MECHANICAL PROPERTIES OF CORN COBS

by

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ABSTRACT

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Ph.D. MECHANICAL PROPERTIES OF CORN COBS Agricultural Engineering

Theoretical equations were developed for calculating the apparent elastic modulus and the strength of corn cob under quasi-static radial compression and simple bending. An empirical equation was derived for calculating its modulus of toughness.

Experimental justification was provided for the application of the Hertz linear elastic contact theory in determining cob mechanical properties in radial compression, since the cob is a composite of three inelastic materials.

In simple bending, the basic flexure formula was modified to account for the composite and tapered structure of the cob.

The relative contributions of the macro-structural components of the corn cob to its mechanical properties were determined.

Cob mechanical properties were found to be significantly affected by corn variety, harvest date and moisture content, but not by loading rate. Further experimental investigations showed that the cob mechanical properties were much dependent on fertilizer type and application rate but less dependent on soil type and condition.

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Ph.D. UCHE G. N. ANAZODO GENIE RURAL

PROPRIETES MECANIQUES DE L'EPI DE MAIS

Des équations théoriques furent développées pour calculer le coefficient d'élasticité apparent et la résistance d'un épi de maïs sous compression radiale quasi statique et flexion simple.

Une équation empirique fut également dérivée pour le calcul du module de dureté.

Des expériences en laboratoire s'avèrent indispensables pour l'application de la théorie linéaire élastique "Hertzienne" afin de déterminer les propriétés mécaniques de l'épi sous compression radiale, étant donné les trois matériaux inélastiques constituants de l'épi.

En flexion simple la formule exprimant le fléchissement fut modifiée pour prendre en considération la composition et la structure particulière de l'épi de maïs.

Les contributions relatives des composantes macro-structurelles de l'épi par rapport à ses propriétés mécaniques furent aussi déterminées.

Les propriétés mécaniques de l'épi se sont avérées significativement affectées par la variété de maïs, la date de récolte et l'humidité de l'épi et non par le taux d'application de la charge.

Des expériences supplémentaires démontrèrent que les propriétés mécaniques de l'épi furent fortement liées au fertilisant employé ainsi qu'aux dosages appliqués, mais peu affectées par le type de sol et sa condition.

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CONTRIBUTIONS TO KNOWLEDGE

There are five principal aspects of the study reported in this doctoral thesis which the author wishes to claim as his original contributions to knowledge.

1. Analyses of the force-deformation curves and failure of the corn cob under radial loadings have not been adequately researched. Hence, no formal equations have been presented in the literature for characterizing the mechanical properties and strength of the corn cob. Previous interpretations of the force-deformation curves of the corn cob under radial loading have been limited to the measurement of the maximum force to crush or break the cob and the determination of the slopes of the upper portions of the curves. Thus the most single important achievement of the present research investigation is the establishment of theoretical and experimental foundations for interpreting, in proper engineering terms, the experimental force-deformation curves of corn cob composite under radial compression and simple bending.

2. Although the application of the Hertz linear elastic contact theory to biological materials is not new, no experimental justification of this approach has previously been presented in the case of radial compression of cylindrical biological materials. Thus the experimental evidence, developed and presented in this study, that the Hertz linear

elastic contact theory accurately predicts the contact area of a radially deformed corn cob composite, despite its non-homogeneous, non-isotropic and inelastic structural composition and mechanical behavior, is considered a very important finding.

3. The bending strength equation developed in this study for corn cob composite loaded as a simple beam is equally applicable to any other linearly tapered composite cylindrical biological structure of two "homogeneous" materials. This equation not only provides an accurate theoretical basis for a quantitative analysis of the force-deflection curves of such agricultural products, it also enables the researcher to investigate the importance of each of the two components of the product in question and also to determine the effect of its tapering structure.

4. For the first time, it is established that a five-parameter empirical equation gives an accurate representation of the force-deformation curve of corn cob composite in radial compression, or indeed for any other biological material with similar force-deformation behavior. Integration of this equation provides a straightforward method for determining the modulus of toughness of a corn cob composite. This finding has an important bearing on the characterization of the mechanical strength of agricultural products, especially in view of the present inability to establish a rational mechanical failure theory (or theories) for most agricultural products.

5. Previously reported investigations of the mechanical properties and mechanical behavior of the corn cob composite considered the cob as a hollow elastic cylinder by disregarding the soft, spongy, cylindrical parenchymatous tissue at the center of the cob. An investigation was conducted to examine this structural simplification of the cob composite, since in radial compression, the mechanical properties of a composite cylindrical body may be significantly modified by the existence of a very weak material within it. Experimental results from this study showed conclusively that the soft pith material at the center of the cob not only contributes substantially to the mechanical properties of the cob composite but it also plays a critical role in the initiation of failure in the cob when loaded in radial compression. Thus, this study contributes to knowledge by providing a better understanding of the relative importance of the corn cob's macro-structural components to its composite mechanical properties; and thereby points out the error in a popularly-held notion about an essential component of the cob.

Furthermore, the experimental results obtained from this study provide quantitative information on the mechanical properties of the corn cob. The major morphological, agronomic and edaphic factors affecting the corn cob mechanical properties were also established in this thesis.

The results of and conclusions from the study herein presented may find practical applications in the following related studies:

1. evaluation of kernel loss and damage during corn combine harvesting,
2. corn production research to determine the agronomic and mechanization system that optimizes economic return, and
3. mathematical formulation of corn combine shelling theory.

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LIST OF SYMBOLS AND ABBREVIATIONS

a	semi-minor axis of an elliptical area
A	cross-sectional area of corn cob
b	semi-major axis of an elliptical area or half width of contact area
c	distance of the extreme fibres of a beam from its neutral axis
C	correction factor for beam tapering
d_1, d_2	average diameters of corn cob at the tip and butt ends
D	total vertical deformation or deflection
D_b	D at pith cracking or maximum deflection at mid-span
D_e	elastic component of D
D_{max}	maximum deflection in simple bending
E	elastic modulus or apparent elastic modulus of corn cob in radial compression
E_1, E_2	E for upper and lower cylinders in contact or for materials I and II of a composite body
E_b	E for corn cob in simple bending
f	ratio of pith radius to cob radius
f-d	force-deformation or force-deflection
F	applied normal load
F_1, F_2, F_b, F_d	defined in Figures 10 and 14
G	shear modulus

I	moment of inertia
I_1, I_2	I for materials I and II of a composite beam
I_e	equivalent I for the transformed section of a composite beam
K	constant which depends on the non-linear shape of the f-d curve
K	bulk modulus (page 180)
kN	kilo-newtons (= 102 kg force = 454 lb)
ℓ	length of cylindrical body or short section of corn cob
L	effective length of a whole-length cob or loading span in simple bending
m	ratio of elastic modulus of pith material to that of the mid-cob material
M	bending moment or maximum bending moment or slope of the straight portion of f-d curve
MC	moisture content
M_o	defined in Figure 14
MPa	mega-pascals (= 10^6 x N/m^2 = 145 psi)
n	constant which depends on the non-linear shape of the f-d curve
NPK	nitrogen, phosphorus and potassium fertilizer combination
q	normal pressure distribution
q_o	maximum contact pressure
r	pith radius
R	principal radius of curvature or cross-sectional radius of a circular cylinder or cob radius
R_1, R_2	R for upper and lower bodies of cylinders in contact

S	stiffness (= M/ℓ)
U	modulus of toughness of corn cob
w	vertical displacement or deformation in the z-direction
x, y, z	cartesian coordinates
Z	term defined as equal to R/b
α_1, α_2	defined in Figure 14
β	per cent degree of elasticity
ε_b	crushing strain
ν	Poisson's ratio
ν_1, ν_2	Poisson's ratios for upper and lower bodies or cylinders in contact
σ_b	bending strength of corn cob
σ_c	crushing strength of corn cob
σ_{max}	maximum bending stress

CHAPTER I

INTRODUCTION

1.1 Importance of the problem

It is well recognized that an adequate knowledge of the mechanical behavior and failure criteria for agricultural products during harvesting and handling is essential to the efficient mechanization of these processes. Consequently, considerable experimental and theoretical research work has been done in identifying and quantifying the mechanical properties of food materials which are important in the optimum design and performance of harvesting and processing machines (Mohsenin and Goehlich, 1962; Mohsenin, 1970, 1977). A workshop on the design applications of mechanical properties of solid food materials (Pennsylvania State University, 1975) has further demonstrated the need for more research information on the mechanical properties and behavior of loaded agricultural products. Mechanical properties of agricultural products have also some important applications in the study of the storage qualities of such products under various storage systems (Mohammed, 1976).

In the case of the corn plant, interest has been focused on studying the physical and mechanical properties of the corn stalk (Prasad and Gupta, 1975) and corn kernel (Balastreire and Herum, 1978). The obvious reasons for this special interest in the stalk and kernel of corn are the needs to reduce losses due to stalk lodging, to minimize the power required to cut the plant during mechanical harvesting and to preserve kernel quality.

On the other hand, little work has been done in characterizing the mechanical properties of other corn plant components, such as the cob. Although corn cob is not a primary product of the corn plant, there is field and experimental evidence that the cob morphological, physical and mechanical properties influence the corn combine shelling efficiency (Sehgal and Brown, 1965; Agnes, 1968; Hall and Johnson, 1970). Both cob moisture content and cob strength are known to affect kernel losses and kernel damage (Waelti and Buchele, 1967).

Thus, a knowledge of the mechanical properties of the corn cob is also important in the design and performance of harvesting and processing machines.

Characterization of the mechanical properties of the corn cob may also be important in furthering the industrial exploitation of this corn by-product. Bichel and Yoerger (1954) listed the following industrial uses of corn cob: manufacture of furfural; soft-grit blasting of metals; absorbents and driers; fur cleaning and abrasives for hand-soap. Johnson and Lamp (1966) stated that the chemical industry uses cob as a carrier for insecticides, herbicides, and as an extender of vitamins and minerals in feedstuff. They also stated that cob flour and fine cob meal are used in pharmaceutical, cosmetic and similar preparations. Corn cobs are also used as animal bedding and as animal feed, mostly for the roughage effect (Table 1). Bargiel et al. (1979) discussed the potential use of corn cobs as a source of heat for crop drying. They developed a cob saver attachment for a corn combine.

1.2 Nature of the problem

Adequate characterization of the mechanical properties and strength of the corn cob has not been achieved because of the complex nature of cob morphology and structural composition. As described in Chapter II, the macro-structure of corn cob consists of three main components, none of which is exactly homogeneous, even on the macroscopic level.

The problem is further complicated by the non-linear, non-elastic and non-isotropic force-deformation behavior of corn cob under external loads, as illustrated in Figure 1.

It could, however, be reasonably assumed that the cob composite is radially isotropic and that each of its three major macro-structural components is homogeneous, elastic and isotropic.

TABLE 1. Average per cent composition and digestible nutrients of corn ear, kernel and cob*

Item	Ear	Kernel	Cob
	Corn and cob meal	Corn dent concentrate	Ground
	%	%	%
Dry matter	86.1	85.0	90.4
Total digestible nutrient	73.2	80.1	45.7
Protein	7.4	8.7	2.3
Fiber	8.0	2.0	32.1
Fat	3.2	3.9	0.4
Calcium	0.04	0.02	0.11
Phosphorus	0.22	0.27	0.04
Nitrogen	1.18	1.39	0.37
Potassium	0.40	0.29	0.82

*From Johnson and Lamp (1966).

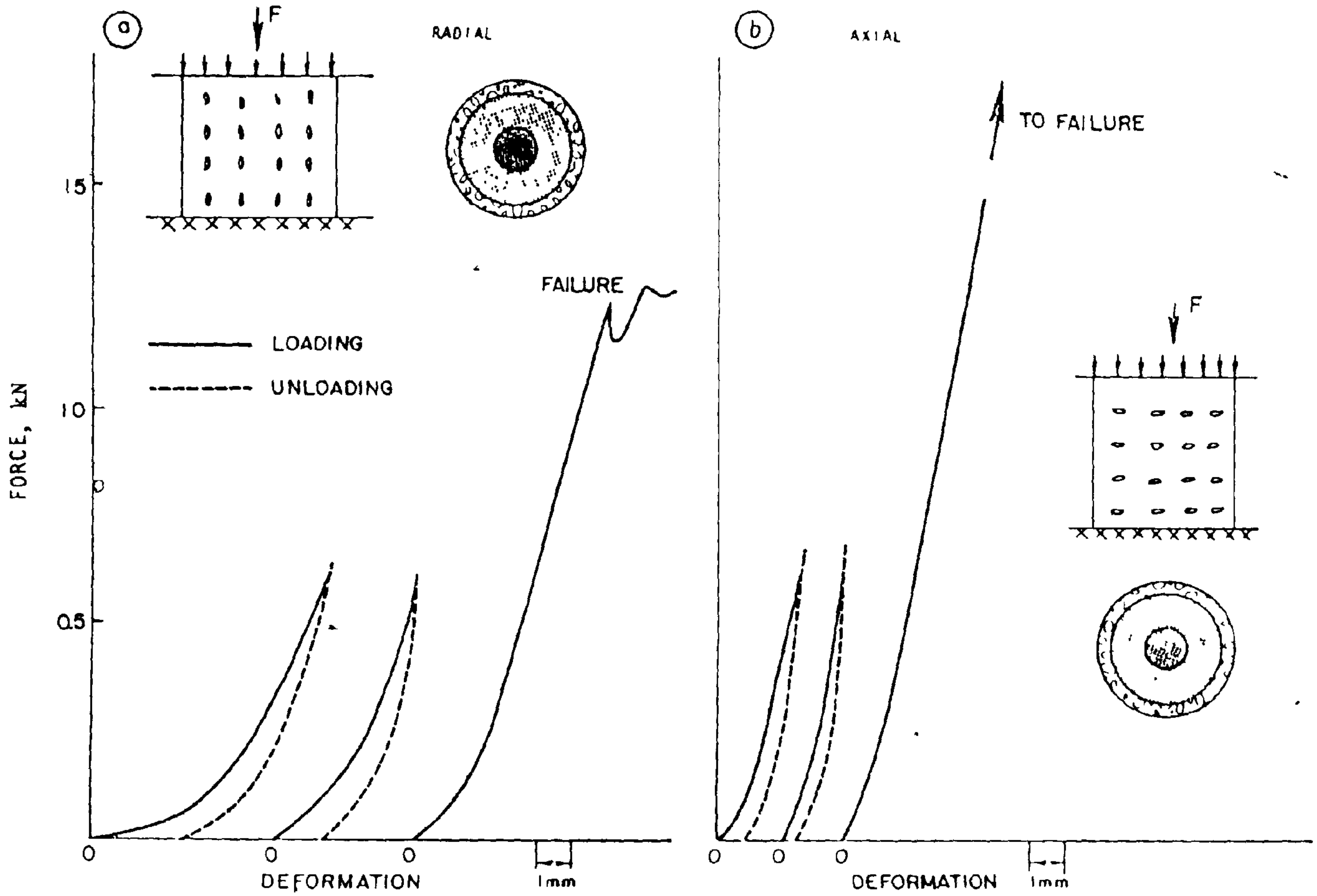

Figure 1. Non-linear, non-elastic and non-isotropic force-deformation behavior of corn cob composite in compression.

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1.3 Objectives of this study

The objectives of this studv were

1 To develop appropriate theoretical and experimental methods for characterizing the mechanical properties of corn cob composite under quasi-static loadings.

2. To determine the effects of rate of loading and cob moisture content on the mechanical properties of corn cob composite

3. To investigate the morphological, agronomic and edaphic factors affecting cob mechanical properties.

1.4 Scope of this study

The scope of this study was limited to theoretical and laboratory experimental investigations under quasi-static loadings

A greater proportion of studies on the mechanical properties of agricultural products is based on quasi-static analysis, which is relatively simpler than dynamic analysis However, for the purposes of applying the material properties determined under laboratory conditions to practical situations in the field, quasi-static analysis should be supplemented with dynamic investigations.

Emphasis in this study was on radial compression of corn cob composite. Axial loading of some cylindrical biological materials has been found to give less useful information on the mechanical properties of the products tested (Snobar, 1973; Sherif et al., 1976). Moreover, in relation to the shelling performance of the conventional corn combine harvester (Figure 2), mechanical properties of corn cob under radial compression are probably more relevant than those determined under axial compression. Also, because cob breakage in the combine cylinder-concave leads to kernel losses and overloading of the separating and cleaning devices of the harvester (Johnson and Lamp, 1966), simple bending tests were also considered important Thus, elastic modulus and strength of corn cob composite in simple bending were also studied in some detail

1.5 Approach to this study

In radial compression, the corn cob problem was considered essentially identical to the contact problem of an elastic cylinder on a rigid plane. The classical solution of the cylinder problem is based on Hertz linear elastic contact theory An implicit assumption in this approach was that, despite the non-homogeneous structural composition of the corn cob composite, the stresses and deformations at the surface of contact between the corn cob and each of the two loading steel plates could be adequately predicted from the Hertzian solution of the contact stress deformation of a homogeneous elastic cylinder on a rigid plane. Experimental justification of this assumption was undertaken.

In simple bending, the approach adopted was to modify the elementary beam flexure formula to account for the tapering of the cob structure and its composite nature. The cob was considered in

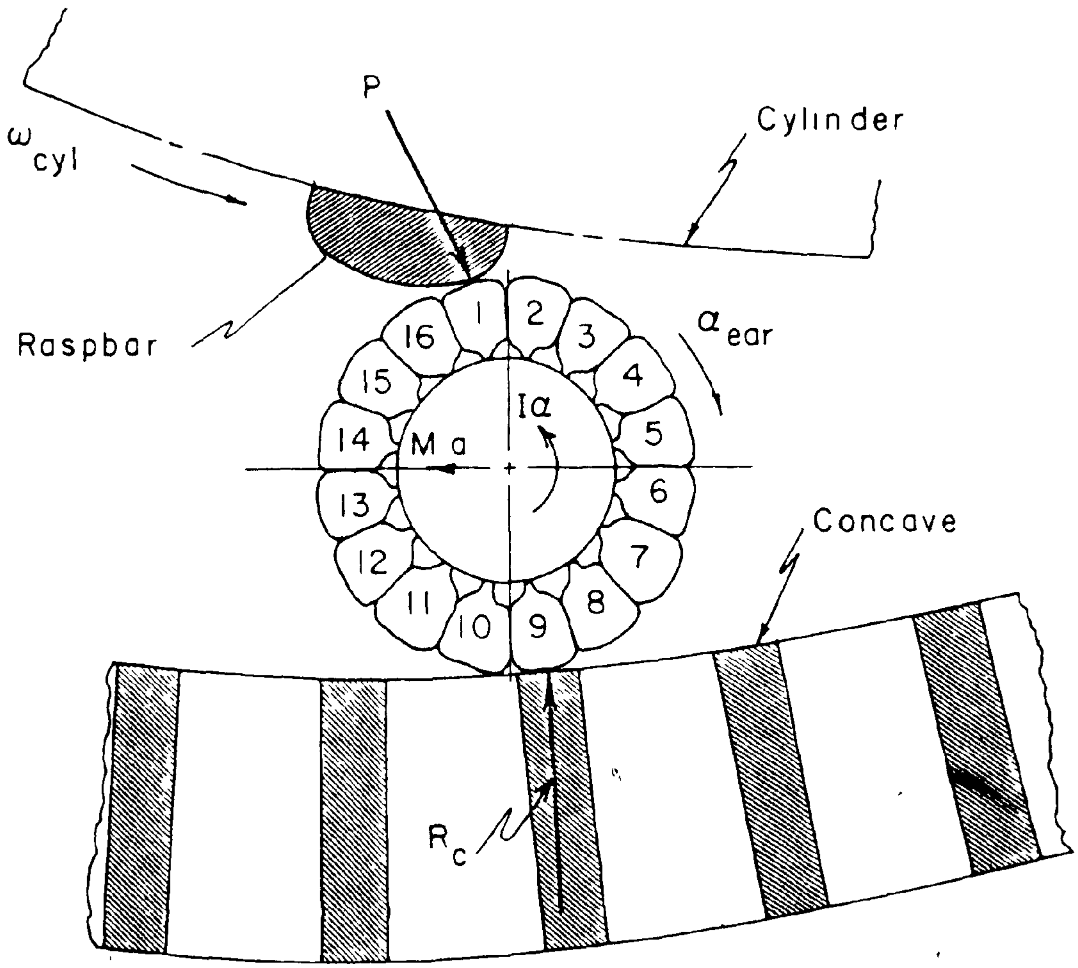


Figure 2 Shelling of corn ear in a combine cylinder-concave (from Waelti, 1968)

simple bending as a tapered cylindrical bodv of two homogeneous materials, the mid-cob and the soft pith at the center. The outer fine fluffy material covering the mid-cob was considered unimportant in simple bending.

CHAPTER II

REVIEW OF LITERATURE

2.1 General

Corn is one of the most efficient crops for converting the sun's energy into food. Although thought to be a native of Mexico, corn is grown throughout the temperate and tropical zones of the world where rainfall is adequate or irrigation water can be provided. It is a fast growing crop that yields best with moderate temperatures and plentiful supply of water (Aldrich et al., 1975).

Corn, more widely known as maize, ranks after wheat and rice as the third most important crop in the world. It has been the leading crop in the north central United States corn belt for about 100 years, and in the province of Ontario, Canada, for the past ten years (Hamilton, 1976). Grain corn production is more predominant than silage corn production in both the United States of America and Canada, although this is the case only in the provinces of Ontario and Quebec, which are the two leading corn producing provinces in Canada.

One of the more important attributes of corn as a grain crop is its high economic return, apart from its vast range of industrial applications (Liebenow, 1968) Besides genetic and edaphic factors (Anderson and Kemper, 1964, Glenn and Daynard, 1974), the main determinants of grain yield are planting date, population density, temperature, photoperiod, fertilizer type, and rate of fertilizer application (Ragland et al., 1966, Bonaparte, 1968, Genter and Jones, 1970; Marley and Ayres, 1972, Kirton, 1973, Arnold et al., 1974; Hunter et al., 1974; Winter et al., 1976)

Mechanization of corn production has greatly enhanced the economic importance of the crop but not without some associated problems. For instance, combine harvesting of corn frequently results in some appreciable amount of kernel losses and damage, particularly when the crop is harvested at relatively high moisture content due to weather constraints. These losses occur chiefly in the machine's gathering, threshing, separating and cleaning devices

Combine losses, expressed on a shelled-corn basis as a percentage of total harvest, may collectively amount to about 16 per cent (Burrough and Harbage, 1953), seven or five per cent (Pickard and Bateman, 1954), or about nine per cent (Byg et al., 1966). For high-moisture corn picker sheller harvesting operations, up to 10 per cent kernel loss may be suffered during shelling alone (Richey et al., 1961). It is important to note that a five per cent grain loss is approximately equivalent to a 25 per cent loss of profit and not five per cent (Friesen, 1972).

Kernel damage during corn combine shelling is even a greater concern to the farmer than kernel loss. Mechanical damage lowers the profits of corn growers by invisible losses (i.e., imperfect shelling, maturity loss and scavenger loss as discussed by Johnson and Lamp (1966)), accelerated deterioration, increased drying costs and lowered market price of grain corn (Burkhardt, 1971).

The kernel loss and damage levels in any given situation will depend on machine design, adjustment and operation, field conditions, weather, and crop morphological, physical and mechanical properties (Hunt, 1964, Sehgal and Brown, 1965, Byg et al , 1966, Johnson and Lamp, 1966; Waelti and Buchele, 1967, Nyborg et al., 1969; Friesen, 1972; John Deere, 1973; Lein et al., 1976).

Moisture content of the crop components is probably the most single important crop factor influencing harvesting and post harvesting operations for corn (Hunt, 1964; Waelti and Buchele, 1967; Prasad and Gupta, 1975, Hamdy et al., 1977). In the shelling of corn, if moisture content is too high, many of the kernels will rupture before breaking away from the cob, and longitudinal cob breakage may increase. If moisture content is too low, field losses due to lodging and dropped ears will be increased, and kernels will be damaged because of their inability to deform when the cylinder bar strikes them (Friesen, 1972).

Crop strength, measured separately as stalk strength, kernel strength and cob strength, has also been found to affect significantly field losses and damage of corn product (Zuber and Grogan, 1961, Thompson, 1963, Waelti and Buchele, 1967).

2.2 Mechanical properties of solid food materials

Mechanical properties may be defined as those having to do with the behavior of the material under applied forces. Mechanical properties that are time dependent may be considered as rheological The physical characteristics which are usually measured in studying mechanical properties of solid food materials include moisture content, shape, size, and density. In some instances, volume, surface area, porosity, color and appearance are also determined.

In the study of the mechanical properties of biological materials, it is assumed that the techniques employed in evaluating the behavior of engineering materials will be applicable to most agricultural products (Mohsenin, 1970, 1977). Linear elastic theory is assumed, although agricultural materials, being composed of solids and fluids, do not act in a purely elastic manner. Rather, their resistance to applied external load is a combination of elastic, plastic and viscous behavior. As a result of these difficulties, many observations are required and the mechanical properties of interest must be evaluated at various stages of maturity in order to specify completely the mechanical behavior.

Frequently, the characterization of the tensile, compressive or bending strength of an agricultural product is limited to the measurement of the maximum force to fail the material. Force, however, is not a valid measure of the strength of a material. The maximum force to fail a material depends on many factors, including the size and shape of the material being tested. Stress or strain at the critical point of failure may be more validly used. Determination of the stress-strain curve from the force-deformation curve obtained during test requires a precise and versatile testing machine with an x-y plot capability. This need is largely satisfied by the Instron universal testing machine, described by Bourne et al. (1966) and Bourne (1967). To simplify the stress-strain analysis, experiments are performed with conveniently shaped specimens of the agricultural product.

However, it must be pointed out that the calculation of stress as force per unit cross-sectional area of the loaded material is not valid for large deformations as occur in loaded biological materials. The contact areas or the loaded areas in both radial and axial loadings of the biological materials do not remain constant. Appropriate theories for calculating the contact stresses in both cases have been developed in classical theory of linear elasticity (Timoshenko and Goodier, 1970). Linear theory of viscoelasticity as developed for polymeric materials (Bland, 1960; Flügge, 1975) is also frequently applied to analyze creep and relaxation experimental data obtained with agricultural materials (Finney _et al._, 1964; Morrow and Mohsenin, 1966; Moustafa, 1967; Mohsenin, 1970; Chen and Fridley, 1972; De Baerdemacker and Segerlind, 1976).

Young's modulus, shear modulus, complex modulus, modulus of toughness, compressive strength, shear strength and tensile strength are some of the parameters often used in characterizing the mechanical properties and behavior of agricultural products. All these terms and certain other features of the force-deformation (f-d) curves of agricultural products are defined by Mohsenin (1970) and, except the complex modulus, may be determined from quasi-static tests using the Instron universal testing machine. Complex modulus calculation requires dynamic tests as described by Finney and Norris (1968), Wen and Mohsenin (1970), and Rao _et al_. (1976). An experimental technique for determining the dynamic strength of food materials is described by Jindal _et al_. (1976).

The application of the linear theory of elasticity to the study of the mechanical behavior and properties of biological materials has been questioned. In an effort to establish a more direct fundamental approach, Murase and Merva (1977) developed an elastic stress-strain constitutive equation to describe the response of vegetative material to environmental pertubations, based on the assumption that the vegetative tissue can be approximated as an elastic, porous, multicelled continuum. However, their equation contains five material coefficients which are not easily determinable.

Thus, as convincingly argued by Mohsenin (1970), until specific laws and principles are derived and established, bio-mechanical properties research will still be based on the application of the basic principles of engineering mechanics and rheology.

A recent contribution to the linear theory of elasticity approach to the study of stress-strain behaviors of agricultural products under applied load is the application of the finite element analysis techniques (De Baerdemaeker, 1975; Cooke et al., 1976; Segerlind, 1976; Sherif, 1976; Gustafson et al., 1977). The finite element method is a numerical procedure for the solution of differential equations. The basic premise behind the method is that any function, existing in a region, can be represented by "a set of piecewise continuous functions defined over a finite number of subdomains" (Segerlind, 1976). However, a numerical solution of the stress-strain behavior of an intact agricultural product under load depends on adequate knowledge of the "elastic constants" of the major constituent materials of the product. Otherwise, the application of this powerful technique will be seriously limited as was the case with the study by Brandini et al. (1978). Experimental verification of the numerical solution is often very difficult to undertake, due largely to the lack of adequate experimental technique for measuring strains in the intact agricultural product when loaded.

Much more difficult to accomplish is the identification of what constitutes failure in a loaded biological material. The maximum-stress theory is usually adopted as the strength theory, but this assumption has been disputed by some authors (Segerlind and Dal Fabbro, 1978; Murase *et al.*, 1979).

Murase *et al.* (1979) stated that failure of a vegetative tissue must be initiated by one or more of the following phenomena:

1. rupture of the wall of an individual cell;
2. rupture of the membrane enclosing the cytoplasm with release of the contents of the cytoplasm into the cellular mass;
3. separation of the middle lamella.

They considered the initiation of a failure to be of utmost importance because it must precede the critical or ultimate failure of the agricultural product.

Mohsenin (1977) considered the threshold of failure in an apple tissue to be the initial cell rupture in the parenchyma tissue which results from excessive elastic or inelastic deformation, exhibited by a discontinuity in the force-deformation curve called a bioyield point. In the case of a corn kernel, he stated that a break in the endosperm may develop from exceeding the elastic or inelastic deformation of the aleurone layer (outermost thin layer of the endosperm containing oil and protein) causing visible or invisible cracks. Initiation of these cracks could be considered as the threshold of failure in such foods as cereal grains. On the other hand, the failure threshold in a meat tissue may be considered as the stress level at which tearing and separation of connective tissue take place (Mohsenin, 1977).

The mechanisms of failure of axiallv compressed cylindrical specimens of solid food materials were studied by Calzada and Peleg (1978). They stated that two antagonistic mechanisms participate in the compressive large deformation process These are.

1. fracture of structural elements which tends to reduce the overall strength,
2. compaction of original and fractured elements to produce a denser structure which tends to increase the overall strength.

Calzada and Peleg (1978) further explained that at each strain level, these mechanisms could balance one another (giving rise to the linear region of the stress-strain curve) or be dominated by one of them. In a case of dominant fracture mechanism the slope of the stress-strain curve decreases with the strain and an upward convex region appears. If compaction dominates the situation, the slope of the curve increases progressively and an upward concave curve will develop.

2.3 Corn physical and mechanical properties

Because of the various losses and damage to corn due to stalk lodging and mechanical injury during harvesting, manv researchers have investigated the mechanical properties of corn stalk and corn kernel. In contrast, little work has been done in characterizing the mechanical properties of other corn plant components, such as the cob.

2.3.1 Corn stalk

Using procedures suitable for laboratory and field testing Pickett et al. (1969) found average compressive and tensile moduli values of 2379 MPa and 7653 MPa for the cortex of corn stalk They also found the rheological properties of corn stalks to be closely associated with the stage of plant development and the radius of the stalk.

In a study involving dry mature corn, Prince et al (1969a) found the apparent elastic modulus of whole-stalk specimens tested in compression to average 2758 Mega-Pascals (MPa); and that of sections of the cortex tested in tension to average 1724 MPa.

Prince et al. (1969b) tested stalk specimens in bending to determine the effect of perimeter and internode position on the mechanical properties of the stalk material. The modulus of elasticity which averaged 4723 MPa for the stalk specimens was found to be significantly different for different positions of the tested specimens on the stalk perimeter.

Prasad and Gupta (1975) studied the behavior of maize stalk under quasi-static transverse compression using a table Instron testing machine. They found that the ultimate compressive strength of the stalk had a linear relationship with the stalk diameter and was observed to decrease with increase in rate of deformation. They also determined that the modulus of toughness, as well as the ultimate shear strength, of the maize stalk decreased with increase in the rate of deformation and the height of cut from ground level. Prasad and Gupta (1975) determined the modulus of toughness of corn stalk to be 0.084×10^6 N-m/m^3 at 10 cm/min and 0.040×10^6 N-m/m^3 at 50 cm/min. They explained that the effects of rate of deformation on stalk mechanical properties mav be because of the visco-elastic behavior of plant material.

Stalk strength, measured principally as the maximum breaking or crushing force, as did Zuber and Grogan (1961), Thompson (1963), and Pickett (1969), has also been found to be affected by the thickness of stem rind, pith strength, stalk lignification, stalk rotting, plant population, plant height or ear height, soil fertility and corn variety (Hunter and Dalbey, 1937; Krantz and Chandler, 1951, Zuber and Grogan, 1961; Josephson, 1962, Thompson, 1963, Liebhardt and Murdock, 1965; Liebhardt et al., 1968, Pickett et al., 1969, Chang, 1971; Liebhardt and Munson, 1976).

2.3.2 Corn kernel

Kernel strength and kernel damage have been extensively studied because of the obvious economic importance of preserving grain quality.

Zoerb and Hall (1960) determined basic mechanical and rheological properties of individual bean, corn and wheat seeds. Moisture content had the greatest influence on the strength of the seed. Resisting force, elastic modulus and stress all decreased with increasing moisture content.

Bilanski (1966) found that the resistance to impact damage of all the grains he tested (including corn) increased as the moisture content increased. He measured the resistance as the minimum energy required to damage the grain. The resistance was also found by Bilanski (1966) to be dependent on how the kernel was positioned with respect to load.

Shelef and Mohsenin (1969) studied the effect of moisture content on the mechanical properties of yellow dent corn by applying uniaxial compression loads to individual kernels. The loading was applied successively with a cylindrical indenter, parallel plates and a spherical indenter. Three moisture dependent variables were evaluated from the force-deformation relationships, viz: the linear load limit, the apparent elastic modulus and the modulus of deformability. It was found that the values determined for each of these parameters decreased with increase in moisture content of the kernel. Their results further showed that at any given moisture content the values of the apparent elastic modulus and the modulus of deformability were in the same order of magnitude for the cylindrical indenter and the parallel plates. These values, particularly at the lower moisture contents, were considerably higher for the case of the spherical indenter.

Research findings reviewed by Mohsenin (1970) gave the compressive apparent elastic modulus of yellow dent corn as 399 MPa in the vertical position, at kernel moisture content of 15.4% d.b. and loading rate of 0.20-1.17 cm/min. In the flat position, with the germ side down, the reported compressive apparent elastic modulus was 1157 MPa, at moisture content of 12.2% d.b (dry basis) and 0.05 cm/min. loading rate. The corresponding values of the ultimate stress were reported as 33 MPa and 17 MPa.

Balastreire and Herum (1978) studied the relaxation modulus of rectangular slabs of corn kernel endosperm in simple bending. They found that the corn endosperm in bending may be represented by a generalized Maxwell model composed of a spring and five Maxwell elements in parallel.

The dependence of corn stalk and corn kernel mechanical properties on moisture content and rate of loading is a typical biomaterial mechanical behavior. Finney (1969) stated that the modulus of elasticity of plant tissues should be influenced by at least three factors: the rigidity of cell walls, the stiffness of the intercellular bonding agents and the turgidity within the cells. He added that, structurally, intercellular adhesion or cementing substances and cell wall strength are factors quite likely to influence toughness of agricultural products. Fletcher (1971) noted that the dependence of mechanical properties of solid food materials on the rate of loading is one reason for the belief that such materials are viscoelastic.

2.3.3 Corn cob

Being usually discarded after corn shelling, the corn cob has not attracted much interest, its role during corn shelling notwithstanding. Most literature dealt with the study of the mechanical properties of the corn cob in a rather haphazard manner The chief concern has been usually kernel properties and quality, while the cob is only treated as a subsidiary problem.

While the importance of cob strength in relation to the mechanization of corn harvesting and drying is not yet fully recognized, the influences of cob moisture content on these processes have been well established (Burrough and Harbage, 1953, Hopkins and Pickard, 1953; Hunt, 1964; Johnson and Lamp, 1966, Agnes, 1968, Hall and Johnson, 1970; Hamdy et al., 1977)

Hunt (1964) pointed out that for small grains kernel moisture is the prime indicator for timing the harvest, but in corn harvesting the stalk and cob moisture contents must also be considered. Johnson and Lamp (1966) emphasized that the research findings of some investigators showed that kernel moisture does not correlate as well to cylinder loss as does cob moisture.

Besides the above references to cob moisture content, a literature search gave limited and inconsistent information on cob strength and cob mechanical properties.

In 1926, Winter reported the breaking strength of corn cob as "the relative strength per unit area of the ligneous part of the cob."

The relative strength was determined as the maximum force to break a four-inch long cob section loaded as a simple beam. Using this strength parameter, Winter (1926) found a high correlation between the average breaking strength of seed-ear cobs and the yields of the resulting corn plants.

Waelti and Buchele (1967) determined cob strength as the maximum compressive force of a one-inch long cob section with load applied radially. The initial cob diameter was taken as the distance between the loading plates at a ten-pound load during the cob strength test. At this force, the cob "glumes" were crushed and laid flat against the cob surface and cob deflection was still at a minimum. An average ultimate strain of 0.379 mm/mm was reported. Cob strength was found by Waelti and Buchele (1967) to be among the most important crop properties affecting kernel mechanical damage in a combine threshing cylinder. Low kernel damage was associated with low detachment force, high kernel strength, low kernel deformation, low cob strength.

Another measure of cob strength reported in more recent studies is cob stiffness, defined as the slope of the upper portion of the force-deformation curve of corn cob in radial compression per unit length of the tested cob sample. Hamdy et al. (1977) found cob stiffness to increase with increase in drying temperature but decreased with increase in moisture content.

None of the above studies included an analysis of cob failure. The first reported attempt to characterize the mode of failure under external load was made by Johnson _et al_. (1969). They considered the cob under radial loading as a hollow thin elastic cylinder subjected to opposite forces uniformly distributed along its length. Classical engineering mechanics for the deflection of a ring (Timoshenko, 1956) was then considered applicable to the corn cob radial deformation. In all their tests, Johnson _et al_. (1969) observed that "the cobs failed piece by piece longitudinally along their planes of symmetry into four quadrants." The surface of failure was found to be irregular.

More recently, Brandini _et al_ (1978) applied the finite element analysis technique to the problem of cob deformation in radial compression. They also considered the cob as a hollow elastic cylinder. The corn cob was simulated as a single material.

Theoretical consideration of the corn cob as a ring or a hollow elastic cylinder is obviously an over-simplification of the complex structure of cob.

2.4 Structure of corn cob

Ordinarily, a corn cob may be considered as the composite of all the structure that remains after the kernels have been removed from the corn ear.

Morphological analysis of the corn cob by Sehgal and Brown (1965) reveals that it is a complex structure composed of glumes, lemmas and paleas, rachillae, glume cushions, rachis nodes and internodes, prophylls, inter-row tissues, inner and outer vascular system, and a soft, spongy, parenchymatous tissue in the center known as the pith. These morphological details of the cob were described by Laubergayer (1949) and Nickerson (1954).

The framework of the cob is composed of numerous clearly defined segments disposed in longitudinal plane. Each segment has two vascular bundles which pass through one or two radial canals in the woody framework. Planes of cleavage occur between the segments, both longitudinal and transverse to the axis of the cob. The transverse plane corresponds to the interval between the weak, diagonal ribs. The longitudinal plane of cleavage is usually zig-zag, and no other line of weakness transverses the cob longitudinally (Reeves, 1950).

The longitudinal rows of cupolate rachis segments are fastened with one another by a "cementing" substance, the inter-row tissue, in a manner simulating zipper fasteners (Sehgal and Brown, 1965). When force is applied on the top, the cob splits or opens like a zipper in the inter-row region. The woody ring of the cob is strengthened and supported by inner and outer vascular system. The bundles have longitudinal course from the base to the apex of the cob and are intra- or inter-row in position.

The pith also shows indefinite transverse planes of cleavage and frequently breaks transversely and longitudinally into segments. It is uniformly composed of parenchyma, except for a few vascular bundles running longitudinally in the region near its periphery (Reeves, 1950) Nickerson (1954) stated that the pith region of cob is generally free of vascular tissue.

The connection between the woody zone and the pith zone is somewhat loose in the mature dry cob as can easily be demonstrated by the ease with which the pith can be removed from the center of the cob.

Four distinct zones can therefore be structurally identified in the cross-section of a corn cob. Sehgal and Brown (1965) described these zones as follows:

1. fine chaff, consisting of lemmas and paleas, upper portions of the first and second glumes,
2. coarse chaff, consisting of the basal portions of the first and second glumes, rachillae base, and glume cushions or the rudimentary leaves;
3. woody ring or mid-cob, consisting of rachis nodes and internodes, inner and outer vascular system; and
4. pith.

In the present study, cob structure is considered to be composed of three distinct macro-structural zones or components. With reference to Figure 3, these are:

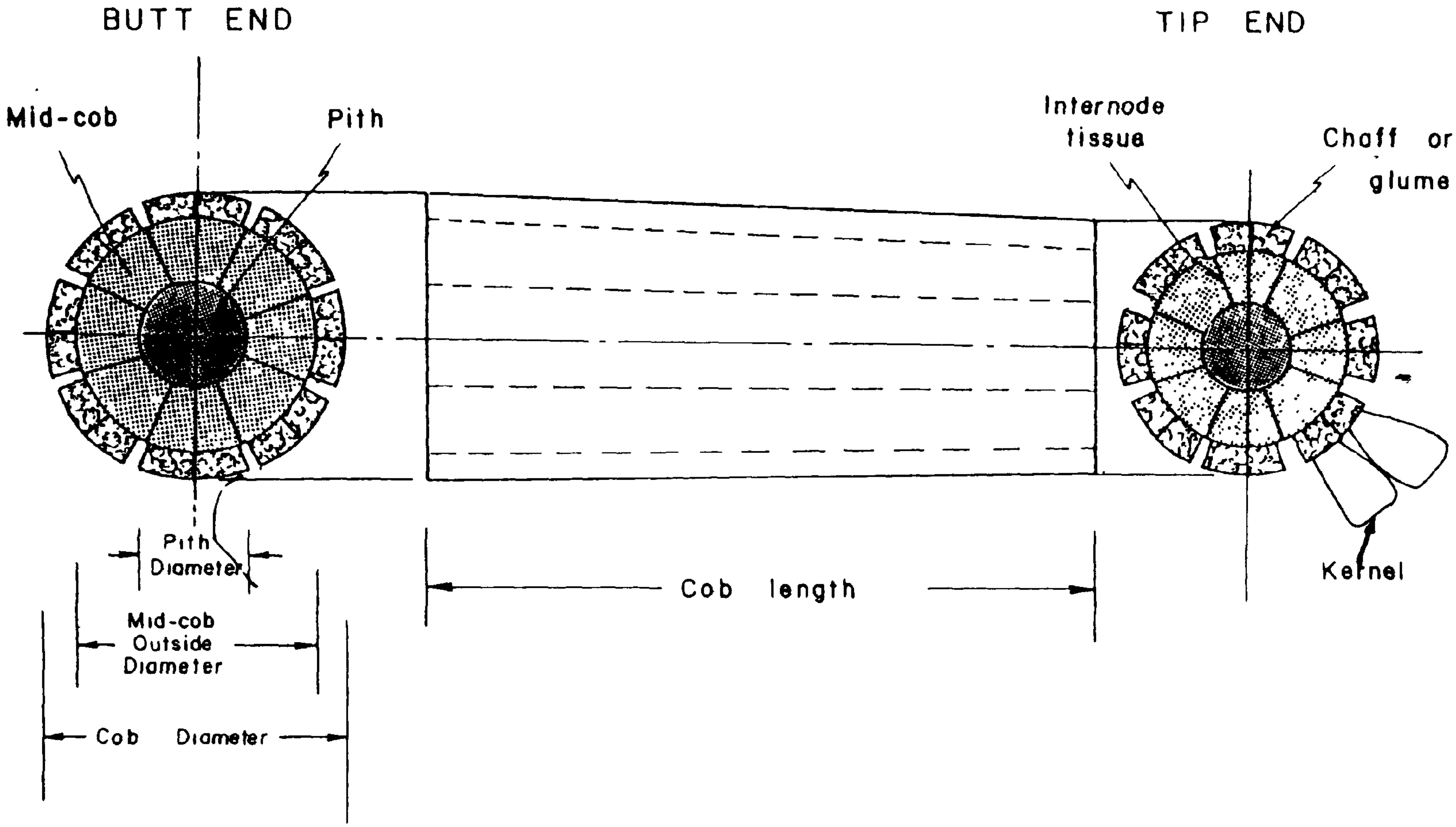


Figure 3 Simplified structure of the corn cob

1. the glume or fine chaff;
2. the mid-cob, including the glume base or the coarse chaff; and
3. the pith.

From the preceding literature review, one may conclude as follows:

1. Corn cob physical, morphological and mechanical properties affect corn combine performance.
2. Corn cob moisture content has a profound effect on both cob breakage and kernel damage.
3. Information on cob mechanical properties and strength is very limited.
4. Corn cob consists of three distinct macro-structural components.

CHAPTER III

REVIEW OF ELASTIC CONTACT THEORY AND ITS APPLICATION TO RADIAL COMPRESSION OF CORN COB COMPOSITE

3.1 General

In this chapter, the theoretical developments leading to the expressions to be adopted in this study for calculating the apparent elastic modulus and the maximum contact stress for a corn cob composite radially compressed between two parallel steel plates are presented and the assumptions in this approach discussed. The stress and strain distributions developed within a radially compressed corn cob composite are not considered because of the complex nature of contact stress-deformation, the composite nature of corn cob, the inelastic and anisotropic behavior of the cob under load (refer to Figure 1).

The primary objective of this study is to determine theoretical and empirical expressions for characterizing the mechanical properties of corn cob using a standard experimental technique. It is hoped that knowledge of cob mechanical properties will enhance subsequent studies of cob failure with respect to corn shelling in a combine cylinder.

3.2 Linear elastic contact theory

When two elastic bodies are in contact under the action of an externally applied load, local compressive stresses are set up, and deformation of the surfaces occurs. In general, the contact stresses so developed may be quite high, even for a relatively small applied load, owing to the very small area of contact.

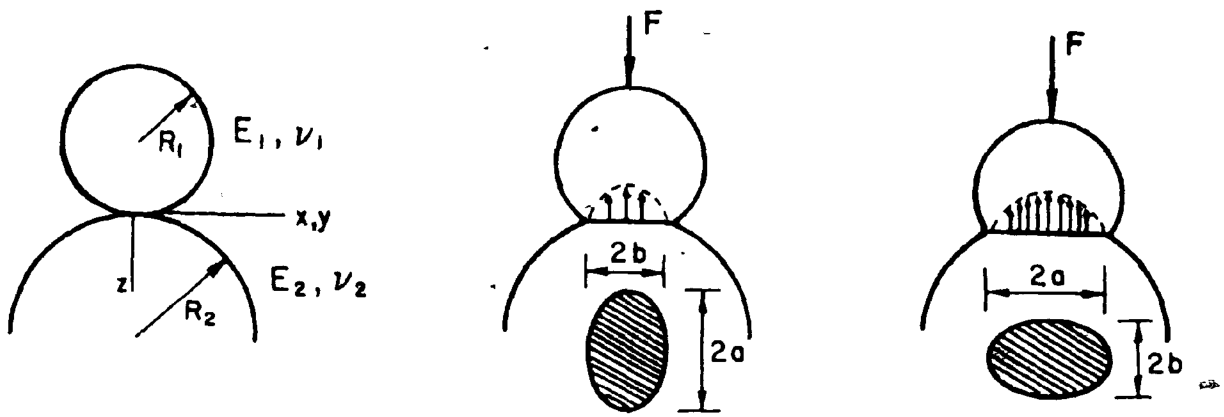
Contact problems are essentially non-linear. Nevertheless, the classical solution for the local stresses and deformations which occur when two bodies are pressed together was developed by Hertz in 1881, based on the linear theory of elasticity.

The two principal types of Hertz elastic contact are illustrated in Figures 4 (a) and (b). Figure 4 (a) represents the contact between two spherical bodies. Figure 4 (b) describes the contact of two cylindrical bodies having radii of curvature R_1 and R_2 near the zone of contact and oriented so that their axes are parallel. The Hertz theory states that the contact area is elliptical for the first type of contact, while it is rectangular for the second type. The latter is of interest in this study.

The normal pressure distribution, q, at the surface of contact of two cylindrical bodies pressed together is, according to the Hertz theory:

$$q = q_o[1 - (x/b)^2]^{1/2} \qquad [1]$$

(a) Contact between two spherical bodies



(b) Contact between two cylindrical bodies

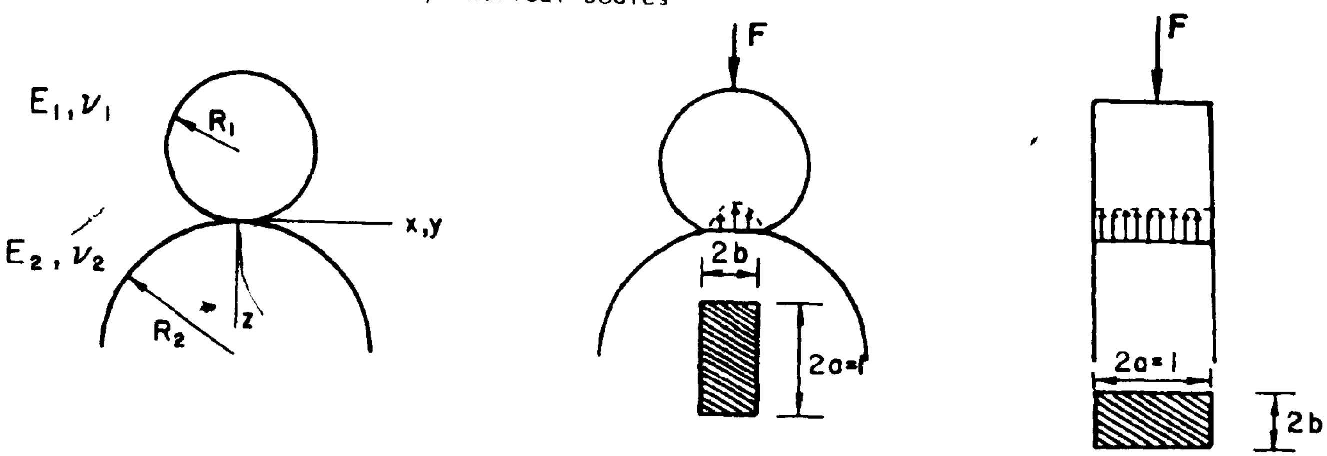


Figure 4. Contact between two elastic bodies (illustrating the area of contact and the distribution of contact pressure)

where

q_o = maximum contact pressure

b = half width of the contact area

x = distance from the center of contact along x-axis (Figure 4b).

The maximum contact pressure, q_o, which occurs at the center of the contact surface is given, according to the Hertz theory, as:

$$q_o = 2F/\Pi \ell b \qquad [2]$$

where

F = applied normal load

ℓ = length of cylindrical body in the y direction (Figure 4b).

For the case of the contact of two long elastic cylinders, it can be shown (Poritsky, 1950; Timoshenko and Goodier, 1970) that the half contact width, b, is given by the expression:

$$b^2 = \frac{4F[((1 - \nu_1^2)/E_1) + ((1 - \nu_2^2)/E_2)]}{\Pi \ell[(1/R_1) + (1/R_2)]} \qquad [3]$$

where, with reference to Figure 4b:

E = elastic modulus

ν = Poisson's ratio

R = radius of curvature

and subscripts 1 and 2 refer to the cylinders in contact, and other symbols as defined previously.

Thus, if the elastic constants, E_1, E_2, ν_1 and ν_2, of the two cylinders are known, b can be calculated from equation [3] and then the maximum contact pressure, q_o, can be determined from equation [2]. Unlike for engineering materials, experimental determination of the elastic constants of biological materials is quite difficult and imprecise because of their relatively complex structural composition. Estimation of the elastic constants of such materials from rectangular slabs or core specimens of convenient shapes is not always reliable Thus, in this study, the apparent elastic modulus of corn cob is determined by testing composite sections of the cob.

3.3 Apparent elastic modulus of a radially compressed cylindrical biological material

On the assumption that their response behavior is essentially that of a linear isotropic material for small deformations, the Hertz elastic contact theory has been applied to cylindrical biological materials (Snobar, 1973; Segerlind et al., 1976; Sherif, 1976; Sherif et al., 1976). The major steps in the derivation of an expression for the apparent elastic modulus of a radially compressed cylinder composed of biological material are presented in this section.

Poritsky (1950) developed analytic equations for determining the two-dimensional deflection and stresses of two cylindrical elastic bodies in contact under a normal load. His mathematical analysis is rather too involved for inclusion in this review. Identical solutions were independently developed by Liu (1950) and Timoshenko and Goodier

(1970). The mathematical analyses in both studies are equally too complicated for any brief presentation.

With reference to Figure 5, Poritsky's solution for the normal deformation, w, at the surface of contact between two cylinders subjected to normal load is:

$$w = 2[((1 - \nu_1^2)/\Pi E_1) + ((1 - \nu_2^2)/\Pi E_2)][\int_{-b}^{b} q(s)\ln(\frac{r}{R})ds] + Cx^2 \qquad [4]$$

where, with reference to Figure 5,

q(s) = pressure at a point due to the applied load

r = the distance between an infinitesimal area at s and the point of observation, x, $r = |x - s|$

C = a constant, the magnitude of which depends on the principal curvatures of the surface of contact

and other symbols are as previously defined. The constant, C, is expressed as:

$$C = 1/2\ R_1 + 1/2\ R_2 \qquad [5]$$

where R_1 and R_2 are as defined previously.

In the case of a cylinder compressed between two parallel plates, Figure 6, it is usual (Wilson, 1927; Thomas and Hoersch, 1930; Lubkin, 1962; Timoshenko and Goodier, 1970) to consider each of the plates to have an infinitely large radius of curvature, that is,

$$R_2 = \infty \qquad [6]$$

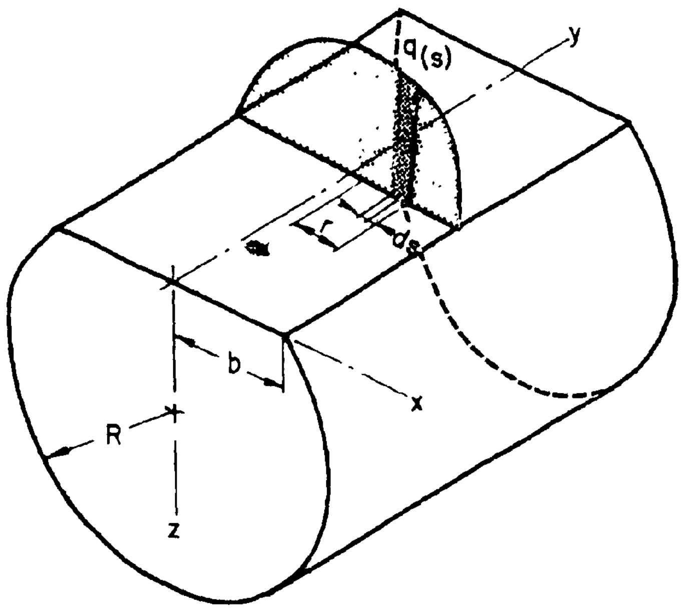


Figure 5. Three dimensional representation of an elastic cylinder subjected to a distributed normal load (from Sherif et al., 1976)

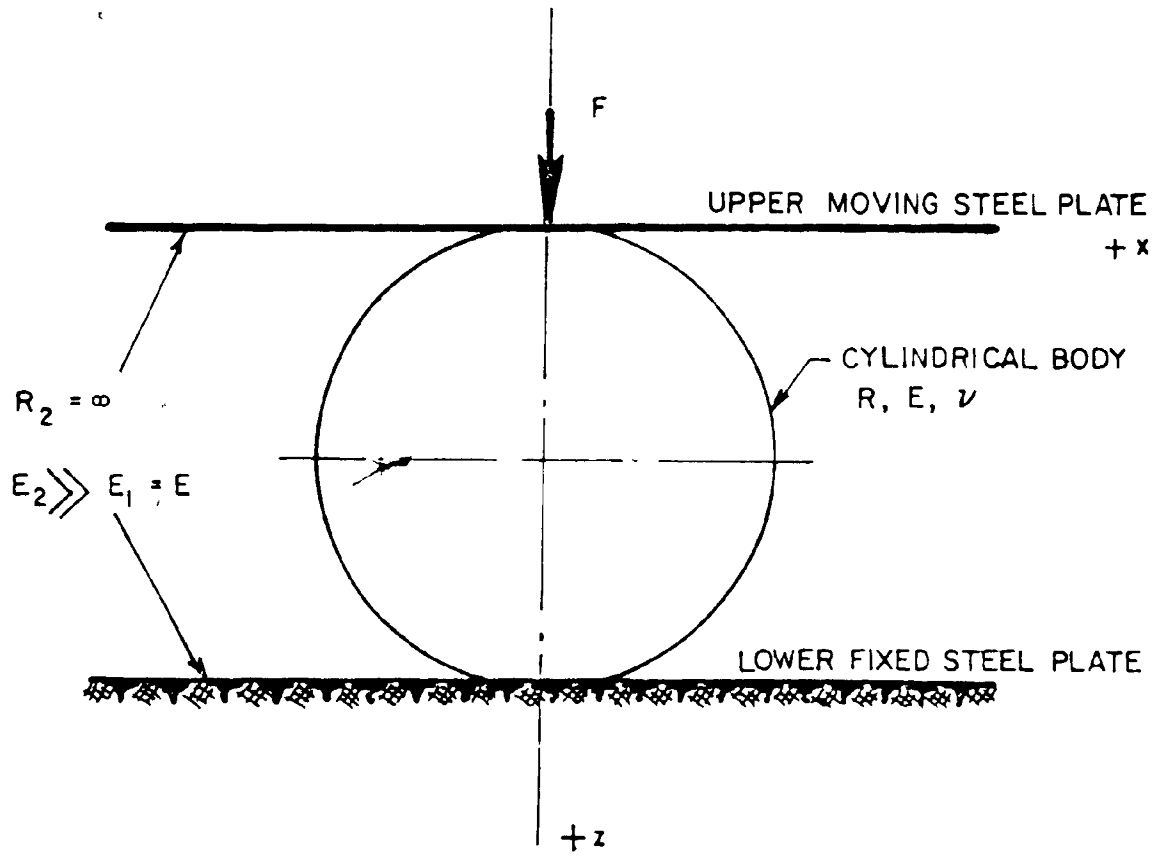


Figure 6. Cylinder compressed between two parallel flat steel plates

and hence,

$$C = 1/2 \; R_1 \qquad [7]$$

If, also, the compressed cylinder is composed of a biological material with an apparent elastic modulus, $E = E_1$, considered very small compared with the elastic modulus of the steel plates, E_2, then,

$$(1 - \nu_2^2)/\Pi E_2 << (1 - \nu_1^2)/\Pi E_1 = (1 - \nu^2)/\Pi E \qquad [8]$$

since $E_2 >> E_1$ and ν_2 is in the same order of magnitude as ν_1 (now replaced by ν, Poisson's ratio of the biological cylindrical material). The range of values of Poisson's ratio is

$$-1.0 \leq \nu_1, \nu_2 \leq 0.5 \qquad [9]$$

If it is further assumed that the pressure distribution on either surface of contact of the compressed cylinder is according to the Hertz theory as expressed in equation [1], then,

$$q(s) = [2F/\Pi b^2 \ell][b^2 - s^2]^{1/2} \text{ for } |s|<b \qquad [10]$$

Employing these simplifying assumptions, Sherif et al (1976) integrated equation [4] and obtained a more manageable expression for the z-component of deformation at the surface of contact, viz.,

$$w = [\frac{2F(1 - \nu^2)}{\Pi \ell E}][\ln(b/2R) - 1/2 - (x/b)^2] + x^2/2R \qquad [11]$$

where

E = apparent elastic modulus of the cylindrical biological material

ν = Poisson's ratio of the cylindrical biological material

R = cross-sectional radius of the cylindrical biological material

and other symbols are as defined previously.

Equating the coefficients of the constant terms in equation [11] will result in

$$w = [2F(1 - \nu^2)/\pi \ell E][\ln(b/2R) - 1/2] \qquad [12]$$

Similarly, equating the coefficients of x^2 will result in

$$b^2 = 4FR(1 - \nu^2)/\pi \ell E \qquad [13]$$

or

$$E = 4FR(1 - \nu^2)/\pi \ell b^2 \qquad [14]$$

Equation [13] or [14] can be used to calculate b if E is known or to determine E if b can be directly measured during test. Otherwise, a second expression is needed.

Sherif et al. (1976) introduced a term, Z, defined as the ratio of the original radius of the cylindrical body to half contact width, thus,

$$Z = R/b \qquad [15]$$

Noting that D = 2w, where D is the total vertical deformation of the radially compressed cylindrical body and w is the z-component of deformation at the surface of contact; eliminating the common term,

$[F(1 - \nu^2)/\Pi \ell E]$, in equations [12] and [13], and replacing b^2 with R^2/Z^2 from equation [15] will yield the additional desired expression as

$$[D/2R] = [1/(2Z^2)][\ln(2Z) + 1/2] \qquad [16]$$

where all the symbols are as defined previously.

Z in equation [16] can be estimated from the table produced by Sherif (1976) or that by Sherif et al. (1976) using the experimentally determined ratio, D/2R. Otherwise, equation [16] will have to be solved by trial and error procedure or by Newton's method as described by Conte (1965).

A validation of Poritsky's solution, equation [4], and those of the subsequent equations from it, equations [11] to [16], can easily be checked by noting that equation [13] is identical to equation [3] for $R_2 = \infty$ and $E_2 >> E_1$. However, experimental verification of the simplifying assumptions introduced in applying Poritsky's solution to biological cylindrical materials was not conducted by Sherif et al. (1976). They used plexiglass cylinder in their test instead of a biological or agricultural product. Nonetheless, realistic values of the apparent elastic moduli of cylindrical samples of potato and apples were determined by Sherif (1976) using the approach outlined here. Snobar (1973) had earlier applied a similar approach in determining the apparent elastic modulus of cylindrical samples of carrot.

The total vertical deformation of the radially compressed cylindrical body, D, consists of two components. These are the elastic component, De, and the plastic component, Dp, as illustrated in Figure 7. The elastic component of the total deformation is determined from the equation,

$$De = \beta D/100 \qquad [17]$$

where

β = degree of elasticity in percentage, as defined in Figure 7, and

D is as defined previously.

To limit the analysis of the force-deformation curve of a cylindrical biological material compressed between two parallel steel plates to the elastic range, D in equation [16] must be replaced by De in equation [17].

3.4 Basic assumptions underlining the Hertz theory

The following basic assumptions underline the Hertz linear elastic contact theory (Radzimovsky, 1953):

1. The bodies in contact are isotropic.
2. The proportional limits of the materials are not exceeded.
3. The loading acts perpendicular to the surface.
4. The dimensions of the compressed areas are small when compared with the whole surface of the bodies pressed together.

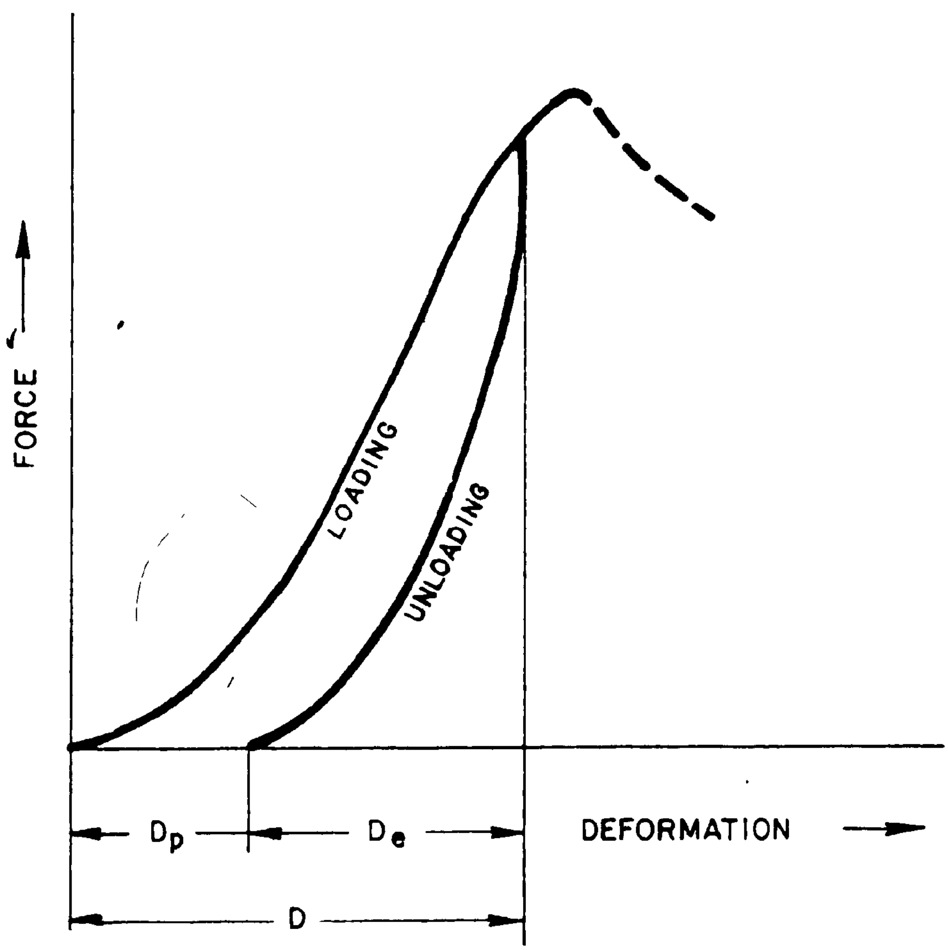


Figure 7. Generalized loading and unloading curve of an agricultural product in compression.

D = total deformation

D_e = elastic or recoverable deformation

D_p = plastic or residual deformation

β = degree of elasticity in percent

= $100\ D_e/D$

[Mohsenin, 1970, page 96]

5. The radii of curvature of the contact areas are very large compared with the dimensions of these areas.

However, based on several theoretical and experimental extensions of the Hertz analysis, Lubkin (1962) stated that the Hertz theory can be checked within a fraction of a per cent, as long as its hypothesis holds; that is, as long as the solid bodies remain linearly elastic and the contact area is small in size compared with the radii of curvature. Beyond the proportional limit, some of the relations predicted by the theory continue to hold approximately, but the divergence increases with the degree of departure from linear elasticity (Thomas and Hoersch, 1930).

In applying the Hertz theory to spherical biological materials, Mohsenin (1970) examined the fundamental assumptions made by Hertz in developing this theory. Mohsenin (1970) stated that it has been demonstrated that Hooke's law holds approximately for several agricultural products at very low levels of load. Notwithstanding, the fact that agricultural products are heterogeneous, anisotropic, and exhibit large deformations under load raises considerable doubts as to the validity of applying elastic contact theory to such materials. In the absence of any other appropriate theory for the characterization of the mechanical properties of agricultural products tested intact in compression, the Hertz theory still remains the basis for interpreting experimental force-deformation data. To minimize errors due to the failure of agricultural products to satisfy the Hertz basic assumptions, the application of this theory must be limited to the linear elastic stage of the force-deformation curve (described in detail in Chapter V for the corn cob). The use of the elastic component of deformation instead of the total deformation, will minimize any errors in the calculated values of the apparent elastic modulus and maximum contact pressure due to large deformation. As a further check on the applicability of the Hertz theory in the particular case of radial compression of corn cob composite, experiments will be described in Chapter VI which compare theoretical estimates of b with directly measured values of b for some corn cob samples.

From the foregoing, it is hereby proposed that, in radial compression:

1. the apparent elastic modulus of corn cob, E, can be estimated from equation [14] to equation [17], where F, D, β and ν are experimentally determined, and

2. knowing the value of b from equation [15], the crushing strength of corn cob composite, σ_c, defined as the maximum contact stress at the center of the deformed surface area of the cob, is estimated from equation [2].

CHAPTER IV

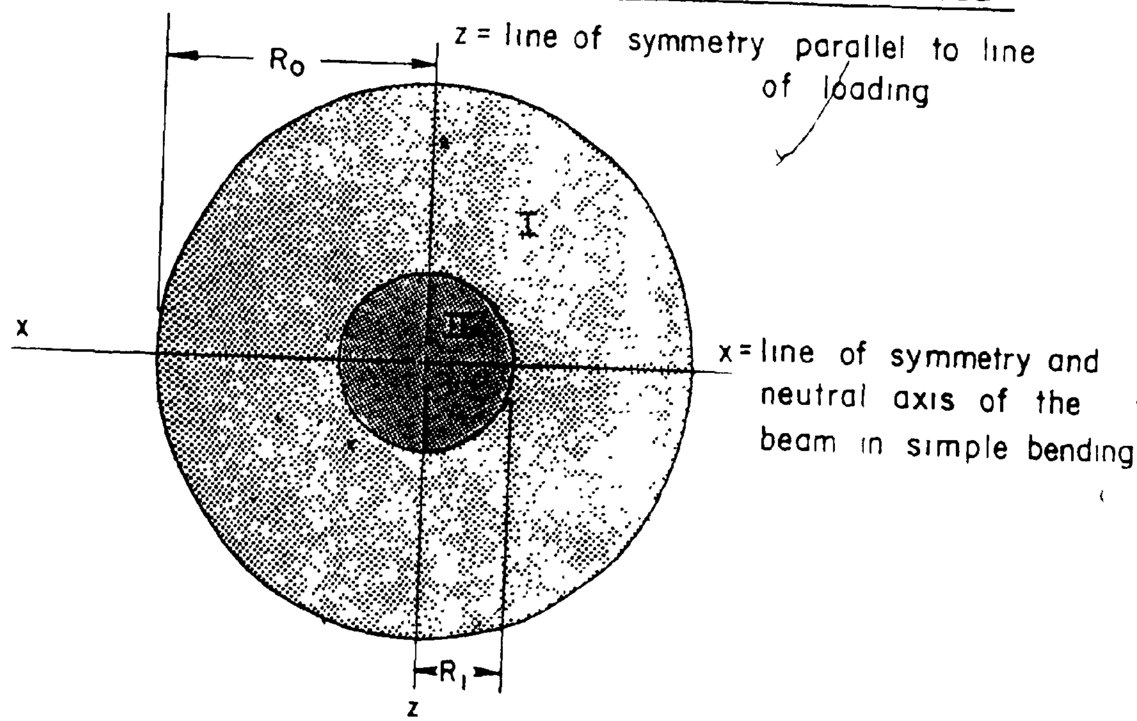
THEORETICAL CONSIDERATIONS IN SIMPLE BENDING

4.1 Transformation of cob's composite section

The corn cob is a tapered cylindrical composite of three different materials. Its cross-section is not exactly circular but could be considered approximately so. The constituent materials of the corn cob are not homogeneous. However, homogeneity could be assumed for each of the three major components of the corn cob. Another geometric simplification that might be reasonably made is to disregard the outermost chaffy zone, the glume.

In this analysis, therefore, the cob is considered as a tapered right circular cylinder of two homogeneous materials (the soft pith at the center and the woody mid-cob on the outside). Two modifications are thus needed in the simple beam formula in order to calculate the maximum bending stress in the cob under a simple bending load.

Consider Figure 8a, which shows the cob cross-section as consisting of two different materials, I and II. The moment of inertia along the xx-axis for the outer material (annular section) is:



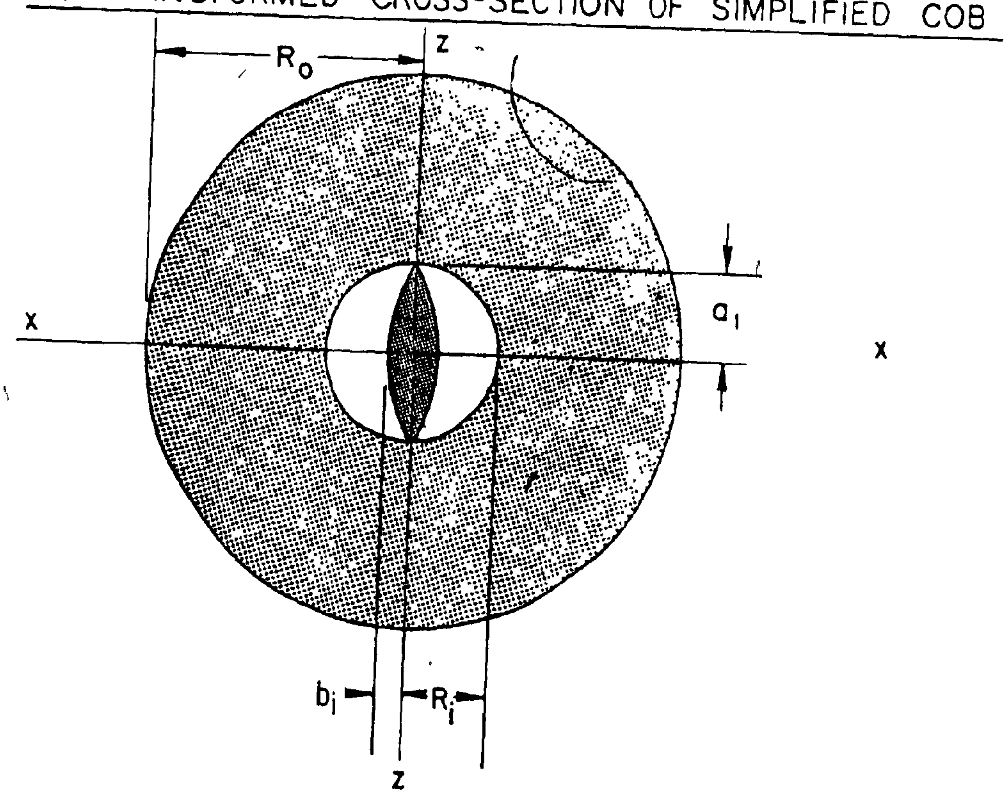


Figure 8. Determination of the equivalent moment of inertia of corn cob composite

$$I_1 = (\Pi/4)(R_o^4 - R_i^4) \quad [18]$$

where

I_1 = moment of inertia of material I

R_o = radius of cob composite with the glumes compressed

R_i = radius of the cob pith

The moment of inertia along the xx-axis for the inner material (circular solid section) is:

$$I_2 = \Pi R_i^4/4 \quad [19]$$

Popov (1968) outlined the procedure for the transformation of a composite section of two different materials into one of a single homogeneous equivalent section. If the equivalent section is desired in material I, then the dimensions corresponding to material I do not change while the dimensions of material II parallel to the neutral axis will be changed by multiplying with the ratio $m = E_2/E_1$, where E_2 and E_1 are the elastic moduli of materials II and I, respectively.

Thus, for the original circular section of Figure 8a, its equivalent section is easily determined as shown in Figure 8b once E_2 and E_1 are known. The modulus of elasticity of the transformed section is equal to that of material I.

Unless the cross-section is symmetrical, the centroid of the transformed cross-section will not coincide with that of the original section (Shanley, 1957). In the case of corn cob, the cross-section is symmetrical and, hence, the neutral axis is still xx in the transformed domain.

With reference to Figure 8b and applying the procedure indicated above, the moment of inertia of the transformed cross-section, Ie, along the neutral axis xx is given by

$$Ie = (\Pi/4)(R_o^4 - R_i^4) + (\Pi/4)(b_i a_i^3) \qquad [20]$$

where, from Figure 8b: $a_i = R_i$; $b_i = mR_i$ and $m = E_2/E_1$. Note that the first term in the right-hand side of equation [20] is from equation [18], while the second term, $\Pi b_i a_i^3/4$, is the moment of inertia of the transformed section of material II which is considered elliptical in shape.

Substituting the values of a_i and b_i in equation [20] will result to

$$Ie = (\Pi/4)[R_o^4 - (R_i^4(1 - m))] \qquad [21]$$

The above transformation of section can be checked with the formula for the equivalent moment of inertia of the cross-section transformed from a composite beam of two materials as given by Duggan (1964) and Ryder (1969). The formula is

$$Ie = I_1 + mI_2 \qquad [22]$$

using the same symbol as before. Substituting for I_1 and I_2 from [18] and [19] in equation [22] will give the same result as expressed in equation [21].

4.2 Maximum bending stress for cob composite

From any book on strength of materials, the maximum bending stress for a simple circular beam freely supported at both ends and loaded at mid-span is given by

$$\sigma max = Mc/I \qquad [23]$$

where

M = maximum bending moment

I = moment of inertia of beam

c = distance of the extreme fibres from the neutral axis.

Figure 9 illustrates the simple bending of a whole corn cob composite. To determine the maximum bending stress for the cob, equation [23] must be modified to account for the tapered structure and composite nature of the corn cob.

The equivalent moment of inertia of the cob composite is given by equation [21]. With reference to Figure 9, "c" in equation [23] can be shown to be equal to $(d_1 + d_2)/4$, where d_1 and d_2 are, respectively, the average diameter of the cob composite at the tip and butt ends.

Applying the above modifications to equation [23], the expression for cob strength in simple bending is presented as follows:

$$\sigma_b = (64\ F_b L)/[\Pi(d_1 + d_2)^3(1 - f^4(1 - m))] \qquad [24]$$

where

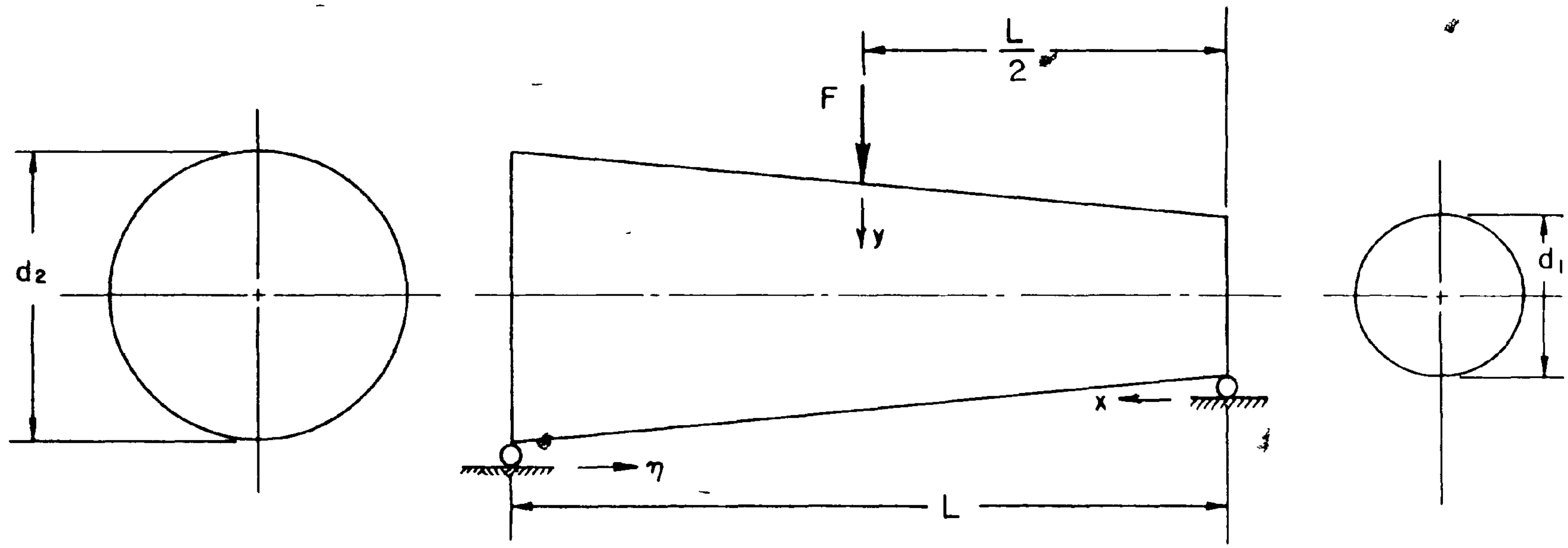


Figure 9. Simple bending of a whole corn cob

F_b = maximum force to break the cob composite

L = effective length of cob or loading span

f = R_i/R_o

Equation [24] can easily be seen to be correct by substituting the values, $d_1 = d_2 = d$; $f = 1$ and $m = 1$, in it to obtain the simple beam solution:

$$\sigma_{max} = 8F_bL/\Pi d^3 = Mc/I \qquad [25]$$

4.3 <u>Elastic modulus of a tapered beam</u>

Schroder <u>et al</u>. (1973) derived a deflection formula for a tapered beam with uniaxial modulus based on the simplified Euler deflection equation. The latter is

$$EI(x)d^2y/dx^2 = -M \qquad [26]$$

where

E = Young's modulus

I(x) = moment of inertia of the cross-section as a function of x

M = bending moment

y = deflection, Figure 9

x = coordinate distance, Figure 9.

For the case of simple bending, the moment on either side of the load can be expressed as

$$M(x) = Fx/2 \qquad [27]$$

and $M(\eta) = F\eta/2$ [28]

where η is defined in Figure 9.

Using equations [27] and [28] in equation [26], then

$$EI(x)d^2y/dx^2 = -Fx/2 \quad [29]$$

and $$EI(\eta)d^2y/d\eta^2 = -F\eta/2 \quad [30]$$

Using the proper expressions for the moment of inertia of a linear tapered homogeneous beam of circular cross-section (Schroder et al., 1973), equations [29] and [30] can be transformed to

$$d^2y/dx^2 = 64Fx/[2\Pi E[d_1 + (d_2 - d_1)x/L]^4] \quad [31]$$

and $$d^2y/d\eta^2 = 64F\eta/[2\Pi E[d_1 - (d_2 - d_1)\eta/L]^4] \quad [32]$$

For the boundary conditions:

$$\begin{aligned} y(x) &= y(o) = 0 \\ y(\eta) &= y(o) = 0 \\ dy/dx &= -dy/d\eta \end{aligned} \quad [33]$$

Schroder et al. (1973) gave the following final solution for the deflection of the tapered beam under simple bending

$$y = 8FL^3C/\Pi E \quad [34]$$

where

F = concentrated load applied at the mid-span of beam

C = correction factor for beam tapering

and other terms are as defined before. The correction factor for beam tapering, C, is given in Schroder et al. (1973) as

$$C = 2[C_1/d_2^4 + C_2/d_1^4] - [C_3/d_2^4 + C_4/d_1^4] \qquad [35]$$

where

$$C_1 = \frac{1}{48} + \frac{K_1}{48} + \frac{K_1^2}{64} + \frac{K_1^3}{96} + \frac{5K_1^4}{767} + \frac{K_1^5}{256} \qquad [36]$$

$$C_2 = \frac{1}{48} - \frac{K_2}{48} + \frac{K_2^2}{64} - \frac{K_2^3}{96} + \frac{5K_2^4}{767} - \frac{K_2^5}{256} \qquad [37]$$

$$C_3 = \frac{1}{8} + \frac{K_1}{6} + \frac{5K_1^2}{32} + \frac{K_1^3}{8} + \frac{35K_1^4}{384} + \frac{K_1^5}{16} \qquad [38]$$

$$C_4 = \frac{1}{8} - \frac{K_2}{6} + \frac{5K_2^2}{32} - \frac{K_2^3}{8} + \frac{35K_2^4}{384} - \frac{K_2^5}{16} \qquad [39]$$

$$K_1 = (d_2 - d_1)/d_2 \qquad [40]$$

$$K_2 = (d_2 - d_1)/d_1 \qquad [41]$$

and d_2 and d_1 are defined in Figure 9.

In applying the above results, originally derived by Schroder et al. (1973), to the corn cob problem in simple bending, it is to be noted that the theoretical implications of the composite nature of the corn cob have not been considered. Thus the elastic modulus of corn cob determined from the deflection formula of a tapered homogeneous material, should be considered as only an estimate. Equation [34] can be re-written as

$$E_b = 8\ FL^3C/\Pi De \qquad [42]$$

where

E_b = apparent elastic modulus of corn cob under a simple bending load

De = elastic component of total deflection at mid-span, similar to that defined in equation [17] for radial compression

and other terms are as defined previously.

CHAPTER V

EMPIRICAL ANALYSIS IN RADIAL COMPRESSION

5.1 Nature of force-deformation (f-d) curve

Derivation of an empirical equation to represent the force-deformation curve of the corn cob composite will be useful in obtaining an expression for calculating cob modulus of toughness. Traditional methods of determining this material property by direct measurement of the area under the f-d curve are tedious and imprecise. Although integrating devices are commercially available for attachment to testing machines with f-d plot capability (as used by Paulsen, 1978), such a facility is not readily available to many researchers.

As observed from 1977 and 1978 laboratory tests with 3 cm-long cylindrical sections of corn cob composite involving more than seven varieties of corn, the rupture point of failure of corn cob composite under radial compression is initiated by the appearance of a crack at the center of the cob pith. The crack is then propagated vertically, simultaneously in both upward and downward directions, first through the pith zone and subsequently into the mid-cob. If compressed further, the cob eventually splits into two halves along the vertical plane of symmetry.

In general, the force-deformation behavior of a radially compressed corn cob composite involves five distinct stages as illustrated in Figure 10. These are:

1. the transient stage, during which the outermost chaffy material covering the cob composite, the glume, is flattened with very little cob resistance. This behavior is non-linear and non-elastic.
2. the apparent elastic stage, which is the primary resistance to deformation stage of the cob in radial compression. The behavior is apparently linear elastic. It terminates with the appearance of a crack at the center of the pith. This is usually a brittle-like failure.
3. the dissipative stage, which is the very short period when the crack is propagated through the pith zone. It is characterized on the f-d curve by a sudden drop in the force and with very little deformation. This stage ends when the force starts to increase again.
4. the plastic stage, which is a secondary resistance to deformation stage of the partially failed cob. The f-d behavior during this period is rather more difficult to explain and much more inconsistent than the preceding stages. This stage ends with the failure of the material in an apparently ductile manner.

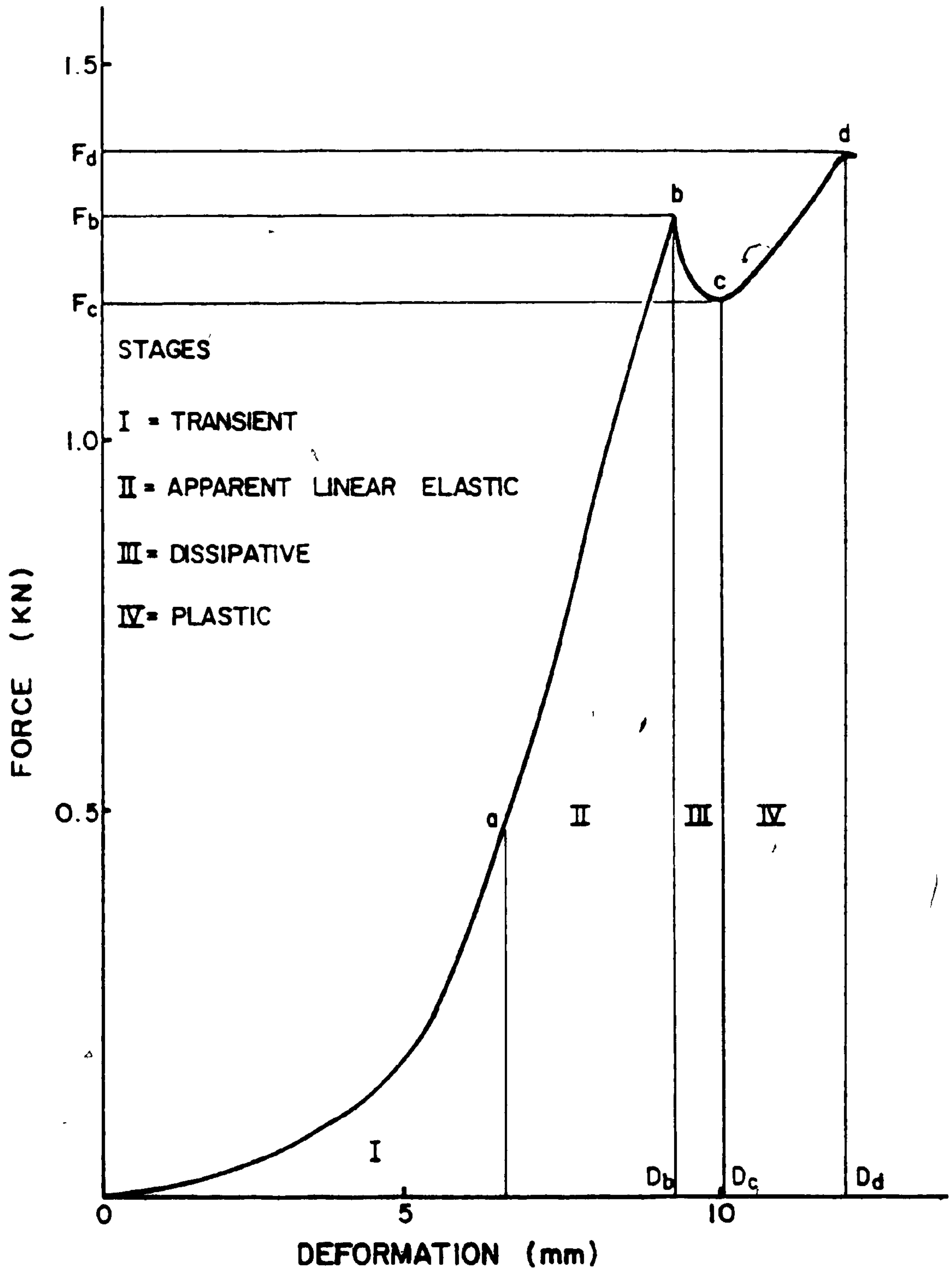


Figure 10. Nature of the force-deformation curve of corn cob in radial compression

5. the ultimate failure stage, when the cob splits into two halves.

From scrutiny of the many f-d curves obtained by radially compressing 3 cm-long cob samples with the Instron testing machine at low rates of loading (0.5 to 3 cm/min), the curves can be categorized into three types, as illustrated in Figure 11. The important difference is in the relative magnitude of the force to crack the pith, F_b, and that to fail the mid-cob, F_d.

However, for the three varieties tested in 1977, it was found that the average values of F_b and F_d were not much different. Moreover, for all the three varieties tested and for all the three test dates, the deformation at mid-cob failure, D_d, is only very slightly greater than the deformation at pith cracking, D_b. Thus, in this thesis, the analysis of the f-d curves of corn cob compressed radially is limited to curve Oab in Figure 10. Pith cracking is, therefore, considered as the critical failure phenomenon. The dissipative, plastic and ultimate failure stages are not considered any further.

5.2 Empirical representation of f-d curve

Liebowitz and Eftis (1971), following the work of Ramberg and Osgood (1943), presented a 3-parameter characterization of the f-d behavior of some engineering alloys (Figure 12) as:

$$D = F/M + K(F/M)^n \qquad [43]$$

where

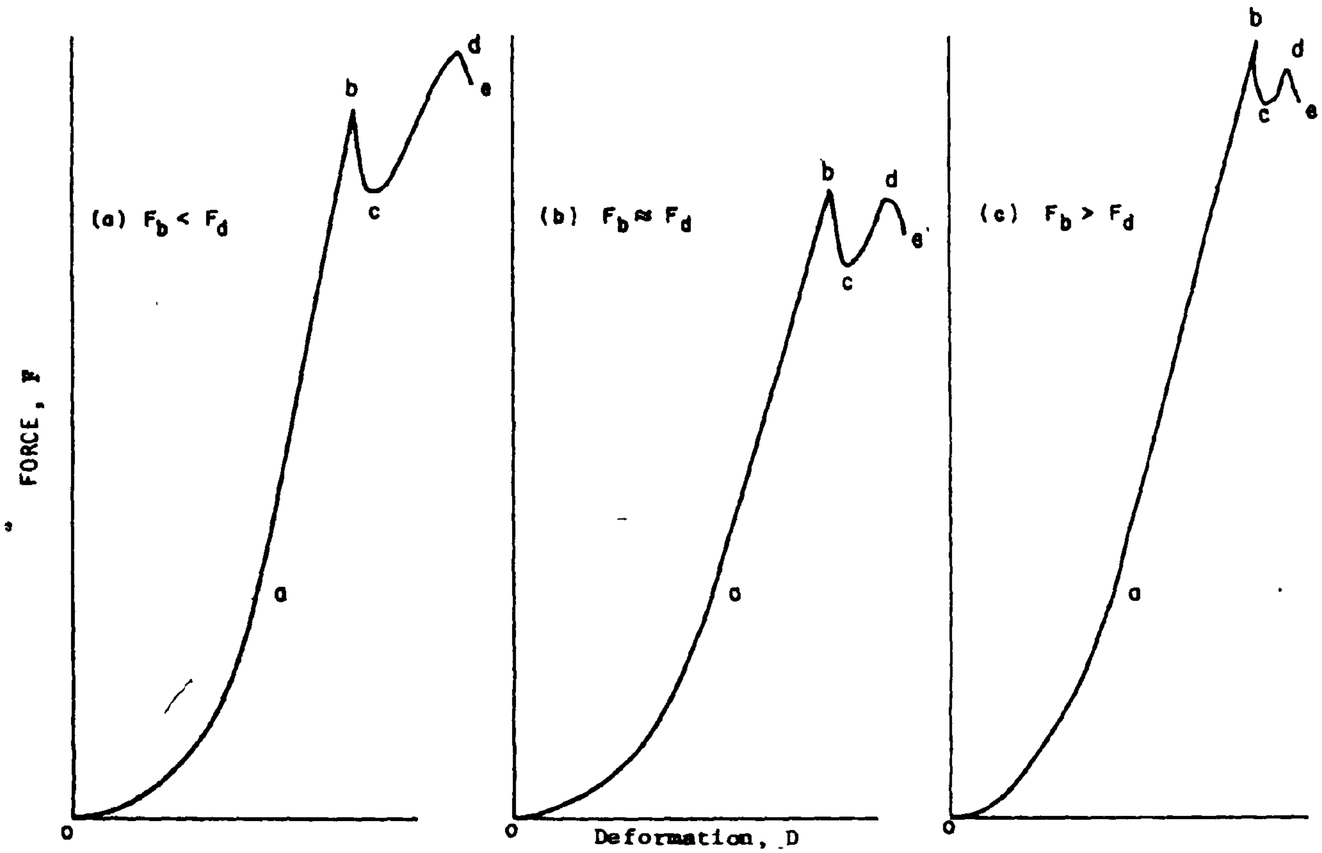
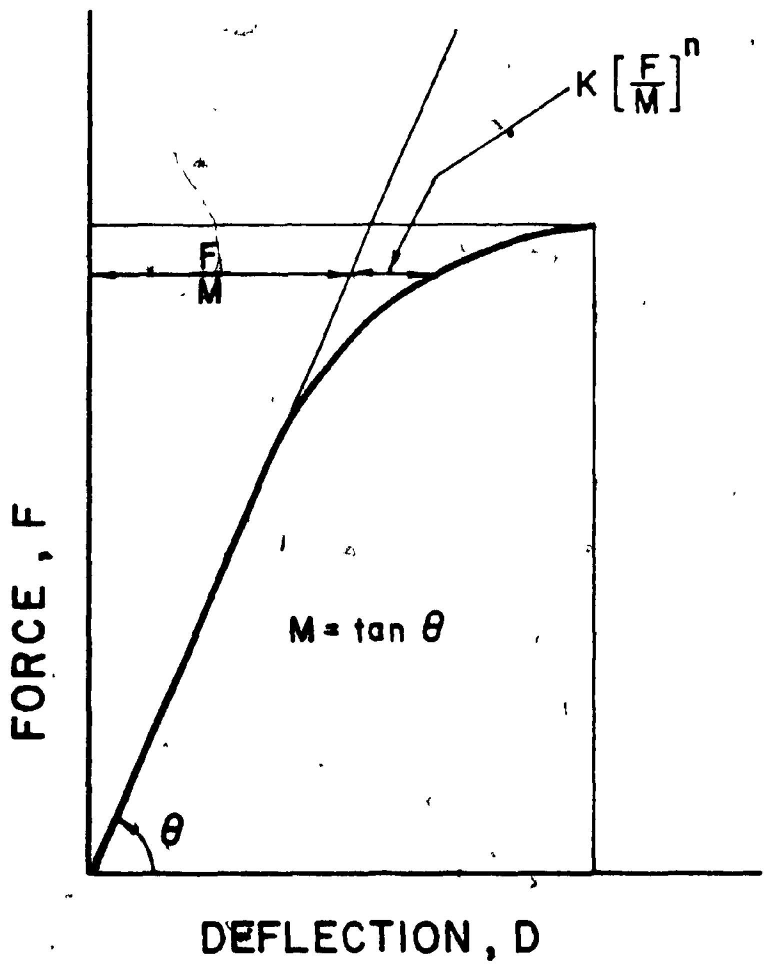


Figure 11. Three types of force-deformation behavior of corn cobs.



$$D = \frac{F}{M} + K\left[\frac{F}{M}\right]^n$$

Figure 12. Three-parameter characterization of f-d curve of some engineering alloys under fracture test (from Liebowitz and Eftis, 1971)

M = slope of the straight portion of curve

n and K = constants which depend on the non-linear shape of the f-d curve.

In the same manner, as illustrated in Figure 13, a 5-parameter characterization of the f-d curve of corn cob in radial compression up to the critical point of failure, pith cracking, is derived as follows:

$$D = F_b/M_o - [F_b - F]/M - K[[F_b - F]/M]^n \qquad [44]$$

where

D = vertical deformation of corn cob

F = applied normal force

F_b = maximum force to crack the pith

M_o = slope of line joining the origin of coordinate axes to the critical failure point

and other parameters are as defined previously.

The constants, n and K, are determined by choosing two points on the non-linear portion of the curve, Figure 14; substituting the corresponding values of the forces, F_1 and F_2, and the slopes, $\alpha_1 M$ and $\alpha_2 M$, in equation [44], and solving the resultant two equations simultaneously to obtain the following expressions:

$$n = \frac{\log[(\alpha_2/\alpha_1)(1-\alpha_1)/(1-\alpha_2)]}{\log[(F_b - F_1)/(F_b - F_2)]} + 1 \qquad [45]$$

$$K = [(1-\alpha_2)/\alpha_2][(F_b - F_2)/M]^{1-n} \qquad [46]$$

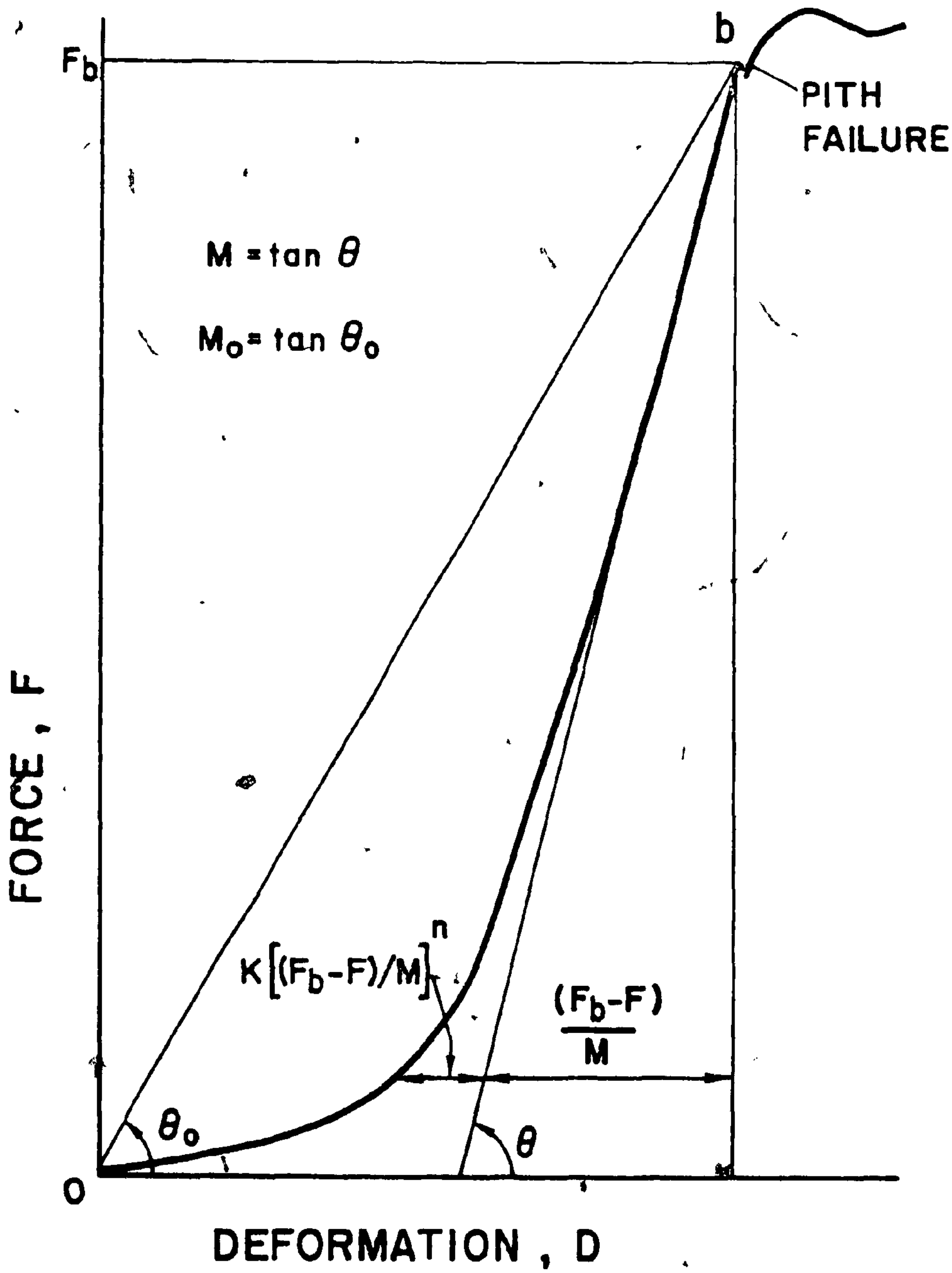


Figure 13. Five-parameter characterization of the f-d curve of corn cob in radial compression

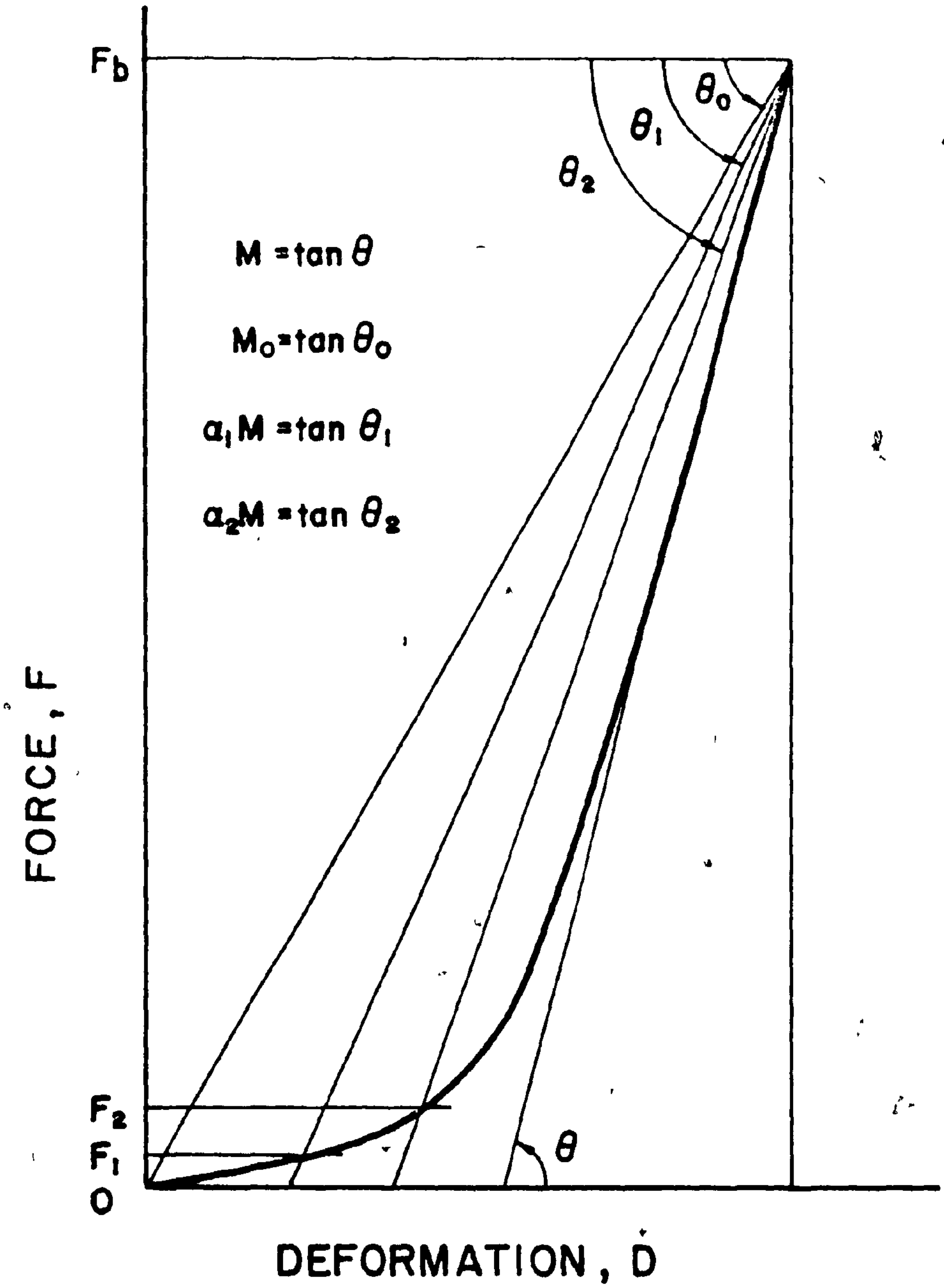


Figure 14. Determination of the empirical constants

where F_1, F_2, α_1 and α_2 are defined in Figure 14.

Figure 15 shows that the empirical equation, equation [44], very closely fits the data for each of the three varieties of corn cob tested in 1977 (details in Tables D5 and D6 in Appendix D).

5.3 Empirical equation for cob modulus of toughness

The toughness of a material under external load is defined as the work per unit volume of the material required to cause rupture of the material. Toughness is calculated as the area under the entire force-deformation curve up to the critical point of failure, per unit volume of the material.

With reference to Figure 16, the work done per unit volume of cob composite, U, may be denoted as:

$$U = [\int_0^{D_b} F\, dD]/\ell A$$

$$\text{or} \quad U = [F_b D_b - \int_0^{F_b} D dF]/\ell A \qquad [47]$$

where

ℓ = length of cob sample tested

A = average cross-sectional area of cob.

Substituting the expression for D from equation [44] in equation [47], then

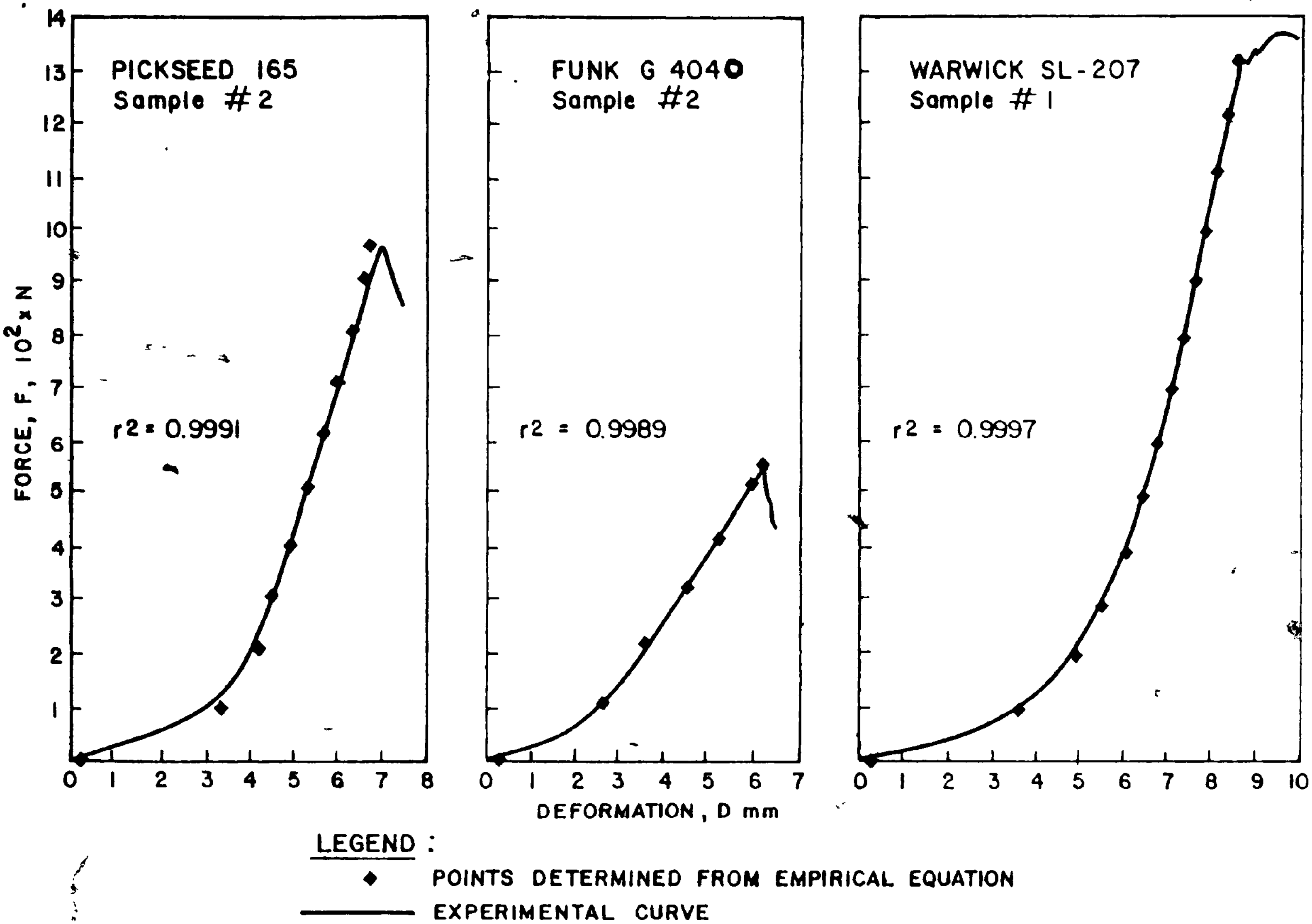
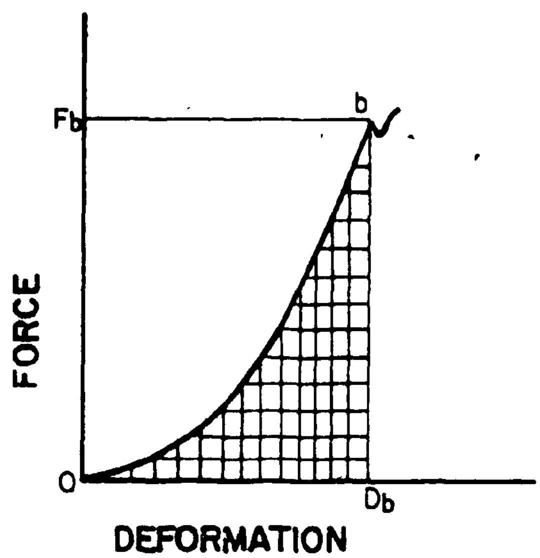


Figure 15 Comparison of the empirical and experimental f-d curves



TOUGHNESS = WORK DONE PER UNIT VOLUME

= SHADED AREA PER UNIT VOLUME

$$= \left[\int_0^{D_b} F\,dD\right] \Big/ AL$$

$$= \left[F_b D_b - \int_0^{F_b} D\,dF\right] \Big/ AL$$

Figure 16. Determination of the modulus of toughness

$$U = [F_b D_b - \int_0^{F_b} [\frac{F_b}{M_o} - \frac{(F_b - F)}{M} - K[\frac{(F_b - F)}{M}]^n] dF]/\ell A \qquad [48]$$

which, upon integration, will yield:

$$U = [\frac{F_b^2}{2M} + \frac{KM}{n+1}[\frac{F_b}{M}]^{n+1}]/\Pi R^2 \ell \qquad [49]$$

where

R = average cross-sectional radius of a short cylindrical sample of the cob composite

and other parameters are as defined previously.

Equation [49] is the desired empirical equation for calculating the modulus of toughness of corn cob in radial compression. The parameters F_b, M, K and n are determined from graphical analysis of the force-deformation curve as outlined earlier.

CHAPTER VI

EXPERIMENTAL WORK

6.1 Test apparatus and materials

All laboratory tests were performed with the Instron Universal Testing Machine, which is a standard instrument used in rheological studies (Figure 17).

Briefly, the testing machine consists of two parts:

1. the drive mechanism, which drives a moving cross-head in a vertical direction by means of twin lead screws at fixed speeds in the range 0.05 to 50 cm/min; and
2. the load-sensing system, which consists of electric bonded-wire strain gauges whose output is fed to a strip-chart recorder. The latter draws a force-distance curve of each test sample performed. A time axis can also be easily obtained from the chart since the recorder chart and the moving cross-head are synchronously driven from the same power supply.

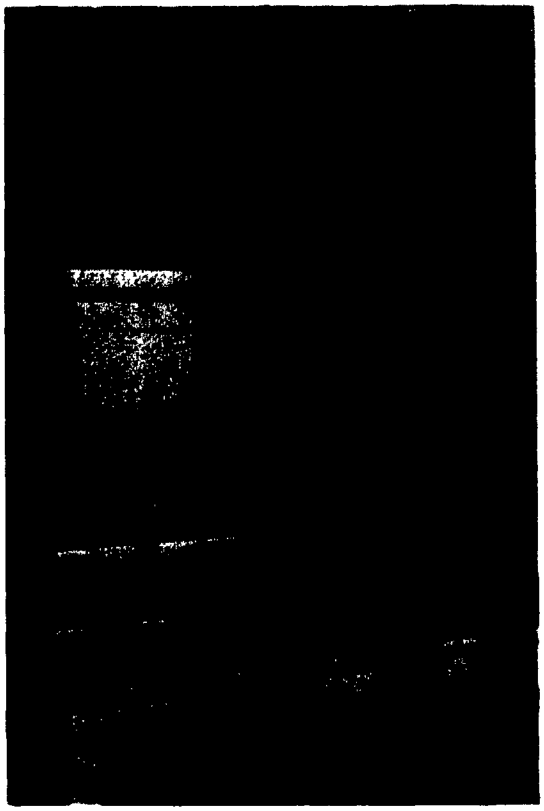


Figure 17. Instron Universal Testing Machine (Table Model) used in all laboratory investigations.

All radial compression tests were performed by compressing 3 cm-long (unless otherwise indicated) cylindrical cob samples between two steel plates attached to the Instron machine (Figure 18).

The 3 cm-long cylindrical samples were sawn off the middle section of each hand-shelled ear, using a power bandsaw. Both cob diameter and pith diameter were measured with a vernier caliper. Each diameter was an average of four readings, consisting of measurements of two mutually perpendicular diameters at each of the two ends of the 3 cm-long cylindrical sample. Cob moisture content and kernel moisture content were determined using the oven method, drying temperature of 103°C and drying duration of 72 hours (Agricultural Engineers Yearbook, 1978-79, p. 376).

The choice of 3 cm-long cylindrical samples was based on a 1977 preliminary test in which 1 cm-long, 3 cm-long and 5 cm-long cob samples were compared. The 3 cm-long sample was found to be suitable for the table model Instron machine used. Samples taken from the middle section of the cob were found less variable in their cross-sectional dimensions than those from the butt end and tip end. Preliminary tests performed both in 1977 and 1978 showed some variation of mechanical properties along the cob length. This test was repeated in 1979 (see Appendix B).

Measurement of cob size, cob and kernel moisture content and the mechanical tests were all performed on the same date the ear samples were hand-shelled. This procedure was adhered to on all test dates.

Figure 18   Radial compression of corn cob composite

In simple bending tests, a whole corn cob was supported as a simple beam on a steel channel section with the flat side on the load cell of the testing machine. The cob was then loaded at mid-span by a transverse steel rod attached to the cross-head (Figure 19).

Whether in radial compression or simple bending, a separate loading and unloading test was performed with representative samples. This was done in order to determine the degree of elasticity of the samples tested and thus determine the elastic component of the deformation or deflection.

The temperature and relative humidity of the centrally heated and controlled laboratory room were monitored throughout the period of the tests using an "Atkins Thermistor Psychrometer." The values recorded in 1978 were 22 ± 1°C and 37 ± 8 per cent, respectively.

6.2 1978 Investigations

Corn ears used in the 1978 laboratory investigations were obtained from two sources:

1. an experimental field at Macdonald College for a soil compaction research investigation by the Agricultural Engineering Department (samples from this source were grouped according to compaction treatments and only samples from one group were used in any one cob mechanical properties test in order to eliminate any possible variations in samples due to compaction treatments).

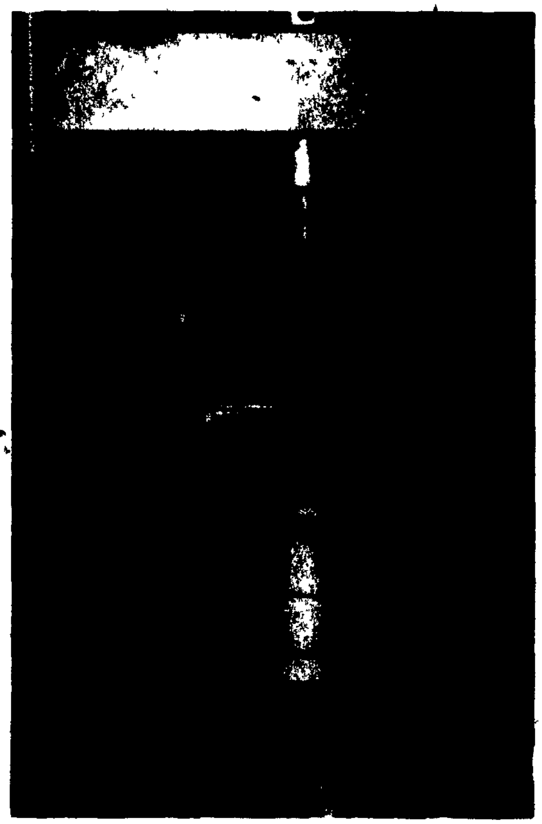


Figure 19. Simple bending of a whole-length corn cob composite.

2. experimental fields at Howick, Ormstown and Riverfield, in Quebec, for variety, fertilizer and site investigations by the Renewable Resources Department of Macdonald College.

Corn ears were hand-picked from the experimental fields, hand-husked and then stored in flat trays at laboratory room temperature. The decision to dry the ears in the laboratory was a result of the little variation in moisture content achieved in 1977 when ears were left to dry naturally in the field and only hand-picked on the laboratory test date.

On each test date, the required number of ears was randomly selected and hand-shelled to obtain corn cobs.

6.2.1 Direct measurement of contact area

Three simple techniques were used to determine experimentally the area of contact of a radially compressed corn cob at the critical point of failure. These techniques are briefly described as follows:

1. <u>Glume method</u>.--Radial compression of 3 cm-long middle section of corn cob composite was performed as usual. At the end of the test run, the width of the area of contact was measured with a caliper from the depressions of the glume on both surfaces of contact of cob with the two flat loading plates.

2. <u>Carbon paper method</u>.—A carbon paper sandwiched between two white plain typing sheets was cello-taped onto the lower flat plate of the Instron. The test sample was placed on the paper and radial

compression test was performed as usual. At the end of the test, the width of contact was measured with a caliper from the contact area imprinted on the lower sheet of paper.

3. Candle carbon method.--A flat piece of glass plate was thinly coated with candle carbon (i.e., soot from a burning candle). The darkened glass plate was allowed to cool and then placed on the lower steel plate of the Instron. The radial compression test was performed as before. The area from which carbon had been removed by the contact of the deformed cob represented the contact area. The width of the contact area was measured with a vernier caliper.

The above experiment to measure the area of contact was conducted first with Coop S265 corn variety obtained from the soil compaction experimental field. It was subsequently repeated with Asgrow RX-30 corn variety from the second source of corn ears. Coop S265 is a medium maturity variety while Asgrow RX-30 is a late maturity variety. Both are high yielding corn varieties.
The three experimental techniques for determining contact area were performed on each of the two test dates at a loading rate of 1 cm/min.

6.2.2 Determination of the effects of moisture content and rate of loading

A 3 x 3 factorial experiment was conducted in 1978 with Coop S265 corn variety. Cob composite sections, 3 cm-long, each cut from the middle of a whole corn cob, were radially compressed between two flat plates in the Instron testing machine. Three loading rates, 0.5, 1.0, and 3.0 cm/min, were used on each of the three test dates.

On each test date, starting from the first date of harvest and repeated twice at an interval of two weeks, nine ears were hand-shelled and a 3 cm-long cob section was cut from the middle of each. Radial compression of each was performed until the cob failed by cracking at the center of the pith. The first group of three cobs was tested at 0.5 cm/min, the second at 1.0 cm/min, and the last at 3.0 cm/min.

Using whole-length corn cobs, another 3 x 3 factorial experiment, similar to the one described above, was performed in simple bending. The three loading rates were 1, 3, and 5 cm/min, instead of those used for the radial compression test.

Preliminary experiments in 1977 and 1978 indicated that the most appropriate combination of loading rate and chart speed in radial compression was 1 cm/min and 10 cm/min. The corresponding combination in simple bending was found as 3 cm/min and 3 cm/min. It was therefore decided to use a range of loading rate with each of these values as the mid-value.

6.2.3 Test to determine the relative contributions of the macrostructural components of the cob

Because the pith is relatively very soft, there has been a tendency to disregard it and thus consider the cob as a hollow cylindrical body with one material (Johnson et al., 1969; Brandini et al., 1978). This simplification needs to be examined more closely since, in radial compression, the mechanical properties of a composite cylindrical body may be significantly modified by the existence of a weak material within it.

A 4 x 2 factorial experiment was therefore performed to test the relative contributions of the three macro-structural components of the corn cob to its mechanical properties. Four simplified structural models of the corn cob, as illustrated in Figure 20, and two levels of moisture content were used in the experiment.

Cob sections, 3 cm long, were cut from the middle of whole cobs, from a single variety, Coop S265. Half of these cob samples were sanded to remove the outer chaffy glume and thus obtain the "smooth cob" samples. Half of these smooth cob samples were poked at the center with a thin rod to remove the pith material and thus obtain the "hollow smooth cob" samples or, simply, mid-cobs. The pith materials from half of the unsanded samples were removed to get the "hollow cob" samples. The remaining half of the unsanded samples represented the cob composite samples.

On each of the two test dates, radial compression tests were performed on each of these samples at 1 cm/min rate of loading with a table model Instron testing machine. Size and moisture content of each cob sample were determined as described earlier.

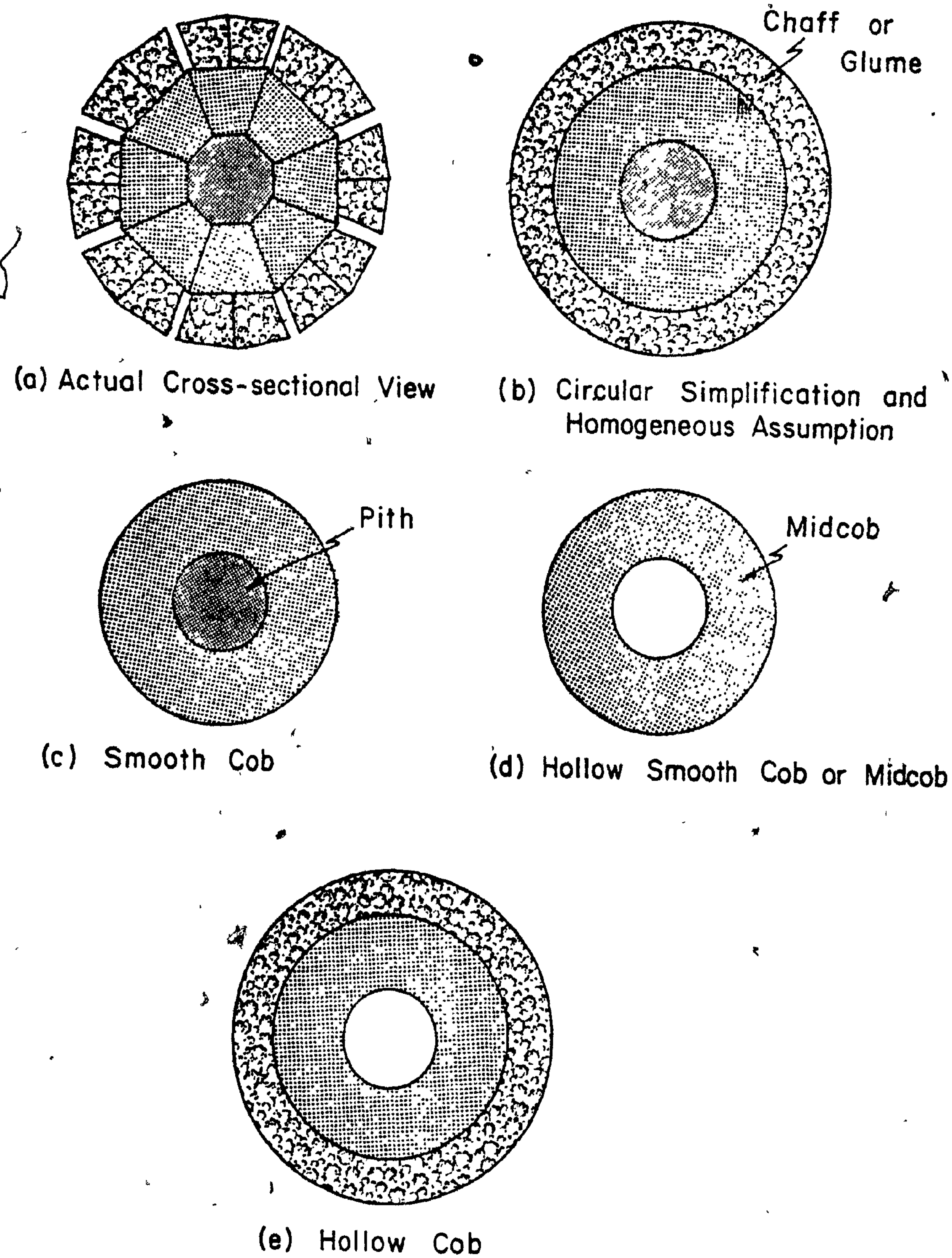


Figure 20. Cross-sectional view of corn cob and those of its simplified structural models

6.2.4 Tests to determine the effects of variety, fertilizer and soil

Corn stalk strength has been found to be significantly influenced by the variety of corn planted, the planting density and the rate of fertilizer applied, particularly potassium (Zuber and Grogan, 1961; Thompson, 1963; Arnold et al., 1974; Loesh et al., 1976). Waelti and Buchele (1967) reported varietal differences in kernel and cob physical and mechanical properties as related to corn kernel damage in corn combine cylinders. Thus, a preliminary investigation was conducted to determine the effects of corn variety, fertilizer rate of application and field location (or soil type and condition) on corn cob mechanical properties.

Corn ear samples were hand-picked from experimental fields designed and grown by the Renewable Resources Department of Macdonald College. Only three of the many sites and four of the twelve fertilizer treatment levels were used in the corn cob analysis. Two varieties of corn, Warwick SL-207 and Asgrow RX-30, were grown in each site. On each test date, the required number of ears was hand-shelled to obtain cob samples. Sections, 3 cm long, were cut from the middle of the cobs. Three test samples for each treatment level of variety, fertilizer or site were individually tested in radial compression at a loading rate of 1 cm/min until the cob pith split. Size and moisture content of each cob sample were determined as described earlier.

Additional experiments were performed to determine the mechanical properties, in particular the elastic moduli, of the cob pith and cob mid-cob tested as rectangular slabs in axial compression (Appendix C). This information is needed for the calculation of "m" in equation [24]. This experiment was repeated in 1979 with three different corn varieties and three rates of loading (Appendix C).

For comparative purposes, mechanical properties of corn kernels and corn cob in axial compression and radial tension were also determined (Appendix D).

6.3 1979 Investigations

Corn ear samples used in all the experiments performed in 1977 and 1978 were obtained from field experiments established for different research objectives other than those of this study. This limited the number of samples used and also influenced the scheduling of the laboratory experiments in 1977 and 1978. It was therefore decided to plant three varieties of corn in 1979 specifically for the corn cob study.

6.3.1 Experimental design

The experiment was designed as a split-plot in time with three corn varieties and three harvesting dates. The three varieties were Warwick SL-207, Funk G4065 and Asgrow RX23. All three varieties are hybrid corn selected in consultation with the Agronomy Research Centre at Macdonald College.

As illustrated in Figure 21, there were three blocks or replications, each of which contained three main plot units. Each main plot unit had three sub-plots. The three corn varieties were randomized within each replication, while the three harvesting dates were randomized within each main plot unit.

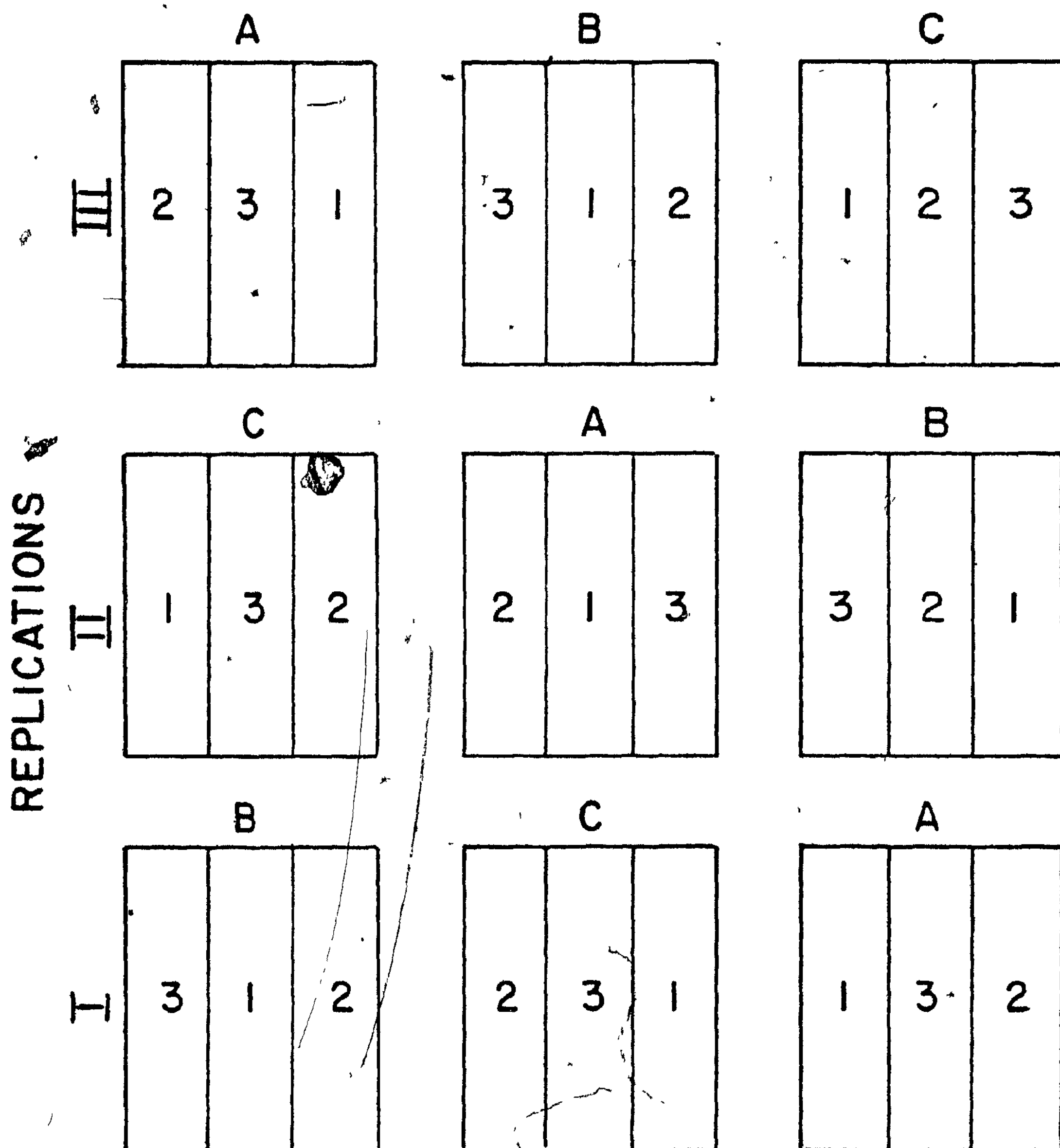
6.3.2 Field preparation, layout and cultivation

The experimental field was prepared for seeding by fall plowing, disc harrowing and fertilizing by the field staff at Macdonald College Farm.

The field was laid out as illustrated in Figure 22. Each main plot had six rows of corn of one single variety. The two outside rows of each main plot were not used in the analysis. Three of the four inside rows constituted the three sub-plots in a main plot unit.

All the three corn varieties were planted on the same day, 9th May 1979, using a two-row planter with a fertilizer attachment mounted on an MF 135 tractor. The row spacing was 75 cm (about 30 inches) between rows and plant spacing within row was 20 cm (about 8 inches). Additional fertilizer, as recommended by the farm manager, was applied during planting. The seeds were treated with an insecticide-fungicide compound supplied by the seed agent. Mechanical weeding with a two-wheeled tractor-rotovator was done on the 29th and 30th June 1979.

HARVEST DATE - VARIETY COMBINATIONS



KEY

CORN VARIETIES	HARVESTING DATES
A = WARWICK SL-207	1 = 22/09/79
B = FUNK G 4065	2 = 06/10/79
C = ASGROW RX23	3 = 20/10/79

Figure 21. Split-plot in time design

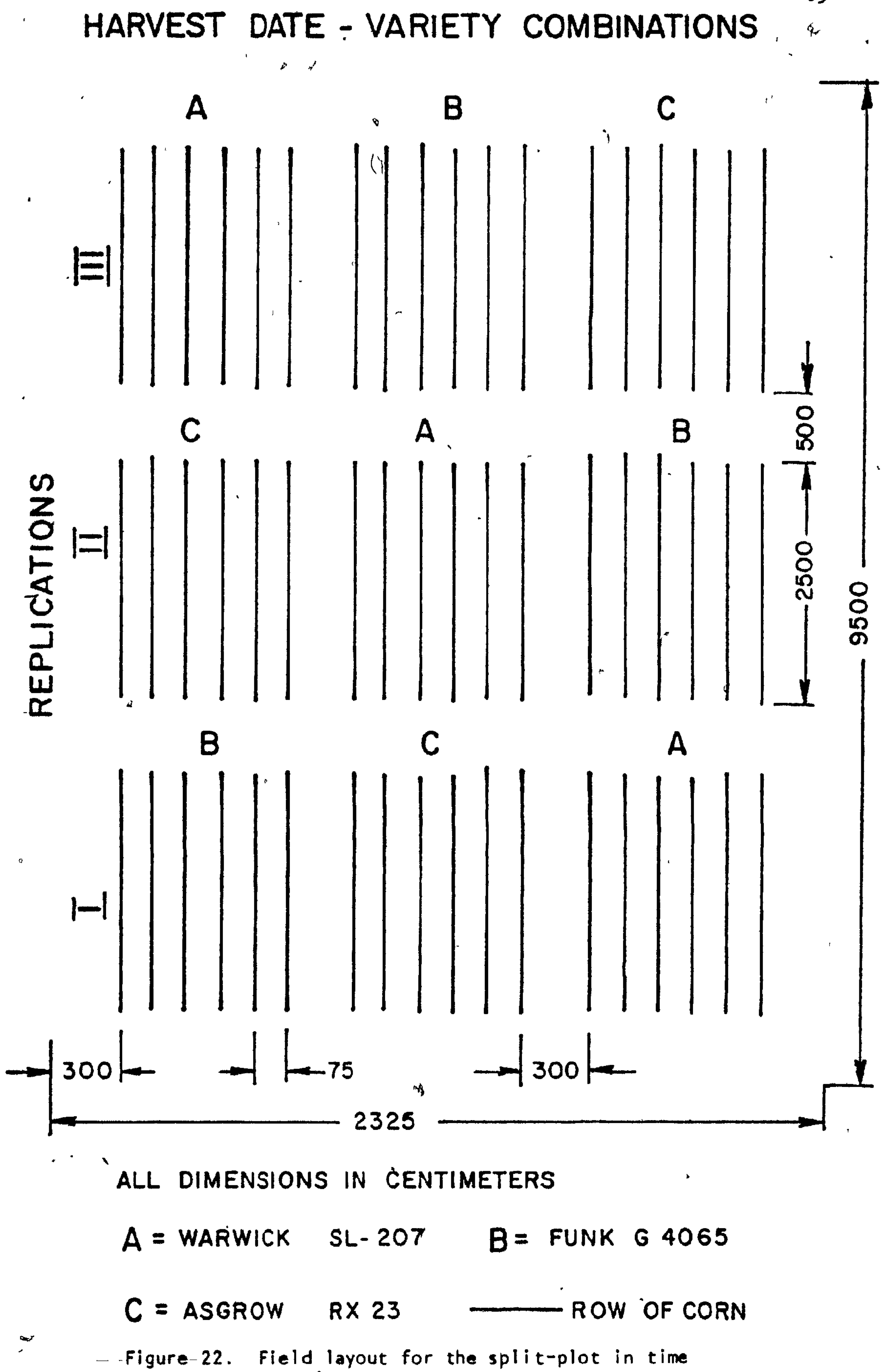


Figure 22. Field layout for the split-plot in time experiment

6.3.3 Laboratory tests

Corn ears were hand-harvested from the experimental field on each test date, starting from 22nd September 1979, when the three corn varieties were deemed to have reached physiological maturity and dry enough to be hand-shelled without breaking the tips of kernels on the cob. Two subsequent hand-pickings were done on 6th October 1979 and 20th October 1979.

Laboratory tests consisted of radial compression tests with 3 cm-long corn cobs and simple bending tests with whole-length corn cobs as described earlier.

Two major experiments were performed in 1979 using corn ear samples from the experimental field established specifically for the corn cob study.

The first was an investigation of the effects of corn variety and harvesting date on cob physical and mechanical properties. Sample preparations and physical and mechanical tests were completed on the same day that the corn ears were hand-picked from the experimental field. Three varieties with three replications and three harvesting dates were involved in this investigation.

The second major investigation in 1979 was to repeat the experiment on the effects of moisture content and rate of loading. Five test dates to give five moisture content levels were used instead of three. The rates of loading were 0.5, 1 and 5 cm/min. Corn ears were hand-picked from a separate block planted next to block III of the split-plot field experiment. Warwick SL-207 corn variety was used in this investigation, which was limited to radial compression. About 300 corn ears were hand-picked from adjacent rows on 19th September 1979 and kept, unhusked, in the laboratory to dry. The required number of corn ears was hand-husked and hand-shelled on each test date and the rest left until they were needed. Sixteen 3 cm-long cob samples instead of three were used for each rate of loading on each test date. Additional three 3 cm-long cob samples for each rate of loading on each test date were used for loading and unloading test.

Additionally, a third experiment was conducted in 1979 to test the effects of increasing the rates of application of nitrogen fertilizer on corn cob physical and mechanical properties. Corn ear samples were hand-picked from a randomized complete block experiment established by the Renewable Resources Department of Macdonald College. Unlike the previous year, potassium and phosphorus fertilizers were kept constant at the recommended rates for Warwick SL-777 corn variety planted at the Agronomy Research Centre. Four blocks and four of the eight fertilizer treatment levels were involved in this study. Five sampling units were used. Radial compression was performed on one test date, 29th September 1979.

As in 1977 and 1978, loading and unloading tests were performed for each experiment with representative cob samples.

CHAPTER VII

RESULTS AND DISCUSSION

7.1 Procedure for calculating cob mechanical properties

Based on the theoretical and empirical equations presented in Chapters III, IV and V, a summary of the methods used in calculating cob mechanical properties in radial compression and in simple bending is given below. Calculations for each of the two loading configurations are made with experimentally determined force-deformation curve of a single test sample.

7.1.1 Radial compression

Consider a corn cob test sample with the following test descriptions and measured physical properties:

Test date = 06.10.79

Variety of corn = Asgrow RX 23

Rate of loading = 1 cm/min

Kernel moisture content = 28.0% w.b.

Cob moisture content = 44.1% w.b.

Cob diameter, $2R$ = 23.1 mm

Pith diameter, $2r$ = 8.0 mm

Test sample length, ℓ = 28.6 mm

The force-deformation curve for the above test sample is shown in Figure 23. From this, the following information is derived:

Ratio of loading rate to chart speed = 1/10

Force at pith cracking, F_b = 71.0 kgf

Deformation at pith cracking, D_b = 84 x 1/10 = 8.4 mm

F_1 = 4.0 kgf

D_1 = 23 x 1/10 = 2.3 mm

F_2 = 12.0 kgf

D_2 = 43 x 1/10 = 4.3 mm

D_3 = 45 x 1/10 = 4.5 mm

where points 1 and 2 are any two reasonably spaced points on the non-linear portion of curve Oab and D_3 is the intercept of line ab (upper straight portion of curve Oab) with the deformation axis.

Degree of elasticity, β%

Because of the destructive nature of the radial compression test, an estimate of the degree of elasticity of the test sample is obtained from loading and unloading another cob sample similar to the test sample. From Figure 24,

β = [AB/OB] x 100%

= [43/138] x 100 = 31.2%

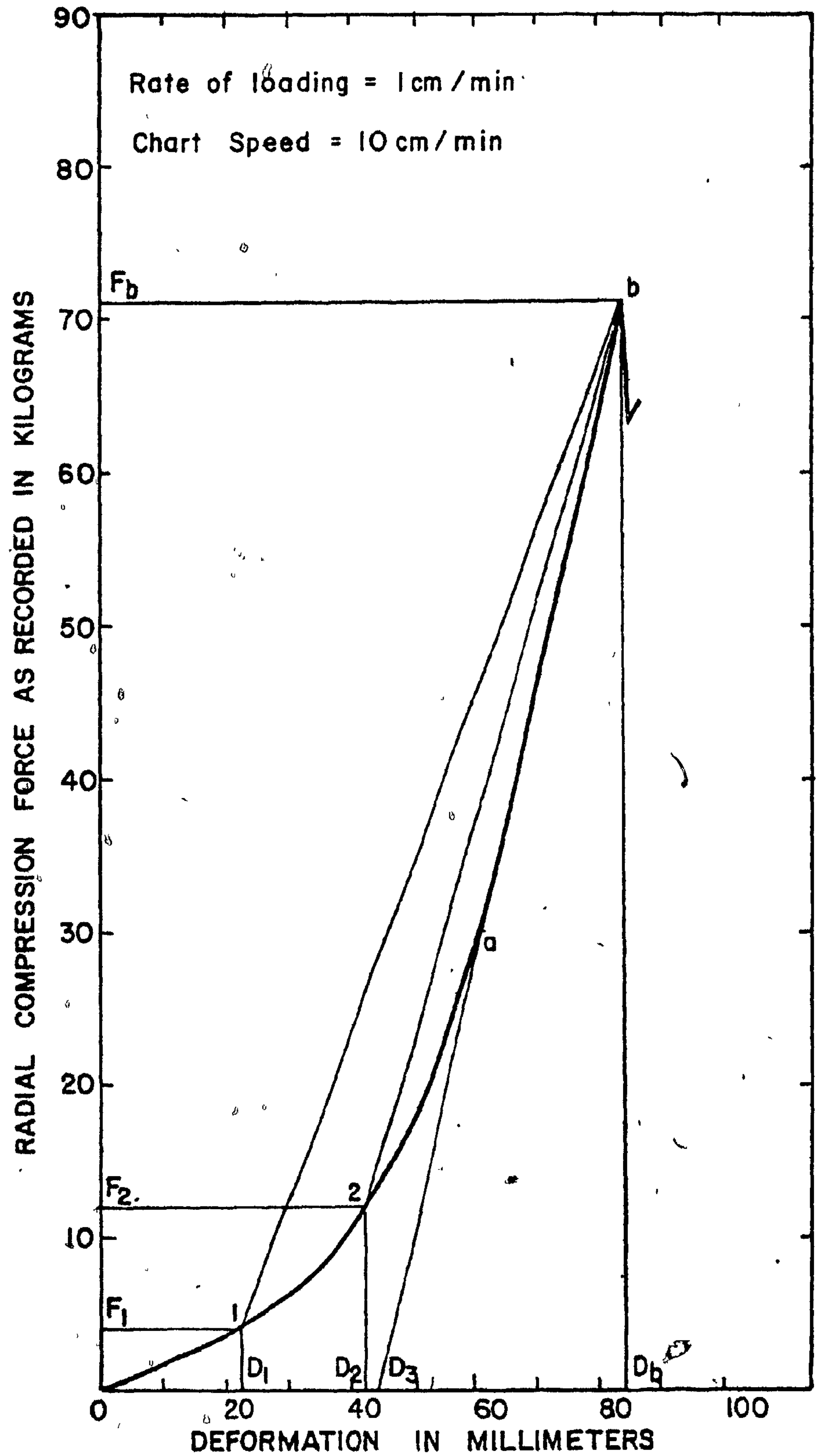


Figure 23. Force-deformation curve of cob in radial compression illustrating method of analysis

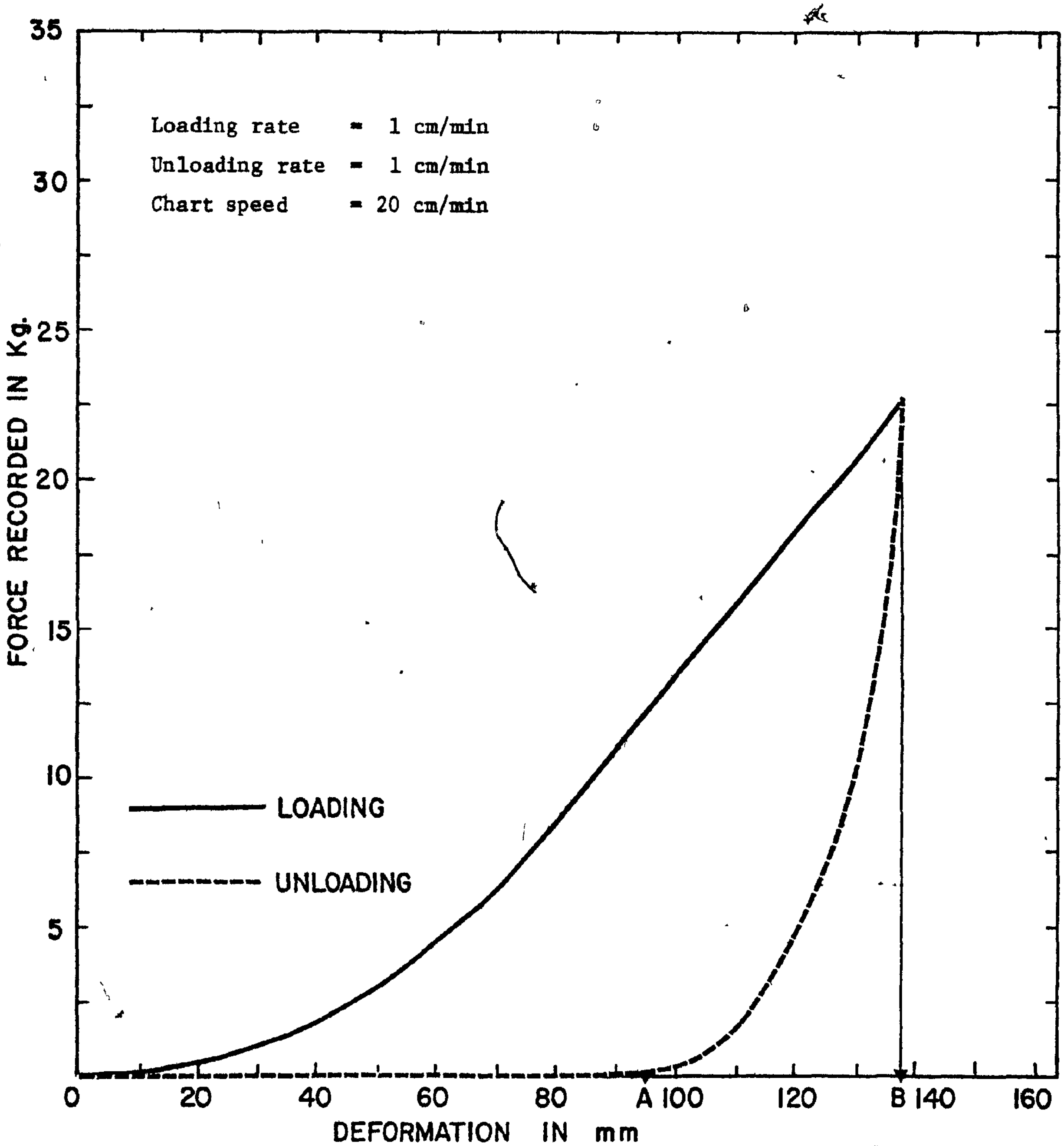


Figure 24. Determination of the degree of elasticity of corn cob in radial compression

Crushing strain, ε_b

From equation [17], viz,

$$D_e = \beta D/100$$

the elastic component of deformation at pith cracking is determined as

$$D_e = 31.2 \times 8.4/100 = \underline{2.6208}\ \text{mm}$$

Cob crushing strain is defined as the ratio of elastic deformation at pith cracking to the original diameter of the cob, hence,

$$\varepsilon_b = D_e/2R$$

$$= 2.6208/23.1$$

$$= \underline{0.11345}$$

Apparent elastic modulus, E, MPa

Determine Z in equation [16], viz,

$$D_e/2R = [1/(2Z^2)][\ln(2Z) + 1/2]$$

by trial and error using the value of $D_e/2R$ already calculated or use the table provided by Sherif et al. (1976) or preferably that by Sherif (1976).

$$\therefore Z = \underline{3.228}$$

Calculate the apparent elastic modulus from equations [14] and [15] which yield:

$$E = [4\ FZ^2(1 - \nu^2)]/(\Pi\ R\ell)$$

As shown in Appendix A, Poisson's ratio of corn cob in radial compression is determined as $\nu = 0.32$. This value is used in all calculations of the apparent elastic modulus of corn cob reported in this thesis.

By substitution:

$$E = \frac{[4(71)(3.228)^2(1 - (0.32)^2)]}{\Pi(23.1/2)(28.6)} \text{ kgf/mm}^2$$

$$= 2.55959 \times 9.8067 \text{ MPa}$$

$$= \underline{25.1} \text{ MPa}$$

<u>Contact width, 2b, at pith cracking</u>

From equation [15], viz,

$$Z = R/b$$

calculate the contact width as

$$2b = 2R/Z$$

$$= 23.1/3.228$$

$$= \underline{7.156} \text{ mm}$$

<u>Crushing strength, σ_c, MPa</u>

From equation [2], viz,

$$q_o = 2F/\Pi \ell b$$

the crushing strength, defined as the maximum contact stress at the center of the deformed surface area of the cob, is calculated as follows:

$$\sigma_c = q_o = 2F_b/(\Pi \ell b)$$

$$= 2(71)/(\Pi(28.6)(7.156/2))\,\mathrm{kgf/mm^2}$$

$$= 0.44170 \times 9.8067\ \mathrm{MPa}$$

$$= \underline{4.3}\ \mathrm{MPa}$$

Modulus of toughness

The relevant equation for calculating cob modulus of toughness is equation [49], viz,

$$U = [\frac{F_b^2}{2M} + \frac{kM}{n+1}[\frac{F_b}{M}]^{n+1}]/[\Pi R^2 \ell]$$

M is the slope of the upper straight portion of curve Oab (Figure 23), hence

$$M = F_b/(D_b - D_3)$$

$$= 71/(8.4 - 4.5)$$

$$= \underline{18.20513}\ \mathrm{kgf/mm}$$

The constants n and k for the non-linear portion of curve Oab (Figure 23) are determined as follows:

From equation [45], viz,

$$n = 1 + \frac{\log[(\alpha_2/\alpha_1)(1 - \alpha_1)/(1 - \alpha_2)]}{\log[(F_b - F_1)/(F_b - F_2)]}$$

where

$$\alpha_1 = \frac{\text{Slope of line 1b}}{\text{Slope of line ab}}$$

$$= M_1/M$$

$$= [(71 - 4)/(8.4 - 2.3)]/18.20513$$

$$= \underline{0.60332}$$

$$\text{and } \alpha_2 = \frac{\text{Slope of line 2b}}{\text{Slope of line ab}}$$

$$= M_2/M$$

$$= [(71 - 12)/(8.4 - 4.3)]/18.20513$$

$$= \underline{0.79045}$$

$$\therefore\ n = 1 + \frac{\log[(0.79045/\ 0.60332)(1 - 0.60332)/(1 - 0.79045)]}{\log[(71 - 4)/(71 - 12)]}$$

$$= \underline{8.14343}$$

From equation [46], viz,

$$K = [(1 - \alpha_2)/\alpha_2][(F_b - F_2)/M]^{1-n}$$

$$= [(1 - 0.79045)/0.79045][(71 - 12)/18.20513]^{1-8.14343}$$

$$= \underline{5.96429 \times 10^{-5}}$$

Finally, the modulus of toughness for the test sample is calculated by substituting all the relevant values in equation [49]. The result is

$$U = 0.0140646 \text{ kgf mm/m}^3$$

$$= 0.0140646 \times 9.8067 \times 10^6 \text{ N-m/m}^3$$

$$= 0.138 \times 10^6 \text{ N-m/m}^3$$

7.1.2 Simple bending

Consider a corn cob test sample (whole-length corn cob) with the following test descriptions and measured physical properties:

Test date = 06/10/79

Variety of corn = Asgrow RX 23

Rate of loading = 3 cm/min

Kernel moisture content = 25.9% w.b.

Cob moisture content = 40.2% w.b.

Tip-end cob diameter, d_1 = 25.7 mm

Butt-end cob diameter, d_2 = 31.7 mm

Loading span, L = 150 mm

The force-deflection curve for the above test sample is shown in Figure 25. From this, the following information is derived.

Ratio of loading rate to chart speed = 3/3 = 1

Maximum bending force, F_b = 11.0 kgf

Maximum deflection, D_b = 26.9 mm

The degree of elasticity in simple bending is determined in a similar manner to that in radial compression. The value determined is

β = 41.8%

Bending strength, σ_b, MPa

The bending strength equation as derived in Chapter IV of this thesis is

$$\sigma_b = (64F_bL)/[\Pi(d_1 + d_2)^3(1 - f^4(1 - m))]$$

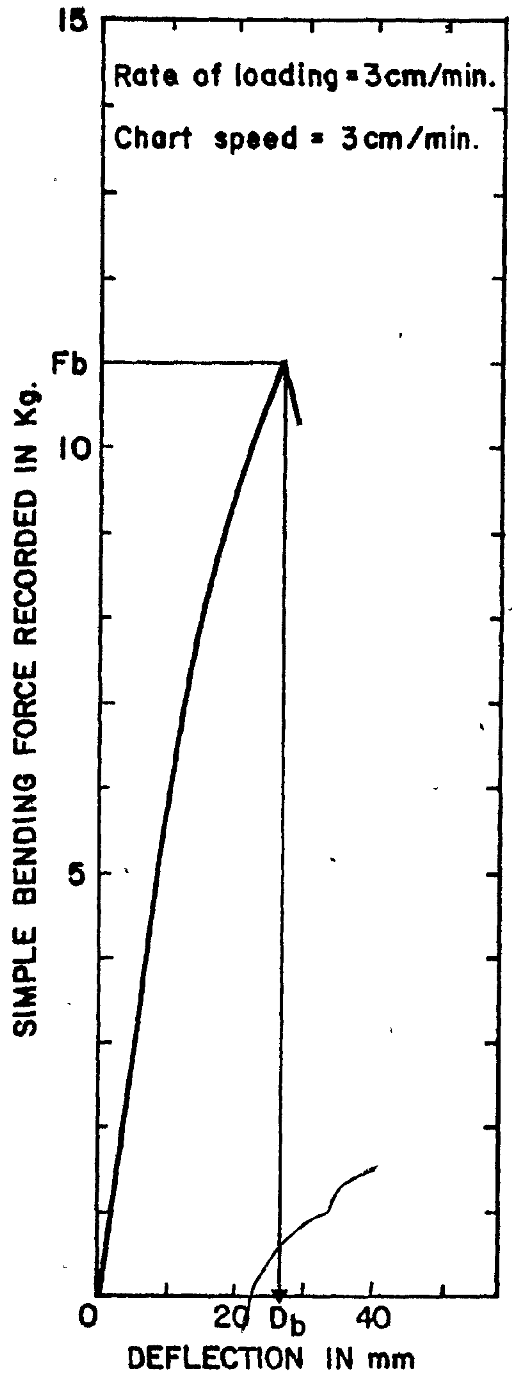


Figure 25. Force-deflection curve of cob in simple bending illustrating method of analysis

The coefficient $(1 - f^4(1 - m))$ is determined in Appendix C for four varieties of corn (including Asgrow RX 23) and at three rates of loading. An average value of 0.98 is used in all calculations.

$$\therefore \sigma_b = (64)(11.0)(150)/\Pi(25.7 + 31.7)^3(0.98))$$
$$= 0.18136 \text{ kgf/mm}^2$$
$$= 0.18136 \times 9.8067 \text{ MPa}$$
$$= \underline{1.8} \text{ MPa}$$

Apparent elastic modulus, E_b, MPa

From equation [42], viz,

$$E_b = 8\ FL^3C/\Pi\ D_e$$

the apparent elastic modulus of the test sample can be calculated, where

$$F = F_b = \underline{11.0} \text{ kgf}$$

C = correction term for cob tapering

$$= \underline{-2.484 \times 10^{-7}} \text{ (using equations [35] to [41])}$$

$$D_e = \beta D_b/100 = 41.8(26.9)/100$$
$$= \underline{11.2442} \text{ mm}$$

$$E_b = 8(11)(150)^3(|-2.484 \times 10^{-7}|)/(\Pi(11.2442))$$
$$= 2.08848 \text{ kgf/mm}^2$$
$$= 2.08848 \times 9.8067 \text{ MPa}$$
$$= \underline{20.5} \text{ MPa}$$

Fortran computer programs (Appendix E) were written to facilitate the calculations of cob mechanical properties in radial compression and in simple bending. Input (data) and output (calculated results) for some of the experiments performed in 1979 are also included in Appendix E for further clarification of the methods of analyses adopted in this study. Statistical analyses included analysis of variance and Duncan's new multiple range test, using Statistical Analysis System (S.A.S.) computer package. Regression analysis was done with a programmable electronic calculator.

7.1.3 Justification for applying the Hertz theory

Table 2 shows that the values of the contact width predicted from the Hertz linear elastic contact theory and those given from direct experimental measurements are reasonably close. The lower values of the carbon paper method and the higher values of both the glume depression and the candle carbon methods are understandable. The resistance of the carbon paper would tend to reduce the true contact area of the deformed cob. On the other hand, the candle carbon coating would introduce some additional tangential forces at the contact surface which would tend to disperse the fine carbon deposits on the glass plate much more than that due to the deformation of the cob alone. The higher values of the glume method could be due to the initial flattening of the glume which is not an elastic deformation as considered in the theory.

TABLE 2. Experimental and theoretical determination of contact width†

Experimental technique	Measured values††			Calculated values†††				
	2 R mm	D_b mm	2 b mm	$D_b/2R$	Z	2b* = 2 R/Z mm	Ratio [2b*/2b]	r^2
Asgrow RX-30 tested on 7th October 1978 with cob moisture = 8.3% w.b.								
Glume depression	23.9	5.9	14.1	0.248	1.95	12.3	0.87	0.983
Carbon paper	24.4	6.3	10.4	0.259	1.89	13.0	1.25	0.543
Candle carbon	26.4	6.3	17.1	0.238	1.99	13.3	0.78	0.692
Coop S265 tested on 16th October 1978 with cob moisture = 30.2% w.b.								
Glume depression	25.4	5.5	15.4	0.217	2.13	12.0	0.78	0.994
Carbon paper	25.4	6.0	11.1	0.234	2.05	12.6	1.13	0.940
Candle carbon	25.9	5.9	16.0	0.230	2.07	12.6	0.79	0.798
Coop S265 tested on 26th October 1978 with cob moisture = 10.2% w.b.								
Glume depression	24.4	6.1	13.9	0.250	1.94	12.6	0.91	0.917
Carbon paper	23.7	6.8	11.2	0.285	1.76	13.5	1.23	0.890
Candle carbon	25.1	6.5	16.0	0.258	1.88	13.3	0.83	0.916

†Each value is the mean of three test samples. Rate of loading = 1 cm/min.

††2R = cob diameter; D_b = deformation; 2b = contact width.

†††Z is determined from equation [16] or from table in Sherif <u>et al</u>. (1976), r^2 = coefficient of determination between measured and calculated contact width using values for each set of three test samples.

The glume depression method, which incidentally, is the easiest method, gave the closest values to those calculated from theory. However, the contact area obtained from the candle carbon method was the most defined (Figures 26a, b and c), and thus it gave the most reliable measurement. The candle carbon technique had previously been found suitable for estimating the contact area of radially compressed rapeseed kernels (Middendorf _et al._, 1973). Wilson (1927) also found the use of "lamp black" as the most satisfactory experimental method for determining the contact area between a steel cylinder and a plane surface.

The contact area in each of the three test techniques was rectangular as predicted in the Hertz theory.

From the above results, it is concluded that, despite the non-homogeneous, non-isotropic and inelastic nature of corn cob, the Hertz linear elastic contact theory can be reasonably applied to determine the apparent elastic modulus and the maximum contact stress at the surface of a radially compressed short cylindrical specimen of corn cob composite.

7.1.4 Comparison of empirical method with the areagraph chart technique

It has already been shown in Chapter V (Figure 15) that the empirical equation derived to represent the force-deformation curve of a radially compressed corn cob fits the experimental data very well. A further check on the empirical approach is provided in Table 3.

Figure 26a. Glume depression method of measuring contact width.

Figure 26b. Carbon paper method of measuring contact width.

Figure 26c. Candle carbon method of measuring contact width.

TABLE 3. Comparison of empirical method with the areagraph chart technique

Sample† number	Length ℓ, mm	Diameter 2R, mm	Area under f-d curve A*, mm^2	Modulus of toughness $10^6 \times N - m/m^3$	
				Areagraph†† method U*	Empirical method U
1	31.1	28.6	209.032	0.041	0.038
2	33.1	27.4	150.967	0.030	0.030
3	33.4	25.4	259.354	0.060	0.062
4	32.3	26.8	211.612	0.046	0.047
5	32.4	26.5	185.806	0.041	0.042
6	34.2	27.2	121.935	0.024	0.024
7	31.4	25.5	250.322	0.061	0.063
8	35.1	26.0	180.645	0.038	0.037
9	31.7	25.8	179.354	0.042	0.043
10	31.6	25.4	178.064	0.044	0.043

Coefficient of determination (r^2) between U* and U = 0.9882

† Variety = Warwick SL-207 tested on 10th October 1979 at 1 cm/min.

†† $U^* = [A^*(0.4)(9.8067)]/[\pi R^2 \ell]$, where 0.4 kg - mm ≡ 1 mm^2 from f-d curves.

Cob modulus of toughness determined from the empirical equation agrees very well with that determined from the traditional areagraph chart method (of 97% degree of precision).

Apart from minimizing the subjectiveness inherent in the traditional methods of measuring the area under a curve, the empirical approach is a faster technique compared with the areagraph method or the planimeter method when many experimental curves are involved and the experiments repeated over many time periods. This advantage is, however, subject to the use of a computer program to calculate the modulus of toughness.

7.1.5 Comparison of the modified bending equations with the basic flexure formulas

A practical method of assessing the significance of the modifications made in the basic flexure formula to account for the composite and tapering nature of corn cob in simple bending is to compare results calculated with the modified equations (equations [24] and [42]) with those calculated with the basic flexure equations (i.e., $\sigma_{max} = Mc/I$ and $y_{max} = FL^3/48\ EI$, where all the symbols are defined in Chapter IV).

Table 4 shows values of cob bending strength and apparent elastic modulus when the cob is considered as:

1. a tapered composite cylinder of two materials,
2. a solid cylindrical straight beam, and
3. a hollow cylindrical straight beam.

TABLE 4. Comparison of the modified bending equations with the basic flexure formulas

Data source[†]	Corn cob mechanical properties (MPa) from						Ratios			
	Modified bending equations		Basic flexure formulas							
			Solid beam		Hollow beam					
	E_b	σ_b	$E_b{*}$	$\sigma_b{*}$	$E_b{**}$	$\sigma_b{**}$	$E_b{*}/E_b$	$E_b{**}/E_b$	$\sigma_b{*}/\sigma_b$	$\sigma_b{**}/\sigma_b$
1	21.758	1.602	20.988	1.570	21.186	1.619	0.965	0.974	0.980	1.011
2	27.174	1.653	26.351	1.620	26.515	1.657	0.970	0.976	0.980	1.002
3	36.284	2.052	35.321	2.011	35.713	2.082	0.973	0.984	0.980	1.015
4	12.369	1.126	12.202	1.103	12.357	1.146	0.986	0.999	0.980	1.018
5	16.037	1.196	15.632	1.172	15.928	1.234	0.975	0.993	0.980	1.032
6	20.479	1.606	19.891	1.574	20.290	1.661	0.971	0.991	0.980	1.034
7	11.988	1.203	11.780	1.179	11.850	1.205	0.983	0.988	0.980	1.002
8	18.209	1.481	17.669	1.452	17.843	1.498	0.970	0.980	0.980	1.011
9	18.153	1.634	17.722	1.601	17.838	1.638	0.976	0.983	0.980	1.002
10	54.727	2.377	52.831	2.329	53.460	2.415	0.965	0.977	0.980	1.016
11	58.278	2.798	57.046	2.742	57.741	2.846	0.979	0.991	0.980	1.017
12	27.269	1.778	26.622	1.742	26.834	1.790	0.976	0.984	0.980	1.007
13	24.797	1.665	24.502	1.631	25.003	1.723	0.988	1.008	0.980	1.035
14	48.232	2.266	47.763	2.220	49.282	2.397	0.990	1.022	0.980	1.058
15	31.242	1.814	30.850	1.778	31.383	1.866	0.987	1.005	0.980	1.029
16	32.167	2.053	31.689	2.012	31.955	2.069	0.985	0.993	0.980	1.008

Coefficient of determination, r^2, for: $E_b{*}$ and E_b = 0.9996, $\sigma_b{*}$ and σ_b = 0.9999,
$E_b{**}$ and E_b = 0.9988 and $\sigma_b{**}$ and σ_b = 0.9962

[†]See details in Appendix E, Tables E5 and E6.

There are very little quantitative differences among the three methods of considerations. The results suggest that the simple beam or the hollow beam consideration is a very good approximation of the structure of the corn cob as regards calculating cob mechanical properties in simple bending. Qualitatively, however, the modified equations present a good basis for evaluating the importance of the composite and tapering nature of the corn cob to its mechanical properties in simple bending.

7.2 Variabilities in cob physical and mechanical properties

The mean, standard deviation and coefficient of variability for each of the nine physical and mechanical properties of the corn cob determined from a 1977 radial compression test are given in Table 5. Forty-five 3 cm-long middle sections of the corn cob composite from a single variety, Pickseed 165, planted at Macdonald College Farm, were radially compressed at 2 cm/min rate of loading. Analysis of the data obtained shows that cob moisture content is the least variable property, while cob modulus of toughness is the most variable property. Based on the variabilities in cob mechanical properties shown in Table 5, the required sample size for a 95% confidence level is about 62 for a 10% precision,* or 16 for a 20% precision (as calculated from methods described by Hahn (1975) and Steel and Torrie (1960)). However, if the experimenter is not interested in calculating cob modulus of toughness, the required sample size is lower. For the same confidence level, it is about 21 for a 10% precision or 6 for a 20% precision.

*The maximum allowable error in estimating the population mean.

TABLE 1. Mean values and variabilities in cob's physical and mechanical properties†

Properties	Symbol	Units	Mean value††	Standard deviation	Coeff. of variability %
Moisture content	MC	% w.b.	44.8	3.9	8.8
Diameter	2R	mm	25.5	2.3	8.9
Pith diameter	2r	mm	7.5	1.1	15.0
Crushing force	F_b	kN	1.2	0.3	25.0
Crushing strain	ϵ_b		0.15	0.02	13.3
Stiffness*	S	MPa	12.3	2.9	23.6
Apparent elastic modulus	E	MPa	25.9	5.7	22.0
Crushing strength	σ_c	MPa	5.3	1.2	22.6
Modulus of toughness	U	10^6 N-m/m^3	0.16	0.06	39.1

†Based on radial compression of 3 cm-long mid-section pieces of corn cob composite tested on 10-10-77. Rate of loading = 2 cm/min. Corn variety = Pickseed 165.

††Forty-five cob samples tested, each sample tested separately.

*Stiffness = M/ℓ, where M = slope of the upper portion of f-d curve and ℓ = length of sample tested.

Similar variabilities have been reported for the mechanical properties of other agricultural products (Finney, 1967; Bunyaphlanan, 1973; Paulsen, 1978). Bunyaphlanan (1973) determined the coefficients of variability for the force at bioyield, deformation at bioyield, modulus of deformability, minimum stress at bioyield and energy at bioyield of 40 carrot tissues. The minimum coefficient of variability determined was 6.61% for force at bioyield and the maximum was 24.40% for energy at bioyield (measured with an areagraph chart). Using an integrating device to measure automatically the area under the f-d curve of soybeans under compression, the variability in soybean toughness as determined by Paulsen (1978) averaged 32% and was in some cases up to 62%, depending on rate of deformation, moisture content or hilum position during test. Variabilities in rupture force and deformation determined for soybean were about 23% and 19% respectively.

7.3 Relation of cob size to cob mechanical properties

Data for Table 5 were grouped according to cob size as given in Table 6. This analysis indicates that, at both low and high cob moisture content levels,

1. cob apparent elastic modulus and cob crushing strength increase as the pith diameter or the ratio of the pith diameter to the cob diameter decreases, but they decrease as the mid-cob thickness (i.e., the difference between cob diameter and pith diameter) decreases;

TABLE 6. Relation of cob size with cob mechanical properties[†]

Size	Mechanical properties		
	Apparent elastic modulus MPa	Crushing strength MPa	Modulus of toughness $10^6 \times$ N-m/m^3
Cob diameter (2R)			
29 to 30 mm	34.2	6.3	0.15
27 to 28 mm	26.3	5.1	0.13
25 to 26 mm	24.3	5.1	0.15
23 to 24 mm	22.9	4.9	0.15
21 to 22 mm	27.2	6.4	0.26
Pith diameter (2r)			
10 mm	25.8	5.0	0.11
9 mm	24.2	4.7	0.19
8 mm	24.4	4.9	0.13
7 mm	26.7	5.7	0.18
6 mm	28.3	5.9	0.16
5 mm	31.8	7.4	0.28
2r/2R			
0.35 to 0.39	20.1	4.2	0.12
0.30 to 0.34	25.0	5.1	0.15
0.25 to 0.29	26.7	5.4	0.15
0.20 to 0.24	32.3	7.0	0.23
(2R - 2r)			
21 to 22 mm	38.6	7.2	0.16
18 to 20 mm	25.8	5.2	0.14
16 to 17 mm	26.6	5.7	0.19
14 to 15 mm	21.2	4.8	0.18

[†] See footnotes for Table 5.

2. cob modulus of toughness increases as cob diameter, pith diameter or the ratio of pith diameter to cob diameter decreases;
3. cob apparent elastic modulus and cob crushing strength are insensitive or not monotonically related to cob diameter; and
4. cob modulus of toughness is insensitive or not monotonically related to the mid-cob thickness.

The above relationships of cob size parameters to cob mechanical properties appear to be substantiated by the experimental work of Sehgal and Brown (1965). They found that there is a tendency for the large-pithed cobs to split more easily during combine harvesting than the small-pithed ones. They also determined that cobs with poorly developed inter-row tissues tend to split rather easily as compared with the ones which have well-developed inter-row tissues. Another supporting evidence from literature may be drawn from the experimental results of Paulsen (1978). He found that the average toughness was, in nearly all cases, greater for the small soybeans than for the large ones. This is in agreement with the dependency of cob modulus of toughness on cob size as determined in the present study.

7.4 Importance of cob macro-structural components

Figures 27a and 27b show that the f-d curves of the four simplified structural models of corn cob under radial compression are different. There are two major qualitative differences, viz,

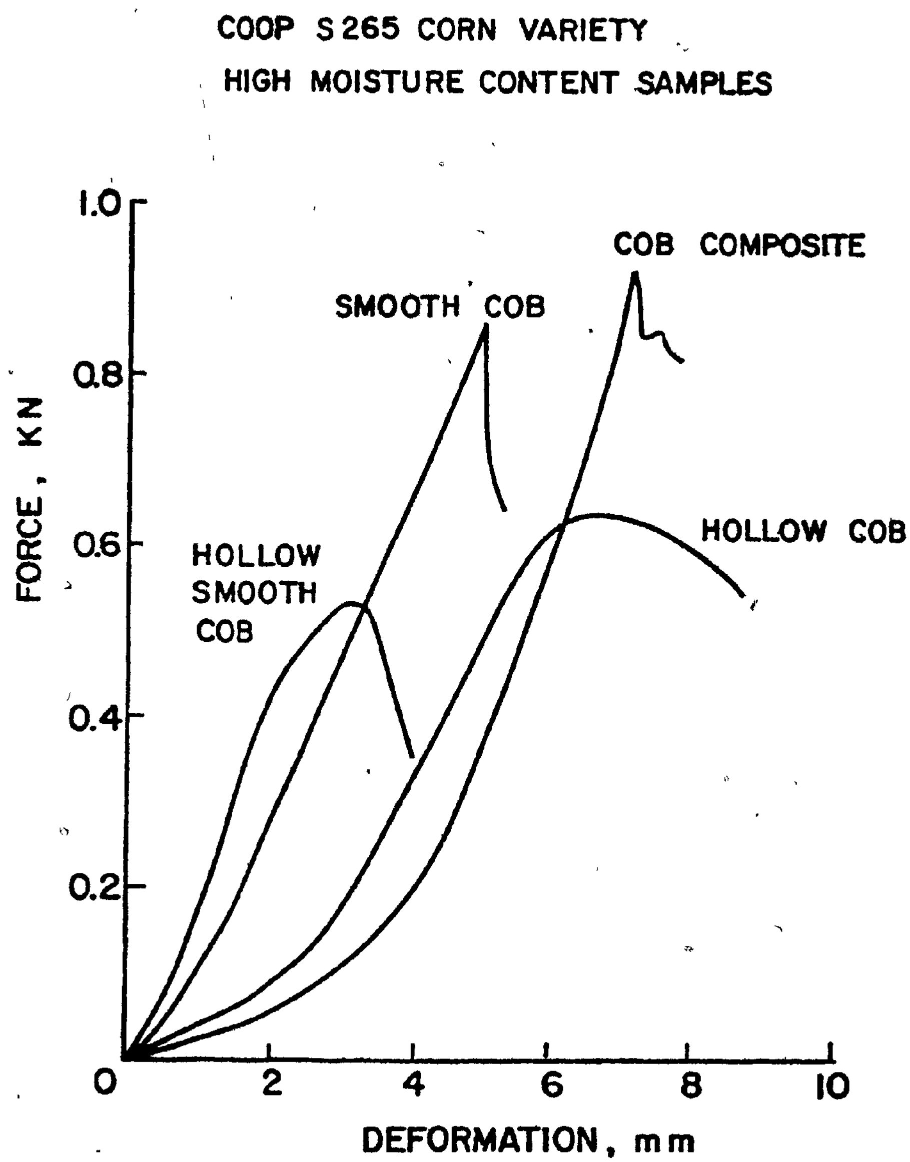


Figure 27(a). F-d curves of cob simplified models at high moisture content under radial compression

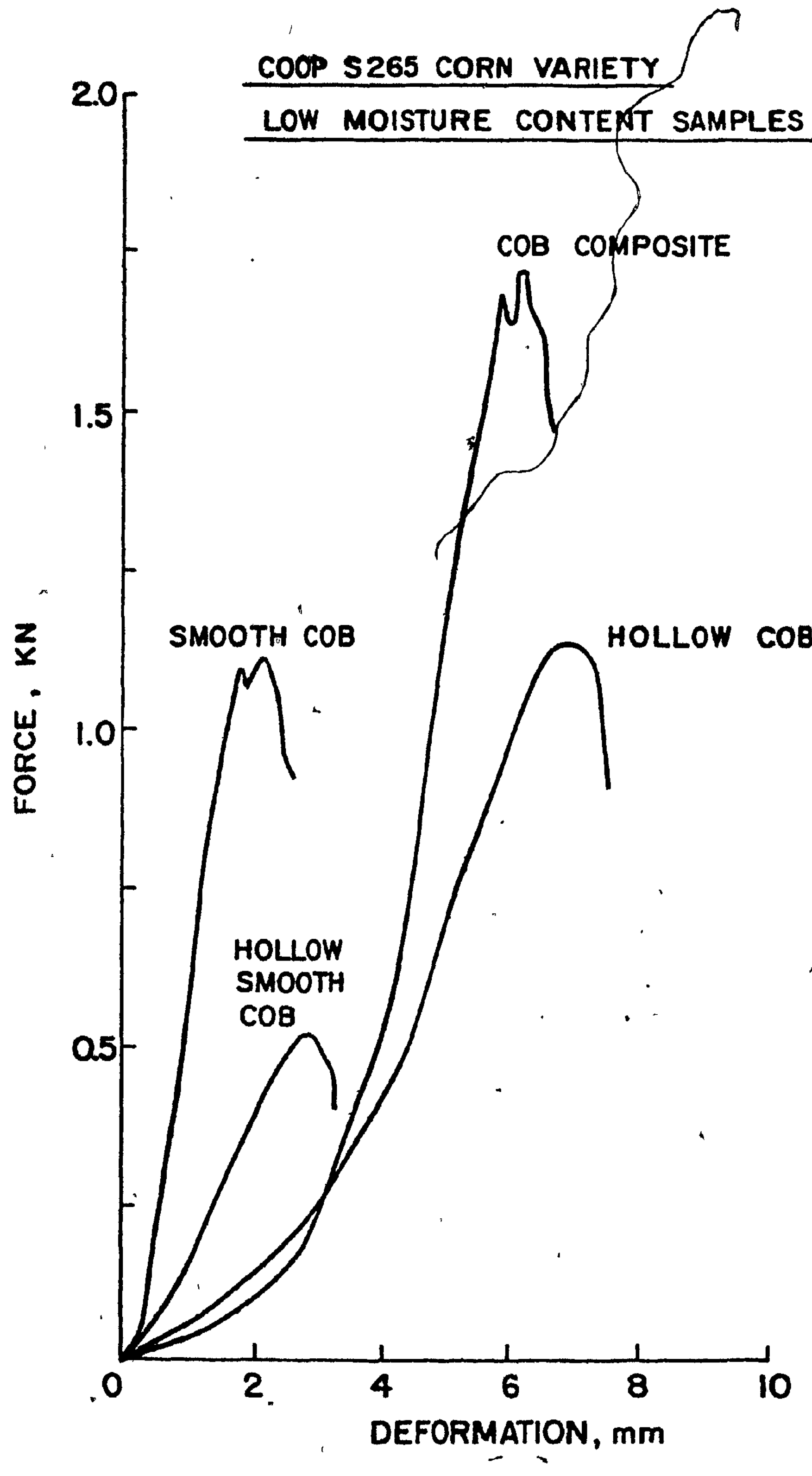


Figure 27(b). F-d curves of cob simplified models at low moisture content under radial compression

1. The initial non-linear behavior of the cob composite is only evident in the behavior of the hollow cob model but almost absent in those of the smooth cob and hollow smooth cob models. This observation establishes that the initial non-linear behavior of the cob composite under radial compression is essentially due to the initial flattening of the glume covering the cob composite.
2. The sudden drop in force at or near the maximum force recorded in the f-d curves of the cob composite and smooth cob models is absent in those of hollow cob and hollow smooth cob models. Thus, it could be concluded that the sudden drop in force at or near the peak force of the force-deformation curve of a radially compressed corn cob composite is due to pith cracking.

Quantitative analyses of Figures 27a and 27b and others similar to them, using the equations presented in this study, lead to the results shown in Table 7 and plotted in Figure 28. The apparent elastic modulus and the crushing strength of the smooth cob are the highest, while those of the hollow cob are the lowest, at both test dates. This immediately suggests that the pith contributes greatly to the apparent elastic modulus and the crushing strength of the corn cob composite. Moreover, the fact that the smooth cob has higher apparent elastic modulus and crushing strength values than the cob composite, indicates that the glume has a negative influence on both of these cob mechanical properties.

Furthermore, to quantify the relative contribution of each of the three major cob components to any mechanical property

TABLE 7. Mechanical properties of corn cob composite and those of its simplified structural models

Test date	Structural models	Properties†				
		MC % w.b.	ε_b	E MPa	σ_c MPa	U 10^5 N-m/m^3
06.10.78	Cob composite	49.8	0.14	20.8	4.1	1.2
	Smooth cob	46.4	0.13	23.2	4.3	1.4
	Hollow smooth cob	42.1	0.08	21.7	3.0	0.3
	Hollow cob	40.3	0.17	10.9	2.4	0.8
20.10.78	Cob composite	9.4	0.10	53.8	8.4	1.7
	Smooth cob	10.4	0.09	71.9	8.7	1.4
	Hollow smooth cob	8.0	0.11	34.2	5.2	0.9
	Hollow cob	10.4	0.15	22.4	4.5	0.9

† See Table 5 for definitions of symbols.

Each value is the average of three test samples.

Corn variety = Co-op S-265. Loading rate = 1 cm/min.

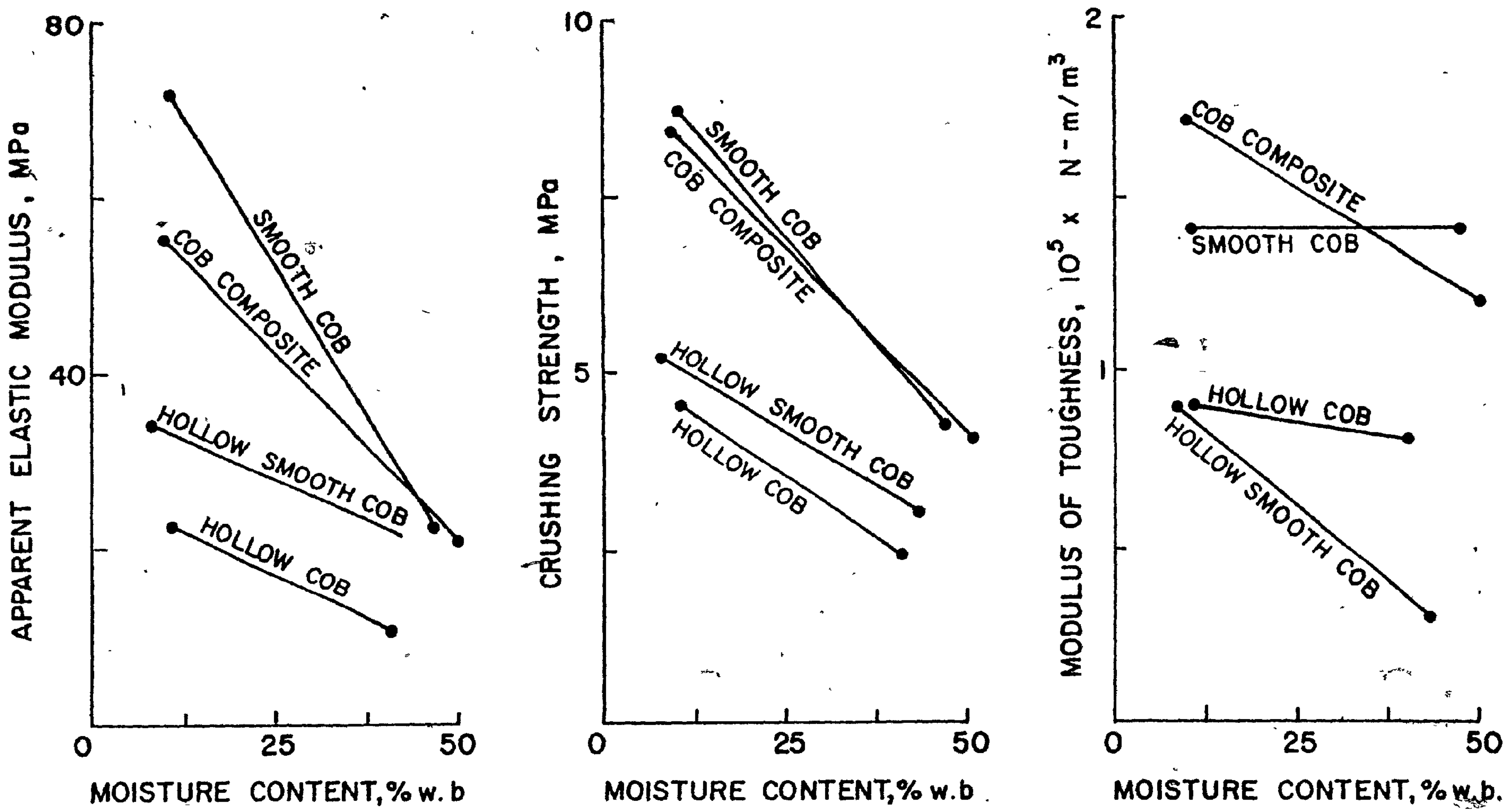


Figure 28. Mechanical properties of simplified models of corn cob in radial compression

of the cob composite, for instance, the apparent elastic modulus, the following approximate expressions were used.

1. For per cent contribution of glume to cob composite elastic modulus, the expression is

   "$100(E_{cc} - E_{sc})/E_{cc}$"

2. Per cent contribution of pith to cob composite elastic modulus is expressed as

   "$100(E_{cc} - E_{hc})/E_{cc}$"

3. Per cent contribution of mid-cob to cob composite elastic modulus is determined as

   "$100\ E_{hsc}/E_{cc}$"

where E is the apparent elastic modulus and the subscripts cc, sc, hc and hsc denote cob composite, smooth cob, hollow cob and hollow smooth cob, respectively. The calculated percentage contributions were then adjusted as shown in Table 8, since the properties of the cob components are not strictly additive.

A negative percentage contribution by any cob component implies that the component in question reduces the cob composite mechanical property being considered. Thus, Table 8 shows that the pith has a very substantial positive contribution to cob mechanical properties, particularly when the cob is dry. The mid-cob, however, has the greatest positive contribution to cob mechanical properties at both levels of moisture content tested. In contrast, the glume tends to lower the values of cob mechanical properties determined. Indeed, the

TABLE 8. Relative contribution of the three major components of corn cob to its mechanical properties

Cob components	Adjusted† percentage contributions††				
	MC	ε_b	E	σ_c	U
Glume					
wet	6.3	16.6	-8.6	-4.6	-41.5
(dry)	(-16.6)	(14.3)	(-38.0)	(-3.4)	(15.0)
Pith					
wet	17.1	-50.0	34.3	37.6	80.5
(dry)	(-16.6)	(-71.4)	(66.1)	(44.3)	(40.0)
Mid-cob					
wet	76.6	133.4	74.3	67.0	61.0
(dry)	(133.0)	(157.1)	(71.9)	(59.1)	(45.0)
†Adjustment ratio	110/100 (64/100)	43/100 (70/100)	140/100 (88/100)	109/100 (105/100)	41/100 (118/100)

††The percentage contributions are calculated from Table 7.

actual importance of the glume to the cob mechanical properties as related to corn shelling in a combine cylinder-concave is questionable. In this respect, the smooth cob may be the most appropriate structural model for determining cob mechanical properties as related to corn combine harvesting.

7.5 Effects of moisture content and rate of loading

Based on 1978 laboratory investigations, Figures 29 and 30 demonstrate the effects of moisture content on the f-d curves of corn cobs obtained in radial compression and simple bending. From similar experimental f-d curves, and using the equations presented in this thesis, the mechanical properties of corn cobs were calculated for the different moisture content levels and rates of loading. The results, including statistical analyses, are presented in Tables 9 to 14 and plotted in Figures 31 to 35.

All the cob mechanical properties determined with the exception of cob modulus of toughness and crushing strain, were found to be significantly affected by cob moisture content. None of these properties was shown to be significantly affected by rate of loading in both radial compression and simple bending. Apart from cob crushing strain, the values of all cob mechanical properties determined increased significantly as the cob moisture content was decreased. Essentially, the values of cob crushing strain determined decreased with cob moisture content, although this was not significant at 0.05

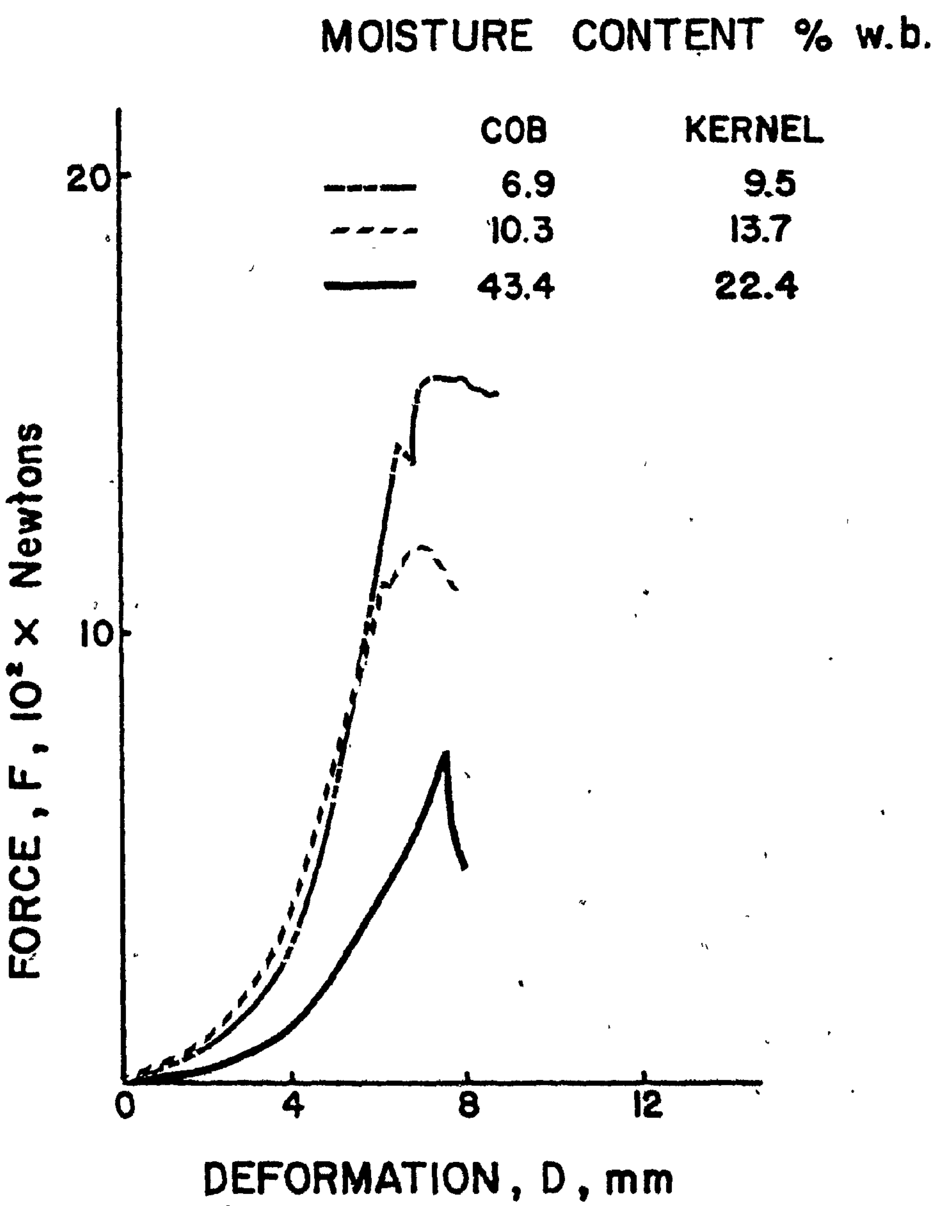


Figure 29. Effects of moisture content on radial compression of corn cob composite

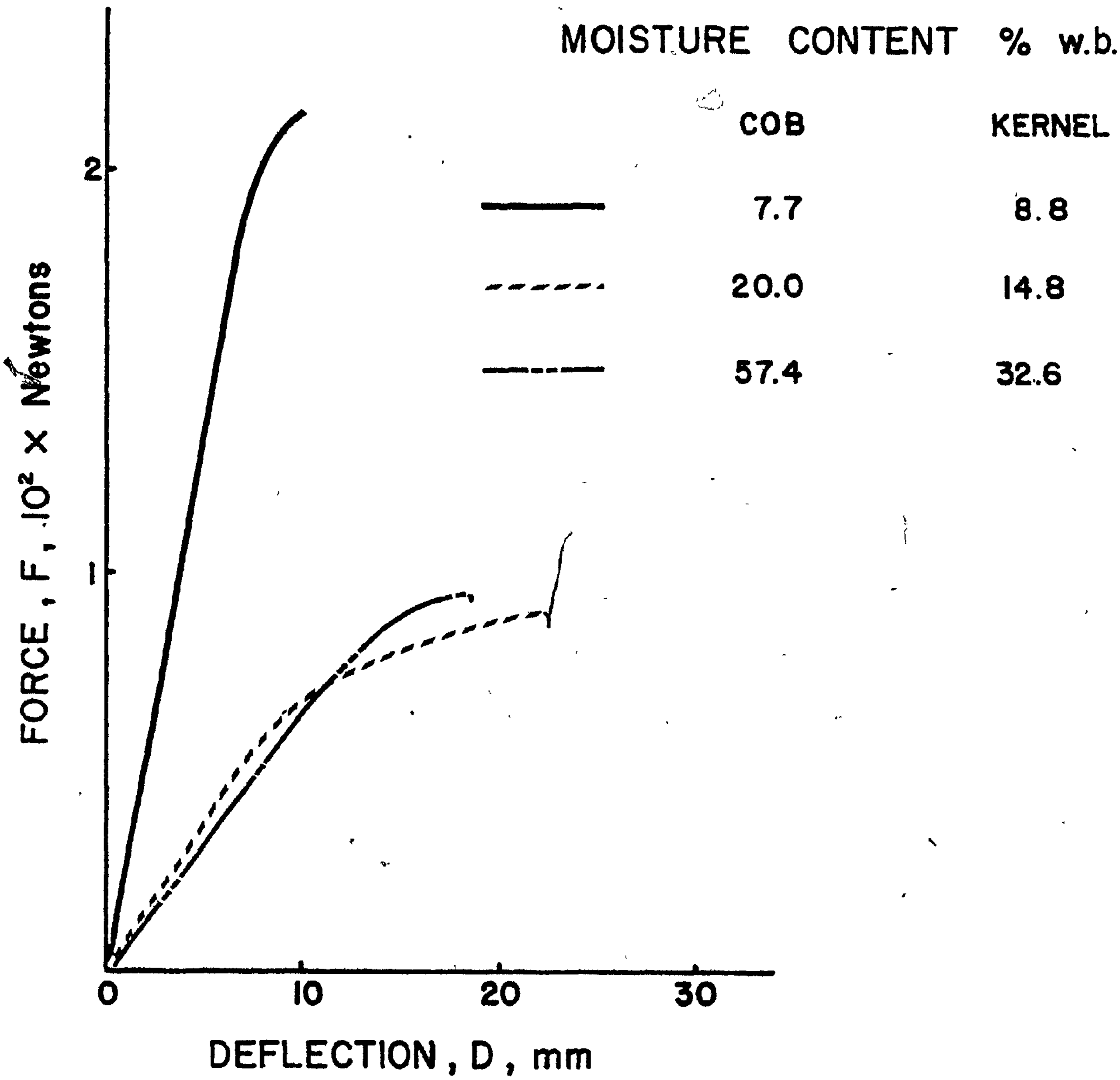


Figure 30. Effects of moisture content on simple bending of a whole-length corn cob composite

TABLE 9. Effects of moisture content and rate of loading on cob mechanical properties in radial compression (1978)†

	Test date								
	13.10.78			27.10.78			07.11.78		
Kernel moisture content, % w.b.	22.4			13.7			9.5		
Rate of loading, cm/min	0.5	1.0	3.0	0.5	1.0	3.0	0.5	1.0	3.0
Cob moisture content, % w.b.	41.4	44.1	44.7	11.9	10.1	8.8	6.9	6.8	7.0
Cob diameter, 2R, mm	26.3	25.6	25.6	24.5	24.4	24.7	25.3	24.8	24.7
Pith diameter, 2r, mm	8.8	8.4	8.3	8.5	8.3	9.0	8.0	8.3	7.9
Crushing force, F_b, kN	0.71	0.73	0.82	0.86	1.07	1.18	1.39	1.24	1.54
Crushing strain, ϵ_b	0.13	0.15	0.15	0.11	0.13	0.11	0.12	0.11	0.13
Degree of elasticity, β, %	48.8	52.1	49.5	44.0	52.4	47.0	47.3	46.9	47.6
Elastic modulus, E, MPa	18.0	16.0	18.0	29.0	31.0	41.0	41.0	43.0	44.0
Crushing strength, σ_c, MPa	3.4	3.2	3.7	5.4	6.1	6.8	7.7	8.0	8.0
Modulus of toughness, U, 10^6 x N-m/m^3	0.09	0.16	0.19	0.14	0.23	0.25	0.26	0.20	0.30

†Each value is the mean of three test samples. Co-op S-265 corn variety. 3 cm-long cob samples used.

TABLE 10. Summary of analyses of variance on effects of moisture content and rate of loading in radial compression (1978)†

Source of variation	Degrees of freedom	F values			
		Elastic modulus	Crushing strength	Modulus of toughness	Crushing strain
Total	8				
Moisture content (test date), B	2	43.23**	123.4**	5.16 ns	4.75 ns
Rate of loading, T	2	1.93 ns	2.75 ns	3.18 ns	0.75 ns
Experimental error, B x T	4				

†1978 radial compression data (Table 9). Analysis of variance performed on means of three test samples.

** Significant at 0.01 level.

ns Not significant at 0.05 level.

TABLE 11. Main effects of cob moisture content and rate of loading on cob mechanical properties in radial compression (1978)†

Test date	Cob moisture content % w.b.	Elastic modulus MPa	Crushing strength MPa	Modulus of toughness $10^6 \times N\text{-}m/m^3$	Crushing strain
13.10.78	43.4	17.3 a	3.4 a	0.15 a	0.143 a
27.10.78	10.3	33.7 b	6.1 b	0.21 ab	0.117 a
07.11.78	6.9	42.7 c	7.9 c	0.25 b	0.120 a
	Rate of loading cm/min	**Elastic modulus MPa**	**Crushing strength MPa**	**Modulus of toughness $10^6 \times N\text{-}m/m^3$**	**Crushing strain**
	0.5	29.3 a	5.5 a	0.16 a	0.120 a
	1.0	30.0 a	5.8 a	0.20 a	0.130 a
	3.0	34.3 a	6.2 a	0.25 a	0.130 a

†Each value is the mean of nine test samples.

In each column, means with the same letter are not significantly different at 0.05 level as determined by Duncan's new multiple range test.

Corn variety, Co-op S-265.

TABLE 12. Effects of moisture content and rate of loading on cob mechanical properties in simple bending (1978)†

	Test date								
	03.10.78			17.10.78			05.11.78		
Kernel moisture content, % w.b.		32.6			14.8			8.8	
Rate of loading, cm/min	1	3	5	1	3	5	1	3	5
Cob moisture content, % w.b.	59.2	57.2	54.5	21.6	18.4	20.0	6.6	9.1	7.3
Tip-end diameter, d_1, mm	22.5	21.8	22.9	22.0	20.7	20.5	22.0	22.7	22.2
Butt-end diameter, d_2, mm	31.5	30.9	32.9	31.5	29.2	29.7	30.9	31.5	30.2
Maximum breaking force, F_b, N	77.5	81.4	96.9	82.4	97.1	78.5	190.2	211.8	223.6
Maximum deflection, D_b, mm	16.7	18.7	17.6	23.7	22.2	22.5	10.4	10.9	11.7
Degree of elasticity, β, %	54.8	55.4	56.9	53.0	52.7	54.0	51.2	53.9	62.3
Elastic modulus, E_b, MPa	23.4	24.0	24.1	18.9	32.1	24.0	106.9	98.1	95.1
Bending strength σ_b, MPa	1.5	1.7	1.7	1.7	2.4	1.9	4.0	4.1	4.8

†Each value is the mean of three test samples. Co-op S-265 corn variety. Loading span = 150 mm.

TABLE 13. Summary of analyses of variance on effects of moisture content and rate of loading in simple bending†

Source of variation	Degrees of freedom	F values	
		Elastic modulus	Bending strength
Total	8		
Moisture content (test date), B	2	158.96**	64.10**
Loading rate, T	2	0.28 ns	1.41 ns
Experimental error, B x T	4		

† 1978 simple bending data (Table 12). Analysis of variance performed on means of three test samples.

** Significant at 0.01 level.

ns Not significant at 0.05 level.

TABLE 14. Main effects of cob moisture content and rate of loading on cob mechanical properties in simple bending†

Test date	Cob moisture content, % w.b.	Elastic modulus MPa	Bending strength MPa
03.10.78	57.0	23.8 a	1.6 a
17.10.78	20.0	25.0 a	2.0 a
05.11.78	7.7	100.0 b	4.3 b
	Rate of loading cm/min	Elastic modulus MPa	Bending strength MPa
	1	49.7 a	2.4 a
	3	51.4 a	2.7 a
	5	47.7 a	2.8 a

†Each value is the mean of nine test samples.

In each column, means with the same letter are not significantly different at 0.05 level as determined by Duncan's new multiple range test.

Corn variety was Co-op S-265.

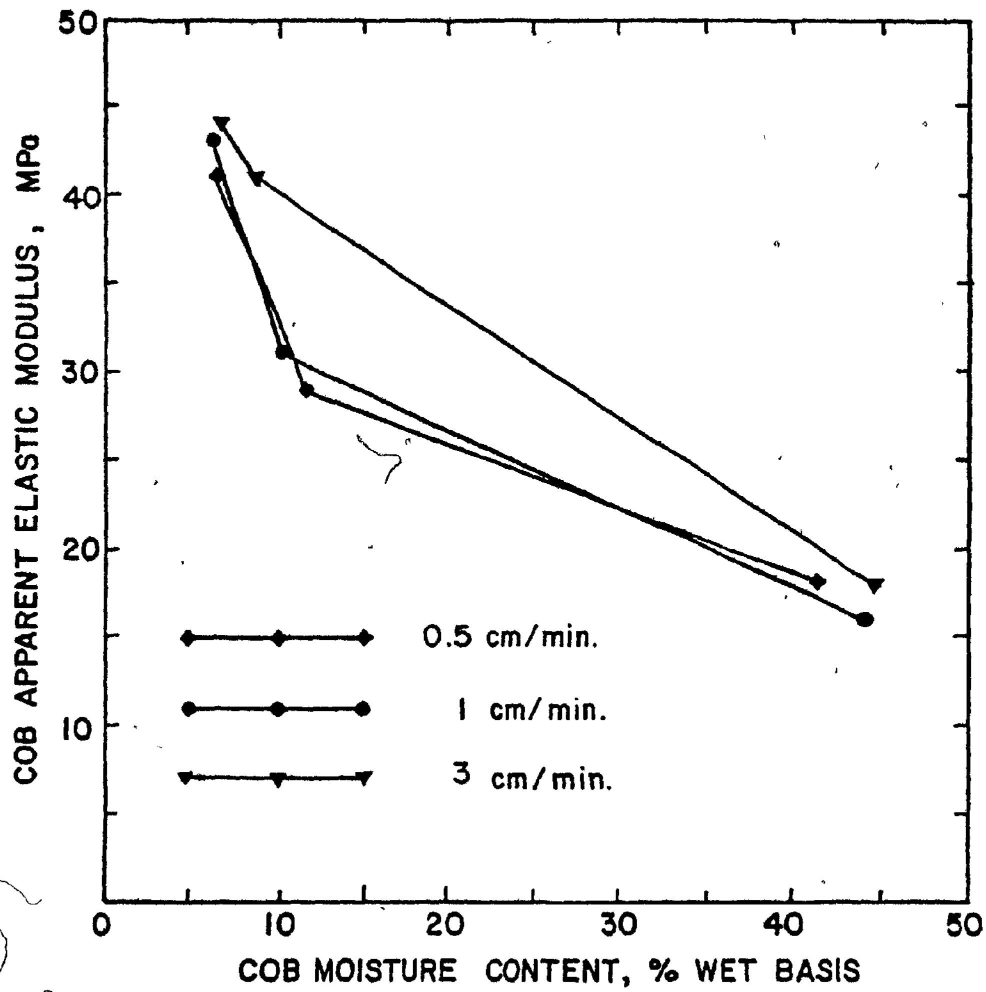


Figure 31. Effects of moisture content and loading rate on cob apparent elastic modulus in radial compression (1978). Each data point is the mean for three test samples.

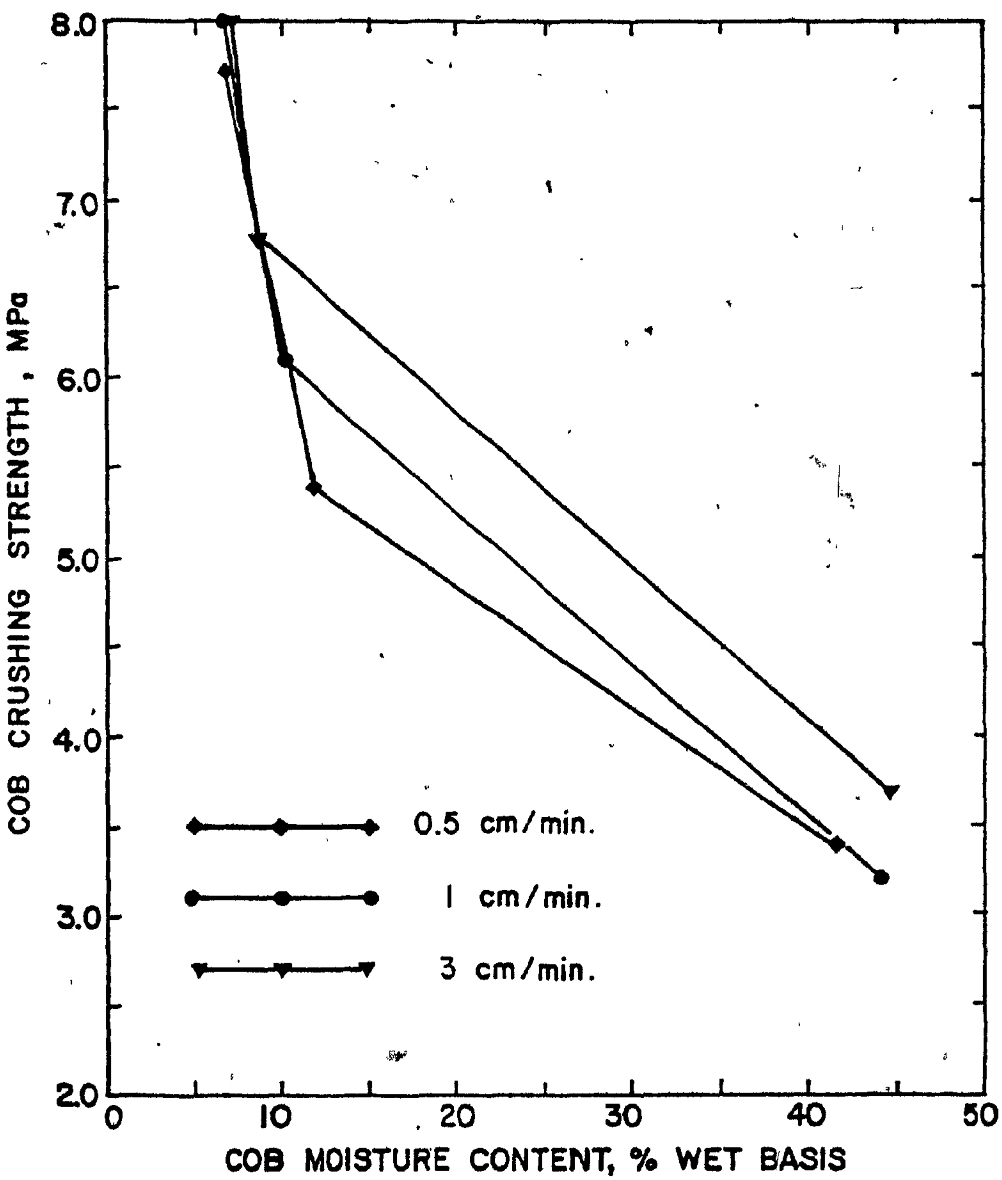


Figure 32. Effects of moisture content and loading rate on cob crushing strength (1978). Each data point is the mean for three test samples.

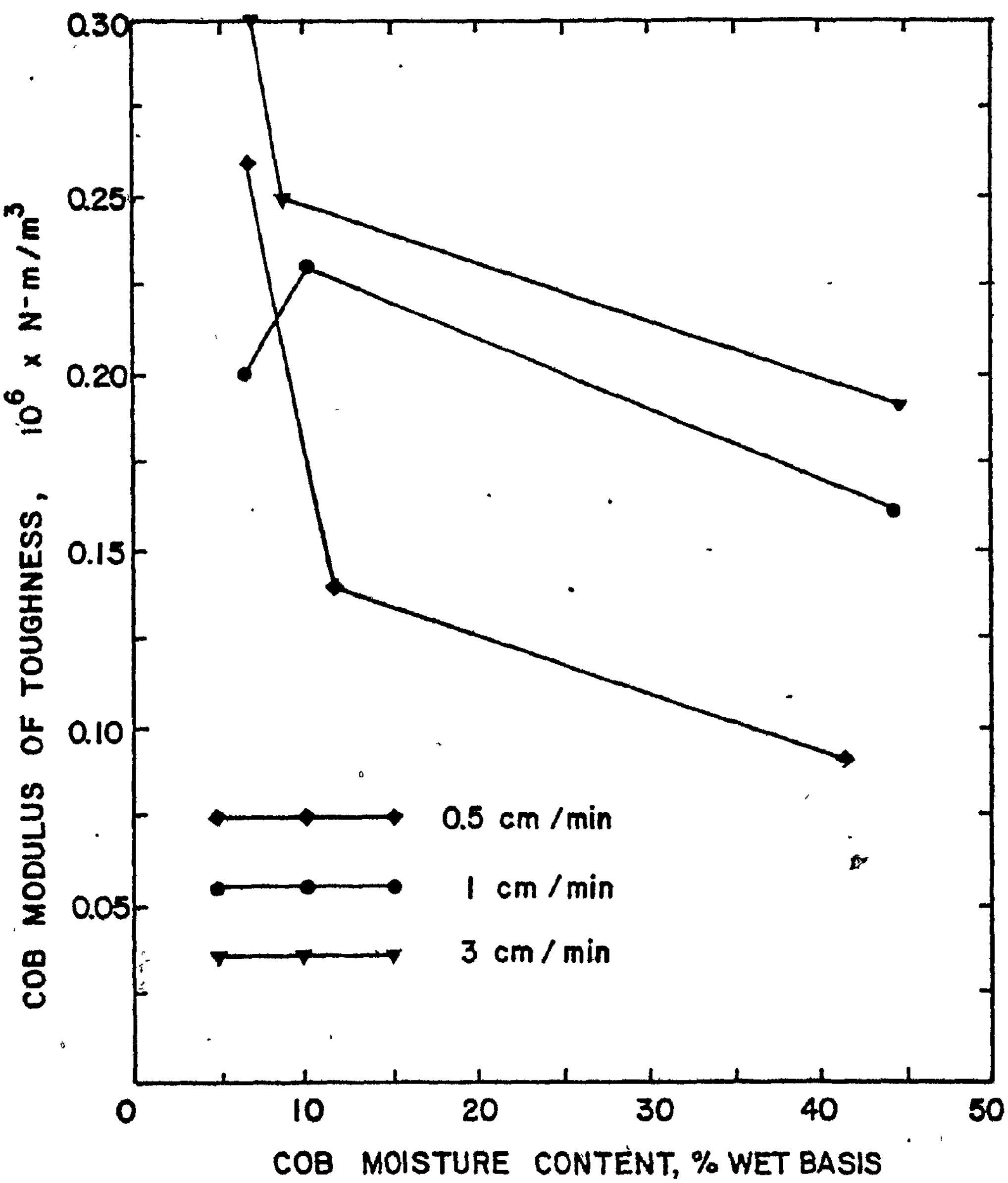


Figure 33. Effects of moisture content and loading rate on cob modulus of toughness in radial compression (1978). Each data point is the mean for three test samples.

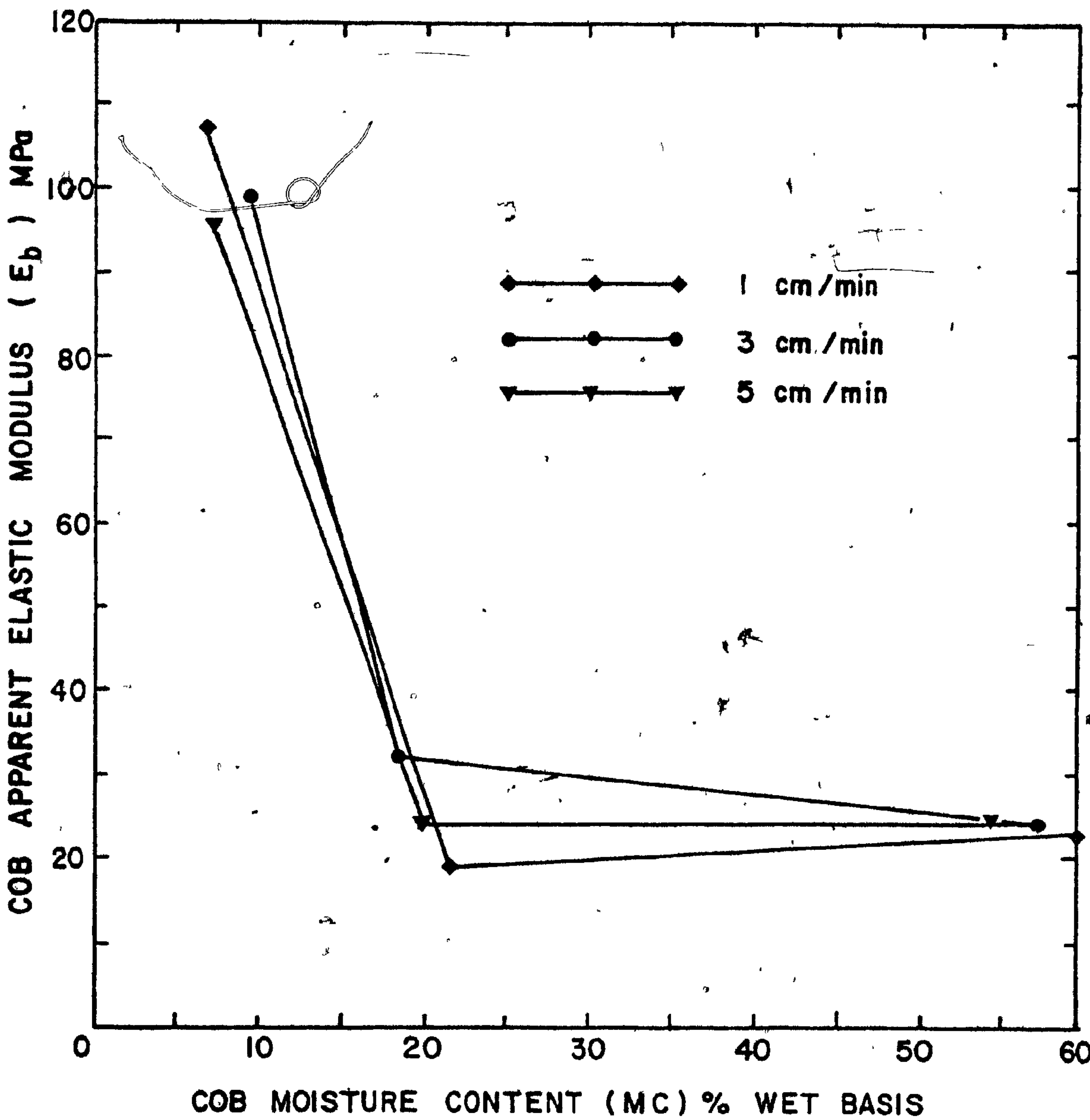


Figure 34. Effects of moisture content and rate of loading on cob apparent elastic modulus in simple bending (1978). Each data point is the mean for three test samples.

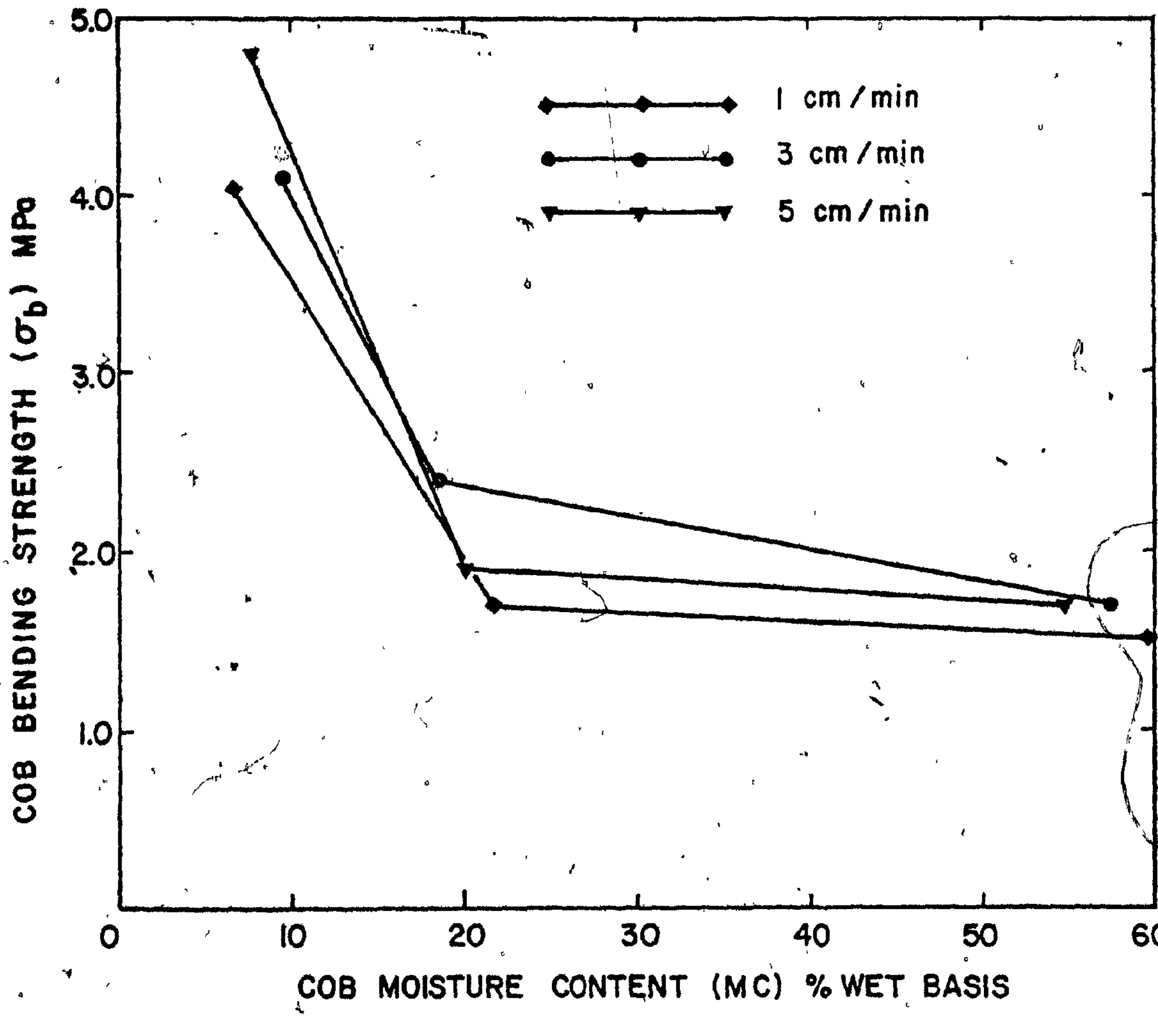


Figure 35. Effects of moisture content and rate of loading on cob bending strength (1978). Each data point is the mean for three test samples.

level. Apart from cob apparent elastic modulus in simple bending, all cob mechanical properties determined tended to increase in magnitude with increase in rate of loading, but the increases were not significant at 0.05 level.

From the 1979 investigations on the effects of cob moisture content and rate of loading in radial compression, Table 15 confirms that cob mechanical properties, including cob modulus of toughness, are significantly affected by cob moisture content, while they are not significantly affected by rate of loading. The interactions between these two factors are not significant at 0.05 level. The same experiment, as shown in Table 16, also confirms that cob mechanical properties increase significantly with decrease in cob moisture content. Regression analyses on the simple effects of cob moisture content on cob mechanical properties at each of the three rates of loading (Table 17) suggest that cob apparent elastic modulus and cob crushing strength are each linearly related to cob moisture content, while cob modulus of toughness has a non-linear relationship with cob moisture content (Table 18 and Figure 36).

The effects of moisture content on cob mechanical properties as determined in this study, are in general agreement with those reported in literature for other agricultural products (Zoerb and Hall, 1960; Shelef and Mohsenin, 1969; Middendorf <u>et al</u>., 1973; Paulsen, 1978). Apparent elastic modulus, ultimate compressive strength and modulus of toughness increase, while ultimate compressive deformation decreases

TABLE 15. Summary of analyses of variance on effects of moisture content and rate of loading (1979)†

Source of variation	Degrees of freedom	F values		
		Apparent elastic modulus	Crushing strength	Modulus of toughness
Total	239			
Moisture content (test date) B††	4	101.06**	239.10**	9.44**
Loading rate, T††	2	1.10 ns	2.70 ns	1.12 ns
Experimental error, B x T†††	8	1.32 ns	0.32 ns	0.56 ns
Sampling error, S (B x T)	225			

†1979 radial compression data on Warwick SL-207. Five test dates: 20/09, 26/09, 04/10, 10/10, and 24/10/79. Three rates of loading: 0.5, 1.0 and 5.0 cm/min. Further details in Appendix E, Tables E1 and E2.

††Tests of hypotheses based on B x T as the error term.

†††Test of hypotheses based on S (B x T) as the error term.

**Significant at 0.01 level.

ns Not significant at 0.05 level.

TABLE 16. Main effects of moisture content on cob mechanical properties in radial compression (1979)†

Test date	Cob moisture content % w.b.	Apparent elastic modulus MPa	Crushing strength MPa	Modulus of toughness 10^6 x N-m/m^3
20.09.79	49.2	14.7 a	2.4 a	0.045 ab
26.09.79	44.0	20.0 a	2.8 b	0.049 b
04.10.79	24.5	35.4 b	3.7 c	0.050 b
10.10.79	20.6	43.1 c	4.0 c	0.041 a
24.10.79	8.5	61.3 d	6.1 d	0.059 c

†Each value is the mean of 48 test samples.

In each column, means with the same letter are not significantly different at 0.05 level as determined from Duncan's new multiple range test. Corn variety = Warwick SL-207.

TABLE 17. Simple effects of cob moisture content on cob mechanical properties at three rates of loading† (0.5, 1.0 and 5.0 cm/min)

Test date	Cob moisture content†† % wet basis			Apparent elastic modulus MPa			Crushing strength MPa			Modulus of toughness 10^6 x N-m/m^3		
	0.5	1.0	5.0	0.5	1.0	5.0	0.5	1.0	5.0	0.5	1.0	5.0
20.09.79	49.6	49.5	48.5	15.6	12.7	15.9	2.3	2.2	2.6	0.040	0.048	0.047
26.09.79	45.1	44.8	42.1	20.1	20.1	19.8	2.8	2.8	2.8	0.053	0.050	0.044
04.10.79	24.6	26.1	22.8	33.0	37.9	35.2	3.5	3.9	3.8	0.049	0.051	0.049
10.10.79	21.3	20.8	19.7	42.8	42.6	44.0	3.8	4.0	4.1	0.036	0.044	0.043
24.10.79	8.6	8.6	8.2	61.4	54.8	67.9	6.1	5.8	6.4	0.056	0.058	0.063

†Each value is the mean of sixteen test samples. Warwick SL-207 variety.

††Kernel moisture contents are, respectively, 30.2, 23.2, 15.4, 15.2 and 10.4% wet basis.

TABLE 18. Regression equations of cob mechanical properties on cob moisture content (MC, % wet basis)†

Mechanical properties	Symbols	Units	Rates of loading cm/min	Regression equations††	Correlation coefficients r
Apparent elastic modulus	E	MPa	0.5	$E = 65.759 - 1.045\ (MC)$	−0.971
			1.0	$E = 63.671 - 1.003\ (MC)$	−0.998
			5.0	$E = 70.651 - 1.206\ (MC)$	−0.960
Crushing strength	σ_c	MPa	0.5	$\sigma_c = 6.041 - 0.078\ (MC)$	−0.918
			1.0	$\sigma_c = 6.097 - 0.079\ (MC)$	−0.971
			5.0	$\sigma_c = 6.311 - 0.084\ (MC)$	−0.921
Modulus of toughness	U	$10^6 \times \frac{N\text{-}m}{m^3}$	0.5	$U = 0.062 - 0.011 \log (MC)$	−0.380
			1.0	$U = 0.065 - 0.010 \log (MC)$	−0.609
			5.0	$U = 0.078 - 0.021 \log (MC)$	−0.790

†Experimental data from Table 17.

††The regression equation with the highest absolute value of the coefficient of correlation was selected for each mechanical property at each rate of loading.

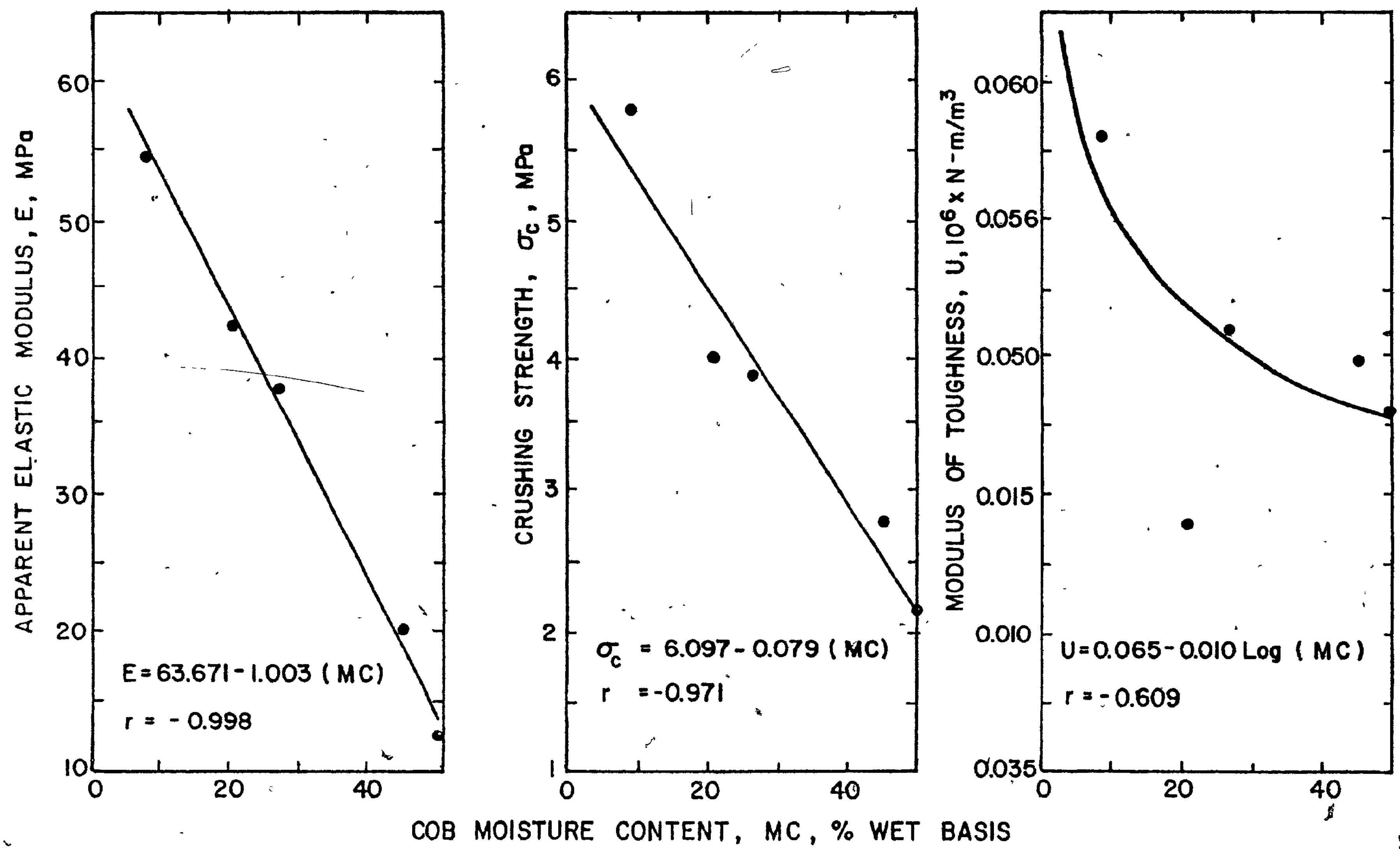


Figure 36. Regressions of cob mechanical properties on cob moisture content (1979). Rate of loading 1 cm/min Each data point is the mean of sixteen test samples.

with decrease in the moisture content of the agricultural product. Stage of maturity of the agricultural product and the inherent variations in biological materials may change some of these effects, particularly that on deformation which is usually the least affected mechanical property.

This dependence of mechanical properties of biological materials on their moisture contents has not been adequately explained. However, as suggested by Shelef and Mohsenin (1969), the addition of water molecules in a dry material could lead to some geometrical re-arrangement of the chain units in the material micro-structure which were previously very close to each other. It could also result in the lowering of the friction coefficient between adjacent cellular units of the material. Under such conditions the deformations under a given load would gradually increase and the modulus of elasticity would decrease with increase in the number of water molecules present (Shelef and Mohsenin, 1969).

On the other hand, while it is generally agreed that rate of loading affects the mechanical properties of agricultural products due to their viscoelastic nature, experimental results reported in the literature did not show a consistent influence (see, for instance, Mohsenin _et al._, 1963; Fletcher _et al._, 1965; Fletcher, 1971; Prasad and Gupta, 1975; Paulsen, 1978). There are, however, some indications that at low rates of loading (less than 10 cm/min) all the mechanical properties increase with increase in rate of loading; while at high rates of loading (above 10 cm/min) there is a reversal in this trend for some of the mechanical properties at some critical loading rate region, shown by Fletcher et al. (1965).

7.6 Effects of corn variety and harvest date

Based on 1978 experimental data, Table 19 and Figure 37 show a strong dependency of corn cob mechanical properties on corn variety, at both moisture content levels. Warwick SL-207, grown as a grain corn, is clearly mechanically stiffer and stronger than Asgrow RX-30, grown as a silage corn. However, at low moisture content, the silage corn has tougher cobs than the grain corn. This varietal effect is not necessarily due to the slight differences in cob moisture content and cob size, as can be seen by studying Tables 6 and 19. It could be due to some undetermined differences in their cob morphological structure and chemical compositions. The two varieties were planted on the same date and on the same site and were hand-harvested on the same date. The same fertilizer treatments and other production inputs were applied to both varieties on the same days.

Table 20 gives a summary of a statistical analysis performed on 1979 experimental data in which the effects of corn variety and harvest date were investigated. Variety is a highly significant factor for cob crushing strength and cob modulus of toughness, a significant factor for cob elastic modulus in simple bending and cob bending strength, but it has no significant effect (at 0.05 level) on cob

TABLE 19. Effects of variety on corn cob physical and mechanical properties†

Properties	Test dates 29.09.78 Varieties Y	Z	18.10.78 Y	Z
Moisture content, % w.b.	49.2	38.2	7.3	7.6
Diameter, 2R, mm	23.9	24.1	24.4	25.3
Pith diameter, 2r, mm	6.5	7.9	6.2	6.4
2r/2R	0.27	0.33	0.25	0.25
Crushing force, kN	1.3	0.8	1.8	2.0
Crushing strain	0.16	0.17	0.10	0.14
Stiffness, MPa	13.0	5.2	25.6	20.4
Apparent elastic modulus, MPa	28.3	16.0	70.5	46.2
Crushing strength, MPa	5.9	3.5	11.2	9.2
Modulus of toughness, $10^6 \times$ N-m/m^3	0.20	0.19	0.20	0.26

† Y = Warwick SL-207; Z = Asgrow RX-30.

Three centimeter-long cob samples at 1 cm/min rate of loading.

Each value is the average of three test samples.

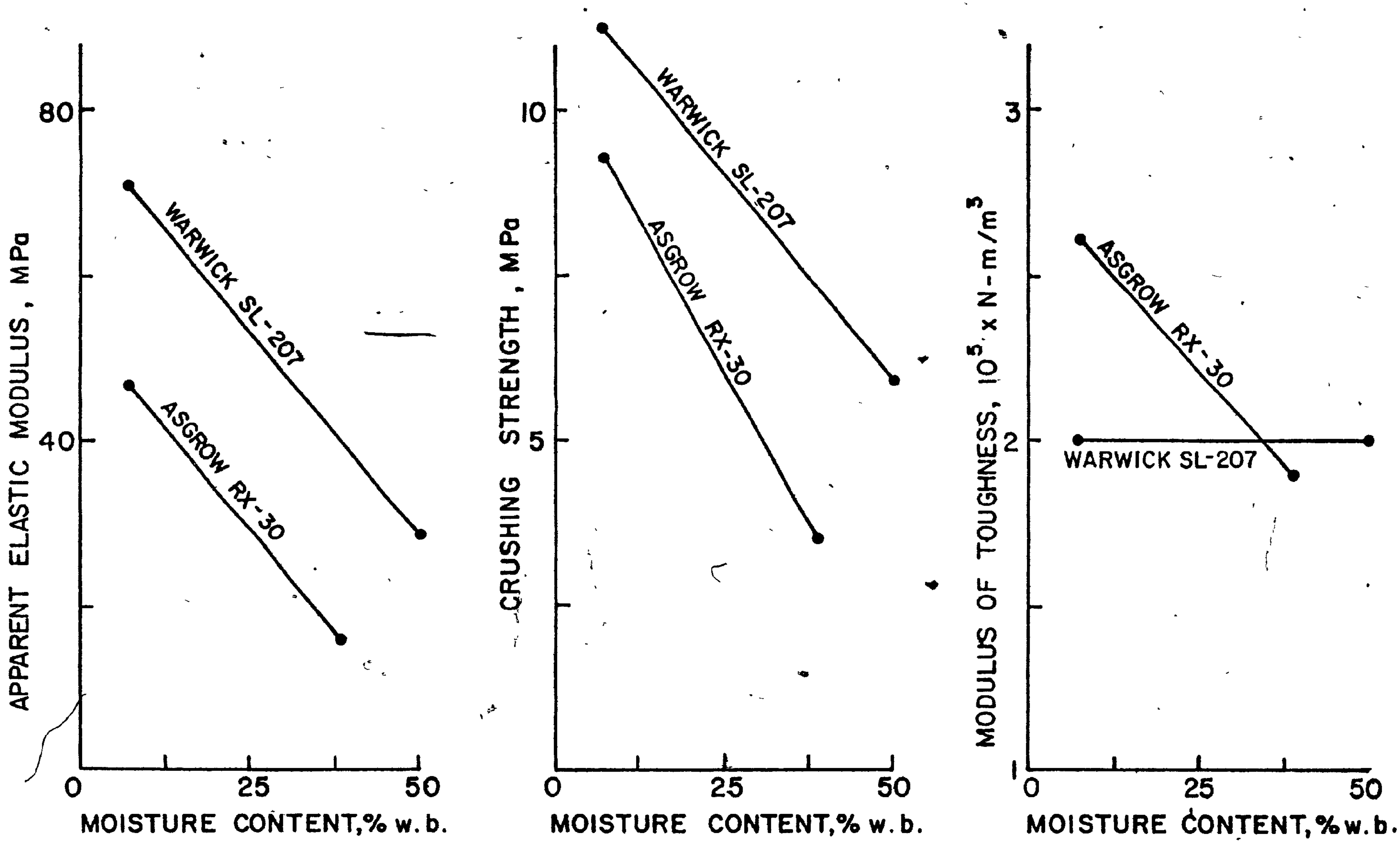


Figure 37. Effects of variety on cob mechanical properties in radial compression (1978).

TABLE 20. Effects of variety and harvest date on corn cob physical and mechanical properties: summary of statistical analyses of variance[†]

Source of variation	Degrees of freedom	F values[††]							
		E[†††]	σ_c	U	E_b	σ_b	MC	2R	2r
Total	26								
Block, R	2								
Variety, A	2	6.00 ns	167.46**	41.10**	15.62*	15.29*	0.34 ns	1.61 ns	11.37*
R x A	4								
Harvest date, B	2	6.24*	0.84 ns	15.64**	8.46**	7.22**	66.83**	18.36**	99.88**
A x B	4	5.05*	6.93**	7.50**	0.81 ns	0.68 ns	2.62 ns	1.38 ns	1.35 ns
A (R x B)	12								

[†]Based on data from 1979 split-plot experiment. Analyses perofrmed on means of seven test samples. Further details in Appendix E, Tables E3 and E4.

[††] ns = not significant at 0.05 level; * = significant at 0.05 level; ** = significant at 0.01 level.

[†††]All symbols defined in the list of symbols and abbreviations.

apparent elastic modulus in radial compression. On the other hand, harvest date is found to be a highly significant factor for cob modulus of toughness, cob elastic modulus in simple bending and cob bending strength, a significant factor for cob apparent elastic modulus in radial compression, but it has no significant effect (at 0.05 level) on cob crushing strength.

The differences in the mechanical properties of the three corn varieties tested could not be directly associated with any differences in cob moisture content nor in cob diameter since these properties were not significantly affected by this factor. On the other hand, the influence of harvest date on cob mechanical properties could be attributed to the highly significant changes in cob physical properties as harvesting was delayed.

In the same analysis, Table 20, it is found that the interactions between variety and harvest date are highly significant for radial compression but not significant for simple bending.

The main effects of variety on cob physical and mechanical properties are shown in Table 21. Asgrow RX 23 has consistently higher values of cob mechanical properties than Warwick SL-207. Cob apparent elastic modulus, in both radial compression and simple bending, and cob bending strength are not found to be significantly different at 0.05 level for Asgrow RX 23 and Funk G4065, but the former has significantly higher values of cob crushing strength and cob modulus of toughness. In simple bending, the values of cob

TABLE 21. Main effects of variety on cob physical and mechanical properties (Duncan's new multiple range test)†

Properties††	Varieties†††		
	Warwick SL-207	Funk G4065	Asgrow RX 23
E, MPa	20.8 a	22.8 ab	24.4 b
σ_c, MPa	2.9 a	3.2 b	3.9 c
U, 10^6 N-m/m^3	0.056a	0.061a	0.107b
E_b, MPa	20.3 a	40.9 b	35.0 b
σ_b, MPa	1.5 a	2.2 b	2.0 b
MC, % w.b.	40.3 a	40.5 a	42.0 a
2R, mm	26.1 a	25.3 a	25.1 a
2r, mm	8.1 a	8.5 a	7.6 b
2r/2R	0.31	0.34	0.30
Kernel MC, % w.b.	24.4	27.9	26.8

† Each value is the mean of 63 test samples.

†† Symbols are defined in the list of symbols and abbreviations.

††† Values in a row with the same letter are not significantly different at 0.05 level.

mechanical properties of Funk G4065 are found to be significantly higher than those of Warwick SL-207, despite the similarity in their physical properties. However, in radial compression, with the exception of cob crushing strength values, the calculated values of cob mechanical properties for Funk G4065 are not significantly higher than those for Warwick SL-207.

The main effects of harvest date on cob physical and mechanical properties are presented in Table 22. Cob apparent elastic modulus in radial compression is found to increase significantly from the first harvest date (22.09.79) to the second harvest date (06.10.79) but it decreased significantly later (20.10.79). Delays in harvesting the three varieties of corn planted did not, in general, lead to any significant differences in the calculated values of cob crushing strength. Cob modulus of toughness, cob elastic modulus in simple bending and cob bending strength initially decreased significantly, but later increased with delay in harvesting.

Tables 23, 24 and 25 show the simple effects of variety and harvest date on cob mechanical properties in radial compression. Examination of these simple effects will give better insight into the effects of variety and harvest date since these two factors interact significantly in radial compression.

TABLE 22. Main effects of harvest date on cob physical and mechanical properties (Duncan's new multiple range test)†

Properties††	Harvest dates†††		
	22.09.79	06.10.79	20.10.79
E, MPa	21.4 a	25.5 b	21.2 a
σ_c, MPa	3.4 a	3.4 a	3.2 a
U, 10^6 N-m/m^3	0.076 a	0.064 b	0.083 c
E_b, MPa	41.9 a	25.4 b	28.9 b
σ_b, MPa	2.2 a	1.6 b	1.9 a
MC, % w.b.	48.9 a	38.3 b	35.6 b
2R, mm	25.8 a	26.1 a	24.6 b
2r, mm	7.4 a	9.4 b	7.4 a
2r/2R	0.29	0.36	0.30
Kernel MC, % w.b.	30.4	25.7	22.6

†Each value is the mean of 63 test samples.

††Symbols are defined in the list of symbols and abbreviations.

†††Values in a row with the same letter are not significantly different at 0.05 level.

TABLE 23. Simple effects of variety and harvest date on corn cob apparent elastic modulus in radial compression (E, MPa)†

Variety ↓	Harvest date →		
	22.09.79	06.10.79	20.10.79
Warwick SL-207	A → 23.1 a ↓	A 21.6 a ↓	A 17.8 a ↓
Funk G4065	A → 22.3 a	A 26.8 a	A 19.3 a
Asgrow RX 23	A → 18.8 a	B 28.0 a	B 26.4 b

†Duncan's new multiple range test.

In a column, values with the same small letter are not significantly different at 0.05 level.

In a row, values with the same capital letter are not significantly different at 0.05 level.

Each value is the mean of 21 test samples.

TABLE 24. Simple effects of variety and harvest date on corn cob crushing strength (σ_c, MPa)†

Variety ↓	Harvest date →		
	22.09.79	06.10.79	20.10.79
Warwick SL-207	A → 3.3 a ↓	AB 2.7 a ↓	B 2.5 a ↓
Funk G4065	A → 3.4 a	A 3.3 b	A 3.1 b
Asgrow RX 23	A → 3.4 a	B 4.1 c	B 4.1 c

†Duncan's new multiple range test.

In a column, values with the same small letter are not significantly different at 0.05 level.

In a row, values with the same capital letter are not significantly different at 0.05 level.

Each value is the mean of 21 test samples.

TABLE 25. Simple effects of variety and harvest date on corn cob modulus of toughness in radial compression (U, $10^6 \times N\text{-}m/m^3$)†

Variety ↓	Harvest date →		
	22.09.79	06.10.79	20.10.79
	A →	B	AB
Warwick SL-207	0.070 a ↓	0.043 a ↓	0.053 a ↓
	AB →	A	B
Funk G4065	0.060 a	0.050 a	0.073 a
	A →	A	B
Asgrow RX 23	0.097 b	0.100 b	0.123 b

†Duncan's new multiple range test.

In a column, values with the same small letter are not significantly different at 0.05 level.

In a row, values with the same capital letter are not significantly different at 0.05 level.

Each value is the mean of 21 test samples.

7.7 Effects of fertilizer level of application

Tables 26 and 27 and Figure 38 demonstrate the influence of fertilizer rate of application on cob mechanical properties, as determined from 1978 experimental data. The effects of fertilizer rate on cob mechanical properties depend greatly on corn variety. Both cob apparent elastic modulus and cob crushing strength increase initially and then decrease with increase in fertilizer rate of application when Warwick SL-207 is considered. On the contrary, these mechanical properties remain initially constant and then increase as the fertilizer rate is increased for Asgrow RX-30. Thus, as regards cob apparent elastic modulus and cob crushing strength, the optimum fertilizer rate for Warwick SL-207 corn variety is about 60 kg/ha (kilograms per hectare), while that for Asgrow RX-30 variety lies beyond 150 kg/ha. It must be added, however, that the desirability for having high values of cob strength and elastic modulus depends on the practical application for which the knowledge of such mechanical properties is sought.

For Warwick SL-207 corn variety, the cob modulus of toughness decreases with increase in fertilizer rate of application. A reverse trend is indicated for the Asgrow RX-30 variety up to 100 kg/ha rate of fertilizer application, after which cob modulus of toughness decreases with further increases in fertilizer rate.

With reference to Table 27, the fact that the F1 level (equivalent to NPK combination of 0:60:120 kg/ha) gave the highest values

TABLE 26. Effect of fertilizer level of application on corn cob physical and mechanical properties†

Properties	Fertilizer levels††		
	F0	F2	F3
Moisture content, % w.b.	13.5	16.2	11.7
Diameter, mm	25.8	26.6	26.4
Pith diameter, mm	7.1	6.9	5.8
Crushing force, kN	1.2	1.4	1.6
Crushing strain	0.13	0.14	0.13
Stiffness, MPa	10.7	8.9	15.8
Apparent elastic modulus (MPa)	32.6	30.6	41.3
Crushing strength, MPa	6.0	6.1	7.8
Modulus of toughness ($10^6 \times N\text{-}m/m^3$)	0.18	0.24	0.22

†Each value is the mean of three test samples. All 3 cm-long cob samples at 1 cm/min rate of loading. Variety of corn used was Asgrow RX-30. Test date was 30.09.78.

††Fertilizer levels: F0 = no fertilizer. F2 = NPK, 120:60:120 kg/ha. F3 = NPK, 180:90:180 kg/ha. NPK = nitrogen, phosphorus and potassium fertilizer combination.

TABLE 27. Fertilizer effect on corn cob physical and mechanical properties†

Properties	Fertilizer levels††			
	F0	F1	F2	F3
Moisture content, % w.b.	6.9	7.3	7.1	6.7
Diameter, mm	23.5	24.4	23.6	24.7
Pith diameter, mm	7.1	6.2	6.9	8.0
Crushing force, kN	1.6	1.8	1.4	1.0
Crushing strain	0.11	0.10	0.12	0.09
Stiffness, MPa	17.0	25.6	17.4	15.4
Apparent elastic modulus (MPa)	55.6	70.5	47.1	41.0
Crushing strength, MPa	8.3	11.2	8.2	6.2
Modulus of toughness (10^6 x N-m/m^3)	0.22	0.20	0.18	0.10

Each value is the mean of three test samples. All 3 cm-long cob samples at 1 cm/min rate of loading. Variety of corn used was Warwick SL-207. Test date was 18.10.78.

Fertilizer levels: F0 = no fertilizer. F1 = NPK, 0:60:120 kg/ha. F2 = NPK, 120:60:120 kg/ha. F3 = NPK, 180:90:180 kg/ha.

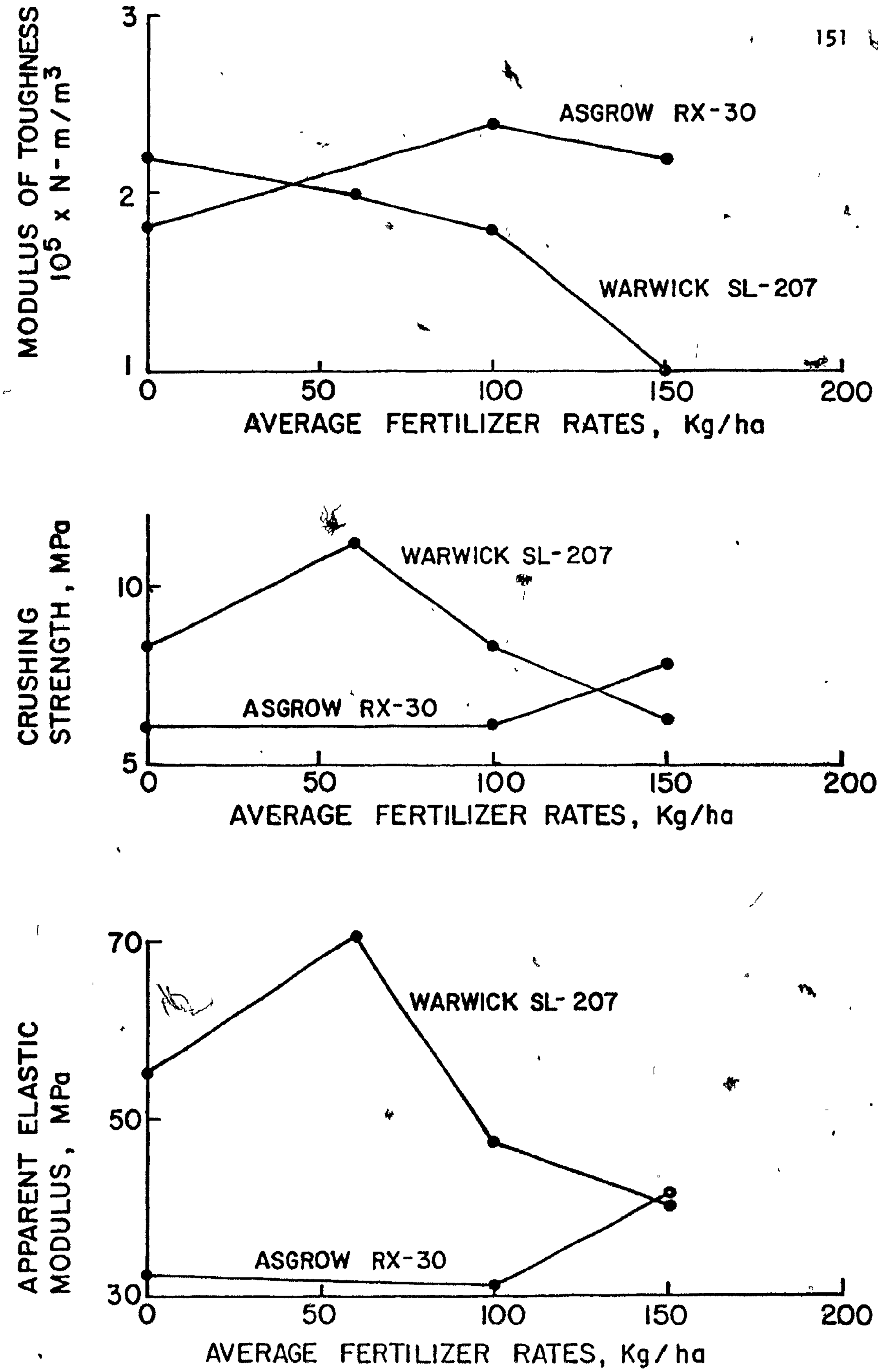


Figure 38. Effect of fertilizer rates on cob mechanical properties in radial compression

of cob apparent elastic modulus and cob crushing strength could be interpreted to suggest that increases in the values of cob mechanical properties are due principally to increases in the amount of potassium fertilizer applied or reductions in the amount of nitrogen fertilizer. The very low values of cob mechanical properties at F3 level (NPK = 180:90:180 kg/ha) seem to substantiate the negative influence of high application of nitrogen fertilizer. Similar fertilizer effects on corn stalk mechanical properties have been reported as reviewed earlier in this thesis.

From the 1979 data, Table 28 shows that increasing the rate of application of nitrogen fertilizer from 0 to 480 kg/ha did not lead to any significant changes in the values of cob mechanical properties, despite the highly significant effects on cob diameter and pith diameter. The rates of phosphorus and potassium fertilizers were kept constant at the recommended levels. Examination of the main effects of nitrogen fertilizer levels on cob mechanical properties (Table 29) shows a slight but consistent decrease in cob apparent elastic modulus in radial compression from 120 to 480 kg/ha rate of application. Both cob crushing strength and cob modulus of toughness tend to increase slightly as the rate of application of nitrogen fertilizer increases from 120 to 240 kg/ha, but then appear to decrease as the rate is increased further to 480 kg/ha. Table 29 also suggests that increasing the rate of application of nitrogen fertilizer from 120 to 480 kg/ha significantly increases cob diameter but has no significant effect on pith diameter. The control plot, 0 kg/ha rate of application, generally behaved differently from plots with fertilizer.

TABLE 28. Summary of analyses of variance on effects of nitrogen fertilizer on corn cob physical and mechanical properties

Source of variation	Degrees of freedom	F values					
		E†	σ_c	U	MC	2R	2r
Total	15						
Blocks	3						
Treatment††	3	0.23 ns	0.26 ns	3.08 ns	2.73 ns	71.52**	27.91**
Experiment error	9						

†All symbols defined in the list of symbols and abbreviations.

††Treatment consists of 0, 120, 240 and 480 kg/ha rates of nitrogen fertilizer application with phosphorus and potassium kept constant at recommended levels.

ns = not significant at 0.05 level.

** = significant at 0.01 level.

TABLE 29. Main effects of nitrogen fertilizer levels on cob physical and mechanical properties (Duncan's new multiple range test)†

Rate of application kg/ha	Apparent elastic modulus MPa	Crushing strength MPa	Modulus of toughness 10^6 N-m/m^3	Moisture content % w.b.	Diameter mm	Pith diameter mm
0	22.7 a	3.8 a	0.118 a	31.8 a	21.8 a	6.4 a
120	24.3 a	3.7 a	0.088 b	28.5 b	25.6 bc	8.0 b
240	24.1 a	3.9 a	0.108 ab	30.3 ab	25.3 b	7.8 b
480	23.1 a	3.7 a	0.103 ab	30.2 ab	26.4 c	7.8 b

†Each value is the mean of 20 test samples.

In each column, means with the same letter are not significantly different at 0.05 level.

Corn variety = Warwick SL-777.

Rate of loading in radial compression = 1 cm/min.

7.8 Effect of soil type and condition

Table 30 and Figure 39 show the effect of soil type and soil condition on cob mechanical properties, as determined in 1978. With reference to the degree of variabilities in cob mechanical properties determined in Table 5, it could be concluded that only cob apparent elastic modulus is substantially affected by soil type and condition. The average apparent elastic modulus of cobs from the silty clay soil was lower than that for cobs from the silty clay loam soil. However, compacting the silty clay soil, as typified by the existence of hard pans, tends to substantially increase the apparent elastic modulus of corn cob.

Table 30 also indicates that the effect of soil type and condition on cob apparent elastic modulus is strongly associated with the effect of these soil factors on cob moisture content. Corn cobs from the silty loam soil had the highest value of apparent elastic modulus and the lowest value of moisture content; while those from the silty clay soil had the lowest value of apparent elastic modulus and the highest value of moisture content. Cobs from the silty clay soil with hard pans had intermediate values.

The above result is in complete agreement with that obtained in a study of the effects of soil compaction on corn ear physical and mechanical properties by the author (Appendix D, Table D4, Figure D2). It was found in that investigation that soil compaction by machinery traffic increases the breaking strength and lowers the moisture content of the corn ear hand-picked at physiological maturity.

TABLE 30. Effects of soil on corn cob physical and mechanical properties†

Properties	Soil types††		
	A	B	C
Moisture content, % w.b.	9.4	8.2	7.0
Diameter, mm	24.6	23.4	24.8
Pith diameter, mm	7.2	7.1	7.7
Crushing force, kN	1.2	1.1	1.1
Crushing strain	0.11	0.09	0.08
Stiffness, MPa	14.4	14.9	16.8
Apparent elastic modulus (MPa)	46.4	53.9	62.1
Crushing strength, MPa	7.3	7.6	7.8
Modulus of toughness (10^6 N-m/m^3)	0.16	0.15	0.11

†Each value is the mean of six test samples. All 3 cm-long cob samples at 1 cm/min rate of loading. Variety of corn used was Warwick SL-207. Dates of testing were 30.09.78 and 18.10.78.

††Soil types: A = Howick silty clay; B = A with some hard pans; and C = Ormstown silty clay loam, as evaluated by the Renewable Resources Department of Macdonald College.

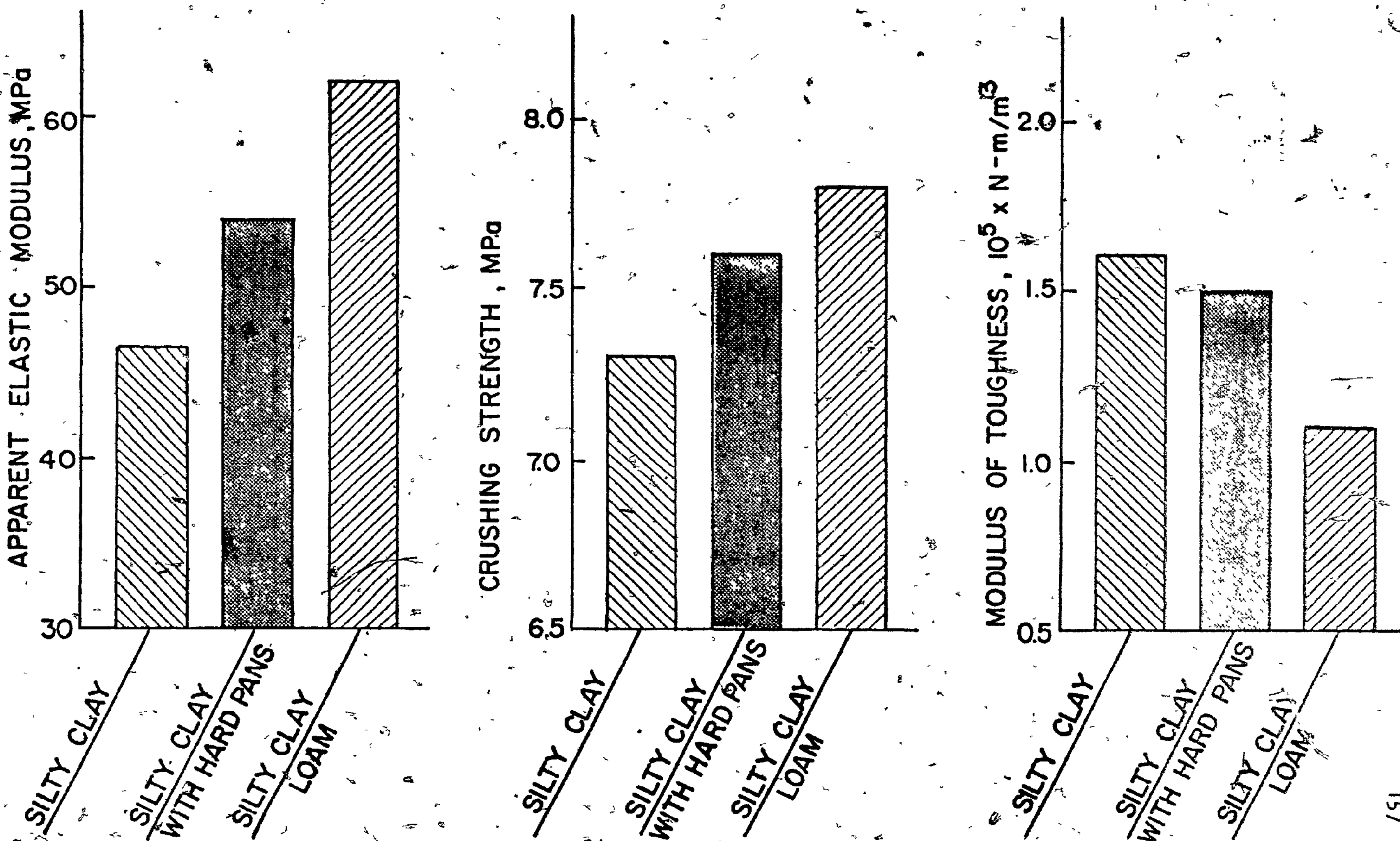


Figure 39. Effects of soil type and condition on cob mechanical properties in radial compression

CHAPTER VIII

SUMMARY AND CONCLUSIONS

Studies of the physical and mechanical properties of corn stalk and corn kernel have been extensively researched. However, little work has been done on the mechanical properties of corn cob, despite the fact that cob strength affects corn combine performance.

The main objective of this study was to establish theoretical and experimental methods for characterizing the mechanical strength of the corn cob under radial compression and simple bending.

The theoretical approach adopted in radial compression was to consider the corn cob problem to be essentially identical to the contact problem of an elastic cylinder on a rigid plane. The classical solution of the elastic cylinder problem is based on the Hertz linear elastic contact theory. An implicit assumption in this approach was that, despite the non-homogeneous structural composition of the corn cob composite, the stresses and deformations at the surface of contact between the corn cob and either the upper or lower steel plate of the testing device could be adequately predicted by the Hertzian solution of the contact stress-deformation of a homogeneous elastic cylinder on a rigid plane.

Experimental justification of the application of the Hertz linear elastic contact theory to the radial compression of corn cob composite was undertaken. The contact area was measured by three simple experimental techniques and the values obtained were compared with those predicted by theory. Reasonable agreement was obtained between experimental and theoretical values.

In simple bending, the theoretical approach adopted was to modify the elementary beam flexure formula to account for the tapering of the cob structure and its composite nature. The cob was considered in simple bending as a tapered cylindrical beam of two homogeneous materials, the mid-cob and the soft pith at the center. The outer fine fluffy material covering the mid-cob was considered unimportant in simple bending. Under these structural simplifications, the cob's composite cross-section was transformed to an equivalent one with a single homogeneous material. The moment of inertia of the transformed section was determined and an equation derived for calculating cob bending strength.

From laboratory tests performed over two years with seven varieties of corn, a five-parameter empirical equation was developed to represent the force-deformation curve of a radially compressed corn cob composite up to the threshold of failure. The latter was deemed to have occurred once a crack was initiated at the center of the cob pith. From the five-parameter equation, an expression was derived for calculating the modulus of toughness of corn cob composite under radial compression.

The major laboratory investigations conducted include the determination of the effects of moisture content, rate of loading, corn variety, fertilizer rate, fertilizer type, soil type and soil condition on the mechanical properties of corn cobs. Another important experimental study undertaken was to determine whether it is valid to disregard the soft pith at the center of the cob and thus consider the corn cob as a hollow homogeneous cylinder as was done by previous investigators.

A split-plot in time field experiment was established in 1979 specifically for the corn cob study. Three varieties of corn were planted in a randomized complete block design with three replications. Each main plot unit consisted of six rows of corn of a single variety. At physiological maturity, corn cobs from the three varieties were subjected to laboratory experiments to examine the effects of corn variety and harvesting date on cob mechanical properties in both radial compression and simple bending. Moisture content (test date) and rate of loading effects were re-investigated in a complete randomized block design with sixteen observations for each of the three rates of loading on each of the five test dates.

Poisson's ratio of corn cob in radial compression was determined as 0.32. This value was used in all calculations of the apparent elastic modulus of corn cob in radial compression, irrespective of the corn variety, moisture content, rate of loading or any other variable factor tested in this study.

Based on the results of this study, the following conclusions are drawn.

1. The Hertz linear elastic contact theory was found to be sufficiently accurate for predicting the contact area of a radially compressed corn cob composite.

2. The classical solution of the elastic cylinder on a rigid plane problem can be applied to determine the contact stresses and deformation on the surfaces of a radially compressed corn cob composite.

3. From scrutiny of a great many force-deformation curves of corn cob in radial compression, it was established that failure was initiated at the center of the cob by pith cracking. This was followed by a progressive propagation of the crack surface through the pith zone and subsequently into the mid-cob zone. The cob finally split into two halves. Crack propagation was observed to be along the vertical plane of symmetry.

4. The force-deformation curve of corn cob in radial compression was accurately represented by a 5-parameter equation which, upon integration, gave an empirical equation for calculating cob modulus of toughness.

5. Modifications of the basic flexure formulas to account for cob tapering and composite structure gave acceptable theoretical equations for calculating cob bending strength and cob apparent elastic modulus in simple bending. However, the experimentally determined values of the coefficients in the modified equations were such that the calculated values of cob mechanical properties in simple bending when the cob was considered as a tapered composite beam of two materials did not differ greatly from those calculated with the basic flexure formulas.

6. The values of cob mechanical properties in radial compression calculated from the equations presented in this study increased as the ratio of pith diameter to cob diameter decreased.

7. The mechanical properties of the corn cob, with the exception of the apparent elastic modulus, varied significantly along the length of the cob. The calculated values of cob elastic modulus, crushing strength, crushing strain and modulus of toughness were highest at the tip-end of the cob and the least at the butt-end, with those of the mid-section always intermediate (details in Appendix B).

8. From qualitative and quantitative analyses of the force-deformation curves of four simplified structural models of the corn cob in radial compression, it is concluded that the usual simplification of the corn cob as a hollow cylinder of one homogeneous material is not valid. The mechanical behavior and properties of the hollow cob model were found to be very different from those of the cob

composite model. The soft pith at the center of the cob contributed substantially to the cob composite mechanical behavior and properties in radial compression, and, as such, cannot be disregarded as has been done by previous investigators.

9. Cob mechanical properties in both radial compression and simple bending were significantly affected by cob moisture content, while rate of loading had no significant effect on these properties.

10. Regression analysis showed that cob apparent elastic modulus in radial compression was linearly related to cob moisture content. The relationship between cob crushing strength and cob moisture content was also found to be linear but that between cob modulus of toughness and cob moisture content was non-linear.

11. Whether in radial compression or in simple bending, the values of cob strength and cob elastic modulus increased as the cob moisture content was decreased.

12. Corn variety and harvest date were found from this study to be highly significant factors affecting cob modulus of toughness in radial compression. Cob crushing strength was significantly affected by corn variety but it was not significantly affected by harvest date. On the other hand, cob apparent elastic modulus in radial compression was significantly affected by harvest date but not by corn variety. Cob bending strength and cob apparent elastic modulus in simple bending were significantly affected by both corn variety and harvest date.

13. The effect of fertilizer rate on cob mechanical properties in radial compression was found to depend very much on corn variety. It also depended on the type of fertilizer applied.

14. The effects of soil type and soil condition were not as important as those for the other factors investigated. However, there was sufficient evidence to believe that substantial changes in cob moisture content due to differences in soil type or soil condition would lead to substantial changes in cob mechanical properties.

CHAPTER IX

LIMITATIONS OF STUDY AND FUTURE WORK

One major problem encountered in this study was the determination of the Poisson's ratio of corn cob composite in radial compression. No adequate experimental technique was identified from past work for determining the Poisson's ratios of intact cylindrical biological materials under radial compression. Fruitless efforts were made to adopt the techniques developed for measuring the Poisson's ratios of conveniently shaped homogeneous specimens of some fruits and vegetables. A photographic technique was finally used as described in Appendix A, but such a method must be considered as approximate.

An even more serious limitation to this study is the lack of any established experimental technique for measuring strains in biological materials. This makes it completely impracticable to verify any theoretical or numerical solution of the stress-strain distributions in radially compressed cylindrical or spherical biological materials with their characteristic composite and orthotropic properties, not to mention their viscoelastic behavior. Consequently, attempts to establish a failure theory for corn cob under radial compression were not conclusive.

Preliminary experiments showed that the corn cob composite exhibited force relaxation behavior in both radial compression and simple bending. Unfortunately, it was not possible to determine satisfactory theoretical relaxation functions which will describe such behaviors, considering the contact stress distribution for the radial compression problem and the composite nature of corn cob. A successful mathematical modeling of corn cob mechanical behavior will enhance the study of a shelling theory for corn ear. In a previous attempt to formulate corn shelling theory for a conventional combine (Halyk, 1968), the corn cob was merely described as a rigid body.

In view of the above three limitations of this study, it is recommended that the following three topics merit further research:

1. There is a need for a more appropriate technique for measuring Poisson's ratio of corn cob composite in radial compression and also for an investigation of the major factors affecting it.

2. Experimental investigation of strain distribution in a radially compressed corn cob composite should be undertaken under quasi-static and dynamic loads in order to establish a failure theory for corn cob as related to corn combine cylinder-concave shelling action. In this respect, it might be advisable to investigate the application of the photo-elastic analysis technique for stress-strain measurement to the cob problem in radial compression (some relevant literature include Stieda, 1965; Arnold and Roberts, 1966).

3. Mathematical analyses of the force relaxation behaviors of corn cob composite in both radial compression and simple bending and their transformation into the stress domain would seem desirable for a complete understanding of the mechanical properties and behavior of the corn cob as related to harvesting and post-harvesting processes.

Finally, in view of the significant effects of cob morphology on cob mechanical properties, the author suggests that plant breeders, in collaboration with agricultural engineers and soil scientists, develop a new variety of hybrid corn with the following cob qualities:

i. a smaller and lignified pith;

ii. a uniform and well developed inter-row tissue; and

iii. a less tapered structure.

Such improved features of the corn cob will minimize cob breakup during corn shelling in a combine cylinder.

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APPENDICES

APPENDIX A

MEASUREMENT OF POISSON'S RATIO FOR CORN COB COMPOSITE

Basic theory

Poisson's ratio is defined as the ratio of lateral unit deformation to longitudinal unit deformation when an elastic body is subjected to a uniaxial tensile or compressive load. It is that property of the material which explains the change in cross-sectional dimensions when a longitudinal loading is applied.

A literature search revealed three basic methods for determining Poisson's ratio of a biological material assumed to be homogeneous, isotropic, and elastic.

1. Uniaxial loading method

From an axially strained specimen in tension or compression, the Poisson's ratio can be computed from

$$\nu = \left| -\varepsilon_t/\varepsilon_a \right| \qquad [A1]$$

where

ν = Poisson's ratio

ε_a = axial strain

ε_t = transverse strain

2. Method based on the fundamental relations among elastic constants

From any book on elastic theory, it is shown that the relationships among the elastic constants for a homogeneous, isotropic, elastic material can be expressed as

$$G = E/2(1 + \nu) \quad \text{or} \quad \nu = [E/2G] - 1 \qquad [A2]$$

and

$$K = E/3(1 - 2\nu) \quad \text{or} \quad \nu = 1/2 - [E/6K] \qquad [A3]$$

where

E = Young's modulus

ν = Poisson's ratio

G = shear modulus

K = bulk modulus

Thus, if any two of E, G, K can be determined, ν can be computed from equations [A2] and [A3].

3. Rigid die test method (Hughes and Segerlind, 1972)

From the generalized Hooke's law for an isotropic body expressed in polar coordinates, Hughes and Segerlind (1972) derived an expression which relates the stress, σ_z, and the strain, ϵ_z, in the direction of applied load to Poisson's ratio as follows:

$$E(\epsilon_z/\sigma_z) = (1 + \nu)(1 - 2\nu)/(1 - \nu) \qquad [A4]$$

The experimental procedure consists of determining E from an unrestrained compression test and determining the ratio, ϵ_z/σ_z, from a restrained test, using two similar cylindrical samples from the same agricultural product. With the knowledge of E and ε_z/σ_z the value of ν for the product is estimated from equation [A4].

Hammerle and McClure (1971), who reviewed the first two methods, discussed the difficulties involved in using any of these two methods in determining Poisson's ratio for an agricultural product. All of the three methods, briefly described above, suffer from some experimental difficulties, due mainly to the

1. complex structure of agricultural product,
2. inherent variability of a biological material,
3. inadequate instrumentation for measuring strains in biological materials.

In addition, none of the three methods is directly suitable for determining Poisson's ratio in the case of radial compression of a cylindrical biological material consisting of two or more distinct macro-structural components. The second method could be applicable if a composite series or parallel model could be formulated for the biological product. In which case, any two of the elastic constants, E, G and K, could be determined for each component of the product, assuming that each of these components is homogeneous, isotropic and elastic. However, apart from experimental difficulties in measuring the elastic constants, particularly G and K, errors in the experimental determination of these constants will be compounded in the values of Poisson's ratio that would be estimated from the selected composite model equations relating ν, E, G and K.

Geometric description of cob deformation

Cob deformation under a pure compressive loading between two parallel steel plates is geometrically represented in Figure A1. The deformation is, for all practical purposes, symmetrical about the vertical and horizontal planes which contain the central longitudinal axis of the cob. This can be readily demonstrated from the fact that it is difficult to tell which side of the contacting surfaces of the deformed cob was up or down during loading. Strict symmetry about each of these two planes is only possible if the cob structure and the applied loading are also symmetric about each of these planes.

From the above symmetries, it may be assumed that the two symmetrical planes remain plane after deformation. Thus, the vertical and horizontal diameters through the cross-sectional centers of the cob (for instance, K_oL_o and M_oN_o in Figure A1) remain straight after the deformation (KL and MN in Figure A1). It may also be assumed that apart from the central points (e.g., O_o or O), points on the vertical symmetrical plane experience only vertical compressive strains while points on the horizontal symmetrical plane suffer only horizontal tensile strains. This implies that these planes are also the principal planes of the cob under radial deformation (as indeed confirmed from theoretical stress-strain distributions within a radially compressed elastic cylinder (Lubkin, 1962)).

Based on the above reasonings and with reference to Figure A2, the total principal lateral extension of the cob can be expressed as

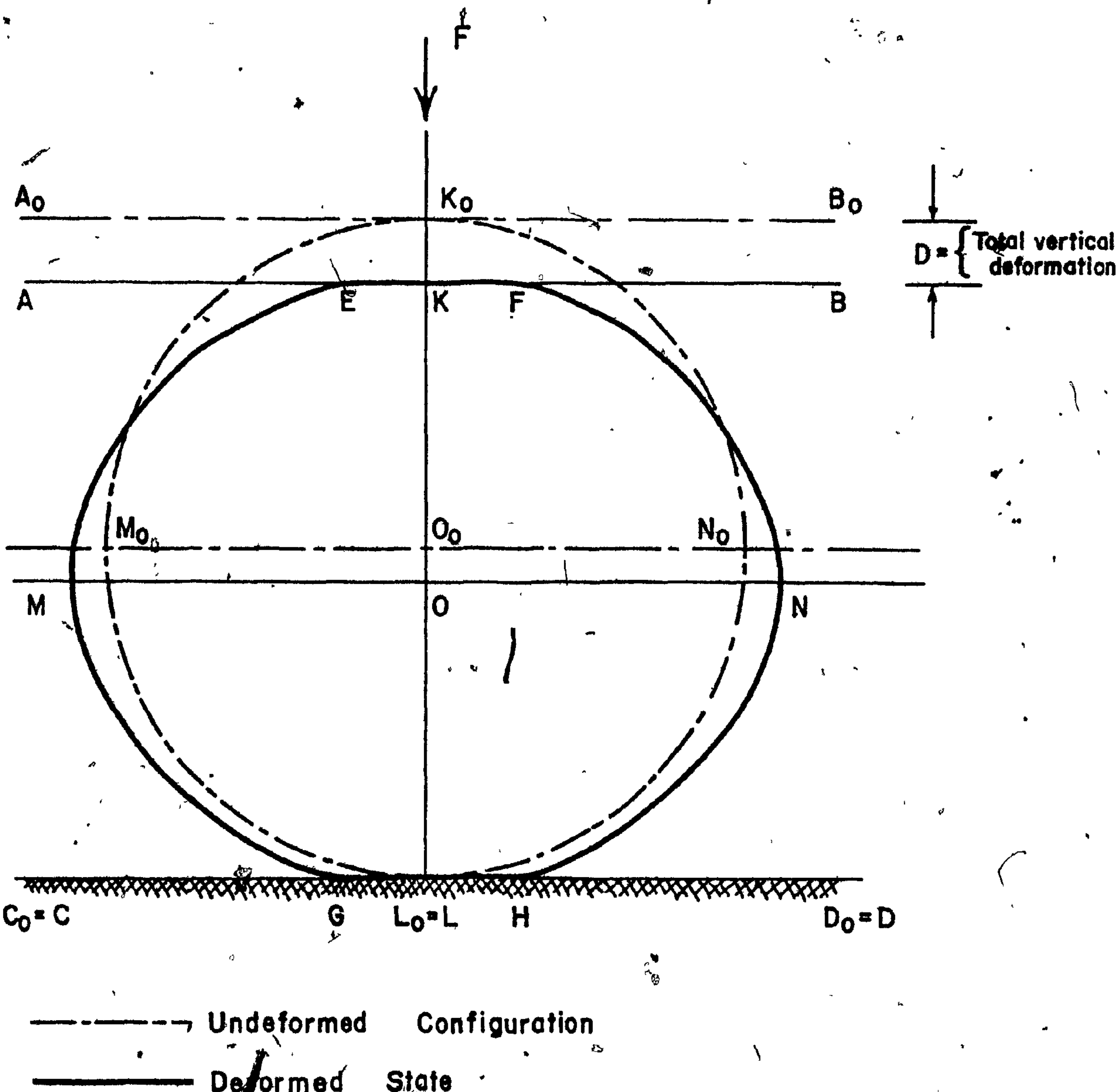


Figure A1. Geometric description of cob deformation under radial compression

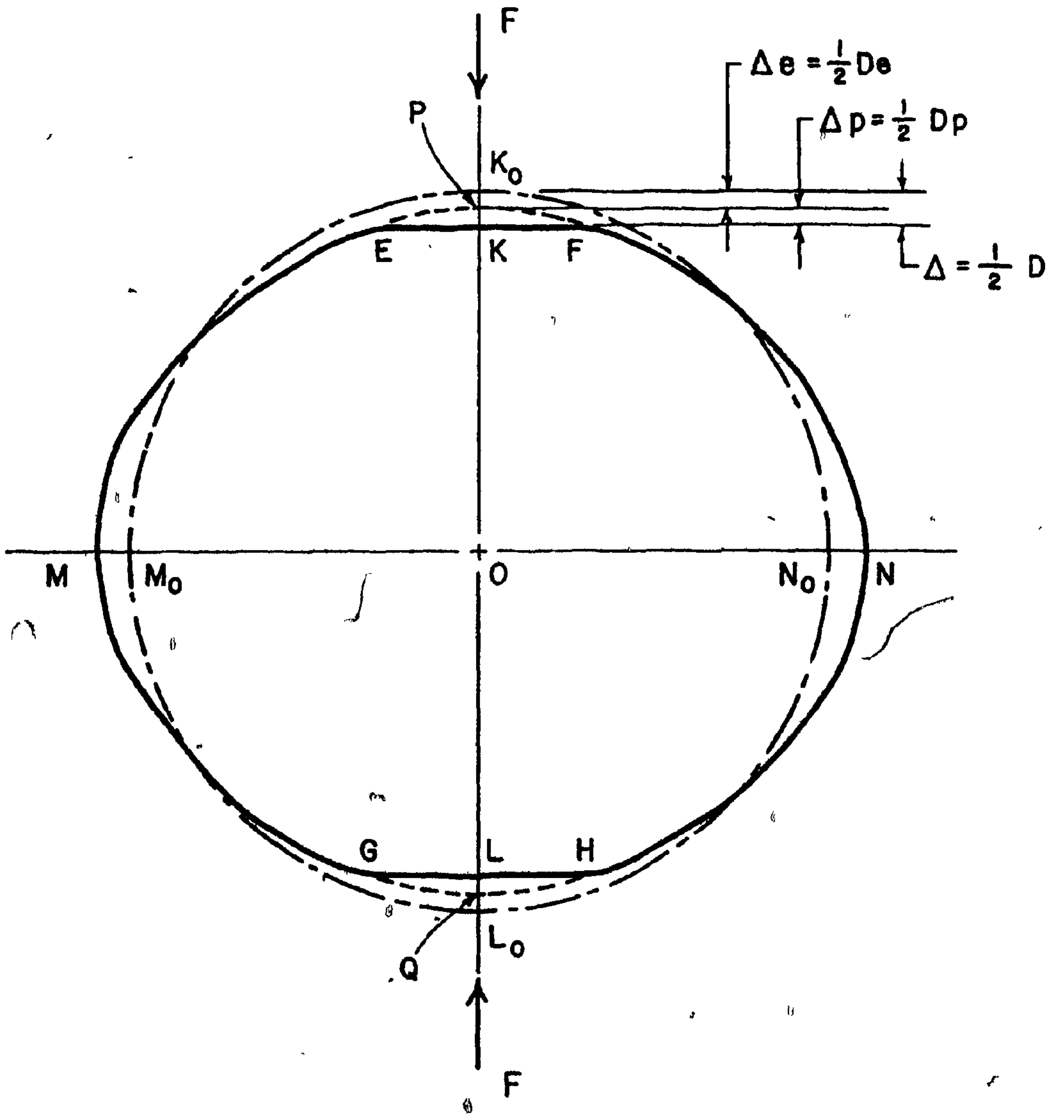


Figure A2. Hypothetical description of the deformed cross-section of corn cob with the center fixed

$$\Delta x = MN - M_oN_o \qquad [A5]$$

Similarly, the total principal normal compression is given by

$$\Delta z = K_oL_o - KL = 2\Delta = D \qquad [A6]$$

where D is the total vertical deformation of the cob obtained from the x-y plot of the Instron testing device; and other terms are defined in Figure A2.

Since Poisson's ratio is an elastic constant, only the elastic components of the unit principal lateral extension and the unit principal normal compression can be used in its estimation. The elastic component of the total vertical deformation is given by

$$D_e = \beta D/100 = \beta[K_oL_o - KL]/100 \qquad [A7]$$

where β is the per cent degree of elasticity, determined as explained in the main thesis. The lateral extension of the cob due to the applied normal load can be considered as completely elastic since no significant differences were obtained by measuring M_oN_o and its corresponding value after the deformed cob was allowed to relax completely.

From the foregoing geometric observations and analysis, an estimate of the Poisson's ratio for corn cob composite in radial compression can be calculated from the approximate formula:

$$\nu = \frac{[MN - M_oN_o]/M_oN_o}{[(\beta/100)(K_oL_o - KL)]/K_oL_o} \qquad [A8]$$

based on the definition of Poisson's ratio as the ratio of unit principal lateral extension to unit principal normal compression.

Photographic technique

MN and KL in equation [A8] must be determined during compression of corn cob because of the relaxation properties of the cob.

Hammerle and McClure (1971) described an instrumentation for monitoring the changes in the cross-section of a cylindrical specimen of potato flesh during axial compression. Their technique was considered rather too involved for an approximate measurement of MN and KL in the present study. Hence, successive photographs of one of the two end-views of the cross-section of cob were taken with a movie camera during radial compression in the Instron machine before pith cracking. The movie slide was later projected on a screen and the cross-sectional end-views at three or more time intervals traced on a plain graph sheet. An illustrative example is shown in Figure A3.

Calculation of Poisson's ratio

The results of the photographic measurement and the calculated values of ν from equation [A8] are shown in Table A1. The over-all average value of ν from this table is 0.23. However, a value of ν = 0.32 was used in all the calculations of E as given in equation [14] of this study. The value of ν = 0.32 is the average of the last two entries in the column for the calculated Poisson's ratio on the presumption that these entries fall into the apparent linear elastic stage of the f-d curve (see Figure 10 of this study).

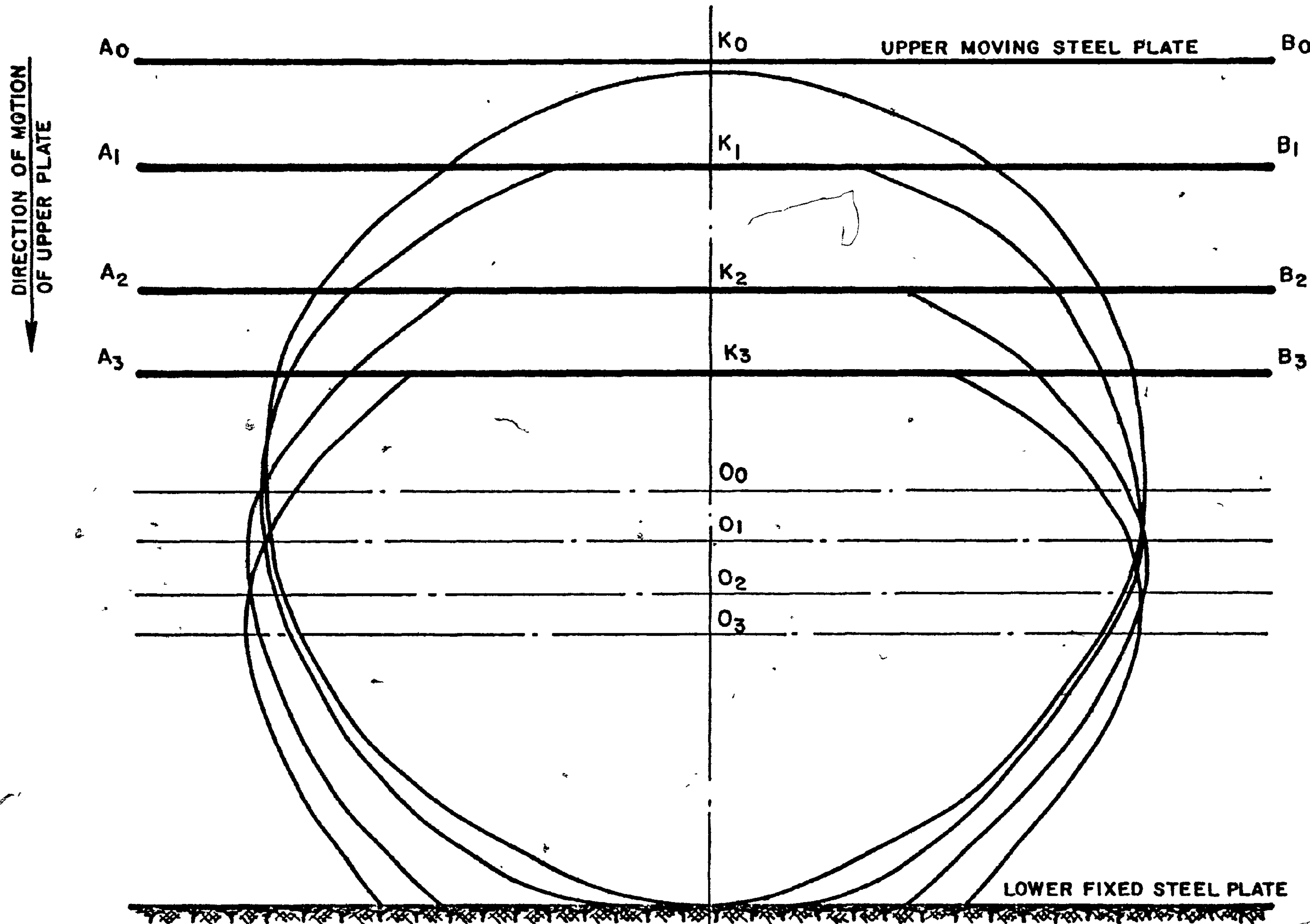


Figure A3. Projected end cross-sectional views of a radially compressed corn cob at various stages of loading (traced)

TABLE A1. Calculation of Poisson's ratio of the corn cob

Estimated elapsed time during loading, seconds	KL,† mm	MN,† mm	Calculated Poisson's ratio
90	19.8	21.7	0.13
144	18.9	21.8	0.16
222	17.6	22.0	0.21
276	16.7	22.3	0.27††
336	15.7	22.7	0.37††

K_oL_o† = 21.3 mm M_oN_o = 21.6 mm Rate of loading = 1 cm/min

†See Figures A1 and A2 for definition of these terms.

††Values used in determining the approximate value of Poisson's ratio of the corn cob.

Remarks

This value of 0.32 for Poisson's ratio of the corn cob composite agrees with those determined for other agricultural products. Hughes and Segerlind (1972) determined the Poisson's ratio of sweet potatoes to average 0.35, that of peaches to average 0.48, and that of apple to be 0.30. Poisson's ratio of the corn stalk was given as 0.23 or 0.36 by Prince et al. (1969a) and that of wood ranged from 0.3 to 0.5 (see Table D3, page 207).

However, Poisson's ratios for biological materials may not be considered as constants as is normally assumed for engineering materials. Finney (1967) found that Poisson's ratio ranged from 0.020 for overmature Rome Beauty apples to 0.236 for the same variety of apple in the early stages of maturation. The range was 0.252 and 0.391 for Kieffer pears. Chappel and Hamman (1968) found that Poisson's ratio of apple flesh under compressive loading was dependent on time and stress. Hammerle and McLure (1971) found that Poisson's ratios of uniaxially compressed cylindrical specimens of sweet potato were dependent on moisture content and per cent strain. The values ranged from 0.25 to 0.45.

There is need for a further investigation of experimental techniques for determining the Poisson's ratios of intact cylindrical biological materials under radial compression. The lack of an experimental procedure for determining Poisson's ratio for a composite material has also been pointed out by Segerlind et al (1976) who were unable to determine the Poisson's ratio for carrots.

APPENDIX B

VARIATIONS IN THE COB'S PROPERTIES ALONG ITS LENGTH

Experiment

An experiment was conducted in 1979 to test if the variations in the cob's physical and mechanical properties along its length determined in previous years (1977 and 1978) were statistically significant.

Corn cob samples, 3 cm-long, were cut from the butt-end, mid-region and tip-end of a whole corn cob. Radial compression was applied at 1 cm/min rate of loading on each sample until the sample failed. Seven whole corn cobs of Warwick SL-207 variety were treated in this manner. The experiment was performed on two test dates (04.10.79 and 10.10.79). All relevant information for radial compression analyses was obtained for each single sample tested.

Results

Statistical analysis of variance, as summarized in Table B1, shows that, with the exception of elastic modulus, all the physical and mechanical properties determined vary significantly along the cob's length. The values of the mechanical properties are the highest for the tip-end samples and the least for the butt-end samples, with those of the mid-region always intermediate (details are shown in Table B2).

TABLE B1. Variations in cob's properties along its length: summary of analyses of variance

Source of variation	Degrees of freedom	F values[†]						
		E	σ_c	U	ϵ_b	2R	2r	MC
Total	41							
Block (test date) B	1							
Treatment,[††] T	2	6.39 ns	23.36*	113.11**	95.99*	64.35**	59.45*	60.09*
B x T	2	1.25 ns	1.16 ns	0.20 ns	0.14 ns	6.05**	1.33 ns	0.23 ns
S(B x T)	36							

[†] ns = not significant at 0.05 level.
 * = significant at 0.05 level.
 ** = significant at 0.01 level.

††Treatment consisted of testing three different regions of a cob, viz., butt-end, mid-region and tip-end.

B x T used as the error term when no interaction existed between B and T. S(B x T) used as the error term when interaction between B and T is significant.

TABLE B2. Variations in cob physical and mechanical properties along cob length (Duncan's new multiple range test)†

Properties††	Butt-end	Mid-region	Tip-end
E, MPa	33.6 a	40.8 a	44.0 a
σ_c, MPa	3.2 a	3.9 ab	4.9 b
U, 10^6 N-m/m^3	0.031a	0.045b	0.069c
ϵ_b	0.043a	0.044a	0.057b
2R, mm	28.5 a	26.6 b	24.2 c
2r, mm	9.5 a	8.7 a	6.7 b
MC, % w.b.	19.1 a	24.3 b	16.5 a
2r/2R	0.33	0.33	0.28
Kernel MC, % w.b.	14.8	15.3	14.2

†Each value is the mean of 14 test samples.
In each row, means with the same letter are not significantly different at 0.05 level.
Corn variety = Warwick SL-207. Rate of loading = 1 cm/min.

††Symbols as defined in the list of symbols and abbreviations.

Remarks

The exclusive use of samples from the mid-region in the investigations reported in this thesis appears to be justified by the above results. However, the values so obtained do not represent the true averages for the whole-length corn cobs. It may thus be necessary to test samples for the three regions of each corn cob in order to obtain better average values.

APPENDIX C

DETERMINATION OF MID-COB AND PITH ELASTIC MODULI

Aim

The ratio of pith elastic modulus to that of the mid-cob in axial compression, m, is needed in the simple bending strength equation - equation [24].

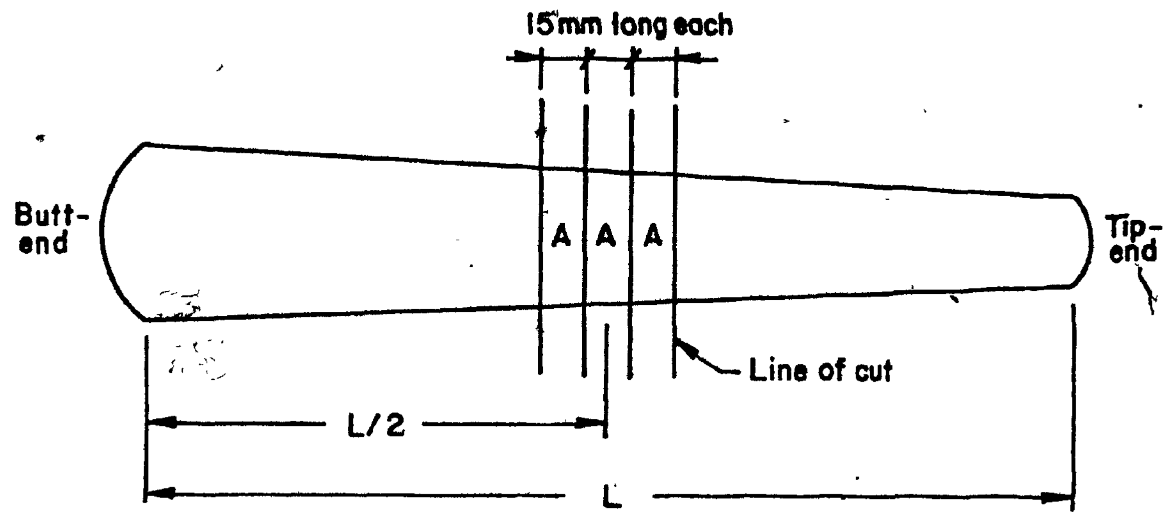
Experiment

Three short sections were cut from the middle of ten corn cobs of a single variety (Figure C1). Rectangular slabs of pith and those of the mid-cob were obtained by sanding each cut piece to shape. Physical dimensions of each of seven pith slabs and seven mid-cob slabs were measured and each piece subjected to axial compression (Figure C2). Loading and unloading tests were performed on three of each type of slab, using one slab at a time.

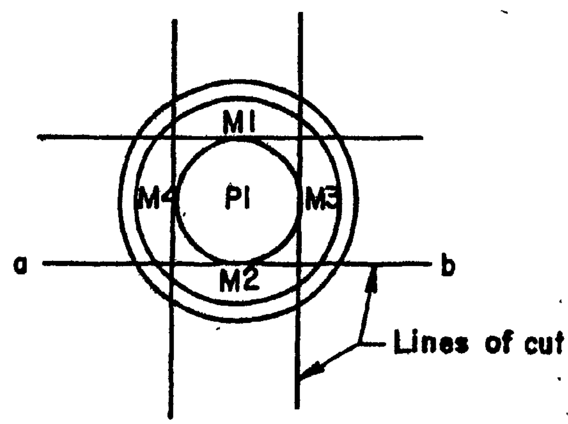
For comparative purposes, the experiment was repeated in transverse compression (Figure C3). Figure C4 shows a photograph of the mid-cob and pith rectangular slabs.

The cob diameter, pith diameter and moisture content of seven short cylindrical samples of corn cob, taken from the mid-region, were determined.

(a) Whole length corn cob



(b) Cross-sectional view of each A in (a) above, enlarged



Legend

A = 1.5 cm - long corn cob section

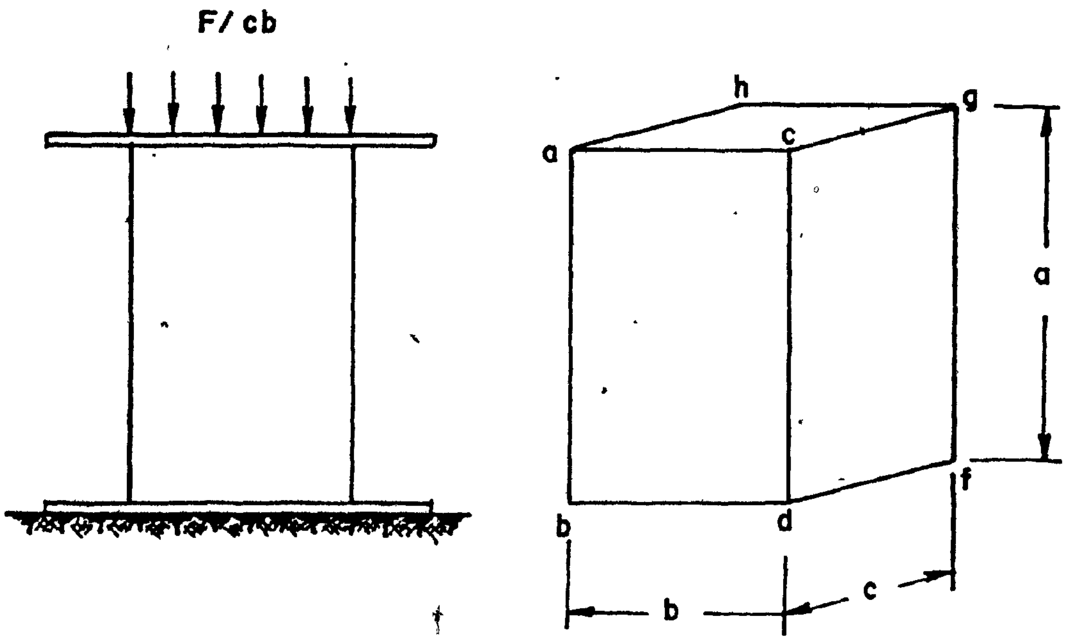
M1 - M4 = Mid-cob slabs

P1 = Pith slab

Figure C1. Method of cutting rectangular slabs of pith and mid-cob from whole-length cob

(a) Axial compression of mid-cob or pith rectangular slab

(b) Physical dimensions of mid-cob or pith rectangular slab



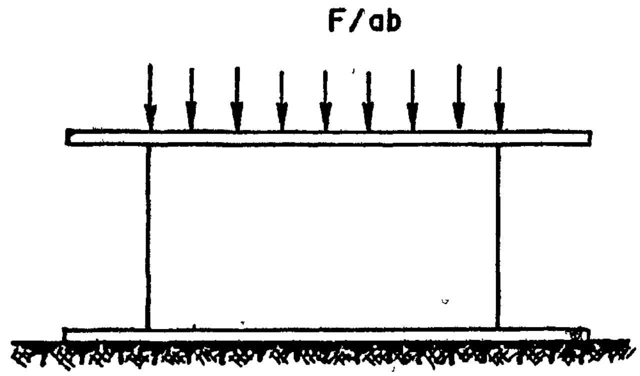
$E_s^* = [F/cb]/[\beta^*D/a] = Ma/bc\beta^*$

where E_s^* = Elastic modulus of slab in axial compression

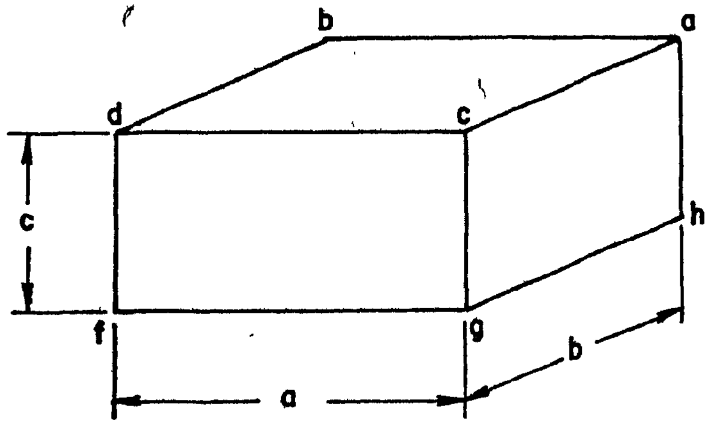
M = Slope of the straight portion of f-d curve of slab in axial compression

β^* = degree of elasticity in decimal

Figure C2. Determination of elastic modulus of pith or mid-cob slab in axial compression



(a) Transverse compression of mid-cob or pith rectangular slab



(b) Physical dimensions of mid-cob or pith rectangular slab

$$E_s = [F/ab]/[\beta^{*}D/c] = Mc/ab\beta^{*}$$

where E_s = Elastic modulus of slab in transverse compression

M = Slope of the straight portion of f-d curve of slab in transverse compression

β^{*} = degree of elasticity in decimal

Figure C3. Determination of elastic modulus of pith or mid-cob slab in transverse compression

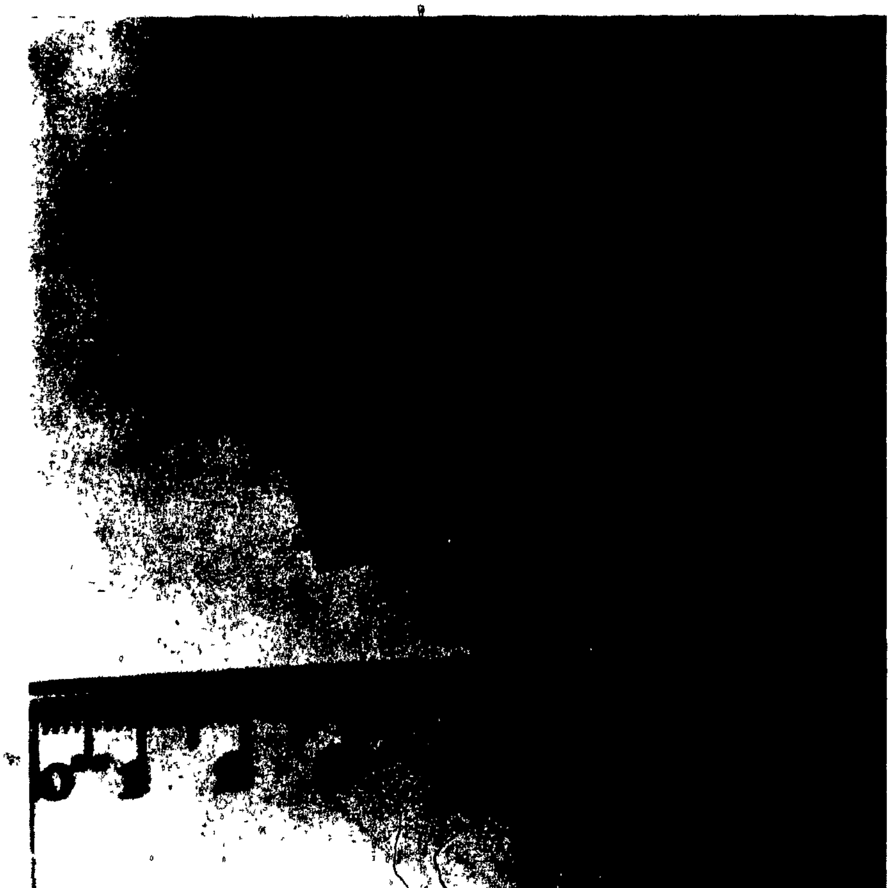


Figure C4. Mid-cob and pith rectangular slabs.

Results

The results are presented in Tables C1 and C2. The ratios of pith elastic modulus and mid-cob elastic modulus, m, ranged from 0.07 to 0.13 for the four corn varieties and three rates of loading tested. The ratios of pith diameter to cob diameter, f, ranged from 0.33 to 0.41 for the four varieties. The values of the coefficient $[1 - f^4(1 - m)]$ ranged from 0.97 to 0.99.

The comparison between the values of the elastic moduli of pith and mid-cob slabs when determined in axial compression and when determined in transverse compression shows that each of these components of the cob composite is not isotropic. The values in axial compression are much higher than those in transverse compression.

Moreover, the high coefficient value of 0.98 for the correction in the bending strength equation suggests that the soft pith at the center of the cob does not contribute substantially to the strength of the cob composite in simple bending.

TABLE C1. Elastic moduli of pith and mid-cob rectangular slabs in axial and transverse compression†

Property††	Pith slab						Mid-cob slab					
	Warwick SL-207		Funk G 4065		Asgrow RX 23		Warwick SL-207		Funk G 4065		Asgrow RX 23	
	Axial	Transv	Axial	Transv	Axial	Transv	Axial	Transv	Axial	Transv	Axial	Transv
a, mm	9.3	17.4	10.4	15.7	9.4	16.2	16.7	18.8	14.4	16.6	16.5	17.5
b, mm	7.1	6.8	6.2	5.8	7.3	6.6	9.7	9.6	8.6	8.8	10.0	9.4
c, mm	6.9	6.3	5.9	5.5	7.1	5.9	7.8	7.3	6.8	6.4	8.0	7.0
β, %	56.7	52.1	71.1	64.8	50.0	56.1	86.1	44.8	72.2	72.5	57.3	51.9
F, kg	1.8	3.2	1.2	3.2	1.8	3.2	15.5	18.0	17.5	16.6	19.3	19.0
D, mm	0.78	2.03	0.69	1.15	0.87	1.01	0.65	1.00	0.60	0.75	0.72	0.94
E_s, MPa	7.6	1.6	6.8	2.5	7.4	3.1	60.0	15.9	97.6	13.1	94.6	16.3

†Each value is the mean of seven test samples except for those of β%, which are means of three test samples. Rate of loading = 1 cm/min.

††All symbols are defined in Figures C2 and C3. Cob moisture content as in Table C2.

TABLE C2. Determination of the coefficient in the bending strength equation†

Property	4.11.78	16.09.79				
	Coop S 265	Warwick SL-207	Asgrow RX-23		Funk G 4065	
Cob moisture content (% w.b.)	6.5	20.2	21.2		20.4	
Cob diameter, 2R (mm)	24.6	24.5	23.0		21.8	
Pith diameter, 2r	8.1	9.0	7.7		9.0	
$f = r/R$	0.33	0.37	0.33		0.41	
Rate of loading, cm/min	1	1	1	1	0.2	5
Pith slab elastic modulus E_s* (MPa)	12.0	7.6	7.4	6.8	7.2	5.2
Mid-cob slab elastic modulus E_s (MPa)	149.0	60.0	94.6	97.6	65.9	39.9
$m = E_s^*/E_s$	0.08	0.13	0.08	0.07	0.11	0.13
$[1 - f^4(1 - m)]$††	0.99	0.98	0.99	0.97	0.98	0.98

†Each value is the mean of seven test samples.

††Coefficient in the bending strength equation.

APPENDIX D

OTHER RELATED RESULTS

Axial and tensile tests

Corn cob samples, 3 cm-long, were individually tested in axial and radial compression using the Instron testing machine (see Figure 1b). Cob composite sections about one centimeter long were also tested in radial tension as well as in radial compression. The tensile arrangement is illustrated in Figure D1. Considerable difficulties were encountered in the tensile test due to slipping of the cob sample between the tension jaws. Too tight a grip tended to induce failure near the gripped positions.

Table D1 indicates that the values of the crushing strain, elastic modulus and crushing strength of corn cob are higher in radial compression than in axial compression. The lower values in axial compression for E and σ_c may be due to the very approximate formulas used in calculating these quantities. Moreover, it is to be noted that the value of the crushing force, F_b, used does not correspond to the highest force that the cob could withstand, particularly in axial compression (see Figure 1). Therefore, it is possible that the ultimate strength of corn cob in axial compression could be much higher than that indicated in Table D1.

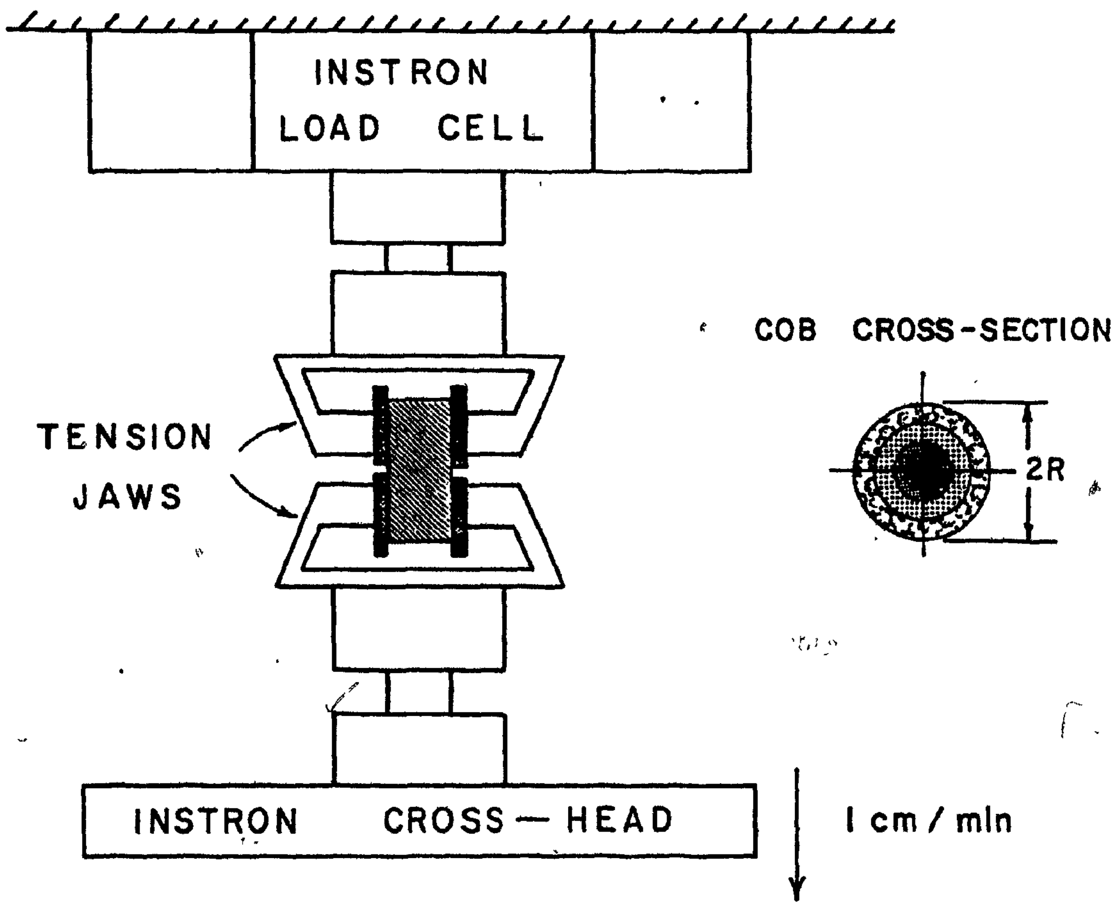


Figure D1. Radial tensile test for corn cob composite

TABLE D1. Mechanical properties of corn cob in radial and axial compression†

Type of loading	MC % w.b.	2R mm	F_b kN	D_b mm	β %	ε_b	σ_c MPa	E MPa
Radial	6.5	24.8	0.86	2.2	55.8	0.050	8.5	69.0
Axial††	6.6	24.6	0.89	1.1	87.2	0.032	1.9	59.4
Radial/axial	-	-	0.97	2.0	-	1.56	4.47	1.16

†Each value is the mean of seven test samples.
Loading rate = 1 cm/min.
Corn variety = Coop S 265.
Test date = 4/11/78.

††In axial compression $\varepsilon_b = \beta D_b/\ell$ where ℓ = 30 mm

$\sigma_c = F_b/\Pi R^2$ where F_b = bioyield force (not maximum force)

$E_b = \sigma_c/\varepsilon_b$

Table D2 indicates that the corn cob is stiffer in tension than in compression, while it is stronger in compression than in tension. As noted above, the results in tension may not be as accurately computed as those in radial compression.

For a more accurate comparison of the properties of corn cob in axial compression with those in radial compression, it is necessary to study the rigorous mathematical treatment of the stress-strain relationships in axially compressed elastic cylinder (Filon, 1902; Pickett, 1944; Hammerle and McClure, 1971).

Comparison of cob mechanical properties with those of corn kernel, corn stalk and wood

As presented in Table D3, the values of corn cob mechanical properties determined in this study are lower than those of corn kernel (determined also by the author), corn stalk (as reported by Prince *et al.*, 1969a, 1969b), and those of wood (as given in the U.S.D.A. Wood Handbook, 1955).

The presence of a relatively large pith at the center of the cob could account for the lower values of the mechanical properties of the cob compared with those of the stalk and kernel. Unlike the cob pith, the stalk pith is stiffened by the presence of the vascular bundles scattered through it (Prince *et al.*, 1969a). The solid filling adds strength to the stalk by preventing its collapse under bending stresses and the strong sheaths of the vascular bundles tend

TABLE D2. Tensile and compressive properties of cob in radial direction†

Type	Stiffness MPa	Strength MPa	Maximum strain
Tension, T	22.9	0.5	0.04
Compression, C	9.9	6.3	0.18
T/C	2.31	0.08	0.22

†Each value is the average for seven test samples.

1 cm-long cob sections from the middle.

Warwick SL-207 corn variety.

Rate of loading = 1 cm/min.

The strength in tension was calculated as bioyield force/test sample length x cob diameter, which should be considered as a very rough estimate.

TABLE D3. Comparison of the mechanical properties of corn cob with those of corn kernel, corn stalk and wood

Properties, MPa	Corn cob[a]	Corn kernel[b]	Corn stalk[c]	Wood[d]
E in compression	29	507 (1441)	2861	10342
E_b in simple bending	55	-	4723	11170
Crushing strength	5.7	14 (33)	6.9	48.5
Bending strength	3.0	-	-	95.8
Poisson ratio	0.32	0.32	0.23 (0.36)[e]	0.3-0.5

[a]Corn cob composite at 15% (w.b.) moisture content for Coop S 265, rate of loading in radial compression = 1 cm/min; rate of loading in simple bending = 3 cm/min.

[b]Corn kernel as determined in this study using expressions given on p. 335-336 of Mohsenin (1970). Values not bracketed are those in vertical position, while those in brackets are in flat position. Moisture content = 9.1% w.b. Rate of loading - 1 cm/min.

[c]Dry stalk specimens as reported by Prince et al. (1969a, 1969b).

[d]White oak wood at 12% moisture content, from USDA Wood Handbook (1955).

[e]Corn stalk with nodes (without nodes).

to increase the tensile strength of the stalk (Duncan, 1975). Also, the reported value in simple bending is for the cortex of a dry stalk. The moisture contents of the stalks tested in axial compression and simple bending could be much lower than 15% wet basis (the measured value for the cobs reported in Table D3). However, the modulus of toughness of corn cob compares very well with that of corn stalk reported by Prasad and Gupta (1975), although the stalk was tested at higher rates of loading.

Effect of soil compaction on corn ear physical and mechanical properties

Most of the samples used in 1977 and 1978 experimental investigations were from experimental fields established for soil compaction studies. It was of interest to determine if soil compaction has some effects on cob mechanical properties.

Experimental work

In a study of the effects of machinery traffic on corn production, Raghavan et al. (1978) established a randomized complete-block experiment on a sub-drained field of Ste-Rosalie clay, a chloritic-illitic soil having about 80% clay particles by weight. There were four replications of 13 treatments, consisting of 1, 5, 10 and 15 passes of tractor having measured wheel contact pressures of 31.4, 41.2 and 61.8 KPa. The control plots had a zero traffic treatment. The silage corn grown was a Coop S265 corn variety.

Further details regarding cultivation and agronomic practices adopted in growing the silage corn are given in the report by Raghavan et al. (1978).

Ear breaking strength (defined as maximum force to break an ear), moisture content, diameter and length measurements, were made on individual samples of the silage corn by the author. Only two of the four planted replications were used in this analysis. Four ears were sampled and tested from each experimental plot, giving a total of 104 ears.

The loading rate was 2 cm/min and the test performed as described for corn cobs in simple bending.

Results

The results are shown in Table D4 and Figure D2. The results indicate that for a typical dry year (1977), a certain amount of soil compaction by machinery traffic increases the breaking strength and lowers the moisture content of the corn ear when compared with an uncompacted soil.

Remarks

In light of the above results, corn samples from the soil compaction experimental field used in 1978 were grouped according to the level of compaction. Only samples from one particular level (usually zero or the moderate level) were used in a given single experiment.

TABLE D4. Physical and mechanical properties of corn ear in simple bending at various soil compaction levels

Compaction level* MPa	Corn ear physical and mechanical properties†			
	Moisture content % w.b.	Length mm	Diameter mm	Strength†† N
0	54.8	192	49	186
0.04	49.3	201	49	223
0.16	45.6	191	49	201
0.21	47.0	203	48	196
0.31	46.9	199	50	224
0.44	48.6	196	49	216
0.62	49.4	200	47	224
0.93	43.9	188	49	201

†Each value is the mean of four corn ears.
Variety of corn = Coop S 265.
Rate of loading = 2 cm/min.
Loading span = 150 mm (simple bending)

††Strength defined as maximum breaking force.

*Compaction level is the product of the number of tractor passes and the tractor tire contact pressure.

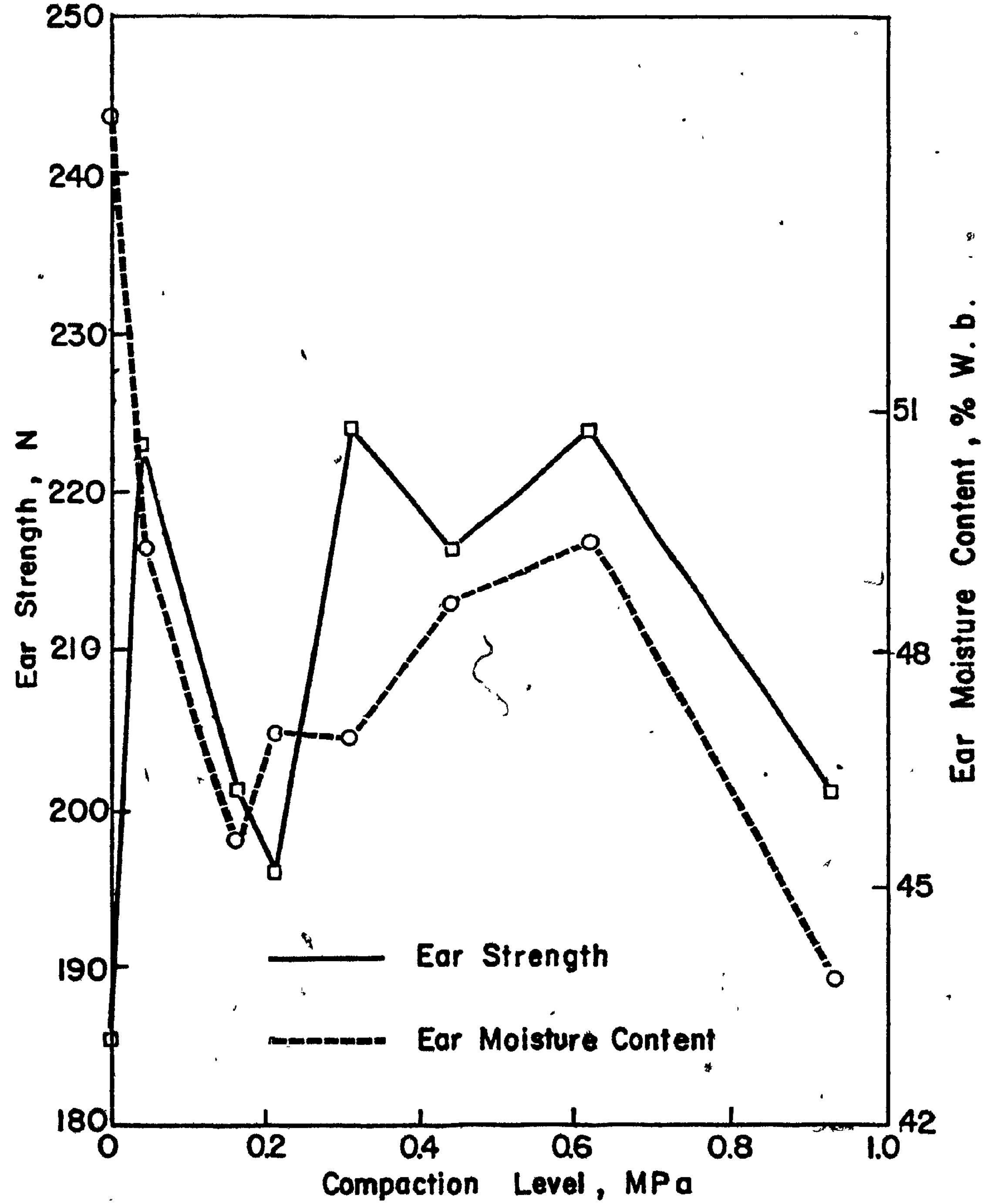


Figure D2. Ear strength and moisture content at various soil compaction levels

<u>Details of the comparison between empirical equation and experimental data</u>
(Refer to Figure 15)

Figure 15 of Chapter V was presented to demonstrate the close fit between empirical equation - equation [44] - and experimental data. Details of this comparison are given in Tables D5 and D6. The coefficient of determination between experimentally determined deformation of corn cob under radial compression and the corresponding calculated deformation using the empirical equation range from 0.9951 to 0.9997 for the samples of three corn varieties tested in 1977.

TABLE D5. Determination of the empirical parameters for nine cob test samples

Sample no.	Measured directly from experimental force-deformation curves							Calculated parameters				Empirical equations for tested samples
	M kg/mm	M_2 kg/mm	M_1 kg/mm	M_o kg/mm	F_b kg	F_2 kg	F_1 kg	α_2	α_1	n	K $\times 10^{-6}$	
Pickseed 165												
1	29.94	20.43	14.69	13.06	94.0	8.0	1.0	0.68	0.49	11.30	8.968	$4.06+0.03F-8.968\times10^{-6}(3.14-0.03F)^{11.3}$
2	28.24	21.33	16.55	13.71	96.0	7.6	2.4	0.76	0.59	14.80	0.046	$3.60+0.04F-0.046\times10^{-6}(3.40-0.04F)^{14.8}$
3	19.49	15.38	11.69	10.00	76.0	8.0	2.6	0.79	0.60	12.03	0.275	$3.70+0.05F-0.275\times10^{-6}(3.90-0.05F)^{12.03}$
Funk G 4040												
1	10.94	9.72	7.45	6.53	35.0	5.2	1.4	0.89	0.68	12.14	1.753	$2.16+0.09F-1.753\times10^{-6}(3.20-0.09F)^{12.14}$
2	13.10	11.48	9.62	8.91	55.8	6.4	1.0	0.88	0.73	10.62	0.388	$2.00+0.08F-0.388\times10^{-6}(4.26-0.08F)^{10.62}$
3	13.93	10.83	8.78	7.74	39.0	5.2	1.2	0.78	0.63	7.56	1000.000	$2.24+0.07F-1.000\times10^{-3}(2.80-0.07F)^{7.56}$
Warwick SL-207												
1	36.39	25.19	17.01	15.06	131.0	13.2	2.2	0.69	0.47	11.41	2.177	$5.10+0.03F-2.177\times10^{-6}(3.60-0.03F)^{11.41}$
2	17.83	16.35	12.83	11.81	68.0	13.0	1.4	0.92	0.72	8.83	12.850	$1.94+0.06F-12.850\times10^{-6}(3.81-0.06F)^{8.83}$
3	35.80	24.17	17.11	14.43	116.0	13.5	2.0	0.68	0.48	8.84	137.00	$4.80+0.03F-137.00\times10^{-6}(3.24-0.03F)^{8.84}$

TABLE D6. Measured and calculated deformation at corresponding load values (from Table D5)†

Sample No.1			Sample No.2			Sample No.3		
F kg	D_m mm	D_c mm	F kg	D_m mm	D_c mm	F kg	D_m mm	D_c mm
Pickseed 165								
0.0	0.0	0.4	0.0	0.0	0.2	0.0	0.0	0.2
10.0	3.2	3.2	10.0	3.3	3.3	5.0	2.3	2.4
20.0	4.2	4.3	20.0	4.2	4.2	10.0	3.4	3.5
30.0	4.8	4.9	30.0	4.6	4.7	20.0	4.5	4.6
40.0	5.3	5.2	40.0	5.1	5.0	30.0	5.2	5.2
50.0	5.7	5.6	50.0	5.4	5.4	40.0	5.8	5.7
60.0	6.0	5.9	60.0	5.7	5.7	50.0	6.3	6.2
70.0	6.2	6.2	70.0	6.1	6.1	60.0	6.8	6.7
80.0	6.6	6.5	80.0	6.4	6.4	70.0	7.3	7.2
94.0	7.0	6.9	96.0	7.0	7.0	76.0	7.6	7.5
r^2 = 0.9986			r^2 = 0.9991			r^2 = 0.9995		
Funk G 4040								
0.0	0.0	0.2	0.0	0.0	0.1	0.0	0.0	0.2
4.0	1.6	2.0	5.0	1.7	1.7	4.0	1.7	1.5
8.0	2.5	2.8	10.0	2.6	2.6	8.0	2.4	2.4
12.0	3.0	3.2	15.0	3.1	3.1	12.0	2.9	2.9
16.0	3.4	3.6	20.0	3.6	3.6	16.0	3.3	3.4
20.0	3.8	4.0	25.0	3.9	4.0	20.0	3.6	3.6
24.0	4.1	4.4	30.0	4.3	4.4	24.0	4.0	3.9
28.0	4.4	4.7	40.0	5.1	5.2	28.0	4.3	4.2
32.0	4.8	5.0	50.0	5.9	6.0	32.0	4.6	4.5
35.0	5.2	5.4	55.8	6.3	6.5	39.0	5.0	5.0
r^2 = 0.9979			r^2 = 0.9989			r^2 = 0.9951		
Warwick SL-207								
0.0	0.0	0.3	0.0	0.0	0.3	0.0	0.0	0.3
10.0	3.2	3.4	5.0	1.2	1.3	10.0	3.2	3.1
20.0	4.9	4.9	10.0	2.0	2.1	20.0	4.5	4.5
30.0	5.6	5.7	15.0	2.5	2.6	30.0	5.1	5.3
40.0	6.1	6.1	20.0	2.9	3.0	40.0	5.6	5.8
50.0	6.5	6.5	30.0	3.6	3.6	50.0	6.0	6.2
70.0	7.1	7.0	40.0	4.1	4.2	60.0	6.4	6.5
90.0	7.6	7.6	50.0	4.7	4.7	80.0	7.0	7.0
110.0	8.2	8.1	60.0	5.2	5.3	100.0	7.5	7.6
131.0	8.8	8.7	68.0	5.7	5.7	116.0	8.0	8.0
r^2 = 0.9997			r^2 = 0.9987			r^2 = 0.9975		

†F = load; D_m = measured deformation; D_c = calculated deformation; r^2 = coefficient of determination for D_m and D_c.

APPENDIX E

COMPUTER PROGRAMS FOR CALCULATING COB MECHANICAL PROPERTIES WITH SOME 1979 DATA AND RESULTS

<u>Notes</u>

Program No.1: Printout of computer program for calculating cob mechanical properties in radial compression.

- Table E1: Radial compression data to determine effects of moisture content and rate of loading.
- Table E2: Calculated results using data in Table E1.
- Table E3: Radial compression data to determine effects of corn variety and harvest date.
- Table E4: Calculated results using data in Table E3.

Program No.2: Printout of computer program for calculating cob mechanical properties in simple bending.

- Table E5: Simple bending data to determine effects of corn variety and harvest date.
- Table E6. Calculated results using data in Table E5.

All symbols used are clearly defined in the programs. SL in data of Program No.1 stands for the length of cob composite section used in radial compression test.

PROGRAM NUMBER ONE

```
$WATFIV UCHE,TIME=10,PAGES=50
C      PROGRAM TO DETERMINE CORN COB MECHANICAL PROPERTIES IN RADIAL
C      COMPRESSION*EFFECTS OF MOISTURE CONTENT AND RATE OF LOADING*
       DIMENSION D(300),FB(300),FA(300),FC(300),Z(300),R(300),B(300),
      1E(300),S(300),U(300),SL(300)
       REAL M(300),MA(300),MB(300)
       INTEGER VHR(300)
C      CONVERSION FACTOR FROM KG/MM**2 TO MEGA PASCALS IS CF = 9.8067
C      CRUSHING STRENGTH IS DENOTED BY S IN MPA
C      MODULUS OF TOUGHNESS IS DENOTED BY U IN 10**6 N-M/M**3
C      PR DENOTES POISSON RATIO
C      E IS MODULUS OF ELASTICITY IN MPA ,
       PI = 3.142
       PR = 0.32
       CF = 9.8067
       DO 10 I=1,240
        READ(5,1)VHR(I),SL(I),D(I),FB(I),FA(I),FC(I),M(I),MA(I),MB(I),
      1Z(I)
     1 FORMAT(3X,I4,8F6.1,F8.2)
    10 CONTINUE
       DO 20 I=1,240
       R(I)=D(I)/2
       B(I)=R(I)/Z(I)
       HH=CF*4*FB(I)*R(I)*(1-(PR)**2)
        E(I)=HH/(PI*SL(I)*B(I)**2)
        S(I)=(CF*2*FB(I))/(PI*SL(I)*B(I))
       CA=MA(I)/M(I)
       CB=MB(I)/M(I)
       IF(CA.EQ.0)CA=0.01
       IF(CB.EQ.0)CB=0.01
       IF(CA.EQ.1.0)CA=0.99
       IF(CB.EQ.1.0)CB=0.99
       DD=(CB/CA)*(1-CA)/(1-CB)
       AA=ALOG10(ABS(DD))
       BB=ALOG10((FB(I)-FA(I))/(FB(I)-FC(I)))
       IF(BB.EQ.0)BB=0.01
       CN=AA/BB+1
       CK=((1-CB)/CB)*(((FB(I)-FC(I))/M(I)))**(1-CN)
       EE=(FB(I)**2)/(2*M(I))
       GG=((CK*M(I))/(CN+1))*((FB(I)/M(I))**(CN+1))
        U(I)=CF*(EE+GG)/(PI*(R(I)**2)*SL(I))
    20 CONTINUE
       WRITE(6,2)
     2 FORMAT('1',10X,'1979 EXPERIMENT TO DETERMINE EFFECTS OF MOISTURE
      1CONTENT OR TEST DATE(V)'79X,'AND RATE OF LOADING(H) **5*3 FACTORIA
      2L EXPERIMENT WITH 16 SAMPLING UNITS(R)')
       WRITE(6,21)
    21 FORMAT(' ',10X,'**RADIAL COMPRESSION DATA** VARIETY IS WARWICK SL
      1 207**')
       WRITE(6,3)
```

```
    3 FORMAT('0',6X,'VHR      SL         2R         FB         F1         F2         M
     1      M1        M2        Z')
      WRITE(6,4)
    4 FORMAT(' ',13X,'MM        MM        KG        KG        KG        KG/MM    KG
     1/MM    KG/MM')
      DO 22 I=1,240
       WRITE(6,41) VHR(I),SL(I),D(I),FB(I),FA(I),FC(I),M(I),MA(I),MB(I),
     1Z(I)
   41 FORMAT('0',6X,I4,2X,8(F6.1,2X),F8.2)
   22 CONTINUE

      WRITE(6,5)
    5 FORMAT('1',10X,'COB MECHANICAL PROPERTIES IN RADIAL COMPRESSION')
      WRITE(6,6)
    6 FORMAT('0',10X,'     VHR        E(MPA)   S(MPA)   U(10**6 N-M/M**3)')
      DO 30 I=1,240
       WRITE(6,7)VHR(I),E(I),S(I),U(I)
    7 FORMAT('0',14X,I4,2(5X,F5.1),5X,F6.3)
   30 CONTINUE
      STOP
      END

$DATA
```

TABLE E1

1979 EXPERIMENT TO DETERMINE EFFECTS OF MOISTURE CONTENT OR TEST DATE(V)
AND RATE OF LOADING(H) **5*3 FACTORIAL EXPERIMENT WITH 16 SAMPLING UNITS(R)
RADIAL COMPRESSION DATA VARIETY IS WARWICK SL 207**

VHR	SL MM	2R MM	FB KG	F1 KG	F2 KG	M KG/MM	M1 KG/MM	M2 KG/MM	Z
1101	38.5	26.0	42.1	1.0	5.0	15.0	8.1	10.6	3.75
1102	34.8	26.0	58.0	1.0	8.0	16.8	9.3	13.5	3.75
1103	36.5	27.0	60.0	1.0	9.0	21.1	10.0	15.5	3.75
1104	35.0	28.7	56.8	1.0	7.0	15.6	10.0	13.3	3.75
1105	38.7	24.5	56.0	1.0	10.0	21.0	10.9	16.2	3.75
1106	37.2	28.5	37.0	1.5	6.0	11.9	6.6	9.1	3.75
1107	36.3	27.6	28.9	1.0	8.0	14.5	7.8	10.5	3.75
1108	36.2	28.2	35.0	1.0	7.0	13.5	6.9	9.7	3.75
1109	35.4	27.8	66.4	2.0	10.0	20.8	12.4	16.0	3.75
1110	37.9	28.4	58.3	1.0	7.0	20.8	11.0	15.1	3.75
1111	39.7	27.9	85.1	2.0	10.0	23.6	12.8	17.5	3.75
1112	35.6	28.0	43.0	2.0	6.0	15.9	9.5	11.9	3.75
1113	36.5	28.6	45.8	2.0	7.0	17.6	10.4	13.4	3.75
1114	37.4	28.1	44.0	2.0	7.0	14.7	8.8	11.2	3.75
1115	36.0	27.3	46.7	1.0	6.0	16.7	9.5	12.7	3.75
1116	36.1	27.7	33.9	1.5	7.0	11.3	7.9	14.1	3.75
1201	39.4	26.5	56.6	1.0	6.0	18.9	10.2	13.3	3.20
1202	36.6	28.2	58.2	1.0	5.0	14.6	9.9	11.6	3.20
1203	37.5	27.9	53.0	2.0	7.5	20.4	11.2	14.4	3.20
1204	37.0	27.0	47.0	1.5	6.0	16.7	9.9	12.0	3.20
1205	37.8	27.4	45.0	1.0	6.0	16.1	9.4	12.2	3.20
1206	38.7	29.2	54.0	1.0	5.0	16.9	9.5	12.3	3.20
1207	26.9	27.7	76.4	2.0	10.0	22.5	11.4	15.2	3.20

1208	37.4	26.6	43.1	1.0	6.0	16.9	9.4	12.0	3.20
1209	38.3	26.2	83.2	2.0	7.0	24.5	13.5	17.3	3.20
1210	40.0	26.3	51.8	2.0	7.5	17.7	10.7	13.8	3.20
1211	39.2	27.0	57.7	1.0	7.5	22.4	10.5	14.9	3.20
1212	37.0	26.6	59.9	1.0	6.7	18.7	11.3	14.0	3.20
1213	40.0	27.8	43.1	1.0	6.0	18.0	8.6	12.1	3.20
1214	37.5	25.7	60.0	1.0	6.5	21.4	11.8	15.7	3.20
1215	38.6	28.1	43.1	1.0	7.0	18.7	8.5	12.2	3.20
1216	32.0	25.8	44.0	1.5	9.0	16.7	[illegible]	11.7	3.20
1301	37.1	28.3	44.5	1.0	2.0	13.9	8.7	9.4	3.47
1302	37.0	26.8	57.0	1.0	4.0	19.0	11.2	13.3	3.47
1303	39.9	25.7	54.6	2.5	5.0	19.5	13.0	14.2	3.47
1304	38.1	28.1	76.0	1.0	6.5	23.0	13.9	17.4	3.47
1305	37.9	27.9	69.2	0.5	5.0	19.2	12.1	14.9	3.47
1306	37.0	27.5	63.7	1.6	5.6	18.2	12.9	15.3	3.47
1307	36.0	26.7	66.6	3.0	7.5	19.0	13.3	15.6	3.47
1308	34.1	25.4	57.9	2.7	6.0	15.6	9.9	11.3	3.47
1309	36.6	26.4	70.1	1.0	8.0	27.0	12.4	17.8	3.47
1310	36.7	29.2	46.3	1.0	5.0	14.0	8.1	10.0	3.47
1311	39.4	29.6	66.0	1.5	7.4	25.4	13.4	18.2	3.47
1312	37.6	27.0	100.0	2.0	8.0	37.6	14.7	20.6	3.47
1313	39.1	27.2	49.4	1.0	7.5	32.1	12.7	19.1	3.47
1314	35.9	27.6	35.0	1.0	5.0	15.9	8.1	10.7	3.47
1315	37.8	27.0	58.0	1.6	8.0	23.3	11.5	15.2	3.47
1316	36.2	26.4	44.1	1.0	5.0	19.9	9.4	11.9	3.47

2101	39.3	27.3	54.0	3.0	10.0	18.6	11.3	14.7	4.05
2102	~~38.1~~	27.0	34.0	1.0	10.0	6.1	4.7	5.2	4.05
2103	40.2	28.0	54.7	3.0	10.0	17.7	11.5	14.4	4.05
2104	37.3	25.0	65.1	2.0	8.0	16.3	10.7	13.9	4.05
2105	36.1	26.2	44.2	1.5	7.0	12.6	8.4	10.6	4.05
2106	37.0	27.8	45.0	2.0	10.0	11.3	8.6	10.9	4.05
2107	37.6	27.8	56.9	2.0	10.0	19.0	11.9	16.2	4.05
2108	35.9	27.6	55.8	2.0	9.0	15.9	10.8	13.8	4.05
2109	37.0	25.8	35.0	2.0	10.0	10.6	7.2	9.6	4.05
2110	38.7	24.9	71.9	3.0	12.0	27.7	15.3	20.7	4.05
2111	35.4	26.6	59.3	5.0	18.0	12.4	9.4	10.3	4.05
2112	37.2	26.5	46.0	2.0	12.0	15.3	9.6	13.1	4.05
2113	36.1	28.5	50.0	5.0	17.0	16.1	11.0	14.4	4.05
2114	38.5	25.2	100.0	9.0	31.0	35.7	19.4	27.6	4.05
2115	38.5	28.3	53.8	2.0	7.0	11.7	9.4	10.6	4.05
2116	34.9	27.4	46.5	2.0	11.0	11.6	8.7	10.4	4.05
2201	35.7	24.5	59.1	2.0	10.0	20.4	10.4	15.3	3.95
2202	37.3	27.5	44.8	2.0	8.0	16.0	10.7	13.1	3.95
2203	36.0	26.3	66.8	2.0	7.0	17.6	11.6	14.2	3.95
2204	38.1	27.5	44.0	1.0	9.0	21.0	9.8	15.2	3.95
2205	35.5	28.8	39.4	1.5	7.0	13.1	8.6	10.8	3.95
2206	38.3	27.3	51.0	1.0	7.0	17.0	10.0	12.9	3.95
2207	34.8	26.2	45.0	1.0	5.0	9.2	7.6	8.7	3.95
2208	36.4	26.7	57.6	1.0	6.5	16.9	10.8	13.5	3.95
2209	39.9	24.4	100.0	2.0	12.0	35.7	16.3	24.4	3.95

2210	37.4	26.9	52.7	2.0	10.0	21.1	12.1	17.8	3.95
2211	38.2	27.4	65.9	2.0	7.0	22.7	12.5	15.9	3.95
2212	38.3	28.0	60.0	2.0	10.0	16.2	11.2	13.9	3.95
2213	38.0	25.4	64.9	2.0	6.0	22.4	12.6	15.1	3.95
2214	35.0	27.2	46.0	1.0	5.0	14.8	8.7	10.5	3.95
2215	35.0	27.1	55.6	2.0	8.0	15.0	10.1	12.2	3.95
2216	34.7	28.7	52.5	2.0	10.0	20.2	11.0	14.7	3.95
2301	35.0	25.5	50.7	3.0	10.0	20.3	12.2	15.7	4.02
2302	36.9	27.6	57.0	2.0	10.0	22.8	12.8	16.8	4.02
2303	33.4	25.0	99.0	5.0	15.0	35.4	18.1	24.0	4.02
2304	35.1	27.3	46.9	2.0	8.0	19.6	11.2	14.4	4.02
2305	35.8	27.7	52.0	2.0	10.0	24.8	13.5	17.5	4.02
2306	38.2	28.2	49.0	2.0	10.0	16.9	11.2	14.4	4.02
2307	37.5	26.8	48.7	2.0	10.0	16.8	10.6	13.8	4.02
2308	36.8	28.6	58.0	2.0	10.0	14.9	10.6	13.0	4.02
2309	38.2	27.7	57.0	2.0	9.0	21.9	12.0	15.0	4.02
2310	36.8	27.3	50.2	2.0	7.5	22.8	11.5	17.8	4.02
2311	34.8	26.7	46.1	1.0	6.0	8.9	7.1	7.7	4.02
2312	37.1	25.0	72.0	2.0	7.0	24.0	13.2	17.1	4.02
2313	34.7	28.7	35.0	2.0	10.0	15.9	9.2	11.4	4.02
2314	38.4	26.2	45.0	2.0	10.0	14.1	9.8	12.5	4.02
2315	34.0	27.9	39.9	2.0	7.0	16.6	9.5	11.8	4.02
2316	35.7	29.3	43.7	3.0	10.0	18.2	11.3	13.0	4.02
3101	30.0	25.4	38.0	1.0	2.0	6.1	5.7	5.9	5.20
3102	29.6	27.9	36.0	2.0	6.0	10.9	9.2	10.0	5.20

3103	32.6	28.4	35.8	2.0	13.0	11.9	9.1	10.9	5.20
3104	29.2	25.8	38.0	4.0	11.0	12.3	9.2	10.8	5.20
3105	30.8	26.0	63.2	4.0	14.0	18.1	13.5	16.4	5.20
3106	30.7	28.0	44.3	2.0	7.0	12.3	10.3	11.3	5.20
3107	29.6	24.9	41.2	4.0	12.0	18.4	14.3	17.2	5.20
3108	33.1	27.6	51.5	4.0	12.0	14.7	11.9	13.6	5.20
3109	32.4	25.2	67.2	2.0	8.0	13.7	11.2	12.9	5.20
3110	29.2	28.6	40.3	2.0	11.0	13.4	10.6	12.2	5.20
3111	32.2	24.1	40.4	2.0	10.0	15.0	10.4	12.7	5.20
3112	35.3	24.3	48.0	4.0	14.0	18.1	11.6	15.5	5.20
3113	33.2	23.3	50.2	4.0	13.0	18.6	13.2	16.2	5.20
3114	31.0	27.0	48.0	4.0	14.0	17.7	11.9	14.8	5.20
3115	31.3	25.6	37.5	4.0	14.0	12.1	9.3	11.2	5.20
3116	29.3	26.8	31.0	4.0	13.0	12.9	10.0	12.0	5.20
3201	33.9	27.0	51.0	2.0	10.0	16.5	12.9	15.8	5.45
3202	32.1	26.5	44.0	4.0	16.0	17.6	12.9	15.6	5.45
3203	33.1	26.4	57.0	4.0	16.0	19.0	12.1	15.8	5.45
3204	31.8	26.1	48.0	3.0	10.0	14.1	9.8	11.9	5.45
3205	31.0	25.2	46.2	4.0	10.0	13.6	10.6	12.1	5.45
3206	32.9	26.6	36.0	4.0	14.0	15.7	11.4	13.8	5.45
3207	33.0	26.5	43.0	6.0	20.0	17.2	11.9	15.3	5.45
3208	31.5	25.7	60.0	4.0	22.0	19.4	16.0	18.1	5.45
3209	31.5	27.7	43.0	2.0	8.0	15.4	10.5	13.0	5.45
3210	29.4	25.5	54.0	4.0	10.0	10.8	10.0	10.5	5.45
3211	31.7	24.5	61.5	5.0	12.2	19.8	14.5	17.1	5.45

3212	32.8	27.4	46.0	4.0	16.0	17.0	12.7	14.3	5.45
3213	33.2	25.4	34.0	4.0	16.0	11.3	8.3	10.6	5.45
3214	33.4	25.3	44.0	4.0	16.0	16.3	11.4	14.7	5.45
3215	31.5	27.2	41.2	6.0	30.0	9.4	7.3	8.0	5.45
3216	34.0	25.0	55.0	4.0	20.0	22.9	14.7	19.4	5.45
3301	30.6	26.3	50.0	1.0	3.0	15.2	12.6	13.8	5.10
3302	30.8	27.4	47.0	2.0	10.0	16.8	11.8	14.2	5.10
3303	30.0	26.2	38.0	2.0	8.0	11.2	9.0	10.3	5.10
3304	30.9	25.8	49.5	2.0	12.0	14.6	11.1	13.9	5.10
3305	31.5	26.2	49.0	4.0	10.0	18.2	14.5	17.0	5.10
3306	30.7	28.0	42.0	4.0	10.0	15.6	10.6	14.6	5.10
3307	30.0	28.9	48.0	2.0	9.0	15.5	11.5	13.9	5.10
3308	30.5	28.3	45.0	2.0	8.0	16.7	13.4	15.4	5.10
3309	29.8	25.9	57.0	2.0	10.0	14.6	12.8	14.7	5.10
3310	33.3	28.0	48.0	2.0	10.0	16.6	11.5	14.6	5.10
3311	31.2	28.1	52.0	4.0	11.0	18.6	14.5	16.4	5.10
3312	33.4	26.0	49.0	2.0	0.4	14.0	12.7	13.2	5.10
3313	33.6	28.9	61.0	2.0	12.0	16.1	11.1	14.9	5.10
3314	32.6	24.1	72.4	6.0	26.0	27.9	17.5	23.2	5.10
3315	31.1	27.7	41.0	4.0	12.0	14.1	8.6	13.8	5.10
3316	31.7	24.6	60.0	4.0	22.0	22.2	16.0	20.0	5.10
4101	33.6	26.5	42.2	1.0	7.0	14.1	11.1	13.0	6.28
4102	33.4	24.1	42.2	2.5	7.5	19.2	14.7	16.5	6.28
4103	34.0	26.6	46.0	1.5	4.5	11.2	9.9	10.6	6.28

4104	34.5	25.2	63.0	4.0	18.0	31.5	19.7	23.7	6.28
4105	32.1	26.3	27.0	1.0	4.0	13.0	9.6	11.5	6.28
4106	35.1	26.8	43.7	2.0	14.0	18.9	12.4	15.6	6.28
4107	33.6	25.8	29.0	3.0	12.0	13.8	9.3	13.1	6.28
4108	33.7	26.2	40.2	1.0	4.0	14.4	11.9	13.4	6.28
4109	30.5	26.4	30.7	2.0	8.0	11.0	8.2	9.9	6.28
4110	34.0	24.0	30.0	2.0	7.0	14.3	9.3	1[illegible]	6.28
4111	30.2	23.1	33.3	2.0	6.0	13.8	11.2	12.4	6.28
4112	31.4	24.6	44.0	1.0	5.0	14.2	10.8	12.6	6.28
4113	32.8	24.4	54.2	3.5	15.0	25.8	15.8	18.7	6.28
4114	33.6	27.0	44.4	2.5	8.5	13.5	10.5	12.0	6.28
4115	34.4	25.0	44.7	3.5	12.0	23.5	16.5	19.2	6.28
4116	33.7	25.6	40.1	0.5	2.0	9.6	7.9	8.7	6.28
4201	33.1	28.6	47.8	2.0	13.0	17.7	11.7	13.9	5.93
4202	33.1	27.4	40.0	1.0	5.0	14.3	10.8	13.0	5.93
4203	33.4	25.4	57.5	5.0	17.0	18.0	13.8	15.6	5.93
4204	32.3	26.8	40.0	1.0	3.0	9.3	8.5	9.0	5.93
4205	32.4	26.5	41.2	1.0	4.0	11.4	10.1	10.9	5.93
4206	34.2	27.2	37.0	0.5	2.0	14.2	11.8	13.0	5.93
4207	31.4	25.5	59.0	5.0	17.0	20.3	14.2	17.5	5.93
4208	35.1	26.0	45.5	1.0	6.0	15.7	12.0	14.6	5.93
4209	31.7	25.8	47.5	5.0	18.0	18.3	13.7	16.4	5.93
4210	31.6	25.4	37.0	0.5	3.0	10.0	8.3	9.2	5.93
4211	32.5	24.4	46.7	3.0	10.0	22.2	15.6	18.4	5.93
4212	33.4	24.3	44.0	2.0	10.0	14.2	11.1	13.1	5.93

4213	33.5	27.3	29.0	2.0	11.0	9.4	7.3	8.6	5.93
4214	33.2	24.2	34.0	2.0	9.0	14.8	9.7	10.9	5.93
4215	32.7	26.2	94.0	5.0	12.0	31.3	16.8	24.9	5.93
4216	31.6	25.8	35.0	1.5	6.0	15.9	11.2	12.6	5.93
4301	31.5	27.5	52.8	1.0	3.0	9.8	8.5	9.4	5.98
4302	34.1	23.7	46.0	1.5	6.0	17.0	13.1	14.3	5.98
4303	33.4	25.2	40.0	1.6	7.0	19.1	13.7	16.5	5.98
4304	30.7	26.6	36.0	2.5	6.0	16.4	12.0	13.6	5.98
4305	32.0	25.5	44.0	2.0	10.0	27.5	15.0	21.3	5.98
4306	31.7	26.4	51.9	5.0	19.0	29.8	17.4	19.4	5.98
4307	34.5	25.5	41.0	3.5	14.0	15.8	12.9	14.2	5.98
4308	34.9	24.4	49.5	5.0	17.0	22.5	15.3	18.1	5.98
4309	30.7	28.8	57.0	3.0	14.0	16.6	12.3	14.3	5.98
4310	34.8	25.8	43.0	5.0	13.5	18.7	12.3	14.8	5.98
4311	30.5	27.4	38.3	3.0	11.6	13.9	10.1	12.7	5.98
4312	32.1	27.7	35.0	3.0	10.0	19.4	12.8	16.7	5.98
4313	30.0	27.6	50.2	4.5	24.0	15.7	12.7	13.1	5.98
4314	32.7	27.6	63.0	7.0	32.0	16.6	12.7	15.5	5.98
4315	33.0	23.4	49.0	3.0	11.0	28.8	15.9	20.0	5.98
4316	32.5	24.0	45.0	3.5	9.0	14.1	12.2	13.1	5.98
5101	30.8	25.5	55.0	1.0	7.0	33.7	18.0	24.0	5.60
5102	30.4	25.7	62.0	2.0	7.0	38.8	23.1	27.5	5.60
5103	28.0	27.1	80.0	2.0	5.0	33.3	19.0	25.0	5.60
5104	30.0	25.3	48.2	2.0	7.0	25.4	16.3	20.2	5.60
5105	28.7	23.8	46.0	1.0	4.0	23.0	15.0	18.3	5.60

5106	31.4	25.3	44.0	1.0	4.0	21.2	13.4	16.7	5.60
5107	30.5	25.0	64.1	1.0	8.0	28.6	16.2	21.6	5.60
5108	30.5	26.7	77.8	2.0	7.0	38.9	25.3	29.5	5.60
5109	29.9	26.1	67.2	3.0	7.5	29.2	21.4	24.9	5.60
5110	28.6	24.3	55.4	2.0	8.0	30.8	16.2	20.6	5.60
5111	31.3	22.0	100.0	1.5	10.0	39.4	26.6	31.0	5.60
5112	27.8	23.9	52.9	2.0	9.0	26.5	15.9	18.3	5.60
5113	30.0	23.3	72.0	1.5	8.7	27.7	18.6	22.6	5.60
5114	29.8	24.9	58.1	1.5	5.0	27.7	17.2	21.2	5.60
5115	28.9	23.9	50.3	2.0	9.0	26.5	15.6	19.7	5.60
5116	29.2	25.9	100.0	4.3	20.0	52.6	19.9	28.6	5.60
5201	28.0	23.3	79.2	3.0	10.0	31.3	19.5	23.1	5.24
5202	30.0	24.2	62.8	3.0	9.0	31.4	17.9	21.3	5.24
5203	29.6	26.6	72.2	1.0	4.5	34.4	20.9	26.0	5.24
5204	31.4	24.0	62.2	4.0	19.0	29.9	20.8	24.0	5.24
5205	28.6	24.3	49.9	1.5	5.7	25.0	14.2	20.1	5.24
5206	30.3	25.2	84.0	3.0	14.0	36.5	23.8	29.2	5.24
5207	31.0	26.6	84.3	2.0	8.0	35.4	22.2	28.3	5.24
5208	27.0	26.0	42.2	1.0	3.0	19.2	11.8	14.5	5.24
5209	31.8	24.2	61.0	2.0	9.0	27.7	18.4	21.7	5.24
5210	28.0	25.7	53.5	1.0	6.0	24.3	15.9	19.8	5.24
5211	28.2	25.0	65.0	4.0	9.0	32.5	21.8	25.5	5.24
5212	29.5	23.6	55.7	1.0	8.0	24.2	16.6	20.7	5.24
5213	30.9	22.5	63.4	2.0	8.0	28.3	18.1	23.1	5.24
5214	29.7	24.7	100.0	7.5	32.0	57.1	27.2	34.0	5.24

5215	30.9	24.7	46.0	2.0	6.0	27.1	16.9	20.0	5.24
5216	29.9	24.8	62.0	5.0	11.0	25.0	18.4	20.4	5.24
5301	32.5	26.0	60.0	2.0	8.0	27.3	16.1	21.0	5.90
5302	31.5	25.6	130.0	4.0	18.0	47.1	25.7	32.0	5.90
5303	28.7	23.6	73.8	6.0	16.0	28.8	19.4	23.1	5.90
5304	31.4	23.4	38.3	4.0	10.0	21.9	14.3	16.6	5.90
5305	28.4	23.5	49.0	2.0	8.0	18.8	14.1	17.8	5.90
5306	31.5	26.3	145.2	4.0	28.0	53.8	27.7	37.8	5.90
5307	30.1	26.5	76.0	4.0	12.0	30.4	22.5	26.7	5.90
5308	29.0	26.4	38.0	2.0	5.0	23.8	16.4	19.4	5.90
5309	28.8	27.3	47.0	2.0	6.5	22.4	15.4	18.4	5.90
5310	29.8	24.7	58.7	2.0	6.0	22.2	17.2	18.8	5.90
5311	30.6	24.7	59.8	5.0	12.0	35.2	18.3	21.7	5.90
5312	27.0	25.6	51.0	5.0	14.0	27.7	15.9	19.5	5.90
5313	29.1	22.9	64.0	2.0	8.0	16.7	13.5	15.6	5.90
5314	31.0	26.1	58.0	2.0	8.0	34.1	17.0	21.7	5.90
5315	30.0	22.3	49.1	2.0	7.0	26.1	15.7	20.0	5.90
5316	29.2	24.7	51.9	4.0	11.0	26.0	17.7	21.5	5.90

TABLE E2. Calculated results using data in Table E1

COB MECHANICAL PROPERTIES IN RADIAL COMPRESSION

VHR	E(MPA)	S(MPA)	U(10**6 N-M/M**3)
1101	13.3	2.0	0.035
1102	20.2	3.0	0.062
1103	19.2	2.9	0.050
1104	17.8	2.6	0.050
1105	18.6	2.8	0.050
1106	11.0	1.6	0.029
1107	9.1	1.4	0.018
1108	10.8	1.6	0.026
1109	21.3	3.2	0.058
1110	17.1	2.5	0.040
1111	24.2	3.6	0.074
1112	13.6	2.0	0.032
1113	13.8	2.1	0.030
1114	13.2	2.0	0.034
1115	15.0	2.2	0.036
1116	10.7	1.6	0.019
1201	12.4	2.2	0.046
1202	12.9	2.3	0.055
1203	11.6	2.0	0.037
1204	10.8	1.9	0.037
1205	10.0	1.7	0.033
1206	11.0	1.9	0.038
1207	23.5	4.1	0.100
1208	9.9	1.7	0.032
1209	19.0	3.3	0.078
1210	11.3	2.0	0.041
1211	12.5	2.2	0.042
1212	14.0	2.4	0.054

1213	8.9	1.5	0.027
1214	14.3	2.5	0.050
1215	9.1	1.6	0.028
1216	12.2	2.1	0.047
1301	11.4	1.8	0.034
1302	15.5	2.5	0.046
1303	14.4	2.3	0.042
1304	19.2	3.1	0.059
1305	17.7	2.8	0.058
1306	16.9	2.7	0.054
1307	18.7	3.0	0.063
1308	18.0	2.9	0.072
1309	19.6	3.1	0.057
1310	11.7	1.9	0.037
1311	15.3	2.5	0.037
1312	26.6	4.3	0.080
1313	12.5	2.0	0.024
1314	9.5	1.5	0.023
1315	15.3	2.5	0.043
1316	12.5	2.0	0.033
2101	18.5	2.5	0.041
2102	12.2	1.7	0.050
2103	17.9	2.5	0.040
2104	25.7	3.5	0.077
2105	17.2	2.4	0.045
2106	16.1	2.2	0.042
2107	20.0	2.8	0.042
2108	20.7	2.8	0.050
2109	13.5	1.9	0.034
2110	27.4	3.8	0.061

2111	23.2	3.2	0.085
2112	17.2	2.4	0.040
2113	17.9	2.5	0.041
2114	37.9	5.2	0.101
2115	18.2	2.5	0.053
2116	17.9	2.5	0.050
2201	23.6	3.3	0.063
2202	15.3	2.2	0.033
2203	24.7	3.5	0.071
2204	14.7	2.1	0.027
2205	13.5	1.9	0.029
2206	17.1	2.4	0.040
2207	17.3	2.4	0.060
2208	20.7	2.9	0.053
2209	35.9	5.1	0.093
2210	18.3	2.6	0.036
2211	22.0	3.1	0.050
2212	19.6	2.8	0.052
2213	23.5	3.3	0.058
2214	16.9	2.4	0.042
2215	20.5	2.9	0.057
2216	18.4	2.6	0.039
2301	20.6	2.9	0.044
2302	20.3	2.8	0.040
2303	42.9	6.0	0.109
2304	17.7	2.5	0.034
2305	19.0	2.6	0.033
2306	16.5	2.3	0.034
2307	17.6	2.4	0.039
2308	20.0	2.8	0.052

2309	19.5	2.7	0.041
2310	18.1	2.5	0.031
2311	18.0	2.5	0.066
2312	28.1	3.9	0.069
2313	12.7	1.8	0.023
2314	16.2	2.2	0.039
2315	15.2	2.1	0.029
2316	15.1	2.1	0.029
3101	30.2	3.2	0.077
3102	26.4	2.8	0.034
3103	23.4	2.5	0.029
3104	30.6	3.3	0.044
3105	47.8	5.1	0.074
3106	31.2	3.3	0.044
3107	33.9	3.6	0.036
3108	34.2	3.7	0.049
3109	49.9	5.3	0.104
3110	29.2	3.1	0.035
3111	31.6	3.4	0.043
3112	33.9	3.6	0.048
3113	39.3	4.2	0.055
3114	34.8	3.7	0.045
3115	28.4	3.0	0.041
3116	23.9	2.6	0.026
3201	37.1	3.8	0.043
3202	34.4	3.5	0.036
3203	43.4	4.4	0.058
3204	38.5	3.9	0.055
3205	39.4	4.0	0.056
3206	27.4	2.8	0.027

3207	32.7	3.3	0.037
3208	49.3	5.0	0.062
3209	32.8	3.4	0.036
3210	48.0	4.9	0.091
3211	52.7	5.4	0.072
3212	34.1	3.5	0.038
3213	26.8	2.7	0.036
3214	34.7	3.5	0.042
3215	32.0	3.3	0.061
3216	43.1	4.4	0.050
3301	36.2	4.0	0.050
3302	32.5	3.5	0.041
3303	28.2	3.1	0.042
3304	36.2	4.0	0.055
3305	34.6	3.8	0.042
3306	28.5	3.1	0.036
3307	32.3	3.5	0.041
3308	30.4	3.3	0.033
3309	43.1	4.7	0.068
3310	30.0	3.3	0.038
3311	34.6	3.8	0.041
3312	32.9	3.6	0.047
3313	36.6	4.0	0.057
3314	53.7	5.9	0.081
3315	27.7	3.0	0.042
3316	44.9	4.9	0.063
4101	41.9	3.7	0.036
4102	46.3	4.1	0.033
4103	45.0	4.0	0.050
4104	64.1	5.7	0.048

4105	28.3	2.5	0.017
4106	41.1	3.6	0.031
4107	29.6	2.6	0.021
4108	40.2	3.6	0.031
4109	33.7	3.0	0.029
4110	32.5	2.9	0.025
4111	42.2	3.7	0.034
4112	50.3	4.5	0.048
4113	59.9	5.3	0.050
4114	43.3	3.8	0.041
4115	45.9	4.1	0.030
4116	41.1	3.6	0.049
4201	39.8	3.7	0.038
4202	34.8	3.3	0.030
4203	53.4	5.0	0.062
4204	36.4	3.4	0.047
4205	37.8	3.6	0.042
4206	31.3	2.9	0.024
4207	58.1	5.5	0.063
4208	39.3	3.7	0.037
4209	45.8	4.3	0.043
4210	36.3	3.4	0.043
4211	46.4	4.4	0.037
4212	42.7	4.0	0.047
4213	25.0	2.3	0.026
4214	33.4	3.1	0.033
4215	86.5	8.1	0.097
4216	33.8	3.2	0.027
4301	48.9	4.6	0.076
4302	45.6	4.2	0.045

4303	38.1	3.5	0.028
4304	35.3	3.3	0.026
4305	43.2	4.0	0.027
4306	49.7	4.6	0.041
4307	37.4	3.5	0.034
4308	46.6	4.3	0.042
4309	51.7	4.8	0.055
4310	38.4	3.6	0.035
4311	36.7	3.4	0.033
4312	31.5	2.9	0.020
4313	48.6	4.5	0.053
4314	55.9	5.2	0.071
4315	50.9	4.7	0.040
4316	46.2	4.3	0.051
5101	49.2	4.9	0.034
5102	55.8	5.5	0.037
5103	74.1	7.4	0.065
5104	44.6	4.4	0.035
5105	47.3	4.7	0.039
5106	38.9	3.9	0.032
5107	59.1	5.9	0.056
5108	67.1	6.7	0.051
5109	60.5	6.0	0.052
5110	56.0	5.6	0.048
5111	102.1	10.2	0.118
5112	56.0	5.6	0.055
5113	72.4	7.2	0.081
5114	55.0	5.5	0.046
5115	51.2	5.1	0.045
5116	92.9	9.2	0.101

5201	74.7	7.9	0.099
5202	53.2	5.7	0.058
5203	56.4	6.0	0.050
5204	50.8	5.4	0.056
5205	44.2	4.7	0.042
5206	67.7	7.2	0.074
5207	62.9	6.7	0.064
5208	37.0	3.9	0.035
5209	48.8	5.2	0.053
5210	45.8	4.9	0.044
5211	56.7	6.0	0.054
5212	49.2	5.2	0.054
5213	56.1	6.0	0.064
5214	83.9	8.9	0.102
5215	37.1	3.9	0.031
5216	51.5	5.5	0.061
5301	55.4	5.2	0.044
5302	125.8	11.9	0.139
5303	85.0	8.0	0.090
5304	40.7	3.8	0.032
5305	57.3	5.4	0.055
5306	136.7	12.9	0.150
5307	74.3	7.0	0.062
5308	38.7	3.7	0.021
5309	46.6	4.4	0.033
5310	62.2	5.9	0.058
5311	61.7	5.8	0.050
5312	57.6	5.4	0.047
5313	74.9	7.1	0.105
5314	55.9	5.3	0.039
5315	57.3	5.4	0.046
5316	56.1	5.3	0.044

TABLE E3

1979 EXPERIMENT TO DETERMINE EFFECTS OF VARIETY OF CORN (V) AND HARVEST DATE (H)
*SPLIT PLOT EXPERIMENT IN A RANDOMIZED COMPLETE BLOCK DESIGN WITH THREE BLOCKS (R)
RADIAL COMPRESSION DATA EACH VALUE IS THE MEAN OF 7 TEST SAMPLES

VHR	SL MM	2R MM	FB KG	F1 KG	F2 KG	M KG/MM	M1 KG/MM	M2 KG/MM	7
111	29.3	25.9	54.3	2.4	9.6	13.2	8.4	9.9	3.473
112	31.4	26.9	61.7	1.8	7.6	18.1	10.8	13.2	4.000
113	31.4	27.3	55.6	2.2	9.5	20.8	10.9	15.0	4.050
121	28.4	25.5	39.2	1.8	7.9	12.7	8.6	9.7	4.250
122	30.0	27.6	39.0	1.8	4.9	12.6	7.8	9.1	4.350
123	30.2	27.2	36.8	1.7	5.4	11.5	8.2	9.4	4.775
131	29.7	23.6	40.4	3.1	10.0	9.4	7.6	8.2	3.420
132	29.8	25.3	39.1	1.9	5.9	11.3	8.9	10.2	4.150
133	32.0	25.9	38.5	2.5	9.6	12.4	9.2	10.5	4.200
211	33.3	25.4	57.1	2.5	8.2	18.8	10.7	14.2	3.575
212	34.7	25.4	65.7	2.9	9.5	24.5	12.8	17.0	3.496
213	33.5	26.4	65.6	2.8	10.8	26.4	13.0	17.5	4.050
221	28.7	26.4	46.1	2.4	6.4	13.8	8.3	10.1	4.325
222	30.3	25.3	48.1	2.3	6.8	19.9	9.9	12.6	4.525
223	29.7	26.1	41.0	2.7	6.6	16.6	8.9	11.2	4.700
231	31.4	24.3	58.0	3.4	9.6	17.8	11.1	14.1	3.235
232	31.9	24.9	54.0	3.2	11.4	17.2	10.9	14.1	3.826
233	30.8	23.9	48.8	3.1	10.0	14.1	9.8	11.6	3.473
311	37.2	25.3	81.4	2.7	10.9	24.8	12.1	17.3	3.275
312	36.1	25.3	83.1	2.8	10.6	27.7	12.2	16.8	3.100

313	38.2	24.5	88.9	2.8	11.8	26.9	11.9	17.5	2.750
321	27.3	26.2	59.0	2.6	6.6	14.6	8.3	10.3	4.000
322	30.4	25.0	64.5	2.6	7.6	18.3	9.0	12.0	3.570
323	27.8	25.3	62.5	2.8	7.5	17.9	9.1	11.9	3.900
331	32.3	25.0	71.1	4.3	14.9	14.4	9.4	12.1	3.500
332	32.8	25.3	79.2	4.1	14.7	19.2	11.7	15.5	3.585
333	31.6	23.6	69.8	4.0	15.5	17.9	10.8	15.0	3.625

TABLE E4. Calculated results using data in Table E3

COB MECHANICAL PROPERTIES IN RADIAL COMPRESSION

VHR	E(MPA)	S(MPA)	U(10**6 N-M/M**3)
111	19.3	3.1	0.09
112	26.2	3.6	0.07
113	23.8	3.3	0.05
121	21.9	2.9	0.05
122	20.0	2.6	0.04
123	22.9	2.7	0.04
131	15.1	2.5	0.07
132	20.0	2.7	0.05
133	18.4	2.4	0.04
211	19.3	3.0	0.06
212	20.4	3.3	0.06
213	27.3	3.8	0.06
221	25.5	3.3	0.06
222	28.8	3.5	0.05
223	26.2	3.1	0.04
231	17.8	3.1	0.08
232	22.3	3.2	0.07
233	17.9	2.9	0.07
311	20.8	3.5	0.09
312	19.6	3.5	0.09
313	16.1	3.3	0.11
321	29.6	4.1	0.10
322	24.2	3.8	0.10
323	30.3	4.3	0.10
331	24.2	3.8	0.13
332	27.5	4.3	0.12
333	27.6	4.2	0.12

PROGRAM NUMBER TWO

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$WATFIV
C       PROGRAM TO CALCULATE CORN COB MECHANICAL PROPERTIES IN SIMPLE BEND
C       ING * EFFECTS OF VARIETY AND HARVEST DATE *
        DIMENSION EB(30),DB(30),BETA(30),D1(30),D2(30),CFT(30),EB(30),SB(3
       10),EBB(30),SBB(30),DM(30),EBH(30),SBH(30),DP(30)
        REAL MI,MH
        INTEGER VHR(30)
        DOUBLE PRECISION C1,C2,C3,C4,CFT,AA
        REAL*8 K1,K2
C       CONVERSION FACTOR FROM KG/MM**2 TO MEGA PASCALS IS CF=9.8067
C       CFT IS CORRECTION FACTOR FOR COB TAPERING STRUCTURE AS DERIVED BY
C       SCHRODER ET AL (1973)
C       EB DENOTES COB MODULUS OF ELASTICITY IN SIMPLE BENDING IN MPA
C       SB DENOTES COB BENDING STRENGHT IN MPA
C       BETA IS THE DEGREE OF ELASTICITY IN SIMPLE  BENDING IN PERCENT
C       CFC IS CORRECTION FACTOR FOR COB COMPOSITE NATURE  WHICH IS
C       EXPERIMENTALLY DETERMINED AS  0.98 FOR ALL THE VARIETIES TESTED
C       THEORETICALLY CFC = 1-F**4(1-M) WHERE F IS THE RATIO OF PITH RADIU
C       S TO MIDCOB RADIUS AND M IS THE RATIO OF PITH ELASTIC MODULUS TO
C       THAT OF THE MIDCOB
C       THE LOADING SPAN IS FIXED AT 150 MILLIMETERS
C       EBB AND SBB DENOTE COB MODULUS OF ELASTICITY  AND BENDING STRENGHT
C       WHEN THE COB IS CONSIDERED AS A SIMPLE HOMOGENEOUS CIRCULAR BEAM
C       WITH MOMENT OF INERTIA MI AND MEAN DIAMETER DM
C       EBH AND SBH DENOTE COB MODULUS OF ELASTICITY AND BENDING STRENGHT
C       WHEN THE COB IS CONSIDERED AS A HOLLOW BEAM OF ONE MATERIAL
C       MH IS THE MOMENT OF INERTIA OF THE HOLLOW BEAM
C       DE IS THE ELASTIC COMPONENT OF THE MAXIMUM DEFLECTION AT MID-SPAN
C       D1 AND D2 ARE THE TIP-END DIAMETER AND BUTT-END DIAMETER OF COB
C       DP IS THE DIAMETER OF THE COB PITH AT MID-SPAN
        PI=3.142
        CFC=0.98
        L=150
        CF=9.8067
        DO 10 I=1,27
        READ(5,1)VHR(I),EB(I),DB(I),BETA(I),D1(I),D2(I),DP(I)
      1 FORMAT(I3,2X,6F6.1)
     10 CONTINUE
        DO 20 I=1,27
        K1=(D2(I)-D1(I))/(D2(I))
        K2=(D2(I)-D1(I))/(D1(I))
        C1=(1.0/48.0)+(K1/48)+((K1**2)/64)+((K1**3)/96)+(5*(K1**4)/767)+
       1 ((K1**5)/256)
        C2=(1.0/48.0)-(K2/48)+((K2**2)/64)-((K2**3)/96)+(5*(K2**4)/767)-
       1 ((K2**5)/256)
        C3=(1.0/8.0)+(K1/6)+(5*(K1**2)/32)+((K1**3)/8)+(35*(K1**4)/384)+
       1 ((K1**5)/16)
        C4=(1.0/8.0)-(K2/6)+(5*(K2**2)/32)-((K2**3)/8)+(35*(K2**4)/384)-
       1 ((K2**5)/16)
        CFT(I)=(2*((C1/(D2(I)**4))+(C2/(D1(I)**4))))-((C3/(D2(I)**4))+(C4/
       1(D1(I)**4)))
```

```
      AA=DABS(CFT(I))
      DE=(BETA(I)*DB(I))/100
      EB(I)=(CF*8*FB(I)*(L**3)*AA)/(PI*DE)
      SB(I)=(CF*64*FB(I)*L)/(PI*((D1(I)+D2(I))**3)*CFC)
      DM(I)=(D1(I)+D2(I))/2
      MI=(PI*(DM(I)**4))/64
      EBB(I)=(CF*FB(I)*(L**3))/(48*MI*DE)
      SBB(I)=(CF*8*FB(I)*L)/(PI*(DM(I)**3))
      MH=(PI*((DM(I)**4)-(DP(I)**4)))/64
      EBH(I)=(CF*FB(I)*(L**3))/(48*MH*DE)
      SBH(I)=(CF*8*FB(I)*L)/(PI*((DM(I)**3)-(DP(I)**3)))
   20 CONTINUE
      WRITE(6,2)
    2 FORMAT('1',10X,'1979 EXPERIMENT TO DETERMINE EFFECTS OF CORN VARIE
     1TY(V) AND HARVEST DATE(H)'/9X,'*SPLIT PLOT EXPERIMENT IN A  RANDOM
     2IZED COMPLETE BLOCK DESIGN WITH THREE BLOCKS (R)')
      WRITE(6,21)
   21 FORMAT(' ',10X,'**SIMPLE  BENDING DATA** EACH VALUE IS THE MEAN OF
     1 7 TEST SAMPLES')
      WRITE(6,3)
    3 FORMAT('0',6X,'VHR     FB(KG)  DB(MM)  BETA(%) D1(MM)  D2(MM)   DP(M
     1M)')
      DO 22 I=1,27
      WRITE(6,4)VHR(I),FB(I),DB(I),BETA(I),D1(I),D2(I),DP(I)
    4 FORMAT('0',6X,I3,2X,6(F6.1,2X))
   22 CONTINUE
      WRITE(6,5)
    5 FORMAT('1',10X,'COB MECHANICAL PROPERTIES IN SIMPLE BENDING')
      WRITE(6,6)
    6 FORMAT('0',6X,'VHR      EB(MPA)   SB(MPA)   CFT             EBB(MPA)
     1   SBB(MPA   EBH(MPA)    SBH(MPA)')
      DO 30 I=1,27
      WRITE(6,7)VHR(I),EB(I),SB(I),CFT(I),EBB(I),SBB(I),EBH(I),SBH(I)
    7 FORMAT('0',6X,I3,2X,2(F8.3,2X),F12.9,4(2X,F8.3))
   30 CONTINUE
      STOP
      END

$DATA
```

TABLE E5

1979 EXPERIMENT TO DETERMINE EFFECTS OF CORN VARIETY(V) AND HARVEST DATE(H)
*SPLIT PLOT EXPERIMENT IN A RANDOMIZED COMPLETE BLOCK DESIGN WITH THREE BLOCKS (R)
SIMPLE BENDING DATA EACH VALUE IS THE MEAN OF 7 TEST SAMPLES

VHR*	FB(KG)	DB(MM)	BETA(%)	D1(MM)	D2(MM)	DP(MM)
111	5.2	23.3	52.0	18.1	28.2	7.2
112	7.3	20.2	44.5	19.5	31.8	7.2
113	7.8	18.5	47.3	18.4	30.4	7.9
121	5.0	27.6	47.8	22.7	28.7	8.6
122	6.4	23.9	43.0	22.9	31.8	10.1
123	8.0	23.5	47.3	22.0	31.4	10.0
131	5.5	28.3	51.1	22.5	29.4	7.2
132	5.7	27.7	45.4	20.1	28.9	7.7
133	7.6	25.5	50.9	22.0	30.2	7.4
211	9.6	17.2	38.6	19.8	30.0	8.2
212	11.1	17.3	42.1	21.1	28.4	8.2
213	7.4	19.4	50.3	21.2	29.1	7.5
221	7.7	22.5	42.6	23.2	28.9	9.8
222	9.6	19.3	35.7	22.8	27.8	10.6
223	9.5	19.9	40.0	24.1	30.2	9.8
231	7.9	21.5	45.2	21.5	27.5	7.4
232	8.4	20.9	37.0	21.3	28.6	7.8
233	8.8	21.1	45.3	19.6	25.5	7.6
311	9.0	19.6	32.6	21.2	27.9	7.0
312	11.0	17.1	43.3	21.4	28.4	7.0

313	8.1	18.5	46.1	20.6	27.5	6.5
321	9.2	23.5	38.3	24.6	31.3	8.4
322	8.2	20.8	43.0	23.4	29.4	8.8
323	7.0	19.8	43.5	23.8	28.5	8.9
331	6.8	26.1	42.3	21.2	28.2	6.9
332	9.5	22.7	48.8	21.4	29.5	7.6
333	7.0	23.2	44.1	18.7	27.5	6.9

TABLE E6. Calculated results using data in Table E5

COB MECHANICAL PROPERTIES IN SIMPLE BENDING

VHR	EB(MPA)	SB(MPA)	CFT	EBB(MPA)	SBB(MPA	EBH(MPA)	SBH(MPA)
111	21.758	1.602	-0.000000602	20.988	1.570	21.186	1.619
112	27.174	1.653	-0.000000397	26.351	1.620	26.515	1.657
113	36.284	2.052	-0.000000483	35.321	2.011	35.713	2.082
121	12.369	1.126	-0.000000387	12.202	1.103	12.357	1.146
122	16.037	1.196	-0.000000306	15.632	1.172	15.928	1.234
123	20.479	1.606	-0.000000338	19.891	1.574	20.290	1.661
131	11.988	1.203	-0.000000374	11.780	1.179	11.850	1.205
132	18.209	1.481	-0.000000477	17.669	1.452	17.843	1.498
133	18.153	1.634	-0.000000368	17.722	1.601	17.838	1.638
211	54.727	2.377	-0.000000449	52.831	2.329	53.460	2.415
212	58.278	2.798	-0.000000454	57.046	2.742	57.741	2.846
213	27.269	1.778	-0.000000427	26.622	1.742	26.834	1.790
221	24.797	1.665	-0.000000366	24.502	1.631	25.003	1.723
222	48.232	2.266	-0.000000411	47.763	2.220	49.282	2.397
223	31.242	1.814	-0.000000311	30.850	1.778	31.383	1.866
231	32.167	2.053	-0.000000470	31.689	2.012	31.955	2.069
232	40.209	2.067	-0.000000439	39.371	2.026	39.751	2.089
233	50.866	2.933	-0.000000656	50.009	2.874	50.662	2.989
311	55.476	2.325	-0.000000467	54.462	2.278	54.824	2.332
312	55.350	2.723	-0.000000442	54.280	2.669	54.621	2.729

313	40.691	2.225	-0.000000508	39.873	2.181	40.087	2.225
321	23.864	1.610	-0.000000277	23.525	1.578	23.718	1.622
322	26.853	1.703	-0.000000348	26.509	1.669	26.841	1.733
323	24.609	1.496	-0.000000359	24.411	1.466	24.743	1.526
331	23.707	1.725	-0.000000457	23.242	1.690	23.384	1.728
332	29.426	2.203	-0.000000407	28.712	2.159	28.942	2.218
333	34.870	2.170	-0.000000605	33.748	2.127	34.019	2.185