Comparative analysis of elasticity and rigidity of morphological parts of wheat grain

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Abstract. The article presents the results of a comparative assessment of the elasticity and rigidity of various morphological elements of wheat grain depending on the nature of the grain (normal, frosted, after drying, after scouring machines). The dependences of the rigidity of wheat grain on the structure, chemical composition and humidity are described. A close correlation was revealed between the structural and mechanical properties of wheat, assessed by microhardness, strength index, and the results of laboratory and industrial grinding of wheat grains of various consistencies. For different consistency of wheat grain, microhardness was determined using the microhardometer "Miniload", and the strength index was determined using the Brabender’s hardness tester. At relatively low stresses, the shells have flexural elasticity. It was detected that with increasing humidity, the rigidity of the shells during bending decreases. It was found that for hard and hard-grained varieties of soft wheat, the compression force is required 2-4 times more than for soft-grained varieties. It is shown that the microhardness of glassy grains of hard-grained and soft-grained wheat varieties is basically at the same level. At the same time, with increasing humidity, the microhardness of the grain decreases regardless of the variety, area of growth and vitreosity of wheat.

1. Introduction

The most important role in the formation of physicochemical characteristics of grain is assigned to structural and mechanical properties. The species (hard and soft), type, variety, region and growing conditions of wheat have a huge impact on the latter. The heterogeneity of the microscopic structure and chemical composition of the individual anatomical parts of the grain (primarily the shells and endosperm) causes differences in their physical and mechanical properties, which must be taken into account when preparing wheat for grinding and processing.

Structural and mechanical properties of grain are characterized by strength, hardness and rheological characteristics. Strength is characterized by tensile strength, yield strength, creep strength. Strength can be estimated by the value of the breaking force or stress at a certain type of deformation (compressive tensile, shear, chipping, bending, impact, abrasion), as well as the energy consumption per unit of the newly formed surface.

The term "relaxation" is understood to mean a gradual decrease in the acting stresses to zero or some value with a constant deformation in time. Studies by many scientists have made it possible to determine the magnitude of the force required to break down grain under compression, shear and bending strains. Scientists noted the effect on the strength properties of grain type and variety of wheat, size and shape, moisture and vitreousness [1].
Shells are less studied than other parts of the grain. Almost all published works on the study of shells concern only their strength and completely do not touch upon such issues as elasticity and rigidity. Meanwhile, the study of these mechanical properties of grain will significantly improve the quality of the products produced.

By "elasticity", as you know, they understand the property of bodies subjected to deformation to return to their original (undeformed) state after the termination of the forces that caused this deformation. In other words, elasticity is the body's ability to experience reversible deformations. “Elastic limit” refers to the maximum stress to which practically no residual deformations are obtained.

The bending stiffness of a beam is numerically expressed as the product of the elastic modulus under linear deformation and the moment of inertia of the beam section relative to the neutral axis. Thus, the magnitude of the elastic modulus is not related to the dimensions of the body and characterizes only the elasticity of the material from which it is made, while the stiffness of the body simultaneously takes into account both the elastic properties of the material and the shape and size of the cross section of this particular body.

This paper presents the results of a study of the elasticity and stiffness of the shells of grain depending on its moisture content and vitreousness. The tests were carried out on a specially designed device. The device consisted of the following main parts: a tripod, on which a disk with two transparent disks was mounted, handles with an arrow to rotate the axis in the center of the disk, axis, spring clip and arrow. The test shell specimen was mounted between the upper and lower clamps. Turning the knob clockwise, the shell sample was bent under the action of the weight of the arrow [2, 3].

2. Materials and Methods

The objects of research were grain samples of hard (Kharkovskaya 3) and soft (Yugo-Vostochnaya 3, Saratovskaya 42, Orenburgskaya 13 and Varyag) wheat of the Orenburg region.

The grain was preliminarily classified in size and vitreousness. For the study, grain screenings from a screen with mesh size of 2.4×20 mm were used. The grain thus selected was placed in containers with water. After the endosperm was so softened that it could be separated from the membranes, they were removed. The grain was placed with a groove up, with grain hair down and cut with a razor into two halves. Endosperm was completely removed from each half, after which the membranes were placed in separate boxes and then their moisture was determined. If the moisture of the shells exceeded the set value, they were dried in a desiccator over water. If the moisture of the shells was within the set limits, they were tested.

The shell was removed from the box, cut in the longitudinal direction from two sides in order to obtain a strip 2 mm wide and 3 mm long, and then clamped with ends in spring clips, one of which was located on the axis of the device and the other on the end of the loading arrow. After fixing the shell in the clamps, the axis of the device was inserted into the hole of the disk so that the angle of rotation indicator and the arrow with the shell fixed were set to zero. It should be noted that when moistened the grain (in particular in the shell) experiences some leaching of water-soluble substances, and some biochemical changes are possible. Nevertheless, this research method provides quite reliable and comparable results.

The microhardness of various parts of the grain was evaluated using a Miniload micropenetrometer, and the index of tensile strength using a Brabender hardness tester.

3. Results

With increasing moisture, the rigidity of the shells during bending decreases. Thus, at a moisture content of 11.7 to 12.5%, the shells of soft wheat from the eastern regions (the studied varieties) are characterized by higher hardness compared to the shells of wheat from the central regions. With increasing moisture of the shells to 48.0%, their rigidity decreases (the shells become more malleable).
Interestingly, this is more characteristic of wheat from the eastern regions than from the central regions.

Hard wheat shells at a moisture content of 11.7 to 12.5% are more rigid than soft wheat shells; with an increase in moisture of up to 47.5%, the resistance of the shells to a change in shape decreases, though to a lesser extent, than that of the shells of soft wheat. Thus, the bending tests of the shells showed that with an increase in their moisture, the elastic modulus decreases.

Since the elastic modulus characterizes the elasticity of a substance, it can be said that with increasing moisture, the shells become less elastic. The elastic modulus for durum wheat is higher than for soft wheat, and that for wheat in the eastern regions (studied varieties) is slightly higher than for wheat in the central regions. Consequently, at the same moisture, the shells of durum wheat have the highest elasticity, followed by the shells of wheat in the eastern regions, while the lowest moisture content is characteristic of wheat in the central regions.

Table 1 shows data on the stiffness and modulus of elasticity of the shells of frosted grain, grain after drying, grain processed in scouring machines with an abrasive cylinder, and grain with subzero temperature. From the data given in the table it follows that the shells of grains damaged to some extent by frost after drying or processing in scouring machines with an abrasive cylinder, as well as grains with subzero temperatures compared with shells of normal grains, have a lower resistance to bending and less elasticity [4, 5].

**Table 1. Rigidity and elastic modulus of grain**

| Wheat variety       | Grain nature  | Bending stiffness, [kg mm²] | Elastic modulus [kg/mm²] |
|---------------------|---------------|----------------------------|--------------------------|
| Saratovskaya 42     | Normal        | 0.145                      | 21.8                     |
|                     | Frosted       | 0.118                      | 18.7                     |
|                     | After drying  | 0.113                      | 18.5                     |
|                     | After abrasive scouring machine | 0.101              | 10.2                     |
|                     | Normal        | 0.135                      | 22.6                     |
|                     | Frosted       | 0.132                      | 16.5                     |
| Orenburgskaya 13    | After drying  | 0.120                      | 14.9                     |
|                     | After abrasive scouring machine | 0.110              | 8.3                      |
|                     | Normal        | 0.145                      | 29.2                     |
|                     | Frosted       | 0.128                      | 16.4                     |
| Varyag              | After drying  | 0.132                      | 14.9                     |
|                     | After abrasive scouring machine | 0.114              | 8.5                      |

Frosted grain is known to usually differ from normal one by its reticular surface, while the grain itself is more or less deformed. The shells of such grains are easily deformed.

When processing grain in scouring machines with an abrasive surface as a result of impacts of grain on an acutely rough surface, cuts, scratches, cracks and other damage are formed in the shells, which leads to a significant decrease in their rigidity and elasticity.

With a decrease in grain temperature, especially during early frosts, when the grain temperature drops to -1 °C or lower, the water between the macromolecules expands and increases the distance between them, weakening the intermolecular adhesion forces. In addition, the free moisture in the shells of the grain, turning into ice, increases the volume of macropores, and this leads to a complication of the stress state of the whole grain.

Thus, the shells experience a load not only from the pressure forces of the increasing volume of the endosperm, but also from the forces resulting from the freezing of water in the pores or capillaries of the grain. Both of these cases can lead to the formation of microcracks in the shells and, therefore, not only to their reduced strength, but also to reduced elasticity and stiffness [6].
There are several hypotheses regarding the causes of cracks on the surface of the material during drying. For example, when wet grain is dried (especially if the latter is conducted at improper temperature conditions), the moisture in the pores of the endosperm and shells turns into steam. The latter, by virtue of its elasticity, exerts pressure on the endosperm and the shell, which leads to the appearance of microcracks on the surface of the latter and a decrease in its resistance to the load.

When the shell is bent, the latter experiences only or predominantly elastic deformations. During this period, due to the elasticity of the shells, they significantly resist bending. After removing the load, the shell sample restores to its original size and shape.

With a further increase in load, the bending of the shell increases, and on the convex side, individual layers of the shell stretch, and on the concave side they are compressed. Since the elongation and shortening of individual layers of the shell are accompanied by transverse compression and expansion, as a result, a relative shift of the individual layers of the shells occurs on the concave and convex sides.

At the same time, a gradual increase in plastic deformation occurs, and the angle measured on the scale decreases. If during the deformation of the shells any section is weaker than others, then the pattern of development of the deformation will be violated. In a weak cross section and in neighboring cross sections, the stresses reach maximum values, which leads to an increase in residual strains and deformation of the sample.

The elasticity, rigidity, strength of the shells of wheat grain depends on the structure, chemical composition, and humidity. Dry shells (with humidity from 11.7 to 12.5%) are characterized by the highest rigidity. With increasing humidity of the shells, their bending stiffness decreases, and their resistance to grinding increases. The presence on the surface of the grain of cracks, scratches and other damage leads to a decrease in resistance and, consequently, to easy destruction of the shells.

In addition, the correlation of the structural and mechanical properties of grains of various consistencies with humidity, temperature, and loading speed was studied. With an increase in the moisture content of grain of the Kharkovskaya 3 variety to 16.0%, the destructive force drops by 18.5%, by 22.7% for Southeast 3 wheat and by 27.7% for Saratovskaya 42 wheat. The destruction work reaches its minimum when the moisture content of Kharkovskaya 3 wheat grain is from 15.0 to 16.0% and Saratovskaya 42 moisture content is from 13.0 to 14.2%. With an increase in the loading rate, the work on the destruction of grain decreases, since the proportion of plastic deformations sharply decreases [7].

Flour-milling technologists came to the conclusion that, depending on humidity, three phases of the grain state can be distinguished, characterized by special deformation properties. At a moisture content of up to 11.0%, the grain is a viscoelastic body; at a moisture content of 11.0 to 13.5%, it is a viscoelastic-plastic body; above 17.0%, it is an elastoplastic body.

Of practical interest are the strength properties of the main parts of the grains—shells and endosperm. Dry shells (grain moisture from 11.7 to 12.5%) of durum wheat (Kharkovskaya 3) are more rigid than soft shells (hard-grain Yugo-Vostochnaya 3 and soft-grain Saratovskaya 42). Similar ratios were revealed for the shell elasticity index. With increasing humidity, the stiffness and elastic modulus of the shells decrease.

In the study of the strength of pure endosperm, it was found that for durum and hard-grain varieties of soft wheat, the compressive force is 2 to 4 times greater than that for soft-grain varieties (23.2, 15.1 and 12.5 kg/mm², respectively). In connection with the anisotropic microscopic structure and the heterogeneous chemical composition of the endosperm of the caryopsis, it is necessary to study the strength properties of its individual sections.

Flour milling technologists studied the topography of the microhardness of the endosperm and the shells of grains of vitreous and mealy fractions of wheat varieties of various consistencies. The microhardness value of the endosperm and the shells of durum and hard-grain soft wheat kernels is usually higher than the similar indicators of soft-grain wheat kernels.
The microhardness of vitreous grains of hard-grain and soft-grain wheat varieties is basically on the same level. The same is observed for mealy grains. With increasing humidity, the microhardness of grain decreases regardless of the variety, growth area and vitreousness of wheat.

When studying slices of three endosperm zones of durum and soft durum wheat, it was found that the microhardness values increase from the center to the periphery of the grain (from 24.1 to 25.5; from 15.5 to 17.8; from 10.7 to 12.5 kg/mm², respectively). For soft-grain varieties of white wheat, the microhardness values are slightly lower.

The microhardness of individual fragments of an intermediate protein and starch granules was studied. The moisture content of the grain ranged from 9.0 to 11.0%. The microhardness values of vitreous grains are on average two times higher than that of mealy ones. The microhardness of the vitreous fraction of grains of soft wheat varieties is similar to the microhardness of semi-vitreous grains of durum wheat. The same ratio was observed for the mealy fraction of hard-grain varieties and the semi-vitreous fraction of soft-grain wheat (Table 2).

| Vitreousness range [%] | Gran microhardness [kg/mm²] | durum wheat | semi-vitreous | mealy | total |
|-----------------------|-----------------------------|-------------|----------------|-------|-------|
|                       |                             | vitreous     |                |       |       | hard grain wheat |
| 80-100                | 20.2                        | 16.5         | 12.1           | 19.5  |       |
| to 40                 | 18.5                        | 14.2         | 11.5           | 15.4  |       |
| 41-60                 | 18.2                        | 14.1         | 11.2           | 16.2  |       |
| 60-80                 | 18.9                        | 14.0         | 11.0           | 16.8  |       |
| 80-100                | 19.1                        | 14.3         | 11.0           | 17.1  |       |
| to 40                 | 13.5                        | 11.2         | 10.2           | 11.2  |       |
| 40-60                 | 13.0                        | 11.0         | 10.3           | 10.8  |       |
| 60-80                 | 12.9                        | 10.9         | 9.7            | 10.5  |       |

The correlation coefficients of vitreousness and microhardness of durum, hard-grain and soft-grain wheat varieties were 0.71, 0.92 and 0.67, respectively.

4. Conclusion

In the course of this study, the rigidity of the shells was determined and the ultimate bending stresses were calculated. In the working area of the roller mills, the shells are deformed under conditions of complex deformation; in this case, the required power or energy consumed for their grinding is determined. In the latter case, with increasing humidity of the shells, due to an increase in their plasticity, resistance to grinding increases and, accordingly, the specific energy consumption.

At relatively low stresses, the shells exhibit bending elasticity, i.e., upon subsequent unloading of the shells, they regain their size and shape.

The modulus of elasticity decreases with increasing humidity of the shells. Consequently, under the same other conditions, dry shells are more resilient than wet ones.

The elastic modulus of the shells of durum wheat is higher than that of the shells of soft wheat, while that of the wheat of the eastern regions (studied varieties) is higher than that of the shells of wheat in the central regions. Consequently, at the same humidity, durum wheat shells are more elastic than the shells of the studied soft wheat varieties, and wheat shells of the eastern regions are more elastic than the wheat shells of the central regions.

The shells of frosted grain, grain dried after processing in scouring machines with an abrasive cylinder and grain with a temperature below 0 °C, are characterized by lower elasticity and resistance to bending compared to shells of normal grains.

A close correlation was found between the structural and mechanical properties of wheat, evaluated by microhardness (according to the Miniload microhardness tester), strength index (by the Brabender
hardness tester), and the results of laboratory and production grindings of wheat grains of various consistencies.

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