Studying the effects of whole-wheat flour on the rheological properties and the quality attributes of whole-wheat saltine...
Studying the effects of whole-wheat flour on the rheological properties and the quality attributes of whole-wheat saltine cracker using SRC, alveograph, rheometer, and NMR technique

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Abstract

Quality attributes of soft wheat products are affected by physicochemical characteristics and rheological properties of wheat flour. Whole-wheat flour has a significant impact on baking qualities (stack height, stack weight, specific volume, and breaking strength) of whole-wheat saltine crackers due to its high water absorption capacity. SRC profiles, alveograph and rheometer parameters were determined to observe the effect of whole-wheat flour on whole-wheat cracker flour blends. NMR technique was utilized to demonstrate the water migration and competition in whole-wheat dough components. Results of SRC testing revealed that the water absorption of whole-wheat flour blends increased with the addition level of whole-wheat flour. The rheological properties (C∗, C′, L, W values) were influenced significantly by the presence of whole-wheat flour. Results of NMR indicated that water migrated from the gluten network into arabinoxylans matrix in whole-wheat dough system, resulting in inferior saltine cracker-baking qualities of whole-wheat flour, i.e., small breaking strength, stack height and specific volume. The stack height, specific volume, and breaking strength of end products showed significant correlations with the arabinoxylans, dough extensibility, and gluten index of whole-wheat flour.

1. Introduction

Crackers are an important product line within the large-scale baking industry, and are a natural fit as portable and convenient foods. Crackers can be divided into three broad categories: saltine cracker (soda cracker), chemically leavened cracker, and enzyme cracker (Moore & Strouts, 2008). The quality of wheat products is determined by the rheological behaviours of dough. The pasting properties of starch gave useful prediction to the quality of soft wheat products such as cookies, crackers and cakes (Serpil, Kevser, Bengihan, & Hamit, 2008). The volumes of bread and puff pastry were correlated with rheological properties of the dough (Sliwinski, Kolster, & van Vliet, 2004). Therefore, understanding the rheological properties and machinability of dough system is essential for guiding the production of wheat products. However, whole-wheat flour has a major impact on the rheological properties of dough and quality attributes of end products. The water absorption of wheat flour, especially the whole-wheat flour can significantly affect the rheological properties of cracker dough and end-product quality. The formation of gluten in dough system was restrained by whole-wheat flour of high-level water absorption capacity, which was undesirable in the functionality of cracker flour (Slade, Levine, Craig, & Arciszewski, 1994). Presumably, the arabinoxylans which are the main non-starch polysaccharides in wheat bran compete for water with the dough main polymers, gluten and starch in whole-wheat dough system, and interrupt the protein aggregation behaviour during heating (Rosell, Santos, & Collar, 2010).

At present, solvent retention capacity (SRC) and alveograph are the two traditional methods for estimating the potential performance of soft wheat flour. The SRC tests were developed to evaluate the quality of soft wheat flour in cookie and cracker products. In general, alveograph is more appropriate for predicting the protein functionality of soft wheat flours, while farinograph and mixograph are commonly used to evaluate hard wheat bread flours (Levine & Slade, 2004). Both the SRC and alveograph results are affected by the presence of wheat bran in flours. Since the alveograph measures the fixed-absorption dough, having bran involved will greatly affect the amount of water available for gluten formation. Further,
bran particles can physically disrupt the gluten matrix, leading to premature bubble rupture (Li et al., 2012).

NMR technique which is a useful tool to detect the macro-water distribution and migration among high-moisture samples non-invasively (Stapley, Hyde, Gladden, & Fryer, 1997) was successfully applied to examine the water migration between macromolecules (arabinoxylans and gluten network) in whole-wheat bread dough system (Li et al., 2012). Thus, the objectives of this study were: 1) to investigate the effect of whole-wheat flour on the rheological properties of whole-wheat saltine cracker flour blends using the rheometer, alveograph, and SRC testing; 2) to verify the mechanism of the impact of whole-wheat flour on the quality attributes of whole-wheat saltine cracker using the NMR technique; and 3) to establish the relationship between the rheological properties of whole-wheat flour blends and end-product quality parameters.

2. Materials and methods

2.1. Materials

Soft white whole-wheat flour (SWWW; Ultragrain®) was kindly provided by ConAgra Flour Mills, Inc. (Omaha, NE, USA). Soft red winter flour (SRW; Golden Shield, enriched and unbleached) and hard red winter flour (HRW; Harvest King winter wheat, enriched and unbleached) were obtained from General Mills, Inc. (Minneapolis, MN, USA). Baking soda (ARM & HAMMER Div. of Church & Dwight, Co., Inc., Princeton, NJ, USA), yeast food (ADM Arkady Inc., Olathe, KS, USA), salt (Morton Salt, Inc., Chicago, IL, USA), Crisco vegetable shortening (trans-fat free) (J.M. Smucker Company, Orrville, OH, USA) and instant dry yeast (Lesaffre Yeast Corporation, Milwaukee, Wisconsin, USA) were purchased from a local supermarket (Portland, Oregon, USA). The chemical reagents (ACS grade) used for performing SRC tests were purchased from Nurnberg Scientific Company (Portland, OR, USA).

2.2. Whole-wheat saltine cracker flour blends preparation and analysis

Whole-wheat saltine cracker flour samples were composited from the blends of SWWW, SRW, and HRW flour (Table 1). HRW flour is suitable for making crackers (Slade et al., 1994) and meets the requirement of relatively high gluten strength for high-quality cracker flour (Kweon, Slade, & Levine, 2011b). From our preliminary trials (data not shown), the optimum addition range of HRW flour was 10e20 g/100 g which was determined by the breaking strength of end products (if HRW was 20 g/100 g, the end-product texture became harder and less crispy), so 15 g/100 g of HRW flour was added consistently in each group, except for the 100 g/100 g SWWW group. The addition levels of SWWW flour in flour blends were 0 g/100 g (control flour blend), 25 g/100 g, 50 g/100 g, 75 g/100 g and 100 g/100 g, respectively.

Protein (AACC 46-30.01), moisture (AACC 44-15.02), ash (AACC 08-15.02), starch damage (AACC 76-33.01), wet gluten and gluten index (AACC 38-12.02) of five different whole-wheat flour blends were determined according to the AACC International Approved Methods and results are shown in Table 2.

2.3. Whole-wheat saltine cracker preparation

2.3.1. Formula

In the sponge, ingredients included flour (65 g/100 g), sourdough starter (4 g/100 g), instant dry yeast (0.3 g/100 g), yeast foods (0.03 g/100 g), and water (27 g/100 g, 29 g/100 g, 30 g/100 g, 32 g/100 g, and 34 g/100 g) water was added into five whole-wheat flour blends, respectively. The sourdough starter was initially supplied by the Oregon State University and was fed every day using old starter (50 g), HRW flour (100 g), and distilled water (50 g). The starter ingredients were mixed (Hobart A-200 mixer) at 1st speed for 5 min until well blended, and the starter dough was placed in a container with a lid until it tripled in volume at room temperature. The dough ingredients included flour (35 g/100 g), shortening (14 g/100 g), salt (0.8 g/100 g), water (1 g/100 g), and baking soda (determined by the total titratable acidity of the sponge). All ingredients were scaled on the basis of 500-g flour weight. Instant dry yeast, yeast foods, and salt were weighed and dispersed separately in the amount of water required in the formula before use.

2.3.2. Baking soda dosage determination

The total titratable acidity (TTA) test was considered as an indication of the fermentation process. To determine the baking soda dosage in the cracker dough formula and to control the final product pH (in the range of 7e8), the TTA of cracker sponge was determined after 18-h sponge fermentation. TTA was prepared by mixing 15 g sponge with 100 mL deionized water and stirred for 30 s at 2nd speed using the Hamilton Beach commercial blender (model 908 Clamshell, Procter-Silex, Inc., USA) until the sponge sample was completely dispersed. Then, the sponge slurry was transferred into a 250 mL beaker with a stir bar inside and placed onto a magnetic stirrer (model PC-520, Corning Laboratory Stirrer, USA). 0.1 M/L NaOH solution was used to titrate (Brinkmann Dispense-it, Germany) the sponge slurry until a final pH value of 6.6. The volume of NaOH solution used for titration was referred as the TTA value (Sutherland, 1989). The relationship between TTA and baking soda dosage is shown in Table 3.

### Table 1

<table>
<thead>
<tr>
<th>Amount of SWWW (g/100 g)</th>
<th>Sponge (65 g/100 g)</th>
<th>Dough (35 g/100 g)</th>
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<tr>
<td></td>
<td>SWWW</td>
<td>SRW</td>
</tr>
<tr>
<td>0</td>
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<td>75</td>
<td>50</td>
<td>15</td>
</tr>
<tr>
<td>100</td>
<td>65</td>
<td>15</td>
</tr>
</tbody>
</table>

* SWWW: soft white whole-wheat; SRW: soft red winter; HRW: hard red winter.

| Table 2

<table>
<thead>
<tr>
<th>Amount of SWWW (g/100 g)</th>
<th>Moisture (g/100 g)</th>
<th>Protein (g/100 g)</th>
<th>Ash (g/100 g)</th>
<th>Wet gluten (g/100 g)</th>
<th>Gluten index</th>
<th>Starch damage (g/100 g)</th>
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</thead>
<tbody>
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<td>8.92</td>
<td>0.734</td>
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<td>22.2</td>
<td>6.6</td>
<td>3.4</td>
</tr>
</tbody>
</table>

* Abbreviations as in Table 1.

b 14 g/100 g mb.

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2.3.3. Production procedures

The sponge ingredients were mixed at 1st speed for 3 min and 2nd speed for another 2 min in a Hobart A-200 mixer equipped with a McDuffy mixing bowl (National Manufacturing, Co. Lincoln, NE, USA). Then, the sponge was fermented at 28 °C and 85% RH in a fermentation cabinet (National Manufacturing Co., Lincoln, NE, USA) for 18 h. After the 18-h fermentation, the remaining flour, water, shortening and dry ingredients (salt and baking soda) were mixed with the sponge and proofed for 2 h (when the dough pH was 6–6.5) under the same conditions as the sponge. After the dough was proofed, 500 g dough was weighed and placed into a plastic container and shaped into a rectangular block (15 × 13.5 × 2.5 cm). The shaped dough block was formed into a thin sheet using the SSO-615 Seewer Rondo Reversible Lamination Machine (Commercial Food Preparing Machine, Rondo Inc., USA) to reduce the thickness until the height, width, and length of the dough sheet were about 1.3 mm, 22.5 cm, and 40.0 cm, respectively. The detailed dough lamination settings were listed as follows:

- Set initial roll gap to 12 mm → 9 mm → 6 mm → folded both ends to the center, and then turned 90° to 12 mm → 10 mm → 8 mm → 6 mm → 4 mm → folded the dough into trifold → 10 mm → 8 mm → 6 mm → turned 90° → 4 mm → 3 mm → folded the dough into trifold → 10 mm → 8 mm → 6 mm → turned 90° → 4 mm → 3 mm → 2 mm → 1.4 mm → adjusted roll gap to achieve a final sheet thickness of 1.3–1.4 mm.

The dough sheet was then transferred onto a specially designed cutter-docker (Pizzinatto & Hoseney, 1980), and sprinkled with salt followed by using a rolling pin to roll on the dough sheet to sufficiently perforate it. The deck oven (PICCOLOI-3 Wachtel Company, Germany) and a specially designed rectangular-shaped baking rack (CB5 baking band) were preheated for 30 min at a 220 °C top temperature and 215 °C bottom temperature. Loaded the deck cracked dough sheet onto the baking rack and baked in the deck oven for 6–7 min (maximum bubbles appeared on the surface of crackers and their color became brown). After baking was complete, the cracker sheet was cooled at room temperature for 30 min and broken into individual pieces for analysis.

2.4. End-product evaluation

Stack height, stack weight, specific volume, texture analysis, color, moisture and pH of the end products were determined. The stack height and stack weight were measured using seven sample pieces. The stack height was measured by a vernier caliper (Mitutoyo Manufacturing Co., Ltd., Japan), measuring once and turning the crackers 90° and measuring again to obtain the average value. The cracker specific volume was determined with the BVM-L 370 TexVol (TexVol Instruments Inc., Viken, Sweden) by dividing with salt followed by using a rolling pin to roll on the dough sheet to sufficiently perforate it. The deck oven (PICCOLOI-3 Wachtel Company, Germany) and a specially designed rectangular-shaped baking rack (CB5 baking band) were preheated for 30 min at a 220 °C top temperature and 215 °C bottom temperature. Loaded the deck cracked dough sheet onto the baking rack and baked in the deck oven for 6–7 min (maximum bubbles appeared on the surface of crackers and their color became brown). After baking was complete, the cracker sheet was cooled at room temperature for 30 min and broken into individual pieces for analysis.

2.5. SRC testing

Solvent retention capacity (SRC) tests including water SRC (W-SRC), lactic acid SRC (LA-SRC), sodium carbonate SRC (SC-SRC), and sucrose SRC (Suc-SRC) of flour blends of varying SWWWW were according to the AACC International Approved Method 56-11.02.

2.6. Rheological measurements

2.6.1. Alveograph analysis

Alveograph parameters were determined by the Alveo-Consistograph (Chopin, Villeneuve-La-Garenne, France) according to the AACC International Approved Method 54-30.02. Dough tenacity (P), extensibility (L) and deformation energy (W) were determined.

2.6.2. Rheometer determination

The rheological properties (storage modulus, G′; loss modulus, G″) of whole-wheat flour blends were determined using an AR1000 Rheometer (TA Instruments, New Castle, USA). The testing probe was a standard steel parallel plate (20 mm diameter, 1 mm-gap distance). Each sample was determined in triplicates under the frequency sweep test (frequency: 0.1–100 Hz; temperature: 28 °C).

2.7. NMR

Water migration between the arabinoylans (AX) matrix and gluten network in whole-wheat cracker dough system was observed using the NMR system which is represented by spin–spin relaxation time (T2). The relaxation measurements were performed on a Niumag Desktop Pulsed NMR Analyzer (Shanghai Niumag Electronics Technology Co. Ltd., China). The detailed parameters and procedures of measurements were described in our previous study (Li et al., 2012).

2.8. Statistical analysis

Statistical analyses were conducted with the SPSS software 17 (SPSS Institute, Chicago, USA). Pearson’s correlation coefficients between quality of end products and SRC and alveograph parameters were also calculated.

3. Results and discussion

3.1. Effect of whole-wheat flour on end-product baking quality

Quality characteristics of end products were affected by different composition levels of whole-wheat flour (Table 4). The stack weight, stack height, specific volume and breaking strength of crackers decreased as the addition level of SWWWW flour increased. The moisture content and pH of the end products were in the commercial range of 2–4 g/100 g and 7–8, respectively. Carbon dioxide gas generation reduced the dough density and dry matter was lost during dough fermentation (Faridi & Johnson, 1977). With the increasing level of whole-wheat flour, more volatile gas and acids were produced resulting in decreased stack height and stack weight of crackers. The higher amount of whole-wheat flour tended to produce an uneven and less puffed appearance and decreased the cracker’s volume and breaking strength of the cracker. The color (L, a*, b*) values of the crackers were determined by the CR-410 Chroma Meter (Konica Minolta Sensing, Inc., Japan). All measurements were conducted at least three times.
AX are a highly water-absorbing component, which exert a negative effect on the quality of crackers, especially on the volume of crackers (Kweon, Slade, & Levine, 2011a). The high water-absorbing components restrained the hydration of the gluten proteins from forming the proper network needed for gas retention. The cracker dough was too tight to allow for puffing during baking, resulting in reduction of the stack height and specific volume of end products (Carey et al., 2002). The generation of discontinuous protein film decreased the breaking strength and reduced the bubbling of the whole-wheat crackers during baking. Thus, the development of the gluten network during dough machining was a decisive factor to the superior baking quality of whole-wheat flour blends. As expected, the color of the end products gradually became browner and darker with the increased ratio of whole-wheat flour (Fig. 1).

3.2. Effect of whole-wheat flour on SRC profiles of whole-wheat flour blends

The gluten performance index (GPI) is defined as

\[
\text{GPI} = \frac{\text{Lactic Acid SRC}}{\text{Sodium Carbonate SRC} + \text{Sucrose SRC}}
\]

and considered as a better predictor of overall performance of cracker flour than the LA-SRC value alone (Kweon et al., 2011b). The SRC values and GPI of cracker flours are shown in Fig. 2. The SRC values of control flour blend (0 g/100 g SWWW) which was a blend of 85 g/100 g SRW and 15 g/100 g HRW were: W-SRC = 55.3 g/100 g, LA-SRC = 95.5 g/100 g, SC-SRC = 72.3 g/100 g, and Suc-SRC = 104.1 g/100 g. Typical standard SRC values for soft wheat sponge-and-dough cracker (e.g., saltine crackers) flour were reported as: W-SRC/C20 = 57 g/100 g, LA-SRC/C21 = 100 g/100 g, SC-SRC/C20 = 72 g/100 g, and Suc-SRC/C20 = 96 g/100 g (Kweon et al., 2011b). The four SRC values of the control flour blend were similar to the typical standard except for the slight differences in LA-SRC and Suc-SRC, which may be due to the addition of 15 g/100 g HRW flour. If there was more HRW, the LA-SRC would be greater, probably over 100 g/100 g. The reduction in LA-SRC compared to the target range was probably due to the SRW, but the increase in Suc-SRC was probably due to the HRW. The SRC values and GPI (0.54) of the control flour blend suggested that it

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Table 4

<table>
<thead>
<tr>
<th>Amount of SWWW (g/100 g)</th>
<th>Stack weightd (g)</th>
<th>Stack heightd (mm)</th>
<th>Specific volumec (mL/g)</th>
<th>Breaking strength (g)</th>
<th>Moisture (g/100 g)</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>27.2 ± 0.2a</td>
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</tr>
<tr>
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<td>32.7 ± 0.3b</td>
<td>1.25 ± 0.02a</td>
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</tr>
<tr>
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</tr>
<tr>
<td>75</td>
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<td>28.9 ± 0.3c</td>
<td>1.02 ± 0.03c</td>
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<td>3.7</td>
<td>7.4</td>
</tr>
<tr>
<td>100</td>
<td>24.9 ± 0.4d</td>
<td>26.8 ± 0.6d</td>
<td>1.00 ± 0.02c</td>
<td>700.6 ± 16.6c</td>
<td>3.6</td>
<td>7.3</td>
</tr>
</tbody>
</table>

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a Data were the mean value ± S.D. Values in the same column followed by the same letters are not significantly different (P < 0.05). Standard deviation was at least three replicate experiments.

b Abbreviations as in Table 1.
c Dry basis.
d Stack of 7 crackers.

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Fig. 1. The color values (L, a* and b*) of the crackers made from five different addition levels of soft white whole-wheat (SWWW) flours. L: lightness; a*: redness-greenness; b*: blueness-yellowness.

Fig. 2. Effects of soft white whole-wheat (SWWW) flour on the solvent retention capacity (SRC) values of whole-wheat flour blends. SRC: solvent retention capacity; W-SRC: water SRC; LA-SRC: lactic acid SRC; SC-SRC: sodium carbonate SRC; Suc-SRC: sucrose SRC; GPI (Gluten Performance Index) = Lactic Acid SRC/(Sodium Carbonate + Sucrose) SRC.
was within a marginal range of soda cracker flour with sufficient gluten strength and good cracker-baking performance. The GPI of other cracker flour blends containing various amounts of SWWWW were much lower than that of the control flour blend, indicating weaker gluten strength and less puffing during baking. As the percentage of SWWWW flour increased in the flour blend, both the SRC values and GPI changed gradually, in proportion to the amount of SWWWW added.

LA-SRC reflects protein content, glutenin characteristics and general gluten functionality; SC-SRC is associated with the level of damaged starch; Suc-SRC is related to the pentosan (also known as arabinoxylans) content; and W-SRC is affected by all of those flour constituents (AACCI Methods 56-11.02). Damaged starch is small particles of starch broken away from the main starch granules in wheat during milling, and has a strong water retention capacity (Mulla, Bharadwaj, Annapure, & Singhal, 2010). When starch granules are damaged, cleavage of the smaller granule will facilitate hydration and swelling during dough preparation (Tester, 1997). The damaged starch of whole-wheat flour blends were at low levels (between 3.1 and 3.4 g/100 g) and increased slightly with the increased level of whole-wheat flour due to the low-level damaged starch (3.1 g/100 g) of Ultragain soft white flour used in the study. Results showed that the W-SRC, SC-SRC, and Suc-SRC values increased with the amount of whole-wheat flour due to the increase of high water absorbent components such as damaged starch and arabinoxylans in flours.

LA-SRC had no linear correlation with the W-SRC, SC-SRC and Suc-SRC values, and the LA-SRC and GPI values did not correlate with the composition level of SWWWW flour. However, the W-SRC increased with the amount of SWWWW flour in the flour blend. The SRC values (W-SRC = 66.2 g/100 g, LA-SRC = 74.9 g/100 g, SC-SRC = 84.2 g/100 g and Suc-SRC = 112.3 g/100 g) of 100 g/100 g SWWWW cracker flour were significantly different from those of the typical standard flour as reported. The SRC values of 100 g/100 g whole-wheat flour exhibited higher water absorption, weak gluten strength (lower level of LA-SRC value), and higher levels of damaged starch and arabinoxylans than other flour blends with less SWWWW flour. The GPI of 100 g/100 g whole-wheat flour was very low (GPI = 0.38), indicating much inferior baking performance than the flour blends of lower content of whole-wheat flour.

Generally speaking, for commercial cracker production, high-quality saltine cracker flour requires relatively high gluten strength within the class of soft wheat, and low water absorption capacity (Kweon et al., 2011b). Thus, flours with higher LA-SRC, lower water S/W, SC-SRC, and Suc-SRC values were preferred for superior quality of commercial crackers for puffing and bubbling (Slade et al., 1994). Also the GPI was shown to have a better correlation with the cracker-baking performance. Cracker flour with a GPI <0.52 produced unacceptable performance and excessive blistering during baking (Kweon et al., 2011b).

3.3. Effect of whole-wheat flour on alveograph parameters of whole-wheat flour blends

The alveograph parameters (Fig. 3) showed that the P-value and P/L ratio had positive correlations with the percentage of SWWWW flour; however the L and W values had a negative correlation with the amount of SWWWW flour.

The “gold standard” of alveograph parameters for ideal-quality refined white cracker flour is P = 35 ± 5, L = 100 ± 10, and W = 90 ± 15. If P-value is too low (<30) or too high (>40), the flour would be too soft to form proper blistering on crackers or too hard for crackers to spread enough, respectively. W-value should not be too low (<75) or too high (>105). If the gluten strength is too weak, gas cells coalesce and gas is released prematurely; if gluten is too strong the cracker dough will be too elastic to resist puffing during baking. If L-value is less than 90, the implication is that the dough is lack of extensibility and bubble breakage will occur during baking (Slade et al., 1994). The destructive and cleaving effects of wheat brans with large-sized particles and native enzymes on the internal gluten network result in less extensibility of gluten matrix (Li et al., 2012). Although the alveograph values of control flour blend had a slight difference from the “gold standard”, the control flour blend had lower P and P/L values, higher W and L values which were preferred for a better cracker-baking quality. Nevertheless, the alveograph parameters of 100 g/100 g SWWWW flour showed very different results from the “gold standard”.

The higher level of P-value (63 mm) was caused by the high level of water-absorbing components (arabinoxylans and damaged starch) in the whole-wheat flour and the dough was too firm to expand. Preston, Kilborn, and Dexter (1987) reported that the starch damage was positively correlated with P, L, W, and P/L of Canadian hard spring wheat doughs. The lower level of L-value (21 mm) and W-value (54 mm) was due to the weak gluten strength of the whole-wheat flour. Moreover, the P/L ratio (3.00) of 100 g/100 g whole-wheat flour was much higher than that of the control flour blend (P/L = 0.32), which indicated that there was a lack of balance between elasticity and extensibility for the whole-wheat cracker dough to retain gas for expansion during fermentation and baking as measured by the alveograph.

3.4. Effect of whole-wheat flour on rheometer parameters of whole-wheat flour blends

The increased level of whole-wheat flour had a destructive effect on the formation of gluten network. Development of gluten in cracker dough during mixing and sheeting was a critical factor of
affecting the cracker quality (Kweon et al., 2011a). In the frequency sweep test, the \( G' \) (storage modulus) of whole-wheat dough reduced with the addition level of SWWW flour, which indicated that the elasticity of whole-wheat cracker dough was restrained. The high water absorbent-capacity of wheat bran competes for water with the gluten network and starch granule in whole-wheat dough system, which inhibited sufficient water absorption and formation of gluten network (Rosell et al., 2010). The AX is the main component of wheat bran, and it shows the ability of sequestrating water and restricting the formation of gluten network in whole-wheat bread dough (Li et al., 2012). However, the \( G' \)-value increased again as the SWWW flour content exceeded 50 g/100 g; the flour blend with 75 g/100 g SWWW had the highest \( G' \) (Fig. 4a), which may be related to the highest protein content of this blend (Table 2). This result indicated that the \( G' \) was more affected by the protein content of flour blend than by the shearing action of wheat bran in the frequency sweep test. \( G' \) represents the dynamic elasticity and \( G'' \) represents the dynamic viscous property. As shown in Fig. 4, the \( G' \) values were larger than the \( G'' \) values, indicating that the dough was more elastic than viscous. However, the high-level \( G' \) (which was correlated with the protein content) did not result in strong elasticity of dough and full formation of gluten network, which may be caused by the high water absorption of wheat bran in whole-wheat dough system. Thus, the preferable baking quality of whole-wheat products cannot be demonstrated by the high-level \( G' \)-value.

The rheological properties of flours have been reported to depend on starch granular structure, amylose to amylopectin ratio, and the presence of phosphate esters (Singh & Singh, 2001). The presence of large starch granules in wheat flour is likely responsible for high \( G' \) and \( G'' \) values (Kaur, Singh, & Soehi, 2002). However, the starch content and its granular size were diluted and sheared by the increased level of wheat bran in whole-wheat flour (Li et al., 2012). Therefore, the result of \( G' \) of cracker dough reduced with the increasing SWWW flour content (Fig. 4b) may be caused by the smaller granular size and shape of the native starches in the system. In addition, the reduced \( G'' \)-value of whole-wheat dough indicated that the \( G'' \) was less to do with the flour protein content and more to do with the bran content in the frequency sweep test. High \( G'' \)-value may be beneficial to the quality of whole-wheat products.

3.5. Water competition and migration

To demonstrate the water migration and competitive water sequestration between the AX matrix and gluten network in whole-wheat cracker flour system, the \( T_2 \) relaxation time of whole-wheat flour blends were determined by NMR. \( T_2 \) relaxation time typical curve of wheat dough (Fig. 5) includes three peaks: \( T_{21} \) (0–1 ms), \( T_{22} \) (1–100 ms), and \( T_{23} \) (100–1000 ms), which represent, tightly, less tightly, and weakly bound water, respectively (Lu & Seetharaman, 2013). X-axis in \( T_2 \) relaxation time curve represents the water activity of food material. A shorter \( T_2 \) relaxation time indicates a lower degree of water freedom. Y-axis in \( T_2 \) relaxation time curve represents the signal amplitude of protons. Peak area of \( T_2 \) curve represents the relative content of hydrogen protons (moisture content) absorbed by hydrophilic components. The peak \( T_{21} \) in \( T_2 \) relaxation time curve represented the water absorbed by the AX matrix and starch. The AX has a strong binding capacity for water due to its polysaccharide structure (Izydorzczyk & Biliaderis, 1995). The peak \( T_{22} \) represented the water absorbed by the gluten network. The gluten has a high-amount water absorption capacity caused by its porous framework (Li et al., 2012). The
results (Table 5) show that the peak area ratio of \( T_{21} \) (Area \( T_{21}/(Area \ T_{21}+T_{22}+T_{23}) \)) had a positive correlation \((r = 0.994; P < 0.05)\) with the increased level of SWWW flour \((0 \ g/100 \ g, 25 \ g/100 \ g, 50 \ g/100 \ g, 75 \ g/100 \ g, 100 \ g/100 \ g)\). A negative correlation \((r = -0.998; P < 0.05)\) was found between the peak area ratio of \( T_{22} \) (Area \( T_{22}/(Area \ T_{21}+T_{22}+T_{23}) \)) and the addition level of SWWW flour. The peak area ratio of \( T_{23} \) did not change significantly. These results indicated that the water migrated from the gluten network into the AX matrix in whole-wheat cracker dough system, and inhibited the water absorption of gluten to form the network structure to maintain its gas-retention ability. Thus, the bubbles and puffy internal structure of whole-wheat crackers were restrained due to the weak gas-retention capacity of whole-wheat dough, resulting in inferior baking quality of end products. Meanwhile, the peak \( T_{23} \) shifted to the left, suggesting that the water holding capacity of AX was enhanced with the increased level of whole-wheat flour.

### 3.6. Correlation analysis

In this research, the \( W\)-SRC was significantly correlated with alveograph values. W-SRC had a positive correlation with the \( P\)-value \((r = 0.98, P < 0.01)\) and was negatively correlated with the \( L\)-value \((r = -0.99, P < 0.01)\) and the \( W\)-value \((r = -0.99, P < 0.01)\). The \( P/L \) ratio was positively correlated with the W-SRC \((r = 0.92, P < 0.05)\). \( P\)-value was positively correlated with SC-SRC \((r = 0.99, P < 0.01)\) and Suc-SRC values \((r = 0.98, P < 0.01)\); both \( L \) and \( W \) values had a significant negative correlation with SC-SRC and Suc-SRC values. The \( P/L \) ratio was positively correlated with SC-SRC \((r = 0.93, P < 0.05)\) and Suc-SRC \((r = 0.92, P < 0.05)\). LA-SRC and GPl were independent of all alveograph parameters.

The correlations among the end-product quality parameters, SRC and alveograph values were also observed (Table 6). The end-product quality parameters were significantly correlated with the SC-SRC, Suc-SRC and W-SRC. LA-SRC values did not show significant correlation with the whole-wheat cracker quality parameters and therefore, was ineffective in predicting the protein functionality in whole-wheat products (Bettge, Morris, DeMacon, & Kidwell, 2002). If such a prediction is desired, SDS-Sedimentation may work better on whole-wheat flour for functional protein prediction. \( P\)-value may not be a good indicator of dough strength in the whole-wheat dough system since the dough was measured at a constant 50 g/100 g water absorption; the addition of SWWW made the dough drier and artificially increased \( P\)-value. Also, this was partly due to the competitive water absorption by wheat bran and the physical disruption to the gluten matrix, as discussed earlier in the Introduction. Both alveograph \( L \) and \( W \) values were positively correlated with the quality parameters of the end product, suggesting that the alveograph may be a useful tool to predict the end-use quality of whole-wheat cracker flour blends. The gluten index also showed significant positive correlations with the quality attributes of whole-wheat cracker. Whole-wheat flour blends of higher gluten index values yielded greater stack height, specific volume, and breaking strength of the end products. Thus, the gluten index may also be useful in predicting the performance of whole-wheat cracker flour and end-product quality.

### 4. Conclusions

The rheological behaviours of whole-wheat flour blends were greatly affected by the addition level of SWWW flour. The \( G^\prime\)-value appeared to be affected more by the protein content than by the shearing action of wheat bran in whole-wheat dough system, and \( G^\prime\prime\)-value was more affected by the bran content. High water absorption capacity of whole-wheat flour had a detrimental effect on the quality attributes (especially oven spring) of whole-wheat saltine crackers. The competition for water by AX from gluten matrix in whole-wheat dough system restricted the proper formation of gluten network, which reduced its gas-retention capability. Alveograph parameters, SRC values, and gluten index appeared to be useful tools to predict the saltine cracker-baking performance of the whole-wheat flour and end-product quality.

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### References


