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Physical properties and compression loading behaviour of corn seed**

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Abstract. The aim of this study was to acquire data on the physical properties and compression loading behaviour of seed of six corn hybrid varieties. The mean values of length, width, thickness, geometric diameter, surface area, porosity, single kernel mass, sphericity, bulk and true density, 1 000 kernel mass and coefficient of friction were studied at single level of corn seed moisture content. The calculated secant modulus of elasticity during compressive loading for dent corn was 0.995 times that of the semi-flint type; there were no significant differences in the value of this mechanical property between semi-flint and dent corn varieties. The linear model showed a decreasing tendency of secant modulus of elasticity for all hybrids as the moisture content of seeds increased.

Keywords: corn, physical properties, secant modulus of elasticity

INTRODUCTION

The importance of corn processing industries is increasing. Recent concepts in corn marketing 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. Parameters useful in the evaluation and recognition of such specific values include, among others, the physical properties of corn kernels. These properties include the three perpendicular dimensions, which affect cleaning and grading processing, the kernel surface, which affects drying, sphericity and thousand kernels mass, which affect packaging of seed, bulk density (affecting storage capacity), true density (affecting vehicle load), porosity (aeration possibility, drying), coefficient of static 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 Karababa (2006) reported similar results on popcorn kernels; sweet corn kernel properties were reported by Karababa and Coskuner (2007) and those of dent corn by Esref and Nazmi (2007). 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. 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 and entangled to form supra- and sub-molecular structures Gaytan-Martinez *et al.* (2006). Proteins form a matrix surrounding and embedding the starch granules. The endosperm of corn, which is horny and floury, is a complex mixture of starch granules and protein. 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. It is well known that floury endosperm is softer and easier to break than horny endosperm. The study of the behaviour of the non-homogeneous organic structure of corn kernels under 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. There are published many papers concerning with physical properties of biomaterials (Balasubramanian *et al*., 2012; Barnwal *et al*., 2012; Gharibzahedi *et al*., 2011; Izli *et al*., 2009; Singh *et al*., 2012).

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The aim of this study was to provide new information describing the primary physical properties of the seeds of six domestic corn hybrids. The compression loading behaviour of corn seeds at different moisture contents was also studied.

MATERIALS AND METHODS

Six corn hybrids (ZP 434, ZP 677, ZP684, NS 640, NS 6010 and NS 4015) from the 2009 harvest season 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 434, which is semi-flint class. Approximately 5 kg of each hybrid seed in plastic bags were delivered from 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 single level of 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.

The moisture content (MC) 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 (1987). Three replicates were measured for each sample. The samples were oven-dried at 103°C for 72 h and then weighed. Sample mass was recorded using a digital balance with an accuracy of ± 0.001 g (Kern, PLJ360-314). The moisture content (kg kg^{-1}) 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. A calliper with accuracy of ±0.01 mm was used to measure three kernel dimensions, length, L, width, W, and thickness, T (mm). A sample of 90 kernels was randomly selected from the bulk of each corn hybrid. The geometric mean diameter, Dg (mm), sphericity, Φ (mm mm^{-1}) and surface area of a single kernel, S (mm^2) were calculated from the three principal dimensions (Babić and Babić, 2011; Babić *et al.,* 2011; Kiani Deh Kiani *et al.,* 2008; Keramat Jahromi *et al.,* 2008; Mohsenin, 1980). An electromechanical kernel counter (Numigral, NUM 3, Tripette et Renaud) and a digital balance were used to measure the thousand kernel mass (g). The liquid displacement method was used to determine seed true density, ρ_t (kg m^{-3}). The bulk density measurement, ρ_b (kg m^{-3}), was performed by measuring the kernel mass using a digital balance and then measuring the total volume in a graduated cylinder (Republic of Serbia Directive, 1987). The porosity, p, was calculated as the relationship between the bulk density, ρ_b, and the true density, ρ_t. The thousand seed mass was determined by counting 100 kernels and weighing them on an electronic balance; the result was multiplied by 10 to give the mass of 1 000 kernels. The coefficient of static friction was measured for one structural material only, a galvanized metal sheet. This test was repeated three times. The friction coefficient, μ, was calculated as the tangent of the measured tilt angle.

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. Stress is the external force upon the unit specimen cross-sectional area, Ao (m^2), the unit is N 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 regular shape such as that of a cylinder or a cube. Biomaterials under compression change in length. The ratio between displacement, δ (mm) and initial specimen length, Lo (mm) is strain, ε (m m^{-1}). The stress-strain diagram is a graphical representation of simultaneous values of force and head displacement recorded during testing. 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 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 (Mohsenin, 1980), it is possible to calculate the secant modulus of elasticity, Es (N mm^{-1}), as a ratio of ultimate strength point force and head displacement. For each hybrid, seeds with four different seed moisture contents were tested (Table 1). Fifteen replicate tests were conducted for each hybrid at four different moisture contents. 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^{-1}, while during compression it was 30 mm min^{-1}. The range of load applied by the measuring head was from 0 to 500 N. The results of the study were statistically processed using Pierson chi-test and Tukey HSD test (StatSoft, Inc., 2010).

Table 1. Corn moisture contents of six hybrids used for compression loading test

Hybrid	Moisture content (kg kg^{-1}, w.b.)			
NS640	0.081	0.121	0.264	0.322
NS6010	0.148	0.223	0.286	0.301
NS4015	0.143	0.167	0.254	0.326
ZP684	0.110	0.123	0.245	0.332
ZP434	0.129	0.170	0.246	0.305
ZP677	0.136	0.183	0.256	0.309

RESULTS AND DISCUSSION

The frequency distribution of the three kernel dimensions in 90-seed samples of all hybrids are presented in Figs 1 and 2. The moisture contents of all hybrids are presented in Table 1. In the NS 6010 hybrid, the largest percentage (53%) of the kernels were long, between 9.51-10.5 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. For NS 4015, 62% of the kernels fell within the range 3.81-4.30 mm in width. In the NS 6010 hybrid, more than half of the kernels (54%) were between 3.56 and 5.05 mm in thickness. The largest number (51%) of ZP 684 kernels were between 9.01 and 10.3 mm in length (Fig. 2). In hybrid ZP 677, 50% of the kernels were between 10.5 and 11.5 mm in length. Approximately 60% of the ZP 677 kernels were 6.51-7.25 mm wide. The width distribution of ZP 434 kernels was split into two parts; 30% of the kernels were in the range of

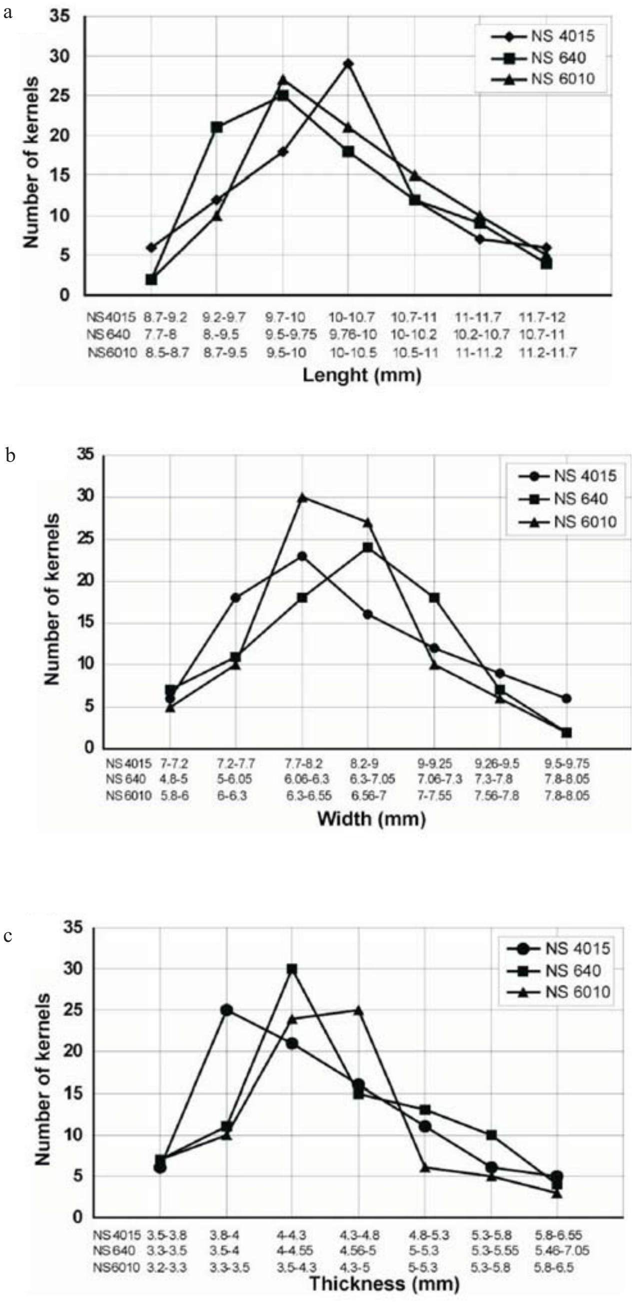

Fig. 1. Frequency distribution curves of seed dimensions (mm) of three NS corn hybrids: a – length, b – width, c – thickness.

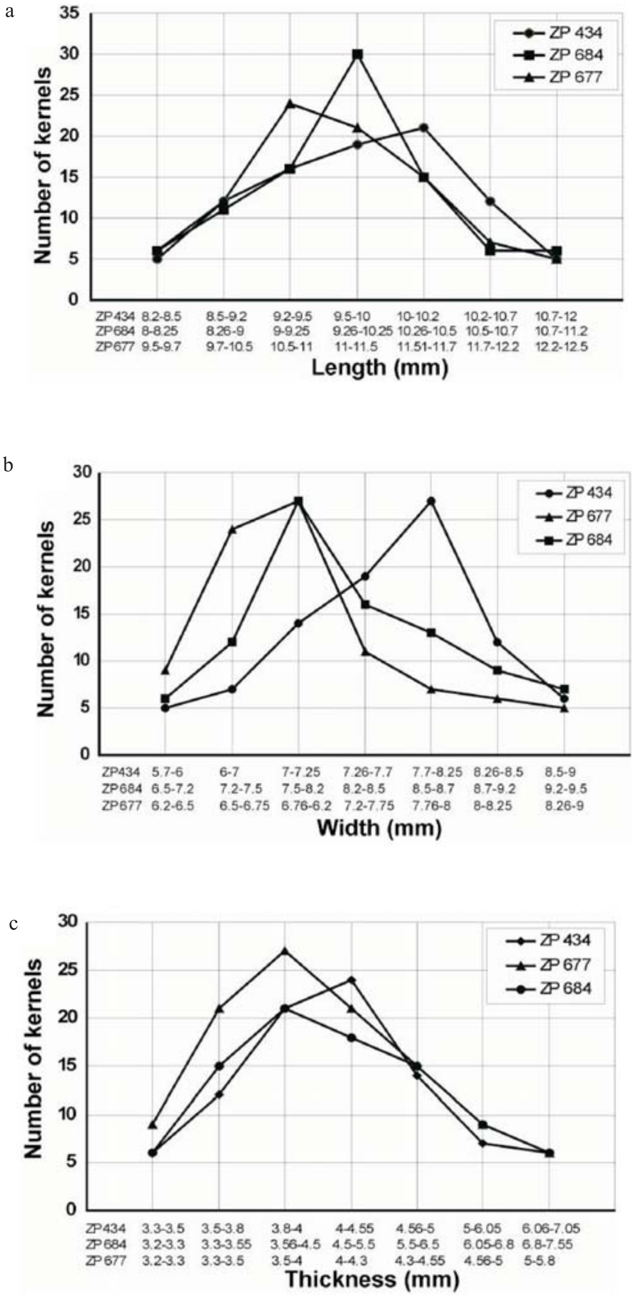

Fig. 2. Frequency distribution curves of seed dimensions (mm) of three ZP corn hybrids: a – length, b – width, c – thickness.

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 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 chi-square test at the 0.95 confidence interval (Fig. 3). 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 0.111 and 0.157 kg kg^{-1} w.b. 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 0.0912-0.1324 kg kg^{-1} w.b. According to the data in Fig. 3, 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, ZP434 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. The mean values of the three axial dimensions, together with other physical properties, are presented in Table 2. Because of the advantage of comparing the mean of every measurement to the mean of every other

Table 2. The mean value and standard deviation of the physical properties of NS and ZP corn hybrids analyzed by Tukey HSD test at a statistical probability level of 95%

Physical property	NS 640	NS 6010	NS 4015	ZP 434	ZP 677	ZP 684
Length (mm)	9.71±0.60b	10.43± 0.66a	10.23±0.72ab	9.78±0.63b	11.25±0.82a	9.60±0.87b
Width (mm)	7.37±0.83a	7.43±0.60a	8.32±0.75b	7.65±0.65a	7.04±0.60b	8.19±0.67c
Thickness (mm)	4.66±0.80a	4.31±0.86a	4.38±0.69a	4.33±0.43ab	3.87±0.58a	4.81±1.26b
Geometric mean diameter (mm)	6.91±0.52ab	6.90±0.53abc	7.18±0.51b	6.83±0.44ab	6.72±0.32a	7.15±0.56b
Surface area (mm^2)	150.12±23.1a	150.6±23.4a	162.5±23.5a	147.0±19.0ab	142.0±13.6a	161.7±25.9b
Single kernel mass (g)	0.298±0.008b	0.320±0.008c	0.350±0.004a	0.333±0.006a	0.324±0.010a	0.333±0.002a
Kernel volume (mm^3)	175.0±41.06a	175.3±41.3a	196.3±43.6a	168.7±32.7ab	159.6±23.2a	195.1±47.7b
Sphericity (mm mm^{-1})	0.71±0.06ba	0.66±0.06a	0.70±0.06a	0.70±0.05b	0.60±0.06a	0.75±0.09b
Porosity (%)	0.336±0.27a	0.299±0.03b	0.351±0.012a	0.315±0.046a	0.333±0.045a	0.331±0.13a
Static coefficient of friction	0.200±0.402b	0.176±0.0ab	0.185±0.06ab	0.167±0.052a	0.203±0.009b	0.176±0.0089ab
Moisture content (kg kg^{-1} w.b.)	0.125±0.005	0.135±0.016	0.139±0.031	0.121±0.005	0.134±0.018	0.116±0.045
Bulk density (kg m^{-3})	779.6±0.58a	633.6±7.47b	760.3±23.6a	762.3±12.48b	784.8±4.82a	775.2±2.89b
True density (kg m^{-3})	1175.7±0.61a	900.9±12.40b	1173.0±24.82a	1112.0±10.97a	1176.6±6.84b	1158.6±3.85c
Mass of 1000 kernels (g)	297.8±8.43b	320.3±8.27c	349.6±3.89a	333.4±5.65a	324.4±9.61a	333.8±1.83a
L/W	1.33±0.17ab	1.41±0.16b	1.24±0.13a	1.29±0.15ab	1.61±0.20a	1.18±0.13b
L/T	2.41±0.39a	2.51±0.49ba	2.38±0.32ba	2.33±0.41b	2.98±0.58a	2.15±0.65b
L/Dg	1.41±0.11a	1.52±0.14a	1.43±0.09a	1.44±0.11b	1.68±0.16a	1.35±0.16b

Mean values ± standard deviation with the same letter are not significantly different ($p<0.05$).

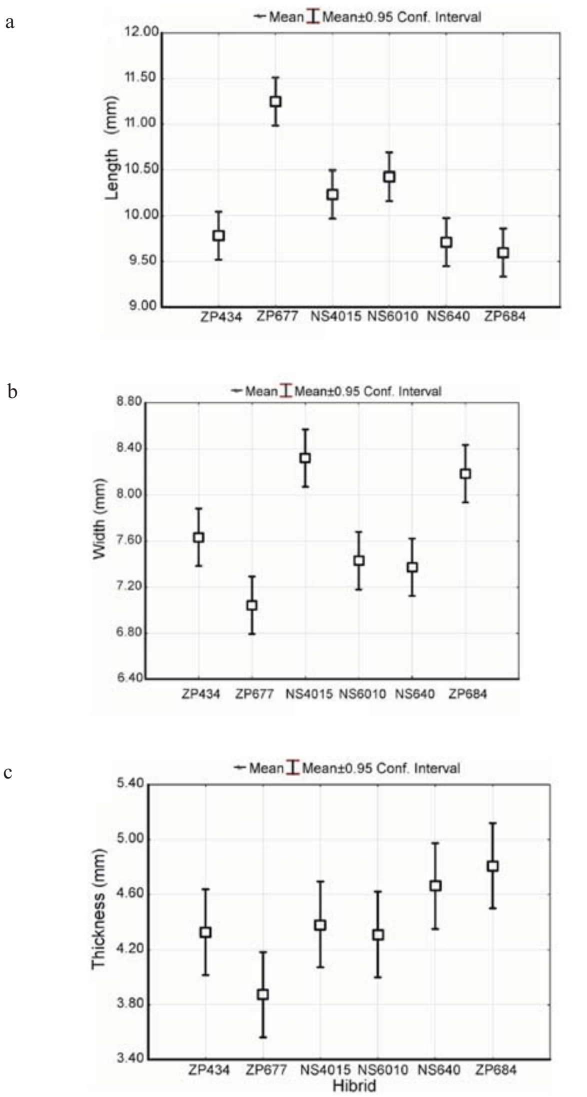

Fig. 3. Mean values of: a – length, b – width, c – thickness of corn hybrid seeds assessed by Pierson chi-square test.

measurement simultaneously, Tukey honestly significant difference (HSD) test was employed. The values of the geometric mean diameters ranged from 6.83±0.44 mm (ZP 434) to 7.18±0.51 mm (NS 4015), similar to the results of the study of sweet corn physical properties reported by Karababa and Coskuner (2007) and the measured data for dent corn kernels presented by Esref and Nazmi (2007). The surface area varied from a low value of 147.0±19.0 mm^2 (ZP 434) to a high value of 162.5±23.5 mm^2 (NS 4015). The highest kernel volume was obtained for NS 4015 (196.3±43.6 mm^3); the lowest kernel volume was observed with ZP 677 (159.6 ±23.2 mm^3). Karababa and Coskuner (2007) reported a similar volume value for sweet corn kernels. Single kernel mass and thousand kernel mass values and SD were highest for the NS 4015 hybrid. Karababa (2006) results for popcorn 1 000 kernel mass values are significantly lower. Similar data were published by Coskun *et al.* (2006) for sweet corn seed. The value of sphericity was the highest for the hybrid ZP 684 kernels (0.75±0.09). The mean value of sphericity observed for NS 6010 (0.66±0.06) is in agreement with the results of Karababa and Coskuner (2007) for sweet corn. However, Esref and Nazmi (2007) concluded that the sphericity of dent corn with moisture content from 0.111 to 0.241 kg kg^{-1} d.b. was 0.675-0.689. The porosity of bulk corn seed ranged from 0.296±0.03 (NS 6010) to 0.336±0.27 (NS 640) and 0.351±0.012 (NS 4015). The high porosity value of NS 4015 was the result of small differences in its length and width dimensions, which indicated spherical or oblong kernel shape. However, the low value of this physical property in NS 6010 was the consequence of a larger distinction between length and width; therefore, NS 6010 kernel shape is more cuboid. This shape results in less dense packing of the kernels.

The mean value of bulk density was the lowest for NS 6010; the highest value was measured for the ZP 677 hybrid. Karababa and Coskuner (2007) reported results that are close to measured ones, and the group of authors (Kawaljit *et al.*, 2007) published similar bulk density values for nine African hybrids. The true density values were similar for hybrids ZP 434, ZP 677, ZP 684, NS 649 and NS 4015 and differed for NS 6010.

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). In this 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.

The highest coefficient of static friction using a stainless steel sheet as a structural surface was observed with ZP 677 (0.203±0.009), followed by NS 640 hybrid kernels (2.00± 0.402). 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.

Different parameters were derived from the slow compression loading studies of the six tested hybrids at various moisture contents. Figure 4 presents the typical compression loading behaviour of the ZP 684 hybrid at two values of seed moisture content.

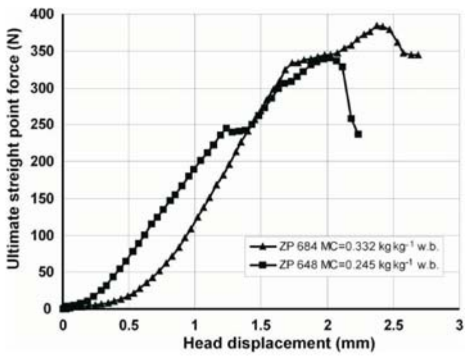

Fig. 4. Force and deformation (head displacement) curves of ZP 684 hybrid seeds at two moisture content values.

The mechanical behaviour of the kernel under uniaxial loading is a function of its moisture content. The water molecules enter the polymeric chain and force it to rearrange (Burubai *et al.*, 2008), 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. 5. The test data show that the semi-flint hybrid ZP 434 displayed the highest force values at all kernel moisture contents. The force values ranged from 408 to 482 N. According to Mohsenin (1980) flint and semi-flint corn kernels exhibit higher compressive properties than dent kernels. It is well known that flint corn has a higher proportion of protein matrix. This characteristic increases the bonds between matrix and starch granules, causing the granules to be closely packed compared with the floury endosperm. The other two ZP hybrids studied are dent types that possess different starch, protein and oil portions. These results are similar to data published by Mohsenin (1980). According to the observed data, hybrid ZP 677 composition is closer to that of semi-flint corn, but with a lower horny endosperm portion compared to ZP 434. The compression load behaviour of dent type ZP 684 corresponds to the results published by Seifi and Alimardani (2010). This hybrid exhibits the decreasing trend of strength force as moisture contents increase. Tarighi *et al.* (2011) reported the same behaviour of DCC 370 hybrid. They observed the rapture force values from 347.5 to 226.2 N.

The mean ultimate strength force values are plotted against the moisture content of NS hybrid seeds in Fig. 6. All hybrids are of 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. As kernel moisture content increases, the ultimate strength force curve has a decreasing tendency.

The highest value of strength point force, 455 N, was recorded for the NS 6010 hybrid at 0.286 kg kg^{-1} w.b. moisture content, while the hybrid NS 4015 showed a maximum force of 432 N at 0.254 kg kg^{-1} 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, δ_H (mm) of ZP hybrid kernels increased slightly as the moisture content MC of the seed increased for all compression tests (Fig. 7). The lowest observed values of head displacement were 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 no linear relationship between head displacement at the ultimate strength point and seed moisture content for the NS hybrids studied (Fig. 8).

The highest head displacement value was observed for NS 6010 in the seed moisture content range of 0.20 to 0.29 kg kg^{-1}. However, the lowest head displacement was measured with the NS 640 hybrid in the moisture content range of

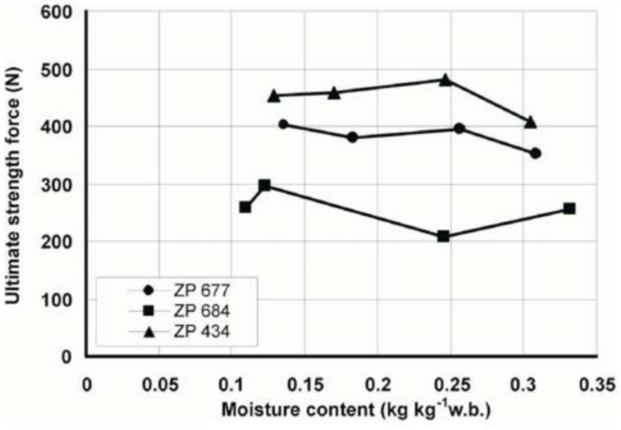

Fig. 5. Ultimate strength force versus seed moisture content of ZP hybrids.

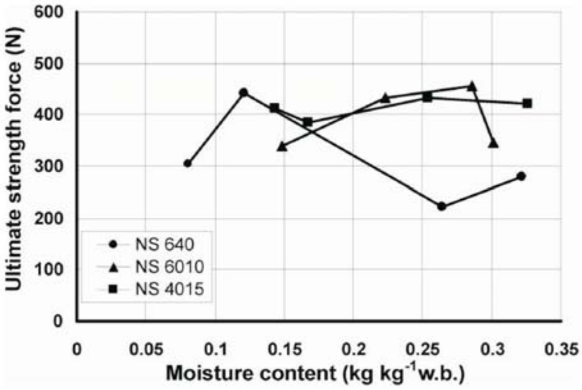

Fig. 6. Ultimate strength force versus seed moisture content during compressive testing of NS hybrids.

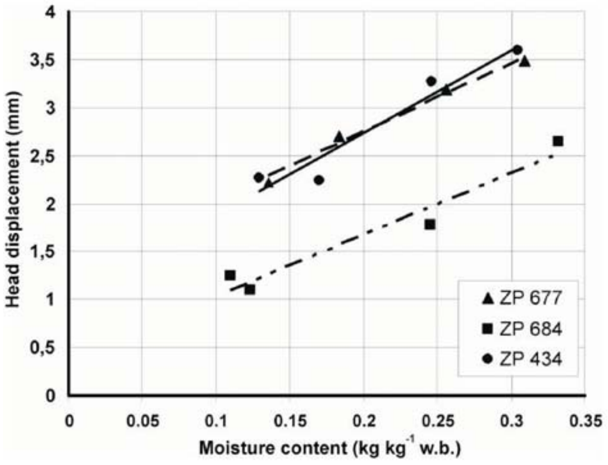

Fig. 7. Relationship between head displacement and moisture content for ZP hybrids (ZP 684: δ_H=6.3979, MC+0.3944, R^2=0.944; ZP 677: δ_H=8.5447 MC+1.0242, R^2=0.9334; ZP 434: δ_H=7.1091 MC+1.3264, R^2=0.9864).

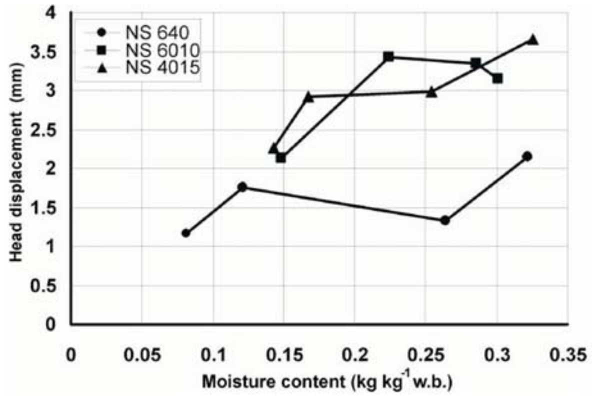

Fig. 8. Relationship between head displacement and moisture con-

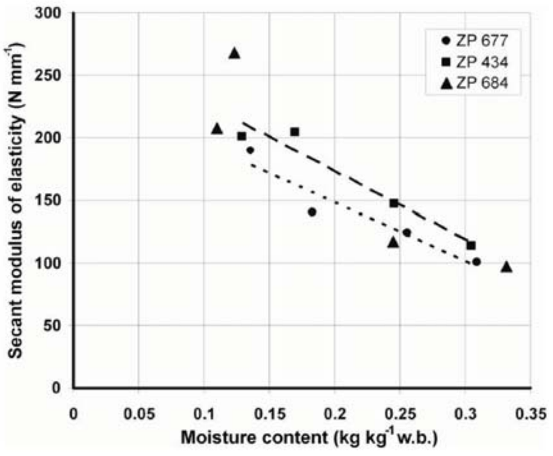

Fig. 9. Secant modulus of elasticity of ZP hybrids (ZP 434: Es = -540.63 MC + 281.41, R^2 = 0.940; ZP 684: Es = -686.47 MC+311.48, R^2 = 0.824; ZP 677: Es = -466.33 MC + 241.78, R^2=0.911).

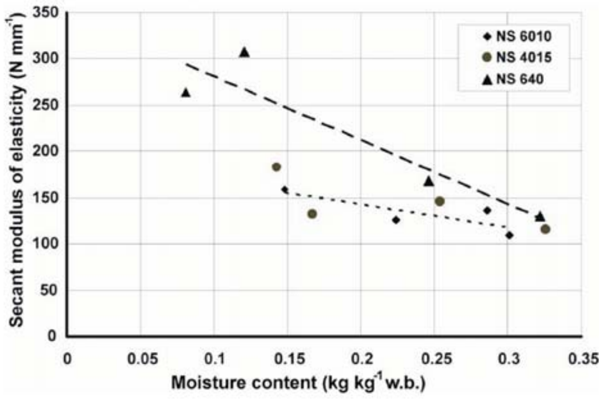

Fig. 10. Secant modulus of elasticity of NS hybrids (NS 640: Es = -688.87 MC + 349.96, R^2=0.867; NS 4015: Es = -252.31 MC + 199.89, R^2=0.545; NS 6010: Es = -246.17 MC + 191.89, R^2=0.677).

0.081 to 0.322 kg kg^{-1} w.b. For the NS 4015 hybrid, head displacement showed an increasing tendency as the moisture content of the seed increased.

The measured 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. 9).

The linear model shows a decreasing tendency of secant modulus of elasticity for all ZP hybrids as the moisture content of the seed increases. There were no significant differences in the values of the secant modulus of elasticity between the semi-flint ZP 434 and the dent-type hybrid ZP 684. The secant modulus of elasticity for the ZP 684 hybrid was 0.995 times that of the ZP 434 values. Mohsenin (1980) reported modulus of roughness values for dent corn that were approximately 0.71 times those obtained for flint corn.

The secant modulus of elasticity for three NS hybrids was also fitted with linear correlation (Fig. 10), but the coefficients of regression had lower values.

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 mechanical properties of the kernel are affected by these two main structural components, the location and quantity of which result from the strain genetic attributes. Thus, every genetically distinct ‘newborn’ corn hybrid produced by researchers is likely to show unique compressive loading behaviour.

CONCLUSIONS

1. 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.

2. The geometric mean diameter of the kernels ranged from 6.72 to 7.18 mm; their surface areas varied from 142.0 to 162.5 mm^2, and single kernel volumes ranged from 159.6 to 196.3 mm^3.

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.

4. The bulk and true densities were between 633.6-784.8 and 900.9-1 176.6 kg m^{-3}, respectively, while the coefficient of friction varied from 0.167 to 0.200.

5. 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 semiflint (ZP 434) and dent-type hybrids (ZP 684, NS 640).

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