

A Rapid General Method for Appraising the Rheological Properties of the Starchy Endosperm of Cereal Grains¹

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ABSTRACT

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A rapid, simple method was developed to prepare small, parallel-epipedal test samples of endosperm of wheat, corn, and rice grains. Compression tests performed on endosperm samples revealed the following mechanical properties: modulus of elasticity (E , GPa), breaking stress (σ_{rup} , MPa), and maximum breaking strain (ϵ_{rup} , %). All tests were performed on several endosperm test samples of each cereal species. The results displayed good repeatability and several significant differences in

the mechanical behavior of different endosperm structures, especially among soft, hard, and durum wheats. Rice and corn endosperm displayed mechanical behavior similar to that of durum wheat endosperm. The method proposed appears to be sufficiently sensitive and repeatable for studying the incidence of hardness and vitreousness of cereal grain endosperm in relation to its suitability for milling.

The complex geometric shapes of wheat grains and the presence of a deep crease have complicated the study of their mechanical and rheological properties. The most frequently used method is based on Hertz's theory (Kozma and Cunningham 1962) and describes the contact stresses between convex bodies subjected to pure compression.

Schpolanskaya (1952) first applied the method to wheat grain and was able to develop a rheological model. Neither the geometric form of the grain nor its position beneath the rheometer were taken into account in this preliminary work. Arnold and Roberts (1965) refined the model by incorporating the curve radii at the contact points of a wheat grain placed beneath the rheometer in its two natural, stable positions. They obtained an equation that gave the modulus of elasticity of the wheat grain. Kozma and Cunningham (1962) reexamined Hertz's equations in detail and obtained a more rigorous value for the modulus of elasticity that was subsequently adapted by Shelef and Mohsenin (1967) for studying wheat grain subjected to pure compression. The method was taken up by several authors (Al Saleh and Gallant 1985, Multon et al 1981) and used to study the conditioning of wheat grains before milling and the effect of moisture content on the mechanical properties and texture of the kernel.

In spite of successive improvements, the methods based on Hertz's theory (Kozma and Cunningham 1962) all have problems. Indeed, it is really the whole structure of the wheat grain (integuments, crease, germ, endosperm, etc.) that is examined, not its constituent materials. Any variability in the form of the grain or the properties of its envelopes introduces errors in the measurement of the rheological characteristics of the endosperm. In addition, Hertz's theory includes the hypothesis of elastic behavior and cannot be extended to the study of more complex behaviors.

To overcome these problems, Glenn et al (1991) developed a method for machining wheat grains to prepare small cylindrical test samples of endosperm (1×3 mm) for use in studying compressive and tensile behaviors. Glenn et al (1991) found a good correlation between the mechanical properties of endosperm and the hardness of different American wheat cultivars. Nevertheless, the machining method seems difficult to use and does not appear to be suitable for use with other types of cereal grains.

The objectives of this study were 1) to develop a method for machining endosperm test samples that is easy to use and can be applied to different types of cereals and 2) to apply the method to plot stress-strain curves for the endosperm of different cereals (wheat, corn, and rice) and deduce the mechanical characteristics of the kernels of these cereals.

MATERIALS AND METHODS

Raw Materials

Two common wheats, one soft (*Triticum aestivum* cv. Scipion) and one hard (*T. aestivum* cv. Baroudeur), a durum wheat (*T. durum* cv. Ardente), a flint corn (cv. Monarque), and a rice (cv. Thaï-bonet) were used in the study. The soft common wheat cultivar

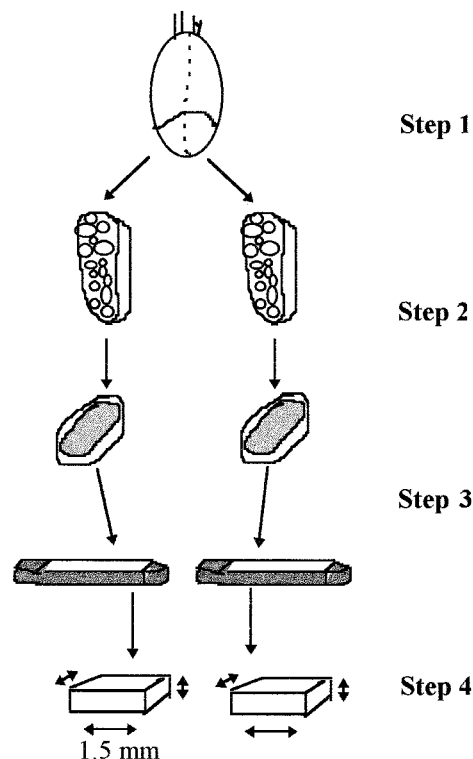


Fig. 1. Different machining steps of wheat grains to produce two parallel-epipedal test samples of the same size. Step 1: grain is cut into two symmetrical parts in relation to the crease. Step 2: Machining the lateral face containing the crease and the opposite face. Step 3: Machining the dorsal and ventral faces of the grain. Step 4: Machining the extremities of the grain into test samples ($0.6 \times 1.5 \times 1.1$ mm).

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consisted of entirely mealy grains. Most of the kernels from the hard common wheat cultivar were both mealy and vitreous, but some of the kernels were entirely mealy or vitreous. Mechanical measurements were made on the entirely mealy or vitreous kernels. The durum wheat cultivar consisted mainly of vitreous grains but also included mealy grains. Mechanical tests were performed on both types of grains. The corn endosperm test samples were prepared from the vitreous part of the endosperm, whereas the endosperm of the rice grains was entirely translucent.

Test Sample Machining Method

The main steps in the manufacture of test samples of grain endosperm are shown in Fig. 1. The rapid, simple machining methods developed are shown in Figs. 2 and 3. The test samples were parallelepipedal and had no trace of the crease. Two endosperm samples could be prepared from a single wheat grain, and 10 samples could be prepared in 30 min.

Corn test samples were prepared based on the same principle, except for step 1, in which fragments of translucent endosperm were cut. Rice endosperm test samples were prepared directly by stage 3 machining. The precise dimensions of the samples were measured with a caliper rule after machining. The samples used were 1.50 ± 0.05 mm long, 0.60 ± 0.05 mm thick, and 1.10 ± 0.05 mm wide (Figs. 4 and 5).

Measurement of Mechanical Properties

Compression tests were performed with static test apparatus (RHEO TA.XT2/25 SMS texture analyzer (Champlan, France) that can handle a 250 N load.

Endosperm test samples were placed directly beneath the rheometer on the 1.5 mm long \times 0.6 mm wide face. A strain rate of 0.1 mm/sec was set for the tests, and the data capture rate was 200 points per second. Samples were placed under controlled temperatures (25°C) and equilibrated in a glass desiccator containing a salt solution of sodium dichromate (65% rh) for six days to allow the water content to stabilize at 12.5% ($\pm 0.5\%$) before measuring mechanical properties.

RESULTS AND DISCUSSION

Compression tests were performed on several endosperm samples of each cereal type. The stress (megapascals) according to sample strain (percent) was plotted as a curve in each test. The stress-strain

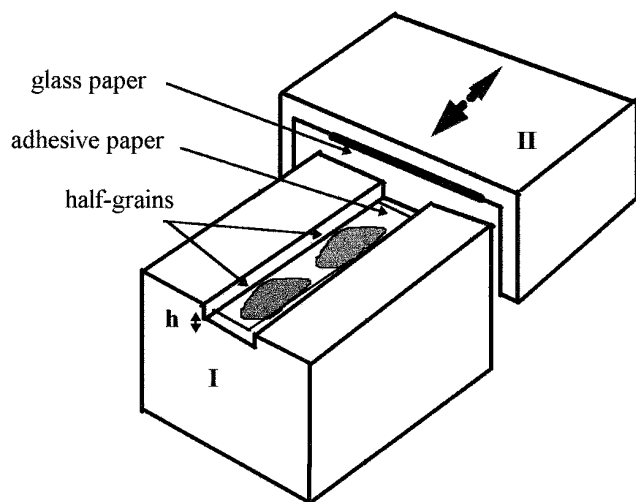


Fig. 2. Step 2 (Fig. 1). Two halves of a grain fixed to adhesive paper placed in the groove of part I (height [h] = 1.7 mm). Alternative movement of part II machines the curve faces of the half-grains by abrasion. The half-grains are turned over and glued in part I (h = 1.2 mm). Two parallel faces are obtained.

curves plotted during the compression of endosperm samples of the wheat cultivars studied are shown in Fig. 6A (soft), B (hard mealy), and C (hard vitreous).

Whatever the nature of the grain tested, similar curves were obtained that displayed an almost linear part related to elastic behavior characterized by modulus of elasticity (E, GPa). Elastic behavior was followed by fracture with or without a plastic stage. Failure stress (σ_{rup} , MPa) and maximum failure strain (ϵ_{rup} , %) represent the extremes of each curve. These figures displayed good test reproducibility in spite of the natural variability of the material. The numerical values of E, σ_{rup} , and ϵ_{rup} for cv. Scipion endosperm are shown in Table I. The coefficient of variation for the measurements was $\approx 15\%$ for the three characteristics measured, and the confidence interval ($\alpha = 0.05$) was 0.25 ± 0.03 GPa for E, 13.3 ± 1.4 MPa for σ_{rup} , and $5.5 \pm 0.08\%$ for ϵ_{rup} . Given the accuracy of the measurements, precise values can be assigned to the average values of E, ϵ_{rup} , and σ_{rup} shown in Table II. Also, the average curves shown in Fig. 7 can be considered as representative of the average rheological behavior of the cereals studied.

One of the observations that can be made from viewing Table II and Fig. 7 is that there is a very distinct separation in the behavior of the grains of various cereals, as shown by a broad range of mechanical characteristics: 0.30–1.10 GPa for E, 10–90 MPa for σ_{rup} , and 4–25% for ϵ_{rup} . The results of Glenn et al (1991) show a range of 0.60 to 2.0 GPa for E, 11 to 70 MPa for σ_{rup} , and 3 to 18% for ϵ_{rup} . However, Glenn et al (1991) worked on American wheat cultivars that differed from those used in this study, and they did not distinguish the vitreous from the mealy endosperm.

Very strong mechanical property sensitivities to vitreousness also were recorded for the same wheat cultivar. The Young's modulus doubled between soft and hard wheats, and the failure stress tripled between mealy and vitreous wheats.

Beyond the numerical values, distinctions can be made between two types of behavior shown in Fig. 7. The first type of behavior was displayed by soft common wheat, hard mealy common, vitreous hard common, and mealy durum, which did not display a plastic stage. This is the behavior of heterogeneous material that fractures because of failures in the links between its different components. The second type of behavior was displayed by vitreous durum wheat, corn, and, to a certain extent, rice, which displayed a plastic stage. Strain before failure is considerable and can attain 25%. This curve pattern should be compared to the behavior of similar homogeneous material. In this case, the failure stresses were much higher and were similar in the three cereals.

The differences observed should be related to how the grain will be used. The plastic stage probably should be related to the suitability of the grain for substantial strain, such as the strain of manufacturing certain foodstuffs (e.g., corn flakes) or for better dehulling. However, differences can be seen between wheat grains without questioning of differences among soft, hard, and durum wheats, although the nonnegligible effect of the vitreousness of the grains on their mechanical properties is stressed.

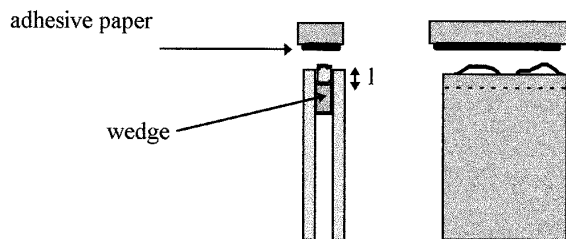


Fig. 3. Step 3 (Fig. 1). Two machined half-grains are placed between two sheets, and a wedge is set at height l of the extremities of the sheets. Dorsal face of the grains and then the ventral faces are machined by adjusting the height between the sheets. Step 4 (Fig. 1). Machining the last faces (germ and hairs) produces two parallelepipedal test samples with the same dimensions.



Fig. 4. Steps 2–4 (Fig. 1). Manufacture of test samples of mealy and vitreous endosperm: after step 2 (left), after step 3 (center), after step 4 (right).



Fig. 5. Two test samples from a mealy grain.

TABLE I
Repeatability of Measurements of the Mechanical Properties of Test Samples of Wheat (cv. Scipion) Endosperm

Test	E (GPa) ^a	σ_{rup} (MPa) ^b	ϵ_{rup} (%) ^c
1	0.25	13.6	5.2
2	0.26	15.4	4.7
3	0.23	12.5	6.6
4	0.19	11.4	5.6
5	0.22	12.3	7.1
6	0.21	11.4	5.4
7	0.29	15.4	5.0
8	0.31	14.7	4.1
Average	0.25	13.3	5.5
Standard deviation	0.04	1.7	1.0

^a Modulus of elasticity.
^b Breaking stress.
^c Maximum breaking strain.

TABLE II
Average Values of the Mechanical Characteristics of Starchy Endosperm of Cereal Grains (12% moisture content)

Cereal	E (GPa) ^a	σ_{rup} (MPa) ^b	ϵ_{rup} (%) ^c
Wheat ^d			
cv. Scipion	0.25 ± 0.04	13.3 ± 1.7	5.5 ± 1
cv. Baroudeur			
Vitreous	0.79 ± 0.11	48.0 ± 6.71	10.8 ± 2.54
Mealy	0.42 ± 0.07	16.5 ± 2.32	5.7 ± 0.4
Durum			
Vitreous	0.93 ± 0.15	72.8 ± 10.1	24.3 ± 6.6
Mealy	0.38 ± 0.09	23.3 ± 1.56	9.5 ± 3.6
Corn			
Flint corn	0.97 ± 0.21	82.5 ± 9.8	24.8 ± 5.94
Rice			
cv. Thaïbonet	1.10 ± 0.24	89.4 ± 6.1	19.9 ± 4.15

^a Modulus of elasticity.
^b Breaking stress.
^c Maximum breaking strain.
^d *Triticum aestivum*.

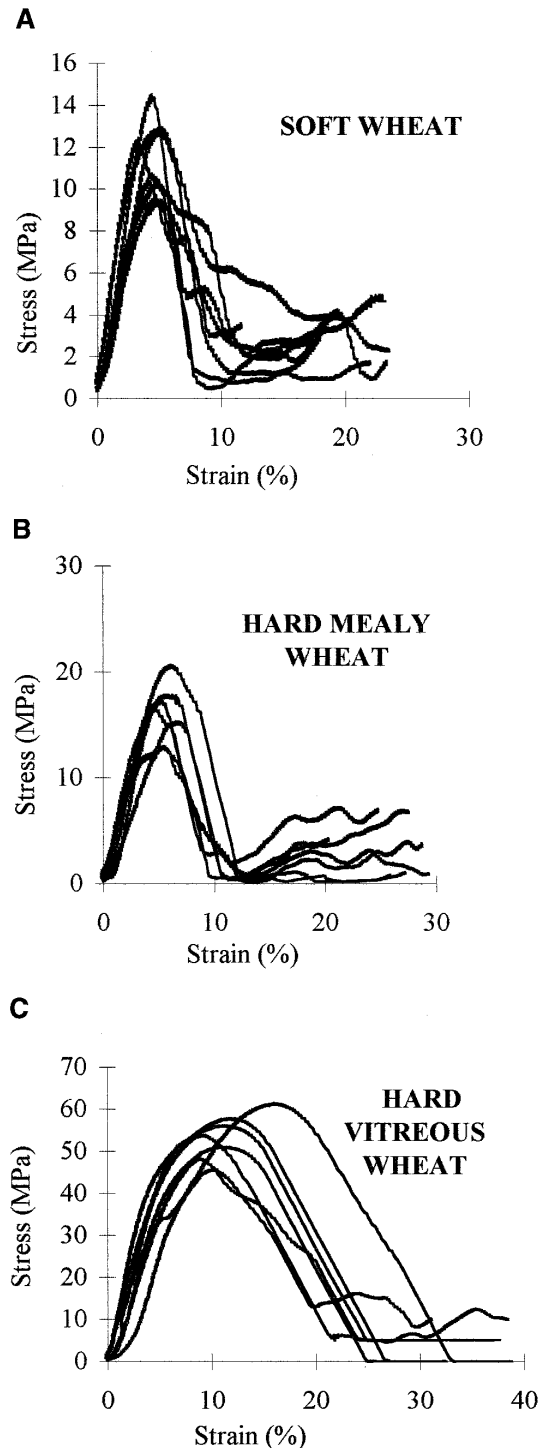


Fig. 6. Stress-strain curves of compression (to failure) tests on several samples of starchy endosperm of soft common wheat (A); hard mealy common wheat (B); and hard vitreous common wheat (C).

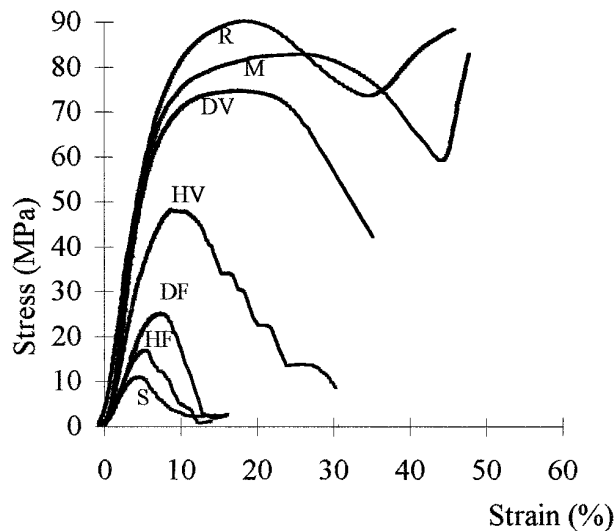


Fig. 7. Average stress-strain curves of starchy endosperm of soft common wheat (S); hard mealy common wheat (HF); mealy durum wheat (DF); hard vitreous common wheat (HV); vitreous durum wheat (DV); flint corn (M); and rice (R).

CONCLUSION

The machining method developed here seems to be well suited to preparation of endosperm samples of all types of cereals and probably of other grains as well. The method is quick and simple and requires only inexpensive, easily transported apparatus, which should make it possible to perform rheological tests at various stages between harvesting and milling for the best possible adjustments of postharvest treatment parameters.

For the mechanical tests performed, measurement repeatability was satisfactory. The mechanical tests made it possible to show characteristic features, such as failure stress, elongation at rupture, and modulus of elasticity of the endosperm of various cereal grains. The tests revealed standard rheological behaviors that should be interpreted in terms of microstructure and bonding between starch grains and protein matrix.

The proposed method has potential as a new means of studying the mechanical properties of grains with regard to objective appraisal of the milling value of the grains and optimization of milling processes.

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