$0.53 \pm 0.06^{c,z}$	$0.76 \pm 0.06^{b,y}$	$45.0 \pm 5.9^{g,y}$	$22.7 \pm 2.5^{g,z}$	$59.9 \pm 5.5\text{f}^{g,y}$	$0.0 \pm 0.0^{f,z}$
35 °C	BP	P	$0.89 \pm 0.10^{a,y}$	$0.93 \pm 0.10^{a,y}$	$34.1 \pm 4.8^{g,y}$	$13.6 \pm 1.8^{g,z}$	$51.3 \pm 4.4^{f,g,y}$	$0.0 \pm 0.0^{f,z}$
WC-pattern								
5 °C	P	P	$0.38 \pm 0.07^{c,d,z}$	$0.51 \pm 0.07^{c,d,y}$	$119.7 \pm 9.9^{f,y}$	$14.9 \pm 2.1^{g,z}$	$0.0 \pm 0.0^{h,y}$	$0.0 \pm 0.0^{e,y}$
15 °C	P	P	$0.31 \pm 0.03^{d,z}$	$0.57 \pm 0.06^{c,y}$	$139.4 \pm 10.2^{e,f,y}$	$16.6 \pm 2.8^{g,z}$	$0.0 \pm 0.0^{h,y}$	$0.0 \pm 0.0^{e,y}$
25 °C	P	P	$0.48 \pm 0.07^{c,z}$	$0.76 \pm 0.07^{b,y}$	$57.3 \pm 4.7^{g,y}$	$15.9 \pm 1.7^{g,z}$	$0.0 \pm 0.0^{h,y}$	$0.0 \pm 0.0^{e,y}$
35 °C	P	P	$0.89 \pm 0.12^{a,y}$	$0.95 \pm 0.11^{a,y}$	$55.6 \pm 7.5^{g,y}$	$15.2 \pm 2.0^{g,z}$	$0.0 \pm 0.0^{h,y}$	$0.0 \pm 0.0^{e,y}$

[a–h] Different superscripts for data in each column represent significant differences ($P < 0.05$).

[y–z] Different superscripts for data in each flow parameter at flour/water ratio of 1/1 and 1/1.5 in each row represent significant differences ($P < 0.05$).

[i] BP: Bingham-pseudoplastic fluid.

[j] P: pseudoplastic fluid.

turn, is affected by batter temperature, ingredient composition, and the solids-to-water ratio. The flow properties of HPMC-enhanced batters demonstrated an extreme sensitivity to temperature within 5–25 °C. Such temperature dependent properties have strong relationship to coating performance (Sanz et al., 2004). In general, batter temperatures between 4 and 16 °C are recommended to optimize batter viscosity and discourage microorganism growth. The most common method to adjust viscosity is to change the solids–water ratio and practice temperature (Suderman, 1993). Therefore, batters with lower ingredient concentrations (e.g., flour/water = 1/1.5) can also achieve a higher consistency and enhanced pick-up in nuggets when applied at a lower temperature.

HPMC is a nonionic polymer. Its solution or gel viscosity is stable over a fairly wide pH range (pH 3 through 11) and is unaffected by metal ions. The addition of HPMC to other gelation systems has been shown to produce a synergistic effect in viscosity and stickiness (Glicksman, 1969). The addition of small amounts of cellulose ethers results in a very significant viscosity enhancement of fluid batter (Naruenartwongsakul et al., 2003). SH-pattern batter revealed a flow behavior index (*n*) at lower temperatures (5 and 15 °C) higher than that of S-pattern batter and a lower index value than that of S-pattern batter at 35 °C (Table 2). The addition of 2% HPMC raised the fluid consistency index (*b*) of S-pattern batter and aided the flow properties at thinner batter consistencies and lower temperatures. HPMC yielded a remarkable decrease in *b* value when the temperature increased from 5 to 35 °C, which was attributed to better hydration of HPMC chains at lower temperatures. The practical consequences of this particular sensitivity to temperature of HPMC-enhanced batters are also reported by Sanz et al. (2004) in the research of batters properties with the different added ingredients.

In addition, SH-pattern batter showed a yield stress value greater than that of S-pattern batter at flour/water = 1/1, but a lower value than that of S-pattern batter at flour/water = 1/1.5 (Table 2). Cellulose and cellulose-rich materials provide a flow conditioning effect in dough (Chen et al., 1996). Its pseudoplastic fluid properties and nearly linear shear stress-shear rate behavior at low shear rates (Chen, 2007) indicate that a 2% HPMC solution may maintain desirable flow properties during battering. Therefore, it is possible that HPMC in higher moisture systems may cause batter start moving with less shear stress. That is, the SH-pattern batter at flour/water = 1/1.5 exhibited high consistency and low yield stress flow properties, and therefore was closer in character to high viscous pseudoplastic fluids.

W-pattern batter showed Bingham-pseudoplastic and showed pseudoplastic fluid properties at higher (flour/water = 1/1) and lower (flour/water = 1/1.5) concentrations, respectively, within the 5–35 °C temperature range (Table 2). Compared with S-pattern batter, W-pattern batter exhibited higher *n* values, and lower *b* and *c* values. This reflects that the gluten exhibited the enhancement effect on consistency and reduced flow properties of batter. Wheat flour provides viscosity and promotes adhesion through gluten formation (Kuntz, 1995). Moreover, the addition of gluten is associated with greater adhesion and better structure and texture (Breuil, 2001).

No noticeable changes in *n* and *b* values were observed when crisping agents were added to W-pattern batter. Nevertheless, the yield stress of WC-pattern batter became zero and showed pseudoplastic fluid properties. This indicates that insoluble crisping agents did not alter the consistency, but contributed to flow conditioning in the W-pattern batter.

3.2. Rheological properties of HPMC

SAOT is often used to determine viscoelastic functions such as storage modulus (G') and loss modulus (G''). The former relates to the elastic response attributable to bonding or junction zone strength. The later relates to a sample's viscous response attributable to friction energy loss (Hamman et al., 1990; Niwa, 1992; Macosko, 1994). It is worth highlighting the employment of SAOT to study structural changes during gelation, since it is possible to monitor the process without altering the evolving sample structure (Sanz et al., 2005). The HPMC and four kinds of batters developed for this study were then subjected to SAOT to evaluate their respective rheological properties.

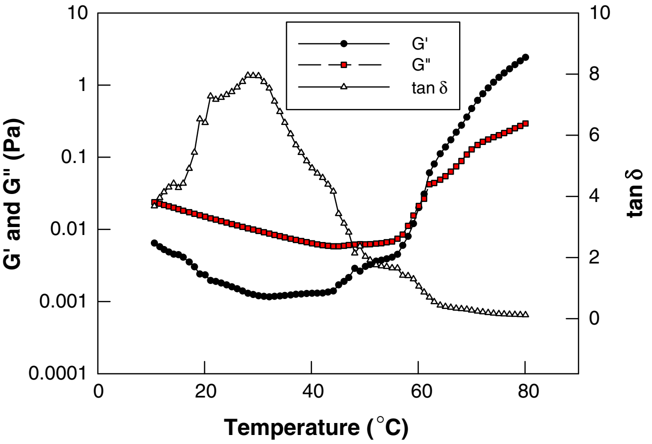

Fig. 2. Rheological modulus of 2% HPMC gel during heating.

The normally very low storage modulus (G') and loss modulus (G'') of the 2% HPMC solution increased markedly when thermal scanning temperature exceeded 53 °C. The G' curve intersected with the G'' curve at 61 °C, with 0.05 Pa. The tan δ curve declined from 8 at 32 °C and $\tan\delta = 1$ at 61 °C (Fig. 2). When a liquid sample either gelled or became solid, both G' and G'' increased noticeably. The increment of G' was larger than that of G'', resulting in $\tan\delta < 1$. Hence, the point of intersection between G' and G'' curves is considered the gelation temperature (Clark and Ross-Murphy, 1987).

HPMC is a thermoreversible material, meaning that its solution viscosity decreases with increasing temperature to the thermal gel point, after which the viscosity rises sharply until the flocculation temperature is reached around 50–90 °C (Zecher and Van Coillie, 1992; Nussinovitch, 1997; Lopes da Silva and Rao, 1999; Chen, 2007). Flocculation results from the weakening of the hydrogen bonds (H-bonds) between polymer and water molecules and the strengthening of interactions between polymer chains. Gels formed as a result of phase separation and are susceptible to shear thinning. This suggests that heated HPMC gel contains both amorphous and crystal-like regions (Glicksman, 1969, 1982) and that the process of HPMC gelation mainly results from the hydrophobic interaction of molecules containing methoxyl groups (Fiszman et al., 2005). HPMC form a thermal gel structure that increases moisture retention (Meyers, 1990), thus adding HPMC changes batter viscosity (Naruenartwongsakul et al., 2003).

3.3. Rheological properties of batter

Three distinct stages of change were observed in G' during thermal scanning. These stages were particularly conspicuous in W-pattern batter with flour/water = 1/1 (Fig. 3). The G' in this curve was originated at around 10 Pa and gradually declined as temperature rose to 40 °C. The G' increased markedly after temperatures rose above 45 °C before reaching a stable high value in the range of 60–80 °C. In the first stage (<45 °C), energized

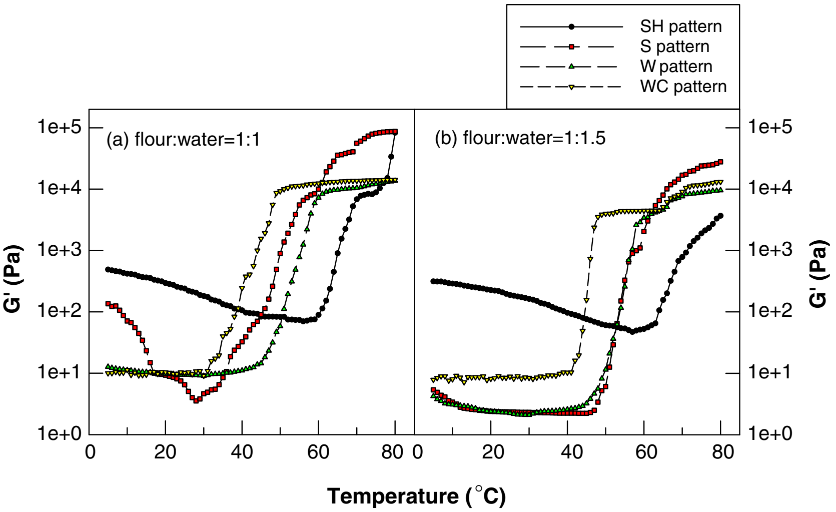

Fig. 3. Storage modulus (G') profile of batter under rising temperature conditions. (Items S, SH, W and WC are as described in Table 1.)

molecules softened batter. Second stage characteristics are attributed to gluten denaturation and starch swelling. Third stage characteristics are believed due to mixture stability consisting of gelatinized proteins and gelatinization starch molecules. The third stage represents a temporary steady state of gelatinized batter mixture. This result leads naturally to a hypothesis that the G' of flour/water = 1/1 W-pattern batter, while higher than that with flour/water = 1/1.5 W-pattern batter at temperatures below 60 °C, becomes similar to that of flour/water = 1/1.5 W-pattern batter as temperatures rise above 70 °C. Such would reveal that the effect of water on G' is more profound at lower scanning temperatures than at higher temperatures.

Addition of crisping agents to W-pattern batter shifted the second stage of the G' curve to lower temperature range, with initial temperature at the second stage at 33 °C and 42 °C, respectively, for flour/water = 1/1 and = 1/1.5 batter. While initial temperature at the third stage was also lower. The crisping agent seemed to accelerate batter solidification. The water insoluble calcium carbonate salts provide nuclei to flocculate proteins (Coombs et al., 1975). This flocculation effect might also occur in batter and result in increases in G' at lower temperatures.

Three stages were also observed in the G' curve in S- and SH-pattern batter. In the second stage, the S-pattern batter temperature range was wider and the final G' higher than those of W-pattern batter. This result was enhanced further when the flour/water ratio was 1/1 (Fig. 3a). The denaturation and gelation of gluten created a more complex structure upon heating, causing increased rigidity.

In addition to its protein increasing batter rigidity during heating, HPMC caused G' values to fluctuate. The G' of SH-pattern batter measured around 500 Pa at 5 °C for both flour/water = 1/1 and 1/1.5, which was higher than that for other batter samples. The first stage of the G' curve extended from 5 °C through 61 °C, after which G' rose markedly. This reveals that HPMC intensified the molecular-level integration of ingredients in the batter and enhanced further a high water holding capacity, resulted in the high consistency and rigidity witnessed even at first stage of the G' curve. Nevertheless, the addition of HPMC delayed batter solidification to a temperature that approximated the thermal gelation temperature of HPMC. Since the G' curve of SH-pattern batter approximated that of HPMC gel during thermal scanning, HPMC flow properties predominated in SH-pattern batter by controlling part of water molecule motion.

The presence of non-starch polysaccharides helps hydrate batter, which restricts water mobility and delays initiation of the gelatinization process. A small increase in wheat flour gelatinization onset temperature in the presence of HPMC was reported by Rojas et al. (1999). The presence of other non-starch polysaccharides in general terms elevates gelatinization temperatures (Tester and Sommerville, 2003). Kobylañski et al. (2004) also concluded that HPMC–water interactions mainly controlled the onset temperature of starch gelatinization in dough.

G'' curves were similar to those of G' curves during thermal scanning (Fig. 4). Batter with higher protein contents (S and SH-patterns) and with higher concentrations (flour/water = 1/1) exhibited higher G'' values. Both HPMC and crisping agents influenced the G'' under conditions of rising temperature. Furthermore, the G'' of W- and WC-pattern batters reached stable values above 45 °C and 60 °C, respectively. Sanz et al. (2005) also found that the viscoelastic moduli of batter decreased at around 80 °C. This study proceeded under the assumption that the gel structure of gluten-lacked batters was more difficult to yield a high viscoelastic at high temperatures than higher gluten content batter.

When temperatures fell below 45 °C at the initial heating stage, tan δ of W- and WC-pattern batters were higher than those of S- and SH-pattern batters. However, the opposite was observed at around 60 °C (Fig. 5a). In general, the

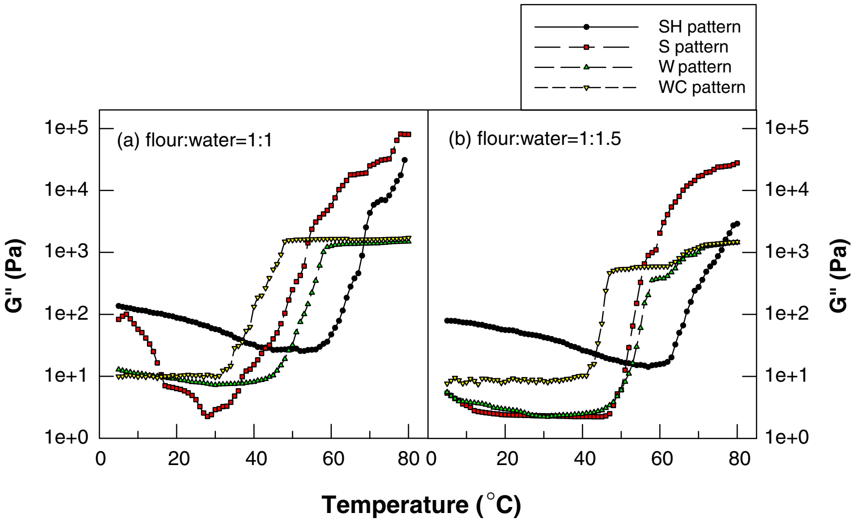

Fig. 4. Loss modulus (G'') profile of batter under rising temperature conditions. (Items S, SH, W and WC are as described in Table 1.)

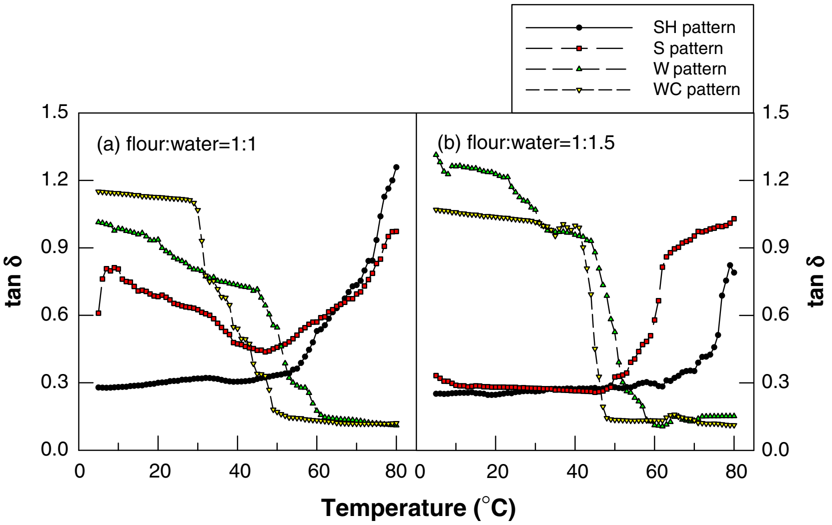

Fig. 5. Loss factor (tan δ) profile of batter under rising temperature conditions. (Items S, SH, W and WC are as described in Table 1.)

point of intersection between G' and G'' curves is considered to be the gelation temperature (Clark and Ross-Murphy, 1987). Nevertheless, prior to thermal gelation, G' is larger than G'' in high viscosity and high concentrate gels. We were unable to use $G' > G''$ (i.e. $\tan\delta < 1$) as the only precondition to determine thermal gelation temperature. For that reason, we referred to Lai et al. (1996) and determined that the thermal gelation temperature of batter based on the following conditions existing simultaneously: $G' > G''$, $G' > 10^3$ Pa, with $\tan\delta$ becoming stable or attaining its lowest point. Therefore, for batter with a flour/water ratio of 1/1, thermal gelation temperatures for SH, S, W and WC were 66.7 °C, 52.4 °C, 60.6 °C and 48.5 °C, respectively. For batter with a flour/water ratio of 1/1.5, thermal gelation temperatures for SH, S, W and WC were 69.5 °C, 58.9 °C 62.1 °C and 48.5 °C, respectively. The gelation temperatures of S-pattern batters were lower than those of W-pattern batters due to the addition of gluten, which lowers gelation temperature. On the other hands, in addition to the higher temperature of HPMC thermogelation, the hydration of HPMC caused the competition in water molecules with the other ingredients, which delayed SH-pattern batter gelation. However, crisping agents again lowered the temperature at which batter would gel. In addition, the $\tan\delta$ corresponding to WC-pattern batter are so variable between 5 and 30 °C. We hypothesize that insoluble calcium carbonate in the crisping agent may have some bearing on batter rheological properties.

The magnitude of the complex viscosity curve values for these batters tracked G' curve values very closely during thermal scanning (Fig. 6). HPMC and crisping agents definitely affected batter flow properties. The batter is a mixture in which interactions between ingredients and gelation materials usually influence its qualitative and

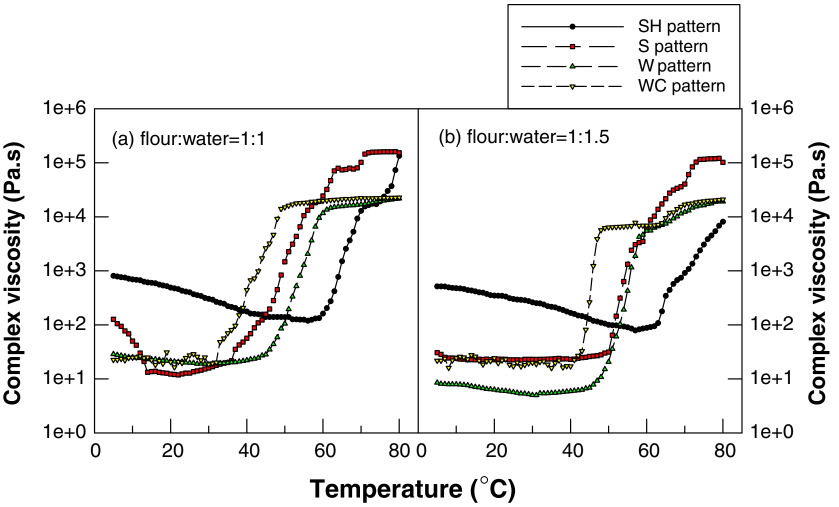

Fig. 6. The magnitude of the complex viscosity (η^*) profile of batter under rising temperature conditions. (Items S, SH, W and WC are as described in Table 1.)

functional characteristics (Meyers and Conklin, 1990; Ang, 1993; Pinthus et al., 1993). The addition of HPMC effectively changed batter flow properties, reduced pasting temperature and enhanced viscosity (Naruenartwongsakul et al., 2003), thus improving batter setting and adhesion (Naruenartwongsakul et al., 2004). The effect of HPMC on rheological property was observed as SH-pattern batter displayed highly magnitude of the complex viscosity, even at the lower temperatures used in this study (<40 °C).

3.4. Pick-up of batter and crispness of crust

As most manufacturers in Taiwan employ a flour/water ratio of around 1/1 in prepared batter, the following experiments evaluated crust pick-up and crispness in different batter patterns with a flour/water ratio of 1/1.

The pick-up of mackerel nuggets battered with S- and SH-pattern were higher than those of W- and WC-pattern, and the HPMC added batter showed particular high values (Table 3). The hydrophilic property of HPMC adsorbed considerable quantities of water molecules and contributed to the viscosity increase of batter (Sahin et al., 2005). In this study, the higher viscosity and rheological moduli the higher batter pick-up was observed. The high consistency of HPMC-added batter was considered to exhibit the strong adhesion to fish mince and resulted in higher pick-up.

Table 3
The pick-up of batter (powder/water ratio of 1/1) and the crispness of crust in fried mackerel nuggets

	Pick-up of batter (%)	Cutting force of crust (g)	Deformation of crust (mm)
S-pattern	36.3 ± 2.4^{b}	630.6 ± 21.8^{a}	4.6 ± 0.3^{a}
SH-pattern	41.2 ± 3.1^{a}	592.9 ± 30.6^{b,c}	4.6 ± 0.2^{a}
W-pattern	30.6 ± 1.9^{c,d}	476.5 ± 31.4^{d}	4.3 ± 0.2^{b}
WC-pattern	32.3 ± 2.7^{c}	611.0 ± 37.5^{a,b}	3.7 ± 0.3^{c}

[a–d] Different superscripts for data in each column represent significant differences ($P < 0.05$).

The lowest cutting force and deformation of crust were obtained in fried mackerel nuggets with W- and WC-pattern batters, respectively (Table 3). Cutting force may represent crust hardness. Meanwhile, the compression distance to cut off samples represents deformation and may be employed to evaluate fracturability, with deformation values correlating negatively with crust crispness. Therefore, the loosest and the most fragile texture were observed in W- and WC-pattern batters, respectively. It revealed that the batters with weak compositions produced softer/looser crusts after frying. Adding a crisping agent to batter can help disconnect the continuous crust matrix and enhance crispness. However, the inferior crispness in gluten-enriched samples prepared from S- and SH-pattern batters was due to the stronger mixture of gelled protein. Though the HPMC decreased the hardness of crust but could not gain the fragile texture.

The thermogelation characteristic of HPMC formed a water barrier in crust during frying (Dziezak, 1991). HPMC gel adsorbs the water molecules that are in batter and diffused from fish meat during heating. Since HPMC and HPMC added batter exhibited high moduli during heating, this moist and soft HPMC gel is considered as the major factor resulted in inferior crispness of crust. Sahin et al. (2005) also found that the addition of 1% HPMC in batter caused the soft and inferior crispy crust after frying and referred this phenomenon to the high water holding capacity of HPMC film that raised the elasticity of crust.

4. Conclusion

By measuring rheological properties, it was found that both G' and G'' increased noticeably when a liquid sample either gelled or became solid. The solidification of batter included protein denaturation and gelatinization during heating. A larger increment of G' than of G'', resulting in $\tan\delta < 1$ for gluten-enhanced batter, reflected the stronger mixture of gelatinized starch and gelled protein. Nevertheless, both protein enrichment and the addition of HPMC enhanced batter viscous properties, resulting in consistency increases, flow ability abatement and pick-up increases. On the contrary, lowering protein content or adding a crisping agent reduced batter viscosity. The rheological properties of batter containing HPMC not only influences product pick-up, but also determines crust texture. Therefore, such have become important indices in the battered nugget process.

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