Effects of Head Density of Cabbages (Brassica oleracea var. Capitata) on Mechanical Properties

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The mechanical properties of cabbages (var. Yumebutai) with different head densities were evaluated by stress relaxation and a puncture test of whole cabbages, and also by a tensile test of strap-shaped specimens. The resistance of whole head to compression at small deformation was well correlated to head density. Mechanical properties in the fifth leaves of cabbages did not correlate to head density, although tensile properties varied within an individual leaf, with direction of tension, and among individual leaves. The observation suggests that head density influences mechanical resistance of whole head at small deformation, and may relate to properties for cutting with an industrial shredder; however it is not a significant factor for mechanical properties of shredded cabbage.

Keywords: mechanical properties, whole cabbage, cabbage leaf, head density

Introduction

Outsourcing in food supply and demand for cut vegetables have recently grown in Japan (Kobayashi, 2006). Not only the food industries, but also food retailers and restaurants require pre-cut vegetables instead of whole raw vegetables. Cabbages (Brassica oleracea var. Capitata) grown in warm regions in Japan and harvested in winter season are commonly employed for industrial uses (Yamamoto, 2007), and shredded cabbage is one of the most consumed cut vegetables.

Cabbages with heavy head weight and high head density yield shredded cabbages with less waste (Yano et al., 1986; Kobayashi, 2006). A recent project of the Ministry of Agriculture, Forestry and Fisheries promotes cabbages with high density for the food service industry. No research has been reported on head density effects on mechanical properties of whole cabbage and some individual cabbage leaves. The purpose of the present study is to clarify the effects of head density on mechanical properties of whole head and shredded cabbage, and on quality of shredded cabbage.

Mechanical properties of whole cabbage were mainly tested in the field by a handy tool, such as the Magnes-Taylor fruit firmness tester (Abbott, 1999). The other methodology is puncture resistance test (Yano et al., 1986; 1990; Saito et al., 2000), where a leaf of cabbage was pressed with a cylindrical plunger (diameter of 2-5 mm) at a constant speed and the resistant load was measured. Yano et al. (1986) successfully expressed suitable varieties for shredded cabbage, but their method and other, previous methods give only the fracture force. Impact and compression tests on whole cabbages were reported to measure the cracking damage of the heads (Holts and Schoorl, 1983). In our previous study, a tensile test of the fifth leaves of cabbages (Kohyama et al., 2008a; b) determined that mechanical properties varied widely depending on direction of veins as reported for other plants (Vincent, 1990; Toole et al., 2000).

Meanwhile, a machinery system that determines the maturity of cabbages in the field was studied (Satow et al.,
Materials and Methods

Cabbages  Cabbages (group ‘Yumebutai’, the name means ‘dream stage’ in English, Takii and Co. Ltd., Kyoto, Japan) seeded on August 8 and transplanted on September 7, 2007 in Kasai City, Hyogo, Japan were used. This cultivar belongs to Winter type, grows well at low temperature, and, according to Takii and Co. Ltd., has soft texture and sweet-tasting leaves. The ratio of core to the whole head is as small as 2.9%, making it suitable for making shredded cabbage by industrial cutters (Saito and Takegawa, 2007). The best harvest period for ‘Yumebutai’ grown in Hyogo Prefecture is during January and February (Yamamoto, 2007). The samples were harvested on 21 January 2008, immediately transported to National Food Research Institute, Tsukuba, Ibaraki, Japan, and tested within 4 days at 20°C.

Weight, diameters (long and short directions), and height were measured for each head. Head volume was estimated based on the spherical ellipsoid formula (Radovich and Kleinhenz, 2004). Head density was calculated as the ratio of weight to volume. The fifth leaf from the outside was used for a tensile test (Kohyama et al., 2008a; b). The weight of the fifth leaf and the ratio to the whole head was calculated. We classified the cabbage samples into three categories by head density; i.e., low, medium, and high density.

Mechanical tests  Mechanical tests were performed using a Universal Testing Machine (Model 5564 or 5542, Instron, Canton, MA, USA) attached to a load cell of 1 kN or 50 N at 20°C (Kohyama et al., 2008a; b).

A head of cabbage was compressed between flat plates (diameter of 150 mm) at a constant speed of 60 mm/min until a compressive strain of 4% of initial height for each head. Load value was measured until 5 min while keeping the strain, and then the upper plate was moved upward. Seven heads belonging to each group were tested.

A simple puncture test was also performed with a cylindrical plunger (diameter of 4.79 mm). Four parts of the top head approximately 30 mm from the center of each cabbage were compressed at a constant speed of 60 mm/min until the compressive strain reached 40% of the initial height. Four heads in each density group were tested.

For a tensile test, the fifth leaf from the outside was taken and the main vein was removed. Rectangular specimens (10 mm in width and 60 mm in length parallel or perpendicular to the secondary vein) were tensioned at a constant speed of 250 mm/min until fracture (Kohyama et al., 2008a; b). More than 8 specimens for each direction were prepared from a leaf, and five individual leaves belonging to each density group were tested. The thickness of the each fractured section was measured with calipers (CD-15, Mitsutoyo, Kawasaki, Japan).

Results

Characteristics of the head and the fifth leaf of each group  We classified the cabbages by head density. The low, medium, and high density groups were 0.510-0.543, 0.581-0.592, and 0.627-0.644 g/cm³, respectively. Mean and standard error values for each density group are shown in Table 1. The heads were similar in diameter, height, the ratio of height to diameter, and volume of each head, but weight was greater in the high-density group. The nature of the fifth leaf was not significantly different among the groups. Thus, when we see the head or the leaf, we cannot discriminate the head density of cabbages.

Mechanical properties of whole head  Figure 1 shows example mechanical relaxation curves for cabbage heads for three groups of head density. They behaved as viscoelastic solids. Time 0 was adjusted when compressive strain reached 4% of initial height, from where the strain was kept for 5
min. The higher the head density, the greater the mechanical load at any time during 5 min, and the higher the load at a defined strain or deformation, because the present samples were of similar height. The mechanical stress relaxed while the strain was kept constant (4%) for 5 min. At any time of the relaxation process, the load similarly decreased independently of head density. Therefore, the relaxation load during 5 min was parallel to the initial load. Thus, the relaxation ratio defined as the ratio of relaxation load to the first load was independently of head density. The statistical results obtained from seven heads are shown in Table 2.

The maximum load value, which was detected at the moment when compressive strain reached 4%, is plotted versus head density (Fig. 2). The head density and maximum load values were significantly correlated ($r=0.76, p<10^{-5}$).

A typical puncture curve is shown in Fig. 3. The load increased linearly to the first peak, where the plunger was inserted into the outer leaf. We recognized that the first leaf from the outside fractured at this moment (arrow B in Fig. 3). The fracture point appeared when the compressive strain was about several %. Then, the load suddenly decreased in some cases, or increased again (arrow M in Fig. 3), probably depending on the structure just under the plunger. The load traced a jagged curve until 40% compressive strain, where the puncture test was finished. The load value sometimes increased steeply when the strain became more than 40%. This behavior occurred because that the plunger was inserted into the hard part close to the core of each head.

As shown in Table 3, in high-density heads, breaking strain was smaller, and elastic modulus and maximum load were greater. Breaking load, energy for breaking, and strain at maximum load were not significantly changed by head density. The elastic modulus and load values for relaxation test exhibited similar tendencies.

**Mechanical properties of cut leaf**  
Figure 4 shows typical tensile curves for specimens parallel and perpendicular to the secondary vein. For both directions, tensile load increased with deformation and then decreased steeply due to fracture. The parallel curve exhibited greater load than the perpendicular counterpart regardless of head density, but they showed similar fracture strain ($F(1, 124) = 1.96, p = 0.033$). Two-way ANOVA revealed that there were significant main effects of orientation of veins in thickness, fracture load, fracture stress, and elastic modulus ($p<10^{-5}$). These four parameters were greater in the parallel direction than in the perpendicular direction (Table 4). Thus, we analyzed the tensile properties separately in the tensile direction (Table 4).

Significant main effects of head density were found in fracture strain in parallel direction, thickness, fracture load, and elastic modulus in perpendicular direction, and fracture stress for both directions (second column in Table 4). Significant effects of individual heads (nested by density) were observed only in fracture stress ($F(12, 138) = 2.693, p = 0.003$) parallel to the vein, while they were found in thickness ($F(12, 124) = 2.26, p = 0.013$), fracture strain ($F(1, 124) = 1.96, p = 0.033$), fracture load ($F = 4.44, p < 10^{-5}$), fracture stress ($F = 3.93, p < 10^{-5}$) and elastic modulus ($F = 1.85, p = 0.048$) in the perpendicular direction.

Figure 5 shows an example of individual variations for fracture strain and fracture stress of the tensile test. The parallel and perpendicular directions exhibited significantly different fracture points, where the fracture stress values of parallel specimens were greater than those of perpendicular specimens. Variances within an individual leaf were great in comparison with those among average values of individual leaves. The fracture properties varied greatly within a leaf; for both directions the greatest values were more than double the smallest values.

**Discussion**

**Errors caused by cabbage shape**  
As shape of a cabbage head is globate, the contact area between the flat plates of

<table>
<thead>
<tr>
<th>Head weight (g)</th>
<th>ANOVA F-ratio</th>
<th>Head density group</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean diameter (cm)</td>
<td>0.045*</td>
<td>1402 ± 38</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>0.612</td>
<td>20.0 ± 0.2</td>
</tr>
<tr>
<td>Height/diameter ratio</td>
<td>0.790</td>
<td>12.7 ± 0.2</td>
</tr>
<tr>
<td>Volume (cm³)</td>
<td>0.233</td>
<td>0.637 ± 0.009</td>
</tr>
<tr>
<td>Mean diameter (cm)</td>
<td>0.770</td>
<td>2659 ± 67</td>
</tr>
<tr>
<td>Head density (g/cm³)</td>
<td>0.000***</td>
<td>0.529 ± 0.005</td>
</tr>
<tr>
<td>Weight of fifth leaf (g)</td>
<td>0.070</td>
<td>68.8 ± 2.9</td>
</tr>
<tr>
<td>Ratio of fifth leaf to head (%)</td>
<td>0.821</td>
<td>4.91 ± 0.15</td>
</tr>
</tbody>
</table>

Mean ± standard error. * and ***, significant differences among the density groups with $p<0.05$ and $p<0.001$, respectively. Mean values marked with different alphabetical letters differed significantly ($p<0.05$) as determined by the Tukey’s test.
Table 2. Results of relaxation test of whole cabbage heads.

<table>
<thead>
<tr>
<th></th>
<th>ANOVA F-ratio</th>
<th>Head density group</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Low</td>
</tr>
<tr>
<td>Deformation at 4% strain (mm)</td>
<td>0.726</td>
<td>5.09 ± 0.07</td>
</tr>
<tr>
<td>Maximum load at 4% strain (N)</td>
<td>0.000***</td>
<td>43.0 a ± 10.8</td>
</tr>
<tr>
<td>Load after 1 min (N)</td>
<td>0.000***</td>
<td>31.0 a ± 7.8</td>
</tr>
<tr>
<td>Load after 2 min (N)</td>
<td>0.000***</td>
<td>29.1 a ± 7.4</td>
</tr>
<tr>
<td>Load after 3 min (N)</td>
<td>0.000***</td>
<td>27.9 a ± 7.1</td>
</tr>
<tr>
<td>Load after 4 min (N)</td>
<td>0.000***</td>
<td>27.0 a ± 6.9</td>
</tr>
<tr>
<td>Load after 5 min (N)</td>
<td>0.000***</td>
<td>26.2 a ± 6.7</td>
</tr>
<tr>
<td>Relaxation load (N)</td>
<td>0.001***</td>
<td>16.8 a ± 4.1</td>
</tr>
<tr>
<td>Relaxation ratio (%)</td>
<td>0.229</td>
<td>39.7 ± 0.5</td>
</tr>
</tbody>
</table>

Mean ± standard error. ***, significant differences among the density groups (p<0.001). Mean values marked with different letters differed significantly (p<0.05) as determined by the Tukey’s test.

Fig. 1. Relaxation curves of whole cabbage.
Load relaxation during 5 min with a compressive strain of 4%. Data from whole heads with low (L, bottom), medium (M, middle), and high (H, upper) head density.

Fig. 2. Relationship between head density and maximum load at 4% compressive strain. The line is drawn by the least squares method for linear regression. Circles: L, low density; M, medium density; and H, high density.
the testing machine used for the relaxation test and cabbage head is not constant. When the upper plate first contacts a sample head, the contact area is a point. Area increases as compressive deformation becomes greater, and reaches the plate area. The individual heads of cabbage varied; the error in compressive stress was greater when the deformation was too small. We found that the stress at compressive strain exceeding 4%, which corresponded to deformation of about 5 mm (Table 2), exhibited less variations within an individual head. The contact area is considered to have become close to 177 cm$^2$; i.e., the area of the plate. Stress relaxation under a large deformation remains as unrecoverable damage. The load values at 4% compressive strain ranged 20 to 203 N, varying with head density of cabbages (Fig. 2). This is a much smaller load than 3000-4500 N to crack the head (Holt and Schoorl, 1983), and similar to <50 N or <30 mm deformation used in a non-destructive test (Satow et al., 2001). This level seems within the load applied to heads during harvesting and transporting by the weight of cabbages in a container. The relaxation load after 5 min was about 40% of the initial load at 4% strain; the relaxation ratio was independent on head density (Table 2). Although 4% strain may not be completely recoverable after longer time, no visible damage to the whole head and any edible parts of cabbage were observed in the relaxation test.

When the cylindrical plunger for the puncture test touches the surface of cabbage, the contact area between the plunger and samples is not completely the same as the cross sectional area of the plunger, but the error is small enough to be ignored. The vertical height at the punctured position about 25-30 mm from the top of the head was less than 3 mm lower than the head height (12.6 cm on average), as the variety tested in this study belongs the Winter type cabbage, which shows a flattened shape (the ratio of height/diameter is 0.60-0.68) and a high head density as shown in Table 1 (Kohyama et al., 2008a). The distance (<3 mm) in head height was sufficiently small. The position was necessary for avoiding to press the just above the core of each head, where the compressive load might be influenced by the hard core.

The errors caused by cabbage shape would vary with
Fig. 4. Example tensile curves parallel and perpendicular to the secondary vein.
The specimens were tensioned at a constant speed of 250 mm/min until fracture at 20°C.

Fig. 5. Variances in tensile fracture properties for samples with different head density.
Greater diamond symbols indicate mean fracture points of each sample with different head density (H, high; M, medium; L, low), and small circles indicate fracture points of the specimens taken from an individual leaf with high head density. Solid symbols represent parallel to the secondary vein results and open symbols are perpendicular to the vein.

Table 4. Results of tensile test of the fifth leaf of cabbages.

<table>
<thead>
<tr>
<th></th>
<th>ANOVA F-ratio</th>
<th>Head density group</th>
<th>Low</th>
<th>Medium</th>
<th>High</th>
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<tbody>
<tr>
<td><strong>Parallel to the secondary vein (character of vein)</strong></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>0.279</td>
<td>1.11 ± 0.08</td>
<td>0.92 ± 0.08</td>
<td>0.98 ± 0.08</td>
<td></td>
</tr>
<tr>
<td>Fracture strain (%)</td>
<td>0.037*</td>
<td>24.0 ± 1.3</td>
<td>28.7 ± 1.4</td>
<td>27.8 ± 1.5</td>
<td></td>
</tr>
<tr>
<td>Fracture load (N)</td>
<td>0.469</td>
<td>7.23 ± 0.35</td>
<td>7.85 ± 0.38</td>
<td>7.63 ± 0.40</td>
<td></td>
</tr>
<tr>
<td>Fracture stress (MPa)</td>
<td>0.000***</td>
<td>0.766 ± 0.045</td>
<td>1.044 ± 0.050</td>
<td>0.900 ± 0.038</td>
<td></td>
</tr>
<tr>
<td>Elastic modulus (MPa)</td>
<td>0.232</td>
<td>5.05 ± 0.27</td>
<td>5.90 ± 0.35</td>
<td>5.36 ± 0.27</td>
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<tr>
<td><strong>Perpendicular to the secondary vein (character of the mesophyll)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>0.007**</td>
<td>0.65 ± 0.03</td>
<td>0.65 ± 0.03</td>
<td>0.78 ± 0.04</td>
<td></td>
</tr>
<tr>
<td>Fracture strain (%)</td>
<td>0.563</td>
<td>26.7 ± 1.2</td>
<td>28.5 ± 1.5</td>
<td>26.2 ± 1.3</td>
<td></td>
</tr>
<tr>
<td>Fracture load (N)</td>
<td>0.005**</td>
<td>3.67 ± 0.20</td>
<td>4.79 ± 0.31</td>
<td>4.09 ± 0.25</td>
<td></td>
</tr>
<tr>
<td>Fracture stress (MPa)</td>
<td>0.000***</td>
<td>0.579 ± 0.034</td>
<td>0.751 ± 0.038</td>
<td>0.518 ± 0.036</td>
<td></td>
</tr>
<tr>
<td>Elastic modulus (MPa)</td>
<td>0.002**</td>
<td>2.25 ± 0.17</td>
<td>2.81 ± 0.15</td>
<td>2.06 ± 0.17</td>
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</table>

Mean ± standard error of five individual head × more than 8 replicates. Significant differences among the density groups with *, p<0.05; **, p<0.01, and ***, p<0.001. Mean values marked with different letters differed significantly (p<0.05) among density groups as determined by the Tukey’s test.
head size and height/diameter ratio. As the heads used in this study were similar in shape and size (Table 1), the errors were common for all groups of head density.

**Puncture test can replace the relaxation test**  The head density of cabbage correlated with load values in the relaxation test (Fig. 2) and also with elastic modulus in the puncture test (Table 3). The load values at 1.5, 3, 4, and 5% compressive strain in the puncture test were highly correlated with each other \( (p < 10^{-4}) \), because the load increased almost linearly until breakage as shown in Fig. 3. We should take a load value at 4% or less strain as the representative of mechanical properties under a small deformation, in consideration that the lowest breaking strain of tested samples was 4.25%. This suggests that load value at a small compressive strain before breaking can be a good measure of head density. Load at a small strain may resemble sensory assessment while humans press cabbage heads in the field by hand. As it is a non-destructive method, it could applied even in the field before the harvest if a handy-type instrument is developed.

Low breaking strain while the first leaf was punctured and high elastic modulus in high-density heads in the puncture test (Table 3) corresponded to the load value applied to the whole head under a small compressive strain (Table 2). As shown in Table 2, high-density heads exhibited a high load >100 N; this is greater than maximum load capable for some food rheometers, and moreover a flat plate with a diameter of 150 mm is too large to attach to some food rheometers. In such cases the puncture methods employing a small probe can be introduced instead of the relaxation test.

Breaking load in the puncture test was similar for the three density groups (Table 3). Conventional firmness test of whole cabbages using a Magnes-Taylor type apparatus would not exhibit the head density effect, because the load value only under a small compressive deformation before the breakage correlated to the head density.

**Dependence of head density on mechanical properties** When consumers eat cut cabbages, the mechanical properties of each leaf of edible part are more important than those in whole head, because they determine the texture of cut vegetables. High head density may be commercially advantageous for farmers who prefer greater heads to achieve specified weight with less effort and for processors who want high yield of shredded cabbages (Kobayashi, 2006). In addition, properties of an individual leaf and shredded cabbage must be acceptable by consumers. As a representative, the fifth leaf from outside was tested by tensile fracture (Kohyama et al., 2008a, b), because the fifth leaf from the outer side of each head of cabbage has the greatest weight among the interval of three leaves for any cultivars (Ninomiya and Sugeno, 1958). The tensile properties of fifth leaves taken from different cultivars differed in direction of tension and varieties (Kohyama et al., 2008a). Although literature on plants fracture by tensile test reported greater mechanical strength in parallel to veins than in the perpendicular direction (Vincent, 1990; Toole et al., 2000), some varieties accorded to the general findings but others did not (Kohyama et al., 2008a). The overall characteristics of ‘Yumebutai,’ especially in direction dependency, were the closest to ‘Satsuki-oh,’ one of the Winter type cultivars harvested in May 2007 (Kohyama et al., 2008a). They were common for all density groups.

The greatest values were observed in the medium density group for many tensile parameters (Table 4). The findings may partially relate to the higher ratio of the fifth leaf to the whole head in the medium density group (Table 1). Unlike mechanical resistance against a small compressive strain (load values in Table 2 and elastic modulus in Table 3), no significant correlation was observed between a tensile parameter and head density. Great individual variances as shown in Fig. 5, and highly significant individual differences, especially in fracture load and stress of the perpendicular tension, may cause the significant differences found in tensile characteristics among the head density groups. This finding was due to heterogeneity in mechanical properties of a leaf of cabbages regardless of head density.

Fracture properties generally have greater variances, because fracture itself is a probabilistic phenomenon. This was also observed in the puncture test (Table 3) with less significance in breaking properties (breaking energy, breaking load, and also breaking strain) and high significance in elastic modulus.

**Application of non-destructive tests** Stress-relaxation tests have been conducted for many vegetables and fruits (Peleg, 1979; Holts and School, 1983; Blahovec 1996a, b; Marquina et al., 2001). Some of the previous studies were conducted under small deformation, whereas others applied a large deformation accompanied by unrecoverable structural change (Holts and School, 1983; Blahovec, 1996a, b). Holt and Schoorl (1982) conducted a compression test of whole cabbages using an Instron machine. As the compression was stopped when the deformation reached 20, 40, 60, 80, and 100 mm, the applied load rose to 3000-4500 N to make cracks. Satow et al. (2001) stated that when the plunger diameter was 20 mm or less, the plunger damaged the cabbage head. Our experiment was designed under the conditions of much less load and deformation (approximately < 150 N and 5 mm) using a great plate (diameter of 150 mm); therefore, the cabbage heads were not destroyed, nor were they damaged visually. The cabbage heads could be offered on the market, at least for industrial processing.

The compressive relaxation test basically gives the paral-
el information to the deformation test described by Bourne (1967). In the deformation test, a sample is compressed at a constant speed using an Instron testing machine and the distance is measured at a defined load. Bourne (1967) reported that soft lettuce exhibited greater deformation (9 mm) than hard lettuce (3 mm) under a load of 9.8 N. As the reported values in deformation and load were small, the deformation test seemed non-destructive. We consider that deformation or creep tests, where deformation is measured at a defined small load, can be used instead of the relaxation test measuring load at a fixed small deformation, although we preferred the relaxation test, because the machine is of movement (compressive deformation) controlled type.

Conclusion
The resistance of whole head to compression at 4% was well correlated to head density of cabbages. The same tendency was also observed in resistance to compression with a small plunger before fracture. None of the mechanical properties of a leaf of cabbages correlated with head density. Although head density may influence properties for cutting with an industrial shredder, it likely does not affect mechanical properties of the final product after shredding. High density heads seems to be suitable for industrial shredded cabbage, because of their high yield and no defects in quality.

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References