PHYSICAL PROPERTIES AND COMPRESSION LOADING BEHAVIOUR OF CORN (Zea mays L.) SEED

FIZIČKE OSOBINE I PONAŠANJE SEMENA KUKURUZA (Zea mays L.) PRI PRITISNOM OPTEREĆENJU

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ABSTRACT

The aim of this study was to acquire data on the physical properties and mechanical behaviour of the six seed corn hybrid varieties. One variety was semi-flint, while others were dent types. The mean values of length, width, thickness, geometric diameter, surface area, porosity, single kernel mass, sphericity, bulk and true density, 1000 kernel weight and coefficient of friction were studied at a single level of moisture content. The longest kernels were those of the ZP 677 hybrid, which ranged from 10.51-11.50 mm in length. The largest width was observed for ZP 684 (7.51-8.50 mm) and ZP 677 (6.51-7.25 mm) kernels, while kernel thickness was greatest in ZP 434 (3.56-4.55 mm) and ZP 684 (3.31-5.55 mm) hybrids. The mean geometric diameters were 7.18; 7.15; 6.91 and 6.72 mm for NS 4015, ZP 644, NS 640 and ZP 677, respectively. The highest value of sphericity, 0.75, was measured for ZP 684, followed by 0.71 for NS 640; the hybrids NS 6010 and ZP 677 had the lowest value of sphericity (0.60). The measured bulk density values ranged from 784.75 kg/m³ (ZP 677) and 779.58 kg/m³ to 633.56 kg/m³ (NS 6010), while true densities ranged from 1176.63 kg/m³ (ZP 677) and 1175.65 kg/m³ (NS 640) to 900.94 kg/m³ (NS 6010). The linear model showed a decreasing tendency of secant modulus of elasticity for all ZP hybrids as the moisture content of seeds increased, with high values of the coefficient of regression. Similar results were attained for NS hybrids but with lower coefficient of regression values.

Key words: corn seed, physical properties, secant modulus of elasticity.

REZIME

Cilj ovih istraživanja je prikupljanje podataka o fizičkim i mehaničkim osobinama šest hibrida kukuruza domaće selekcije. Jedan od njih je polu tvrdunac, dok su ostali zubani. Srednje vrednosti dužine, širine i visine pojedinačnih zrna su dobijeni merenjima na uzorku od 90 semena, a zatim su izračunati srednji geometrijski prečnik, površina pojedinačnog zrna, kao i srednja sferičnost. Nasiplna i sopstvena gustina, masa 1000 zrna i koeficijent trenja po metalnoj podlozi su takođe mereni za sve hibride pri jednoj vrednosti vlažnosti zrna. Ustanovljeno je da su najduža zrna bila kod ZP 677 hibrida i to u rasponu od 10.51-11.50 mm. Najveća širina semena je konstovana za zrna ZP 684 hibrida (7.51-8.50 mm) i ZP 677 (6.51-7.25 mm), dok je najveća debelina uočena kod semena ZP 434 (7.51-8.50 mm) i kod hibrida ZP 677 (6.51-7.25 mm). Srednji geometrijski prečnici su 7,18; 7,15; 6,91 i 6,72 mm izmereni kod hibrida NS 4015, ZP 644, NS 640 i ZP 677, respektivno. Najveća vrednost sferičnosti je konstovana kod ZP 684 semena (0,75), a zatim sledi hibridi NS 640 (0,71), dok hibridi NS 6010 i ZP 677 imaju najnižu vrednosti sferičnosti od 0,6. Nasiplna gustina semena kukuruza je 784,75 kg/m³ (ZP 677) i 779,58 kg/m³ do 633,56 kg/m³ (NS 6010), dok su vrednosti sopstvene gustine u dijapazonu od 1176,63 kg/m³ (ZP 677) i 1175,65 kg/m³ (NS 640) do 900,94 kg/m³ (NS 6010). Linearni model zavisnosti sektanog modula elastičnosti od vlažnosti zrna kukuruza je ustanovljen za sve ZP hibride sa visokim vrednostima koeficijenta regresije. Slična zavisnost je ustanovljena i za NS hibride, ali sa nižim vrednostima ovog koeficijenta.

Ključne reči: some kukuriza, fizičke osobine, sektan modul elastičnosti.

INTRODUCTION

Corn is the most important farm crop in the Republic of Serbia. According to data from the Statistical Office of the Republic of Serbia (www.webzr.stat.rs), over the two last decades the cultivable corn land was approximately 1.2 million of hectares, with corn gross production between 6-7 million tons per year. Corn growing has a long tradition in the Balkan Peninsula. The crop was introduced by Turkish conqueror tribes in the 17th century with the intent that corn consumption would eventually substitute for wheat consumption. In the Balkans, corn is used for bread-making, in the preparation of several kinds of porridges and in production of the juice named boza; a large number of cakes use corn flour as a main ingredient, and a brandy is even produced from corn kernels. Corn also provides feed for cattle and raw material for the industrial preparation of brandy. It is presently used primarily for feed and for processing in three major industries: wet milling, dry milling and distilling (Radosavljevic et al. 2000).

The importance of corn processing industries emphasise the identification of the specific, rigorous quality needs of individual users, and there is considerable interest in grain quality as an end-use value. Overall, corn quality could be increased if its specific values were more closely matched to user demands. Parameters that are useful in the evaluation and recognition of such specific values include, among others, the physical properties of the corn kernels. The handling of corn kernels from harvesting to processing is affected by the physical properties of the kernels. These properties include their three perpendicular dimensions, which affect cleaning and grading processing, the kernel surface, which affects drying, sphericity and thousand kernels weight, which affect packaging of seed, bulk density (affecting storage capacity), true density (affecting vehicle load), porosity (aeration possibility, drying), static coefficient of friction (moving on inclined plane) and compression loading behaviour, which affects milling, extruding and flake preparation.

Previous studies have described the physical properties of corn kernels. Coskun et al., (2006) determined sweet corn seed properties as a function of moisture content, while Karaba (2006) reported similar results on popcorn kernels; sweet corn kernel properties were reported by Karababa and Coskuner.
The quality of corn kernels is not evaluated solely by the physical traits mentioned above. The behaviour of the corn kernel during compressive loading is one of its textual properties. The processing of corn for food and feed requires various types of mechanical treatment that depend on external forces. Wet or dry milling is conducted with the help of mechanical forces that separate the corn kernels into four principal components, starch, protein, germ and fibre (Radosavljević et al. 2000). The intensity of the external force necessary to crush the kernel depends on the composition of the corn and the arrangement of its structural elements. The main component of corn kernels is starch granules; these have a complex hierarchical structure consisting of polysaccharide macromolecules that are partially arranged in ordered conformations as single and double helices (Gaytan-Montinez et al. 2006) and entangled to form supra- and submolecular structures. Proteins form a matrix surrounding and embedding the starch granules (Kawaljit Singh Sandhu et al. 2007). The endosperm of corn, which is horny and floury, is a complex mixture of starch granules and protein. The physical structure of endosperm depends on the interaction between these two components; it is also associated with the degree of packaging of cellular compounds, the thickness of the cell wall, and the thickness of the protein matrix that is in contact with the starch granules, which depends to some extent on the strength of adhesion between these two compounds (Pereira et al. 2008). The proportion of horny and floury endosperm in the kernel differs in different types of corn, the general classes of which are flint corn, dent corn, floury, sweet corn and popcorn. The class of corn is influenced by breeding processes. It is well known that floury endosperm is softer and easier to break than horny endosperm (Kawaljit Singh Sandhu et al. 2007). However, according to Dobrasczyk et al. (2002), it is possible that genetically horny endosperm can be made soft by changing the environment and the drying conditions. The study of the behaviour of the non-homogeneous organic structure of corn kernels on compression loading offers a basis for general conclusions regarding how this type of change might be achieved. Furthermore, because compression behaviour is important in corn processing, studies that measure such behaviour over a wide spectrum of kernel moisture content are desirable.

The compression loading test shows the response of biomaterials to an applied external force that deforms the body and induces a change in dimension, shape or volume. This test provides important information about elastic or plastic behaviour. The force-deformation curve is a graphical measure of the mechanical properties of a biomaterial. The compression loading behaviour of a biomaterial should be differentiated from its hardness, which defines the resistance of metal to deformation, usually by indentation.

The objectives of this study were to provide new information describing the primary physical properties of the seeds of six domestic corn hybrids. To this end, the kernel dimensions, geometric mean diameter, kernel surface area, bulk and true density, porosity, sphericity, thousand kernel weight, moisture content and static coefficient of friction of kernels from the six hybrids were tested. The compression loading behaviour of corn seeds at different moisture contents was also studied. The results of the study were statistically processed using STATISTICA for Windows version 9.0; the significance of differences between physical properties was tested by Tukey's honestly significant difference (HSD) test.

MATERIALS AND METHODS

Corn samples

Six corn hybrids from the 2009 harvest season (ZP 434, ZP 677, ZP684, NS 640, NS 6010 and NS 4015) were tested. Hybrids ZP 434, ZP 677 and ZP 684 were obtained from experimental fields of the Maize Research Institute, Zemun Polje, Belgrade, while hybrids NS 640, NS 6010 and NS 4015 were obtained from fields of the Institute of Field and Vegetable Crops, Novi Sad. All hybrids are dent class except ZP, which is semi-flint class. Approximately 5 kg of each hybrid seed in plastic bags were delivered from the seed processing plants of the Institutes to the Faculty of Agriculture. The kernels were manually cleaned and culled to remove all foreign matter and broken kernels. Each sample was divided into two parts; one part was used for the analysis of physical properties at constant seed moisture content after process drying, and the other part was divided into four groups that were adjusted to different moisture contents for testing compression loading. The kernels were kept in sealed plastic bags and stored in a refrigerator at 4°C. Before each compression test, the necessary amount of sample was removed from the refrigerator and allowed to equilibrate to room temperature. Moisture content was determined by the oven method.

Physical properties

The moisture content of seed from each corn hybrid was measured according to the specific regulations for the quality of agricultural crops mandated by the Republic of Serbia. Three replicates were measured for each sample. The samples were oven-dried at 103°C for 72 hours and then weighed. This procedure was repeated until the observed change in mass was less than 0.01 g. The samples were then placed in desiccators and allowed to cool to room temperature. Sample weight was recorded using a digital balance with an accuracy of ± 0.001 g (Kern, PLJ360-314). The moisture content (Mc (%)) of the samples was expressed on a wet basis (w.b.). Specimens that had been sealed in polyethylene bags to reach different moisture contents were similarly treated. Prior to each test, the seeds were removed from the refrigerator and allowed to come to ambient air temperature. The mean moisture content values in percentages of wet basis and their standard deviations were calculated. The values of corn seed moisture content studied were 8.00-32.00% w.b. because corn harvesting, husking, drying, handling and storing operations are typically performed within this moisture range.

A calliper with accuracy of ±0.01 mm was used to measure three kernel dimensions, length (L), width (W) and thickness (T). The dimensions are reported in millimetres (mm). The length represents the distance from the tip cap to the kernel crown, while the width is the widest distance from one point to another in the plane parallel to the face of the kernel (Mohsenin, 1980). Thickness was measured in the plane perpendicular to the length and width. For these measurements, a sample of 90 kernels was randomly selected from the bulk of each corn hybrid; the mean kernel dimension values and standard deviation (SD) were determined and used to establish the kernel size distribu-
tion. The geometric mean diameter, $D_g$ (mm), sphericity, $\Phi$ (mm/mm) and surface area of a single kernel, $S$ (mm$^2$), were calculated from the three principal dimensions according to the following relationship (Mohsenin, 1980; Babić and Babić, 2000; Babić and Babić, 2001; Ersan and Yulcin, 2007):

$$D_g = (LWT)^{1/3}$$  \hspace{1cm} (1)

$$\Phi = \frac{D_g}{L}$$  \hspace{1cm} (2)

$$S = \pi D_g^2$$  \hspace{1cm} (3)

An electromechanical kernel counter (Numigral, NUM 3, Tripette et Renaud) and a digital balance (KERN, PLJ360-314) were used to measure the thousand kernel weight in grams. The test was repeated three times. The mean value of a single kernel, $M$ (g), as well as its standard deviation (SD) was calculated to ascertain the uniformity in measurement.

The liquid displacement method was used to determine seed true density, $\rho_t$ (kg/m$^3$). For this method, water was placed in a graduated cylinder, and a known weight of seeds was added to the water; the displacement was recorded quickly before water was absorbed by the kernels. The ratio between kernel weight and the volume of displaced water represents the true density of each specimen. This test was repeated three times, and the mean and standard deviation (SD) of the density were calculated for all corn hybrids. The liquid (water) displacement method is widely used despite some potential for error. In displacement tests, particularly those using water, errors can occur due to the trapping of air in the space between the grains, within the crease or in the brush hair.

The bulk density measurement, $\rho_b$ (kg/m$^3$) was performed by measuring the kernel’s mass using a digital balance and then measuring the total volume in a graduated cylinder (Republic of Serbia directive 47/1987). To achieve uniformity in the bulk density measurement, the graduated cylinder was tapped 10 times to consolidate the seeds. This procedure was repeated three times. The bulk density was calculated as the ratio of the weight of the kernels to their volume in the cylinder. The porosity, $p$ (-), was calculated as the relationship between the bulk density ($\rho_b$) and the true density ($\rho_t$), as follows (Mohsenin, 1980):

$$p = \left(1 - \frac{\rho_b}{\rho_t}\right) \times 100$$  \hspace{1cm} (4)

The porosity of the six corn hybrids was also measured. For this, the seeds were poured into a graduated cylinder, and the total volume was recorded. A second graduated cylinder was filled with water, and the water was poured into the first cylinder until all of the grains were covered with water. The remaining volume of water in the second cylinder was recorded, and the difference in volume between the cylinder filled with water and remaining water was calculated. The difference in the volumes before and after pouring the water within the second cylinder was obtained, and the porosity was calculated as the ratio between the difference in the volumes (previous explanation) and the volume of the seeds in the first cylinder (Saiedirad et al. 2008). The test was repeated three times, and the results of this test were compared with the porosity values obtained using equation (4).

The thousand seed weight was determined by counting 100 kernels and weighing them on an electronic balance; the result was multiplied by 10 to give the mass of 1000 kernels.

The static coefficient of friction was measured for one structural material only, a galvanised metal sheet. An adjustable tilting surface (Gupta and Das, 1997) with a graduated scale was used for these tests. A plastic cylinder 100 mm in diameter and 50 mm high, open at both ends, was placed on the tilting surface and filled with the seed sample. The inclined surface supporting the cylinder was then lifted up with the help of a screw device until the cylinder began to slide down. At this point, the angle of tilt, $\alpha$ (°), was recorded. This test was repeated three times for each corn hybrid, and the mean values of the results were taken as the representative values. The friction coefficient, $\mu$ (-), was calculated as the tangent of the measured tilt angle (Babic and Babić, 2000), as follows:

$$\mu = \tan \alpha$$  \hspace{1cm} (5)

The stress-strain uniaxial compression test shows the response of biomaterials to an externally applied force that deforms the body of the material, causing changes in dimension, shape, or volume. This test provides important information about elastic and plastic behaviour. The stress-strain biomaterial behaviour should be differentiated from hardness, which defines the resistance of metal to plastic deformation, usually by indentation. This term may also refer to resistance to stiffness or tempering, as well as resistance to scratching, abrasion, or cutting.

Stress is the external force $F$ (N) upon the unit specimen cross-sectional area, $A_o$ (m$^2$). An important aspect of this is not necessarily the quantity of force but its application on the unit of cross-section area. For this reason, all specimens have a regular shape such as that of a cylinder or a cube. According to the straining action, stress is identified as compressive, tensile, or shearing and is referred to using the Greek letter $\sigma$. The unit of stress is (N/m$^2$); its equation (Dordević, 1999) is

$$\sigma = \frac{F}{A_o}$$  \hspace{1cm} (6)

Biomaterials under compression change in length. The ratio between displacement $\delta$ (mm) and initial specimen length $L_o$ (mm) is strain $\varepsilon$ (m/m); its equation is:

$$\varepsilon = \frac{\delta}{L_o} = \frac{(L-L_o)}{L_o}$$  \hspace{1cm} (7)

where displacement is $\delta = (L-L_o)$. Strain is a internal reaction of elementary biomaterial particles that is induced by an external force. The stress-strain diagram is a graphical representation of simultaneous values of force and head displacement recorded during testing. The graph indicates biomaterial properties associated with elastic and inelastic behaviour. The typical shape of this curve is presented in Fig 1. Point P is known as the proportional limit. Stress and strain are in linear correlation; the slope of the straight line portion of this correlation is called the modulus of elasticity (E or Young’s modulus).

$$\frac{\sigma}{\varepsilon} = E$$  \hspace{1cm} (8)

or

$$\sigma = E \varepsilon$$  \hspace{1cm} (9)

Fig. 1. Force and head displacement curve (Dordević, 1999)
P- Proportional limit, E- Elastic limit, Y- Yield point, U- Ultimate strength point, R- Rupture strength

The unit of Young’s modulus is (N/m$^2$). An expression that describes the relationship between stress and deformation [9] is well known as Hook’s law. The point E in Fig. 1 represents the
maximum stress that can be applied without resulting in permanent deformation when specimen is unloaded, while point Y is the elastic limit or yield point. Beyond the peak of this curve, the resistance of the material to the stress decreases, and the “yield of displacement” is observed. The ultimate strength point represents the external force that is sufficient to cause kernel cracking.

From an engineering point of view, especially with respect to milling processing, information about the value of the ultimate strength point force F (N) and head displacement δ_H (mm) for different corn hybrids is interesting and relevant. For this reason, tests of corn seed stress-strain compression in this study were conducted using whole kernels. In such a case, it is possible to calculate the secant modulus of elasticity, Es (N/mm), which represents the slope of the secant drawn from the origin to ultimate strength point on the force-head displacement curve (Mohsenin, 1980). For each hybrid, seeds with different seed moisture contents were tested. The moisture contents of NS 640 kernels were 8.1%, 12.1%, 26.4% and 8.5% w.b.; those of NS 6010 were 14.8%, 22.3%, 28.6% and 30.1%; and those of NS 4015 were 14.3%, 16.7%, 25.4% and 32.6%. For the hybrid ZP 684, seeds with moisture contents of 11.0%, 12.3%, 24.5% and 33.2% w.b. were used; for ZP 434, 12.9%. 17.0%, 24.6% and 30.5% w.b. were used, and for hybrid ZP 677, 13.6%, 18.3%, 25.4% and 30.9% w.b. were used.

The slow loading compression test was performed with all corn hybrid kernels. Fifteen replicate tests were conducted for each hybrid, and four different moisture contents of each hybrid were tested. The testing equipment consisted of a loading cell and a computer running the TMS-PRO Texture measurement system (Food Technology Corporation); a trigger load from 0.5 to 450 N was used. The constant deformation rate before contact with the specimen was 60 mm/min, while during compression, it was 30 mm/min. The range of load applied by the measuring head was from 0 to 500 N. Each individual seed was placed on the lower plate of the machine with the germ side down. The result of each test is presented in a table and in a graph as a curve with force F (N) at the ultimate strength point, loading head displacement and time. The secant modulus of elasticity Es (N/mm) is the ratio of strength point force F and machine head displacements (mean value- δ_H (mm)) for certain hybrid and moisture content. All statistical analyses were performed using Microsoft Office Excel.

RESULT AND DISCUSSION

The frequency distribution of the three kernel dimensions in 90-seed samples of ZP 684, ZP 434, ZP 677, NS 640, NS 4015 and NS 6010 hybrids are presented in Figs. 2 and 3. The moisture contents of hybrids ZP 684, ZP 434 and ZP 677 were 11.6%, 12.0% and 13.4% w.b., respectively, while hybrids NS 640, NS4015 and NS 6010 had moisture contents of 12.9%, 13.9% and 16.8% w.b. In the NS 6010 hybrid, the largest percentage (53%) of the kernels were long, between 9.51-10.50 mm, whereas in the hybrid NS 4015, 52% of the kernels fell within the length range of 9.76-10.75 mm; in hybrid NS 640, 51% of the total kernels were between 8.01 and 9.75 mm in length.

With respect to width, 63% of the NS 6010 kernels were between 6.31-7.05 mm wide, 47% of the hybrid NS 640 kernels were 6.06-7.05 mm wide and 45% of NS 4015 kernels fell within the range of 7.26-8.25 mm. For NS 4015, 62% of the kernels fell within the range 3.81-4.30 mm in width, but another 30% of the kernels were between 4.31 and 5.30 mm wide. In the NS 6010 hybrid, more than half of the kernels (54%) were between 3.56 and 5.05 mm in thickness, while 50% of the NS 640 kernels were from 4.06 to 5.05 mm in width.

The largest number (51%) of ZP 684 kernels was between 9.01 and 10.25 mm in length, and 29% were either 8.26 to 9.00 mm or 10.26 to 10.50 mm long (Fig. 3). In hybrid ZP 677, 50% of the kernels were between 10.51 and 11.50 mm in length; a similar result was found with ZP 434, in which 45% of the kernels were between 9.51 and 10.20 mm long.

Approximately 60% of the ZP 677 kernels were 6.51-7.25 mm wide, while 48% of the ZP 684 hybrid kernels were 7.51-8.50 mm wide. The width distribution of ZP 434 kernels was split into two parts: 30% of the kernels were in the range of 7.76-8.25 mm, while 34% fell between 7.26-7.75 or 8.26-8.50 mm. For the ZP 677 hybrid, 76% of the kernels were between 3.31 and 4.30 mm in thickness; the largest percentage (63%) of grains of ZP 434 were between 3.56 and 4.55 mm thick, and 60% of ZP 684 seeds were 3.31-5.55 mm wide.

The measured values for length, width and thickness of the 90 tested corn kernels from each of the hybrids fell into a normal distribution. This result was confirmed by Pierson’s chi-square test (Fig. 4) at the 0.95 confidence interval. This test assesses the random sampling data for a fixed distribution and the goodness of fit.
This result indicates that the sample size used in this study was sufficiently large and that the measurements were independent of each other. The three axial dimensions for all of the tested hybrids have peaks that are near the mean values, which is an indication that the axial dimensions are relatively uniform. The results agree with the measurements of Esref and Nazmi (2007) for a corn moisture content between 11.14 and 15.74% w.b. in their surveys of NS 6010, NS 4015 and ZP 677 hybrids. The length mean values for NS 6010 (10.43±0.66 mm) ZP 434 (9.78±0.63 mm), ZP 677 (11.25±0.82 mm) and NS 4015 (10.23±0.72 mm) are similar to the results reported by Karababa and Coskuner (2007) for kernels of sweet corn moisture content 9.12-13.24% w.b. According to the data in Fig. 4, the hybrids ZP 434, NS 6010, NS 4015 and NS 640 have the shortest length, while the smallest width dimension is seen with NS 6010 and ZP 677 and the lowest thickness with ZP 677. The largest mean length was observed with ZP 677 and NS 6010; for the width dimension, the largest was NS 4015, and for thickness, ZP 684, ZP 434 and NS 6010 had the highest values. This information is valuable with regard to the design of cleaning and separation equipment. For instance, the hybrid ZP 684 has the smallest mean length compared to the other hybrids, but it also has the greatest mean thickness and comparatively large width. These data indicate that the shape of ZP 684 kernels is ovate; however, the three axial dimensions of ZP 677 suggest that it has an oblong shape.
Single kernel mass and thousand kernel weight values and SD were highest for the NS 4015 hybrid, 0.3496±.389 g and 349.6±4.89 g respectively, followed by ZP 434 (0.3334±.056 g and 333.4±0.56 g) and ZP 684 (0.3330±.183 g and 333.0±1.83 g). The lowest single kernel mass and thousand kernel weight were observed for the NS 640 hybrid (0.2978±.048 g and 297.78±0.84 g). These results correspond to those of Pomeranz et al. (1984), who surveyed thousand kernel weight values for commercially dried dent and flint corn. Pan et al. (1996) reported single kernel mass values of 0.3111 and 0.3184 g for two varieties of dent corn dried at an air temperature of 30°C. However, the low value of this physical property in NS 6010 was the consequence of a larger distinction between length and width (the thickness is similar with NS 4015); therefore, NS 6010’s kernel shape is more cuboid. This shape results in less dense packing of the kernels. Similar results have been published by Esref and Nazmi (2007) for dent corn. On contrary, higher values of porosity were observed for popcorn (Karababa 2007) and for bulk sweet corn by Karababa and Coskuner (2007).

Table 1. The mean value and standard deviation ± SD of the physical properties of NS corn hybrids analysed by the Tukey HDS test at a statistical probability level of 95%

<table>
<thead>
<tr>
<th>Physical property</th>
<th>NS 640</th>
<th>NS 6010</th>
<th>NS 4015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm) L</td>
<td>9.71±0.60c</td>
<td>10.43±0.66b</td>
<td>10.23±0.72bc</td>
</tr>
<tr>
<td>Width (mm) W</td>
<td>7.37±0.83ab</td>
<td>7.43±0.60ab</td>
<td>8.32±0.75c</td>
</tr>
<tr>
<td>Thickness (mm) T</td>
<td>4.66±0.80bc</td>
<td>4.31±0.86abc</td>
<td>4.38±0.69abc</td>
</tr>
<tr>
<td>Geom. mean diam. Dg (mm)</td>
<td>6.91±0.52ab</td>
<td>6.90±0.53abc</td>
<td>7.18±0.51b</td>
</tr>
<tr>
<td>Surface area (mm²)</td>
<td>150.12±23.08ab</td>
<td>150.56±23.39ab</td>
<td>162.53±23.48b</td>
</tr>
<tr>
<td>Single kernel mass (g)</td>
<td>0.2978±0.84b</td>
<td>0.3202±8.27c</td>
<td>0.3496±3.89a</td>
</tr>
<tr>
<td>Kernel volume (mm³)</td>
<td>175.00±41.06ab</td>
<td>157.27±41.31ab</td>
<td>196.30±43.62b</td>
</tr>
<tr>
<td>Sphericity</td>
<td>0.71±0.06bc</td>
<td>0.66±0.06d</td>
<td>0.70±0.06cd</td>
</tr>
<tr>
<td>Porosity (-)</td>
<td>0.336±0.27</td>
<td>0.299±0.03</td>
<td>0.351±0.012</td>
</tr>
<tr>
<td>Static coeff. of friction (+)</td>
<td>0.200±0.40b</td>
<td>0.176±0.00ab</td>
<td>0.185±0.06ab</td>
</tr>
<tr>
<td>Moisture content (%) w.b.</td>
<td>12.5±0.48</td>
<td>13.5±1.56</td>
<td>13.9±0.31</td>
</tr>
<tr>
<td>Bulk density (kg/m³)</td>
<td>779.58±0.58</td>
<td>633.56±7.47</td>
<td>760.31±43.82</td>
</tr>
<tr>
<td>True density (kg/m³)</td>
<td>1175.65±0.61</td>
<td>900.94±12.40</td>
<td>1172.98±24.82</td>
</tr>
<tr>
<td>Weight of 1000 kernels (g)</td>
<td>297.8±0.84b</td>
<td>352.25±8.27c</td>
<td>349.63±3.89a</td>
</tr>
<tr>
<td>L/W</td>
<td>1.33±0.17bc</td>
<td>1.41±0.16b</td>
<td>1.24±0.13dc</td>
</tr>
<tr>
<td>L/T</td>
<td>2.41±0.39c</td>
<td>2.51±0.49bc</td>
<td>2.38±0.32bc</td>
</tr>
<tr>
<td>L/Dg</td>
<td>1.41±0.11bc</td>
<td>1.52±0.14b</td>
<td>1.43±0.09bc</td>
</tr>
</tbody>
</table>

Mean values±SD with the same letter are not significantly different (p<0.05)

The value of sphericity was the highest for the hybrid ZP 684 kernels (0.75±0.09), followed by that for the NS 640 (0.71±0.06) and NS 4015 (0.70±0.06) hybrids. The high value of sphericity observed with the ZP 684 hybrid was a result of small differences in its length and width dimensions, which result in the shape of each single kernel being spherical or oblong. However, the highest static coefficient of friction using a stainless steel sheet as a structural surface was observed with ZP 677 (0.2030±0.009), followed by NS 640 hybrid kernels (2.00±0.402). Other tested hybrids showed similar values in the range of 0.167±0.052 (ZP 434 hybrid) to 0.185±0.06 (NS 4015). These results correspond with the observations of Mohsenin (1980) and Esref and Nazmi (2007) for the same structural surface area and value of kernel moisture content.

The mean value of bulk density was the lowest for NS 6010 (633.56±7.47 kg/m³). The highest value, 784.75±4.82 kg/m³, was measured for the ZP 677 hybrid. Radosavljevic et al. (2000) reported a similar result for the same hybrid, as did Karababa and Coskuner (2007) in their study of dry sweet corn. The bulk density values for other tested hybrids ranged from 760.39±23.58 kg/m³ (NS 4015) to 779.58±0.58 kg/m³ (NS 640). Karwaljit Singh Sandhu et al. (2007) published similar bulk density values for nine African hybrids. The true density values were similar for hybrids ZP 434 (1112.0±10.97 kg/m³), ZP 677 (1176.63±6.84 kg/m³), ZP 684 (1158.61±5.85 kg/m³), NS 649 (1175.65±0.61 kg/m³) and NS 4015 (1172.98±24.82 kg/m³) and

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differed for NS 6010 (900.90±12.40 kg/m³). All of the physical properties in Tables 1 and 2 were measured at the values of seed moisture content (M (%) w.b.) presented in the tables.

Tables 2 and 3 also show the L/W L/T and L/Dg ratios. The L/T relationship exhibited the highest ratio, followed by L/Dg and L/W. The values of L/W ranged from 1.18 (ZP 684) to 1.41 (NS 6010). Karababa (2006) reported similar results. In our study, the L/Dg and L/W values were equal for the NS 4015 hybrid and were very close for ZP 677 and NS 640 seeds.

Different parameters were derived from the slow compression loading studies of the six tested hybrids at various moisture contents. The generalised force-head displacement curve shows the viscous-elastic response of the whole kernel during compression. At the beginning of compression, a linear relationship between force and displacement is observed because the seed offers low resistance toward compression; therefore, this part of the curve describes the elastic behaviour of the sample. The outer coat of the kernel could offer sufficient resistance to oppose the external force. As the extent of compression is increased, the inside core of the kernel offers considerable resistance, resulting in the non-linear part of the curve (the plastic region). The maximum value on the non-linear part of the curve is marked as the ultimate strength point, followed by the rupture point. Fig. 5 presents the typical compression loading behaviour of the ZP 684 hybrid at two values of seed moisture content obtained during the tests.

The mechanical behaviour of the kernel under uniaxial loading is a function of its moisture content. The presence of a larger amount of water molecules in the kernel increases its volume. The molecules enter the polymeric chain and force it to rearrange (Singh et al. 1991), which results in an effect on the compressive behaviour of the whole kernel. The ultimate strength force-moisture content curves for ZP 677, ZP 684 and ZP 434 hybrids are shown in Fig. 6. The test data of ultimate strength force values ranging from 351 N to 402 N at different moisture contents. Thus, according to the observed data, this hybrid’s composition is closer to that of semi-flint corn, but with a lower horny endosperm portion compared to ZP 434.

The mean ultimate strength force values are plotted against the moisture content of NS hybrid seeds in Fig. 7. The hybrids NS 640, NS 6010 and NS 4015 are the dent type; however, they did not demonstrate similar behaviour during compressive loading. The hybrid NS 640 shows high strength force values at lower moisture contents between 8% and 14% w.b. As kernel moisture content increases, the ultimate strength force curve has a decreasing tendency. For the NS 4015 hybrid, the data indicate that the values of ultimate strength force do not decrease with increasing moisture content, while hybrid NS 640 does show such a trend. The variation in the testing results of these three dent-type hybrids may be related to the quantity of horny endosperm and its position in the kernel structure. The highest value of strength point force, 455 N, was recorded for the NS 6010 hybrid at 28.6% w.b moisture content, while the hybrid NS 4015 showed a maximum force of 432 N at 25.4% w.b kernel moisture content. Thus, according to the results of compressive loading tests, the hybrids NS 4015 and NS 6010 exhibited mechanical behaviour that is more like that of semi-flint types of corn.

The deformation - head displacement at the ultimate strength point δh (mm) of ZP hybrid kernels increased slightly as the moisture content (MC) of the seed increased for all compression tests (Fig. 8). The relationship between these two physical properties can be expressed mathematically as follows:

\[-for \text{ZP 684}: \delta H=0.064 \text{MC} + 0.3944 \quad R^2=0.944\]
\[-for \text{ZP 677}: \delta H=0.0854 \text{MC} + 1.0242 \quad R^2=0.9334\]
\[-for \text{ZP 434}: \delta H=0.0711 \text{MC} + 1.3264 \quad R^2=0.9864\]
The lowest observed values of head displacement or kernel deformation were 1.25 mm to 2.25 mm for all hybrids at low values of seed moisture content. Similar results were reported by Burubai et al. (2008) for African nutmeg fruit and seed compressive load tests.

There was not a linear relationship between head displacement at the ultimate strength point and seed moisture content for the NS hybrids studied (Fig. 9). The highest head displacement value was observed for NS 6010 in the seed moisture content range of 20% to 29%. However, the lowest head displacement, from 1.16 mm to 2.15 mm, was measured with the NS 640 hybrid in the moisture content range of 8.1% to 32.2% w.b. For the NS 4015 hybrid, head displacement showed an increasing tendency from 2.26 mm to 3.65 mm as the moisture content of the seed increased. Similar trends in the variation of head displacement (kernel deformation) with moisture content under compressive loading were observed for sunflower seed and kernels by Gupta and Das (2000). Laskowski and Lysiak (1999) reported that deformation up to the rapture point increased as the seeds’ (horse bean, pea, lupine and vetch) moisture content increased.

Our data statistically confirm with a high coefficient of regression that there is a linear relationship between the secant modulus of elasticity and seed moisture content for all ZP hybrids studied (Fig. 10). The linear model shows a decreasing tendency of secant modulus as a function of seed moisture content for these three hybrids are as follows:

For ZP 434:  
$$E_s = -5.4063 \times MC + 281.41$$  
$$R^2 = 0.9399$$

For ZP 684:  
$$E_s = -6.8647 \times MC + 311.48$$  
$$R^2 = 0.8237$$

For ZP 677:  
$$E_s = -4.6633 \times MC + 241.78$$  
$$R^2 = 0.8668$$

The secant modulus of elasticity for three NS hybrids in our data was also fitted with linear correlation (Fig), but the coefficients of regression had lower values than in the case of the ZP hybrids. Based on the pooled data, the equations that express the secant modulus as a function of seed moisture content for these three hybrids are as follows:

For NS 640:  
$$E_s = -6.8887 \times MC + 349.96$$  
$$R^2 = 0.8668$$

For NS 4015:  
$$E_s = -2.5231 \times MC + 199.89$$  
$$R^2 = 0.545$$

For NS 6010:  
$$E_s = -2.4617 \times MC + 191.89$$  
$$R^2 = 0.6773$$

The hybrids NS 4015 and NS 6010 displayed similar secant modulus of elasticity values; compared to NS 640, the slopes of the regression lines were smaller, even though all three hybrids are dent types. The difference between NS 640 and the other hybrids in the dependence of the modulus of elasticity on moisture content may result from the ratio and spatial distribution of the floury and horny endosperm structure in the kernels. The corn endosperm is composed of starch and matrix (protein), both of which are natural polymeric substances. The mechanical properties of the kernel are affected by these two main structural components, the location and quantity of which result from the strain’s genetic attributes. Thus, every genetically distinct “new-born” corn hybrid produced by researchers is likely to show unique compressive loading behaviour.

**CONCLUSION**

The mean values of length, width and thickness of six tested corn hybrids fell within the range of 9.60-11.50, 7.04-8.50 and 3.87-5.55 mm, respectively. The geometric mean diameter of the kernels ranged from 6.72 to 7.18 mm; their surface areas varied.
from 141.95 to 162.53 mm$^3$, and single kernel volumes ranged from 159.59 to 196.30 mm$^3$. The measured sphericity of the kernels was between 0.60 and 0.75, while porosity measurements showed a minimum value of 0.299 and a maximum value of 0.351. The bulk and true densities were between 6.33-784.75 kg/m$^3$ and 900.94-1176.63 kg/m$^3$, respectively, while the coefficient of friction varied from 0.167 to 0.200.

In general, kernel compressive strength properties decreased as the moisture content increased. This trend was confirmed by plotting the mean values of secant modulus of elasticity versus the seed moisture contents for all tested hybrids. As expected no significant differences in secant modulus of elasticity values were observed between semi-flint (ZP 434) and dent-type hybrids (ZP 684, NS 640).

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