MECHANICAL AND RHEOLOGICAL PROPERTIES OF CORN AS AFFECTED BY COMBINE HARVESTING

by

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MECHANICAL AND RHEOLOGICAL PROPERTIES OF CORN AS AFFECTED BY COMBINE HARVESTING

Introduction:

Grains forming on the plant are not uniform in their physico-mechanical and biological properties. This lack of uniformity may be explained by differences in nutrition, formation and ripening on the plant. The grain mass dealt with by the combine-harvester reflects the individual peculiarities of millions of separate grains of different degrees of ripeness and moisture content. There is a great deal of evidence that grain attaining full ripeness is not as firmly attached to the ear as less ripe, insufficiently developed grain, and less mechanical action is needed to separate it. Strong mechanical action causes considerable damage to the more valuable grains which are more brittle than unripe ones. The operational regime of threshing mechanisms is based on the separation of all grains from the ears. If these conditions are optimum for undersized, unripe seed, they are too severe for fully ripe grain.

Together the farmer and the industrial food processor handle grain in a variety of operations from planting through harvesting to processing. Mechanical damage to corn during combining depends on the variety of corn, stage of maturity, moisture content, combine cylinder speed and other combine variables. Certain data such as specific heat, dielectric constant, thermal coefficient of expansion, coefficient of friction, equilibrium moisture content etc. are often not available for more than one grain. Moreover, mechanical properties such as compressive strength, impact shear resistance and modulus of resilience, are important engineering data needed to study size reduction and seed resistance to cracking under harvesting, handling and drying conditions. When basic data are known, new uses for the product and new methods of processing can be developed.

The mechanical properties of a material are those that describe the behavior under applied forces. Strength, stiffness, elasticity, plasticity, ductility and brittleness are generally considered to be the fundamental mechanical properties.

Rheology generally considers those stress-strain relationships of the material which are time dependent. It considers the time effect during the loading or stressing of a body under test. Thus, rheologically the mechanical behavior of a material is expressed in terms of three variables: stress,strain and time. The time effect (rate of straining) is important for a material that flows or is not perfectly elastic.

In the design of machines, structures, processes and controls to be used in production, handling, and processing of foods and agricultural products, certain physical properties of the material should constitute important and essential engineering data. Physical properties of the material will influence the efficiency of the machine or operation and the quality of the final product.

The knowledge of mechanical, rheological and physical properties of the biological products is essential to agricultural engineers in order to design efficient machines for harvesting, handling and processing the biological products.

Purpose of the Investigation

Kernel moisture content at the time of harvesting the corn is one of the prime factors which affect shelling efficiency and kernel damage. Moisture content has the greatest influence on the mechanical and rheological properties of grains. All strength properties decrease in magnitude as harvest moisture increases.

Soundness of grain has a great influence on the storage of grains. Damaged grains are more susceptible to insects and microorganisms than undamaged grains. In order to minimize mechanical damage in combining corn it is essential to establish optimum conditions of harvesting. Harvesting at different moisture content and at different periods will show the influence on mechanical and rheological properties in corn. Bruising and injury to agricultural commodities resulting from excessive stresses during mechanical handling have been problems encountered in agricultural engineering. The biomechanical study of the biological products would assist agricultural engineers in the design of efficient machines and structures to be used in production, handling and processing of agriçultural products.

Review of Literature

The need for more efficient corn harvesting methods has been shown in reports of tests made during the past several years. Some of the earliest attempts to use the combine for harvesting corn were made in Australia in 1924, in Iowa in 1928 and in Kansas and Nebraska in 1930. With an ideal corn harvesting machine in mind, work was started in 1950 at Nebraska. A self-propelled combine was used during the harvest season of 1954.

The effects of different variables of the combine harvester on cereal grains and visible damage to the grains have been found by King et. al. (8).

The effect of harvest damage on barley at 14 to 28 per cent harvest moisture content has been reported by Arnold (1). Considerable mechanical damage to grain during threshing has been found by Kolganov (9).

Some of the mechanical and rheological properties, such as modulus of elasticity, maximum stress, load vs. deformation relationship, shear stress and hysteresis loss in cereal grains were reported by Zoerb et. al. (16). They have established parameters at different moisture levels.

The application of physical properties of agricultural products in design and analysis of machines, structures and processes for handling, storage and conditioning were studied by Mohesin (12).

The mechanical properties of pea beans under impact loading have been studied by Perry et. al. (13). They found that the total force on individual beans due to impact loading varied from 22.2 to 39.8 lbs. These forces correspond to pressures of 1010 to 1870 psi on the beans.

The application of the principles of mechanics was applied by Finney et.al.(4) to potato tubers considering as a visco-elastic body when deformed by mechanical loading. Graphical, inflection and geometric series methods of representing characteristic time constants were investigated by them. They have reported that stress relaxation within the tuber was represented qualitatively by the equivalent response of 4 Maxwell models in parallel.

Significant differences were reported between certain potato varieties in their response to applied stress or surface pressure by Finney et. al. (3). They also have indicated that after a month curing period, the energy the tubers could withstand increased by 30 to 80 percent.

The study on germination and seedling vigor of sugar beets by impact effects was done by Kurnze et. al. (10). They have found that the impact energy of 29 gram-centimeters is approximated by an impact-velocity of 70 ft./sec. when the fruit weight is 0.0125 grams.

Corn harvested at initial moisture near 20 percent showed breakage of 4.7% as compared to 9.8% breakage for corn harvested at 30 percent moisture content as reported by Thompson et. al.

(15). They have also reported that the breakage after drying the corn was 15.2% for the corn harvested at 20 percent moisture content as compared to 20% breakage for that corn harvested at 30 percent moisture content.

Modulus of elasticity from a stress-strain curve was determined in agricultural products using a 3/8 inch diameter loading plunger by Timbers et. al. (14). They have reported the modulus of elasticity in potato tuber to be from 533 psi to 3260 psi. The modulus of elasticity in corn was reported by Zoerb et. al. (16) to be from 58,600 psi to 31,740 psi for corn tested at 15.4% to 23.0% moisture content (dry basis) respectively. They also have investigated the variation in maximum stress from 4811 psi to 2892 psi for that corn tested at 15.4% to 23.0% moisture content (dry basis) respectively.

Materials and Methods

The corn was planted near Manhattan, Kansas, in the fourth week of April, 1967. The variety of yellow corn was Funk 4680. Three successive harvests at three week intervals at three different moisture levels were made. The first harvest was taken in the first week of October for which harvest moisture was 28%. The second harvest was taken at 23% moisture content in the last week of October, and the third one was made at 18% harvest moisture content in the third week of November.

The field corn was irrigated three times during the growing season. The three different harvests were made at similar environmental conditions. The average plant population was approximately 20,000 plants per acre. The average weight of ears was 0.62 pounds. The input flow of ears into the combine was kept about 5.67 bushels per minute during the three harvests. The yield of harvested corn kernels was approximately 155 bushels per acre. There was not much variation in plant stands over the field. The ground speed of combine was 2.5 m.p.h. The combine cylinder speed was kept as near 530 r.p.m. as possible. The concave setting was kept about 1 1/4 inches in the front and 5/8 inches at the rear.

Representative samples of shelled corn were collected from each harvest after combine harvesting. Moreover, a random sample of ears was collected and these were shelled by hand and the corn so obtained was used as a control. The samples were passed through a Boerner Sampler and the moisture content was taken with a dielectric moisture meter immediately after harvest. In order to avoid error three readings were taken each time. The temperature of the corn was recorded. The moisture meter is shown in Fig. 1.

The sample of shelled corn was evaluated for mechanical damage by physical damage evaluation tests. A sample of 1500 grams was taken each time for all the tests. The weighed sample was passed through a Carter dockage tester. The weight of dockage was recorded.

Then corn was poured into the test weight testing equipment and the structure was leveled by use of a wooden stick. Thus, the test weight per bushel was recorded.

Again the sample was divided by Boerner Sampler and a sample of about 150 gms was weighed. This sample was passed through a 3/16-inch round hole sieve to remove the smallest pieces. The weight of the smallest pieces was recorded. The remaining sample was visually examined for damaged kernels. The broken pieces and cracked kernels were picked out by hand. The damaged kernels were classified into four different groups (Fig. 2) as smaller pieces, larger pieces, those with smaller cracks and those with larger cracks. Each group of damaged kernels was weighed separately. The percentage of damaged kernels was calculated on a weight basis. This test was made three times on three different samples.

Again, the bulk sample was divided by divider and three samples of 100 gms each were taken from it. These samples were

Explanation of Fig. 1

Motomo Model 919 Moisture Meter.

Fig. 1

Explanation of Fig. 2

Classification of Damaged Kernels. Left to right columns: 1-4

1. Smaller cracks
2. Larger cracks
3. Larger pieces
4. Smaller pieces

1 2 3 4

Fig. 2

used for the breakage test. The commercial breakage tester (Fig. 3) was used for this test. The sample was dropped into a closed cylindrical container having a 3.6" diameter and a 3" depth. The impeller revolving at approximately 1765 r.p.m. was located near the bottom of the container. The switch was pushed for starting the machine. The device was equipped with a self timer and operated for 2 minutes. The sample was taken out after 2 minutes and placed on a 3/16-inch sieve and was shaken horizontally for 30 times. The broken pieces that passed through the sieve were weighed. Then the broken kernels were visually observed and picked out by hand. The damaged kernels were classified into four groups (Fig. 2) as smaller pieces, larger pieces, those with smaller cracks and those with larger cracks. Each group of damaged kernel was weighed separately and the percentage of damaged kernels was calculated.

Since corn kernels have heterogeneity in shape and size, previous workers have reported greater variation in the rheological parameters. In order to eliminate this variation each sample of hand shelled kernels was passed through a grading machine and was classified according to size and shape into four distinct groups (Fig. 4) as large flat, medium flat, small flat and round and butt. The percentage of each group was calculated on a weight basis out of 100 gms of three samples each harvested at 28% and 18% moisture.

The load, in compression, in a flat position, was applied to 10 kernels of each of the above four groups. These data were

Explanation of Fig. 3

Stein Corn Breakage Tester

Fig. 3

Explanation of Fig. 4

Classification of Kernels According to Shape and Size.

Left to right columns: 1-4

1. Round and Butt
2. Small flat
3. Medium flat
4. Large flat

Fig. 4

statistically analyzed and the standard deviation and coefficient of variation were established for each group.

The medium class of kernel size showed greater contribution to the population of the kernels. Therefore, five kernels of medium flat class were used for load vs. deformation and hysteresis loss studies.

The grain was less elastic and quite viscous above 15% moisture content. Therefore, the samples of three harvests were brought down to 12% moisture content and the rheological study was done at this level. All dimensions of core specimen made by cutting off each end of the kernels were measured by a micrometer.

The load in compression, with kernel in an edge position, was applied by use of a Dillon Universal Testing Machine (Fig. 5) until the grain failed. Load vs. deformation curves were obtained for five kernels of each of the three harvests. The smallest contact area was taken for converting load into stress. The curves were plotted on stress-strain axes by taking the average value of five kernels.

Hysteresis loops for the three harvests were obtained by loading and unloading in an edge position, in compression, below the yield point at constant deformation for each of five kernels.

Explanation of Fig. 5

Dillon Universal Testing Machine.

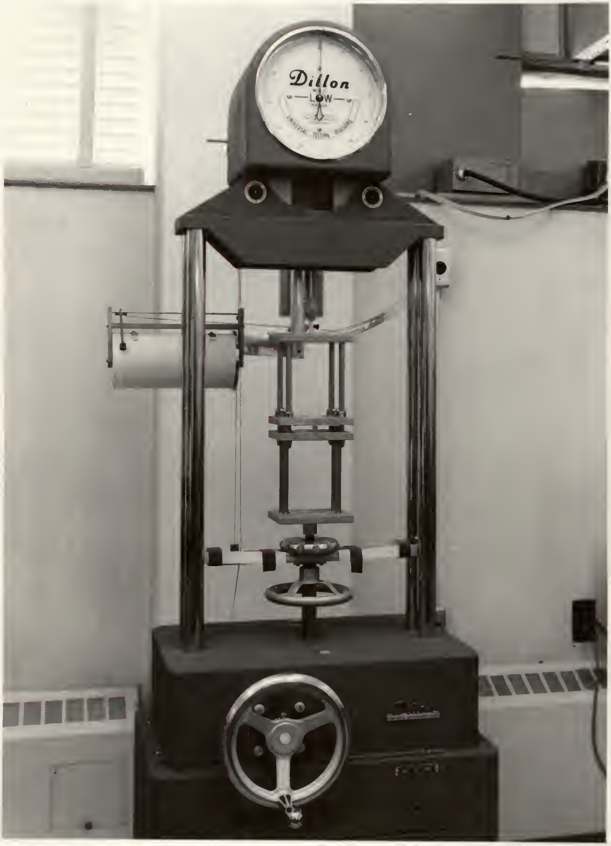

Fig. 5

Results and Discussion

Combine harvested shelled corn samples of three harvests were tested for dockage, damaged kernels, test weight and stein breakage test, after determination of moisture content. The results are shown in Table 1. It is apparent from the results that there was greater dockage and more damaged kernels as corn was harvested at higher moisture content. Moreover, the stein breakage test showed increased potential against damage of kernels at lower moisture content at the time of harvesting.

In order to determine the basic heterogenity characteristics of corn kernels, the hand shelled corn samples harvested at 28% and 18% moisture content were classified into four distinct groups according to size and shape. The contribution of each group in an average population is shown in Table 2. It was apparent from the results that there was a greater contribution from the medium flat class of kernels in the population. While large flat and round and butt groups of the kernels contributed nearly in the same percentages and in small amounts.

In order to overcome the variation described by previous workers in the study of rheological properties, ten kernels at 18.5% moisture content were randomly chosen from each of the four groups and loaded with the kernel in a flat position in a compression machine. The maximum applied load for each is given in Table 3. Applied load was statistically analyzed, and standard deviation and coefficient of variation for each group were calculated as follows:

Table: 1 Summary of evaluation of physical damage of the kernels.

Test	Moisture content at harvest 18% (W.b.)	23% (W.b.)	28% (W.b.)
1. Dockage, %	.32	.83	1.20
2. Test Wt., lb/bu.	58.10	57.57	51.53
3. Damaged kernels, by visual observation, %	5.08	8.60	11.11
4. Stein breakage test: damaged kernels, %	6.75	10.18	13.92

Table: 2 Classification of hand shelled kernels according to size and shape.

a. Moisture content at harvest, 28% (W.b.)

Sample No.	Weight gms.	Wt. per 100 grams in groups indicated			
		Large flat	Medium flat	Small flat	Round and Butt
1	100	12.58	53.92	19.60	12.65
2	100	14.60	52.15	20.80	11.48
3	100	15.52	54.94	17.18	14.00
Total	300	42.70	161.01	57.80	38.13
Av.,%		14.23	53.67	19.20	12.71

b. Moisture content at harvest, 18% (W.b.)

Sample No.	Weight gms.	Wt. per 100 grams in groups indicated			
		Large flat	Medium flat	Small flat	Round and Butt
1	100	14.10	53.48	16.12	15.90
2	100	13.05	58.10	18.00	10.40
3	100	14.75	55.70	15.20	13.70
Total	300	41.90	167.28	49.32	40.00
Av.,%		13.97	55.76	16.44	13.33

Table: 3 Statistical analysis of load in compression applied in a flat position to different groups of kernels until failure of kernels. Hand shelled corn. Moisture content 18.5% (W.b.)

Kernel No.	Group			
	Large flat	Medium flat	Small flat	Round and Butt
	Load in lbs.			
n	x	x	x	x
1	125	131	62	58
2	128	106	94	52
3	230	110	125	50
4	147	133	100	44
5	161	111	87	76
6	114	95	80	68
7	218	80	100	30
8	234	84	85	34
9	178	106	82	50
10	152	86	74	32
Total	1687	1042	884	494
Av. ($\overline{x}$)	168.7	104.2	88.4	49.4
Std. deviation (S)	44.60	18.39	19.39	15.20
C.V. %	26.44	17.65	21.94	30.78

$$S = \frac{\Sigma X^2 - \frac{(\Sigma X)^2}{N}}{N - 1}$$

where,

S = Sample standard deviation

X = Load in lbs. of individual observation

N = Total no. of observations

$$C.\ V. = \frac{S}{\overline{X}} \times 100$$

where,

$\overline{X}$ = Mean load in lbs.

C. V. = Coefficient of variation.

For medium flat class

$$S = \frac{111620 - 1085764/10}{9}$$

$$= 18.3896$$

$$C.\ V. = \frac{18.3896}{104.2} \times 100 = 17.65\%$$

The complete results are shown in Table 3. It was apparent from the results that there was less variation for the medium flat class.

In order to improve the deviation and coefficient of variation in applied load, the core specimens made by cutting off each end of medium flat class kernels were loaded into the compression equipment in an edge position, which showed more consistent results and the coefficient of variation was then only 2.03%.

After establishing a consistent method for loading the kernels, the rheological parameters were studied. All the dimensions of core specimens were recorded before loading the kernels. Plots of load vs. deformation obtained for 5 tests, for each of the harvests, by use of the Dillon Universal Testing Machine were converted into stress and strain by dividing contact area into the load and length of the kernels into the deformation. Several points were obtained at intervals of 15 lb. of load on the plot. The average value of 5 tests was recorded for each point and it was plotted on stress-strain axes as shown in Fig. 6. The rheological parameters were calculated from this figure and are shown in Table 4. It is apparent from the results that yield stress and maximum stress decreased as moisture content of harvest increased. Due to lack of more sophisticated equipment the inconsistency in the results of modulus of elasticity were not confirmed by further rheological tests such as relaxation time.

Core specimens of medium flat class kernels of three harvests were loaded and unloaded in the compression equipment, in an edge position, below yield point. Hysteresis loops for 5 tests of each harvest were obtained by use of the Dillon Universal Testing machine as shown in sample plots given in Fig. 7. It was apparent from the results that there was considerable hysteresis loss for the kernels harvested at 28% and 23% moisture content, while kernels harvested at 18% moisture content showed negligible hysteresis loss. This indicated that kernels harvested at 18% moisture content are more elastic than those harvested at 28% and 23% moisture content.

Table: 4 Summary of mechanical properties of corn (core specimens) tested at 12% moisture content (W.b.) for three different harvests.

Moisture content at harvest %(W.b.)	Test moisture content, %(W.b.)	No. of tests	Yield stress, lb/sq.in.	Maximum stress, lb/sq.in.	Modulus of elasticity, E, lb/sq.in.
18.0	12.0	5	1340	2280	57,000
23.0	12.0	5	1050	2060	66,000
28.0	12.0	5	990	1980	45,500

Explanation of Fig. 6

Stress/strain for yellow dent corn, Funk 4680 at 12% moisture content (wet basis) for three different harvests.

Kernels (core specimen) placed on edge; compression. Each point is the mean value of 5 tests.

A: Combined at 18% moisture content

B: Combined at 23% moisture content

C: Combined at 28% moisture content

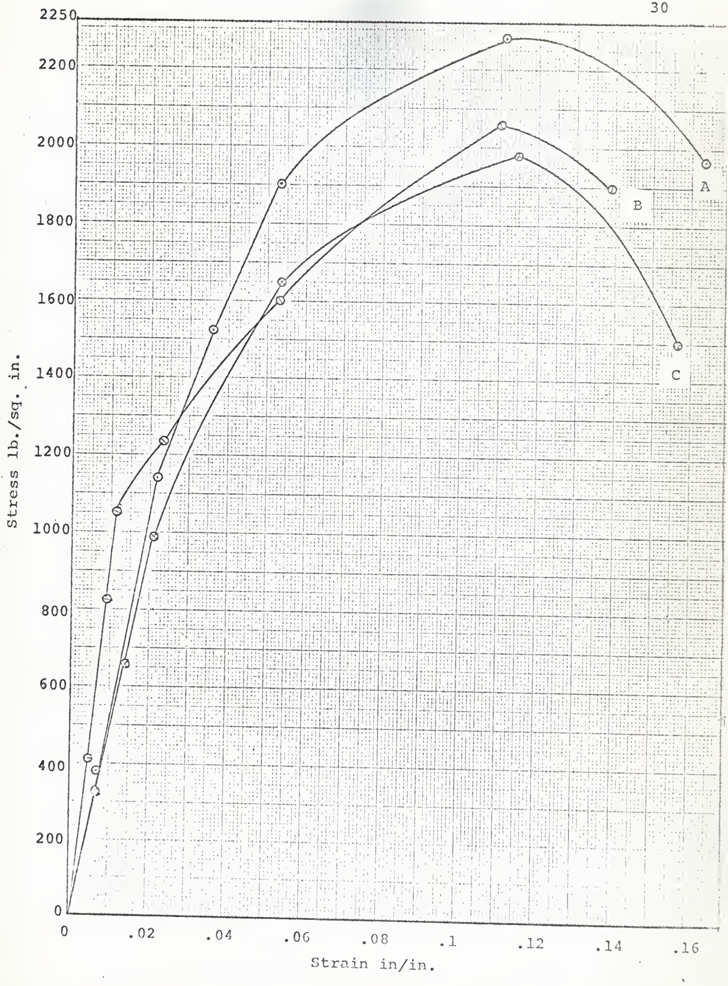
2250
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Stress lb./sq. in.
0
.02
.04
.06
.08
.1
.12
.14
.16
Strain in/in.
A
B
C

Fig. 6

Explanation of Fig. 7

Hysteresis loops for corn kernels obtained by loading and unloading at 12% moisture content (wet basis)

Top to bottom: 1-11

1-3: Combined at 23% moisture content

4-7: Combined at 28% moisture content

8-11: Combined at 18% moisture content

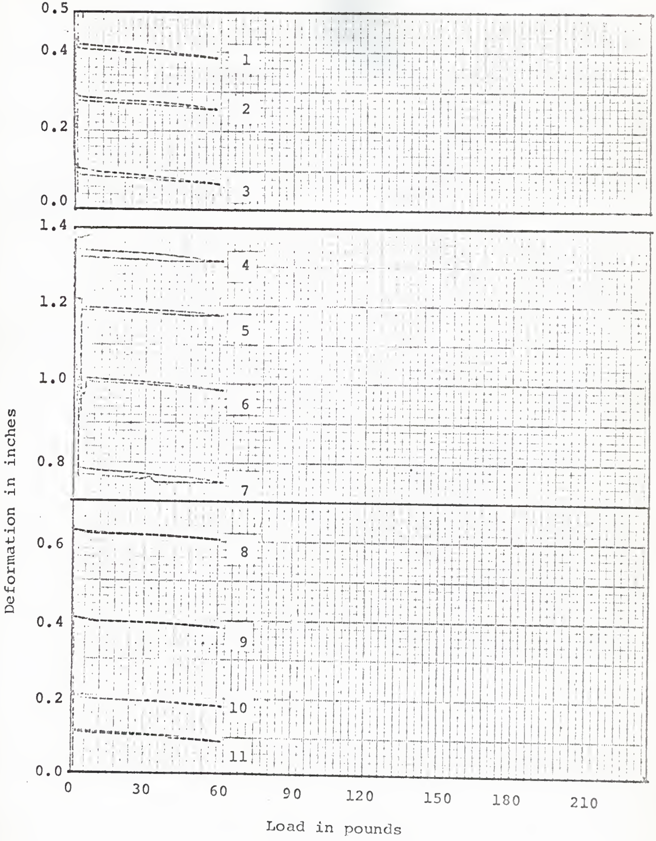
0.5
0.4
0.2
0.0
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1
2
3
4
5
6
7
8
9
10
11
0
30
60
90
120
150
180
210
Deformation in inches
Load in pounds

Fig. 7

In order to compare the results at uniform moisture level the samples of three harvests were exposed in the room and the moisture content of all the samples were brought down to equilibrium moisture content, i.e. 12% (w.b.) at constant relative humidity. All the rheological properties were studied at 12% moisture content for the three harvests of different moisture content. Atmospheric temperature and relative humidity of the room were kept constant throughout the study.

Summary and Conclusions

Funk 4680 variety of yellow dent corn was planted in the third week of April near Manhattan, Kansas. Three successive harvests were taken at 28%, 23% and 18% moisture content at intervals of three weeks starting from the first week of October.

The samples of shelled corn were evaluated for mechanical damage by physical damage evaluation tests. A basic study of the heterogenity of corn kernels was done and a consistent method of loading the kernels in compression machine was established before making a rheological parameters study. The rheological study was done at 12% (W.b.) moisture content for all the harvests.

The results obtained by mechanical and rheological tests showed considerable variation in the parameters under study. There was considerable evidence that the soundness characteristics of the corn decreased as the moisture content of grain increased at the time of combining.

A method was described for basic studies of the heterogenity of corn kernels by which avoidance of variation was possible. This is of prime importance and essential for biological products and overcame the inconsistency reported by previous workers.

The mechanical and rheological properties under study constituted powerful tools for understanding the strength characteristics of corn kernels. Moreover, these properties gave considerable evidence of the stage at which the kernels were harvested.

Due to lack of more sophisticated equipment a relaxation time study was not made. This is an important rheological property in order to confirm the results of other rheological parameters. Moreover, it enables the establishment of a time constant (τ) and mechanical models, which will indicate how fast the grain can dissipate stress after undergoing a sudden deformation. Therefore, such a study should be included in future work of a similar nature.

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Moisture content at harvest of the corn kernel has great influence on shelling efficiency and kernel damage. In order to minimize kernel damage at the time of harvesting it is of utmost importance to know the optimum condition for harvesting the corn.

Soundness of the kernels has a great influence on the storage of grains. Damaged grains and trash may hold more moisture than sound kernels and invite microorganisms and insects during storage of corn.

Funk 4680 variety of yellow dent corn was planted in the fourth week of April near Manhattan, Kansas. Three successive harvests were taken at 28%, 23% and 18% moisture content at intervals of three weeks starting from the first week in October.

Tests to evaluate mechanical damage carried out for the three harvests showed considerable variation. Corn harvested at 18% moisture had 5.08% damaged kernels as compared to 8.6% and 11.11% for that harvested at 23% and 28% moisture content respectively. Moreover there was the least percentage of dockage in the grain harvested at 18% moisture content.

A basic study of the heterogenity of corn kernels was made and a consistent method of loading the kernels in compression machine was established before rheological parameters were studied. This overcame the variation in the rheological parameters reported by previous workers. The rheological study was done at 12% moisture content (wet basis) for all the harvests.

Rheological parameters studied from the stress-strain diagram of three harvests have indicated a variation in yield stress, maximum stress and hysteresis loss. The corn harvested at 18% moisture content showed 1340 psi yield stress as compared to 1050 and 990 psi for that harvested at 23% and 28% moisture content respectively. There was greater maximum stress for kernels harvested at 18% moisture content. Moreover, hysteresis loops for kernels harvested at 18% moisture indicated negligible hysteresis loss as compared to the kernels of the other two harvests. These parameters indicated that the corn combined at 18% moisture content had kernels more elastic in nature and higher in specific damping capacity.

Mechanical and rheological studies indicated that for Funk 4680 variety of yellow dent corn, combined at 18 percent moisture content with 530 r.p.m. cylinder speed to be the better condition of combining in the Manhattan area in 1967. This knowledge would have assisted the farmer in combining corn at that time and could be of future use under similar conditions.

The physical and biomechanical study of corn would assist agricultural engineers in the design of efficient machines and structures to be used in production, handling, and processing of corn.