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RHEOLOGICAL AND ULTRASTRUCTURAL STUDIES OF WHEAT KERNEL BEHAVIOUR UNDER COMPRESSION AS A FUNCTION OF WATER CONTENT

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Abstract

The rheological behaviour of two wheat varieties (Triticum durum), cultivated at different sites, was studied by INSTRON* as a function of water content. Patterns of crushed grains were investigated by scanning electron microscopy. The apparent modulus of elasticity of the wheat grains was apparently related to their vitreosity. The mealy grain generally had an apparent modulus of elasticity lower than that of the vitreous one and the modulus appeared to be related to the air spaces in mealy endosperm. Humidification favoured the conversion of vitreous endosperm to the mealy state. Grain morphology and particularly the kernel crease played an important role during grain crushing.

Introduction

The final products of the milling process (flour, semolina, etc.) and baking are related to a number of factors including the grinding quality of wheat grains. The aim of milling is to remove the endosperm from bran. The endosperm is transformed into semolina and the bran should be kept in large flakes to aid its separation from the semolina particles.

In flourmilling, wheat grains pass a number of times between different fluted rolls in the break system and then through the smooth reduction rolls. Then, it becomes impossible to separate any endosperm particle without crushing the bran into fine particles which would contaminate the flour and modify the color and texture of bread (Lockwood, 1950). Best grinding is the process which produces mainly coarse semolina and large bran flakes. Wheat variety, water content, hardness and vitreosity of grain are all factors affecting milling quality.

In milling the following mechanical actions take place:

- Shear: In breakmilling, this phenomenon occurs because of the difference in peripheral speeds of the rolls. The wheat grain is held by the grooves of the slow roll whilst the grooves of the fast roll exercise a cutting action (shear) on the grain;
- Compression: Compression is used to reduce the semolina to flour. This mechanism of fragmentation occurs mainly in the reduction system.

In recent years, many workers have investigated wheat grain hardness. Barlow et al. (1973) have used a micropenetrometer (Leitz Miniload hardness tester) to measure the hardness of starch and protein separately. Simmonds et al. (1973) suggested that adhesion between starch and storage protein was a more important factor in determining wheat grain hardness than the protein matrix composition. Stenvert and Kingswood (1977) found that the wheat hardness was determined by the physical structure of the endosperm protein matrix. Moss et al. (1980) concluded that the manner in which the wheat grain fractured was determined by hardness and water content of the grain. Yamazaki and Donelson (1983) used the particle size index (PSI) to express wheat hardness as a function of protein content.

Key Words: Apparent modulus of elasticity, crushing, image analysis, scanning electron microscopy, vitreosity, water content, wheat grain.

*Instron Universal Testing Instrument, Model 1122.
Until now, grain vitreosity has not been investigated sufficiently. The aim of this study was to investigate the role of grain vitreosity and water content on rheological behaviour of wheat under uniaxial compression. Crushed grain particles were studied microscopically to determine the changes in physical structure during grinding.

Materials and Methods

Two wheat varieties (Triticum durum L.), Agathe and Mondur harvested in 1982 were studied. Agathe was cultivated in three different regions of France, whereas Mondur was cultivated only in two regions (table 1). Ecological factors influenced the physical characteristics of harvested grains.

The study of wheat grain fragmentation was carried out over a range of conditioning moisture levels between 10.0 and 17.5%. The water content of the grain was determined by the French standard method NF-V/03-701. After harvesting, the water content of the varieties varied between 11.0 and 13.7% (table 1). The samples were desorbed to about 9% water content with phosphorus pentoxide under vacuum (Al Saleh et al., 1984). To obtain a uniform water content for all grains within every sample, the samples held for 5 days prior to the determination of water content. Each sample was divided into 4 portions. Portions were equilibrated to 10.0, 13.8, 16.7 and 17.5% water content using saturated saline solution (Multon et al., 1980). Wheat grain vitreosity was determined at 10.0% water content, by the Pohl grain cutter (Al Saleh et al., 1984).

Measurement of wheat grain apparent modulus of elasticity

The Instron Universal Testing Instrument, Model 1122, was used to carry out the apparent modulus of elasticity determination. Forty six grains of each sample were taken at random, then positioned individually between the plates of the Instron instrument so that the crease was down (fig. 1). To minimize the effect of the crease on the behaviour of the grain during the compression, a piece of silicon carbide adhesive paper (Transfol-N° STRUERS Cie) was used to avoid lateral displacement of the grain (thin arrows, fig. 1). The apparent modulus of elasticity was measured under the following conditions: the wheat grains were submitted to five successive identical compressions, the loading rate was 0.05 mm/min and the maximum load reached 500g. Preliminary loading-unloading tests showed that wheat grain deformation was approximately linear. Therefore, the behaviour of the wheat grains was considered to be Hookean. These observations are in agreement with those of Shelef and Mohsenin (1967) and Multon et al. (1981).

Calculation of apparent modulus of elasticity

We adopted Hertz's solution for the contact stresses between two elastic bodies submitted to uniaxial compression to calculate the apparent modulus of elasticity. According to Kozma and Cunningham (1962), who reviewed Hertz's solution, the material must be homogeneous, the contacting bodies must be large, and the radii of curvature, illustrated in fig. 2, must be very large when compared with the dimensions of the contact area. The study of Morrow and Mohsenin (1966) showed that the previous assumptions were applicable in the case of wheat grains. To determine the apparent modulus of elasticity, Arnold and Roberts (1969) showed that the utilization of uniaxial compression on the whole grain gave the best results.

Using the simplified Hertz equation that takes into consideration the geometrical characteristics of the wheat kernel (length, width and thickness), the apparent modulus of elasticity was calculated:

\[ E = \frac{0.5 P (1 - U)^2}{D_T^{3/2}} \cdot \left[ \frac{1}{R_1} + \frac{1}{R_2} \right]^4 \]

\[ E : \text{apparent modulus of elasticity} \]
\[ P : \text{applied compressive load} \]
\[ U : \text{Poisson's ratio} \]
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\[
\begin{align*}
R_1 & \simeq H/2 \\
R'_1 & \simeq \frac{H^2 + L^2 / 4}{2H}
\end{align*}
\]

Fig. 2. Approximation of \(R_1\) and \(R'_1\) for wheat grain (after Mohsenin, 1978).

\[D_t: \text{total grain deformation}
\]
\[R_1, R'_1: \text{principal radii of the grain at the contact surface.}
\]

Shelef and Mohsenin (1967) showed that the total deformation \(D_t\) within the linear range of the loading-unloading curve consisted of residual deformation \(D_r\) and elastic deformation \(D_e\). Our preliminary tests showed that the residual deformation became practically constant after the fourth loading-unloading cycle (fig. 3). For that reason, in the apparent modulus of elasticity calculation we used the average of the fourth and the fifth loading-unloading cycles.

\[
\begin{align*}
D_t & = D_r + D_e \\
D_r & \approx 0.5 (D_1 + D_2)
\end{align*}
\]

Shelef and Mohsenin (1967) showed that the total deformation \(D_t\) within the linear range of the loading-unloading curve consisted of residual deformation \(D_r\) and elastic deformation \(D_e\). Our preliminary tests showed that the residual deformation became practically constant after the fourth loading-unloading cycle (fig. 3). For that reason, in the apparent modulus of elasticity calculation we used the average of the fourth and the fifth loading-unloading cycles.

**Wheat grain crushing**

Wheat grain crushing was performed immediately after the measurement of elasticity, each grain staying in the same position. The crushing conditions were: load rate 1 mm/min, maximum load 50 kg. The general shape of the load-deformation curve is represented in figure 4.

**Scanning electron microscopy**

After crushing, surfaces produced by INSTRON fracturing were coated with a thin layer of gold (40 nm) and observed with the scanning electron microscope (JEOL 50A). Many fragments were investigated from all samples. The general appearance of the crushed grain was observed with an accelerating voltage of 10 keV, whereas grain ultrastructure was observed under 20 keV.

**Statistical analysis of images**

A semi-automatic image analyser composed of a Kontron digiplan (Reichert Jung) MOP 1 interfaced with a microcomputer (Commodore CBM 3032) was used on enlarged (7.75X) photographs.

**Results and Discussion**

**Vitreosity**

The mean vitreosity values of the different varieties indicated (table 2): (i) there is a significant difference between the vitreosity values of the same variety cultivated in different geographical regions; and (ii) at most sites, the variety Agathe is more vitreous than the variety Mondur.

<table>
<thead>
<tr>
<th>Variety</th>
<th>Agathe 3002</th>
<th>Agathe 1023</th>
<th>Agathe 1093</th>
<th>Mondur 1021</th>
<th>Mondur 1091</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vitreosity %</td>
<td>98.8</td>
<td>97.9</td>
<td>77.7</td>
<td>95.2</td>
<td>46.8</td>
</tr>
</tbody>
</table>

**Apparent modulus of elasticity of wheat grain**

Agathe 3002. The apparent modulus of elasticity of Agathe 3002 (10% water content) shows a normal distribution (fig. 5 a). At 13.8% water
Table 3. Mean apparent modulus of elasticity ($E.10^{10}$ dynes/cm²).

<table>
<thead>
<tr>
<th>Variety</th>
<th>Agathe 3002</th>
<th>Agathe 1023</th>
<th>Mondur 1021</th>
<th>Agathe 1093</th>
<th>Mondur 1091</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Content %DM</td>
<td>10.0%</td>
<td>13.8%</td>
<td>16.7%</td>
<td>17.5%</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2.16±0.06</td>
<td>1.60±0.05</td>
<td>1.72±0.04</td>
<td>1.95±0.09</td>
<td>1.57±0.07</td>
</tr>
<tr>
<td></td>
<td>2.06±0.05</td>
<td>1.59±0.05</td>
<td>1.69±0.04</td>
<td>1.89±0.07</td>
<td>1.53±0.06</td>
</tr>
<tr>
<td></td>
<td>1.96±0.06</td>
<td>1.47±0.04</td>
<td>1.55±0.05</td>
<td>1.77±0.06</td>
<td>1.34±0.05</td>
</tr>
<tr>
<td></td>
<td>1.79±0.05</td>
<td>1.37±0.04</td>
<td>1.49±0.05</td>
<td>1.75±0.05</td>
<td>1.27±0.03</td>
</tr>
</tbody>
</table>

Fig. 5. Histograms of the apparent modulus of elasticity of Agathe 3002 at: a) 10.0%; b) 13.8%; c) 16.7% and d) 17.5% water contents.

Fig. 6. Histograms of the apparent modulus of elasticity of Agathe 1023 at: a) 10.0%; b) 13.8%; c) 16.7% and d) 17.5% water contents.
content the histogram (fig. 5 b) has an appearance similar to that of the preceding histogram, but it undergoes a slight shift towards the low end on the elasticity scale. This trend is repeated at high moisture levels and is a function of the water content (fig. 5 c). The mean value of the modulus of elasticity decreased by 3.7 x 10^9 dynes/cm^2 as the water content increased from 10.0 to 17.5% (table 3).

Statistical calculations showed that the difference between the mean values of the different moduli of elasticity was significant.

Agathe 1093. This is a vitreous variety (table 2) for which the values of the apparent modulus of elasticity at 10.0% water content (fig. 6 a), were distributed between 1.1 x 10^10 and 2.0 x 10^10 dynes/cm^2. This distribution stayed practically the same with 13.8% water content (fig. 6 b). With increasing water content there was a reduction in the mean value of the apparent modulus of elasticity (figs. 6 c, d). At 17.5% water content the reduction in mean value was 16% (table 3).

Agathe 1093. The wheat grains of Agathe 1093 can be divided into three categories: mealy, intermediate and vitreous. Each one of these categories corresponds to a part of the histogram figure 7a. The mealy wheat grains are represented by the values of the apparent modulus of elasticity lower than 1.6 x 10^10 dynes/cm^2. The vitreous wheat grains are represented by the values greater than 2.1 x 10^10 dynes/cm^2, whereas the values between 1.6 x 10^10 dynes/cm^2 and 2.1 x 10^10 dynes/cm^2 represent the intermediate wheat grains. The increase in the water content from 10.0 to 13.8% produces a diminution of the values of the apparent modulus of elasticity,
Fig. 9. Histograms of the apparent modulus of elasticity of Mondur 1091 at: a) 10.0%; b) 13.8%; c) 16.7% and d) 17.5% water contents.

particularly, that part representing the vitreous grains (fig. 7 b). The largest decrease of the apparent modulus of elasticity corresponded to vitreous wheat grains indicating that they are more sensitive to variations in water content. Grain humidification initiated the amalgamation of the original three categories of wheat types (fig. 7 b). At 16.7% water content there was only one grain population. This trend was mainly due to the reduction of the apparent modulus of elasticity of the vitreous and intermediate wheat grains. At 17.5% water content, the distribution of the values of the apparent modulus of elasticity was approximately Gaussian (fig. 7 d). The increase in water content from 10.0 to 17.5% produced a decrease in the mean value of the apparent modulus of approximately $2 \times 10^8$ dynes/cm$^2$ (table 3).

Fig. 10. Vitreous wheat grain crushed (Agathe 1093) at 10.0% (a) and 16.7% water content (b), showing grain crushing mode.

Fig. 11. Mealy wheat grain crushed (Mondur 1091) at 10.0% (a) and 16.7% water content (b), showing the fashion with which the grain crushed by INSTRON.
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Table 4. Changes in endosperm texture in function of water content.

<table>
<thead>
<tr>
<th>Variety</th>
<th>Agathe 3002</th>
<th>Agathe 1023</th>
<th>Mondur 1021</th>
<th>Agathe 1093</th>
<th>Mondur 1091</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content % DM</td>
<td>% surface area of mealy endosperm</td>
<td>% intermediate area of mealy endosperm</td>
<td>% surface area of mealy endosperm</td>
<td>% intermediate area of mealy endosperm</td>
<td>% surface area of mealy endosperm</td>
</tr>
<tr>
<td>10.0</td>
<td>1.9</td>
<td>6</td>
<td>3.9</td>
<td>26</td>
<td>4.4</td>
</tr>
<tr>
<td>13.6</td>
<td>2.0</td>
<td>6</td>
<td>6.7</td>
<td>29</td>
<td>9.6</td>
</tr>
<tr>
<td>16.7</td>
<td>2.8</td>
<td>9</td>
<td>12.2</td>
<td>57</td>
<td>19.8</td>
</tr>
<tr>
<td>17.5</td>
<td>6.5</td>
<td>26</td>
<td>15.7</td>
<td>63</td>
<td>18.3</td>
</tr>
<tr>
<td>Vitreosity at 10% H2O DM</td>
<td>98.8</td>
<td>97.9</td>
<td>95.2</td>
<td>77.7</td>
<td>46.8</td>
</tr>
</tbody>
</table>

* % mealy whole grains.

Mondur 1021. In this vitreous variety, the values of the apparent modulus of elasticity were not altered to any appreciable content as the water content was increased from 10.0% to 13.8% (fig. 8 a, b). A significant decrease of the values of the apparent modulus of elasticity was only observed at 16.7% water content (fig. 8 c). This decrease was more marked at 17.5% water content (fig. 8 d). The difference between the mean value of the apparent modulus of elasticity at 10.0 and 17.5% water content was 0.23 x 10^10 dynes/cm^2 (table 3).

Mondur 1091. This variety was the most mealy of those studied, and at 10.0% water content, it had the lowest mean value of the apparent modulus of elasticity (table 3). This mean value progressively decreased as the water content increased (fig. 9 a). A displacement of the whole histogram was observed (figs. 9 b, c). At 17.5% water content, the mean value of the apparent modulus of elasticity decreased at about 20% compared to that at 10.0% water content (table 3).

Statistical analysis of images

Agathe 3002. Humidification to 17.5% water content of Agathe 3002 grains increased the percentage of mealy endosperm area from 1.9 to 6.5% (table 4). This was at the expense of the vitreous area. The conversion of vitreous endosperm to mealy state also associated with an increase in the number of intermediate wheat grains from 6 to 26% when the water content increased from 10.0 to 17.5% (table 4). The change of endosperm texture from vitreous to mealy is a function of the water content and is responsible for the decrease in the apparent modulus of elasticity. This change appears to be due to the expansion of the protein matrix and starch of vitreous endosperm.

But Agathe 3002 showed a high resistance to texture change because of the important compactness of its endosperm.

Agathe 1023. In this very vitreous variety, the percentage of mealy endosperm increased from 3.9 to 15.7% as the water content increased from 10.0 to 17.5% (table 4). At the same time, the percentage of intermediate grains increased by 37%.

Mondur 1021. This variety is also vitreous and the percentage of mealy endosperm increased by 14.4% as the water content increased from 10.0% to 17.5% (table 4). At the same time there was a four-fold increase in the number of intermediate grains. A comparison of the data for Agathe 3002 and Mondur 1021, showed that Mondur 1021 was more susceptible to the textural changes as a function of increased water content. This difference between the two varieties is related to vitreosity and is important in the technological processing of wheat grains.

Agathe 1093. The percentage of the vitreous endosperm in Agathe 1093 is dominant but its mean value decreased as a function of water content. The increase in water content enlarges the mealy endosperm areas. Above 16.7% water content, one observes the appearance of some completely mealy grains (table 4). At 17.5% water content, the intermediate grains reached the very high percentage of 87% (table 4).

Mondur 1091. Mealy endosperm predominated in Mondur 1091. The amount of mealy endosperm increased by 10% when the water content increased from 10.0 to 13.6%. However, a further increase in water content did not significantly increase the amount of mealy endosperm (maximum level
approximately 72%). The decrease of the percentage of intermediate grains was due to the amalgamation of adjacent mealy spots. This conclusion was confirmed by the increase of the whole mealy grains from 2 to 30%.

**SEM of crushed wheat grain**

Whole crushed wheat grains. The most vitreous wheat grains crushed by the INSTRON, showed a longitudinal fragmentation along the major axis. This fragmentation pattern is shown in fig. 10a. Humidification did not change the fracture pattern of the vitreous grains during crushing. One observed a similarity between the aspect of the crushed wheat grain in the same variety at 10.0 and 16.7% water contents (figs. 10 a, b). The longitudinal fragmentation of vitreous wheat grain was principally caused by the morphology of vitreous grain. The deeper crease of the vitreous grains created a zone of low resistance to crushing.

In contrast, the mealy grains, represented by Mondur 1091, crushed transversally to the major axis (fig. 11 a). This difference between vitreous and mealy grain crushing relates also to the grain morphology, mealy grains being wider and the crease depth less than those of the...
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Fig. 13. Mealy endosperm (Mondur 1091) at 10.0% water content (a) showing the crushing zone when compared to non-crushed zone at same water content (b). With higher water content (17.5%) the crushing zone is important (c); uncrushed zone at 17.5% water content (d).
Same abbreviations as figure 12.

Vitreous grains that favoured the lateral crushing (fig. 11 a). The increase in water content from 10.0 to 16.7% did not change the fracture pattern of the mealy grain, the grain only becoming flat (fig. 11 b).

Behaviour of wheat grain bran under compression. Compression applied to wheat grains at 13.8% water content caused detachment between the bran and the rest of the grain. This detachment was observed both in the vitreous variety, Agathe 1023 (figs. 12 a, b), and in the mealy one, Mondur 1091, particularly at the level of cross cells (figs. 12 c, d). This detachment is limited to the crushing zone. At high water content (17.5%), bran detachment was not observed.

Compression influenced on wheat grain as a function of water content. Crushing the mealy grain Mondur 1091, produced disruptions in the endosperm. The appearance of the endosperm after crushing differed depending on grain water content. At low water content (10.0%), the structure of the crushed zone was totally disrupted (fig. 13 a). Compared to the undamaged zone (fig. 13 b) the crushed zone was not very deep. At higher water content (17.5%) the crushing zone was more extensive (figs. 13 c, d). Under compression, at the same water content, the vitreous grains such as Agathe 1023 behaved differently than the mealy grains such as Mondur 1091. Comparing the two
Fig. 14. Vitreous endosperm (Agathe 1023) at 10.0% water content (a), showing the very limited crushing zone compared with the intact zone (b). At 17.5% water content the crushed zone increased considerably (c); uncrushed endosperm grain (d). Same abbreviations as figure 12.

Photomicrographs a and b (fig. 14) representing Agathe 1023 at 10.0% water content, one observed that the crushed zone was limited to the aleurone layer, this limitation being caused by the low water content. However, at higher water content (17.5%) the crushed zone was larger (figs. 14 c, d).

Relation between endosperm crushing and vitreosity

Investigations of Agathe 3002, vitreous endosperm, outside the crushed zone showed that the first fissures occurred at the intercellular boundary (fig. 15 a). Similar data were observed in the other vitreous varieties such as Agathe 1023 (fig. 15 b). Therefore, cell walls play an essential role during wheat grain crushing. This is in accordance with the report of Moss et al. (1980) that the cell constituents (starch and protein) of vitreous wheats are very compact and the zones of weakness in the grain are the intercellular boundary. With increasing compression inter-cellular fissures spread within the cells. The mealy endosperm showed a totally different fracture aspect than that observed in the
Fig. 15. Vitreous endosperm (Agathe 3002) at 17.5% water content, showing fractures at cell walls level; b) vitreous sub-aleurone (Agathe 1023) at 17.5% water content, showing inter cellular fractures; c) mealy endosperm (Agathe 1093) at 17.5% water content, showing fractures at the level of the proteic matrix; d) mealy endosperm (Mondur 1091) at 17.5% water content, showing air spaces and non compact structure.

Same abbreviations as figure 12.
mealy and vitreous endosperms. The air spaces in the endosperm of mealy grains result in a more open structure, and make the grain behaviour less of 1 oad-deformat ion curves have shown that more than is the case for vitreous grains where the endosperm to mealy endosperm due to the expansion cation favours the transformation of vitreous makes the endosperm destruction easier. The number of air spaces. Grain humidification of the protein matrix and starch which increases physical structure is more compact. Humidifi­
cations control; 


**Conclusion**

At the same water content, the apparent modulus of elasticity of vitreous grains is greater than that of mealy grains. This appears to be related to the difference in the texture of mealy and vitreous endosperms. The air spaces in the endosperm of mealy grains result in a more open structure, and make the grain behaviour less elastic. The load initially expells the air from the grain structure, therefore, slopes and aspect of load-deformation curves have shown that more time is necessary for compression of mealy grains than is the case for vitreous grains where the physical structure is more compact. Humidification favours the transformation of vitreous endosperm to mealy endosperm due to the expansion of the protein matrix and starch which increases the number of air spaces. Grain humidification makes the endosperm destruction easier.

**References**


**Acknowledgments**

The authors thank Drs J. Abecassis and P. Feillet (INRA, Montpellier) for sample availability and Drs J.L. Doublier and J.P. Melcion (INRA, Nantes) for helpful advice and assistance throughout the rheological study. Gratitude is expressed to Mrs. Martine Chapeau for typing this paper.

**Discussion with Reviewers**

P. Resmini: Can the authors give additional information about the vitreosity determination by the "Pohl grain cutter"?
Authors: The "Pohl grain cutter", namely "Farinome de Pohl" is a hand device used for the vitreosity determination. This device is described by Mauze et al. (1972). It consists of a steel undermatrix supplied with 50 seed-holes where the seeds are placed vertically, and an overmatrix. Then the seeds are pressed between the two matrices, and a cutter is slid in a special slit in order to cut the seeds into two parts. The 50 half-parts of the seeds remaining on the undermatrix are viewed and mealy, vitreous and intermediate grains are counted. This operation is done 6 times for each sample. Percentages are calculated from the cumulated data.

R. Moss: Fig. 12 c, the endosperm does not appear to be very vitreous when compared to other published photomicrographs. It would be helpful to readers comparing rheological data if the hardness of the grains tested was indicated using a standard method (e.g., particle size index or pearling resistance).
Authors: Our study was based on the vitreosity of wheat grain varieties and not on their hardness, which has not been measured.
The apparent modulus of elasticity gives an idea of the hardness of the seeds. But if we consider table 3 where the varieties are ranged decreasingly in function of the vitreosity, data of mean apparent modulus of elasticity do not follow the same pattern, probably because the rate of intermediate grains is more important in the case of Agathe 1093.

We agree that it should be interesting to compare hardness to vitreosity. To our knowledge such a comparison has not yet been published.

R. Moss: A comparison of the endosperm at 10.0-17.7% water content would be interesting (only 17.5% shown in fig. 15 a) and the air spaces are not very apparent.

P. Resmini: Fig. 15. The air spaces are very difficult to recognize.

Authors: Airspace recognition needs some enlargement to see more details. That has been done under the microscope but was not possible to show in these pictures taken at lower magnification to show general features. Air spaces are similar to those already published elsewhere (Moss et al., 1980).

R. Moss: The crushed zone (fig. 15 a) in the endosperm is not clearly distinguishable from the remaining endosperm.

Authors: In comparison to non-crushed (fig. 13 b), peripheral part (aleurone layer) of crushed seeds is totally collapsed so that its apparent structure seems lost. In fact, it is condensed into a very thin layer by crushing.

P. Resmini: The authors should give information about the methods used for their statistical calculations. Is the tested difference significant from a statistical stand point?

Authors: The statistical method was the two way analysis of variance (Snedecor GW, Cochran WG. (1967). Statistical methods (6th ed.) The Iowa State University Press (ed), Ames, Iowa, chapter 11) and was performed using the Hewlett Packard 9825 A Calculator. The tested difference is significant P(0.5%) varying from 1.6 to 1.8.

P. Resmini: Can the authors give some explanation for the phenomenon by which the number of air spaces increases? Is it perhaps due to protein shrinkage?

Authors: During hydration, same physical competition between proteins and starch occurs as described by Resmini and Pagani (1983) in pasta cooking. In our case, differences are the very low moisture and low temperature: starch cannot swell nor protein coagulate.

At room temperature and in saturated water, affinity for water by starch is about 40% (diameter increase of starch granule is 15%) and affinity by protein is about 150%.

In our case, at room temperature and low moisture, although the starch percentage is volumetrically higher (80%) than proteins (12%), competition for water must be overcome by the proteins of the seed. Thus, we think that, under low hydration proteins must swell and not shrink.