

Mechanical Properties of Wheat Seed Coats

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ABSTRACT

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The crumbliness of starchy endosperm and the resistance of bran are key characteristics that enhance milling behavior of wheat and are dependent on the genetic origin and moisture content of the grain. A method was developed to measure the mechanical properties of bran samples based on the measurement of tensile stress and strain. Tests conducted with this highly reproducible and sensitive method documented cultivar and moisture-content effects (6.3, 13.8, and 18%, wb) on rheological behavior of wheat seed coats.

A moisture-dependent reduction in stress to fracture (–15 to –30%) and in Young's modulus (–45 to –55%) was quantified. An increase in deformation to fracture of seed coats was also correlated with bran size differences after milling. The energy required to fracture a sample (from 0.4 to 1.3 J/mm³) was considered the most valid of all presented parameters for assessing the milling behavior of wheat seed coats and the size of bran fractions.

Millers attempt to optimize yield by retaining the coarsest possible bran fractions during grinding to facilitate endosperm separation, reduce speckiness, and stabilize the ash content of the flours produced. This latter property is often correlated with high milling efficiency (Lineback et al 1978). However, bran thickness or grain-size measurements (Abecassis 1993) cannot completely account for size differences between bran particles (Larkin et al 1951). Simmons and Meredith (1979) explained that bran geometry also has an impact on milling yield, thus highlighting the importance of accurately describing bran size and shape to understand its grinding behavior. Crewe and Jones (1951) noted that irregularities in the aleurone layer thickness promote adherence of endosperm fragments on bran particles. Willm (1995), in a study on milling behavior of French wheat cultivars, highlighted variability in these characteristics, especially in bran size, which was dependent on the genetic origins of the cultivars.

The mechanical properties of wheat seed coats have never been investigated in detail, despite the important technological implications. Glenn and Johnston (1992) published the only study to date, investigating the effects of several factors on the mechanical properties of wheat bran. They tested bran strips and found that bran is isotropic and that there are no differences in the mechanical properties of hard or soft wheat bran, but some differences among cultivars were noted. Increasing the moisture content made the bran more pliable and less resistant, but the energy required to break the sample was not altered by these moisture changes. There was, however, no follow-up to assess the effects of kernel morphology on the mechanical properties of wheat bran, or to compare the rheological characteristics with the milling behavior of different cultivars. This lack of further investigations could be explained by the fact that preparing and studying the mechanical properties of samples is very complicated and time-consuming.

The present study was aimed at developing a quicker sampling technique, requiring less equipment and adapted for serial testing of a high number of wheat samples. The effects of moisture content, strain rates, and cultivars on the mechanical properties of wheat seed coats such as stress, deformation, modulus of elasticity, and energy to fracture are described. The observed differences are discussed and compared with the milling behaviors of the cultivars.

MATERIALS AND METHODS

Mechanical properties were measured in three wheat (*Triticum aestivum*) batches of French cultivars. One hard wheat (cv. Baroudeur, PSI = 17.5, determined by Approved Method 55-30 [AACC

2000]) with an average milling yield; a medium-hard wheat (cv. Soissons, PSI = 20) with an excellent milling yield; and a soft wheat (cv. Scipion, PSI = 26) with a good milling yield were assessed. The hectoliter weights of these three cultivars (measured with a Nilema-litre, Tripette & Renaud, Villeneuve-la-Garenne, France), were close to and slightly higher than the mean weight of French cultivars (Baroudeur, 77.9 kg/hL; Scipion, 78.3 kg/hL; and Soissons, 77.9 kg/hL). Wheat grain batches were sampled according to the NF V 03-700 standard technique and kept in cold storage (4°C).

The samples were prepared with whole kernels that were soaked in distilled water for 2 hr (Scipion soft and Soissons medium hard) or 6 hr (Baroudeur hard) to soften the endosperm. The two tips of the wheat kernels were then cut with a scalpel (Fig. 1A) into a slice 3–4 mm thick. These kernel slices were then soaked in distilled water for 10 min, rinsed, and opened along the crease. The moist endosperm was readily removed with the dull edge of the scalpel (Fig. 1B), and the samples were recut to a thickness of 2.7 mm (± 0.7). The lengths (L) ranged from 7 to 10 mm, as measured with a micrometer. At 12% moisture content, the sample thickness, measured with a tintometer, was higher for Baroudeur (115 μm) compared with Scipion (87 μm) and Soissons (83 μm). The samples were sandwiched between two glass slides to dry for 24 hr under ambient relative humidity conditions. The two tips of the sample were then secured (cyanoacrylate adhesive) to two small pieces of plastic (polycarbonate crystal) to facilitate clamping and to remove slippage between grips during the tensile tests (Fig. 1C). By this method, ≈ 30 samples/day could be prepared.

The strips obtained by this procedure were not completely flat (Fig. 1). Due to the kernel shape, the diameter of the median zone was greater than that of the lateral zones; there was a difference of $\approx 8\%$ for kernels of average size and shape. Flattening the samples between two glass slides during drying blocks traction stress with-

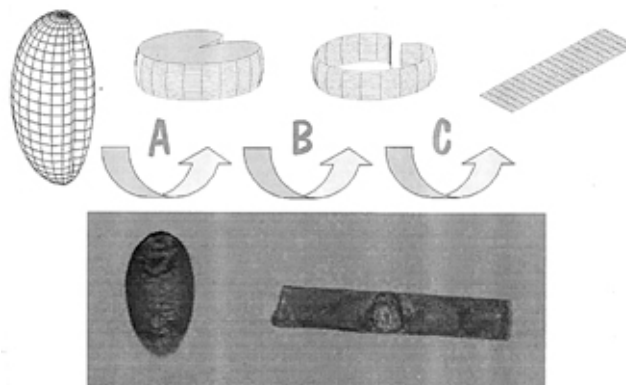


Fig. 1. Wheat seed coat sample preparation procedure, including a picture of a sample. A, tips cut; B, endosperm removed; and C, tips secured.

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in the fibres of the lateral parts of the sample. The samples can be moistened to enable partial release of this stress and recover the initial shape.

Wheat seed coats are made up of two overlapping tissue layers. On a kernel of average width, the external layer (pericarp) is $\approx 3\%$ longer than the internal layer (aleurone). This length difference is not uniform over the whole circumference; it is higher in areas where there is a local increase in curvature. It is hard to accurately define the stress and strain status of a sample before a tensile test because of the initial shape of the seed coat on wheat kernels.

Sample moisture levels (6.3, 13.8, and 18%, wb) were adjusted by conditioning at constant relative humidity (7, 52, and 75%) in saturated saline solutions (KOH, Na_2CrO_7 , and NaCl, respectively) for 60 hr at 25°C.

The mechanical properties were measured with a static tensile testing device (RHEO TA-XT2, Champlan, France), fitted with a 50N force cell (accuracy: 0.1 g, resolution: 2.5 μm). Each result represents a mean of eight replicate measurements, tested randomly. Samples were clamped between the protective pieces of plastic. When the rupture occurred near the protective pieces of plastic, the test

was removed and started again on another sample. (This kind of rupture represents $<10\%$ of the samples.) Tensile stress was measured at constant displacement rates of 0.01, 0.1, and 1 mm/sec. Moisture levels in the samples were not controlled during the tensile tests. We considered that there would be very little fluctuation because the sample setup was quick and easy and the tensile testing time was very short. Total testing times were ≈ 30 sec, 1 min, and 3 min for displacement rates of 1, 0.1, and 0.01 mm/sec, respectively.

Stress-strain curves were recorded for each trial. Several rheological parameters were measured and expressed per unit area: deformation to fracture, stress to fracture, energy to fracture, and Young's modulus. A graph of the characteristics measured to describe the mechanical behavior on a stress-strain chart is shown in Fig. 2. Deformation to fracture, $\epsilon = \Delta L/L$, represents the peak strain that a sample can sustain. Stress to fracture, σ , represents the peak sustainable force measured per unit area. Young's modulus, E , which is the initial maximum tangent proportionality stress-strain coefficient, highlights the stiffness of the sample. Finally, the energy to fracture, U , corresponds to the tensile strength and is expressed in fractured surface units.

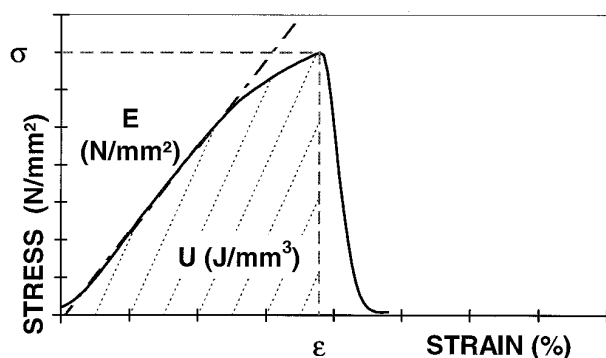


Fig. 2. Mechanical properties of wheat seed coat samples. E = Young's modulus; U = energy to fracture.

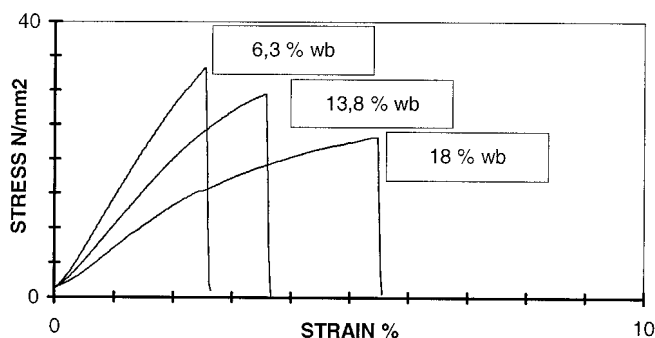


Fig. 3. Effects of Scipion sample moisture content on stress and deformation during tensile tests (0.10 mm/sec).

TABLE I
Mean Mechanical Characteristics of Wheat Seed Coats^a

| Cultivars, Moisture Content (%wb) | Strain Rate (mm/sec) | ϵ (%) | σ (N/mm ²) | E (N/mm ²) | U (J/mm ³) | |
|-----------------------------------|----------------------|----------------|-------------------------------|--------------------------|--------------------------|------------|
| Soissons | 6.3 | 0.01 | 3.1 (0.3) | 26 (2.4) | 940 (90) | 0.49 (0.1) |
| | | 0.10 | 4.0 (0.8) | 30 (3.5) | 930 (110) | 0.77 (0.2) |
| | | 1.00 | 3.9 (0.4) | 30 (1.4) | 990 (90) | 0.68 (0.1) |
| | 13.8 | 0.01 | 3.8 (0.2) | 26 (2.1) | 860 (90) | 0.58 (0.1) |
| | | 0.10 | 5.3 (0.5) | 25 (1.8) | 610 (120) | 0.79 (0.1) |
| | | 1.00 | 2.7 (0.4) | 28 (3.6) | 1,110 (130) | 0.56 (0.1) |
| | 18 | 0.01 | 6.2 (0.9) | 23 (2.8) | 510 (90) | 0.96 (0.2) |
| | | 0.10 | 6.1 (0.6) | 23 (2.0) | 500 (60) | 0.91 (0.1) |
| | | 1.00 | 6.2 (0.8) | 28 (3.2) | 590 (80) | 1.28 (0.3) |
| Scipion | 6.3 | 0.01 | 3.3 (0.5) | 33 (4.7) | 1,150 (170) | 0.63 (0.2) |
| | | 0.10 | 2.3 (0.5) | 31 (4.7) | 1,390 (120) | 0.42 (0.2) |
| | | 1.00 | 3.1 (0.6) | 32 (3.8) | 1,130 (60) | 0.67 (0.1) |
| | 13.8 | 0.01 | 4.2 (0.6) | 27 (3.2) | 960 (130) | 0.77 (0.2) |
| | | 0.10 | 4.1 (0.6) | 30 (3.3) | 1,050 (210) | 0.77 (0.2) |
| | | 1.00 | 3.2 (0.4) | 26 (1.9) | 960 (90) | 0.60 (0.1) |
| | 18 | 0.01 | 6.8 (1.0) | 17 (1.8) | 330 (140) | 0.76 (0.1) |
| | | 0.10 | 5.3 (0.7) | 23 (3.2) | 650 (120) | 0.84 (0.2) |
| | | 1.00 | 4.9 (1.2) | 26 (2.7) | 800 (120) | 0.90 (0.3) |
| Baroudeur | 6.3 | 0.01 | 3.1 (0.5) | 23 (2.6) | 800 (90) | 0.42 (0.1) |
| | | 0.10 | 3.7 (0.4) | 25 (4.0) | 830 (110) | 0.57 (0.1) |
| | | 1.00 | 2.1 (0.5) | 20 (3.8) | 1,010 (140) | 0.31 (0.1) |
| | 13.8 | 0.01 | 2.7 (0.9) | 22 (4.5) | 940 (110) | 0.49 (0.2) |
| | | 0.10 | 4.6 (0.6) | 20 (2.0) | 530 (60) | 0.62 (0.2) |
| | | 1.00 | 3.7 (0.4) | 22 (2.9) | 660 (50) | 0.57 (0.1) |
| | 18 | 0.01 | 7.6 (1.1) | 17 (1.5) | 330 (80) | 0.89 (0.2) |
| | | 0.10 | 4.3 (1.1) | 15 (1.7) | 440 (70) | 0.47 (0.1) |
| | | 1.00 | 5.9 (0.9) | 18 (1.4) | 450 (100) | 0.81 (0.2) |

^a ϵ = deformation to fracture, σ = stress to fracture, E = Young's modulus, and U = energy to fracture. $n = 8$. Standard deviations in parentheses.

The results were assessed by variance analysis using the Statgraphics software package (Manugistics, Rockville, MD).

Measurement of Mechanical Properties

There was high homogeneity in all of the tests, with an overwhelming linear behavior of the samples under stress, and brittle fractures noted in >90% of cases. Parameters measured for the three cultivars in the tensile tests (deformation to fracture, stress to fracture, energy to fracture, and Young's modulus) are given in Table I. The measurement reproducibility was satisfactory. The variation coefficient for each measured parameter was $\approx 10\%$, which is in line with rheological tests performed on biological material.

The stress to fracture results (≈ 20 Mpa) were comparable to those obtained by Glenn and Johnston (1992). However, our strain results were fourfold lower than their results. This was shown by differences in the Young's modulus and energy to fracture results. Even though the samples analyzed were of different origins, the differences in the results between the two studies could not be solely attributed to physical characteristics of the wheat batches. Differences likely were also due to other factors such as the

geometry of the samples or conditioning during the test. Samples obtained for our study were twice as wide, therefore kernel morphology had a greater impact.

The effects of deformation rates on the mechanical characteristics are shown in Table I. They had very little effect, whereas the deformation rate varied by 100-fold. Energy to fracture was not markedly affected by the deformation rate, and stress to fracture was only slightly altered (+3%). The increase in Young's modulus (Soissons at 13.8%, wb; Scipion at 18%, wb) at low deformation rates is hard to explain.

The proposed method is sensitive enough to highlight the effects of moisture content on the mechanical properties of seed coats (Fig. 3). Increased moisture prompted an increase in deformation to fracture (70–100%) but a drop in stress to fracture (–15 to –30%) and in the Young's modulus (–45 to –55%). The deformation and Young's modulus results for each cultivar are shown in Fig. 4, as well as the cultivar trends relative to the overall results as a function of moisture content and batch effects. These graphs clearly indicate that the greatest modifications in the mechanical properties occurred between 13.8 and 18%, wb. Similar to the deformation to fracture patterns, energy to fracture in the samples increased with the moisture content. However, this increase was not as marked as the deformation patterns because it also was influenced by the decrease in peak strain.

With respect to the origins of the wheat cultivars, this method distinguished between the three batches studied with a 90% confidence index. The variance analysis revealed that Baroudeur had lower stress to fracture and stiffness, whereas Scipion and Soissons showed no significant differences. In Soissons, energy to fracture was significantly higher ($P < 0.01$) than levels in Baroudeur and Scipion, but no significant differences were noted when the latter cultivars were compared. Energy to fracture depends on both the stress to

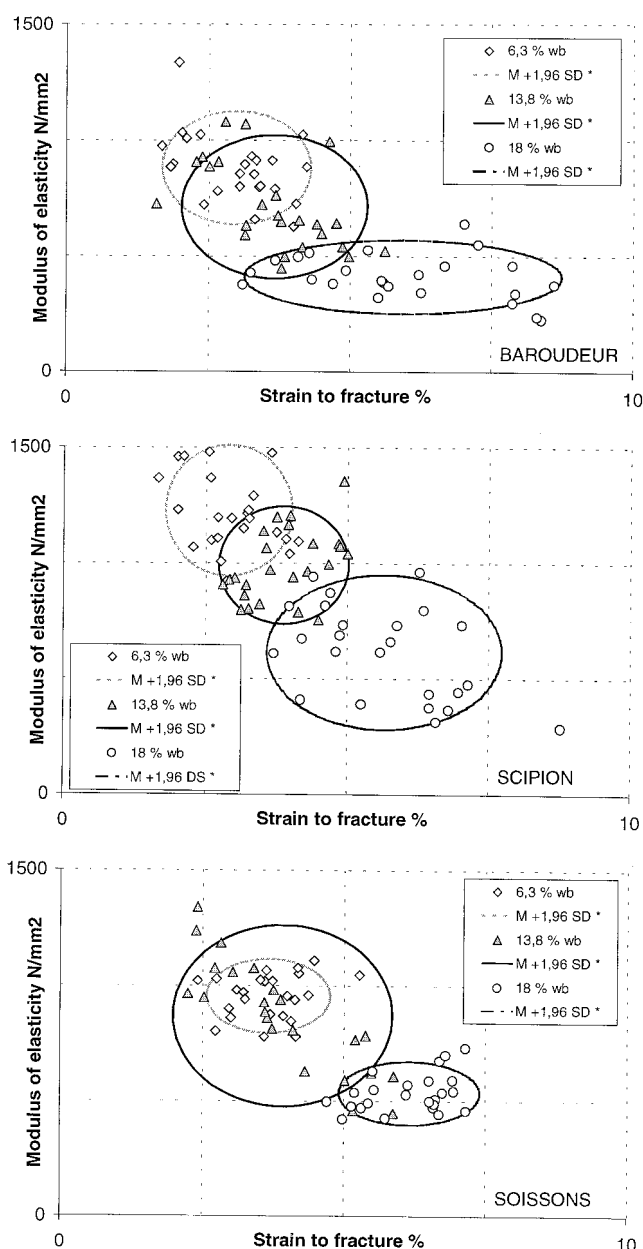


Fig. 4. Effects of moisture content on reduction of Young's modulus in three wheat cultivars.

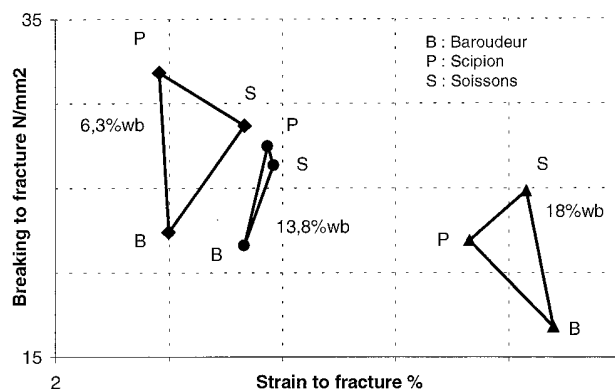


Fig. 5. Modification of deformation and stress to fracture in relation to moisture content for three wheat cultivars. Half-lengths of the ellipse axes are 1.96 the standard deviation and intersect at the mean modulus and at the mean strain of the batch.

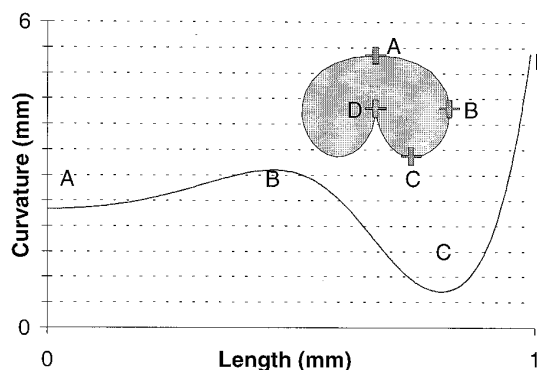


Fig. 6. Curvature of median section of a wheat kernel.

fracture and deformation to fracture. This parameter can, therefore, reflect general trends in the mechanical behavior of wheat seed coats.

DISCUSSION

Bran is simply a composite bilayer material, with the aleurone layer as support coated with a pericarp film. When samples are dried flat, tension zones are created in the aleurone layer and compression zones on pericarp surface. During rheological tests, tensile stress is only exerted in areas of the pericarp where it adheres to the aleurone layer, and nonadherent areas are not initially affected. This factor complicates modeling of rheological behavior. By our proposed method, milling behaviors can be interpreted and compared with respect to the cultivar or moisture content.

The thickness of the seed coat, which includes cell cavities, is not representative of the volume of tissues stressed during tensile tests. The mechanical characteristics of different seed coats could be compared by expressing them in terms of width units, without taking thickness into account. Otherwise, these properties could be expressed as strength, stiffness, and energy per unit length. Unit length variables correspond to the overall characteristics of the tested material. They are probably more suitable for describing bran behavior during break grinding.

The unit length strength to fracture results of the samples seemed almost identical for the three cultivars (between 1.7 N/mm at 6%, wb and 2.8 N/mm at 18%, wb). The same trend was noted for unit length stiffness (between 45 N/mm at 6%, wb and 107 N/mm at 18%, wb). A comparison of unit length and unit surface moduli revealed equilibrium between the intrinsic mechanical properties of seed coats and the thickness of these tissues, indicating that these three cultivars have equivalent seed coat stiffness and resistance. This equivalence in the unit length properties of seed coats could be attributed to differences in cell sizes and, thus, to the constant volume of cell walls stressed during the tensile tests. A histological analysis of the organization and structure of seed coat cell walls in the three cultivars would be necessary to confirm this hypothesis.

It would be hard to accurately highlight genotype effects by investigating single batches for each cultivar, irrespective of the cropping year, site, or conditions. In this study the results are discussed in terms of batch effects, not cultivar effects, to account for differences noted among Baroudeur, Scipion, and Soissons.

The mean stress to fracture and deformation to fracture results for the three batches and moisture contents are shown in Fig. 5. It clearly shows the variations in these two characteristics in relation to seed coat moisture contents, along with between-batch differences in these characteristics.

These mechanical tests give important information on the mechanical behavior of seed coats, even when they are performed at 100-fold lower deformation rates than occur during break grinding.

Generally, mixtures of wheat cultivars are processed in flour mills, with very little adjustment of mill rolls to adapt to specific characteristics of grain to be milled. Indeed, apart from the initial break process involving intact wheat kernels, it could be considered that the stresses and moisture contents (16–16.5%, wb) are almost identical for all wheat cultivars in subsequent milling phases. Thus, the size of bran particles is dictated by the mechanical properties of seed coats. The batch classification drawn up in this study on the basis of seed coat mechanical properties is in line with the milling test results of Willm (1995) obtained with single wheat cultivars under controlled conditions. In milling, Soissons produced >6.5% coarse bran, whereas Baroudeur produced only 4%. In mechanical trials, the Soissons batch had more pliable seed coats, with a higher energy to fracture level.

This agreement with the results of Willm's milling tests demonstrates that, for the batches studied, seed coat mechanical property measurements, as proposed in the present study, could be used to

predict the size of bran particles, despite the fact that our test is conducted at low strain rates under uniaxial tensile conditions and therefore is not representative of the complexity and severity of stresses involved in break grinding operations.

Wheat kernels do not have a flat hull and each peripheral zone on this surface can be characterized by local curvature (Fig. 6). For an average-sized kernel, the curvature ranges from 0.5 mm around the apical ends to 4 mm in the middle of the hull. This curvature gives the tridimensional shape of the bran particle and determines where deformations will occur in highly stressed zones. A simplified simulation can be made to calculate bran size by considering spherical bran caps of radius equal to the radii of the curvatures of apical and median parts of the kernel. For a given deformation, this calculation involves determining the maximum area that bran caps can possess without shearing when flattened as a disk. For 4% deformation, corresponding to 13% moisture content, the area of bran particles obtained ranges from 0.2 to 12 mm². At a bran moisture content of 6.3%, wb, there is 3% deformation to fracture and the particle areas decrease (0.14–8.8 mm²). Conversely, at a bran moisture content of 18%, wb, deformation to fracture increases to 7% and the bran particle areas are 0.3–20 mm². Thus, bran size depends on the kernel morphology and on the mechanical properties and deformability of the bran.

Differences in the mechanical properties of seed coats unfortunately cannot fully explain differences in flour milling yields when comparing Scipion and Baroudeur. These differences also certainly depend on the endosperm texture (i.e., seed coats still adhering to the endosperm will be fractured during break grinding). As pointed out by Butcher (1973), millers' decisions on the extent of kernel moisture conditioning are based on a trade-off between reducing endosperm crumbliness and increasing seed coat deformability. In the light of recent studies to assess the mechanical properties of endosperm (Haddad 1998), it is now possible to measure the mechanical properties of endosperm and seed coats. Together, these two measurements should facilitate wheat milling quality assessment and determining valid mechanical criteria for making cultivar choices and improving milling processes.

CONCLUSIONS

Wheat grain shape and size affect the mechanical properties of seed coats during tensile tests. These factors also have an impact on milling yield; they determine the ratio between the endosperm volume and the seed coat area. The presence of highly curved zones complicates separation of the seed coat from the endosperm. An accurate description of wheat kernel morphology could use geometrical curvature of samples on mechanical models of wheat bran to explain seed coats fractionation.

Tensile testing of wheat seed coat strips is a simple method to characterize compression stress applied to grain during grinding between two mill rolls, but the method proposed in this study also is quite easy to implement, and sensitive and accurate enough to document differences in mechanical properties.

These results, associated with the measurements of the endosperm characteristics, constitute the essential technological properties for the achievement of a mechanical model to understand the differences among wheat cultivars in grinding behavior. Widening the application of these tests to include different cultivars and cropping conditions could provide a complementary approach for assessing wheat milling quality. Nevertheless, these assessments should be supplemented with histological analyses of seed coat structure and composition.

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