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Effects of flour particle size on the quality attributes of reconstituted whole-wheat flour and Chinese southern-type steamed bread

Naifu Wang a, b, Gary G. Hou b, *, Arnaud Dubat c

a School of Tea and Food Science, Anhui Agricultural University, No. 130 West Changjiang Road, Hefei, Anhui 230036, China
b Wheat Marketing Center, Inc., 1200 NW Naito Parkway, Suite 230, Portland, OR 97209, USA
c Chopin Technologies, Villeneuve-la-Garenne Cedex 92396, France

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A B S T R A C T

In this study, reconstituted whole-wheat flour (WWF) samples of different particle sizes from U.S. soft white winter (median diameters: 164.0, 110.7 and 97.8 μm) and soft red winter (median diameters: 154.3, 112.8 and 99.9 μm) wheat cultivars were obtained by fine grinding of bran and shorts from roller milling and re-combining with the remaining fractions. Extensibility tests showed that reducing the particle size of WWF strengthened the gluten network of dough. Mixolab results indicated that reducing the particle size of WWF resulted in shorter development time and longer mixing stability of dough. Meanwhile, the starch hot-gel stability and retrogradation increased with the WWF particle size reduction. The Chinese southern-type steamed bread (STSB) making test showed that SB made from WWF of smaller particle size had a significantly larger specific volume than that made from WWF of larger particle size. C-cell analysis of the crumb grain of SB revealed that the grain cells became smaller with thinner cell walls as WWF particle size was reduced. These results indicate that reducing the particle size of WWF could improve the quality of Chinese STSB.

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1. Introduction

Whole-wheat flour (WWF) can be produced by different milling procedures, such as single-stream milling (stone, hammer) or multiple-stream milling (roller) with recombination of mill fractions. Different milling techniques result in WWF of various particle sizes and functionalities (Maldonado, 2012). Previous studies have confirmed that bran particle size has a considerable influence on dough properties and quality of finished products. Some studies showed that reducing the particle size of bran had a beneficial effect on foods, such as Asian noodle, snack cracker and flat bread (Chen et al., 2011; Niu, Hou, Lee, & Chen, 2014a; Wang, Hou, Kweon, & Lee, 2016; Majzoobi, Farahnaky, Nematalahi, Mohamadi Hashemi, & Taghipour, 2013), while other researchers found that smaller bran particle size had a detrimental effect on bread quality (Cai, Choi, Hyun, Jeong, & Baik, 2014; Noort, van Haaster, Hemery, Schols, & Hamer, 2010; Zhang & Moore, 1999). These inconsistent observations might be caused by the different milling procedures used, bran particle size ranges, and end products made.

Chinese steamed bread (SB) is a fermented wheat flour product that is cooked by steaming. It is the most popular traditional fermented wheat food in China, representing approximately 40% of the country’s wheat consumption (Hou & Popper, 2006). It is also widely consumed in other Asian countries, accounting for 5–15% of total wheat consumption, and has become increasingly popular in North America and some European countries. There are two major types of SB in China. The northern-type steamed bread (NTSB) has a very cohesive, elastic and dense texture. The southern-type steamed bread (STSB) is commonly known for a more open crust structure, softer texture and a white surface, and it has long been popular as a “dim sum” item in Chinese restaurants (Hou & Popper, 2006). STSB typically requires a refined soft wheat flour of 7.5–9.0% protein (14% mb) to give a desired soft and elastic chewy texture.

Liu et al. (2015) reported that Chinese NTSB made from bran recombining processes had larger height/diameter and specific volume than those made from entire grain grinding processes. They attributed the results to the smaller particle size of WWF from whole grain grinding. As of yet, no research has examined the

Abbreviations: WWF, whole-wheat flour; SWW, soft white winter; SRW, soft red winter; SG, straight-grade.

* Corresponding author.
E-mail address: ghou@wmcinc.org (G.G. Hou).

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quality of Chinese STSB made from WWF of different particle sizes. The aim of this study was to investigate the effects of WWF particle size on dough characteristics using Mixolab and extensibility tests, and on the quality characteristics of Chinese STSB.

2. Materials and methods

2.1. Materials

Two U.S. soft wheat cultivars, a soft white winter (SWW, Eltan) and a soft red winter (SRW, VA05W), were used in this study. Their protein contents were 11.1% and 11.4% (dry basis), respectively. After cleaning, the two wheat samples were tempered in plastic bags at room temperature to 14.5% moisture and milled on a pilot-scale Miag Multomat mill (Buhler, Inc., Braunschweig, Germany) with a straight-grade (SG) scale. Their extraction rate of 72.5 g/100 g for SWW and 72.7 g/100 g for SRW. The resulting bran, shorts, and red dog fractions were collected separately and weighed. The yield of each fraction was expressed as the percent of its weight in the total recovered product weight.

2.2. Preparation of reconstituted WWFs of different particle sizes

After milling, bran and shorts were dusted using a laboratory bran finisher (MLU-302, Buhler, Inc., Uzwil, Switzerland). To prepare WWFs of different particle sizes, bran and shorts were further ground each around 1 to 4 times using a Pertem Instruments, Hägersten, Sweden equipped with a 0.8 mm mesh sieve. Since there was very small difference in flour particle size when grinding 3 or 4 times, these two treatments were combined as one sample ‘3rd grinding’. The resulting brans (no, 1st and 3rd grindings), shorts (no, 1st and 3rd grindings), bran-dusted flour, shorts-dusted flour, and red dog fraction were blended with the SG flour in accordance with their respective yields during milling to obtain reconstituted WWFs (WWF-0, -1 and -3). The particle size distribution and median particle diameter of SG flours and reconstituted WWFs were determined using a Ro-Tap testing sieve shaker (Model R-30050, W.S. Tyler, Mentor, OH, USA) according to the method described by Liu, Hou, Lee, Marquart, and Dubat (2016). The damaged starch (DS) content of WWF and SG flour was determined according to the AACC International Approved Methods (AACC 76–30.02).

2.3. Extensibility measurement of dough

The extensibility measurement of dough was determined according to the method described by Londono, Smulders, Visser, Gilissen, and Hamer (2014). Dough samples were prepared in a Farinograph (Brabender, Duisburg, Germany) mixing bowl using 50 g flour and 1 g salt according to the AACC International Approved Method 54-21. The mixing time was based on the Farinograph development time. Dough resistance to extension (maximum force) and extensibility (distance at maximum force) were measured using a TA.XT-Plus Texture Analyzer (Texture Technologies Corp., Hamilton, MA) equipped with a SMS/Kieffer dough and gluten extensibility rig (Model: TA-105). After mixing, dough was flattened by a rolling pin and placed onto the paraffin oil-coated, grooved base of a Teflon dough form. The upper block of the dough form was then positioned on top of the dough sample and pushed down firmly by tightening the clamp until the two blocks came together to produce dough strips. After the dough rested for 45 min on a form press in an enclosed plastic bag, dough strips were taken one by one and the extensibility measurements were taken. The testing parameters were: mode, measured force in tension; option, return to start; pre-test speed, 2.0 mm/s; test speed, 3.3 mm/s; post-test speed, 10 mm/s; target mode, distance; distance, 12 cm; trigger force, 5 g; and data acquisition rate, 200 PPS.

2.4. Evaluation of dough mixing and starch pasting properties

Mixing and starch pasting properties of dough were determined using the Mixolab analyzer (Chopin Technologies, Villeneuve-La-Garenne, France) according to AACC International Approved Method 54–60.01. The parameters obtained from the Mixolab included the percent of water required for the dough to produce a torque of 1.1 ± 0.05 Nm (water absorption, %), the time to reach maximum torque at 30 °C (C1 time (dough development time), min), the elapsed time that the torque was kept at 1.1 Nm (stability, min), weakening of protein network (C2, Nm), starch gelatinization (C3, Nm), stability of the hot formed gel (C3-C4, Nm), and starch retrogradation during the cooling phase (C5, Nm).

2.5. Chinese STSB preparation

The formulation of STSB prepared in this study was as follows: flour (SG or WWF), 400 g; instant dry yeast (SAF-Instant® Yeast, Gold Label, Lesaffre Yeast Co.), 4 g; sugar, 60 g; baking powder (double-acting), 4 g; shortening (Crisco), 16 g; and water (75% of Mixolab water absorption). Before dough mixing, sugar and yeast were dissolved in water (15 °C) separately. To begin dough mixing, sugar and yeast solutions were poured into wheat flour in the mixing bowl (N50, Hobart, Troy, OH, USA) with a flat beater. Mixing was conducted at speed 1 for 1 min, after which shortening was added and mixing continued for another 4 min. After resting in a plastic bag at room temperature for 10 min, dough was sheeted 10–12 times on the Oshikiri sheeter/molder (Model: WFS Moulder, Oshikiri Machinery Co., Kanagawa, Japan) until the dough sheet surface was smooth. Then the dough sheet was rolled into a cylinder and stretched by hand to a length of approximately 100 cm. Next, the dough was divided into pieces of 25–30 g and proofed in a fermentation cabinet (Model 505–SS 2/3, National MFG. Co., Lincoln, NE, USA) at 35 °C, 75% RH. Proof time was determined by dough volume increase. In this method, 25 g of SB dough was placed into a 45 mL plastic centrifuge tube (3 cm in diameter). The initial dough volume was approximately 21–22 mL. After proofing, the final dough volume reached 38 mL. At this point, the proofed SB dough was steamed for 12 min in a steamer (SelfCookingCenter, Rational USA Inc., Schaumburg, IL) and cooled at room temperature for 1 h before analysis.

2.6. Quality evaluation of SB

The specific volume of SB was determined using a laser volume analyzer (BVM-L370, TexVol Instruments Inc., Viken, Sweden) by dividing volume by weight. Structural characteristics of the crumb grain (area of cells, mean cell diameter and cell wall thickness) were evaluated using the C-cell food imaging system (Calibre Control International Ltd., Warrington, UK). The textural profile analysis (TPA) of SB was determined using the TA.XTPlus Texture Analyzer equipped with a 35 mm diameter acrylic cylindrical probe. SB was sliced horizontally and a flat piece of 15 mm thickness was compressed to 50% of its original height. The test conditions were: pre-test speed, 2 mm/s; test speed, 1 mm/s; post-test speed, 1 mm/s; and trigger force, 5 g.

2.7. Statistical analysis

All measurements were performed at least in triplicate. Statistical analyses were carried out with the software SPSS 16.0 for Windows using one-way analysis of variance (ANOVA). Duncan's
test was used to compare means, and a $P < 0.05$ was considered to be statistically significant. Pearson’s correlation coefficients among flour particle size, dough property and end product quality were calculated.

3. Results and discussion

3.1. Particle size distribution and median particle diameter of SG flours and reconstituted WWFs

The particle size distribution and median particle diameter of SG flours and reconstituted WWFs are shown in Fig. 1. A large portion of unground WWF (WWF-0) remained on top of the 500-μm sieve: 15.6% for SWW and 14.3% for SRW. After 1st grinding, the amount of WWF retained on the 500-μm sieve decreased by 92.3% for SWW and 90.9% for SRW. After three times of grinding, all flour fractions passed through the 500-μm sieve, while the amount of WWF retained on the 300-μm sieve decreased by 83.9% for SWW and 81.3% for SRW.

For both cultivars, the mass median particle diameter of WWFs was significantly ($P < 0.05$) reduced with an increased number of grinding times (0–3 times). The median diameters of WWFs containing original bran and shorts (WWF-0) were 164.0 μm for SWW and 154.3 μm for SRW. After the 3rd grinding (WWF-3), the median diameters decreased to 97.8 μm for SWW and 99.9 μm for SRW, which remained significantly ($P < 0.05$) larger than their corresponding SG flours.

3.2. Effect of particle size on DS content and dough extensibility of WWFs

With enhanced water absorption and forming a gel more easily, DS can affect the mixing and starch pasting properties of flour. As shown in Fig. 2, For SWW and SRW, WWFs had lower DS content than their corresponding SG flours because of dilution of WWF starch by bran. Reducing particle size significantly increased the DS content in WWFs. For SRW, the DS content continued to increase from WWF-1 to WWF-3 (112.8–99.9 μm). However, the DS content of SWW didn’t show significant change ($P > 0.05$) from WWF-1 to WWF-3 (110.7–97.8 μm). Ma et al. (2016) reported that Chinese NTSB made with refined flour of higher DS content had relatively lower hardness, gumminess and chewiness, probably due to increased SB proofing, which is also desirable for making STSB. However, too high level of DS can lead to too much water absorption and the production of excessive sugar by enzymatic hydrolysis and thus, the formation of softer and stickier dough, which can’t support the volume of SB (Liu et al., 2014). Therefore, a proper level of DS is required for optimum flour performance in SB making.

The Kieffer dough and gluten extensibility rig is a small-scale version of the Brabender Extensograph, and the data can be expressed in terms of stress and strain (Dunnewind, Sliwinski, Grolie, & van Vliet, 2003). The results of the dough extension tests are shown in Fig. 3. Although SWW had a slightly lower protein content than SRW, SWW exhibited a higher maximum resistance to extension and longer extensibility in the groups treated with the same number of grindings. For both cultivars, WWFs containing original bran and shorts (WWF-0) exhibited a lower maximum resistance to extension and shorter extensibility than their counterpart SG flours. The addition of fiber into wheat flour showed a negative effect on formation of the gluten network due to dilution of gluten protein (Ahmed, Almusallam, Al-Salman, AbdulRahman, & Al-Salem, 2013) and/or fiber-gluten interaction (Noort et al., 2010; Wang, Oudunnoen, van Vliet, & Hamer, 2003). For both cultivars, WWFs of smaller particles showed higher maximum resistance to extension and longer extensibility than those of larger particles.

Using a large biaxial deformation by Lubricated Squeezing Flow test, Le Bleis, Chaunier, Chiron, Della Valle, and Saulnier (2015) hypothesized the formation of gluten network could have been inhibited because the bran particles reduced flour protein aggregation. However, Zhang and Moore (1997) reported the bran particle size effect on dough extensibility, resistance and area under the extensigraph curve was not apparent after a 45-min rest period; after a 180-min rest, dough containing fine bran had significantly higher resistance and area values than dough containing coarse bran. Finer bran particles might have less destructive
influence on gluten network formation in dough after a longer resting time.

SB quality is generally related to gluten elasticity and extensibility. Suitable dough extensibility allows for the sufficient expansion of gas bubbles during proofing and steaming, and adequate elasticity is essential to avoid the rupture of gas cells in order to produce a loaf with a large volume and a smooth and elastic inner structure (Zhang, Jondiko, Tilley, & Awika, 2014). In a study of Chinese NTSB, He, Liu, Peña, and Rajaram (2003) reported the dough strength and extensibility were positively correlated with SB volume. However, a common problem in the production of whole-wheat products is the weakened gluten strength caused by the shearing and dilution of gluten by bran particles. The results of our study showed that grinding WWF to smaller particle size improved dough maximum resistance to extension and extensibility, which could prevent air cells from collapsing and result in larger SB volume.

3.3. Effects of particle size on dough mixing and starch pasting properties of WWFs

A typical Mixolab curve can be divided into two phases. The first phase determines the protein properties during dough mixing at 30 °C. As shown in Table 1, WWFs had significantly higher water absorptions than their corresponding SG flours due to greater amount of arabinoxylans present in bran (Sanz Penella, Collar, & Haros, 2008). Under the condition of C1 = 1.10 ± 0.05 Nm, the water absorption of WWFs decreased with the reduction of particle size from WWF-0 to WWF-1 (from 160 to 110 μm). Similar results were reported by Liu et al. (2016) in three U.S. hard wheat classes using Mixolab analysis. This may be attributed to the fact that the water-binding capacity of fiber was reduced with decreasing bran particle size (Le Bleis et al., 2015; Noort et al., 2010). However, contrasting studies showed that reduced wheat bran particle size after fine (median diameter from 206 to 164 μm) and superfine (median diameter from 125 to 43 μm) grinding processes increased the Farinograph water absorption of reconstituted WWF (Niu et al., 2014a; Niu, Hou, Wang, & Chen, 2014b). However, all of these studies dealt with hard wheat samples, and higher damaged starch in finer WWF was the main cause of higher water absorption. For SWW, the water absorption continued to decrease from WWF-1 to WWF-3, but the water absorption of SRW increased slightly from WWF-1 to WWF-3. The difference in water absorption change between SWW and SRW may be due to the changes of DS content (Fig. 2). For SWW-WWF, its DS content significantly increased from WWR-0 to WWF-1, but did not change significantly from WWF-1 to WWF-3 as the flour particle size reduced further. However, for SRW-WWF, its DS content continued to increase from WWF-0 to WWF-3.

The addition of coarse bran and shorts into SG flour (WWF-0) significantly improved the C1 of dough (Table 1). This is because coarse bran and shorts require longer time to hydrate (Torbica, Hadna, & Cercev, 2010). C1 decreased with the particle size, probably because of faster water absorption by bran of finer particle size (Sanz Penella et al., 2008). Similar results were observed by Zhang and Moore (1997) using Farinograph analysis (bran particle size decreased from 609 to 278 μm). For both WWF groups, with the decrease of flour particle size, dough stability time increased. Using Farinograph analysis, Niu, Hou, Lee, & Chen (2014a) reported that there was a significant increase in the Farinograph stability time for hard wheat classes with the reduction of particle size. Liu et al. (2016) also confirmed that the mixing stability time for the three classes of U.S. hard wheat WWF increased with the reduction of particle size using the Mixolab analysis. The increase of dough mixing stability due to fine grinding of brans could contribute to the increased interactions through hydrogen bonding involving the hydroxyl groups present in fibres molecules (Rosell, Santos, & Collar, 2010). C2 indicates a dough consistency loss during exposure to physical-mechanical and thermal stress. The C2 values of WWFs did not show a significant change (P > 0.05) with the decrease in particle size.

SB quality exhibited positive correlations with protein content and gluten strength in wheat varieties with low to medium gluten strength (He et al., 2003; Huang, Yun, Quail, & Moss, 1996). Reducing the particle size of WWFs effectively improved their SB making performance (Tables 2 and 3 and Fig. 4), but C1 decreased while the mixing stability increased with the particle size reduction (Table 1). In particular, WWF-1 and WWF-3 for SRW had longer stability times than their corresponding SG flour, but their SB quality (specific volume and texture) was inferior to the SG flour. Therefore, the dough C1 and mixing stability do not apply equally to refined flour and WWF in terms of their relationship to SB making performance.

The second phase of the Mixolab curve shows the starch pasting properties of dough under mixing and heating constraints. C3 represents the degree of starch gelatinization. For both cultivars, the WWFs had lower C3 values compared to their counterpart SG flours. This may be due to lower starch content and/or higher enzyme activity in WWF. Within the SRW-WWF groups, the change in C3 values was not significant (P > 0.05) with the decrease in particle size. However, for SRW, the C3 values of WWF-1 and WWF-3 showed significant increases (P < 0.05) compared to WWF-0. Similar to our results, Liu et al. (2016) found that there was no significant (P > 0.05) difference in C3 values between the hard white and hard red winter WWFs of different particle sizes, and
that hard red spring WWF with finer milled feeds exhibited higher C3 values than that with coarser milled feeds. Peak viscosity has been reported to show a positive correlation with the total score of NTSB (He et al., 2003; Huang et al., 1996). C3-C4 values reflect the hot-gel stability/amylase activity of dough. With the decrease in particle size, the C3-C4 values of WWFs decreased from WWF-1 to WWF-3, indicating a lower degree of starch disintegration and a more stable starch gel. C5 is the maximum torque of the cooling stage, which reflects starch retrogradation. With the reduction of particle size, the C5 values of WWFs increased. This result agrees with Cai et al. (2014) and Liu et al. (2016), who reported that finer bran induced a larger degree of starch retrogradation than coarser bran. It is unclear whether WWF of finer particle size will cause significantly faster staling of SB during storage.

### 3.4. Effect of particle size on textural properties of SB

The textural parameters of SB determined by TPA analysis are shown in Table 2. WWFs containing the original coarse bran and shorts (WWF-0) showed higher hardness and chewiness, and lower springiness, cohesiveness, and resilience values, than their counterpart SG flours.

Hardness is often considered as the index of the total textural attributes (Rizzello, Cassone, Coda, & Gobbetti, 2011). For STSB, soft texture is a desirable quality characteristic. Majzoobi et al. (2013) found that smaller bran particle size resulted in significantly different textural parameters of different particle sizes. A. Wang et al. (2017) reported to show a positive correlation with the total score of NTSB values than that with coarser millfeeds. Peak viscosity has been reported to show a positive correlation with the total score of NTSB (He et al., 2003; Huang et al., 1996). C3-C4 values reflect the hot-gel stability/amylase activity of dough. With the decrease in particle size, the C3-C4 values of WWFs decreased from WWF-1 to WWF-3, indicating a lower degree of starch disintegration and a more stable starch gel. C5 is the maximum torque of the cooling stage, which reflects starch retrogradation. With the reduction of particle size, the C5 values of WWFs increased. This result agrees with Cai et al. (2014) and Liu et al. (2016), who reported that finer bran induced a larger degree of starch retrogradation than coarser bran. It is unclear whether WWF of finer particle size will cause significantly faster staling of SB during storage.

### Table 1

<table>
<thead>
<tr>
<th>Samples</th>
<th>WA (°)</th>
<th>C1 time (min)</th>
<th>Stability (°)</th>
<th>C2 (Nm)</th>
<th>C3 (Nm)</th>
<th>C3-C4 (Nm)</th>
<th>C5 (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG</td>
<td>53.2 ± 0.04</td>
<td>5.09 ± 0.44</td>
<td>8.69 ± 0.05</td>
<td>0.43 ± 0.03</td>
<td>2.39 ± 0.01</td>
<td>0.51 ± 0.01</td>
<td>3.11 ± 0.04</td>
</tr>
<tr>
<td>WWF-0</td>
<td>63.5 ± 0.00</td>
<td>6.87 ± 0.78</td>
<td>8.51 ± 0.06</td>
<td>0.48 ± 0.01</td>
<td>2.17 ± 0.02</td>
<td>0.39 ± 0.01</td>
<td>2.94 ± 0.04</td>
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<tr>
<td>WWF-1</td>
<td>61.0 ± 0.00</td>
<td>6.35 ± 0.35</td>
<td>8.39 ± 0.23</td>
<td>0.48 ± 0.01</td>
<td>2.20 ± 0.01</td>
<td>0.14 ± 0.00</td>
<td>3.16 ± 0.02</td>
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<tr>
<td>WWF-3</td>
<td>60.3 ± 0.04</td>
<td>4.03 ± 0.35</td>
<td>8.92 ± 0.13</td>
<td>0.46 ± 0.02</td>
<td>2.21 ± 0.01</td>
<td>0.11 ± 0.01</td>
<td>3.19 ± 0.05</td>
</tr>
<tr>
<td>SRW</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>SG</td>
<td>55.4 ± 0.14</td>
<td>1.15 ± 0.07</td>
<td>6.73 ± 0.21</td>
<td>0.42 ± 0.02</td>
<td>2.22 ± 0.04</td>
<td>0.58 ± 0.02</td>
<td>3.01 ± 0.04</td>
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<tr>
<td>WWF-0</td>
<td>64.0 ± 0.10</td>
<td>6.49 ± 0.23</td>
<td>6.81 ± 0.30</td>
<td>0.50 ± 0.02</td>
<td>2.03 ± 0.04</td>
<td>0.85 ± 0.04</td>
<td>2.80 ± 0.04</td>
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<tr>
<td>WWF-1</td>
<td>61.9 ± 0.11</td>
<td>3.80 ± 0.18</td>
<td>9.21 ± 0.40</td>
<td>0.52 ± 0.01</td>
<td>2.11 ± 0.11</td>
<td>0.83 ± 0.06</td>
<td>3.05 ± 0.06</td>
</tr>
<tr>
<td>WWF-3</td>
<td>62.4 ± 0.08</td>
<td>3.62 ± 0.04</td>
<td>9.68 ± 0.07</td>
<td>0.53 ± 0.03</td>
<td>2.12 ± 0.00</td>
<td>0.70 ± 0.04</td>
<td>3.04 ± 0.01</td>
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</table>

* Values for the same wheat cultivar in the same column followed by the same letter are not significantly different (P > 0.05).

### Table 2

<table>
<thead>
<tr>
<th>Samples</th>
<th>Hardness (N)</th>
<th>Chewiness (N)</th>
<th>Springiness (°)</th>
<th>Cohesiveness (°)</th>
<th>Resilience (°)</th>
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<tbody>
<tr>
<td>SWW</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>SG</td>
<td>17.66 ± 0.63</td>
<td>10.69 ± 0.31</td>
<td>0.893 ± 0.005</td>
<td>0.678 ± 0.010</td>
<td>0.331 ± 0.008</td>
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<tr>
<td>WWF-0</td>
<td>24.40 ± 0.53</td>
<td>11.72 ± 0.34</td>
<td>0.794 ± 0.008</td>
<td>0.609 ± 0.003</td>
<td>0.259 ± 0.003</td>
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<tr>
<td>WWF-1</td>
<td>25.13 ± 1.41</td>
<td>12.05 ± 0.14</td>
<td>0.806 ± 0.005</td>
<td>0.595 ± 0.012</td>
<td>0.251 ± 0.007</td>
</tr>
<tr>
<td>WWF-3</td>
<td>22.41 ± 0.86</td>
<td>10.54 ± 0.30</td>
<td>0.806 ± 0.006</td>
<td>0.583 ± 0.009</td>
<td>0.238 ± 0.006</td>
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<tr>
<td>SRW</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG</td>
<td>15.52 ± 0.58</td>
<td>8.95 ± 0.24</td>
<td>0.841 ± 0.064</td>
<td>0.693 ± 0.010</td>
<td>0.303 ± 0.007</td>
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<tr>
<td>WWF-0</td>
<td>29.46 ± 1.16</td>
<td>14.25 ± 0.88</td>
<td>0.788 ± 0.009</td>
<td>0.612 ± 0.014</td>
<td>0.253 ± 0.003</td>
</tr>
<tr>
<td>WWF-1</td>
<td>24.29 ± 1.00</td>
<td>11.62 ± 0.43</td>
<td>0.790 ± 0.007</td>
<td>0.614 ± 0.015</td>
<td>0.235 ± 0.002</td>
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<tr>
<td>WWF-3</td>
<td>29.90 ± 0.59</td>
<td>13.96 ± 0.15</td>
<td>0.788 ± 0.005</td>
<td>0.587 ± 0.005</td>
<td>0.223 ± 0.003</td>
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</tbody>
</table>

* Values for the same wheat cultivar in the same column followed by the same letter are not significantly different (P > 0.05).

### Table 3

<table>
<thead>
<tr>
<th>Samples</th>
<th>Specific volume (ml/g)</th>
<th>Area of cells (%)</th>
<th>Mean cell diameter (mm)</th>
<th>Cell wall thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG</td>
<td>2.12 ± 0.07</td>
<td>46.73 ± 1.38</td>
<td>1.14 ± 0.03</td>
<td>0.341 ± 0.003</td>
</tr>
<tr>
<td>WWF-0</td>
<td>1.62 ± 0.19</td>
<td>51.07 ± 0.84</td>
<td>2.71 ± 0.06</td>
<td>0.456 ± 0.129</td>
</tr>
<tr>
<td>WWF-1</td>
<td>1.79 ± 0.01</td>
<td>49.87 ± 0.49</td>
<td>1.90 ± 0.15</td>
<td>0.419 ± 0.010</td>
</tr>
<tr>
<td>WWF-3</td>
<td>1.87 ± 0.03</td>
<td>48.83 ± 0.40</td>
<td>1.55 ± 0.12</td>
<td>0.394 ± 0.006</td>
</tr>
<tr>
<td>SRW</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SG</td>
<td>1.98 ± 0.11</td>
<td>47.30 ± 0.87</td>
<td>1.27 ± 0.10</td>
<td>0.356 ± 0.005</td>
</tr>
<tr>
<td>WWF-0</td>
<td>1.68 ± 0.03</td>
<td>52.43 ± 0.76</td>
<td>2.18 ± 0.04</td>
<td>0.431 ± 0.011</td>
</tr>
<tr>
<td>WWF-1</td>
<td>1.84 ± 0.04</td>
<td>50.77 ± 0.25</td>
<td>1.87 ± 0.05</td>
<td>0.411 ± 0.003</td>
</tr>
<tr>
<td>WWF-3</td>
<td>1.90 ± 0.03</td>
<td>49.23 ± 0.38</td>
<td>1.58 ± 0.05</td>
<td>0.392 ± 0.008</td>
</tr>
</tbody>
</table>

* Values for the same wheat cultivar in the same column followed by the same letter are not significantly different (P > 0.05).

Abbreviations (SG, WWF-0, 1, 3) are the same as in Fig. 1.
In Table 2, the changes in the chewiness of SB exhibited the same hardness values. Unlike pan bread, SB is cooked by steam and thus, WWFs of a smaller particle size did not always yield lower SB hardness compared to WWF-0 (154.3 m) and WWF-3 (99.9 m). Thus, WWFs of a smaller particle size did not always yield lower SB hardness values. Unlike pan bread, SB is cooked by steam and thus, both dough strength and starch gelatinization properties could have effects on its texture. The chewiness of SB is significantly related to hardness (Sun, Zhang, Hu, Xing, & Zhuo, 2015). As shown in Table 2, the changes in the chewiness of SB exhibited the same pattern as hardness. The cohesiveness and resilience values of SB made from WWFs decreased with the reduction of particle size from WWF-0 to WWF-3. Similarly, Cai et al. (2014) reported that hard red WWF bread containing fine bran exhibited lower cohesiveness than bread containing coarse bran. However, Niu, Hou, Lee, & Chen (2014a) reported that the springiness, cohesiveness and resilience values of WWF noodles increased with the decrease in millfeed particle size. According to their study, noodle dough containing finer bran exhibited more extensibility and resistance than coarser bran, which resulted in increase in springiness, cohesiveness and resilience of WWF noodles. In our experiment, dough containing finer bran also exhibited greater extensibility and resistance than that containing coarser bran (as shown in Fig. 3), but the cohesiveness and resilience of SB decreased with the reduction of particle size. SB and noodle vary significantly in formulation and process, so bran particle size is expected to exert different influence on end product texture. For SWW, reducing the particle size of WWF resulted in a higher springiness of SB. Meanwhile, within SRW-WWF groups, there was no significant change in springiness with the decrease in particle size.

3.5. Crumb grain properties of SB

The cell size information, given by cell diameter, wall thickness and cell area in this study, is shown in Table 3. The area of cells as a percentage of total slice area is used to quantitatively describe crumb grain properties. Higher value of cell area indicates a more open texture (Hager & Arendt, 2013). With the reduction of WWF particle size, the area of cells of SB also decreased. The mouthfeel of bread is known to be strongly influenced by cell characteristics. Finer, thin-walled uniform cells yield a softer and more elastic texture than coarse, thick-walled cell structures (Scanlon & Zghal, 2001). For both cultivars, reducing the particle size of WWFs resulted in significantly smaller cells and thinner cell walls of SB. Thus, the mouthfeel of SB is expected to improve with a reduced WWF particle size.

Both dough maximum resistance to extension and extensibility correlated significantly and negatively with SB crumb grain cell area, cell diameter, and cell wall thickness (p < 0.05; data not shown). These results suggested that dough extensibility test is very useful to predict the crumb grain characteristics of STSB.

3.6. Specific volume of SB

The SB made from WWFs of different particle sizes are shown in Fig. 4. As expected, SB made from WWFs of smaller particle size had a smoother surface than that made from WWFs of larger particle size. Specific volume is one of the most important visual characteristics of SB, strongly influencing the consumer’s choice. Overall, the specific volume of SB made from the WWFs was smaller than that of the corresponding SG flours (Table 3). The fiber particles in WWF disrupt the gluten network and reduce the extensibility of dough, which restricts gas cell expansion and gas retention, resulting in a reduced specific volume of bread (Gan, Galliard, Ellis, Angold, & Vaughan, 1992).

For both cultivars, reducing the particle size of WWF increased the specific volume of SB. It is widely accepted that the gluten network is required to form dough with good gas retention properties. Extensibility and Mixolab test results (Fig. 3 and Table 1) showed that reducing the particle size of WWF increased its dough strength and thus the specific volume of SB.

4. Conclusions

Both dough properties and SB making quality were affected by the particle size of soft wheat WWF. Reduction of WWF median particle sizes from ~160 to ~98 m effectively strengthened the gluten network of dough. Mixolab test results showed that dough development time was significantly decreased, but dough stability, and starch hot-gel stability and starch retrogradation were significantly increased as WWF particle size became smaller. The SB making test showed that SB made from WWF of smaller particle size exhibited a larger specific volume and better crumb grain...
structure. These results suggest that reducing the particle size of WWF from ~160 μm to ~100 μm could be an effective way to improve the quality of whole-wheat SB. Dough extensibility test appears to be a promising tool to predict the crumb grain structure of STSB.

References