Physical Properties of Various Fractions in Commercial Corn Samples[1]

A. SONG,[2] D. S. CHUNG,[2] C. K. SPILLMAN,[2] and S. R. ECKHOFF[3]

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ABSTRACT

Separation of fractions in a grain mixture is usually based on physical and aerodynamic characteristics of grain. In this study, commercial corn samples were separated into whole kernels, broken kernels, and light materials. Air flotation velocity, length, width, thickness, weight, density, and moisture were measured. Geometric dimensions and air flotation velocity both followed Weibull distribution. Through cumulative distribution analyses, we were able to see how these properties could be used to obtain complete separation of whole kernels from a given sample. Results indicated that complete removal of broken kernels was infeasible, whereas light materials could be aspirated from whole kernels completely. The effects of moisture content and particle size on densities and porosity were investigated. True density linearly decreased with an increase in moisture content. Bulk density was a third-order polynomial function of moisture. As particle sizes decreased, measured true density and porosity increased and bulk density decreased.

Shape, size, surface area, volume, density, and porosity are important physical characteristics for product behavior analysis of agricultural materials. Grain cleaning and separating processes usually take advantage of differences in shape, size, and aerodynamic properties for various components in grain mixtures. The successful setup of a separation process or the optimal selection of cutting line (defined as the numerical value of a physical property that cuts the mixture into two parts) for a given characteristic depends on knowledge of the numerical interval in which the differentiating property is located.

Nelson (1980), Edison and Brogan (1972), and Goss (1965) reported geometric measurements of whole kernels of corn. Early aerodynamic studies of corn were published by Uhl and Lamp (1966), Hawk et al (1966), Goss (1965), Garrett and Brooker (1965), and Bilanski et al (1962). Flotation velocities of corncobs, husks, straw, and leaves were reported by Smith and Stroshine (1955). However, data could not be found for broken kernels. Furthermore, because of the small sample size used, no distribution function for any physical property has been given except by Goss (1965).

Besides shape, size, and aerodynamic properties, physical properties such as volume, density, and porosity are also important since they closely tie to storage, handling, and aeration processes. In addition, test weight (bulk density) is an important grading factor in the *Official United States Grain Standards* (USDA 1987), and it influences selling price. Since moisture content is a fundamental factor affecting test weight (Nelson 1980) and marketing of grain, relationships between bulk density and moisture content are of interest.

Information on moisture-dependent bulk and true densities has been presented by a number of authors (Chung and Converse 1971, Gustafson and Hall 1972, Hall 1972, Hall and Hill 1974, Brusewitz 1975, Nelson and Stetson 1976). Nelson's (1980) work describes the relationship between true or bulk density and moisture content as a third-order polynomial equation with a very high correlation coefficient. Unfortunately, few data have been published on the variation of true and bulk densities of different size fractions with respect to moisture content.

The objectives of this study were 1) to determine the particle size (length, width, and thickness), flotation velocity, and weight of each particle in a given sample and their distribution; 2) to investigate what combination of these properties would give a complete separation of whole kernels from a sample; and 3) to evaluate the effects of moisture content and particle size on true and bulk density and porosity.

MATERIALS AND METHODS

Geometric Dimensions and Flotation Velocity Measurements

Five 250-g corn samples graded by the Federal Grain

[1]Contribution no. 89-453-J of the Kansas Agricultural Experiment Station.

[2]Graduate research assistant and professors, respectively, Department of Agricultural Engineering, Kansas State University, Manhattan 66506.

[3]Associate professor, Department of Agricultural Engineering, University of Illinois, Urbana 61801.

Inspection Service (FGIS) were obtained. We separated each sample by hand into three fractions: whole kernels, defined as those with less than one-fourth of the kernel removed; broken kernels, defined as three-fourths or less of a whole kernel; and light materials, including corncobs, husks, straw, and leaves but not dust. Since the light material sample was too small to make a distribution analysis, an additional 45 kg of corn was obtained from the Manhattan Milling Company. The light materials were picked out by hand and added to those removed from the FGIS samples.

The length, width, and thickness of each particle were determined using a digital micrometer (Fowler Digitrix II marketed by Fowler Company, Newton, MA). Each particle was weighed on a Mettler PM200 digital balance. The accuracies of the micrometer and balance were 0.001 mm and 0.001 g, respectively, and each was interfaced to a personal computer to record the data on floppy disks.

Special equipment—consisting of two boxes, a fan with a variable speed motor, and a tapered column—was constructed for measuring flotation velocity. The air was pulled by a blower through a standard 50.8-mm (2-in.) nozzle installed in one side of box I (length × width × height = 0.9 × 0.9 × 0.9 m), and exhausted into box II (0.8 × 0.7 × 0.5 m). The air was stabilized in box II and then allowed to exit up through a tapered column (1.5-m high, 1.82° slope, and 75.2-mm diameter at the smaller end). The tapered column provided a variable cross-sectional area permitting a continuously varying air velocity along the column for a single volumetric flow rate. A tape measure was attached to the side wall of the column to observe the floating height of a kernel. The pressure drop across the nozzle was measured by a micromanometer with an accuracy of 0.00254 mm of water.

Density Measurement

The 45 kg of commercial corn was first cleaned using a Labofix Model Mini-Cleaner and Grader (Emceka-Gompper GmbH & Co., West Germany). The dust particles were removed by the aspirator in the machine. Other light materials had been picked by hand earlier and used for geometric dimension and flotation velocity analysis. Then the sample was separated into broken and whole kernels. The broken kernels were screened using U.S. Standard Sieves nos. 3½, (5.61 mm), 4 (4.76 mm), 5 (4.0 mm), and 6 (3.35 mm). About 1 kg of corn in each size fraction was used in all the tests.

The bulk density of each fraction was determined with a Boerner test weight apparatus (USDA 1953). True densities were calculated from the exact weight of the samples, and kernel-volume measurements made with a pycnometer (Multipycnometer Quantachrome Corp.) using helium gas.

Bulk and true density tests were made at moisture levels from 11 to 25% wet basis. All measurements were repeated three times. Moisture levels of corn were increased by adding the calculated amount of water to the samples and mixing thoroughly. Samples were stored in an incubator at 5°C for one week and stirred once a day to insure uniform water absorption.

Moisture Determination

The moisture content of various fractions of corn was determined by the standard air-oven method (AACC 1983). A two-stage procedure was followed for moisture above 16%. For comparison, two 15-g samples of whole kernels were also dried at 103°C for 72 hr (ASAE 1987). The results from the two procedures were in good agreement (within 0.2%).

RESULTS AND DISCUSSION

Geometric Dimensions

Particle length is defined as the longest dimension. Width is the longest dimension perpendicular to length. Thickness is the longest dimension perpendicular to the length by width plane. The mean values and associated deviations are presented in Table I for whole kernels, broken kernels, and light materials.

The collected data were divided into discrete ranges and distributions were obtained. Figure 1 shows cumulative percentage of undersized kernels versus width. Statistical regression analyses were made to fit the data using both linear and nonlinear functions, with the Weibull distribution best simulating the data. The Weibull function is:

$$W(\%) = 100\,\{1 - \exp[-\alpha(x - \gamma)^n]\} \tag{1}$$

where γ = position parameter, α = scale parameter, n = shape parameter, x = random variable (length, width, thickness, etc.), and W = percentage of undersized kernels.

Preliminary regression analyses indicated that the regression parameters for the five samples studied (α, γ, and n) were not significantly different. Therefore, data for the five samples were pooled together. The constants (α, γ, and n), obtained by fitting equation 1 to experimental data, using a software called "Regres," and the corresponding correlation coefficients for different geometric dimensions are presented in Table II for whole kernels, broken kernels, and light materials.

Figure 1 indicates that the cumulative distribution of the width of each of the three fractions overlap, and complete separation is unlikely if width is used as a differentiating parameter. Plots of cumulative distribution against length and thickness showed a similar pattern. Thus, whether the cleaning unit has a round-hole screen, a slotted screen, or an indented cylinder, it is infeasible to completely separate whole kernels from the remainder of the sample.

The dashed line on Figure 1 is drawn at a width equal to 4.76 mm (12/64 in.), which USDA (1987) defines as the upper limit of broken corn and foreign material (BCFM) in the *Official United States Grain Standards* (USDA 1987). When using a 4.76-mm round-hole sieve, at most, 9% of the broken kernels and 37% of the light materials of the samples in this study can be separated from whole kernels. A line at a width equal to 6.35 mm (16/64-in.) was also drawn on Figure 1 (dotted line), which illustrates that about 50% of the broken corn and 72% of the light materials can be separated using this opening.

The possibility of using two geometric parameters to separate

TABLE I
Dimensions (mean ± SD) for Whole Kernels, Broken Kernels, and Light Materials

Dimension	Whole Kernels	Broken Kernels	Light Materials
Length, mm	11.564 ± 1.483	8.618 ± 2.057	6.531 ± 2.088
Width, mm	7.972 ± 0.929	5.588 ± 1.287	4.553 ± 1.471
Thickness, mm	4.630 ± 0.785	3.419 ± 0.863	3.091 ± 0.934

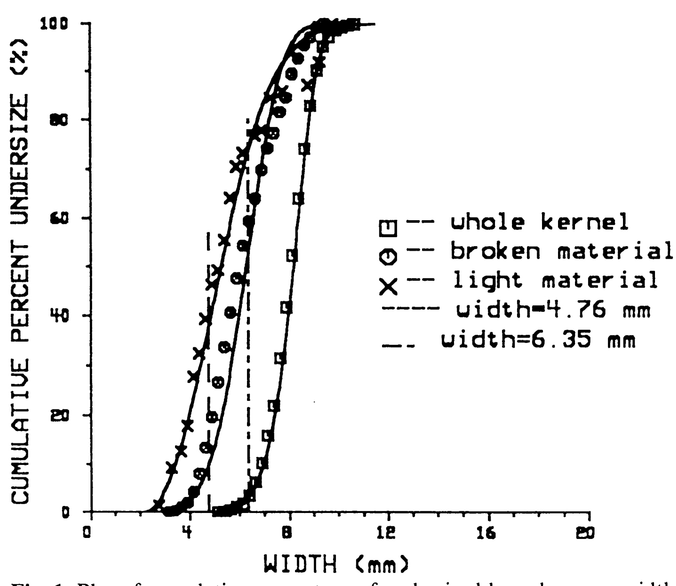

Fig. 1. Plot of cumulative percentage of undersized kernels versus width.

whole kernels from broken kernels in two stages is considered. Figure 2 is a plot of width versus length for both whole and broken kernels. There are 661 data points for whole kernels and 543 data points for broken kernels. Two straight lines, one vertical at length = 9.5 mm and one horizontal at width = 6.35 mm, are drawn on Figure 2. The two lines divide the data points into four quadrants with only the materials falling in quadrant IV collected. Therefore, the broken kernels in quadrant IV, 12% of the total, cannot be separated from the whole kernels. Quadrants I, II, and III of the bottom graph show that 10% of the whole kernels will be removed together with broken corn. Figure 3 is a similar plot for light materials. There are 145 data points for light materials. Again, if width and length are selected as differentiating parameters and if the cutting lines are set as on Figure 3, about 5% of the light materials will be retained in the group of whole kernels.

TABLE II
Constants in Cumulative Distribution Functions for Geometric Dimensions of the Materials Studied

Material/ Dimension	Equation: $W(\%) = 100\{1 - \exp[-\alpha(x-\gamma)^n]\}$ γ	α	n	R^2
Whole kernels				
Length, mm	5.0	9.166×10^{-6}	5.943	0.9987
Width, mm	3.0	6.656×10^{-6}	7.02	0.9959
Thickness, mm	2.5	4.411×10^{-2}	3.393	0.9329
Broken kernels				
Length, mm	3.0	2.957×10^{-4}	4.155	0.9898
Width, mm	2.0	6.853×10^{-3}	3.527	0.9695
Thickness, mm	0.0	1.408×10^{-4}	6.244	0.9674
Light materials				
Length, mm	3.0	1.684×10^{-2}	2.420	0.9574
Width, mm	2.0	4.774×10^{-2}	2.260	0.9584
Thickness, mm	1.0	6.594×10^{-2}	2.458	0.9486

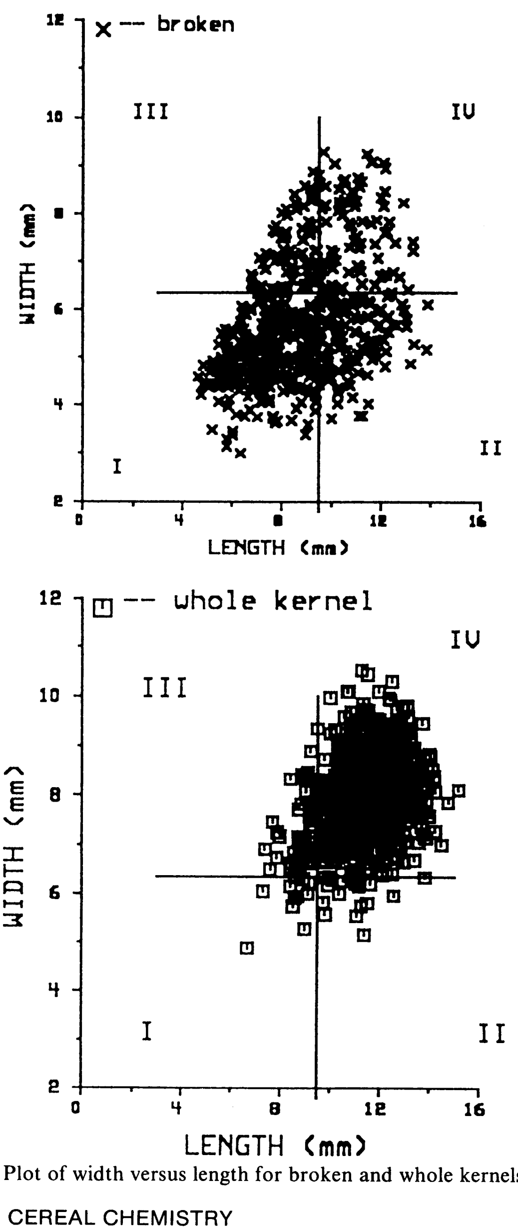

Fig. 2. Plot of width versus length for broken and whole kernels.

Plots of width versus thickness and thickness versus length were made for whole kernels against broken kernels and whole kernels against light materials. Analyses indicted that complete separation of whole kernels from broken corn and light materials was not feasible using geometric parameters, regardless of the dimension combinations used. When a certain tolerance was set, the proper cutting lines could be selected to meet the requirement of a maximum percentage of allowable broken corn while minimizing the amount of whole kernel loss.

Flotation Velocity

The mean values of air flotation velocity are 9.72 meters per second (m/sec) for whole kernels, 8.06 for broken kernels, and 5.28 for light materials (Table III). Cumulative distribution of air flotation velocity for the three fractions is shown in Figure 4. The Weibull distribution function is used to fit the data, which gives an R^2 above 0.92 for each fraction. The parameters in the Weibull distribution function (α, γ, n) were obtained by fitting Weibull function to experimental data using a software package called "Regres," and listed in Table III.

Previous analyses indicated that complete separation between light materials and whole kernels is infeasible. Figure 4 indicates 95% of light materials can be removed by aspiration at an air velocity equal to 7.5 m/sec, whereas only 35% of broken kernels can be removed from the mixture at the same air velocity.

Density and Porosity

Attempts were made to describe the relationships between true density and moisture content with first-, second-, and third-order polynomial functions. The improvement obtained by using second

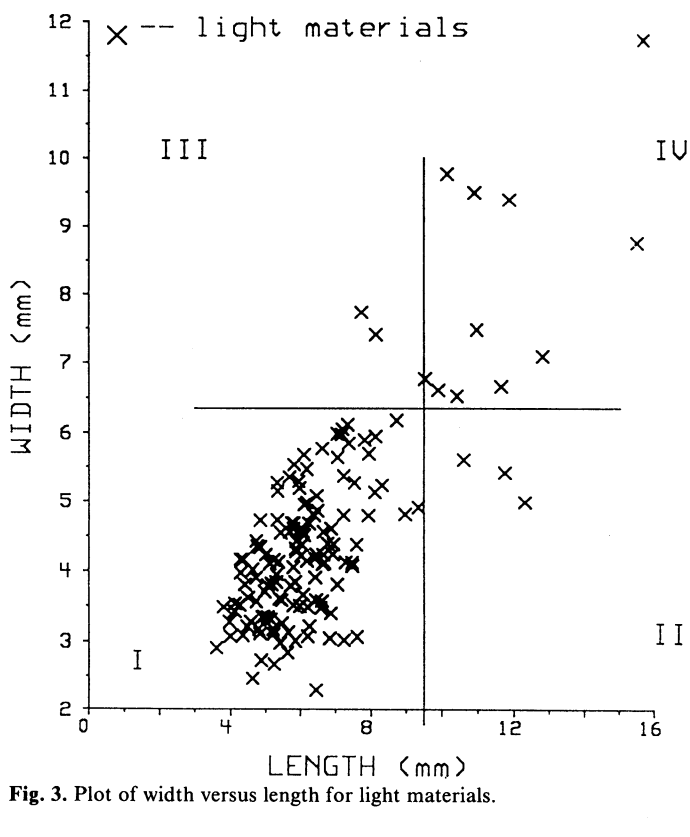

Fig. 3. Plot of width versus length for light materials.

and third degree was small. Thus, this linear model was selected. Preliminary model fitting was made for all six fractions of corn, i.e., whole kernels, broken kernels remaining on the no. 3½, no. 4, no. 5, and no. 6 sieves, and everything passing through the no. 6 sieve. All six lines representing true density versus moisture content appeared to be parallel. To test whether the true densities of the five fractions of broken kernels significantly differed from each other, pairwise comparisons were made. Test results indicated that true densities of broken kernels on the no. 3½ and no. 4 screens were not significantly different; neither were there significant differences for broken kernels on no. 6 and those passing through the no. 6. As a result of this preliminary analysis, data for kernels on the no. 3½ and no. 4 screens were pooled together, as were those for kernels on the no. 6 and below no. 6. Figure 5 plots measured true density (apparent density) versus moisture content for the four regrouped size fractions of corn. As the particle size decreases, apparent density increases. The reason for this is that the specific surface area increases as the size becomes smaller. Since broken kernels are porous materials, more space becomes available to the helium gas, which results in a low reading on the volume occupied by the solid materials of corn.

Comparison of grain density data with those reported by others is difficult because of the wide natural variation in physical properties of the same kind of grain. Large variations in bulk density can be found even in the same varieties because of the difference in environmental conditions under which the grain is produced.

Kernel densities given by Chung and Converse (1971) and Brusewitz (1975) agree very well with our results for whole kernels in the moisture range of 10–25%. However, our results differ from the data reported by Nelson (1980).

Nelson (1980) described the relationships between bulk density and moisture content with a third-order polynomial equation. Similar equations were used to simulate the data in this study for each size fraction. The 95% confidence intervals for bulk density at each moisture level were calculated and plotted. It appeared that the confidence intervals of bulk densities overlapped for kernels remaining on the no. 3½ and no. 4 sieves and for those on the no. 6 and below no. 6. Therefore, data from the no. 3½ and no. 4 sieves were pooled together, and so were those for the no. 6 and below no. 6. Figure 6 shows bulk density versus moisture content for four size groups of the corn sample. As particle size increases, the curves become flat, which means moisture has less effect on bulk density. A smaller particle size produces a lower absolute value of bulk density. Table IV presents the coefficients in the polynomial equations and the accompanying

TABLE III
Variables in Cumulative Distribution Functions of Flotation Velocity for the Materials Studied

Material	Mean ± SD	Constants in Cumulative Distribution Functions[a] γ	α	n	R^2
Whole kernels	9.720 ± 0.740	3.5	3.573×10^{-4}	10.11	0.905
Broken kernels	8.060 ± 1.060	3.0	9.525×10^{-6}	5.717	5.914
Light materials	5.280 ± 0.840	0.0	2.44×10^{-5}	5.914	0.9292

[a]Equation: $W(\%) = 100\{1 - \exp[-\alpha(x-\gamma)^n]\}$.

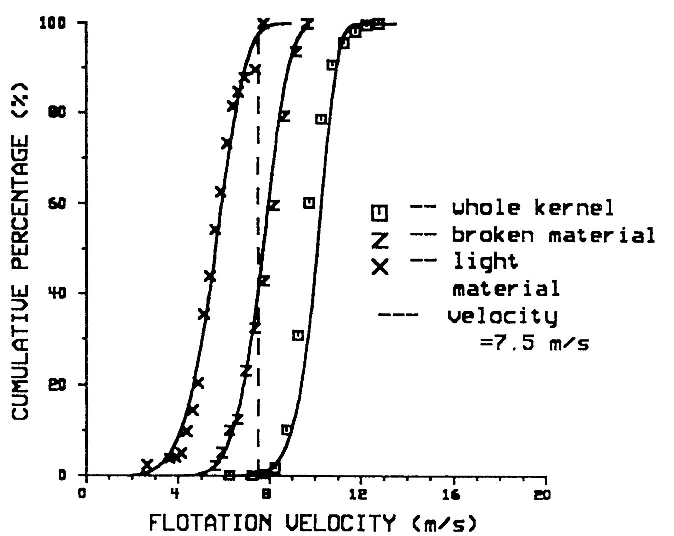

Fig. 4. Cumulative distribution of flotation velocity for various fractions of corn.

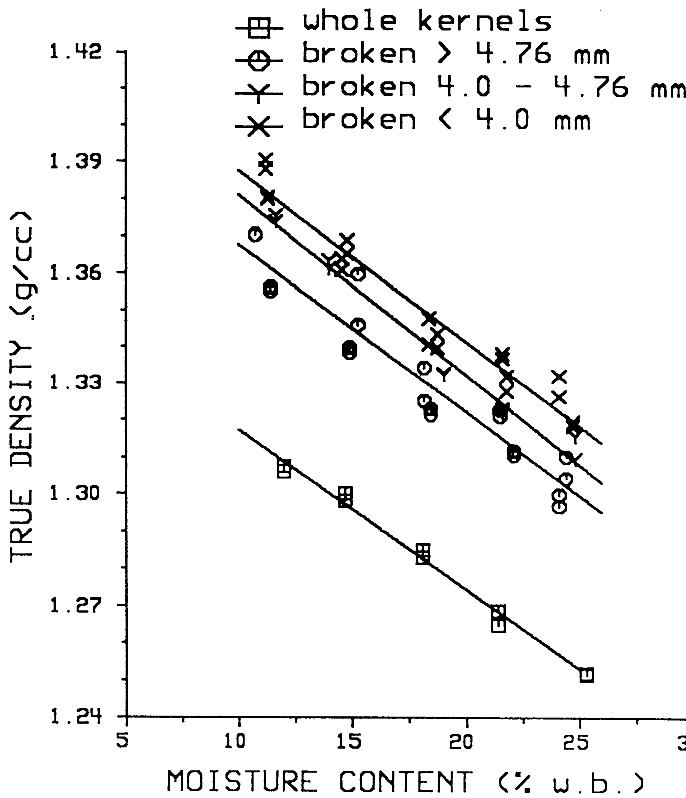

Fig. 5. Relationship between true density and moisture content for various fractions of corn.

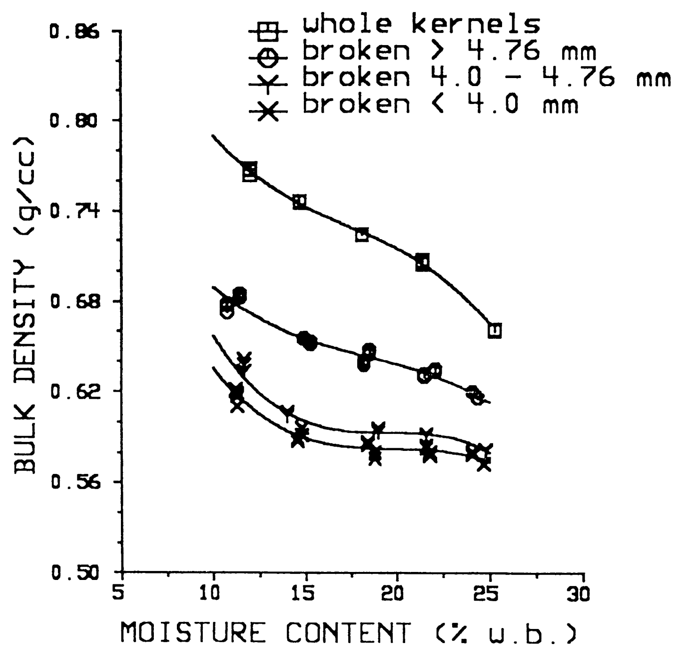

Fig. 6. Relationship between bulk density and moisture content for various fractions of corn.

TABLE IV
Coefficients in Polynomial Equations[a] Describing Relationships of Bulk Density and Moisture

Sample	Equation: $\rho_b = C_1 + C_2M + C_3M^2 + C_4M^3$				
	C_1	C_2	C_3	C_4	R^2
Whole kernels	1.0939	−0.05231	0.002709	-5.2113×10^{-5}	0.9987
Broken kernels (≥ 4.76 mm)	0.9188	−0.03878	0.001935	-3.4920×10^{-5}	0.9619
Broken kernels (≥4 mm <4.76 mm)	1.1384	−0.08387	0.004307	-7.3816×10^{-5}	0.9922
Broken kernels (<4 mm)	1.0074	−0.06411	0.003237	-5.4673×10^{-5}	0.9568

[a] In equation, ρ_b is bulk density (g/cm^3), M is moisture content (%, wb), and C_1, C_2, C_3, and C_4 are constants in a regression equation.

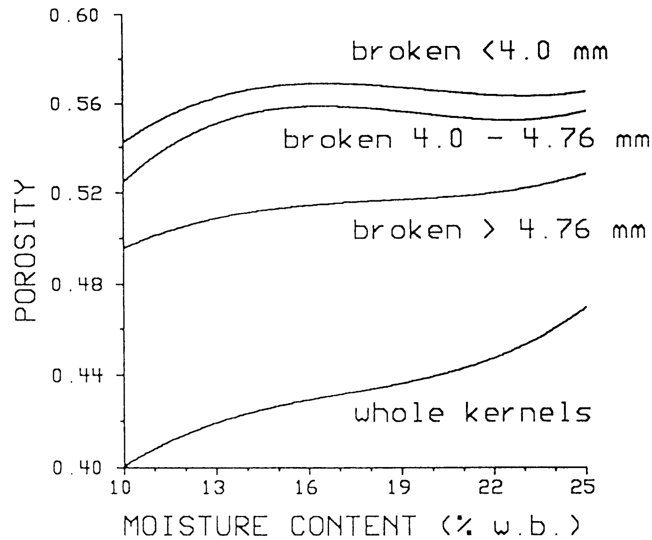

Fig. 7. Relationship between porosity and moisture content for various fractions of corn.

correlation coefficients obtained from regression analyses.

Knowing the true density (ρ_T) and bulk density (ρ_b), the porosity can be calculated as follows:

$$\epsilon = 1 - \rho_b/\rho_T \tag{2}$$

Figure 7 illustrates the relationship between porosity and moisture content for the different size groups. As the size decreases, porosities are less dependent on moisture. The porosity increases as the size decreases.

CONCLUSIONS

Geometric dimensions and flotation velocity of corn particles follow Weibull distribution.

Physical property analysis provides a basis for the design of cleaning and separating machines. If certain tolerances are set, appropriate cutting lines, sieve opening, or airflow rate can be selected.

Complete removal of light materials from whole kernels is feasible.

True densities of all size fractions of corn are linear functions of moisture content. The relationships between bulk density and moisture content can be described by a third-order polynomial function for each size fraction.

Particle size affects true density and bulk density. As particle size decreases, true density and porosity increase while bulk density decreases.

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