Chapter 2

Mechanical Properties in Wheat (*Triticum aestivum*) Kernels Evaluated by Compression Tests: A Review

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Abstract

To assess the quality of food grains, it is necessary to consider the following two aspects: their general characteristics and their intrinsic quality. Analyzing the quality of wheat kernels is complex due to the particularity of wheat proteins and the diversity of products that can be developed. In contrast, basic factors are used to assess quality aspects, with a focus on kernel hardness. This parameter is usually measured by the force that is required to make the grain rupture. The application of force must be controlled, and hence, the grain will exhibit other mechanical attributes and behavioral characteristics that can be used to evaluate it more objectively. This has led to the development of nondestructive evaluation methods based on the mechanical properties of kernels. This review carried out research on grain wheat, in which the main objective was to evaluate mechanical properties, including the viscoelasticity of the wheat kernels, by using compression tests. The study examined different methods of applying those techniques and the parameters they evaluated. Finally, the results obtained by the different investigation groups that applied the compression tests on wheat kernels were discussed.

Keywords: wheat kernels, mechanical properties, viscoelasticity, compression, hardness

1. Introduction

Wheat is one of the cereals with the highest production worldwide, occupying the second place after rice, with an annual production of 600 million tons per year, almost 70% of which is used by the food industry [1–3]. *Triticum aestivum* (genetically hexaploid) is distinguished from other species in commercial terms and includes two grain categories, that is, soft and hard, that are both destined for the production of flours used in the preparation of bakery products. In contrast, *Triticum durum* (genetically tetraploid) is used to obtain semolina to produce pastas [4].

The commercial value of wheat is characterized by its unique property to form dough. This attribute basically depends on the structure and interaction between the storage proteins of the grain and the gluten fraction, which gives this grain an advantage over other cereals [2]. The industrial quality of wheat is evaluated mainly by the physical, chemical and rheological parameters related to its milling and bakery properties [5].

The latter conducted several investigations that focused on developing methods and evaluation techniques to increase the efficiency of the selection, processing, merchandising and end use of grains [6]. The study of the mechanical properties of wheat grains offers acceptable quality criteria during the milling process, specifically the conditioning parameters, the optimization of energy consumption and the quality of the produced flour.

The mechanical properties as "those related with the behavior of the material under the application of forces" [7], which are linked to the structure, physical state and rheological properties of solid and semisolid materials, which are, in turn, also related to the stress and strain parameters [8, 9]. The study of the mechanical properties of biological materials is complicated and is more complex when these properties are determined in kernels that have small dimensions or elaborate geometric shapes [10], materials that possess a heterogenic nature or those that exhibit viscoelastic behavior [11].

The evaluation of mechanical properties is carried out by using uniaxial compression tests, which require a deformation of the material that may or may not be permanent. Specifically for wheat kernels, the most important properties are the fracture strength and hardness, and both parameters are highly correlated with yield calculations and milling efficiency [12]. By applying tests to evaluate the fundamental mechanical properties of a material, it is possible to clarify more detailed aspects about the material that are not necessarily dependent on the sample geometry, loading conditions, or equipment used during the evaluation [13].

The aim of this chapter is to review the studies that have evaluated the advantages and disadvantages of the mechanical properties of intact wheat kernels by using compression tests and their relations to some aspects of quality.

2. Mechanical properties and compression tests on grains

The analyses performed on intact kernels represent a nondestructive, rapid, objective and complementary evaluation alternative to other methods. This method generates interesting information about the original state of raw materials and the possible functionality of the product [14]. The compression tests contribute substantially to the determination of the mechanical properties and other control aspects of the quality of the kernels, for example in grain flow systems. It is important to determine the material mechanical properties as well as the strain on individual kernels [15, 16].

The study of the stress-strain behavior in grains in their natural state is an interesting approach that provides measurements and objective data and could be used to improve specific processes applied to kernels [17]. However, when a kernel is cut or dissected, its structure and mechanical behavior are modified, particularly when the grain is small. To obtain reliable data, the mechanical properties of biomaterials must be evaluated by using intact kernels [11].

The determination of mechanical properties by compression tests comes from the information provided by a force-strain curve. Some concepts, such as the elastic limit, inflection point, yield point, rupture, apparent elasticity modulus, force and maximum resistance, can be realized from the curve. Those concepts are based on the application of quasi-static loads instead of impact loads [13, 18, 19]. Hooke's law does not apply during the compression of agricultural materials because these materials' properties are greatly affected by other factors, such as the moisture content and temperature [20].

The stress-strain response of grains to compression is determined by the following two aspects: (a) the shape and type of the applied compression (space between surfaces, velocity, sample orientation, among others) and (b) botanical differences in the kernel layers at the compression momentum [21]. The type of equipment, specific conditions of sample preparation, sample geometry and the test velocity must be considered during compression assays [19, 22].

The compression tests are commonly performed at a constant velocity or constant strain. The latter implies that strain increases due to the progressive reduction in the longitude (length), which means that if a fracture is present in the material, the stress-strain curve will show a tendency to decline, despite the deformation and the effect of the increase in velocity. On the contrary, if a contact mechanism dominates, the curve will shows an increase on the slope under a higher velocity, implying an increase in strain [23].

The mechanical behavior of kernels under load compression is time dependent, which means that their characterization should consider the principles of the viscoelastic theory. Viscoelastic materials exhibit the stress-relaxation phenomenon, mainly when sufficiently small stresses are applied. This behavior may be represented by the Maxwell's generalized model [7, 11, 18, 24], which is the Debora's number, a key of the dimensional groups [25].

The most efficient way to evaluate the stress-relaxation phenomenon was through the application of constant deformation (commonly by compression) and measuring the stress as a function of time. The tests at a constant deformation velocity allowed the simultaneous determination of the losses of the relaxation properties [26]. Starting from this point, Khazaei and Mann [27] established that the relaxation time determines how the material dissipates the stress after a rapid and sudden deformation was applied such that the result of the relaxation test could be useful in estimating the susceptibility of materials to damage. The evaluation of mechanical properties in grains is particularly difficult because these parameters may be seriously affected by the percentage of strain, temperature and moisture content [6].

3. Mechanical properties on intact kernel

3.1. Hardness

Hardness has been considered the principal quality parameter of wheat kernels. Hardness delimits the nature of the product that will be elaborated [28]; however, other mechanical properties are essential to design the equipment used in postharvest and processing operations [3]. Marzec et al. [29] defined hardness as the mechanical resistance of the caryopsides to be modified in their nature or as a property that is determined by the measure of their behavior during focal deformation. Grain hardness is governed by genetic factors, and the *locus hardness* (H_a) is located on the short arm of the 5D chromosome, which allows the association of this grain's characteristics and environmental conditions during plant growth [30–32].

Soft, hard and durum wheat are genetically considered qualitative classes, depending on the presence and nature of puroindolin [4]. In contrast, Gazza et al. [33] reported that hereditary factors and mechanical properties are related, though there were no correlations between grain hardness and the puroindolin levels in soft and hard wheat. Osborne et al. [34] noted that the hardness of soft wheat is related to the fracture along the interphase starch/protein, whereas in hard wheat, adhesion on the interphase starch/protein is higher and is located at the cell limits.

The endosperm is the largest component of grains (>80% of weight) and is 63–72% composed of starch granules [4]. Other studies [35–37] consider that the grain hardness is determined mainly by the degree of adhesion between the starch granules and the protein matrix, whereas the endosperm density is affected by the fracture force [38].

During wheat milling, the main parameter that influences the process quality is the difference between the mechanical properties of bran and endosperm; thus, after the bran is removed, less energy is required to continue the milling [39]. Both, the endosperm and bran affect grain hardness [40]. In addition to the properties of intact wheat kernel properties, physical properties of endosperm are associated to the way of how the kernels breaks [37, 41].

Hardness is the factor that mostly affected the mechanical behavior of grains. However, there is no universally accepted definition of hardness. Some authors describe it as an individual mechanical property of a single kernel or some endosperm fragments, but it is also known as the resistance to strain or breaking. The concepts and terms used to define hardness are very extensive, as are the methods used to measure the hardness, and it is thus difficult to evaluate [1]. There is little information about the hardness of wheat kernel and its relation to other fundamental mechanical properties [15].

Since the early 1900s, studies have focused on evaluating the hardness of wheat grain. Lai et al. [42] cited Robert, who in 1910, designed equipment to quantitatively measure the fracture force of individual kernels to detect differences among hardness levels. Later, researchers developed automated equipment (CASK-HaT) that was capable of measuring the stress-strain relation between compression and the fracture force of intact kernels, thus creating the ability to distinguish between mixes of soft and hard wheat with high reliability.

Pomeranz et al. [43] developed a semiautomatic feeder instrument to measure hardness characteristics that considered the moisture content and grain size. Individual kernels were compressed between two flat surfaces, which allowed the evaluation to differentiate the degree of hardness of soft and hard wheat mixes. Nevertheless, the authors concluded that the measurements and results were strongly affected by the heterogeneity among grains (size differences and moisture content). Over time, there have been multiple equipment designs for evaluating grain hardness by applying compression loads or methods supported by cutting and puncture tests [14, 44, 45].

3.2. Elastic modulus

In addition to hardness, the elastic modulus, or Young's modulus, is considered an interesting mechanical property due to its viscoelastic nature. Shelef and Mohsenin [46] performed an experiment in which four uniaxial compression methods were evaluated in the determination of the elastic modulus on individual wheat kernels. The results concluded that the data obtained were dependent on the method that was used. Moreover, the moisture content and kernel size significantly affected those measurements.

Afkari and Minaei [15] applied a quasi-static load (at a constant velocity) on soft and hard intact wheat kernels at two moisture content levels. The values of the apparent elastic moduli were higher in hard wheat varieties with a low moisture content. In the same way, from the data obtained from the stress-strain curves, it was possible to differentiate between wheat varieties, and the effects of the geometry and shape of the kernels were detected. Elbatawi and Arafa [28] performed a test of inflection on three points, and the force distribution on the rupture of wheat kernels was determined. It was also found that forces were significantly related not to the width and height of kernels but to their thickness. The values of the apparent elastic moduli, inflection force and fracture force increased as the moisture content decreased.

Khodabakhshian and Emadi [17] described the importance of evaluating the elastic modulus by using intact kernels. They considered that this parameter allowed the measurement of firmness (a texture attribute) and that it is possible to determine the fracture stress by using the elasticity theory. The indentation as an alternative method to compression with parallel plates to assess Young's modulus. They established that when a load was applied and released at the same velocity, it was possible to evaluate the viscoelasticity (elastic and plastic work) of materials [47].

3.3. Viscoelasticity

Ponce-García et al. [6] proposed and validated an innovative method of using the compression load to evaluate the viscoelastic properties by using intact soft, hard and durum wheat kernels at different moisture levels. The viscoelastic behavior of the wheat kernels was calculated using compression experiments. The total work of compression was determined from the loading/unloading curve (**Figure 1**), represented by the Maxwell's generalized model. The area under the loading curve gives the total work done (W_t) by the loading device during compression. The reversible elastic contribution (W_e) of the total work can be deduced from the area under the unloading curve, and the energy absorbed by plastic deformation (W_p) alone is the difference between the two ($W_p = W_t - W_e$). The results showed that the yield point presented a similar fracture force in all samples, independent of the wheat class and moisture level, whereas the tendency of the force-deformation curves allowed the determination that hard wheat kernels showed a higher plastic work than durum wheat and thus had a higher elastic behavior.

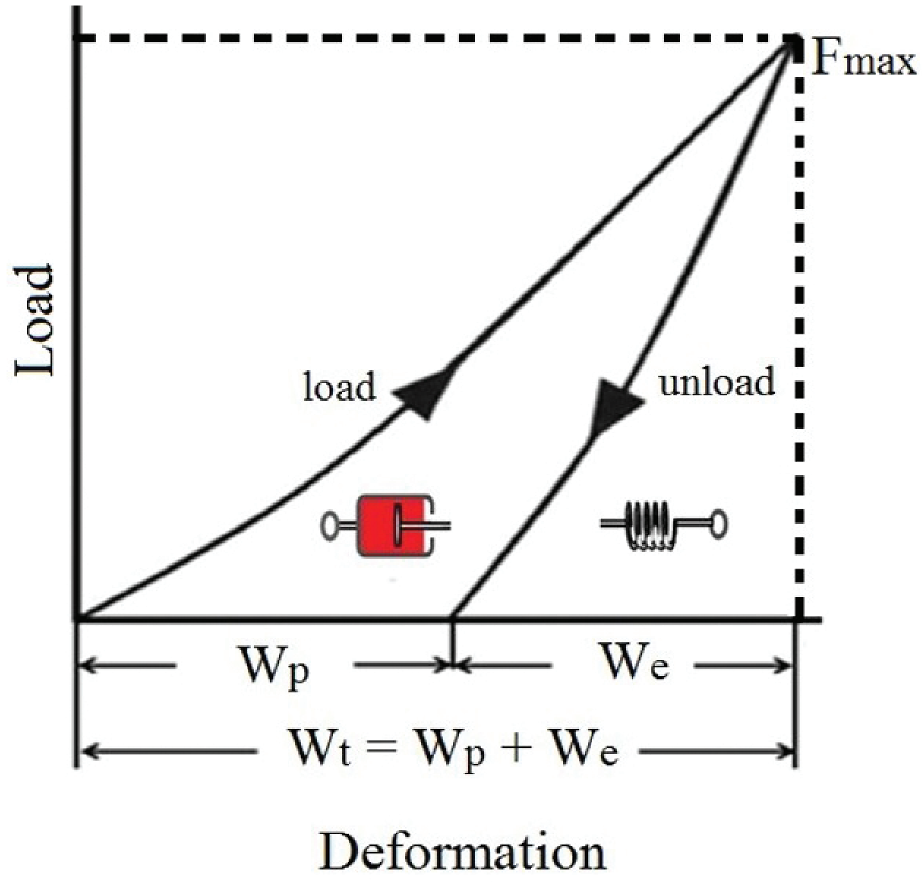

Figure 1. Compression cycle schematic. Abbreviations: F_{max}, maximum load; W_p, plastic work dissipated; W_e, elastic work performed during unloading; and W_t, total work. In Maxwell's generalized model, piston and spring represents dissipated and elastic work, respectively.

Using the latter method, Ponce-García et al. [48] evaluated the viscoelastic behavior of individual wheat kernels at two different moisture content levels through the uniaxial compression test under small strain (3%) to create experimental conditions that allowed the use of the elasticity theory to explain the viscoelasticity of wheat kernels. The results showed that this method could be a useful tool to distinguish among wheat classes, cultivars, and different moisture levels in the kernels.

The viscoelastic behavior of wheat that genotypically differs in the composition of their high molecular glutenins subunits (HMW-GS) was evaluated [49]. Those authors performed uniaxial compression tests and electrophoresis on polyacrylamide gels in presence of dodecyl sodium sulfate (SDS-PAGE) and reported an association among the viscoelastic properties of grains, the HMW-GS composition, and the viscoelastic parameters of gluten. The general tendency was that greater size and elastic work of the kernel corresponded to the best rheological quality of dough.

We are continuously looking to establish relations among protein composition, viscoelastic properties of dough, and bakery quality. In that sense, Figueroa et al. [50] conducted uniaxial compression and stress-relaxation tests on intact wheat kernels. The force-deformation curves showed at least two inflection points: the first was related to the mechanical properties of bran layers, and the second was related to the closer limit to the aleurone layer. It was concluded that bran layers showed a higher degree of elasticity than did those inside the endosperm.

The mechanical properties of wheat bran were significantly correlated with the elastic behavior of intact kernels and are related to the sedimentation volume, allelic composition of glutenin subunits, and elastic work. In the same manner, there was a directly proportional relation between the elastic modulus and kernel size. In general, kernels of hard wheat showed higher elasticity and better quality than soft wheat did [51–53].

3.4. Resistance to fracture

Several investigations have described the behavior of grains as a function of their resistance to fracture. Because of this description, the evaluation of mechanical properties of wheat kernels is strongly related to the milling processes.

Milling is a unitary operation that reduces the average volume of solid particles by dividing and/or fractioning a solid sample. The applied force depends on the magnitude, direction and velocity and allows the particles to absorb the force as a form of tension, which produces a deformation in their structure [54]. Nevertheless, when a limit is exceeded, the material is fractured, thereby provoking new surfaces. The amount of energy necessary for milling is a function of the initial and final size, the applied force and the characteristics of the raw material. Other factors that limit the reduction in size should be considered, such as the moisture and lipid contents and the sample geometry.

Gorji et al. [3] measured the resistance to fracture in terms of force and energy. The load application was carried out by placing the conditioned (tempered) grains at three moisture levels in vertical and horizontal positions and evaluating the grains at two load speeds. The force required to initiate the kernel fracture decreased when the moisture content increased. It was also established that grains in horizontal positions were more elastic and that the mechanical maximum force was associated with low moisture contents and lower test speeds.

In a similar study, Kalkan and Kara [55] determined the effect of the moisture content on individual wheat kernels submitted to *quasi-static* compression loads in two directions: (X-X) and (Y-Y). The force of rupture values in grains decreased with the increase in the moisture levels and was higher for the X-X orientation. In general, the strain of grains obtained by the rupture values showed irregular variations, independent of the moisture content.

Marzec et al. [29] developed a method that uses mechanical tests of uniaxial compression and acoustic emission to determine the quality parameters for wheat grains. The mechanical assays showed the prevalence of significant differences in almost all mechanical properties. The standard deviation was sufficiently wide to reveal the heterogeneity of the biological material, which is caused by the interactions that occur inside the endosperm between protein components and starch granules.

Finally, it can be established that studies that have reported on applying compression loads to intact wheat kernel make the measurement of mechanical properties possible, which have to be considered in future works to improve the quality and development of nondestructive methods in the evaluation of different agricultural products. It is worth noting that one of the problems affecting destructive evaluations of grains is the dissection and cutting of the sample, which make some evaluations impossible to perform. Non-destructive analyses on intact wheat kernels diminish those drawbacks and are quick tests [35].

4. Conclusion

Stress, strain, elastic modulus, stress deformation, viscoelasticity, fracture resistance and hardness are the principal mechanical properties evaluated in intact wheat kernels. Hardness clearly dominates due to its close relation with other quality characteristics of the kernels.

The moisture content is the main factor that affects the mechanical properties of grains. In general, the mechanical resistance and deformation capacity of wheat kernels decrease and increase, respectively, when the moisture content is higher. The latter applies because the energy absorption capacity is higher in moist grains than in dry grains, which incrementally increase the mechanical resistance during compression loading.

The separation of rheological parameters during kernel evaluations, such as the elastic, viscoelastic and viscous flow properties, allows the indirect measurement of wheat characteristics associated with the chemical composition (including nongluten components) and classes.

The evaluation of mechanical properties from applying compression loads on intact kernels provides important and useful information that could be considered to optimize and improve related aspects of postharvest and processing. The determination of mechanical properties should not be considered a unique method of evaluation to establish grain quality. However, it might be considered an alternative and helpful supplementary tool and complementary of other analyses.

Wheat kernels manifest a time-dependent behavior similar to other viscoelastic materials. Nevertheless, it is important to notice, at all possible times, the differences among the equipment, methods, moisture content and geometry of the grains during the development of tests.

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Finally, to take advantage of the major benefits of the potential of raw materials in their natural state (intact kernel), the creation of a database that allows the evaluation of different wheat classes and cultivars according to their specific mechanical properties is recommended.

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