MECHANICAL AND RHEOLOGICAL PROPERTIES OF GRAIN

Thesis for the Degree of Ph. D.

MICHIGAN STATE UNIVERSITY

Gerald Charles Zoerb

1958

This is to certify that the

thesis entitled

MECHANICAL AND RHEOLOGICAL PROPERTIES OF GRAIN

presented by

Gerald C. Zoerb

has been accepted towards fulfillment
of the requirements for

Ph.D. degree in Agricultural Engineering

Major professor
Carl W. Hall

Date March 4, 19[illegible]8

MECHANICAL AND RHEOLOGICAL PROPERTIES OF GRAIN

by
Gerald Charles Zoerb

AN ABSTRACT

Submitted to the School for Advanced Graduate Studies at Michigan State University of Agriculture and Applied Science in partial fulfillment of the requirement for the degree of

DOCTOR OF PHILOSOPHY

Department of Agricultural Engineering

1958

Approved Carl W. Hall

ABSTRACT

Little information has been found describing physical properties of individual grain kernels. A library search revealed no information pertaining to mechanical properties, such as compressive strength, modulus of elasticity, etc. Problems such as kernel crackage during threshing and handling may be analyzed more readily when basic information concerning mechanical properties of grain is made available. The objective of this study was to determine some basic mechanical and rheological properties of individual bean, corn and wheat kernels.

A SR-4 strain gage transducer was designed and built to measure load and deformation for the individual kernel under test. By means of electronic equipment, load, deformation, and time relationships were recorded simultaneously. A pendulum impact tester was constructed and used to measure the energy required for impact shear.

The desired relative humidity was obtained with various saturated salt solutions in a dynamic equilibrium moisture chamber. The grain reached equilibrium much faster than in a static chamber, thus preventing excessive mold formation at the higher moisture levels.

The effect of moisture content on kernel properties was the chief parameter studied. Other parameters investigated were the effect of rate of deformation, and the relation of kernel position, edge or flat, to strength characteristics.

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The following mechanical properties were investigated: yield strength and maximum compressive strength of the kernel in the edge and flat positions, average shear stress, modulus of elasticity in compression, modulus of resilience and modulus of toughness. Comparison was made of the energy required to rupture the grain kernel by impact shear and by static shear. A preliminary study of kernel hysteresis loss, obtained from loading and unloading cycles, was carried out.

Moisture content had the greatest influence on the strength properties of grain. The compressive strength, modulus of elasticity, maximum compressive stress and shear stress generally decreased in magnitude with an increase in moisture content. Energy requirement for impact shear was higher than static shear at high moisture; the reverse was true at low moisture. Modulus of resilience and modulus of toughness did not vary greatly with moisture change.

Some rheological properties of pea beans were examined. The effect of rate of deformation on the resulting force was qualitatively examined for pea beans. Stress relaxation with time was studied for three moisture levels and three deformation rates. Initial rate of deformation had more effect on the rate of stress relaxation than moisture content or the initial amount of deformation. Relaxation time was constant with various deformation amounts. A two-term exponential equation was obtained graphically to express the stress relaxation-time relationship.

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TABLE OF CONTENTS

LIST OF TABLES

Tables in Appendix

LIST OF FIGURES

INTRODUCTION

Definition Of The Problem

Grain farming represents one of the largest segments of the agricultural industry, particularly in central United States and in western Canada. Both the farmer and the industrial food processor handle grain in a variety of operations from planting through harvesting to processing. Many problems are encountered in the various operations. A good example is the problem of pea bean crackage during handling in elevators. Grain cracking during the threshing operation is always a potential hazard affecting the quality of the final product. Also, relatively high power requirements are needed in the grain size reduction process. In spite of the tremendous expenditure of time and labor in the various operations associated with grain, very little is known about the basic mechanical properties of the individual kernel.

Certain basic data, such as specific heat, dielectric constant, thermal coefficient of expansion, coefficient of friction, equilibrium moisture content, etc., have been obtained to a small extent in the last 10 years. These data are still scattered and often not available for more than one grain. No information has been uncovered to this date on the mechanical or rheological properties of grain. Basic data, such as compressive strength, impact shear resistance, modulus of resilience, are important and in some cases necessary engineering data in studying size reduction as well as seed resistance to cracking under harvesting, handling and drying conditions. From an energy standpoint, this information can be used to determine the best method (shear, impact or static crushing, etc.) to break-up or grind grain. Data for other properties will have singular or multiple uses. Furthermore, and perhaps much more important, when basic data are uncovered, new uses for the product and new ideas for further research will become available.

It is essential that the civil and the mechanical engineer know the mechanical or engineering properties of steel, wood, coal, stone, plastic or other materials with which he is dealing. Similarly, the agricultural engineer must have basic information about grain, one of our chief agricultural products.

Statement Of The Thesis Problem

The four parts of the thesis problem are:

1. The design and construction of an apparatus suitable for measuring the mechanical and rheological properties of individual grain kernels.
2. The determination of compressive and shear strength characteristics of corn, wheat, and beans at various moisture levels and rates of deformation.
3. The determination of energy relationships in seed deformation, failure by impact, and surface area

produced.

4. A qualitative study of some rheological properties of one grain (pea beans).

Objective

The broad objective of this thesis study is to obtain some basic knowledge of the mechanical properties of grain. The ultimate goal through increased knowledge of grain properties is greater efficiency of operation and the unveiling of new methods and perhaps new uses for grains.

REVIEW OF LITERATURE

There has been no work reported on the determination of the mechanical properties of grains investigated in this study. However, certain physical properties of individual kernels, such as specific gravity, coefficient of friction, coefficient of thermal expansion and equilibrium moisture content have been reported by various investigators. The available basic data and properties for bulk grain such as thermal conductivity and angle of repose have been summarized by Hall (1957).

The only data available related to the mechanical properties of individual seeds are some preliminary work by Brown (1955) on pea beans. He was chiefly interested in the relationship between bean crackage and moisture content. He measured the load required to crack the bean seed coat and found a large variation in the force required. His moisture content range was small, from 8.0% w.b.* to 9.2% w.b. For tests on ten seeds in the flat position, the force required to crack the bean seed coat using a static load testing machine varied from 11 to 43 pounds. The average moisture content was 8.6% w.b. and the average force was 21.7 pounds. No impact tests were conducted.

Although no measurements of energy of deformation for in-

---

* w.b. = wet basis: $\frac{\text{moisture weight}}{\text{moisture weight} + \text{dry weight}} \times 100$

dividual grain kernels have been reported, extensive experiments on feed grinding with commercial burr and hammer mills have been carried out. These studies have shown the relationship when grinding between power requirements, grain moisture, fineness, speed and rate of feeding. Krueger (1927) found that the capacity for corn, lb/hp-hr, increased as the speed decreased, though not in direct proportion. In addition, the product becomes coarser with decreased speed. Although less horsepower is required per pound of material as the speed decreases, nothing is known of the relation between input energy and the surface area produced. Silver (1931) demonstrated that at a given rate of grinding, the power increased with increased fineness and with higher moisture content.

In the grinding process most of the mechanical energy is dissipated in the form of heat. This raises the tmeperature of the product and the surrounding air. The actual temperature rise of the grain will depend on its specific heat, its thermal conductivity and the distribution of heat losses from the grain by conduction, radiation and convection. Silver found temperature rises of up to 50° F for fibrous material being finely ground.

When a solid is deformed by application of a load and the load is then released, a hysteresis loop is formed. Thus the energy required to deform it will be greater than the energy given up when the load is released (except for perfectly elastic solids). The energy retained in the material appears as heat. In the grinding process, the rise in temperature is said to be due to "friction" created between the burrs or hammers and the grain. As a kernel of grain or fragment of a kernel is encountered by successive ribs on the grinding plate, it is no doubt deformed several times before it fractures or is reduced in size by the rubbing action. This repeated deformation plus the rubbing action raises the grain temperature. Since the efficiency of grinding is considered to be higher with less temperature rise, a preliminary investigation of elastic hysteresis of grain kernels is carried out in this study. This information should be useful in future studies in size reduction of grain.

The relationship between energy of crushing and new surface produced in the crushing of rock, has been studied by many investigators. In most instances the uncertainties in measurement of surface area made the results questionable. Kwong et al (1949) have worked with quartz, glass, halite, and fluroite, and have used water and air permeability methods to determine the surface area. For material larger than 65 mesh, water permeability was used, and between 65 and 200 mesh, air permeability was used. Energy was applied by impact. These researchers found a linear relation between the net input work to crushing and the new surface area produced, except for halite. When the energy was applied by slow compression, a slightly curved relation was observed showing decreasing surface produced per unit of energy with increased crushing.

In grinding of agricultural grain, tests have been reported on the basis of energy per pound of ground feed, hp-hr/lb, at a given "fineness modulus". Since a certain fineness modulus figure can be obtained by an infinite combination of weight retained on the various screens, it does not give a true picture of the surface area produced. Nicholas and Hall (1957) have developed a mathematical method for expressing the average particle size in a ground grain. An expression is developed in this study for the total surface area in a sample of ground grain.

Steenberg (1949) has obtained stress-strain (actually load-elongation) curves for paper. When the load was applied, and then released, a definite hysteresis loop was obtained. The slope of the load-elongation curve was steeper on the second loading than on the first. Steenberg called this a "strain hardening" process, similar to the one occurring in metals. A considerable permanent set was observed. Furthermore, on the second loading the paper showed a pronounced yield point at the maximum stress of the first process. This is caused by the first straining process changing the properties of the paper.

The influence of the rate of straining of materials on strength properties has been investigated by many workers. Kimmich (1940) states that the speed of load application in testing rubber makes little difference in ordinary ranges of 1/8 to 2 in/min. In tension tests on 14 metals, Jones and Moore (1940) concluded that, except for stainless steel, the general statement could be made that a variation in rate of strain from N percent per minute to 2N percent per minute would introduce a variation not greater than one percent in the value of yield strength or tensile strength. Davis et al (1941) state that the effect of speed variations within the range of normal rates of loading on the strength of brittle materials such as cast iron appears to be small.

The rate of straining has more effect in the case of a "plastic" or "visco-elastic" material. With impact tests for newsprint where the time of straining was of the order of one-thousandth of a second, Steenberg found that an increase in the rate of straining of one million times (over static tests) increased the breaking load ten times. However, for ragbond paper, the corresponding increase in breaking load was only 60%.

Bachinger et al (1957) have measured the work required to shear asparagus at various speeds. Work was determined by measuring the area under the force-displacement curve. A high correlation was obtained for both work and maximum force with fibrousness of asparagus.

Physical properties of single wool fibers have been investigated by Montgomery and Evans (1953). During the force-extension curve, they found a definite elastic or hookean region from which an elastic modulus was computed. Other parameters obtained were stress at 20 percent extension, relative work at 20 percent extension, and stress at the breaking point. A rate of extension of 0.5 in/min was used. These investigations were carried out on wool from various sheep and their properties compared at various stages of the manufacturing process.

Rheological properties of many materials have been investigated. Rheology is defined as the deformation and flow of matter. Its goal is to describe the mechanical behavior of a material in terms of the three variables, stress, strain, and time. As stated by Mason (1948), when a body is subjected to a loading, the strain consists essentially of two components:

> 1. An instantaneous deformation associated with an ideal elastic body. This is assumed to be completely recoverable.
> 2. A time-dependent portion, representing "flow" characteristics of a viscous liquid.
>
> Of the time-dependent strain, part is recoverable. This is known as "primary creep". The non-recoverable or irreversible creep is called "secondary creep".*

The above quote indicates that the stress-strain relationships for a visco-elastic material depend on the rate of stressing or straining. Mason obtained curves for paper which showed higher stress for a given strain with increased straining rates. His rates of straining were 0.046, 0.11 and 0.22 percent per minute.

The elastic deformations in cheese are not large. The material does not show high elasticity. Davis (1937) has described the elastic properties in terms of a modulus of elasticity which gives the relationship between the amount of elastic deformation and the applied force but does not say anything about the maximum elastic deformation which can take place.

Load-deformation relationships are used in measuring the

*Mason, S. G.; "Rheology of Paper"; Pulp Paper (Mag.) Can.; 49, No 3 - 207.

staling process of bread as indicated by Scott-Blair (1953). Many devices have been employed for measuring the changes in the force deformation relationships of the crumb. (Technically "crumb" refers to "crumb-structure", i.e., the texture of the material not necessarily following crumbling.) Recently attention has been drawn to the measurement of crumb "firmness" (load required to produce constant deformation). Bice and Geddes (1949) in their experiments on bread state that both elastic and plastic properties are present. They note that plastic flow is an appreciable factor in the compression when fresh bread is subjected to stress, but that the possibilities for plastic flow decrease when the crumb becomes more rigid. The elastic properties then predominate and the behavior of the crumb closely approaches that of a pure elastic material.

Physical tests are made on bread dough to determine the "dough" and baking properties of wheat flours. Various instruments -- the Farinograph, Extensograph, Fermentograph and Amylograph -- measure the rheological properties of the dough. The data obtained from these tests allow prediction of the type and quality of product to be expected.

When a plastic body is strained it cannot preserve its elastic potential energy indefinitely. Thermodynamically, the potential energy may be gradually converted into heat, leaking out, so to speak, by relaxation of the stresses. The time in which the stress is reduced to its e^{th} part is called the time of relaxation, t_r. For a "true" liquid $t_r = 0$ and for an ideal elastic solid $t_r = \infty$

The practical importance of stress relaxation in paper has been pointed out by Steenberg. If for example, a sack of cement is dropped or a sudden jerk is applied to newsprint on a rotary printer the resultant stress must be released rapidly or brittle fracture occurs. The rate of stress relaxation varies with different kinds of papers. Steenberg noted that the stress decay did not fit into a simple logarithmic formula, and advanced the possibility that the relaxation process after rapid straining, in contrast to the slow relaxation process, is a function of the preceding rate of straining.

Mason obtained relaxation curves for paper at various amounts of strain. The log of stress plotted against time produced parallel straight lines on semi-log paper, except for the first part of the stress decay which was very rapid. He also found that increasing humidity (moisture content of paper) resulted in a substantial increase in the rate of relaxation.

Hlynka (1957) in working with structural relaxation of bread dough found that the relaxation curve closely approximated the equation of a hyperbola of the form $(L-L_A)t = C$, where L is the extensogram load at constant sample extension at rest period t, L_A is the theoretical load which the relaxation curve approaches asymptotically at long rest periods, and C is a constant. The constant C describes the curvature of the hyperbola and is inversely related to the rate of relaxation (called relaxation constant). L_A describes the upward displacement of the hyperbola or the asymptote that it approaches at infinite time. Hlynka used these constants from the relaxation curve in studying the visco-elastic behavior of dough as modified, for example, by the addition of improving agents.

APPARATUS

Requirements

To determine experimentally the mechanical and rheological properties of grain it is necessary to have some means of measuring the applied load or force and the amount of seed deformation as a function of time. It is also highly desirable to have a recording unit to provide a continuous and permanent record of the existing relationships. To satisfy these requirements a load cell testing unit was built with SR-4 strain gages as the sensing means. Equipment was available for amplifying and recording the output signal from a strain gage transducer.

It is necessary for the strain gage load cell to meet the following requirements;

1. Measure the total force applied to the seeds.
2. Measure the deformation of the seed.
3. Record the above parameters simultaneously in relation to time.
4. Be capable of applying a load or force at various rates.
5. Have a relatively high capacity (250 pounds) but with good sensitivity (measure to one ounce of force).
6. Have very small or negligible deflection as the load is applied so that the observed deformation is that due to the seed and not the deflection of the

transducer supporting the seed.

7. Sufficient flexibility to allow interchange of the various testing heads (shear, compression) to be mounted on the same unit.

Figs. 1, 2, and 3 show the load cell and component units.

Design

Load Transducer

The maximum force encountered in testing the three grains would occur in a compressive test on corn at low moisture level with the seed in the flat position. This force was measured to be approximately 200 pounds. To allow for some "factor of safety" the load cell was designed for a maximum capacity of 250 pounds.

The most difficult requirement to meet is the small deflection of the transducer as in part 6. It was for this reason that a preliminary setup based on a cantilever beam was dismissed. To minimize deflection of the load transducer with applied load, a pair of intersecting mutually perpendicular beams were used. These "fixed" beams were formed by cutting slots in a 6" X 2" channel. See Fig. 2.

For a beam fixed at both ends with a concentrated load at the center, the maximum bending moment is at the center and ends. In this case it was desirable to have a built up or raised seed platform at the center of the beams. Consequently the ends of the beams were selected as locations for the strain gages.

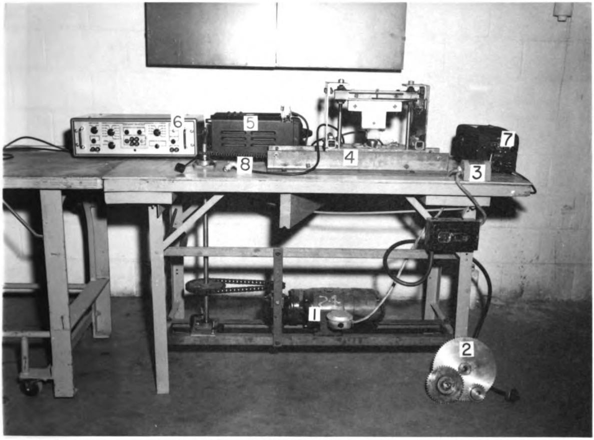


Fig. 1. General view of apparatus.

1. Electric motor and speed reducer (1725 to 9.6 RPM).
2. Sprockets for upper end of vertical shaft to give various speeds to the crosshead.
3. Forward-off-reverse switch.
4. Load cell testing unit with compressive "head" in place.
5. Brush amplifier BL-320 used in the cantilever beam deformation circuit.
6. Brush amplifier BL-520 used in load measuring circuit.
7. Brush oscillograph, BL-202, used to record output from load and deformation circuits.
8. Plug to connect load bridge to BL-520 amplifier.

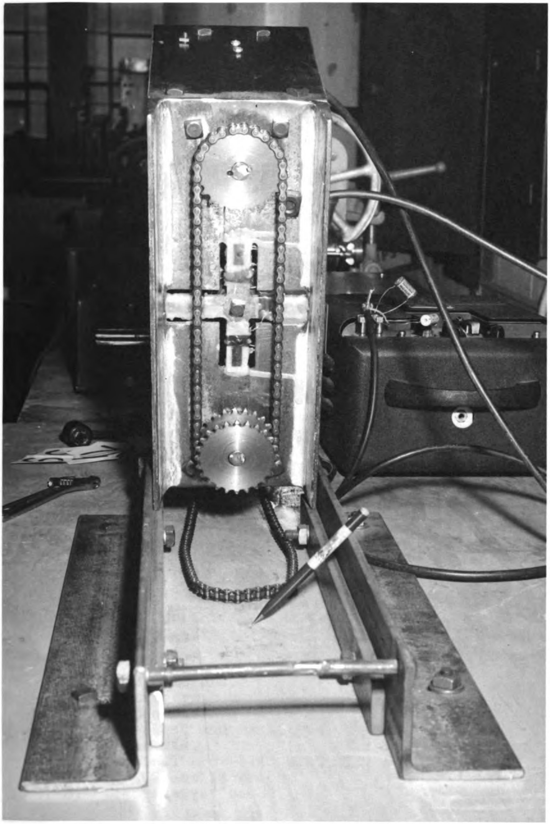


Fig. 2. The under-side of the load cell unit showing location of strain gages and the crosshead drive mechanism.

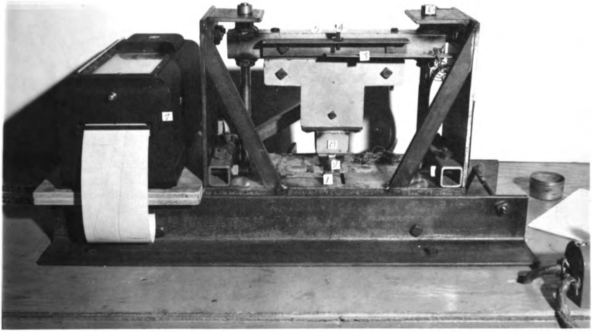
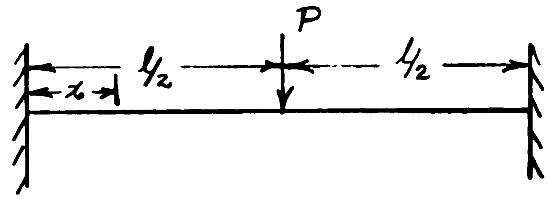


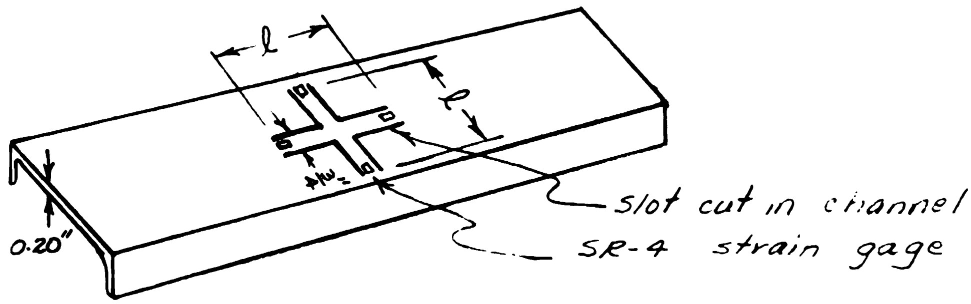
Fig. 3. Load cell unit ready for a compressive test on a kernal of corn in the "flat" position.

1. SR-4 strain gages under a wax covering.
2. Seed platform.
3. Cantilever beam
4. Zero clearance adjustment screw between crosshead and cantilever beam.
5. Crosshead.
6. Vertical crosshead shaft.
7. BL-202 oscillograph.
8. Compressive "head".

Design calculations.

$$M_{max} = \frac{Pl}{8}$$





Beam design of load cell

Fig. 4

Maximum stress in beams. For a 250 pound load, each beam will essentially carry 125 pounds.

For beams, 0.20" X 0.75" X 5",

$$M_{max} = \frac{Pl}{8} = \frac{125 \times 5}{8} = 78.2 \text{ in-lb}$$

$$\text{and } s = \frac{6M}{bd^2} = \frac{6 \times 78.2}{0.75 \times (.2)^2} = 15,620 \text{ psi.}$$

This value is well below the elastic limit for steel.

Maximum deflection at middle of beams.

$$\Delta_{max} = \frac{Pl^3}{192\,EI} = \frac{125 \times 5^3 \times 12}{192 \times 30 \times 10^6 \times .75 \times (0.2)^3}$$

$$= 0.00544''$$

It is apparent that the beams in this situation are not perfectly fixed at each end, with the result that the actual deflection for a load of 125 pounds (250 pounds total) may be somewhat different from the calculated value above. The greatest accuracy in deformation measurements is needed at low loads, that is, while the force on the grain kernel is still below its elastic limit. With larger loads and corresponding deformations, the importance of great accuracy in measuring deformation is decreased. The actual deflection of the beams as measured was found to be linear and 0.001 inch per 60 pounds of load. A correction for this deflection will be made during the tests.

Deformation Transducer - Cantilever Beam.

A cantilever beam arrangement, as seen in Fig. 3, was used to measure the vertical travel of the crosshead. When the compression head was lowered to contact the seed, the adjusting screw mounted on the crosshead was set just to touch the cantilever beam. Any additional travel of the crosshead would deflect the cantilever beam. Hence, by mounting SR-4 strain gages near the cantilever support, the strain produced by bending would indicate seed deformation.

A Brush BL-202, two-channel oscillograph was used to record the crosshead movement. One channel recorded the load while the other recorded vertical travel or deformation. It should be noted that the crosshead movement is linear with time, producing a straight line on the chart with the slope dependent upon chart speed and the crosshead speed. Consequently, for given chart and crosshead speeds the vertical movement or seed deformation could be related to the product of a constant and a horizontal displacement on the chart. Thus, the deformation chart line may appear to be redundant. Although the vertical movement could be determined from the chart without the cantilever when analyzing data, it would be practically impossible to know the magnitude of the deformation during a test. The deformation line was a constant guide as to how much movement had taken place at any time. It was also extremely useful where it was desired to stop the crosshead at a point corresponding to a predetermined deformation.

Design calculations. The only requirement for the cantilever beam was that it be capable of a deflection at the free end equal to the largest desired deformation without exceeding the elastic strength of the steel in the beam. This deflection was considered to be 0.4 inch.

A steel beam 1" X .05" X 7.25" was chosen.

For a cantilever beam, the deflection at the free end is given as:

$$\Delta_{max} = \frac{Px^3}{3EI}$$

from which $$P = \frac{0.4 \times 3 \times 30 \times 10^6 \times 1 \times (.05)^3}{(7.25)^3 \times 12}$$

$$= 0.983 \text{ lb}$$

$$s = \frac{Mc}{I} = \frac{0.983 \times 7.25 \times 0.5 \times 12}{1 \times (.05)^3} = 17{,}100 \text{ psi.}$$

Strain Gage Configuration

Load cell transducers. The location of the SR-4 strain gages for the load cell is shown in Fig. 5. Type A5 gages of

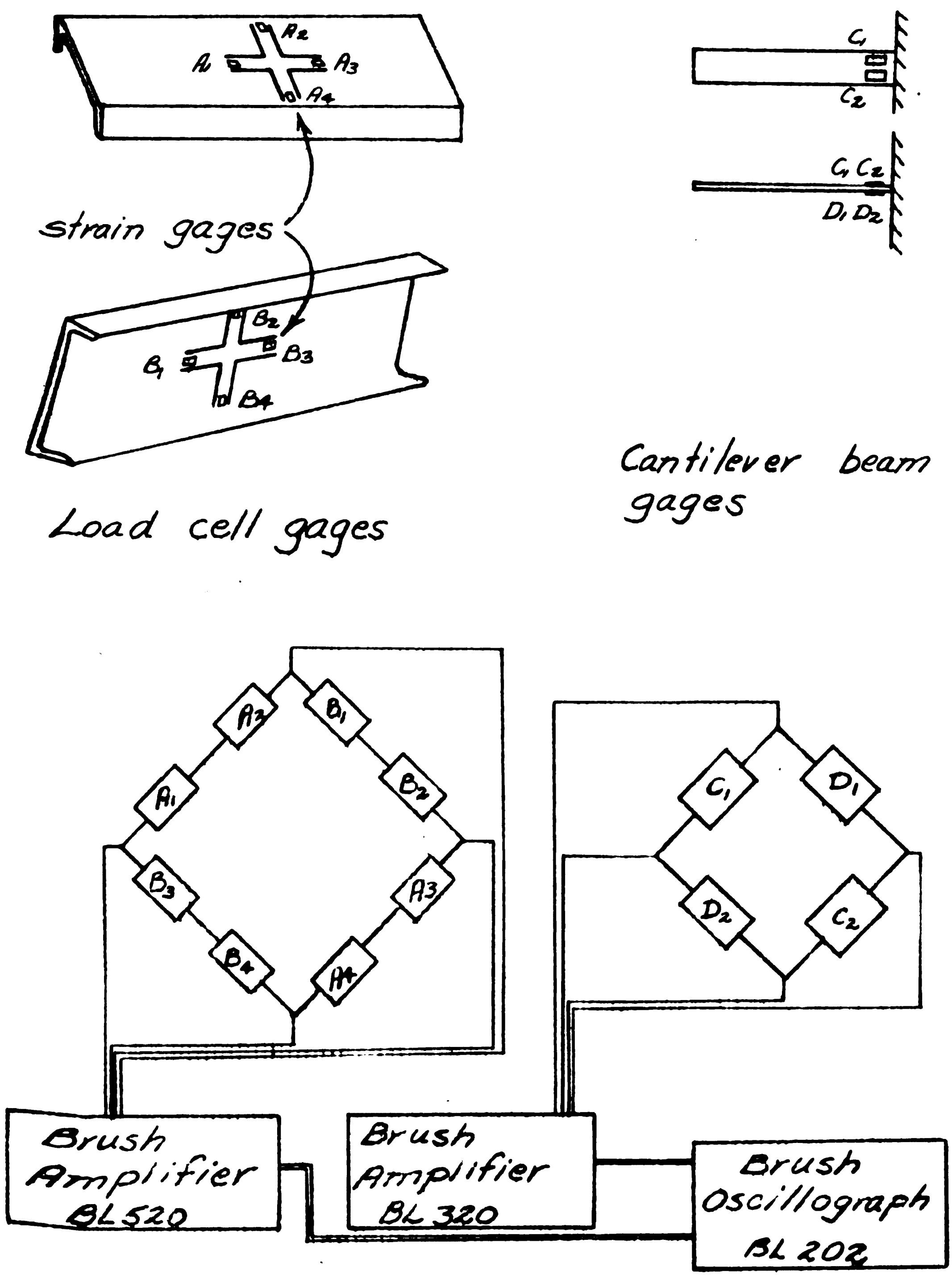
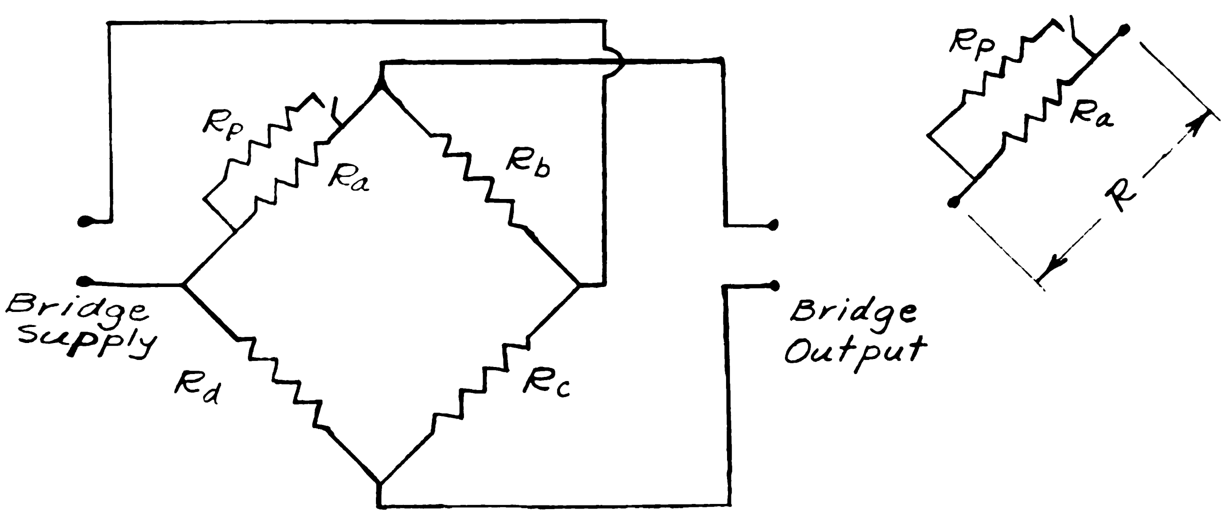


FIG. 5. PHYSICAL & ELECTRICAL LOCATIONS OF SR-4 STRAIN GAGES

½-inch gage length were used. Although the maximum bending moment is at the end of the beams, the gages had to be mounted just inside the ends to insure locating the gage where strain would be present.

The use of four active arms (eight gages) instead of one, quadruples the sensitivity of the unit. This increase is important since the deflection or strain for a given load is small as pointed out above. The "A" gages are in tension under load and the "B" gages are in compression. Accordingly the "A" and "B" gages must be placed in adjacent arms of the bridge circuit. A principal advantage of the arrangement of the strain gages is that the electrical output is independent of the point of load application on the seed platform.



Wheatstone bridge circuit
Fig. 6

In calibration, the strain gage resistance in one leg of the Wheatstone bridge circuit, R_a, is shunted by an opencircuited resistor of considerably higher value, R_p. When R_p is shunted across R_a, the bridge is unbalanced. This unbalance can be considered as an artificial strain which can be calibrated on the oscillograph.

In the above figure:

$$R = \frac{R_a R_p}{R_a + R_p} \quad \text{and} \quad \Delta R_a = R_a - R = R_a - \frac{R_a R_p}{R_a + R_p} = \frac{R_a^2}{R_a + R_p}$$

The gage factor is defined by: $GF = \frac{\Delta R_a / R_a}{\Delta L / L} = \frac{\Delta R_a / R_a}{e}$

$$e = \frac{\Delta R_a / R_a}{GF} = \frac{R_a^2}{(R_a + R_p)(R_a)(GF)} = \frac{R_a}{GF\,(R_a + R_p)}$$

For the Brush BL-520 amplifier, R_p = 390,000 ohms. With the bridge circuit of Fig. 5, the total resistance in each arm is 2 X 120.4 = 240.8 ohms. The simulated strain when R_p is shunted across R_a is:

$$e = \frac{240.8}{1.97\,(390{,}000 + 240.8)} = 313 \times 10^{-6} \text{ in/in.}$$

Since there are four active bridge arms, the indicated strain during operation will be four times the actual strain as given by the above calibration. Hence, to estimate the sensitivity during operation, the simulated strain is:

$$e = \frac{313 \times 10^{-6}}{4} = 78.3 \times 10^{-6} \text{ in/in.}$$

In calibration, a total of 750 attenuator lines was used -- a pen deflection of 15 lines with the attenuator set on 50. This setting is equivalent to 78.3/750 = 0.104 μ in/in per attenuator line on the chart.

For a $\frac{1}{4}$-pound load on each beam ($\frac{1}{2}$ pound load on the seed), the bending moment under the center of the strain gage, at a distance $x = \frac{1}{4}$ inch, from the end is:

$$M = \frac{F}{8}(4x - l) = \frac{0.25}{8}(4 \times 1/4 - 5) = -0.125 \text{ in-lb}$$

Then

$$s = \frac{6M}{bd^2} = \frac{6 \times 0.125}{.75 \times (.2)^2} = 25.0 \text{ psi}$$

This stress corresponds to a strain of

$$e = \frac{25.0}{30 \times 10^6} = 0.833 \times 10^{-6} \text{ in/in}$$

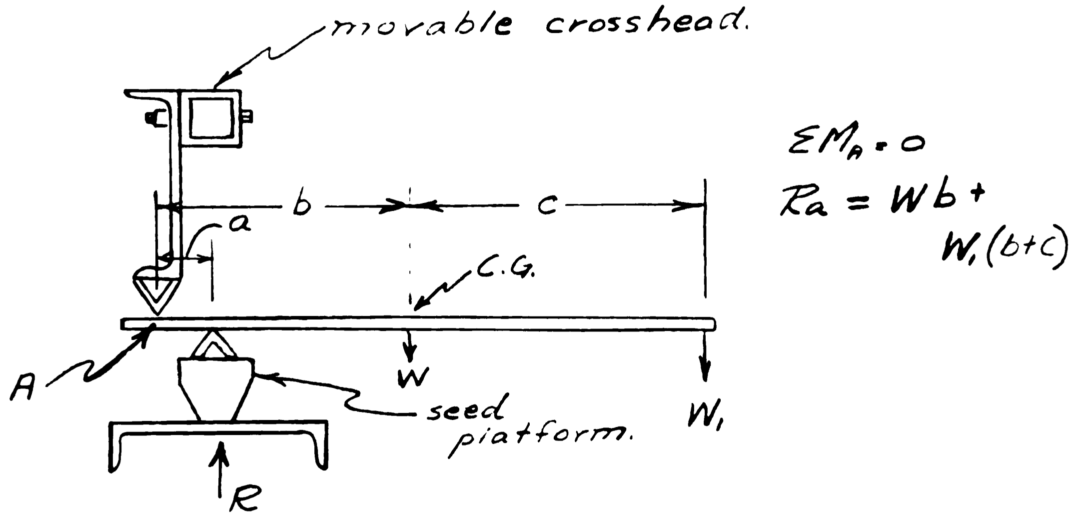
for 8 ounces of load or 9.61 ounces per μ inch. Thus a pen deflection of one line is equivalent to 0.104 μ in/line X 9.61 oz/μ in = 1.0 ounces of force. Accordingly, to measure a force of 200 pounds, the oscillograph would require 200 X 16 = 3200 attenuator lines. This could be obtained by an attenuator setting of 100 with 32 chart lines. (The chart has a total of 40 lines.)

Cantilever deformation beam. The arrangement of the strain gages and the bridge circuit is also shown in Fig. 8. For purposes of estimating the sensitivity in advance, the BL-320 amplifier used in this circuit has about 1/10 the amplification of the BL-520. One line on the chart would be equivalent to about one μ inch. From the calculations above, a deflection of 0.4 inch produces a stress of 17,100 psi. This is equivalent to a deflection of .0007 inch per μ in. of strain or per attenuator chart line.

Calibration

Load Cell

In the calibration of the load cell unit it was considered important to note the number of lines of deflection on the oscillograph for a given load on the unit with the crosshead moving down as it would be during an actual test. Accordingly a channel-iron support member was bolted to the crosshead and the load was applied through a first class lever system as illustrated schematically in Fig. 7. For each loading, W_1, the value from the chart was taken when the bar was in a horizontal position.



Schematic setup for calibration of load cell unit
Fig. 7

The calibration curve is given in Fig. 8. As expected the relationship is linear. Some points are off the line slightly due probably to the difficulty of estimating the exact number of lines of chart deflection. Of course this error is exaggerated at the higher attenuator settings.

This calibration curve shows a sensitivity of 2.11 ounces per attenuator line. This is about twice as high as the calculated value or one half the calculated sensitivity. The principal reason for this discrepancy is probably due to the fact that the load is not truly a concentrated one, since it

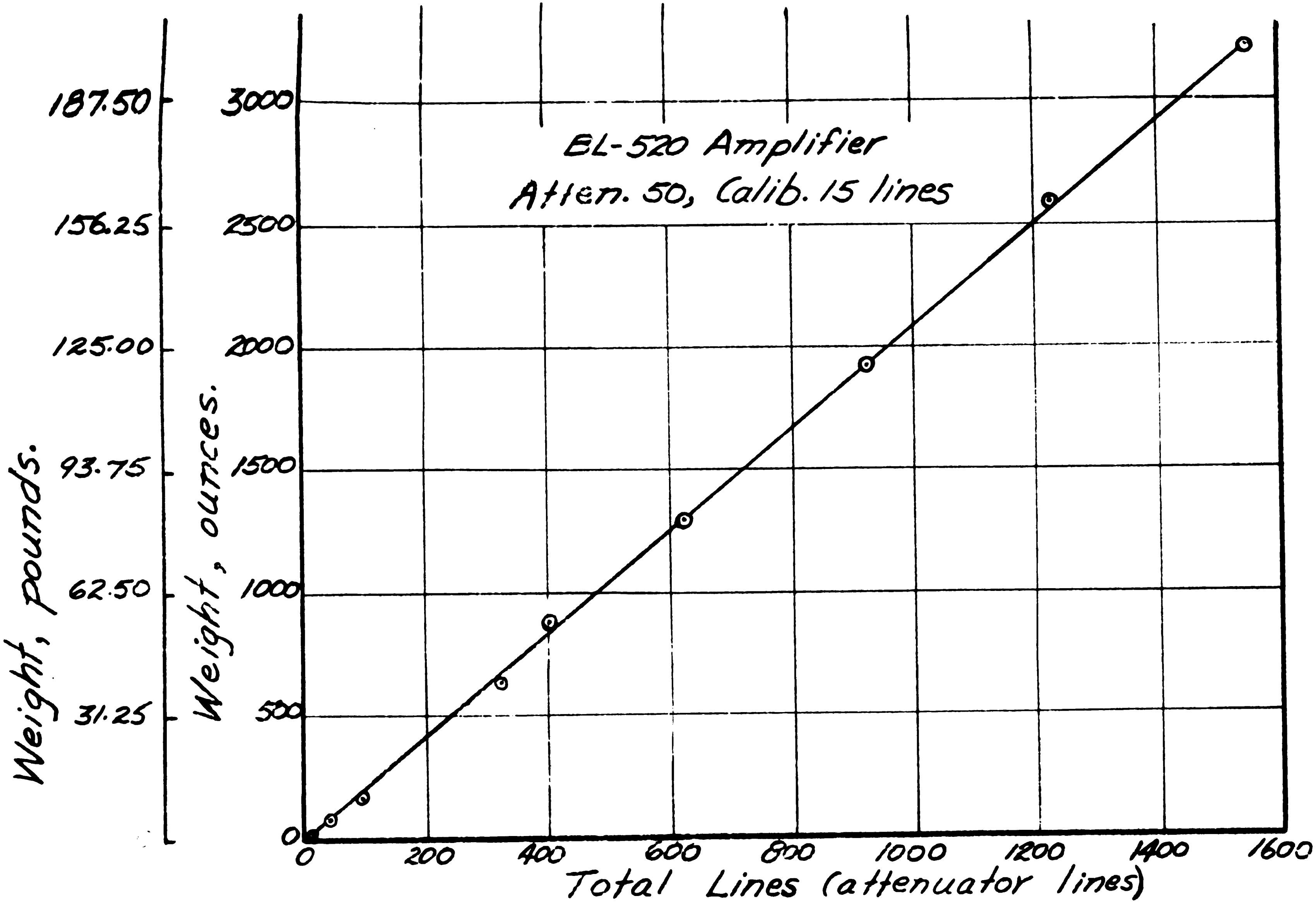
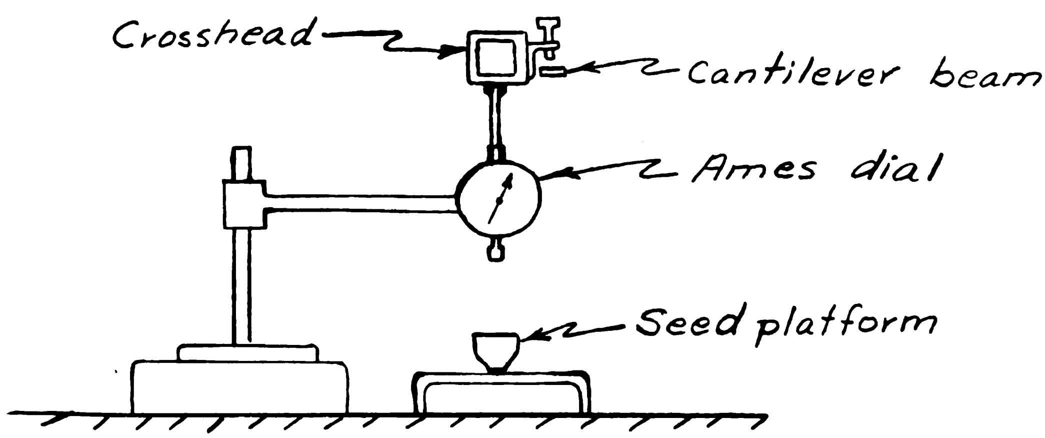


FIG. 8. CALIBRATION OF LOAD CELL UNIT

is spread over the width of the seed platform. Furthermore, in the calculation of the strain it was assumed that the beams were ideally fixed. The beam widths were actually cut somewhat wider on the milling machine than the calculated three-quarters inch. These conditions, would cause the calculated stress to be higher than the actual stress.

Cantilever-beam Calibration

Fig. 9 shows schematically the setup used for calibration of the deformation unit. This calibration showed that one chart line represented a vertical deflection of 0.0012 inch.



Schematic setup for calibration of deformation unit

Fig. 9

Other Features of the Apparatus

Crosshead speeds. Fig. 10 is a schematic diagram showing the drive mechanism. Table 1 gives rates of deformation available. The load cell unit itself was clamped between two large angle irons on a track, so when the speeds were changed, the unit was simply moved along the track until the new chain center distance was reached. This feature may be seen in

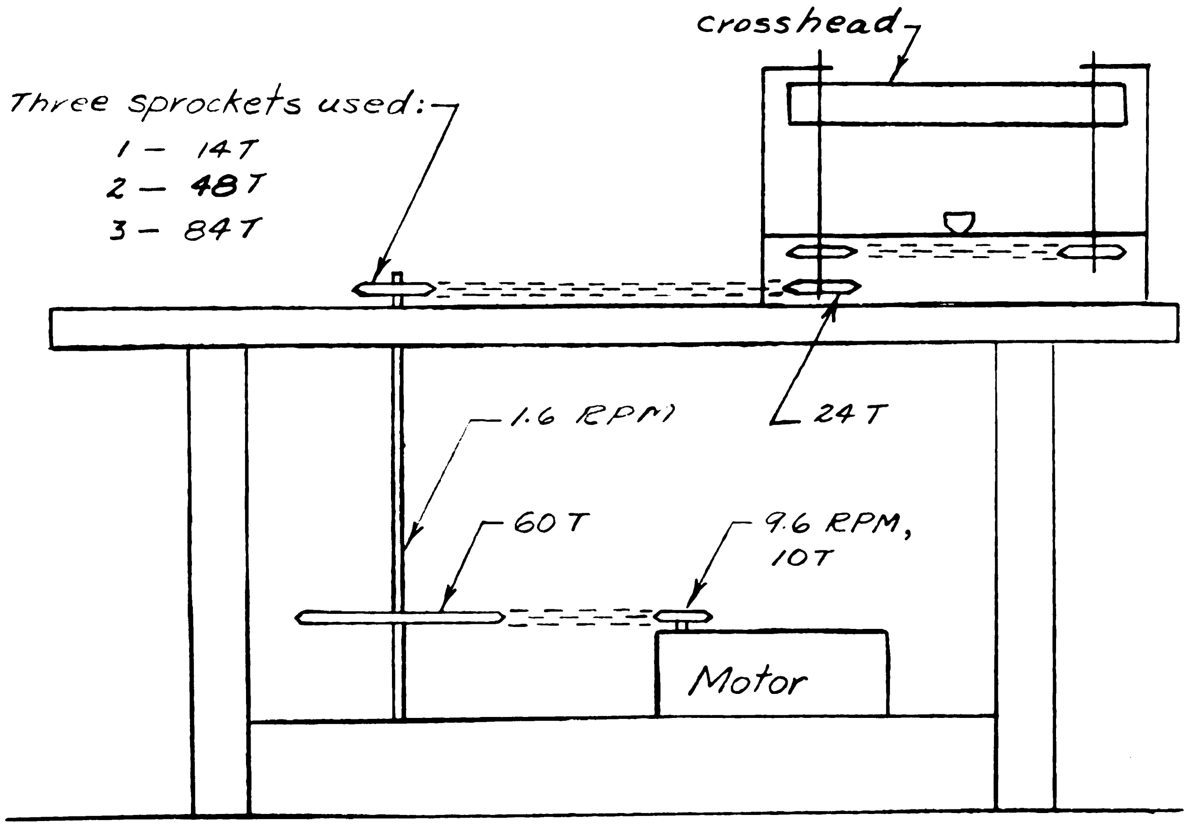


Fig. 10 Schematic diagram of drive mechanism

TABLE 1

CROSSHEAD SPEEDS

Sprocket on Shaft A	Speed of Crosshead Shafts RPM	Vertical Speed of Crosshead, in/min
14T	0.93	.0777
48T	3.20	.2666
84T	5.60	.4667

Fig. 2 and 3.

Relationship between chart speed and crosshead travel. For the purposesof expediting the removal of information from the oscillograph chart, the relationship between head speed and chart speed is summarized in Table 2. This relationship made it possible to get the total deformation by simply finding the product of the appropriate constant and the number of 5 mm chart divisions.

TABLE 2

VERTICAL DEFORMATION,
INCHES/5mm OF CHART TRAVEL

Chart Speed	Slow Crosshead .0777 in/min	Medium Crosshead .2666 in/min	Fast Crosshead .4667 in/min
Slow, 5mm/sec	.001295	.00444	.00778
Fast, 25mm/sec	.000259	.000888	.00155

Use in testing other materials. Fig. 11 shows how the apparatus was used in another research project to measure and record the load-deformation relationship for epoxy resin-glass cloth laminated beam specimens.

Pendulum Impact Tester

The simple pendulum shown in Fig. 12 was constructed to measure the impact strength of grains at the various moisture levels. With this unit the impact load was applied in shear.

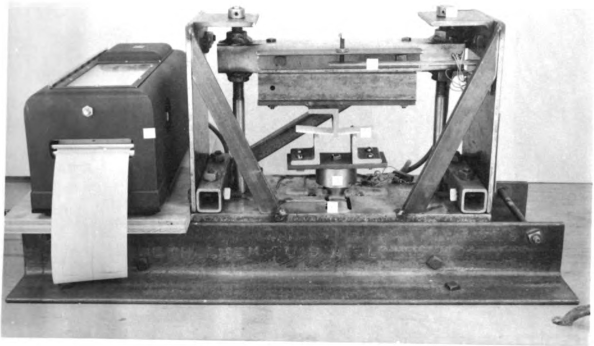


Fig.11. Load cell unit employed (in another research project) to measure and record the load-deformation relationships for epoxy resin-glass cloth laminated beam specimens.

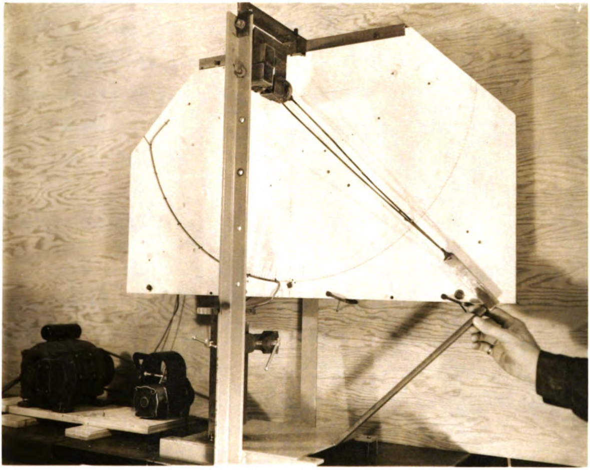


Fig. 12. Pendulum Impact Tester.

The kernel was held in the jaws of the small vise shown in the center of the figure.

Due to the extremely small size of the grain kernels, it was impossible to apply an impact load in flexure as is most commonly done for steel. The seed specimens were held by means of a vise mounted on the pendulum frame. The pendulum leading edge swings by the face of the vise with as little clearance as possible. The seed is thus broken off by a combination of a shearing and a bending action.

Design Calculations

Some preliminary trials were conducted to determine what initial potential energy would be needed to break the tougher high moisture grains. It was found that about 3 inch-pounds of energy was sufficient. Accordingly, a bar ¼" X 1" X 5" was chosen as the hammer and a 1/8 inch section as the double arm.

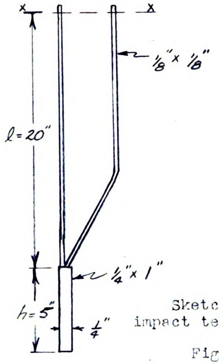
It was necessary to choose a pendulum such that the center of percussion would be located in the hammer rather than up on the arm. The radius of gyration is given as:

$$k = \sqrt{I/M} \quad \text{--------- (1)}$$

The moment of inertia of the pendulum shown below in Fig. 13 about the axis of rotation is given by:

$$I_{xx} = 2\left(\tfrac{1}{3} M_1 \ell^2\right) + M_2\left(\frac{h^2}{3} + \ell^2 + h\ell\right) \quad \text{---- (2)}$$

where M_1 is the mass of the arms and M_2 is the hammer mass.

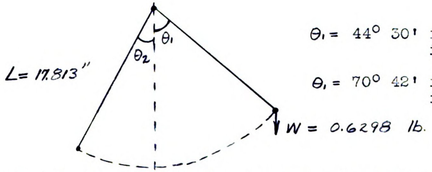


Sketch of impact tester

Fig. 13

For a density of 0.285 lb per cu in, M_1 = .00553 lb-sec^2/ft and M_2 = .01105 lb-sec^2/ft. Upon substituting in equation (2), the moment of inertia is 0.04927 lb-sec^2-ft, from which k = 20.7 in. This value means that the center of percussion of 0.7 in below the top of the hammer.

Energy Relations



θ_1 = 44° 30' for low velocity impact tests

θ_1 = 70° 42' for high velocity impact tests

Schematic of impact tester for determining energy relationships

Fig. 14

By the use of a knife edge, the center of mass of the pendulum was found to be 17.813 inches from the axis of rotation. The total weight was 0.6298 pounds. A fixed initial angle θ_1 (angle of fall) of 44° 30' was used for the lower velocity impact tests.

Energy to rupture seed:

$$E = WL \cos\theta_2 - WL\cos\theta_1 \quad ---- (3)$$

$$E = 11.22 \cos\theta_2 - 8.00, \text{ in.-lb.}$$

For the high velocity tests, with $\theta_1 = 70.7°$,

$$E = 11.22 \cos\theta_2 - 2.01, \text{ in.-lb}$$

In original tests, the maximum travel of the pendulum, as measured by θ_2 was indicated by a friction pointer. To improve the accuracy , an electrical indicating means was devised. As shown in Fig. 12, a tractor magneto driven by an electric motor supplied the necessary voltage to arc the gap between a pointer on the pendulum arm and a stationary grounded wire mounted on the graduated quadrant. A sheet of thin paper was placed between the grounded wire and the pendulum pointer. Since the pendulum stopped for an instant at its maximum travel, several concurrent holes were burned in the paper. It was then easy to see the graduated scale behind the paper and thus read θ_2

Correction for Losses

With the electrical indicator, there were no losses from the indicator arm, but there were losses due to bearing friction in the pendulum and air drag on the pendulum. The following procedure as given by Davis et al (1941) was used to determine these losses.

Without any seed in the vise, the pendulum was released in the normal manner. Angle θ_2 was recorded as B_1. The pendulum was again released and allowed to make 11 swings (6 forward and 5 back). The magneto was not connected to the frame

until the last swing. This angle was called B_2.

The energy lost in air drag and bearing friction of the pendulum was assumed to be distributed uniformly over their ranges of action. As an example, B_1 was found to be 44.3 ° and B_2 was 39.6°. The average angle of rise between readings B_1 and B_2 is $\frac{1}{2}(B_1 + B_2)$; hence, a complete average swing, down and up, is approximately $\frac{1}{2}(B_1 + B_2) \times 2 = 83.9°$. The energy lost in air drag and pendulum friction during one average forward swing is represented by an angle,

$$\frac{B_1 - B_2}{11} = \frac{44.3 - 39.6}{11} = 0.427^{\circ}$$

The energy lost in this manner during either a downward or upward swing of 44.3° is represented by an angle,

$$\frac{1}{2}\left(\frac{44.3 \times 2}{83.9} \times 0.427\right) = 0.226^{\circ}$$

Thus the effective angle of fall θ_1, was $44.3 + .226 = 44.526°$. The corrected angle of rise after rupture of the seed, θ_2 is:

$$\text{observed angle} + \frac{0.226 \times \text{observed angle}}{44.3}$$

The small amount of energy lost in imparting motion to the broken kernel is negligible.

METHODOLOGY

Three grains, corn, wheat, and beans, were used in this study. The three principal parameters in the determination of compressive strength were moisture content, rate of loading and the seed position (either flat or on edge). In the shear tests, a constant speed was used, and the kernel was held in the "flat" position. Thus the moisture content was the only parameter. In practically all series of tests, 10 replications were run. To reduce the large number of tests, the effect of temperature on the mechanical properties was not studied. A total of 753 tests on individual kernels was conducted.

The size (edge, flat and length dimension) of each seed was measured with a micrometer and was recorded before each test. Grain seeds of one variety and one stage of maturity were used in all tests. The corn used was a hybrid variety commonly grown in Central Michigan. Selkirk soft red winter wheat and Michelite pea bean varieties were used in this study. No attempt was made in this study to measure mechanical properties of different varieties of each grain.

It was necessary to have a means of regulating the grain moisture level for each of the tests. Since grain is hygroscopic, its moisture content will depend upon the relative humidity and temperature of the surrounding air. A moisture equilibrium box was designed and constructed to produce four different relative humidities at a constant temperature. Since the air in these chambers is kept in motion by means of a fan, the unit was called a "dynamic equilibrium moisture chamber". This unit is shown in Fig. 15 and 16. Static equilibrium chambers could be used for grain at the lower moisture levels. However, for higher moisture contents the grain may mold (after a period of about three to six days) before the equilibrium moisture content is reached. With the dynamic equilibrium chamber, equilibrium is reached in one day.

The expected grain moisture content was calculated from the empirical equation:

$$1 - RH = e^{-cTM_e^n} \; *$$

in which RH, the relative humidity, is represented as a decimal; T, the absolute temperature, deg R; M_e, the equilibrium moisture content, percent, d.b.; and c and n are constants varing with the materials.

Compressive Tests

The load cell unit with a compressive head mounted in place is shown in Fig. 3. Each grain was tested in the flat position and on its edge. (The design of the load cell allowed the kernel to be located at any place on the seed platform without affecting the magnitude of the indicated force.) To determine if there was any speed effect each grain was tested

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*Hall, C. W.; Drying Farm Crops; Edwards Bros. Inc., Ann Arbor, Michigan, 1957, Ch.2, p.19.

Fig. 15 Dynamic Equilibrium Moisture Chamber, showing thermostat and heating element (light bulb).

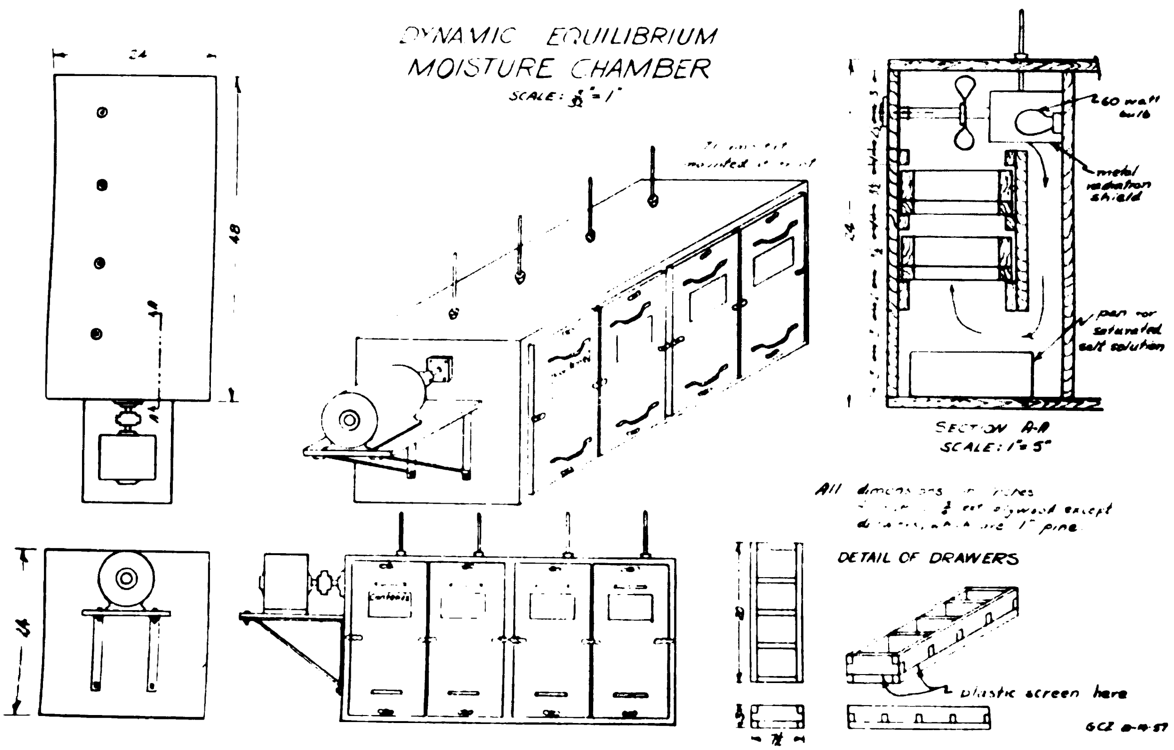
MOISTURE CHAMBER
60 watt bulb
metal radiation shield
pan for saturated salt solution
SECTION A-A
DETAIL OF DRAWERS
plastic screen here

Fig. 16

at the three head speeds of 0.0777 in/min, 0.2566 in/min, and 0.4667 in/min given in Table 1. In the following pages, these speeds will be referred to as slow, medium and fast. From the oscillograph chart, values for proportional limit, yield point and maximum strength were recorded in pounds.

In the compressive tests the strength is expressed in terms of pounds per kernel rather than in pounds per square inch of cross section perpendicular to the direction of load application. In determination of strength properties of nearly all materials, the various parameters (yield point, maximum strength, etc.) are expressed in terms of force per unit area. With a grain kernel, its irregular shape makes this impossible. The force could be divided by an estimated average cross-section area of the kernel, but this would only give a superficial or apparent stress value. Furthermore, the actual strength of the kernel in pounds may be more valuable information in design of equipment.

Since a value for compressive stress could not be obtained using the entire kernel, it was decided to cut a "core" from the kernel to obtain a specimen of known deminsions. For each grain these cores were made by cutting each end off the kernel, leaving a middle section of approximately three-fifths the original length. With corn, a rectangular parallelepiped was formed, while wheat and beans became barrel-shaped pieces. The faces were cut with a razor blade and the dimensions measured to the nearest thousandth inch with a micrometer. See Fig. 17, parts (4), (5), (6).

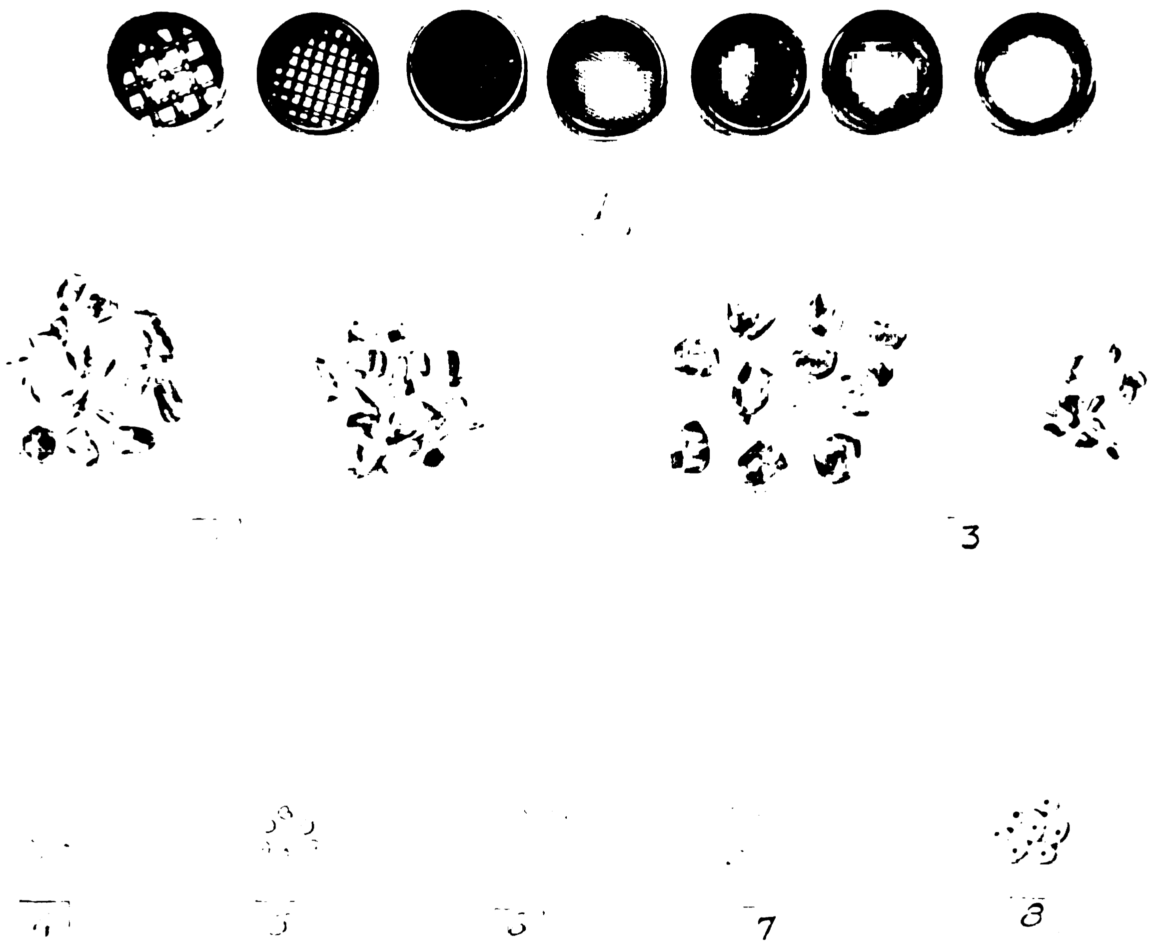

Fig. 17

1. Minature Tyler sieve series, six sieves and pan.
2. Corn which has been fractured from the edge position by compressive tests. At left and right is the material retained on the top and second sieve respectively.
3. Same as 2, except corn was tested from the flat position.
4. Corn "core" specimens, before test.
5. Wheat "core" specimens, after test.
6. Bean "core" specimens, after test.
7. Bean slabs, showing the hole made by the punch shear test.
8. Pea Beans after the punch shear test.

The load was applied parallel to the original length of the kernel, or perpendicular to the cut faces. For wheat and beans, the cross sectional area was calculated by taking the area of a circle whose diameter was equal to the average of the major and the minor diameters of the kernel. For 20 wheat kernels, the average major diameter ("edge" dimension) was 0.134 inch; the average minor diameter ("flat" dimension) was 0.114 inch. With corn, the sides were shaved with the razor blade, giving a rectangular parallelepiped whose dimensions could easily be taken.

These cores were used in tests to determine the following parameters at four moisture levels:

1. Maximum stress, psi.
2. Slope of stress-strain curve in the elastic range, k, lb/in of deformation.
3. The percent deformation at maximum strength ($\Delta L/L$).
4. The modulus of elasticity, psi.

These cores are not considered to be perfect specimens as far as uniformity of dimension is concerned, since in the case of wheat and beans they are slightly barrel-shaped rather than cylindrical. However, the calculated values of stress should be much closer to the actual average stress than by using the entire kernel and trying to estimate the cross-sectional area.

Shear Tests

Two types of "static" shear tests were used; a punch test in which a core or plug was removed from the kernel; and a single shearing-action test in which the complete kernel was sheared in half.

The load cell unit with the head used for the punch tests is shown in Fig. 18. The platform (2) has holes drilled in it corresponding in size to the punch above. Two punch sizes were tried. The larger one, 1/8 inch in diameter, proved unsucessful, since for corn it caused a crack to occur during the test between the punch hole and the edge or pericarp. This cracking resulted in a sudden decrease in applied force and was not a measure of the shearing force, so that rather than shearing out a core, the kernel merely cracked or broke apart. The smaller punch, 1/16 inch in diameter, was also not suitable for testing wheat or corn. For wheat, even a punch of this size tended to crush the entire kernel rather than to shear out a core. With corn, the kernel cross section is extremely inhomogeneous. Thus the shear stress would depend entirely on whether the embryo or starchy endosperm was chosen for the test. The kernel is very hard throughout the outer flinty endosperm section, and quite soft in the central embryo section. It was decided to use the vise shear test in which the entire kernel was sheared off. This test would give an "average" value for the shear stress.

The punch test was used for a series of tests on beans at the higher moisture levels. Below about 15% d.b.* (13% w.b.), the bean is so brittle it merely fractures and no core can be

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*d.b. dry basis: $\frac{\text{moisture weight}}{\text{dry weight}} \times 100$

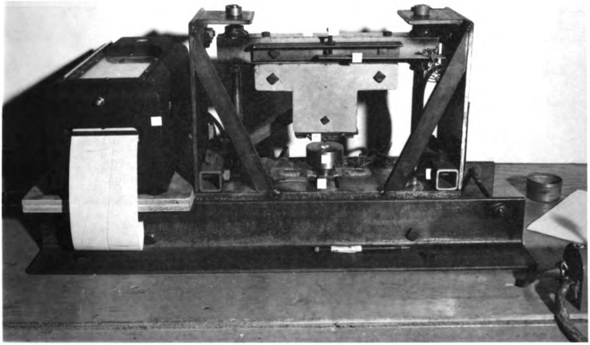


Fig. 18 Apparatus for punch shear tests.

2. Base plate containing holes to match the punches used. The interior of this base plate was machined to provide space for the plugs sheared from the kernels.
8. Punch shear "head".

Other parts are identified in Fig. 3.

sheared from the bean.

Originally the punch test was considered to be a suitable means of measuring shear strength because the shear area would be known fairly accurately. However, in an actual test, the bean deforms slightly under the punch until a force is reached which shears the plug out. This means that the shear area should include the "effective" thickness, that is, the thickness under the punch at the point when the maximum force is observed on the oscillograph chart. If the product of the original bean thickness and the punch circumference is used for the area, this phenomenon of initial compression (plus shear) will give a different calculated shear stress for different thicknesses of the same homogeneous material. This effect was observed more closely by taking shear plug tests on bean slabs of various thicknesses. (Except for the seed coat, pea beans may be considered homogeneous.) Oscillograph charts for two punch tests on bean slabs of different thickness, but the same moisture content, are shown in Fig. 19, charts 2 and 3. Charts 1, 4 and 5 are examples of compressive tests on corn and beans, which will be discussed later.

Static tests in single shear were conducted with the apparatus shown in Fig. 20. A rigid plate, Fig. 20, (9) is bolted to the seed platform (2). This plate contacts the kernel which is held by the vise (8). Thus parallel forces are applied through the plate and the vise to the kernel. The average unit shearing stress was calculated by dividing the total force by the cross sectional area of the kernel parallel

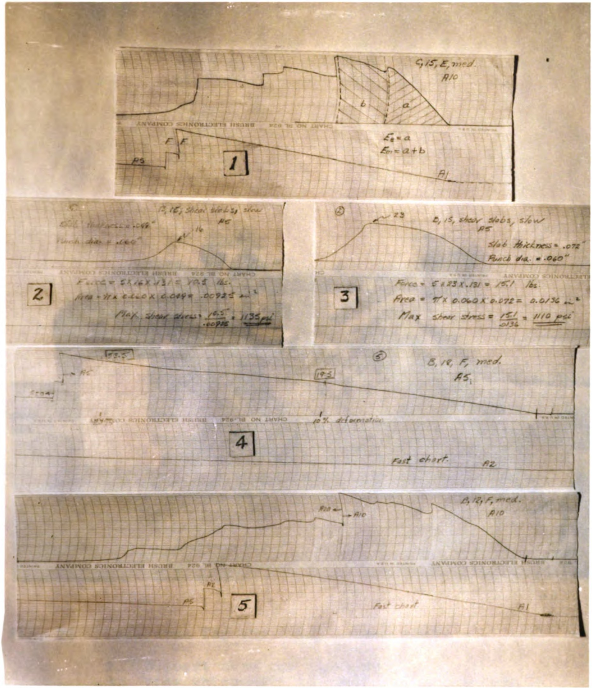


Fig. 19 Representative Oscillograph Charts.

1. Compressive test on corn at 15.8% d.b. and at medium speed with the kernel in the edge position. Area "a" represents the modulus of resilience while area "a" plus area "b" represents the modulus of toughness.

2 & 3. Punch shear tests on pea beans at two slab thicknesses

4. Compressive test on pea beans at 22.8 % d.b.

5. Compressive test on pea beans at 10.6 % d.b.

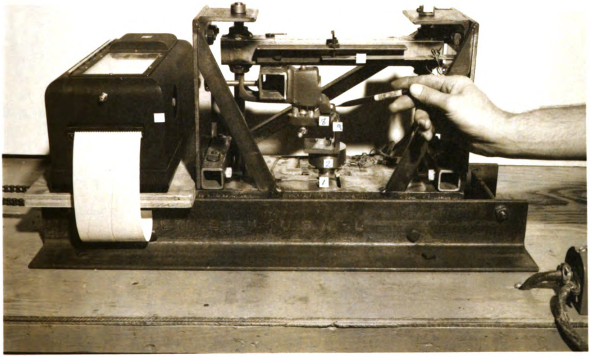


Fig. 20 Apparatus for the static shear test.

2. Support base for shear bar.
8. Vise which held the grain kernel in the flat position.
9. Shear bar or plate.

Other parts are identified in Fig. 3.

to the applied force. It should be noted that this arrangement does not produce a shearing stress entirely free from bending or compressive stresses. Even if double shear could have been used, there would be shear combined with bending. Pure shear, free from bending and compression, could be secured by torsion, but of course this is physically impossible with grain kernels.

Measurement of Energy

Impact Tests

The measurement of energy required to break the kernel by impact shear was obtained by use of the impact tester shown in Fig. 12. The same vise as used in the static shear tests (Fig. 20) was employed to hold the seed. The energy required to rupture the grain kernel is equal to the difference in potential energy of the pendulum between its initial and final position. This was given earlier by equation (3) as:

$$E = WL \cos\theta_2 - WL \cos\theta_1$$

where W is the weight of the pendulum, lb, L is the length of the arm to the center of mass, inches, and θ_1 and θ_2 are initial and final angles respectively. For a given initial point, the second term in the above equation becomes a constant. Most of the tests were conducted with an initial angle of 44° 30'. This produced a theoretical velocity of impact of 5.24 ft/sec. With the pendulum arm length used, it was impossible to increase this velocity to any great extent by using larger initial angles. With the speed range available, one would not expect a noticeable velocity effect. However, one series of tests was carried out on beans at 22.8% d.b. with $\theta_1 = 79^\circ\ 42'$. This greater angle produced a theoretical velocity at impact of 8.87 ft/sec.

Energy of Deformation

One of the chief objectives of this study was the determination of the energy required to deform kernels of grain under various conditions. Specifically, it was desired to measure the resilience and toughness of the kernel.

The resilience is evaluated by the area under the elastic portion of the stress-strain curve. This area represents the work required to deform the material to its elastic limit, i.e., the energy that the kernel can absorb without undergoing permanent deformation. Schmidt and Marlies (1948) define the <u>modulus of resilience or resilient energy</u>, of a material as the energy required per unit volume to deform the material to its elastic limit. In this study the modulus of resilience is expressed in terms of energy per kernel. This energy was obtained directly from the oscillograph chart by measuring the area under the force-deformation curve with a planimeter. For each test the appropriate constant was calculated, with account taken of crosshead speed, chart speed, amplifier attenuator setting, and planimeter constant for the test conditions. To obtain the energy value, then it was necessary merely to take the product of the planimeter reading and its constant.

"Toughness" involves the idea of energy required to rupture a material. The <u>modulus of toughness</u> is given by Davis <u>et al</u> (1941) as the amount of work per unit volume of a material required to carry it to failure under static loading. For grain the energy was measured on the oscillograph chart, up to the point of maximum strength. Toughness is an important property of a material from the standpoint of its ability to withstand impact loads which cause stresses above the yield point. Fig. 19, chart 1, shows the area representing the modulus of resilience and of toughness for corn at 15.8% d.b. Crosshatched area "a" represents the modulus of resilience. The modulus of toughness or the energy up to the maximum strength, E_m, is given by area "a" plus area "b". In this particular test, the elastic limit was reached at a deformation of 2.0 percent and the maximum strength at 3.6 percent deformation.

Hysteresis Loss

By loading and unloading the grain kernel hysteresis loops were obtained. The difference between the work of compression and the work of retraction represents the hysteresis loss. This energy is dissipated as heat. The hysteresis loops were obtained by plotting load versus deformation up to a given load. From this point the unloading curve was plotted back towards the origin.

Total Energy Versus Surface Area

During compression tests on corn, the kernel fractured into many small peices. The amount of "grinding" or pulverizing action produced depended upon the grain moisture content and whether the kernel was loaded in the edge or flat position. In each case the loading was continued until the kernel was deformed to one half of its original dimension. After each test the crushed kernel and small fragments were scooped into a metal container. The contents of the can, containing all the material from ten tests, was oven dried to constant weight at 212° F. It was then put through a minature Tyler sieve series by shaking the unit in a Ro-Tap machine for 5 minutes. The minature sieves are shown in Fig. 17, (1).

The minature Tyler sieves were constructed to facilitate accurate weighing of the fractions retained on each sieve. The sieves were soldered to sections of $1\frac{1}{4}$ inch thin walled pipe which were machined at the top and bottom to allow the sections to fit tightly together. Each sieve section was light enough that it could be weighed on an analytical balance. Each fraction of material retained on the various sieves was weighed to the nearest tenth millogram.

Fig. 17 also shows the different type of crushing action obtained by the static compression tests. In Fig. 17, (2), the corn has been under compression from an edge position. The material at the left was retained on the top screen, and that at the right remained on the second sieve. In Fig. 17, (3), the corn has been crushed from a flat position. Again the left and right pictures represent the material remaining on the first and second sieve respectively. These pictures show the tendency for the corn to split down the center to form relatively large fragments or "slabs" when compressed from the edge position. In the flat position, the kernel cracks on the outer edges and forms many very small particles. The material retained on the other four sieves and on the pan is not shown.

Calculation of Surface Area

To compare energy input and surface area produced, it is necessary to have a suitable means of expressing the total surface area as a function of the weights of material retained on the individual sieves. The chief difficulty encountered in studies of rock crushing by various investigators has been the problem of surface area determination. From the derivation of average surface area by Nicholas and Hall (1957) we have:

$$\bar{a} = \frac{\sum n_i a_i}{\sum n_i} = \frac{\sum 6 n_i e_i^2}{\sum n_i}$$

where N_i is the number of particles on sieve i, e_i is particle edge dimension, and a_i is the surface area of a particle. The particles are assumed to be cubes. The total area can be found by adding the particle area on each sieve. The derivation of the expression for the total surface area for the minature sieve series used is given as follows: The number of particles, N, contained in a weight W of

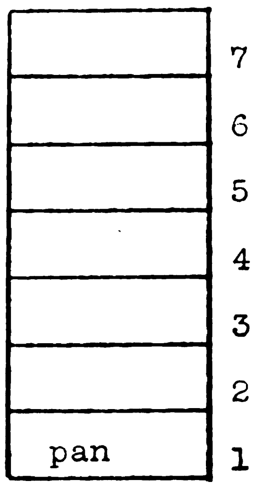


Fig. 21 Numbering system for Tyler sieves

particles of edge, e, is:

$$N = \frac{W}{\rho e^3}$$

(assuming cubes) where ρ is the density. For the Tyler sieves each sieve has an opening twice as large as the one below it. Hence

$$s_i + 1 = 2 s_i$$

The particles on sieve s_i are assumed to be half way between s_i and $s_i + 1$.

Then $$e_i = \frac{s_i + s_i + 1}{2} = \frac{s_i + 2s_i}{2} = \tfrac{3}{2} s_i$$

The total area for the material remaining on sieves 2 to 7 is

$$A = \sum_{i=2}^{7} A_i = \sum_{i=2}^{7} 6 e_i^2 N_i = \sum_{i=2}^{7} \frac{6 e_i^2 W_i}{\rho e_i^3} = \sum_{i=2}^{7} \frac{6 W_i}{\rho e_i}$$

$$= \sum_{i=2}^{7} \frac{6 W_i}{\rho \cdot \frac{3}{2} s_i} = \sum_{i=2}^{7} \frac{4 W_i}{\rho s_i}$$

where A_i is the total surface area on any sieve i between 2 and 7. Since the pan has zero opening, the surface area of the particles remaining on the pan is

$$A_1 = 6 e_1^2 N_1 = \frac{6 e_1^2 W_1}{\rho e_1^3} = \frac{6 W_1}{\rho e_1} = \frac{6 W_1}{\rho \cdot s_2/2} = \frac{12 W}{\rho s_2}$$

The total surface area is the sum of the above expressions:

$$A_t = \frac{12 W_1}{\rho s_2} + \sum_{i=2}^{7} \frac{4 W_i}{\rho s_i} \qquad \text{----------} \quad (4)$$

with the numbering according to Fig. 21.

To use the above equation, it was necessary to determine the grain density. The corn kernels were placed in a mixture of chloroform (sp. gr. 1.475 @ 25° C) and acetone (sp. gr. 0.7880 @ 25° C). The ratio of the mixture was varied until five out of 10 kernels floated and five sank. The kernel specific gravity was obtained by weighing a known volume (50 cc) of this solution. For corn this value was found to be 1.175. By combining this value with the other constants in the equation, the total surface area (in^2) on each sieve was the product of the fraction weight in grams and a constant.

Rheological Properties

As mentioned earlier, rheology may be defined as the study of deformation and flow of matter. It attempts to describe the mechanical behavior of a material in terms of three variables, stress, strain and time.

When a perfectly elastic body is deformed, it takes its final shape immediately without any time lapse. In other words, the deformation is time independent and a function of the applied load (or stress) only. For a perfectly elastic body Hooke's law applies:

$$e = \sigma / E \qquad \text{---------- (5)}$$

where e is strain, in/in; σ is the applied stress, force per unit area; and E is Young's modulus of elasticity in tension or compression. In shear, this equation is:

$$\gamma = s/G \qquad \text{---------- (6)}$$

where γ is the shear strain, s is shear stress and G is the modulus of shear or rigidity.

When a very small force is applied to a liquid it will deform since it has a zero elastic limit or zero elasticity. The force required to move a plate of area A, separated from another plate by a distance d, is directly proportional to the area and the velocity, and inversely proportional to the separating distance.

$$F = \eta \left(\frac{vA}{d}\right) \qquad \text{---------- (7)}$$

where η is the coefficient of viscosity.

From the above, F/A = shear stress, s, and v = dx/dt, so that $s = \frac{\eta}{d}\frac{dx}{dt}$.

Integrated, this equation may be written

$$\gamma = \frac{x}{d} = \frac{s}{\eta}t \qquad \text{---------- (8)}$$

where γ is the shear strain. For an ideal liquid (Newtonian) the rate of flow is s/η. The above type of flow is called viscous flow.

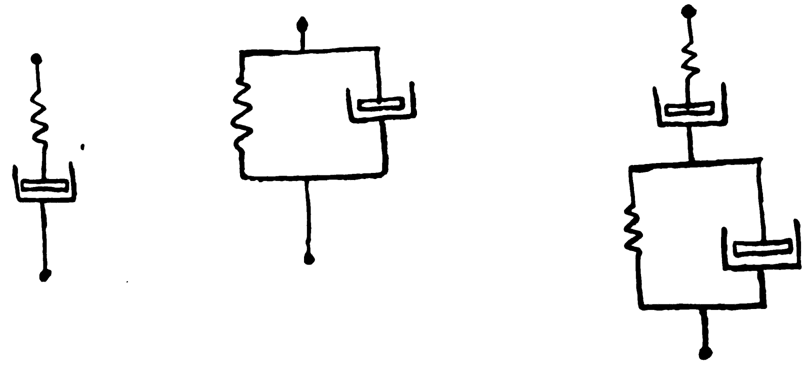
Between the extremes of elastic deformation and viscous flow, is a type of flow called plastic flow. When a solid is deformed beyond its yield point, it will flow and experience a permanent deformation. This phenomenon is called plastic flow. Beyond the elastic limit the flow may be linear as in the case of viscous flow, or it may be non linear. For the ideal linear we get an equation similar to equation (8) above,

$$\gamma = \frac{(s - s')t}{\eta'} \qquad \text{---------- (9)}$$

Schmidt and Marlies (1948) call η' the pseudoviscosity or plastic viscosity.

> Hookean ideal elastic deformation in a solid and Newtonian flow in a liquid may be considered as the two extremes of rheological behavior. It may be said that there are three basic types of deformation, elastic deformation, plastic flow and viscous flow. Many products such as rubber and plastics may be considered as combinations and modifications of the three behaviors. The action of these complex materials under load is often represented by mechanical models composed of elastic and viscous elements acting in series, in parallel or both.*

When a body possesses both elastic and viscous characteristics it is sometimes called "visco elastic". To help visulize the relationship between deformation, load, and time, a mechanical model is often used as shown in Fig. 22.



(a). (b) (c)

Fig. 22 Mechanical models used to represent rheological behavior; (a) a Maxwell unit, (b) a Voigt unit (c) a Maxwell and a Voigt unit in series.

*Schmidt and Marlies; Principles of High-Polymer Theory and Practice; McGraw Hill, 1948. Excerpts from Chapter 7.

In the case of the Maxwell unit a given stress will cause an instant elongation (or compression) of the elastic spring plus a deformation due to movement of the piston in the dashpot. If a certain model represents the behavior of a particular material, rheological equations may be written. For example Steenberg (1949) considered that rheological characteristics of paper could be represented by a model as in Fig. 22 (c), except that a spring would be added in series with the dashpot in the parallel unit.

For a Maxwell unit the strain at any time will be the sum of the elastic and viscous elements. From equations (6) and (8) above:

$$\gamma = S/G \quad \text{and} \quad \frac{S}{\eta} t$$

$$\gamma_{total} = S/G + \frac{S}{\eta} t \qquad \text{----------- (10)}$$

$$\frac{d\gamma}{dt} = \frac{1}{G}\frac{dS}{dt} + \frac{S}{\eta} \qquad \text{---------- (11)}$$

$$\frac{dS}{dt} = G\frac{d\gamma}{dt} - \frac{G}{\eta}S$$

$$\text{or} \quad \frac{dS}{dt} = G\frac{d\gamma}{dt} - \frac{S}{\tau} \qquad \text{---------- (12)}$$

where $\tau = \eta/G$ is a constant called relaxation time or the time constant. The analogous equation for tensile or compressive stress (assuming $E_c = E_t$) is

$$\frac{d\sigma}{dt} = E\frac{de}{dt} - \frac{\sigma}{\tau} \qquad \text{--------- (13)}$$

E and G are related in the elastic range by

$$E = 2G(1+\mu) \qquad \text{---------- (14)}$$

where μ is Poisson's ratio.

Rate of Deformation

From Fig. 22 above, it is apparent that the rate of deformation will be important in determining the resultant force (or stress) on the unit at any time. If the load is applied very quickly, the dashpot will not have time to operate. It will act as if "frozen". The Maxwell unit will behave almost like the elastic portion alone. On the other hand a slow deformation will cause the dashpot to have much more influence. From equation (13) it can be seen that the magnitude of the time constant, τ, is very important. If the rate of deformation is low, i.e., the time of deformation is long, with respect to τ, the viscous element will dominate the action. Similarly a short time of deformation with respect to τ, means that the spring or elastic segment will be most important.

The effect of rate of deformation was examined for pea beans at the higher moisture levels. Data were also plotted for wheat at slow and fast speeds but at a lower moisture level.

Stress Relaxation

As mentioned, one rheological distinction between a liquid and a perfectly elastic solid is the relaxation time; for an ideal liquid it is zero, and for a perfectly elastic solid it is infinite. It is obvious that for a visco-elastic body such as grain, the relaxation time will have some value between these extremes. Relaxation time is a measure of how fast the grain can dissipate stress after receiving a sudden deformation. It is therefore considered an important rheological property of grain.

In the tests on pea beans, the kernel was given a certain percent deformation, at a given crosshead speed. After the crosshead was stopped, the relaxation of stress appeared on the oscillograph, since the chart continued to travel. From this record, the logarithm of force was plotted against time on semi-log paper. The instant at which the crosshead stopped was taken as zero time. This relationship of stress relaxation was measured for three deformation speeds and for various amounts of deformation.

The basic equation (13) above which assumes a Maxwell unit representation, is restated:

$$\frac{d\sigma}{dt} = E\frac{de}{dt} - \frac{\sigma}{\tau}$$

Since the deformation rate is zero when the crosshead is stopped, the term E de/dt is zero. By integration, we obtain

$$\sigma = \sigma_0 e^{-t/\tau} \qquad \text{----------} \ (15)$$

where σ_0 is the initial stress when t = 0. This equation shows that one expects a straight line relation between stress and time on semi-log paper. In such a case, the time constant τ, is the time for the original stress to relax to one e^{th} its original value. This time, as previously stated, is the relaxation time.

It should be noted that for pea beans, force rather than stress was plotted against time, since the cross sectional area of the bean is not known. Since stress is merely force divided by a constant (area) the shape and the time constant of the curves is unaltered by plotting force instead of stress.

RESULTS AND DISCUSSION

Compressive Tests

Compressive Tests for Corn

Considerable variation was obtained in the results of compression tests on individual kernels. Two reasons for the high variance are the inhomogeneous nature of the corn seed and the stress concentration set up by its irregular shape or irregular bearing surface. That the irregular bearing surface was a big factor is apparent upon comparing the results of corn tested on the edge and the flat position. Since the edge surface of most kernels is quite smooth and relatively straight, the point loads are minimized in the edge test. When loaded in the flat position, many kernels are slightly dome shaped, which caused early failure and a low apparent maximum strength. Kernels having straight, flat sides are able to take higher loads than domed shaped kernels before failure.

Results from these original tests are given in Tables A1, A2, A3, A4 and A5. In each case the average value, the standard deviation, σ, and the coefficient of variation*, C, are given. Since the absolute value of the standard deviation may be quite different in two sets of data, use of

---

* $C = \sigma / \text{Ave} \times 100$

the coefficient of variation allows direct comparison of the two groups. It will be referred to henceforth as the C value.

In tests at three speeds on corn, at one moisture level, (14.3% d.b.), C was around 20 percent for the edge tests and averaged about 35 percent for the flat tests. (Tables A1 and A2) Approximately the same range of C values is given in Tables A4 and A5 where the forces at the yield point and maximum point are given for four moisture levels.

It should be noted that the yield point is not too definite in tests at higher moisture contents. The indefinite location of yield point is particularly noticeable for the flat tests. The force-deformation curves are often curved to the maximum strength. For consistency in tabulating the data, the yield point was taken as the point where an increase in deformation occurs without increase in force. With high moisture kernels, a definite maximum point is not always indicated. In most cases a maximum point is reached, followed by a drop in the force on the chart. Further deformation causes the force to increase again. This increase should not be considered as representing kernel strength, but rather as the force resulting from the crushing action. By the time the maximum point was reached, the kernel had failed, i.e., its original dimensions were destroyed. With high moisture, the force simply increased with deformation, and no maximum was shown on the chart. In this case the kernel was "plastic" in nature.

The force-deformation curve varied from one kernel to another, and the curves in Fig. 23 represent an average for 10 tests. Thus, each point on the curve is the average force for 10 tests at that particular deformation. Beyond the maximum strength, the lines are dotted as the force variation beyond this point is quite irregular. The curves in Fig. 23 show a definite maximum point. As would be expected at higher moisture levels, the maximum force was reached with greater deformation. The yield point is not indicated in these curves because of the averaging process. Yield and maximum force values for edge and flat tests are given in Tables A4 and A5.

Compressive Tests for Pea Beans

Fig. 24 illustrates the result of compressive tests on pea beans at two moisture levels. At 10.6% d.b., the beans showed elastic properties, for both the edge and flat positions. In the flat position, a yield point was reached at about 5 percent deformation. In the edge test, no yield point was apparent; the elastic limit and maximum strength were identical points. This difference was probably due to the small space between the two cotyledons. (It should certainly have more effect when a compressive load is applied in the flat position than in the edge position.) Thus, the apparent yield point in the flat test was most likely the compressive failure point of one or both of the bean halves. After this slight "yield" or relative deformation between the two cotyledons, the force again increased because no

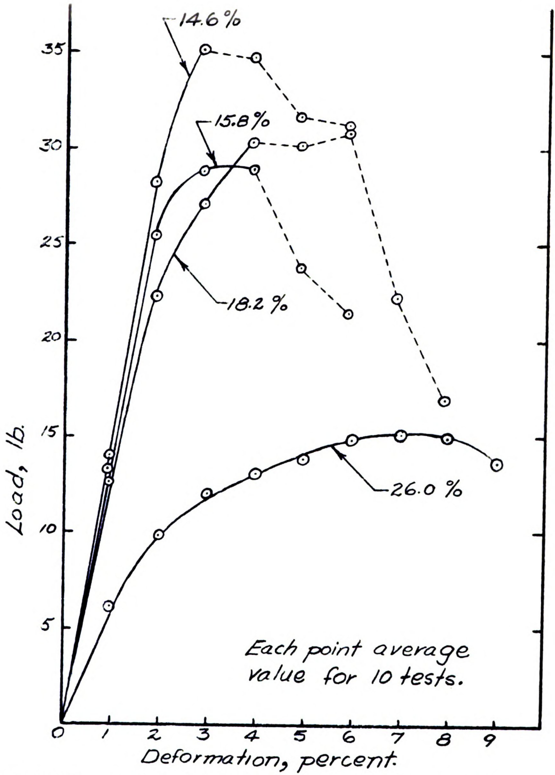


FIG. 23 LOAD-DEFORMATION CURVES FOR YELLOW DENT CORN AT FOUR MOISTURE LEVELS (% d.b.) WITH THE KERNEL PLACED ON EDGE. MEDIUM SPEED.

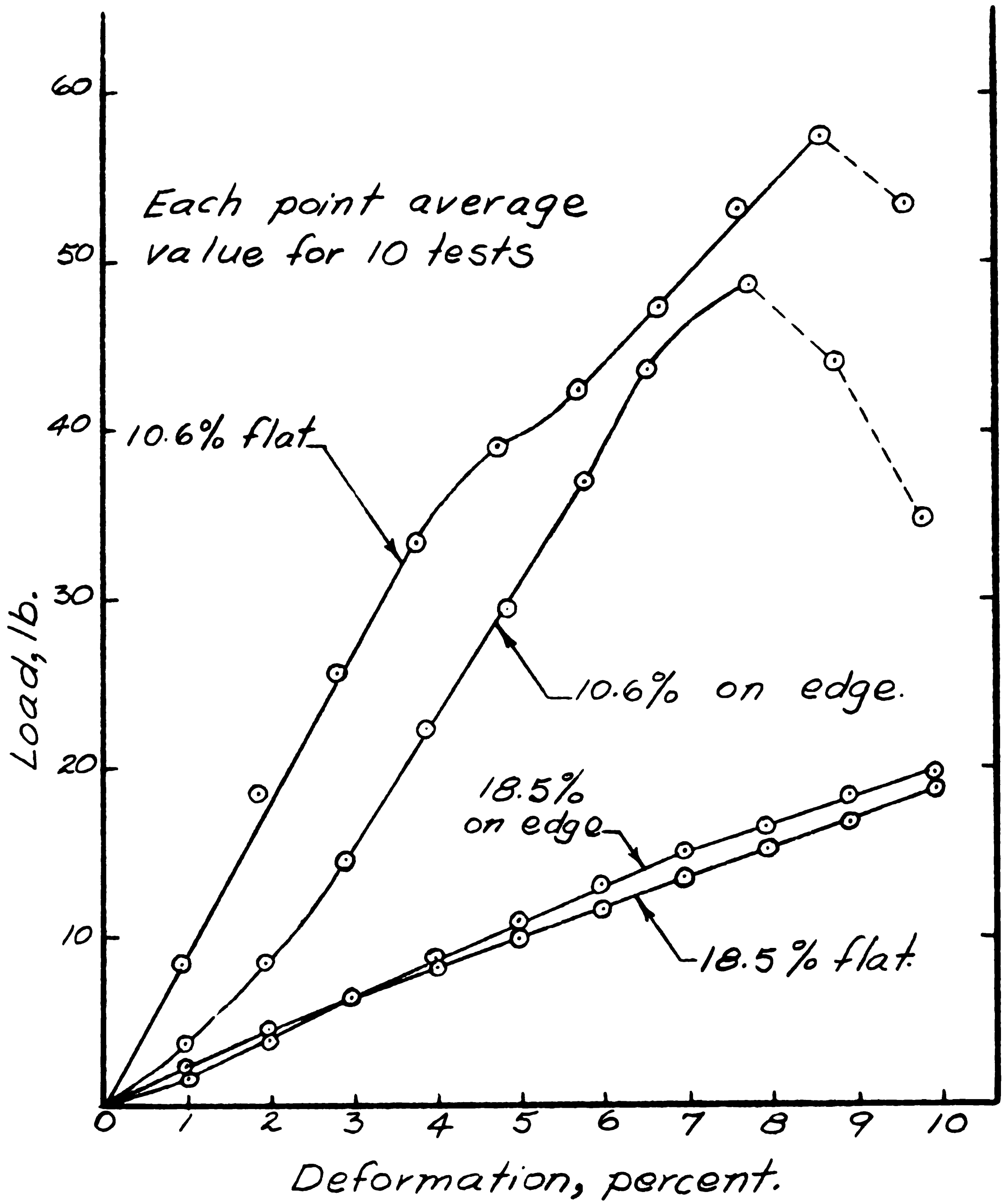


FIG 24. LOAD-DEFORMATION CURVES FOR PEA BEANS AT MEDIUM SPEED (0.267 in/min) AND AT TWO MOISTURE LEVELS (% d.b)

more space was available for further deformation. The next drop-off of force was the maximum strength of the entire bean. The above explanation accounts for the two distinct straight-line portions of the curve for the flat test at 10.6 percent moisture.

The first portion of the curve for the edge tests is curved upward slightly. No explanation has been found to explain qualitatively this upward curvature. The remainder of the curve is linear almost to the breaking point.

With high moisture, less difference occurs between the edge and flat positions. It appears that the plastic or even viscous properties predominate over the elastic effect. At the low moisture, the cross-sectional area has a definite effect; at the high moisture it does not. Although the actual cross-sectional area is not known numerically, it is obviously greater for the flat tests. Hence, there is a higher force at low moisture in the flat position than in the edge position for a given deformation (and a given stress). The high moisture curves in Fig. 24 are good examples of increasing force with deformation without any apparent yield or maximum point.

The force required to reach yield point and maximum strength at 10.6% d.b. is given in Table A3. The yield point and maximum values are higher in the table than in Fig. 24, since the tabulated values are the peaks on the load-deformation curve, whereas the points in Fig. 24 are the average of 10 values at even percent deformations.

[illegible]

[illegible]

[illegible] and sections [illegible]

[illegible] The yield [illegible]

[illegible]

[illegible] Fig. 25 and [illegible]

[illegible] tions.

It is of interest to note the relationship obtained for large deformations, up to 40 or 50 percent. As shown in Fig. 25, portions of the deformation range appear as a straight line on semi-log paper. In compressing these high moisture beans, the volume under the loading head remains almost constant, and is equal to A x h, where h is the bean height and A is the average cross-sectional area. At a deformation of 50 percent h is equal to one-half its original value. Then A must be very nearly twice as large to keep V constant. The curves shown in the insert on rectilinear scale were obtained from the semi-log curves by reduction of the force or load to a load per unit area.

The 22.8 and 32.8 percent moisture curves in Fig. 25 slope to the right at the higher deformation due to a failure of the seed coat. In case of the 18.5 percent beans, the strength of the seed coat has a smaller effect owing to the more rigid material within in bean.

Compressive Tests for Wheat

Preliminary tests showed that there was no significant difference in the force required to deform wheat from either the flat or edge position. Consequently, all further tests were made with the kernel in the flat position.

Load-deformation curves for wheat up to 10 percent deformation are given in Fig. 26. A definite elastic range is shown for the two lower moisture levels. The yield and maximum points were quite indefinite for the 20.8 percent

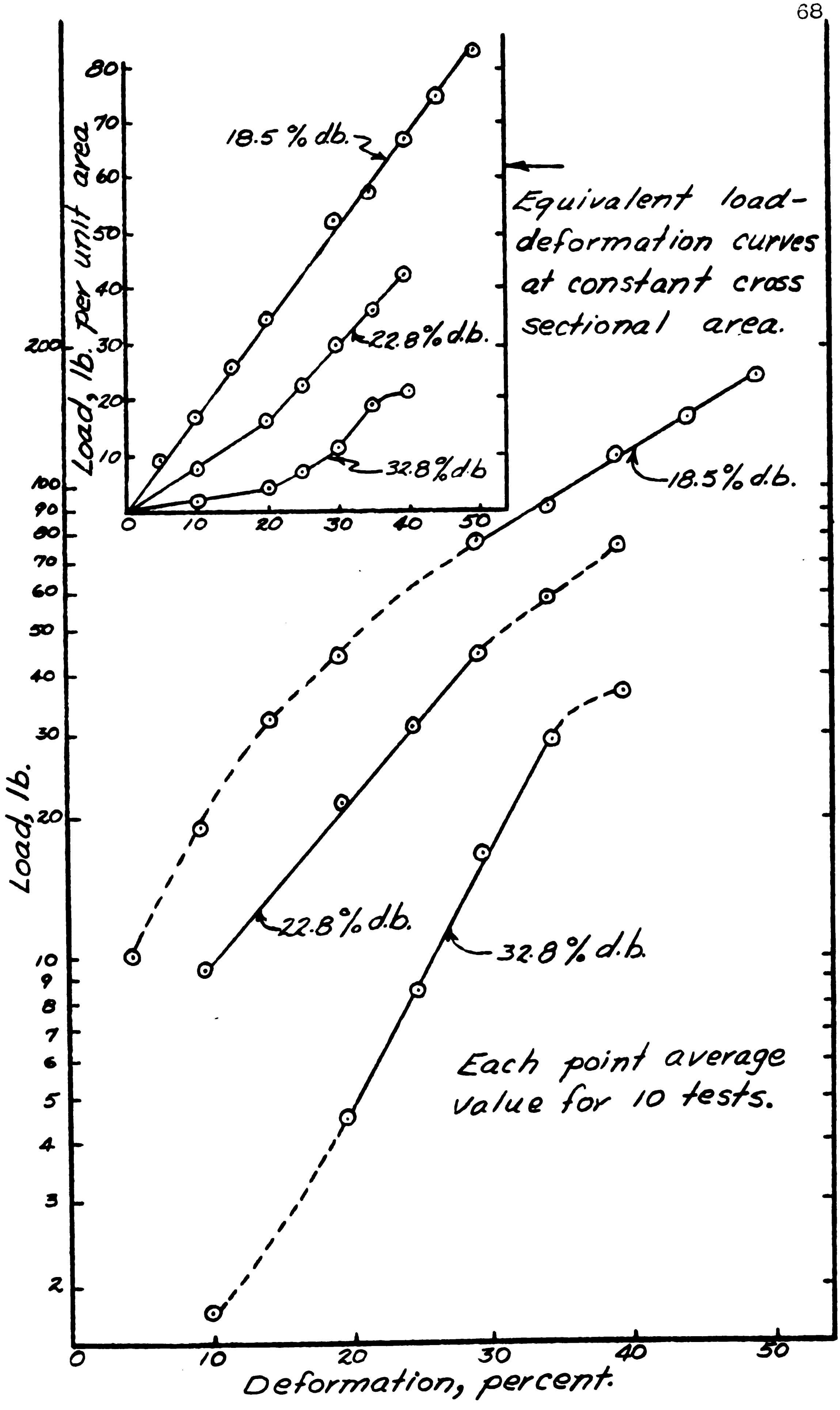


FIG. 25 LOAD-DEFORMATION FOR PEA BEANS

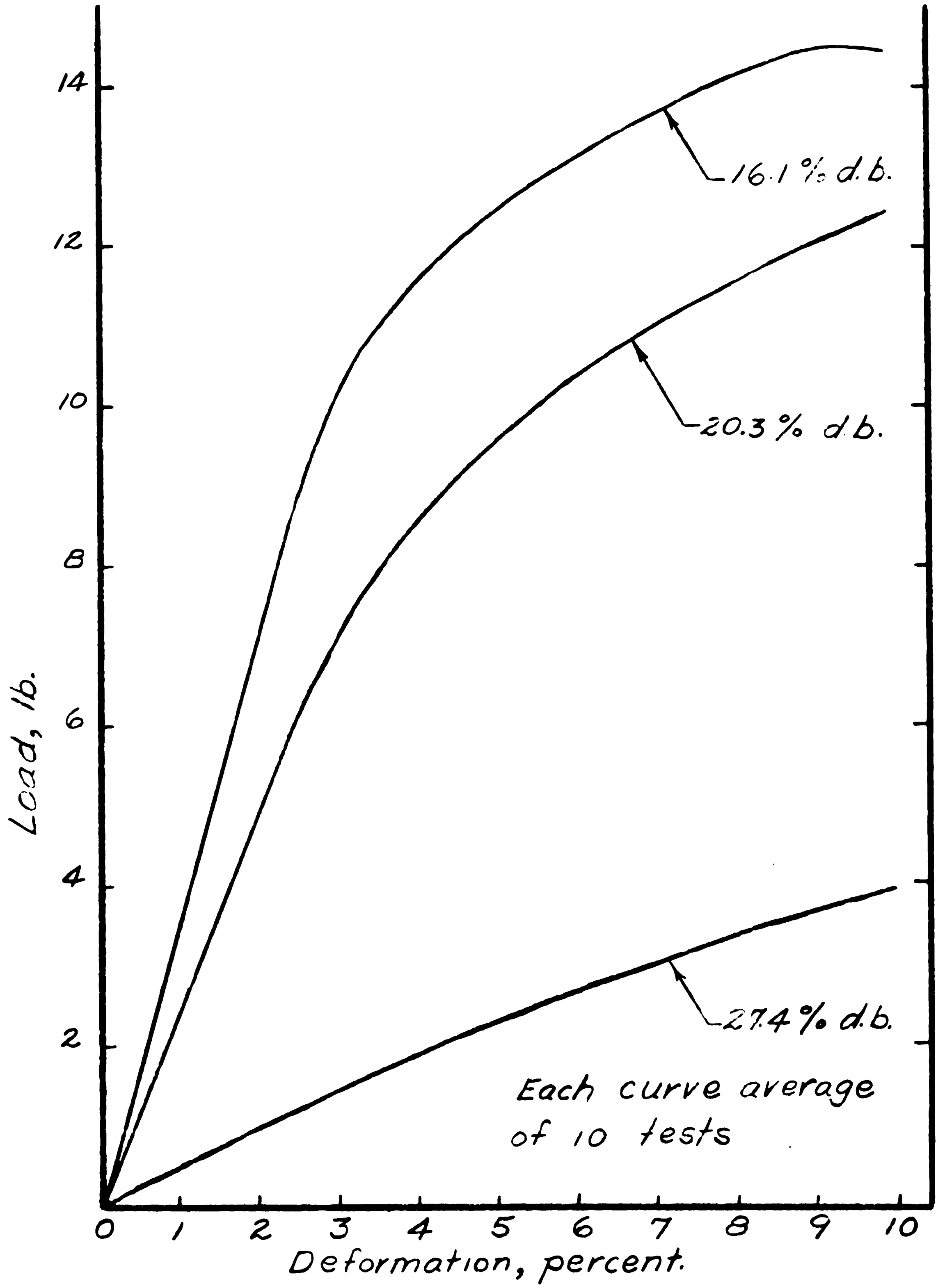


FIG. 26 LOAD-DEFORMATION CURVES FOR SOFT RED WINTER WHEAT AT THREE MOISTURE LEVELS.

curve, while no maximum was shown for the 27.4 percent test. With the logarithm of force plotted against deformation on semi-log paper, essentially a straight line relationship was obtained, especially between 20 and 55 percent deformation.

Original data are tabulated in Tables A7 and A8.

Core Compressive Tests

As mentioned earlier, cores were cut from the grain kernels and used as compressive test specimens. The use of these cores allowed the data to be expressed in terms of average stress, since the cross-sectional area of the core could be determined. These cores are shown in Fig. 17.

The most important properties studied with the cores were the modulus of elasticity in compression and the maximum compressive stress. These properties are shown graphically for corn in Fig. 27 and for wheat in Fig. 28 and 29. Properties that were investigated are summarized in Table 3.

Modulus of elasticity and maximum stress versus moisture are plotted in Fig. 27. A linear relation holds in both cases between 15.4 and 18.8 percent moisture. There appears to be a transition between the 18.8 and 23.0 percent levels. This effect is later shown in impact tests. The corn is quite elastic below 18.1 percent but more plastic towards the 23 percent point. Tests at other moisture levels are needed to describe the behavior in this range.

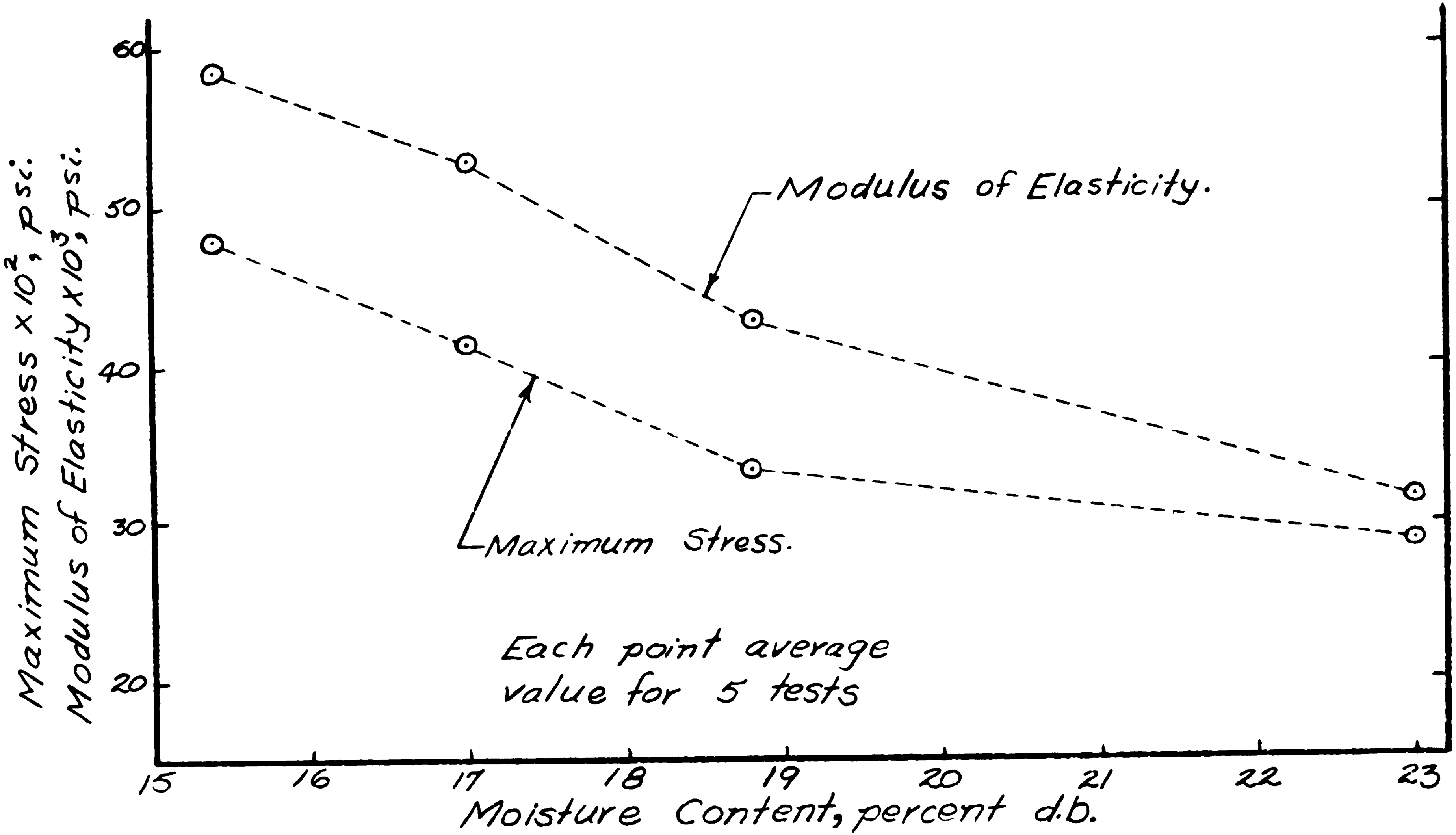


FIG. 27 RELATION BETWEEN MODULUS OF ELASTICITY, MAXIMUM STRESS AND MOISTURE CONTENT FOR YELLOW DENT CORN IN COMPRESSION

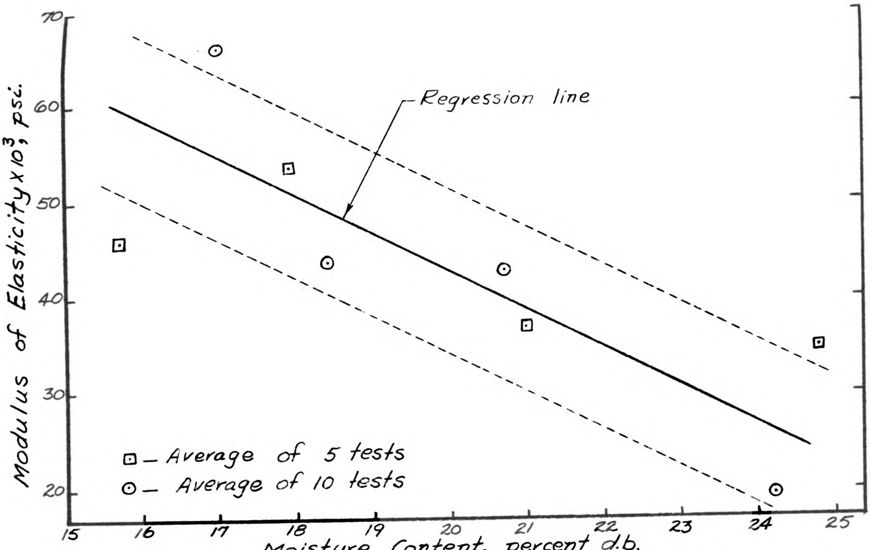


FIG.28 RELATION BETWEEN MODULUS OF ELASTICITY IN COMPRESSION AND MOISTURE CONTENT FOR SOFT RED WINTER WHEAT.

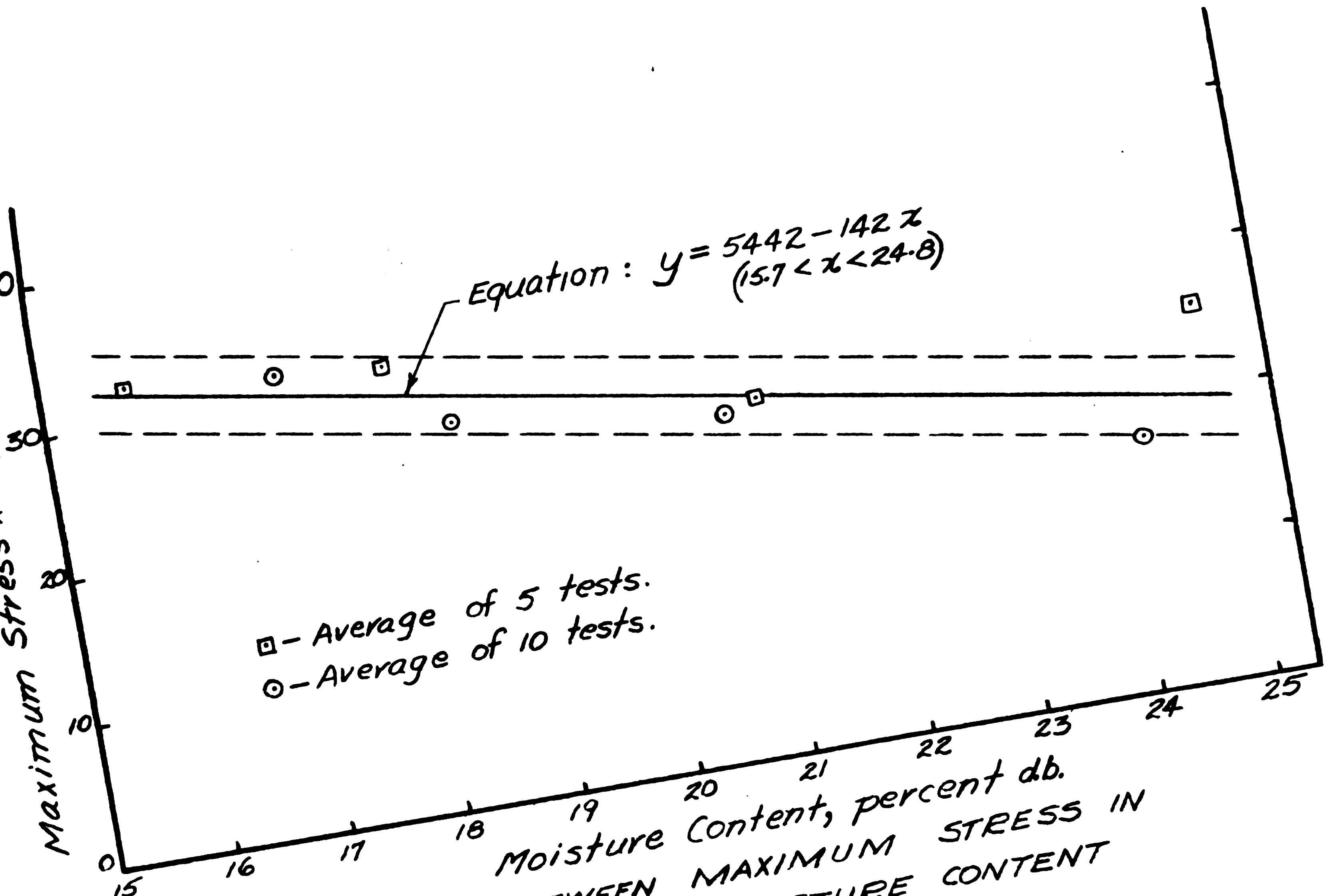


FIG. 29 RELATION BETWEEN MAXIMUM STRESS IN COMPRESSION AND MOISTURE CONTENT FOR SOFT RED WINTER WHEAT.

TABLE 3

SUMMARY OF PROPERTIES OF GRAINS
AT FOUR MOISTURE LEVELS

Grain	Percent Moisture d.b.	Tests To Compute These Average Values	Slope Of Stress-Strain Curve In Elastic Region k, lb/in	$\Delta L/L$ At Maximum Strength %	Max. Stress psi	Modulus Of Elasticity psi
Corn	15.4	5	11,980	14.2	4811	58,600
	17.0	5	12,260	15.7	4145	52,800
	18.8	5	9,630	13.1	3333	42,800
	23.0	5	6,780	19.7	2892	31,740
Beans*	6.4	3	16,550	9.6	4370	64,200
Wheat	15.7	5	5,168	11.8	3259	46,040
	17.9	5	6,143	8.9	3094	53,600
	21.0	5	4,148	22.1	2438	38,950
	24.8	5	3,556	23.7	2574	34,700
	17.0	10	6,640	10.0	3161	66,190
	18.4	10	5,083	11.3	2627	43,540
	20.7	10	4,508	11.5	2391	42,460
	24.2	10	1,920	20.3	1741	19,210

*No elastic properties for higher moisture levels.

Regression lines are drawn in Fig. 28 and Fig. 29 for wheat. Ten extra tests at each moisture level were run in an effort to explain the apparent peak obtained at 17.9 percent moisture during the first series of tests. The dashed lines represent a variation of one standard deviation on each side of the regression line.

Equations are given to represent the relationships in Figs. 27, 28, and 29 between the moisture limits specified.

Shear Tests

Punch Shear Tests

The punch shear tests were used only for pea beans and pea bean slabs. The effect of initial compression on the calculated shear stress is shown in Fig. 30. Since the shear slabs are homogeneous, the calculated shear stress should be constant regardless of the thickness. The values plotted in Fig. 30 are calculated on the basis of the original slab thickness. Typical oscillograph curves obtained for these tests are shown in Fig. 19, with sample calculations on the chart. Actually, the shear stress should be expressed in terms of an "effective thickness". This thickness would be that present at the time the maximum force is reached on the oscillograph chart. By using an effective or equivalent thickness, calculated stress would be constant with slab thickness. The thinner the slab, the more nearly correct the calculated stress should be, i.e., the closer

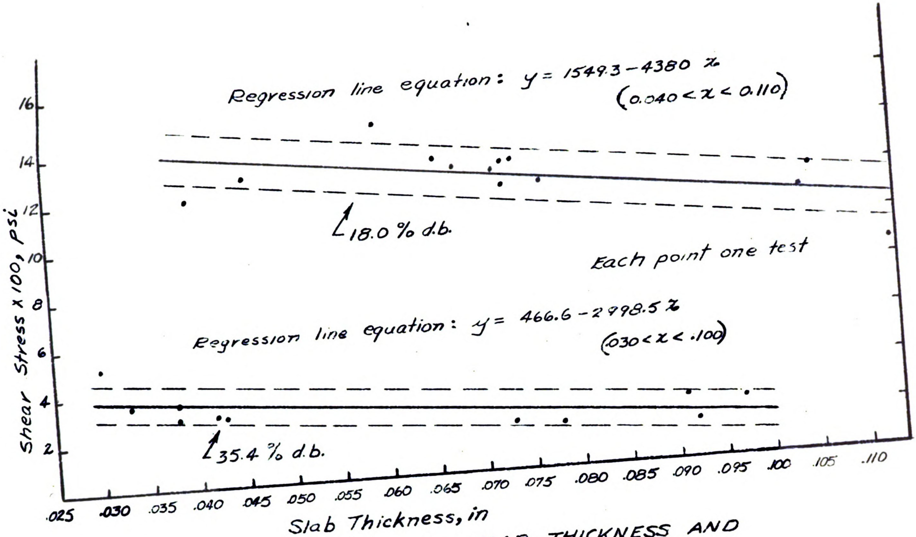


FIG 30 RELATION BETWEEN SLAB THICKNESS AND CALCULATED SHEAR STRESS FOR PEA BEANS USING PUNCH TEST.

required to shear the seed is divided by the cross-sectional area parallel to the applied force, $s = F/A$. There was some compression and bending before failure by shear took place. Perhaps the calculated shear stress should be termed "breaking" stress. Failure by bending (tensile failure) instead of shear was more common at the low moisture levels.

Fig. 31 summarizes the relation between maximum shear stress (or breaking stress) and moisture content for wheat and corn. The bending strength of corn decreased more than wheat with increasing moisture content. In compression tests, a greater variation in compressive strength was found for corn than for wheat with changes in moisture content.

Shear stress is plotted against moisture content for pea beans in Fig. 32, over a wide moisture range. Relatively high shear stress was found around 18 percent moisture content. This increase in strength may be explained as follows. At the low moisture level (6.4% d.b.) the bean kernel is brittle, and failure by bending occurs (tension in the lower edge). In the intermediate range, the bean is relatively tough, raising the shear stress. At very high moisture levels (37.6% d.b.) the bean becomes very soft, and thus requires much less force to shear it in half.

Measurement of Energy

Impact Tests

Results from the impact tests for wheat using the impact

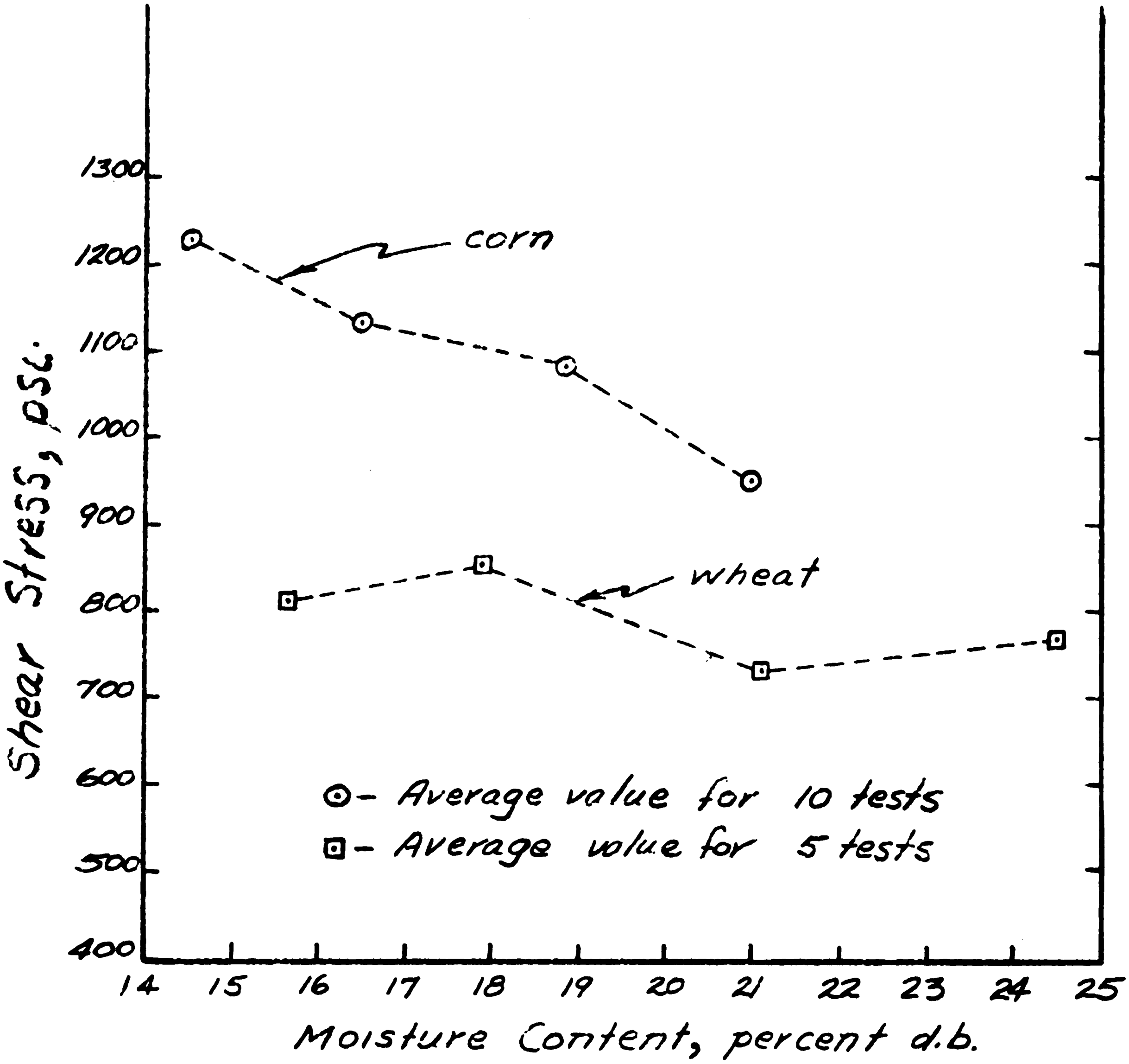


FIG 31 RELATION BETWEEN SHEAR STRESS AND MOISTURE CONTENT FOR SOFT RED WINTER WHEAT AND YELLOW DENT CORN.

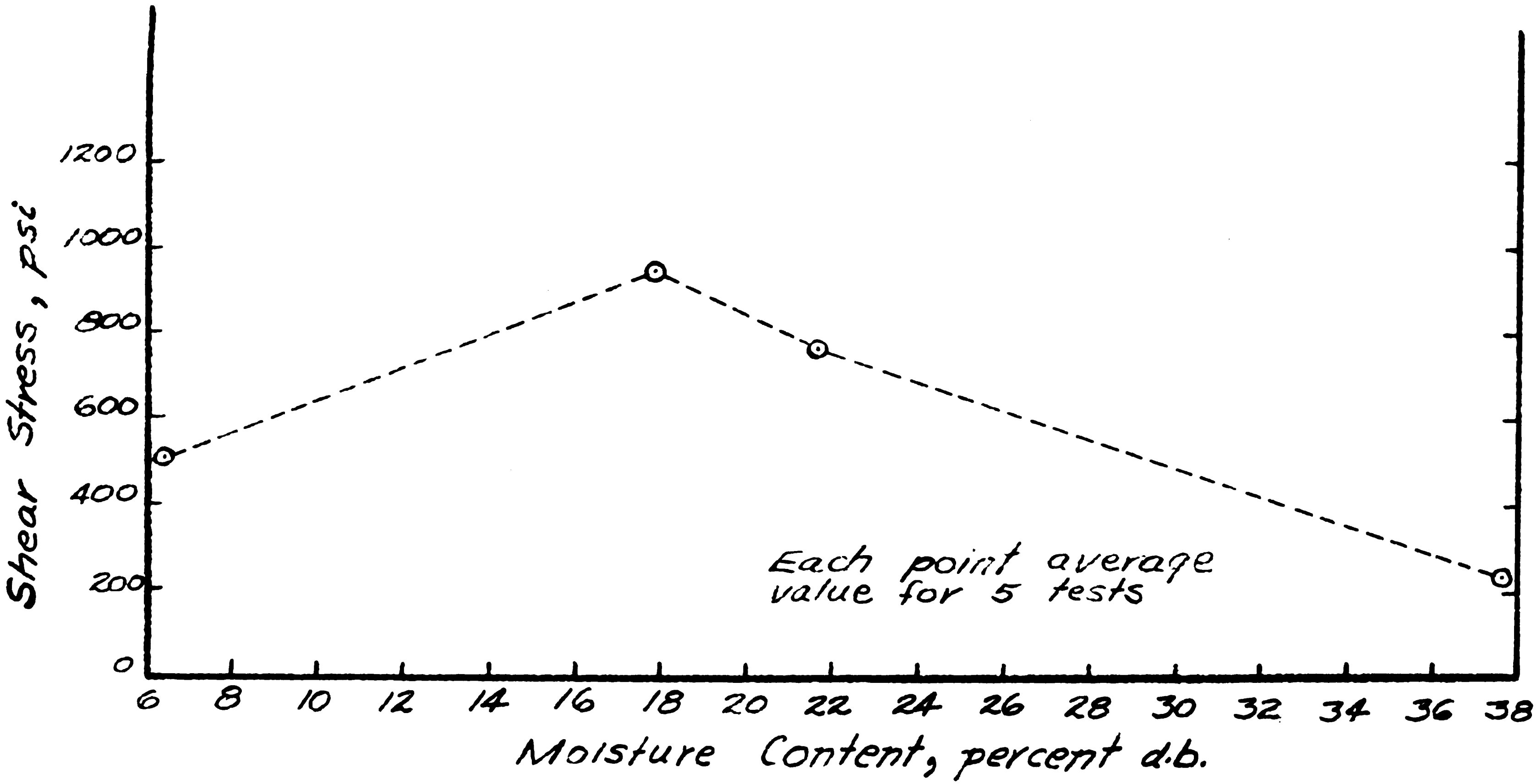


FIG 32 RELATION BETWEEN SHEAR STRESS AND MOISTURE CONTENT FOR PEA BEANS.

tester (Fig. 12) are shown graphically in Fig. 33. The energy is expressed in terms of the kernel cross-sectional area in order to reduce the variance, and also to serve as a better means of comparison with the other grains. The graph shows a linear relation between 10.9 and 21.7 percent moisture. The relatively sharp increase at the high moisture level is accounted for by the soft or spongy nature of the kernel. At lower levels a more brittle material explains the lower impact energy required.

Fig. 34 shows impact energy required to rupture corn. Results were similar to wheat. It was decided to make a comparison of the energy required to rupture the kernel by static shear with that required in the impact tests. The static energy figure was obtained from the oscillograph chart by means of a planimeter. The total energy under the curve up to the point of rupture was divided by the seed cross section to get a value in terms of in-lb/in^2. In each type of test, the kernel was held (by the same vise) in the flat position. The effect of a brittle and a tough material in impact and static tests was apparent. At low moisture (brittle kernel) more energy was required by static shear; at high moisture, more energy is required in impact. While the curves cross-over, the energy for static shear was found to increase with moisture after the initial drop.

This cross-over effect is even more evident with pea beans in Fig. 35. The greater spread in energy values as compared with that in Fig. 34 is partly due to the greater

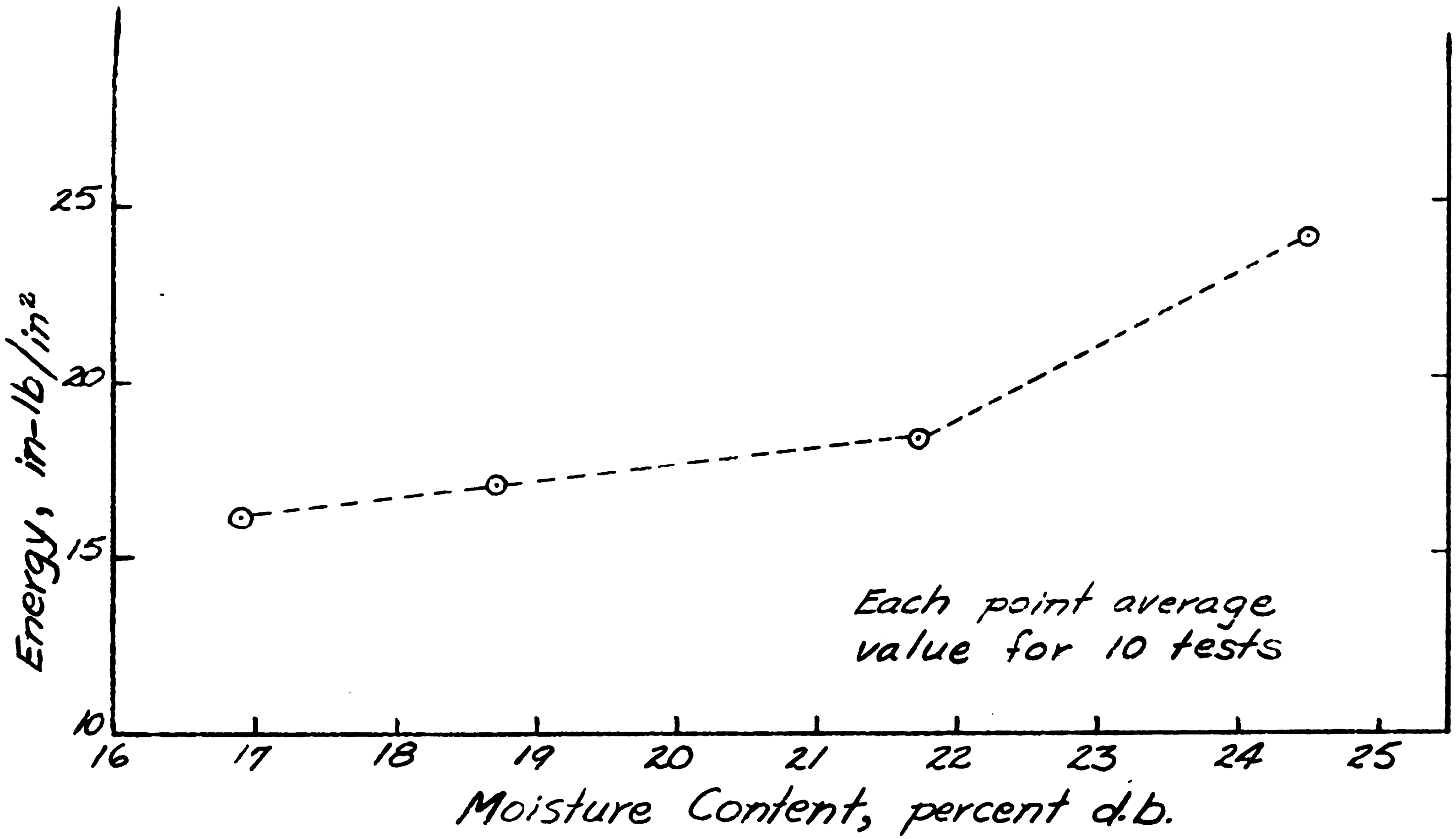


FIG. 33 ENERGY REQUIREMENTS FOR RUPTURE OF SOFT RED WINTER WHEAT KERNELS BY IMPACT SHEAR AT FOUR MOISTURE LEVELS.

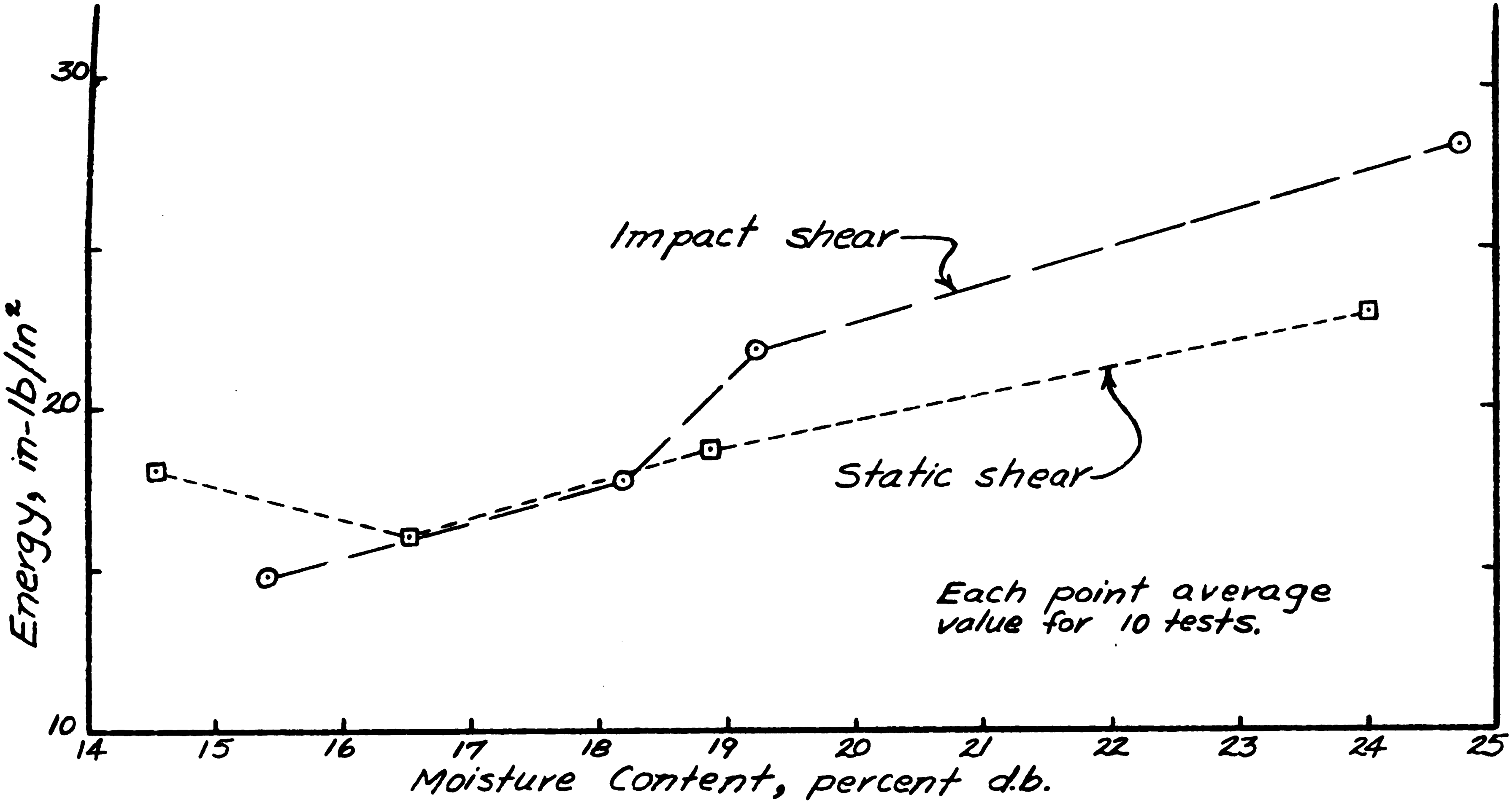


FIG. 34 ENERGY REQUIREMENTS FOR RUPTURE OF YELLOW DENT CORN KERNELS BY IMPACT AND STATIC SHEAR.

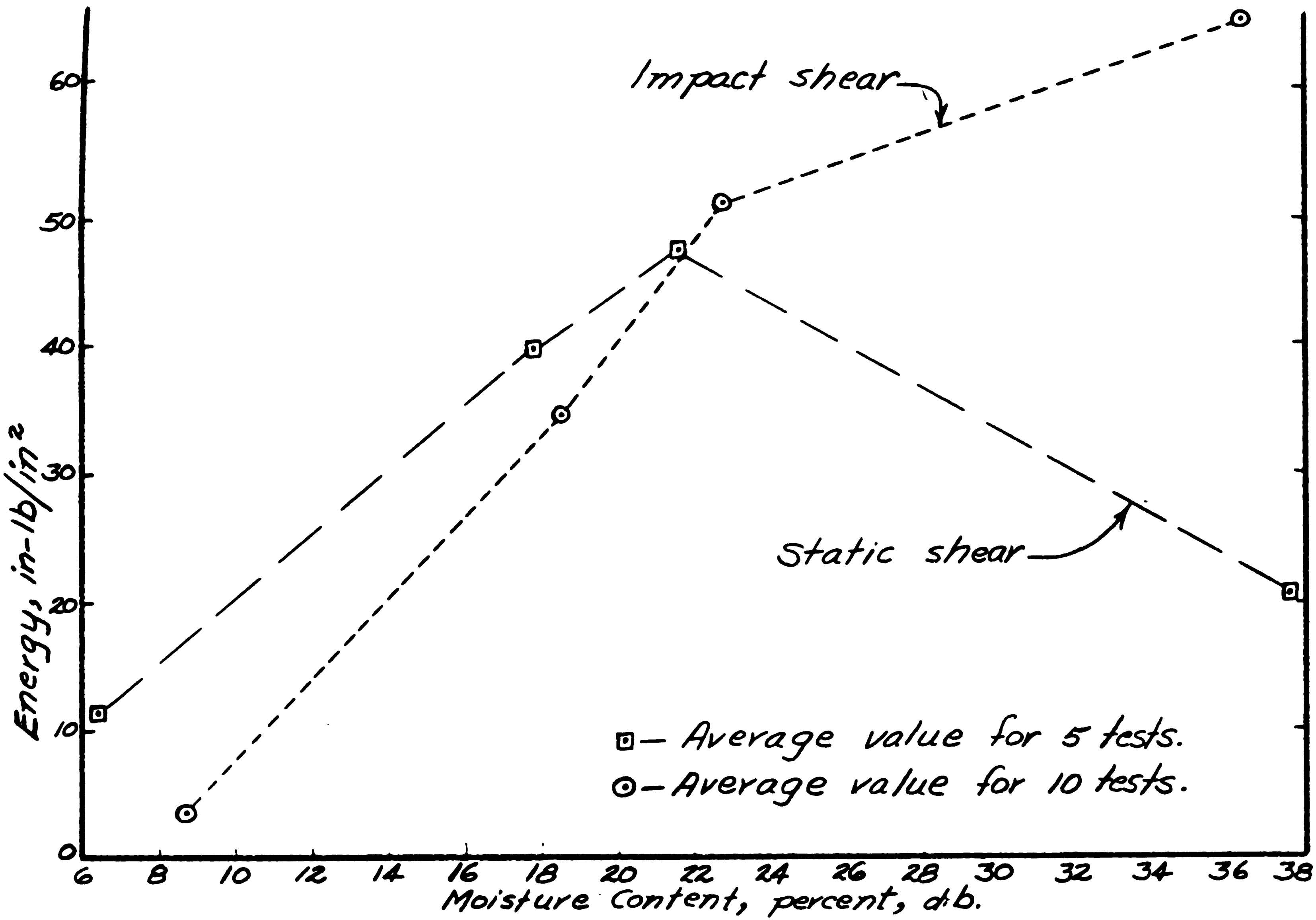


FIG. 35 ENERGY REQUIREMENTS FOR RUPTURE OF PEA BEANS BY STATIC SHEAR AND IMPACT SHEAR.

moisture range used for the pea beans. For a given moisture range, however, pea beans vary in brittleness or toughness more than corn or wheat. It may be concluded from Fig. 34 and 35, that impact methods are more efficient for size reduction at low moisture, but static shear is more efficient at high moisture levels. Between 13% d.b. and 23% d.b. there is little difference in the two methods. The greater the moisture variation in either direction from this central moisture level, the greater the energy difference becomes between the two methods. For corn (Fig. 34), the energy requirements are about the same between 16.5% d.b. and 18.5% d.b. On either side of this range the energy is divergent.

Original data for impact shear tests on the three grains are tabulated in Appendix A, Tables A9, A10, A11, and A12.

Hysteresis Loss

When a material is loaded in compression, the area under the force-deformation curve represents the work expended in loading the specimen. The area under the unloading curve represents the energy returned to the machine by the specimen. Except for perfectly elastic materials, the area under the loading and unloading curves will not be equal. The difference is due to the failure of the material to recover its original dimensions instantly. An inelastic deformation is produced which may be temporary or permanent. The enclosed hysteresis loop represents energy dissipated as heat. The relative size of the hysteresis loop is a good measure

of how much the temperature of a material will increase when repeatedly stressed. It is also a measure of the ability to damp vibrations.

Yerzley (1939) dealing with rubber, expresses the percent hysteresis loss:

$$\text{Hysteresis loss, \%} = \frac{\text{Hysteresis loss} \times 100}{\text{Energy expended in loading}}$$

This is sometimes also called the "specific damping capacity". Yerzley refers to the energy returned to a test machine by the specimen on unloading as the resilience of the test specimen. He expresses resilience also as a percent:

$$\text{Resilience, \%} = \frac{\text{energy returned in unloading} \times 100}{\text{energy expended in loading}}$$

(This meaning is different from that used in "modulus of resilience" in the next section.) It follows from the definition that,

$$\text{\% hysteresis} + \text{\% resilience} = 100$$

Hysteresis loops were obtained by loading and unloading grain kernels with the load cell testing unit. Fig. 36 shows examples of oscillograph charts from which loops were plotted. The loops were obtained by plotting the loading curve up to a given load; from that point, the unloading curve was plotted back towards the origin. It should be noted in Fig. 36, charts 2 and 3, that the initial loading line has a lower slope than the succeeding loading lines. This is due to a mechanical conditioning action that takes place during the maiden loading. Each loading line after the initial loading, has almost exactly the same slope.

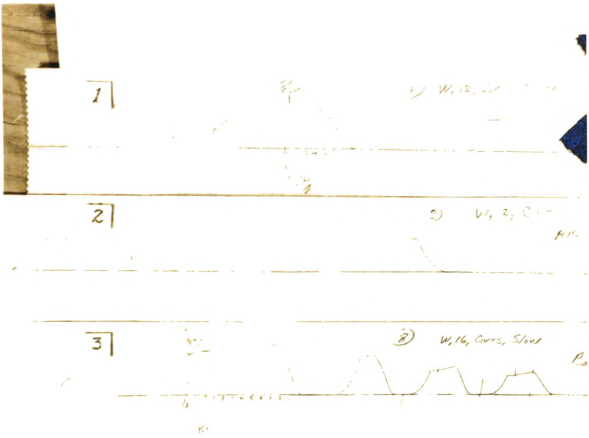


Fig. 36 Representative oscillograph charts for wheat core tests, with increasing deformation (and time) from right to left, and force on vertical axis.

1. Compressive core test.
2. Loading-unloading cycles from which hysteresis loops were obtained.
3. Loading-unloading cycles and compression to failure.

The effect of this mechanical conditioning is further shown in the hysteresis loops drawn in Fig. 37.

Loop A_1, Fig. 37, is the maiden loading-unloading cycle for wheat cores at 17.0 percent moisture. It is obtained from Fig. 36, chart 2. This loop shows a larger hysteresis loss than loop A_2 which was obtained from the second loading-unloading cycle. Also, as shown in the oscillograph charts, the loading line slope is greater for A_2 than for A_1. Loop B_1 is the result of an initial loading-unloading cycle at 20.7 percent moisture. The magnitude of the hysteresis losses (percent) is given in Fig. 37. The percent resilience is simply 100 minus these values.

Similar hysteresis loops are plotted for corn at two moisture levels in Fig. 38. As in Fig. 37, a greater hysteresis loss is shown at higher moisture levels as well as on the initial loading-unloading cycle. In each figure, the point where the unloading line meets the x-axis is a measure of the inelastic deformation of the kernel. This deformation may be recoverable with time.

Fig. 39, for pea beans, shows that moisture content has a great influence on the hysteresis loss and on the degree of set.

Modulus of Resilience and Modulus of Toughness

The energy to deform grain kernels to the elastic limit is the modulus of resilience. The energy to deform grain kernels to the maximum strength is the modulus of toughness.

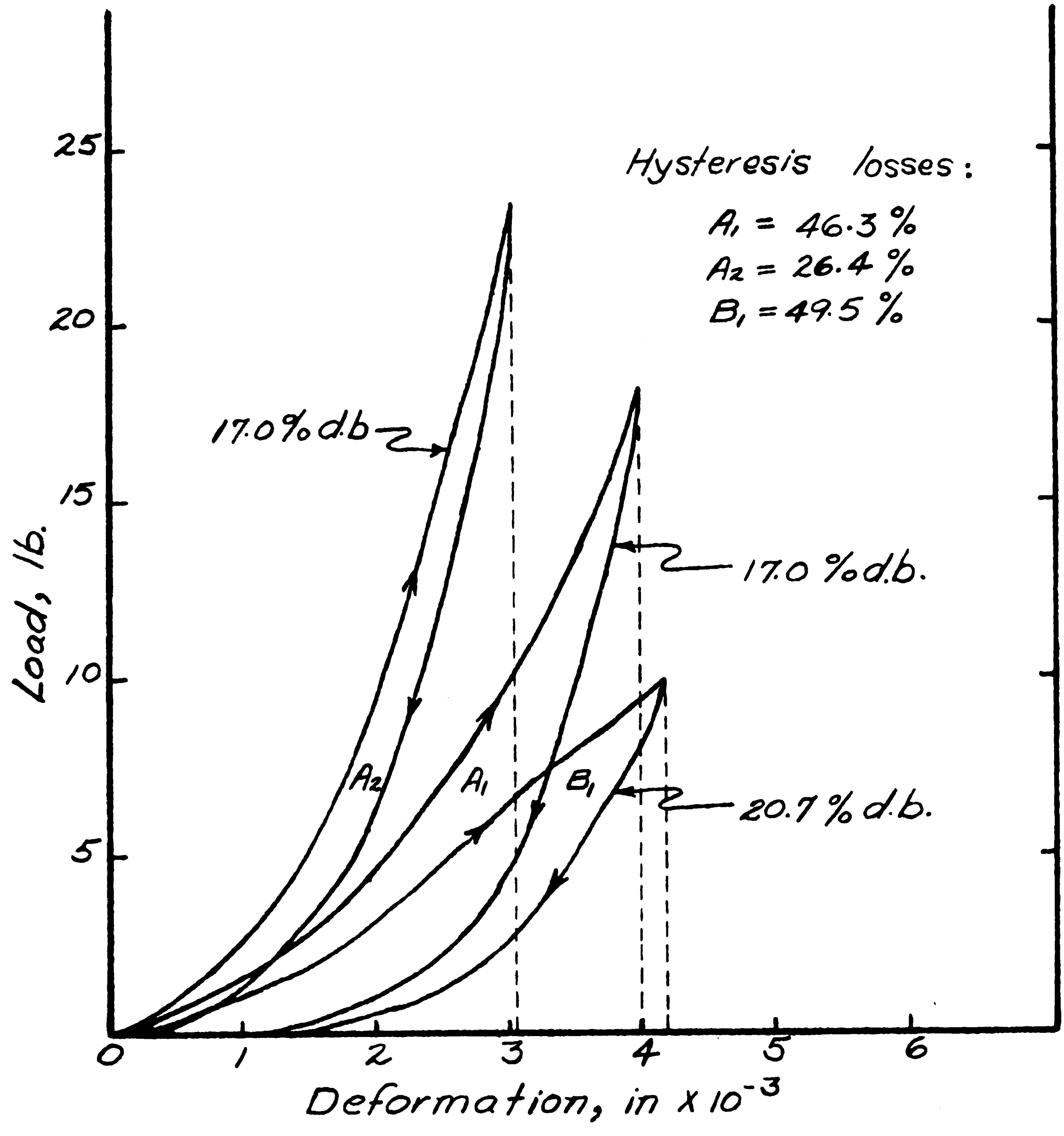


FIG. 37 HYSTERESIS LOOPS FOR SOFT RED WINTER WHEAT CORES. LOOPS A_1 & B_1, MAIDEN LOADING CYCLES, LOOP A_2, SECOND LOADING CYCLE.

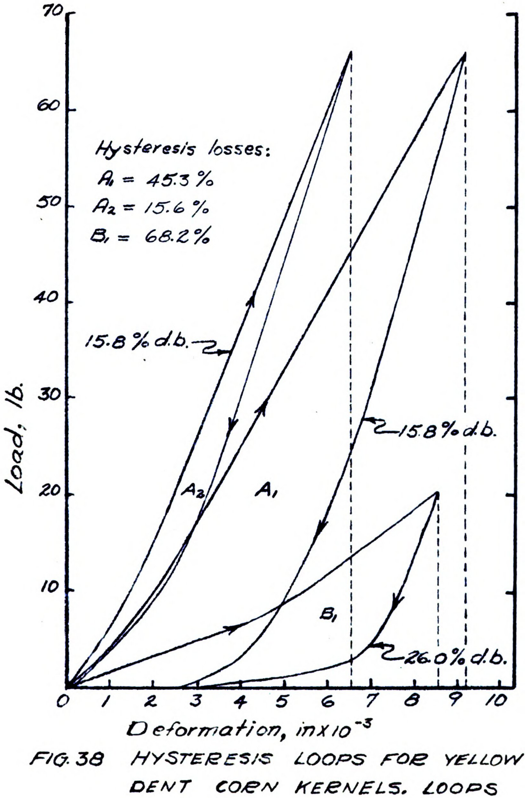


FIG. 38 HYSTERESIS LOOPS FOR YELLOW DENT CORN KERNELS. LOOPS A_1 & B_1 MAIDEN LOADING CYCLES, LOOP A_2 SECOND LOADING CYCLE.

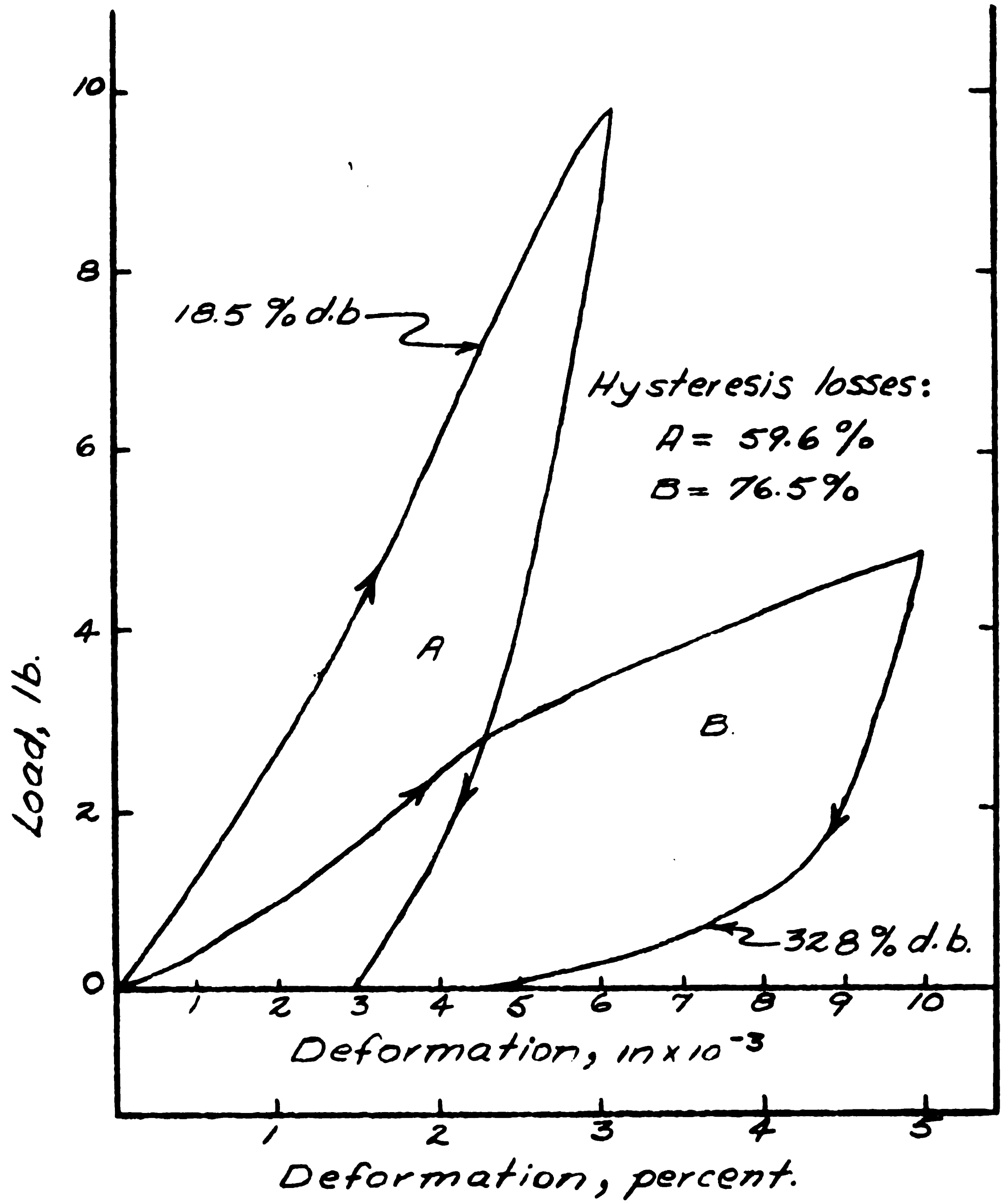


FIG. 39 HYSTERESIS LOOPS FOR PEA BEANS AT TWO MOISTURE LEVELS. LOOP A, SECOND LOADING CYCLE; LOOP B FOURTH LOADING CYCLE.

The energy required to deform pea beans to the elastic limit and wheat to the elastic limit and maximum strength, is shown graphically in Fig. 40. Although the ultimate strength for beans was shown to be greater (Fig. 24) in the flat position, the modulus of resilience is higher in the edge position. Fig. 40 shows the greater variation between individual tests (ten tests conducted for each position) in the edge position.

Fig. 41 gives energy to deform corn to the elastic limit in the edge and flat positions. A greater variation in energy is noted in the flat position. This was also true for the force required to reach the elastic limit. (Tables A4 and A5)

Energy required to deform corn to the maximum strength in the edge and flat positions is presented graphically in Fig. 42 and 43, respectively. A direct comparison of energy in these figures is difficult owing to the different scales used. A greater energy variation occurred in the flat tests.

A study of Figs. 40, 41, 42, and 43 shows that the range of energy values for any given grain and type of test is approximately the same for each moisture level. On the other hand, when force alone is considered in these compressive tests, the variation with moisture content is considerable. The decrease in strength (or elastic property) with increased moisture is offset by the increased deformation required to reach the elastic limit or maximum strength point. Thus the energy values in contrast to the force values, remain

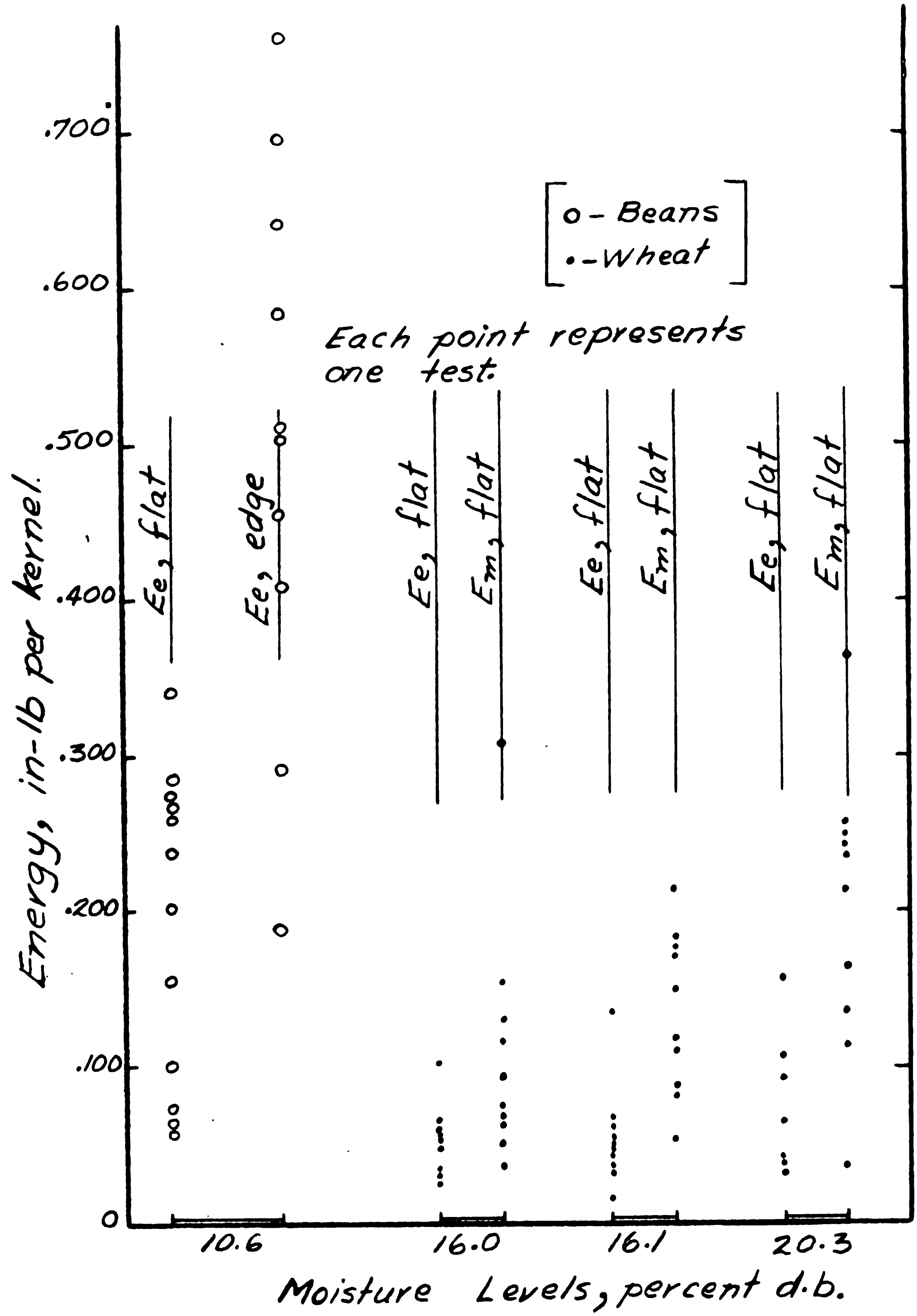


FIG. 40 ENERGY TO DEFORM PEA BEANS TO YIELD POINT AND SOFT RED WINTER WHEAT TO THE YIELD POINT AND MAXIMUM STRENGTH AT MEDIUM SPEED.

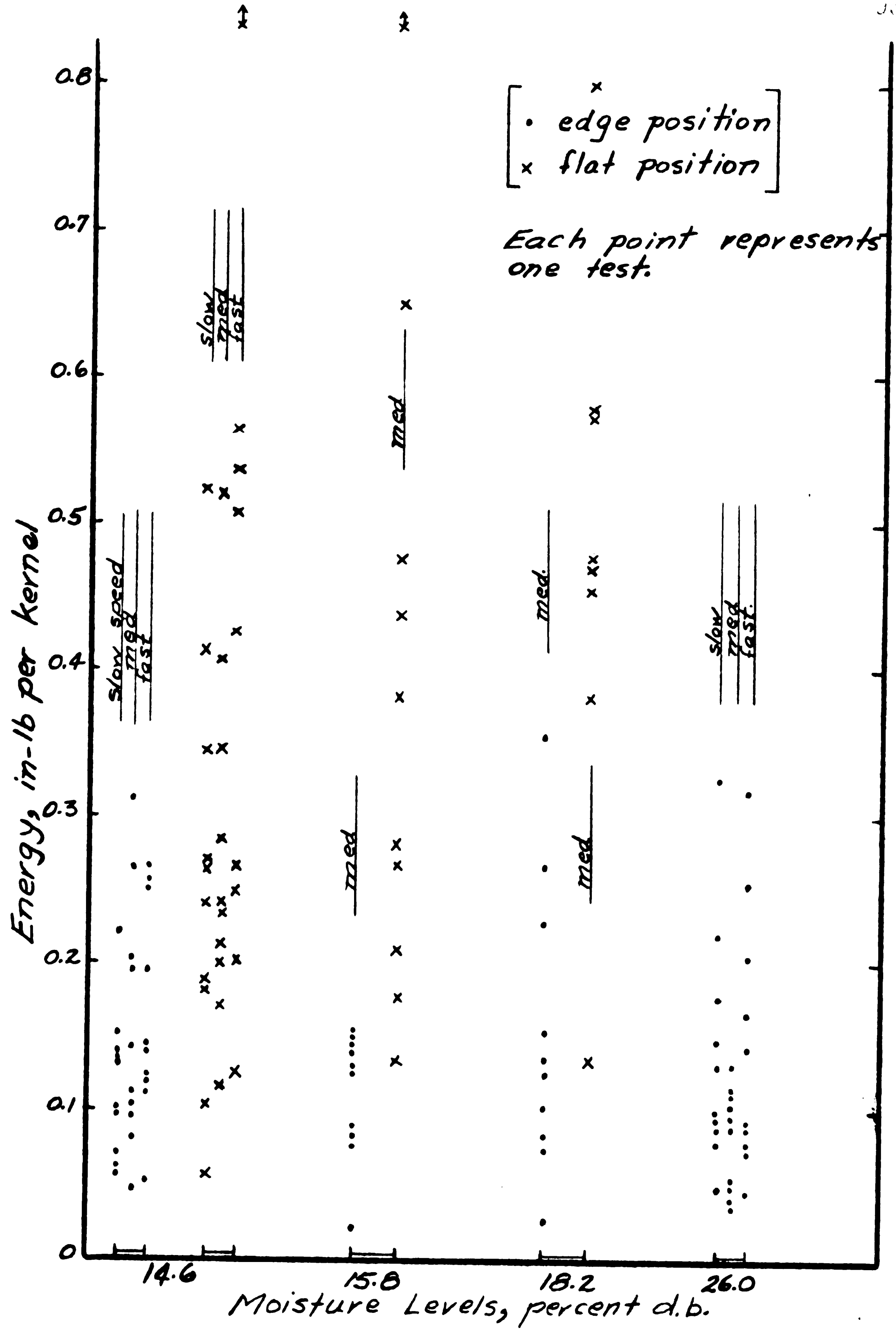


FIG. 41 ENERGY TO DEFORM YELLOW DENT CORN TO THE YIELD POINT IN EDGE AND FLAT POSITIONS.

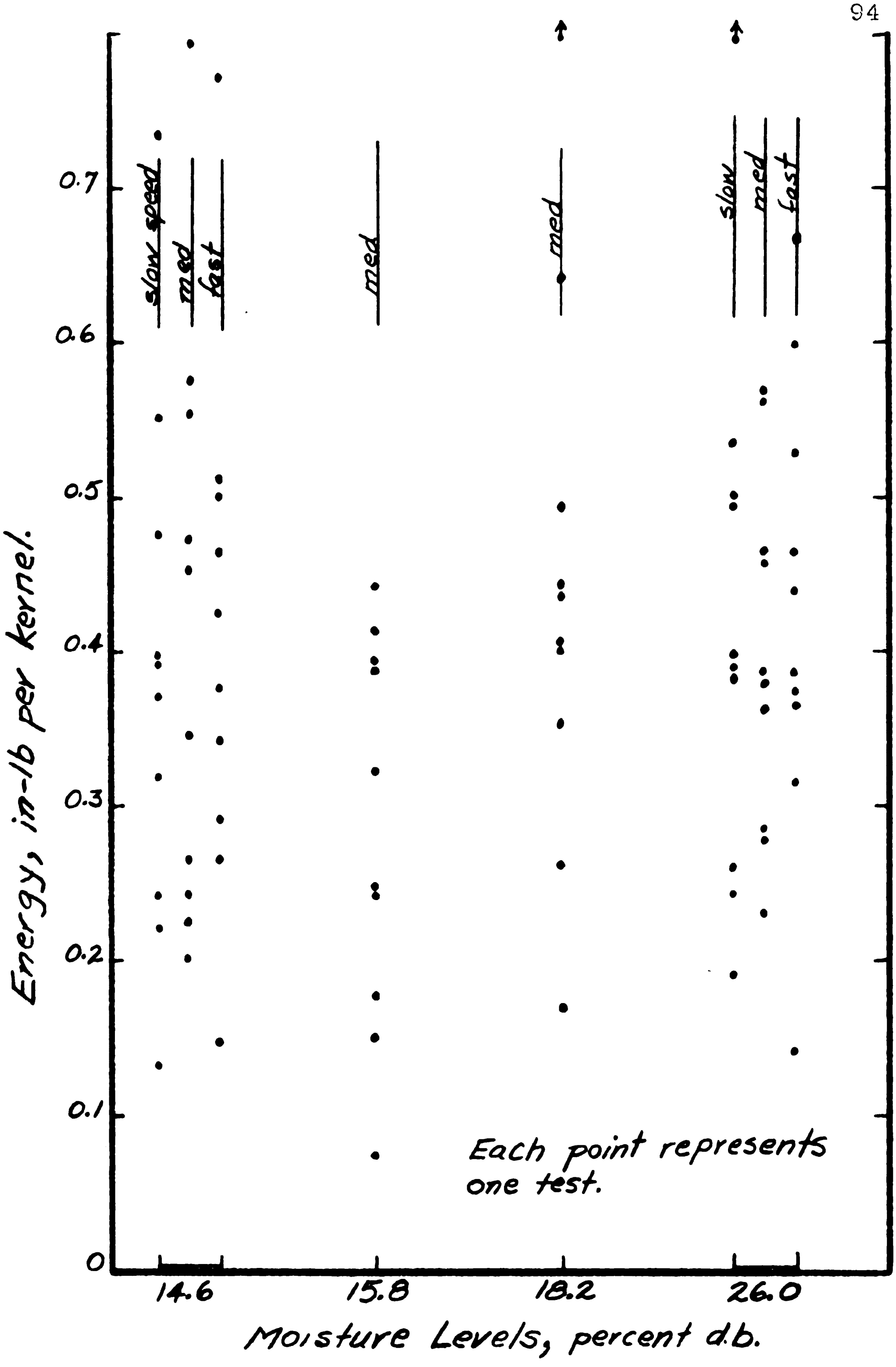


FIG. 42 ENERGY TO DEFORM YELLOW DENT CORN TO MAXIMUM STRENGTH IN THE EDGE POSITION.

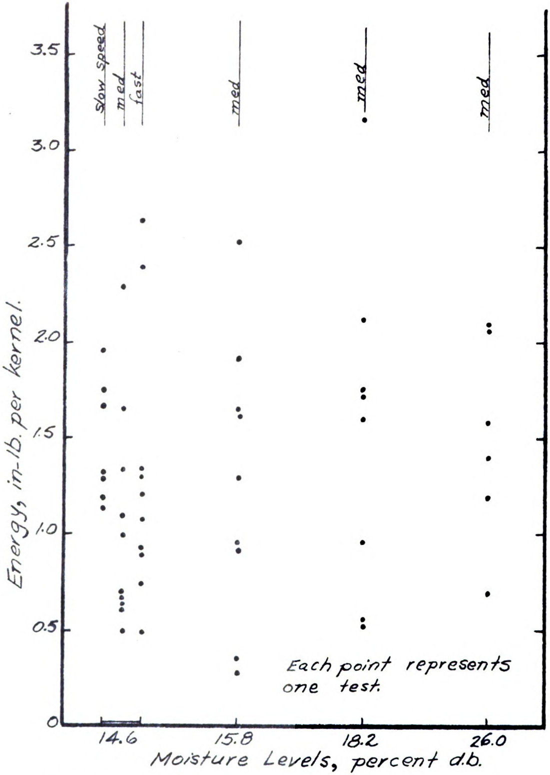


FIG. 43 ENERGY TO DEFORM YELLOW DENT CORN TO THE MAXIMUM STRENGTH IN THE FLAT POSITION

relatively constant.

Total Energy Versus Surface Area

The total energy to deform corn to one-half its original dimension from the edge or flat position, was obtained from the oscillograph by means of a planimeter. The crushed material from 10 tests was oven dried and a sieve analysis was made with the minature Tyler sieves (Fig. 17). The surface area was calculated from these weight fractions by equation (4).

$$A_t = \frac{12 W_1}{\rho S_2} + \sum_{i=2}^{7} \frac{4 W_i}{\rho S_i}$$

This equation was derived assuming the particles to be cubes, but the same result is obtained if spheres are assumed.

The results are summarized in Table 4. This phase of the energy study was quite unsuccessful owing to the unsatisfactory measurement of the surface area. The above equation is believed to represent the total surface area if a reasonable grinding action occurs as with commercial grinders. In crushing the corn kernels by compression, insufficient break up of the kernel occurred (Fig. 17). As a result the top sieve retained too much material which amount accounted for 50 percent of the calculated surface area in most cases. It is apparent that the material in the top sieve was made up chiefly of original surface area (surface coating), rather than <u>new</u> area produced by fracture. The total energy index

TABLE 4

RELATIONSHIP BETWEEN ENERGY AND SURFACE AREA FOR CORN IN EDGE AND FLAT POSITIONS

Grain Position and Head Speed	Moisture % d.b.	Total Energy in-lb/kernel Applied to Kernel to Crush to One-half Initial Dimension	Total Surface Area in^2	Index, Total Energy ÷ Surface Area
EDGE				
Slow	14.6	13.06	5.91	2.2
Med	14.6	12.77	5.31	2.4
Fast	14.6	10.92	5.25	2.1
Med	15.8	9.45	4.63	2.0
Med	18.2	13.51	4.67	2.8
Slow	26.0	10.90	3.36	3.2
Med	26.0	8.72	3.29	2.6
Fast	26.0	13.94	3.30	4.2
FLAT				
Slow	14.6	69.93	4.57	15.3
Med	14.6	62.29	7.79	8.0
Fast	14.6	62.12	5.06	12.3
Med	15.8	60.52	5.90	10.3
Med	18.2	80.33	5.85	13.7
Med	26.0	64.43	3.39	19.0

was obtained by dividing the total energy by the calculated surface area as shown in Table 4. This index figure is merely a relative figure for comparison. No weight should be put on it in an absolute sense. The index value shows an advantage for crushing the kernel in the edge position rather than in the flat position.

Rheological Properties

For a perfectly elastic material the resultant stress is independent of the rate of loading. For a viscous material the rate of straining is very important. From equation (8),

$$\gamma = \frac{st}{\eta} \quad \text{or} \quad s = \frac{\gamma \eta}{t}$$

where γ is the shear strain, s is shear stress and η is the coefficient of viscosity. If t is large, i.e., $d\gamma/dt$ is small, the stress will be low and vice versa. Fig. 44 shows a slight but not important difference in the resultant load (stress) for three rates of deformation. The difference in stress would probably be greater if larger variations in deformation rates could be used, and if the beans were tested at a somewhat lower moisture content. At 32.8 percent they are extremely soft. A check on the speed effect for wheat at 14.3 percent moisture showed no noticeable difference between slow and fast speed. At this moisture, the wheat is more elastic.

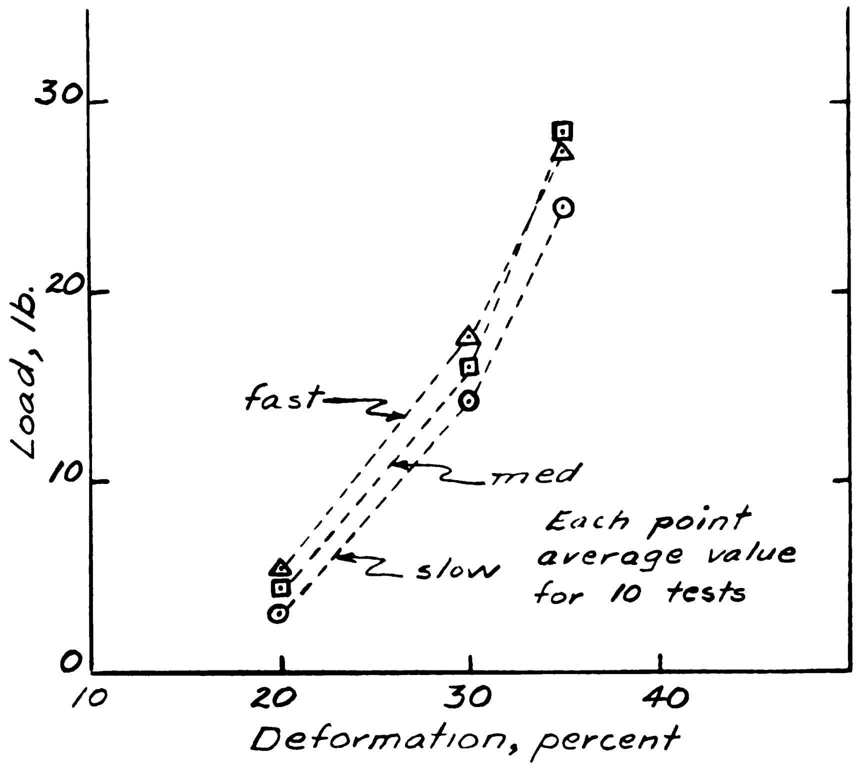


Fig. 44 Load-deformation curves for pea beans at 32.8 percent moisture (d.b.) for three speeds.

The velocity effect is presented in a different way in Fig. 45, with rate of deformation plotted against compressive force. Fig. 46 is given below as a means of qualitatively explaining the curves of Fig. 45.

At the 20 and 30 percent deformation points, the pea beans (32.8% moisture, d.b.) act as an ideal plastic solid Fig. 46 (c). However, at greater deformations of 35 and 40 percent the beans behave as a quasi-plastic material as in Fig. 46 (d).

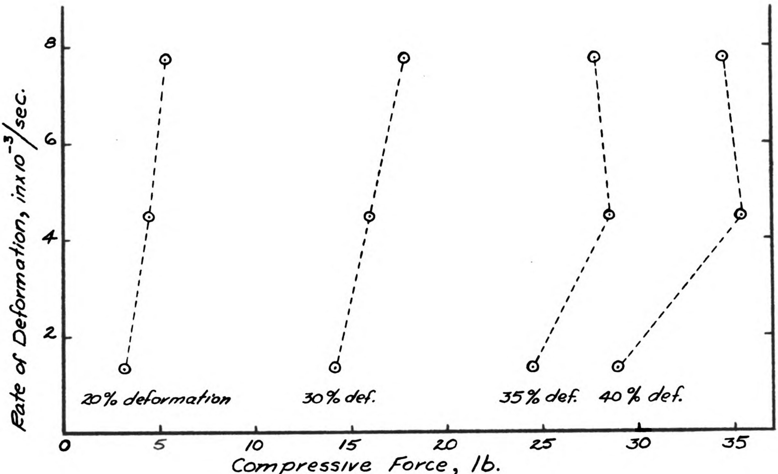


FIG. 45 EFFECT OF RATE OF DEFORMATION ON THE RESULTING COMPRESSIVE FORCE FOR PEA BEANS AT 32.8 PERCENT MOISTURE (db)

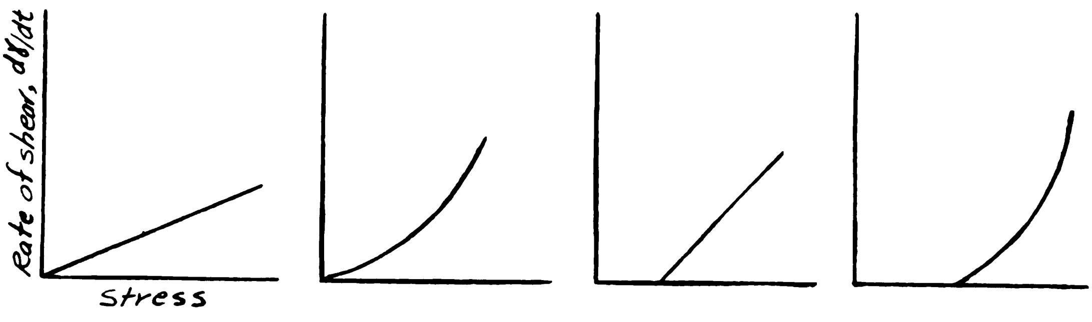


Fig. 46 Rate of shear strain as a function of stress for four types of fluid: (a) Newtonian or viscous liquid; (b) non-Newtonian or quasi-viscous liquid; (c) idealized plastic solid, Bingham solid; (d) quasi-plastic material.*

Stress Relaxation

Stress relaxation of pea beans was studied at several moisture contents, at various amounts of deformation and at three initial deformation rates. The beans were deformed to a certain fraction of their original dimension, and the crosshead was stopped. The oscillograph chart continued to move so that a continous force-time record was obtained.

Relaxation curves are shown in Fig. 47 for three moisture levels. Curves 3 and 4 are for the same moisture, but different amounts of deformation. All of these curves represent relaxation after deformation at a medium speed. The speed effect on relaxation is shown later.

The curves in Fig. 47 are nearly parallel and plot as

*Alfrey, Turner, Jr.; Mechanical Behavior of High Polymers; Interscience Publishers, Inc. New York, 1948; p 34.

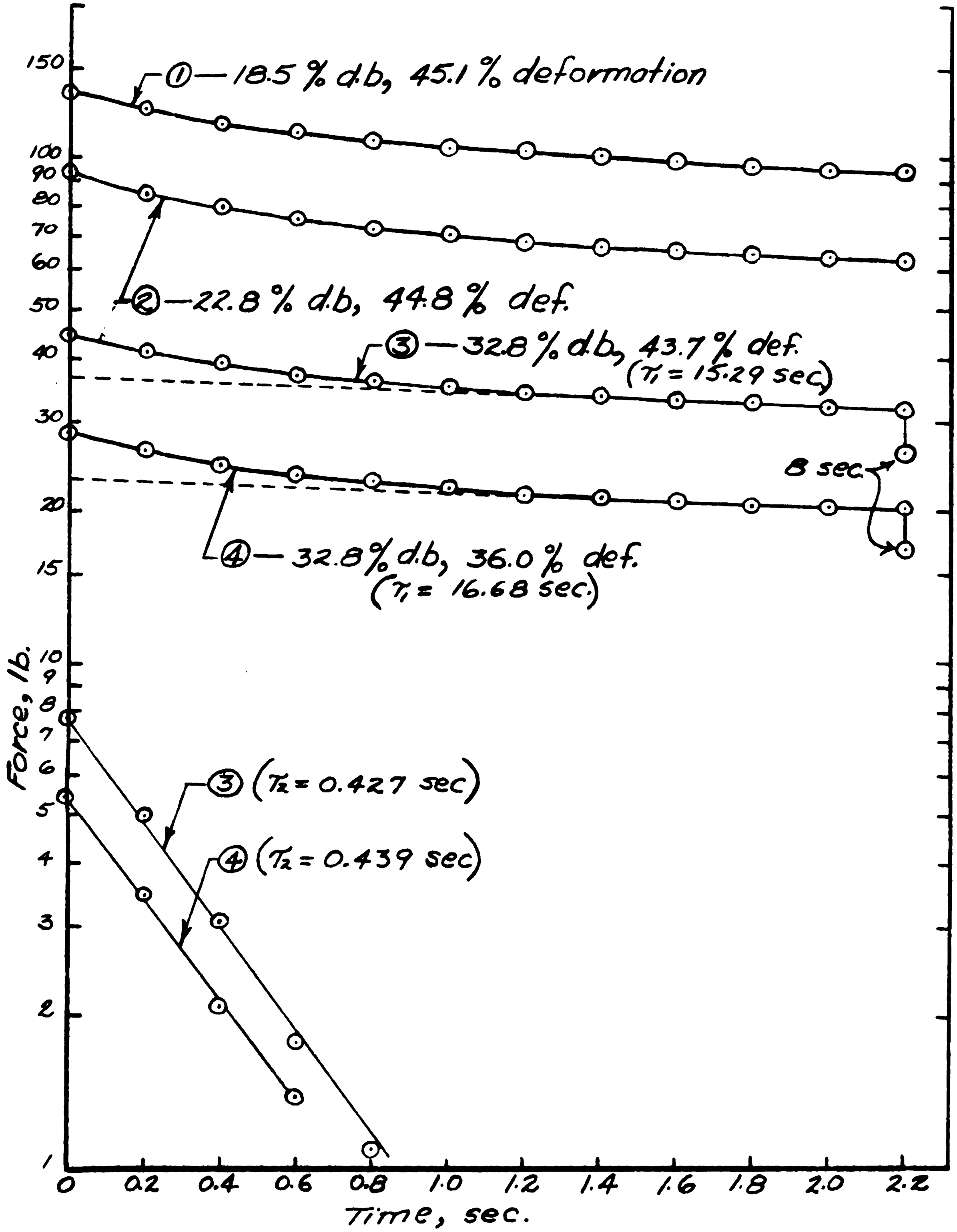


FIG. 47 STRESS RELAXATION FOR PEA BEANS AT VARIOUS MOISTURE LEVELS AND AMOUNTS OF DEFORMATION.

straight lines after a time of about 1.4 seconds. It was decided to try to express the stress relaxation in equation form which would describe it during the initial second as well as for greater lengths of time. In addition, description of the early portion of the curve would aid in describing the rheological behavior (and/or mechanical model) of beans under stress relaxation. It has been shown that equation (15)

$$\sigma = \sigma_0 e^{-t/\tau}$$

gives the stress relaxation for a material that may be represented as a model, by a Maxwell unit.

Since the stress relaxation curves are not true exponential relationships, i.e., straight lines on semi-log paper, it is desirable to express the variation with time by means of a small number of exponential terms. A graphical method* is used. Fig. 48 illustrates the proceedure. When plotting force (or stress) against time it was observed that the relation is linear on semi-log paper at the larger values of time. A straight line through these points projected up to zero time gives the exponential term with the largest time constant, τ_1 . This is subtracted from the original force-time curve in the range of small time values, and a new line of the log of the difference is similarly plotted. This gives the exponential term with the next largest time constant, τ_2 . This could be carried out a third time, but

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*________; Essays in Rheology; Pitman & Sons Ltd; 1947; Chapter 3.

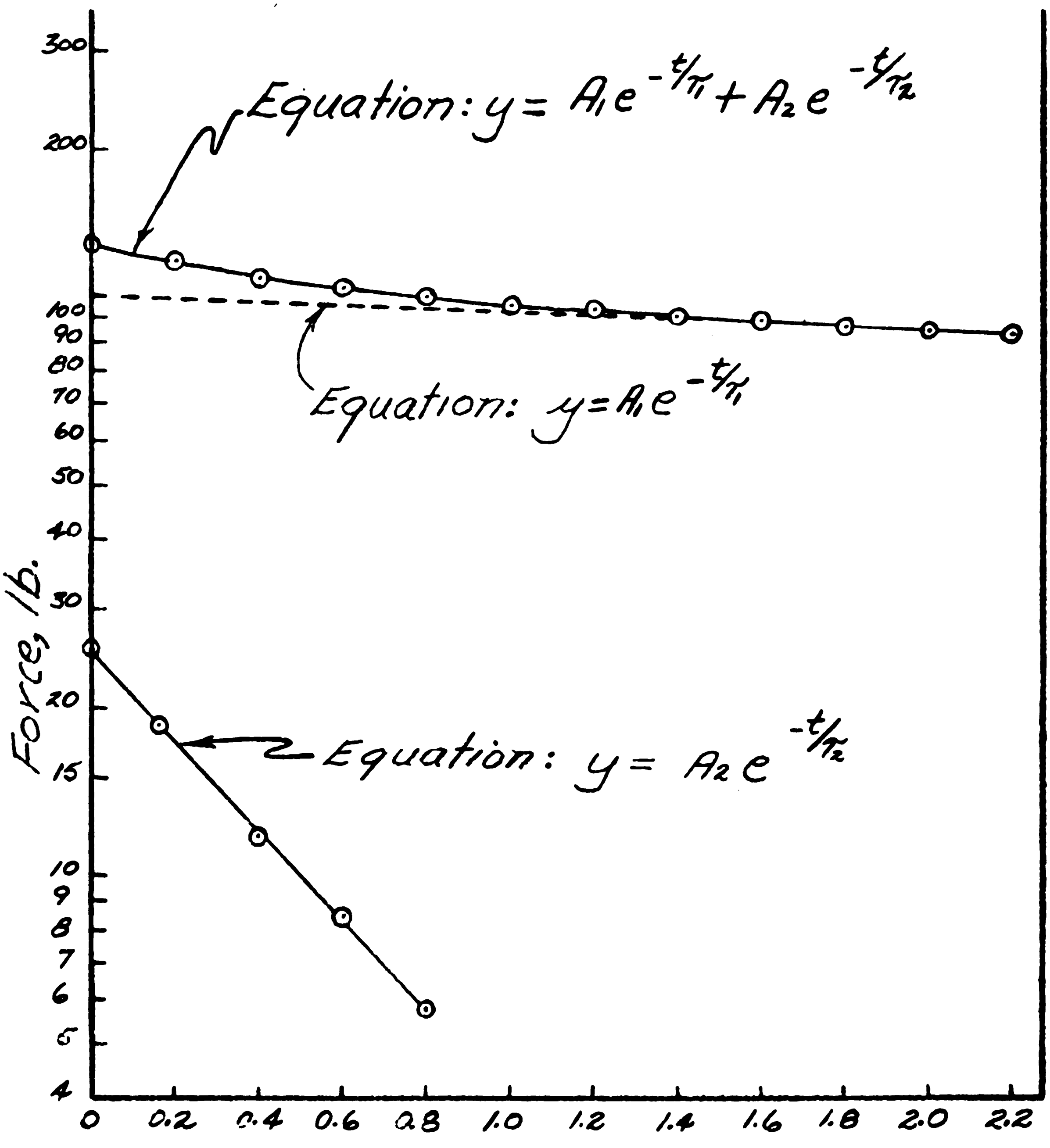

FIG. 48 GRAPHICAL DETERMINATION OF STRESS RELAXATION EQUATION FOR PEA BEANS AT 18.5 PERCENT MOISTURE AND 45.5 PERCENT DEFORMATION.

the chance for error becomes greater as the differences become smaller. For pea beans, the relaxation is expressed very well by two exponential terms. As shown in Fig. 48, the complete equation is:

$$y = A_1 e^{-t/T_1} + A_2 e^{-t/T_2} \qquad \text{------------ (17)}$$

The constants A_1 and A_2 are evaluated by setting $t = 0$. Graphically A_1 and A_2 are simply the y-intercepts of the dashed line and of the log force-time difference line. The time constants, which also represent the <u>relaxation time</u> are found by taking the slope of two straight lines:

$$T = \frac{t_2 - t_1}{\ln F_1 - \ln F_2}$$

Evaluating the constants for the curve of Fig. 48, the force-time relaxation equation is:

$$F = 109.5\, e^{-t/14.67} + 25.8\, e^{-t/0.537}$$

The relaxation times (time constant) are given in Fig. 47 by curves 3 and 4, for beans at the same moisture (32.8% d.b.), but at a different amount of deformation. The relaxation times are practically equal. This was found to be true at other moisture levels. That is, regardless of the amount of deformation, at a given moisture level, the relaxation times were equal. Of course the greater the deformation, the larger the force value.

Relaxation curves are plotted in Fig. 49 for varying rates of deformation on rectilinear paper. This allows the

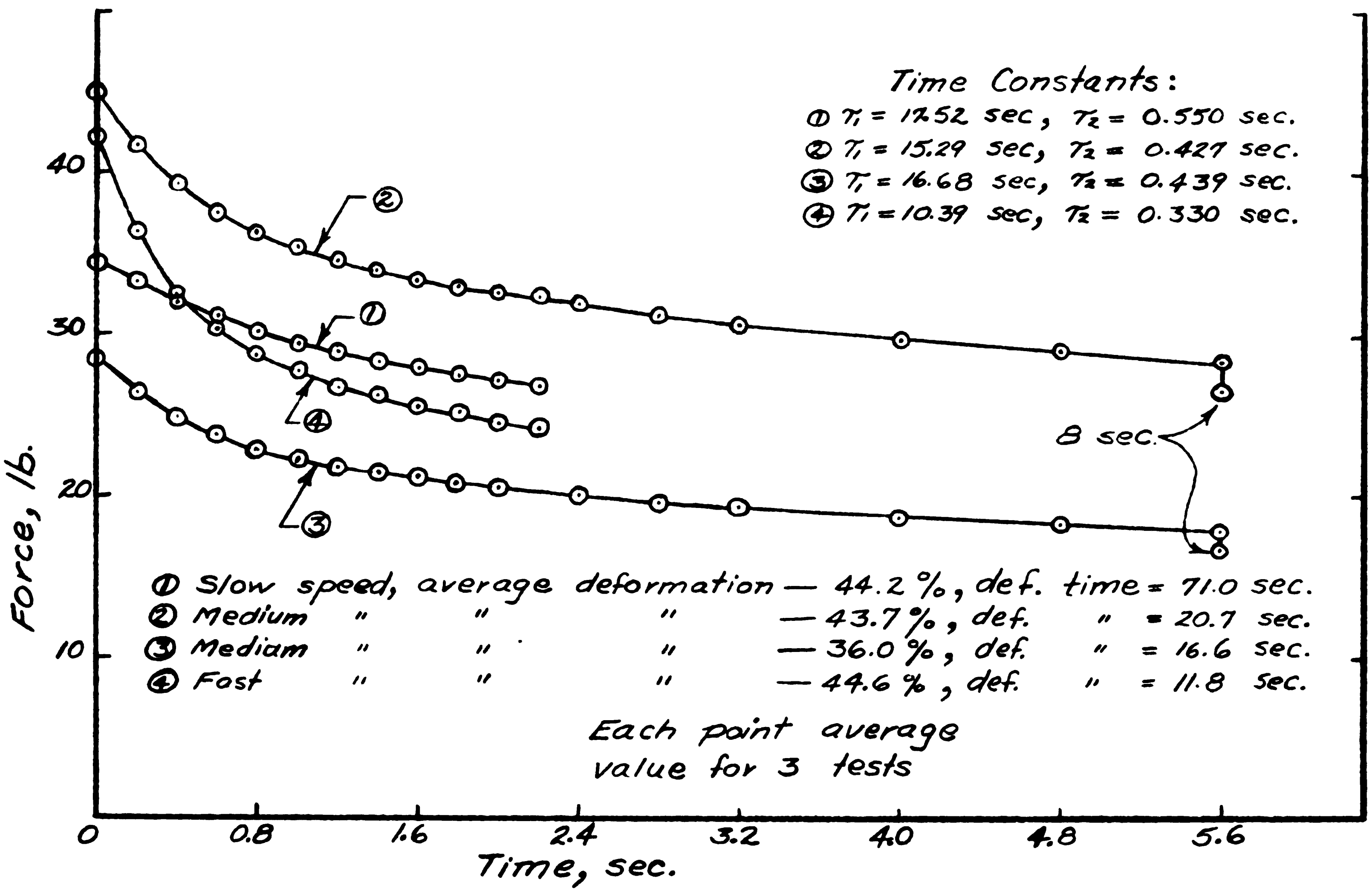

FIG. 49 STRESS RELAXATION CURVES FOR PEA BEANS AT 32.8 PERCENT MOISTURE (db) IN FLAT POSITION.

stress relaxation rates to be more noticeable. (Curve 2 and 3 in Fig. 49 are curves 3 and 4 plotted in Fig. 47.) Fig. 49 shows that the initial rate of deformation has a definite effect on the relaxation rate. Time constants corresponding to the first and second exponential terms, are summarized in the figure. Considering the amount of deformation and the rate of deformation, the time for the bean to be deformed, is also listed.

It is apparent that with the slower rates of deformation, time is allowed for the material to creep or to even begin stress relaxation before the crosshead movement is stopped. When the crosshead is stopped, less relaxation is necessary than in the case of rapid initial deformation. Thus in considering the effect of rapid deformation upon stress relaxation in beans, the rate of deformation will chiefly determine the relaxation time, while the amount of deformation will determine the initial magnitude of the force at the beginning of stress relaxation (or end of deformation) period.

Since the force at any time during relaxation can be expressed by the sum of two exponential terms of the form $Ae^{-t/\tau}$, it is concluded that pea beans can be represented rheologically by two Maxwell units in series. As above, $\tau = \eta/E$, where η is the viscosity of the viscous element (dashpot) and E is the modulus of elasticity of the elastic element. Representing the behavior of beans in this manner accounts for the distinct actions represented by the two exponential terms. E_1 and E_2 are different as are η_1 and η_2.

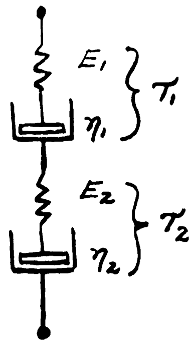

Fig. 50 Mechanical representation of pea beans by two Maxwell units in series.

It must be borne in mind that the model suits the ideal case; actually the viscous phase of the bean is probably quasi-viscous or quasi-plastic and the elastic segment is certainly not perfectly elastic.

A Practical Application from the Results

In comparing the various parameters investigated with moisture content, it became apparent that in many cases the variation of the dependent variable was great enough that it could be used as a measure of moisture content in grain. Specifically, the force-deformation curves for beans and the punch shear tests on beans showed promise in this respect. Fig. 51 shows the relationship between force and moisture at various deformations. The greater the slope of the line, the more desirable the situation for determining moisture.

At first glance it appears that the 40 percent deformation curve would be the best one to use. However, if one standard deviation above or below the line is considered,

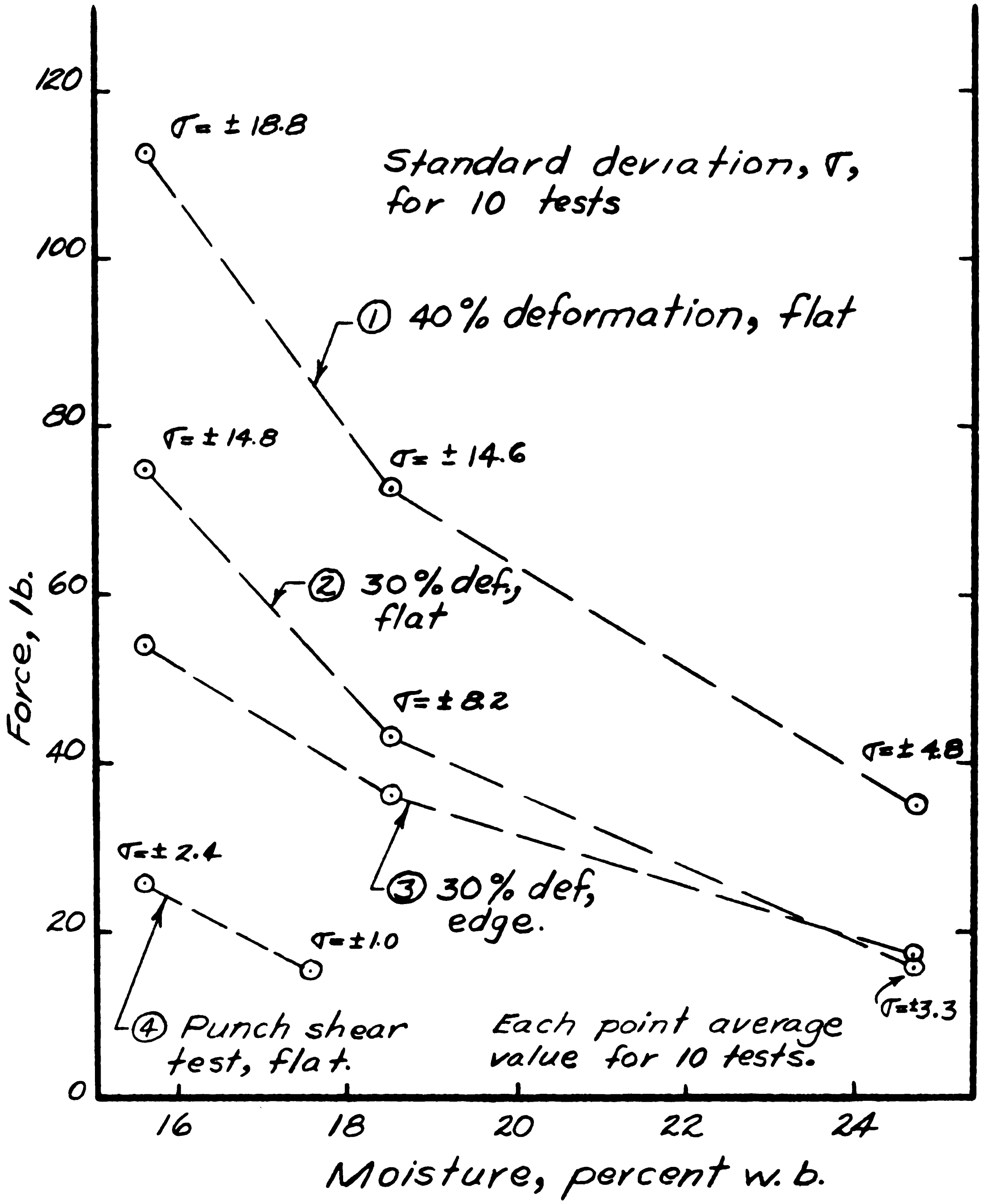

FIG. 51 FORCE REQUIRED FOR DEFORMATION OF PEA BEANS AT MEDIUM SPEED (0.267 in/min)

the punch shear test, curve 4, would be chosen. Consider the steepest portion of the 40 percent deformation curve, i.e., between 15.6% w.b. and 18.5% w.b., and the punch shear test (curve 4). These two curves are redrawn to a larger scale in Fig. 52.

In Fig. 52, one standard deviation is subtracted at the 15.6% w.b. point of the top curve, and one standard deviation is added at the 18.5% w.b. point. By joining the points A and B, a relatively flat line is obtained. This line has the lowest possible slope that can be obtained between the 15.6% w.b. and 18.5% w.b. points without deviating from either original point on curve 1 by more than one standard deviation. The steepest possible slope (maintaining a maximum variation of one standard deviation) would be obtained by adding and subtracting one standard deviation in the reverse order from above.

For the moisture range of 2.93% w.b., the line A B gives a value of 2.15 lb/percent moisture. Making the same calculations for the punch test, line C D, Fig. 52, gives 3.32 lb/percent moisture. This means that within this moisture range (assuming a linear relationship for the present), it is only necessary to be able to measure the force required to "punch" out a core to within 3.3 pounds to determine moisture content to the nearest percent. It would seem that an inexpensive mechanical moisture tester could be built to measure this range quite easily.

At the present time the farmer is without any inexpensive

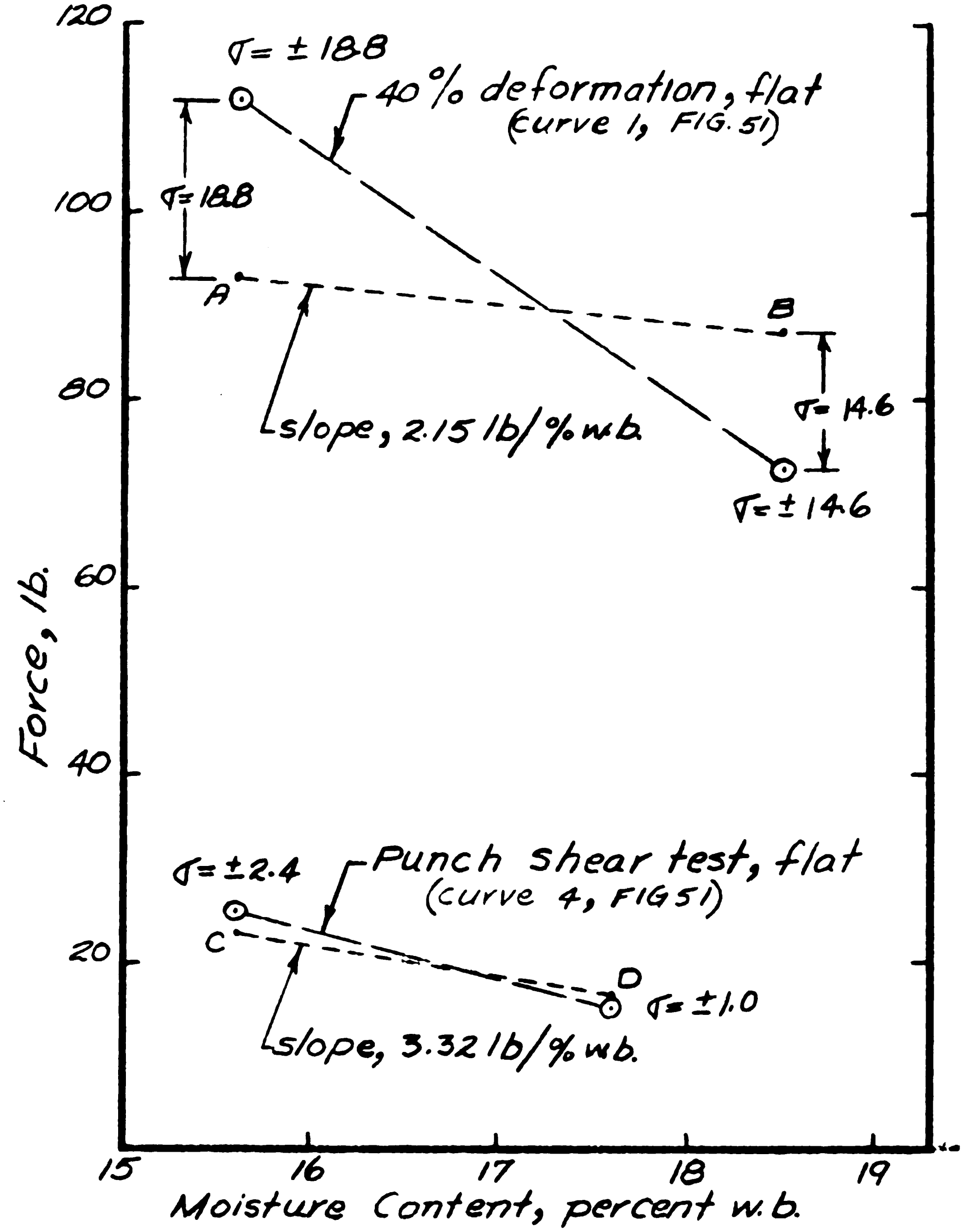

FIG. 52 GRAPHICAL PICTURE OF SENSITIVITY OF MECHANICAL MOISTURE METER FOR PEA BEANS.

means of determining moisture content of grain. Most commercial moisture meters operate on the principle of electrical conductivity variation with moisture level. Consequently, they are relatively expensive. It is very important to know moisture content for safe storage; it is also extremely useful to know the field moisture level to help predict maturity before harvest.

SUMMARY

Mechanical Properties

The mechanical properties of grain are needed to analyze problems encountered in grain harvesting, handling, and processing. Seed crackage and damage by crushing are encountered during threshing and handling operations. Grinding grain is a relatively high energy process accompanied by low efficiency. To solve these problems or make improvements in existing operational techniques, investigation should begin with the determination of basic properties of the individual grain kernel.

A strain gage transducer was designed and built to measure the mechanical and rheological properties of grain. Electronic equipment was used to amplify and record load-deformation relationships.

Properties were examined for three grains -- corn, wheat, and pea beans. The effect of moisture content on the mechanical properties of grain kernels, was the chief parameter investigated. Four moisture levels, ranging from 10.6% d.b. to 32.8% d.b., were used. Other parameters studied were the effect of rate of deformation and kernel position (edge or flat), on strength characteristics. Rates of deformation of 0.0777 in/min, 0.267 in/min, and 0.467 in/min, were used. Temperature effect was not studied. All data were obtained at room temperature. Ten replications were made for practically all tests.

This investigation consisted of a quantitative study of the following mechanical properties and/or characteristics for each grain with the variables indicated:

1. Maximum kernel strength, lb. -- edge and flat position, four moisture levels, three deformation rates.

The maximum strength of the kernel depended greatly on moisture content and seed position for the test. The average maximum compressive force for corn kernels in the edge position decreased from 45.3 to 17.5 pounds with a moisture increase from 14.6% d.b. to 26.0% d.b. In the flat position the compressive force decreased from an average of 96.7 to 73.7 pounds for the same moisture range. Variation between individual tests was much greater in the flat position than in the edge position. These tests were run at the medium speed of 0.267 in/min.

The maximum compressive strength of wheat kernels increased slightly up to 20 percent moisture. Above this level no elastic properties and no point of maximum strength were found.

Pea beans showed slightly higher strength in the flat position than in the edge position at low moisture. Seed position made little difference at higher moisture.

Rate of deformation had no significant effect on the resulting compressive force at low moisture levels. A significant speed effect was noted at the five percent level, however, for corn in the edge position at 26.0% d.b. The fast deformation rate produced an average maximum strength of 22.3 pounds while the medium and slow rates gave strength averages of 17.5 and 16.1 pounds respectively.

2. Yield Strength, lb. -- edge and flat position, four moisture levels, three deformation rates.

Moisture, kernel position and rate of deformation had the same effect on yield strength as on maximum strength. Maximum strength values ranged from about 30 percent to 60 percent higher than the yield strength values.

3. Maximum Compressive Stress, psi -- core specimens, four moisture levels, one deformation rate. (slow).

A linear relation existed between maximum stress and moisture from 15.4% to 18.8% d.b. for corn. Maximum stress ranged from 4800 psi to 2900 psi for a moisture variation from 15.4% d.b. to 23.0% d.b. The same relative effect of moisture was found for wheat, but the magnitude of the values was about 30 percent lower.

4. Modulus of Elasticity, psi. -- core specimens, four moisture levels, one deformation rate (slow).

Modulus of elasticity relationship with moisture paralleled maximum stress. The range for corn was 50,000 psi to 29,000 psi for a moisture change from 15.9% to 23.0% d.b.

Modulus of elasticity of corn decreased 42 percent with a 49 percent moisture increase. Similarly, for wheat a 52 percent decrease in modulus of elasticity was obtained from a 53 percent moisture increase. Because of the non-elastic nature at high moisture, data were obtained for pea beans at only one moisture level.

5. Shear Stress, psi -- flat position (in vise), four moisture levels, slow deformation rate.

Shear stress for corn decreased from about 1250 psi to 950 psi for a moisture increase from 14.5% to 21.0% d.b. Shear stress for wheat stayed relatively constant at about 800 psi within the 15.7 to 24.5% d.b. range.

6. Static and Impact Energy Requirements for Kernel Rupture, in-lb/in^2 -- flat position (in vise), four moisture levels, slow speed (0.0777 in/min) and pendulum impact velocity (5.24 ft/sec).

For corn, impact and static energy values were about equal at intermediate moisture content (13.5% to 18.5% d.b.). At moisture levels below this range, however, impact energy was lower than static shear energy, and above this moisture range impact shear energy was higher than static shear energy. At 21% d.b., impact and static shear energy requirements were about equal; at a moisture of 36% d.b., energy required to rupture the kernel was 2.8 times as great by impact shear as with static shear.

Corn and wheat impact energies ranged from about 15 to 25 in-lb/in^2 for a moisture variation from 15% to 25% d.b. Pea bean impact energies went from a low of 3.5 in-lb/in^2 at 8.7% d.b. to 65 in-lb/in^2 at 36.2% d.b.

7. Modulus of Resilience, in-lb/kernel -- edge and flat positions, four moisture levels, one deformation rate (except at low and high moisture levels).

The modulus of resilience showed a relatively large variation between individual kernels at a given moisture content. The absolute variation was, however, quite constant from one moisture level to another. A typical value for wheat was 0.06 in-lb/kernel. For corn 0.12 in-lb/kernel and 0.3 in-lb/kernel were typical values for the edge and flat positions respectively.

8. Toughness or Modulus of Toughness, in-lb/kernel -- edge and flat position, four moisture levels, one deformation rate (except at low and high moisture levels).

Larger variation between individual kernels was observed for modulus of toughness than for modulus of resilience. Modulus of toughness values averaged from two to five times greater than the modulus of resilience energies.

9. Hysteresis Loss, percent, -- flat position (corn and beans), core specimens (wheat), two moisture levels, two deformation levels.

Hysteresis losses were greater with higher moisture content and with the initial loading-unloading cycle. For wheat, the initial cycle produced a hysteresis loss of 44.5 percent, and the second cycle a loss of 20 percent. For the same conditions with corn, the losses were 39.3 percent and 14.9 percent. Also with corn, initial cycle loss was 39.2% for 15.8% d.b. and 62.6% loss for a moisture content of 26.0% d.b. Similar losses were obtained for pea beans.

Rheological Properties

1. Rate of Deformation -- pea beans, one moisture level, three deformation rates.

The variation in rates of deformation used in this study was not great enough to cause an important difference in the compressive force on pea beans at a moisture content of 32.8% d.b. Ideal plastic properties seemed to be present at the lower amounts of deformation (20 percent), and quasi-plastic effects appeared at greater deformations (35 percent).

2. Stress Relaxation -- pea beans, three moisture levels, three deformation rates for one moisture level.

The rate of stress relaxation in pea beans was found to be a function of the preceding deformation rate. Stress relaxation rate was somewhat dependent on the amount of deformation. Stress relaxation time, however, was found to be completely independent of amount of deformation. This phenomenon was checked for two moisture levels of 18.5% d.b. and 32.8% d.b. Moisture content had very little effect on relaxation time. Pea bean relaxation may be represented rheologically by a mechanical model consisting of two Maxwell units in series.

Other Observations

The feasibility of indirectly determining grain moisture content by means of a mechanical test on single grain seeds was considered. The possibilities of such a moisture meter appear quite good, particularly for pea beans.

CONCLUSIONS

As a result of this study of mechanical and rheological properties of grain, the following conclusions are presented:

1. Of the parameters investigated, moisture content has the greatest influence on the mechanical properties of grain. All strength properties generally decrease in magnitude as moisture increases. Energy required for seed rupture by impact increases as moisture increases. Variation in mechanical properties with moisture change is greater for beans than for wheat or corn. Elastic properties are present at low moisture; plastic properties appear at high moisture content.
2. Rates of deformation varying from 0.0777 in/min to 0.478 in/min in compressive tests, have no effect on kernel strength at low moisture, but show some significant difference at high moisture for corn at the five percent level.
3. Maximum compressive strength of corn at all moisture levels, depends greatly on whether the kernel is in an edge or flat position. For wheat, there is no significant difference in strength for either position of the kernel. With pea beans, seed position makes a difference on strength at low moisture, but not at the higher levels.

4. Punch shear tests are unsatisfactory as a means of determining shear stress of corn and wheat.

5. Modulus of elasticity values for wheat and corn are very similar, ranging from 50,000 psi at around 15.5% d.b. to approximately 25,000 psi at 23% d.b. Maximum compressive stress for wheat varied from approximately 3300 psi to 1700 psi for a moisture change from 15.5% d.b. to 23.0% d.b. This moisture range produced a compressive stress change for corn from 5000 psi to 2500 psi.

6. At high moisture more energy is required to rupture grain kernels by impact shear than by static shear. The reverse is true at low moisture.

7. Specific damping capacity and relative elastic properties can be evaluated in grain by means of hysteresis loops. Hysteresis loss depends chiefly on strain history (whether the loading-unloading is maiden cycle or some later one) and on moisture content.

8. The force required to deform grain to the elastic limit and maximum strength points decreases as the moisture content increases. The range of modulus of resilience and modulus of toughness, however, is quite constant with the four moisture levels. The decrease in strength was found to be compensated for by an increase in ductility or toughness.

9. Stress relaxation with time can be represented by two Maxwell units as used in rheology studies.

Quantitatively, stress relaxation with time can be given by the sum of two exponential terms. Initial rate of deformation has more effect on the rate of stress relaxation than moisture content or the (initial) amount of deformation. Relaxation time is constant with various deformation amounts.

10. The use of the strength properties of grains appears promising as the basis for the development of an inexpensive but accurate mechanical moisture meter.

SUGGESTIONS FOR FURTHER STUDY

It is difficult in one investigation to study in detail all phases of mechanical and rheological properties of grain. Certain phases of the investigation suggested additional problems for study.

1. The effect of temperature on mechanical and rheological properties should be studied.

2. Impact data, obtained by impinging grain against a hard surface, would be useful in analyzing bean crackage.

3. Hysteresis losses in grain kernels should be investigated in more detail. By a preliminary mechanical conditioning, the grain kernel can be made more brittle; this action may reduce energy requirements during the grinding process.

4. Rheological properties of grains may be studied more conveniently if strain is measured as the result of a constant applied stress. In this study, stress (force) was recorded as a result of a constant strain rate.

5. The possibilities of a mechanical moisture meter should be investigated further.

6. Grain hardness should be investigated. Perhaps hardness can be used as an indirect measure of moisture content.

7. Determination of the coefficient of thermal expansion of grain kernels by means of strain gages should be investigated

8. Properties of other grains, and other varieties of corn, wheat and beans, should be studied.

APPENDIX

TABLE A 1

FORCE, lb, REQUIRED TO REACH PROPORTIONAL LIMIT, YIELD POINT AND MAXIMUM STRENGTH, FOR YELLOW DENT CORN AT 14.6% d.b. (12.7% w.b.) IN THE EDGE POSITION AT THREE SPEEDS

	Proportional Limit			Yield Point			Maximum Strength		
	Slow	Med.	Fast	Slow	Med.	Fast	Slow	Med.	Fast
	26.2	28.8	26.3	28.2	49.8	39.4	29.2	49.8	39.4
	16.1	28.8	34.1	22.9	29.6	35.4	24.9	48.7	35.4
	22.3	22.2	18.3	23.6	58.9	20.9	39.3	58.9	28.0
	36.7	26.9	21.6	36.7	35.4	37.4	36.7	38.0	40.0
	13.1	19.7	23.6	28.8	21.6	34.1	42.7	32.1	37.3
	31.5	13.1	22.3	36.7	39.3	41.2	63.0	40.7	41.2
	28.8	27.5	21.6	30.8	30.4	33.4	43.2	48.5	48.5
	27.5	28.2	31.5	35.0	37.4	46.4	45.8	44.5	49.8
	32.8	26.2	30.2	39.3	32.1	32.8	45.9	45.8	46.5
	36.7	24.9	24.9	49.8	40.6	52.4	49.8	40.6	52.4
Ave:	27.2	24.6	25.4	33.2	37.5	37.3	42.1	44.8	41.8
σ:	7.6	4.8	4.8	7.7	10.1	8.1	10.1	10.4	7.1
C*:	27.9	19.5	18.9	23.2	27.0	21.7	24.0	23.2	17.0

f_{exp} for porportional limit (slow, med, fast) = 0.44; $f_{.95}$ = 3.35

f_{exp} for yield limit (slow, med, fast) = 0.72; $f_{.95}$ = 3.35

f_{exp} for maximum strength (slow, med, fast) = 0.27; $f_{.95}$ = 3.35

$C^* = \sigma / \text{Ave} \times 100$

TABLE A 2

FORCE, lb, REQUIRED TO REACH PROPORTIONAL LIMIT, YIELD POINT AND MAXIMUM STRENGTH, FOR YELLOW DENT CORN AT 14.6% d.b. (12.7% w.b.) IN THE FLAT POSITION AT THREE SPEEDS

Proportional Limit			Yield Point			Maximum Strength		
Slow	Med.	Fast	Slow	Med.	Fast	Slow	Med.	Fast
41.9	44.5	85.0	59.0	81.3	95.0	59.0	81.3	216.0
40.6	45.9	62.2	44.5	55.0	80.5	203.0	55.0	91.7
88.3	65.5	32.8	88.3	65.5	32.8	131.0	75.3	91.7
35.4	28.8	29.5	35.4	52.4	45.8	94.2	56.1	105.0
38.0	27.4	72.0	55.0	42.7	78.6	55.0	42.7	115.2
39.3	49.8	41.0	52.4	49.8	50.7	81.2	120.0	50.7
39.3	32.7	40.8	60.2	51.1	40.8	68.0	84.7	245.0
73.3	32.8	89.0	90.4	34.1	91.7	90.4	89.2	144.0
40.6	88.5	36.2	40.6	88.5	65.5	157.0	167.0	65.5
21.0	62.9	95.0	21.0	63.6	131.0	170.5	86.5	131.0
Ave:								
45.8	47.9	58.3	54.7	58.4	71.4	110.9	85.8	125.6
σ:								
18.7	18.6	24.0	20.7	15.9	28.7	48.8	34.0	59.0
C*:								
40.8	38.8	41.2	37.9	27.2	40.2	44.1	39.6	47.0

f_{exp} proportional limit (slow, med, fast) = 0.96; $f_{.95}$ = 3.35

f_{exp} yield point (slow, med, fast) = 1.39; $f_{.95}$ = 3.35

f_{exp} maximum strength (slow, med. fast) = 1.56; $f_{.95}$ = 3.35

C* = σ/Ave X 100

TABLE A 3

FORCE, lb, REQUIRED TO REACH
YIELD POINT AND MAXIMUM STRENGTH FOR YELLOW DENT CORN
AT 26.0% d.b. (20.65% w.b.) IN THE EDGE POSITION
AT THREE SPEEDS

	Yield Point			Maximum Strength		
	Slow	Med	Fast	Slow	Med	Fast
	9.2	13.1	22.9	10.5	17.3	22.9
	10.5	13.1	13.8	13.1	16.5	18.3
	7.9	15.7	19.7	9.8	22.3	27.5
	16.6	8.5	14.4	18.3	13.6	20.8
	7.9	8.3	19.7	12.8	14.4	26.2
	18.3	14.4	22.3	21.3	17.7	22.3
	11.1	9.8	6.6	18.3	13.5	11.8
	20.0	16.2	19.7	21.8	23.6	20.0
	12.4	15.7	23.6	21.3	17.0	27.1
	9.6	13.1	28.0	13.8	19.6	29.3
Ave:	12.1	12.8	19.1	16.1	17.5	22.6
σ:	4.4	2.8	5.7	4.4	3.3	5.0
C*:	36.4	21.9	29.8	27.3	18.9	22.1

f_{exp}, yield point (slow, med, fast) = 6.50; $f_{.95}$ = 3.35

f_{exp}, maximum strength (slow, med, fast) = 5.79; $f_{.95}$ = 3.35

C* = σ/Ave X 100

TABLE A 4

COMPARISON OF COMPRESSIVE FORCE (lb)
AT MEDIUM SPEED REQUIRED TO DEFORM YELLOW DENT CORN
TO THE YIELD POINT AND TO MAXIMUM STRENGTH
AT FOUR MOISTURE LEVELS (% d.b.)
WITH THE KERNEL ON EDGE

	Yield Point				Maximum Strength			
	14.6	15.8	18.2	26.0	14.6	15.8	18.2	26.0
	49.8	21.0	19.6	13.1	55.0	26.2	26.7	17.3
	29.6	30.1	37.3	13.1	48.7	36.7	49.7	16.5
	58.9	43.8	24.9	15.7	58.9	51.7	35.4	22.3
	35.4	38.0	39.3	8.5	38.0	43.2	44.5	13.6
	21.6	18.3	20.3	8.3	32.1	21.7	24.9	14.4
	39.3	24.9	18.3	14.4	40.7	41.9	26.2	17.7
	30.4	18.3	31.8	9.8	48.5	21.6	35.4	13.5
	37.4	21.9	22.3	16.2	44.5	24.9	27.5	23.6
	32.1	23.6	28.8	15.7	45.8	30.8	47.1	17.0
	40.6	36.7	32.8	13.1	40.6	36.7	34.9	19.6
Ave:	37.5	27.7	28.5	12.8	45.3	33.5	35.2	17.5
σ:	10.2	8.6	7.2	2.8	7.6	9.7	8.7	3.3
C:	27.2	31.0	25.2	21.9	16.8	28.9	24.7	18.4

TABLE A 5

COMPARISON OF COMPRESSIVE FORCE (lb)
AT MEDIUM SPEED REQUIRED TO DEFORM YELLOW DENT CORN
TO THE YIELD POINT AND TO MAXIMUM STRENGTH
AT FOUR MOISTURE LEVELS (% d.b.)
WITH THE KERNEL LYING FLAT

	Yield Point				Maximum Strength			
	14.6	15.8	18.2	26.0	14.6	15.8	18.2	26.0
	81.3	39.3	69.5	52.4	81.3	116.0	--	75.2
	55.0	49.2	99.6	--	111.0	100.0	144.0	--
	65.5	98.1	85.3	73.4	75.3	104.7	137.5	86.5
	52.4	58.4	60.9	96.9	70.7	124.5	65.5	96.9
	42.7	100.0	--	121.2	81.2	170.3	196.5	--
	49.8	39.3	157.0	36.7	120.0	41.9	--	52.4
	51.1	74.4	144.0	95.4	84.7	203.0	144.0	95.4
	34.1	63.5	45.9	34.1	89.2	82.0	45.9	35.6
	88.5	44.5	36.0	--	167.0	135.0	52.4	--
	63.6	55.8	55.0	--	86.5	55.8	128.0	--
Ave:	58.4	62.3	83.7	72.9	96.7	113.3	98.0	73.7
σ:	15.9	21.1	40.2	32.3	27.2	46.4	50.2	22.7
C:	27.2	33.9	48.0	44.3	28.1	40.9	51.2	30.8

$C = \sigma/\text{Ave} \times 100$

TABLE A 6

COMPRESSIVE FORCE (lb) REQUIRED
AT MEDIUM SPEED TO DEFORM PEA BEANS
TO THE YIELD POINT AND MAXIMUM STRENGTH
AT 10.6% d.b. IN THE EDGE AND FLAT POSITIONS

	Yield Point		Maximum Strength	
	Edge	Flat	Edge	Flat
	64.2	44.5	64.2	68.1
	53.7	55.0	53.7	73.4
	83.8	55.0	104.8	84.8
	65.5	39.3	65.5	82.5
	43.2	22.9	43.2	40.9
	52.4	19.1	52.4	70.7
	60.3	52.4	62.9	73.4
	28.8	58.9	45.6	94.3
	73.4	16.8	73.4	60.3
	55.0	49.8	55.0	96.9
Ave:	58.0	41.4	62.1	74.5
σ:	14.5	15.2	16.8	15.7
C:	25.0	36.7	27.0	21.1

$C = \sigma/\text{Ave} \times 100$

TABLE A 7

FORCE, lb, REQUIRED TO DEFORM SOFT RED WINTER WHEAT TO THE PROPORTIONAL LIMIT, YIELD POINT AND MAXIMUM STRENGTH AT 16.0% d.b. (13.8% w.b.) IN THE FLAT POSITION AT THREE SPEEDS

Proportional Limit			Yield Point			Maximum Strength		
Slow	Med.	Fast	Slow	Med.	Fast	Slow	Med.	Fast
5.6	6.9	7.9	13.1	10.5	12.5	13.9	11.8	23.1
7.2	5.2	7.6	13.1	11.9	14.4	22.2	13.4	15.5
7.2	5.6	5.9	9.8	15.1	12.5	9.8	19.0	20.7
9.5	7.2	11.1	21.0	11.8	15.1	21.0	12.1	19.0
6.5	7.9	4.9	8.5	15.1	14.1	17.0	16.1	16.4
6.5	7.5	7.2	10.5	12.5	12.6	11.5	12.5	15.7
6.5	7.5	7.5	14.4	13.7	20.3	19.0	14.1	20.3
7.5	6.2	5.6	15.7	8.5	9.5	17.7	8.9	10.9
5.9	8.3	11.5	11.4	12.5	16.4	13.8	18.0	16.4
5.2	7.2	6.5	11.1	11.1	9.8	13.8	11.8	11.5
Ave:								
6.8	6.9	7.6	12.9	12.3	13.7	15.9	13.8	16.9
σ:								
1.1	.9	2.1	3.4	2.8	3.0	3.9	3.0	3.7
C:								
16.2	13.0	27.6	26.4	22.8	21.9	24.6	21.7	21.9

f_{exp}, proportional limit (slow, med, fast) = 0.74 ; $f_{.95} = 3.35$

f_{exp}, yield point (slow, med, fast) = 0.51; $f_{.95} = 3.35$

f_{exp}, maximum strength (slow, med, fast) = 1.92; $f_{.95} = 3.35$

TABLE A 8

COMPARISON OF COMPRESSIVE FORCE (lb)
AT MEDIUM SPEED REQUIRED TO DEFORM SOFT RED WINTER WHEAT
TO THE YIELD POINT AND TO MAXIMUM STRENGTH
AT TWO MOISTURE LEVELS (% d.b.)
WITH THE KERNEL IN THE FLAT POSITION

	Yield Point		Maximum Strength	
	16.0	20.3	16.0	20.3
	10.5	17.7	11.8	19.6
	11.9	16.4	13.4	16.4
	15.1	13.1	19.0	13.8
	11.8	8.8	12.1	12.6
	15.1	21.6	16.1	21.6
	12.5	18.3	12.5	19.0
	13.7	17.7	14.1	19.0
	8.5	15.7	8.9	15.7
	12.5	8.5	18.0	8.5
	11.1	9.8	11.8	11.5
Ave:	12.3	14.8	13.8	15.8
σ:	1.9	4.3	2.9	3.9
C:	15.5	29.0	21.0	24.7

$C = \sigma/\text{Ave} \times 100$

TABLE A 9

ENERGY FOR FAILURE OF YELLOW DENT CORN
BY IMPACT SHEAR AT FOUR MOISTURE LEVELS,
INCH-POUNDS PER SQUARE INCH

	13.4% d.b.	18.1% d.b.	19.2% d.b.	24.7% d.b.
	13.5	17.9	19.6	24.8
	13.6	13.4	19.6	31.9
	9.8	17.0	26.0	28.5
	16.8	17.6	20.4	26.5
	27.5	19.9	21.5	19.3
	15.6	14.6	21.4	26.3
	15.2	21.1	13.9	44.7
	14.9	22.7	21.7	20.4
	11.4	19.8	35.2	28.3
	9.3	14.2	19.8	31.2
Ave:	14.8	17.8	21.9	28.2
σ:	4.8	2.9	5.2	6.7
C:	32.4	16.3	23.7	23.8

$C = \sigma / \text{Ave} \times 100$

TABLE A 10

ENERGY FOR FAILURE OF SOFT RED WINTER WHEAT
BY IMPACT SHEAR AT FOUR MOISTURE LEVELS
INCH-POUNDS PER SQUARE INCH

	16.9% d.b.	18.7% d.b.	21.7% d.b.	24.5% d.b.
	18.3	18.9	19.6	20.6
	12.9	20.0	18.0	28.9
	19.7	11.5	16.0	37.1
	10.4	17.6	15.7	26.6
	16.7	11.0	19.8	21.0
	17.0	19.3	18.0	26.6
	19.4	19.4	20.7	23.7
	21.4	17.6	16.5	21.6
	25.5	16.4	18.8	17.5
	12.7	18.9	19.6	17.5
Ave:	16.1	17.1	18.3	24.1
σ:	3.5	3.1	1.6	5.7
C:	21.8	18.1	8.7	23.6

TABLE A 11

ENERGY FOR FAILURE OF PEA BEANS
BY IMPACT SHEAR AT FOUR MOISTURE LEVELS
INCH-POUNDS PER SQUARE INCH

	8.7% d.b.	18.5% d.b.	22.8% d.b.	36.2% d.b.
	3.14	36.8	40.1	72.6
	1.54	48.7	55.7	74.5
	2.13	30.7	45.0	48.8
	3.03	36.9	45.2	69.3
	2.81	37.3	44.1	53.3
	4.95	34.6	46.4	54.3
	5.00	40.8	55.2	83.3
	2.70	26.1	57.2	59.5
	3.40	31.4	62.5	63.2
	5.94	22.8	62.6	73.5
Ave:	3.46	34.6	51.3	65.2
σ:	1.32	7.0	7.6	10.6
C:	38.2	20.2	14.8	16.3

TABLE A 12

ENERGY REQUIRED TO RUPTURE PEA BEANS
22.8% d.b. (18.6% w.b.) BY IMPACT SHEAR
AT TWO VELOCITIES, INCH POUNDS PER SQUARE INCH

	$\theta_1 = 44^\circ\ 30'$ (Vel. of Impact 5.24 ft/sec)	$\theta_1 = 79^\circ\ 42'$ (Vel. of Impact 8.87 ft/sec)
	40.1	46.8
	55.7	57.2
	45.0	49.1
	45.2	43.8
	44.1	39.4
	46.4	44.3
	55.2	48.2
	57.2	57.2
	62.5	51.7
	61.6	41.9
Ave:	51.3	48.0
σ:	7.2	5.7
C:	14.0	11.9

$f_{exp} = .80, \quad f_{.95} = 4.41$

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