ASAE S368.4 DEC2000 (R2008)
Compression Test of Food Materials of Convex Shape

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Keywords: Compression, Food, Test

1 Purpose and scope

1.1 This Standard is intended for use in determining mechanical attributes of food texture, resistance to mechanical injury as a result of static loading, and quasi-static force-deformation behavior of food materials of convex shape, such as fruits and vegetables, seeds and grains, and manufactured food materials.

1.2 Compression tests of intact biological materials provide an objective method for determining mechanical properties significant in quality evaluation and control and maximum allowable static load for minimizing mechanical damage. The results apply to quasi-static loading rather than impact loading. The equations given are adapted from the theory of contact between convex surfaces made of elastic materials. Most food and biological materials exhibit non-linear behavior at larger (e.g., 5% strain or greater) deformations. Furthermore, to completely characterize the material, a study of its viscoelastic behavior is needed. However, these simplified tests give information that can be used to quantitatively determine the differences caused by factors such as variety, drying temperature, storage technique, maturity, and processing technique. The applicability of the analysis can be validated by plotting the log of applied force as a function of the log of deformation. If the equations are valid, the slope of the line should be 1.5 (Fridley *et al.*, 1968; Arnold and Mohsenin, 1971).

1.3 Compression tests on food materials are routinely conducted using fully automatic test equipment such as the Instron Universal Testing apparatus. Factors such as sample conditioning prior to testing, loading geometry, and loading rate can influence the results of such tests. Therefore, it is desirable to standardize testing and reporting procedures so that data from various sources can be more easily compared.

1.4 Determination of compressive properties requires the production of a complete force-deformation curve. From the force-deformation curve, stiffness; apparent modulus of elasticity; toughness; force and deformation to points of inflection, to bioyield, and to rupture; work to point of inflection, to bioyield, and to rupture, and maximum normal contact stress at low levels of deformation can be obtained. Any number of these mechanical properties can, by agreement, be chosen for the purpose of evaluation and control of quality.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this Standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this Standard are encouraged to investigate the possibility of applying the most recent edition of the standards indicated below. Standards organizations maintain registers of currently valid standards.

ASTM E4-94, *Practices for Force Verification of Testing Machines*

ASTM E83-94, *Practice for Verification and Classification of Extensometers*

3 Definitions

3.1 bioyield point: A point such as shown in figure 1 where an increase in deformation results in a decrease or no change in force. Examples of bioyield points for apples, potatoes, and pears loaded with a cylindrical plunger are given by Mohsenin and Göhlich, 1962.

3.2 force-deformation curve: A diagram plotted with values of deformation as abscissae and values of force as ordinates.

3.3 apparent modulus of elasticity: The following equations can be used to estimate the value of the apparent modulus of elasticity, E, of food materials that are relatively firm and homogeneous. These equations are based on the Hertz equations for contact stresses used in solid mechanics. The Hertz equations assume that deformations are small and the material being compressed is elastic. However, they are useful for making comparisons of the deformation behavior of viscoelastic materials when the deformations and loading rates are similar for all samples tested.

For Parallel Plate contact (Figure 2a):

$$E=\frac{0.338F(1-\mu^2)}{D^{3/2}}\left[\mathrm{K_U}\left(\frac{1}{R_U}+\frac{1}{R'_U}\right)^{1/3}+K_L\left(\frac{1}{R_L}+\frac{1}{R'_U}\right)^{1/3}\right]^{3/2} \qquad (1)$$

where E = apparent modulus of elasticity, Pa, (psi); D = deformation, m (in.); μ = Poisson's ratio (dimensionless); F = force in N (lbf); R_U, R'_U = radii of curvature of the convex surface of the sample at the point of contact with the upper plate, m (in.); R_L, R'_L = radii of curvature of the convex surface of the sample at the point of contact with the upper plate, m (in.). R_u and R_L are the minimum radii of curvature of the sample at the point of contact R_L and R'_L are the maximum radii of curvature. The constants K_U and K_L are determined from Table 1 using cos θ. Equation 7 in clause 3.6 is used for calculating cos θ. For K_U, cos θ is calculated using the radii of curvature of the upper surface, $\mathrm{R_U}$, $\mathrm{R'_U}$, m (in.). The radii of curvature of the upper plate (not indicated in figure 2) are $R_{PU}R'_{PU}$=∞, giving $R_{PU}{}^{-1}+R'{}_{PU}{}^{-1}=0$. When K_L is calculated, the

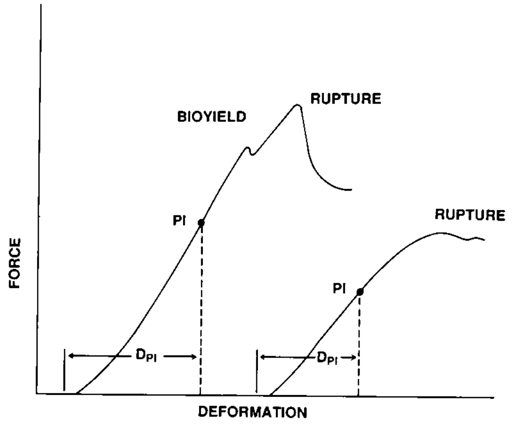

Figure 1 – Force-deformation curves for materials with and without bioyield point. PI=point of inflection, D_{pi}=deformation at point of inflection

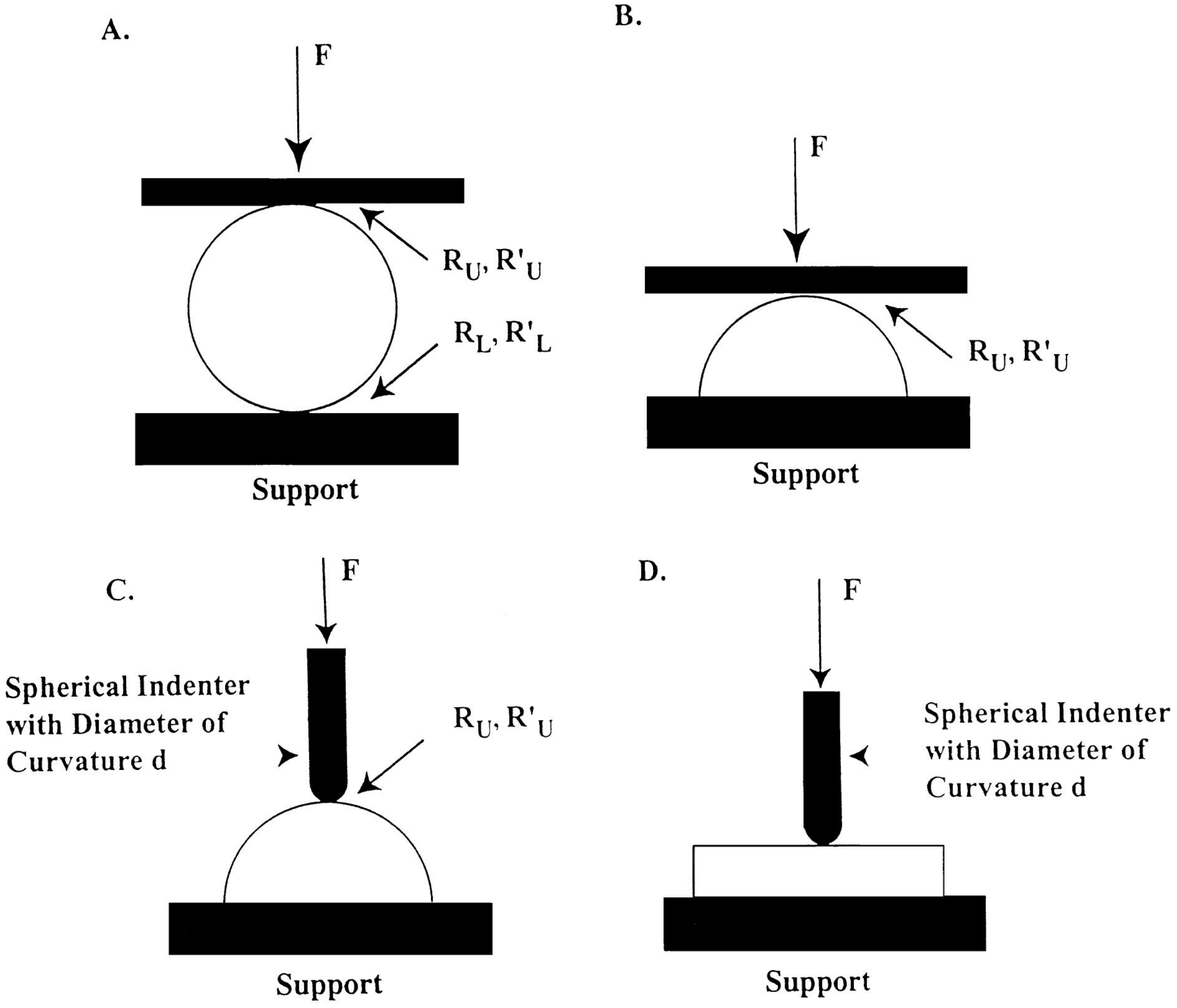

Figure 2 – Loading geometries for determining apparent modulus of elasticity. A. Parallel plate in contact with a curved surface. B. Single plate in contact with a curved surface. C. Spherical indenter in contact with a curved surface. D. Spherical indenter in contact with a flat surface. The formulas used for calculating E are given in clause 3.

value of cos θ is determined using the radii of curvature for the lower surface, R_L, R'_L m (in.), while the radii of curvature of the lower plate, $R_{PL}=R'_{PL}=\infty$.

For single plate contact (figure 2b):

$$E=\frac{0.338K_U^{3/2}F(1-\mu^2)}{D^{3/2}}\left(\frac{1}{R_U}+\frac{1}{R'_U}\right)^{1/2} \qquad (2)$$

where *E, F*, µ, and *D* have the same definitions as in parallel plate contact and R_U, R'_U= radii of curvature of the convex surface of the sample, m (in.) at the point of contact with the flat plate used to compress the sample. Also, R_u is the minimum radius of curvature of the sample at the point of contact and R'_u is the maximum radius of curvature. K_U is determined from table 1 after calculating cos θ (equation 7 in clause 3.6) using the radii of curvature of the upper surface, R_U, R'_U. The radii of curvature of the flat plate (not indicated in figure 2) are $R_{PU} = R'_{PU} = \infty$, giving $R_{PU}^{-1}+R'_{PU}{}^{-1}=0$. It is asssumed that the force along the bottom surface of the specimen is distributed over a large area. Therefore, the deformation along the bottom surface should be negligible in comparison to the deformation at the point where the flat plate makes contact with the specimen. For materials with relatively low apparent elastic moduli or for cases where the applied force, *F*, is large, this assumption will not be valid.

For a spherical indenter on a curved surface (figure 2c):

$$E=\frac{0.338K_U^{3/2}F(1-\mu^2)}{D^{3/2}}\left(\frac{1}{R_U}+\frac{1}{R'_U}+\frac{4}{d}\right)^{1/2} \qquad (3)$$

where *E, F*, µ, and *D* have the same definition as in parallel plate contact, R_U,R'_U= radii of curvature of the convex surface of the sample at the point of contact with the spherical indenter, m (in.) and d = diameter of curvature of the spherical indenter, m (in.). K_U is determined from table 1 after calculating cos θ (equation 7 of clause 3.6) using the radii of curvature of the upper surface, R_U,R'_U and the radius of curvature of the spherical indenter ($R_{SI} = d/2$). Also, R_u is the minimum radius of curvature of the sample at the point of contact and R'_u is the maximum radius of curvature.

For a spherical indenter on a flat surface (figure 2d):

Table 1 – Value of c_1 c_2 and K (dimensionless) for various values of θ (degrees) (adapted from Kozma and Cunningham, 1962)

θ	50	55	60	65	70	75	80	85	90
cos θ	0.6428	0.5736	0.5000	0.4226	0.3420	0.2588	0.1736	0.0872	0.0
c_1	1.754	1.611	1.486	1.378	1.284	1.202	1.128	1.061	1.000
c_2	0.641	0.678	0.717	0.759	0.802	0.846	0.893	0.944	1.000
K	1.198	1.235	1.267	1.293	1.314	1.331	1.342	1.349	1.351

$$E=\frac{0.338K_U^{3/2}F(1-\mu^2)}{D^{3/2}}\left(\frac{4}{d}\right)^{1/2} \tag{4}$$

where *E, F*, µ, and *D* have the same definition as in parallel plate contact, and d=diameter of curvature of the spherical indenter, m (in.). For a spherical indenter, $R_{SI}=R'_{SI}=d/2$. For a flat surface, $R_U=R'_U=\infty$ giving $R_U{}^{-1}+R'_U{}^{-1}=0$. Therefore, equation 7 in clause 3.6 will give cos $\theta=0$ and K_U will be 1.351 (table 1).

The definition of apparent modulus of elasticity given in this standard corresponds to the definition of modulus of deformability used in several early papers (Shelef and Mohsenin, 1969; Arnold and Mohsenin, 1971; Arnold and Roberts, 1969). Their definition of apparent modulus of elasticity does not correspond to this definition. They calculated the apparent modulus using recovered deformation, taken from the unloading curve. Most food materials are not truly elastic. Therefore, the calculated value of apparent modulus of elasticity E may vary with loading rate and the applied force or deformation and the force applied and/or deformation at which E was calculated should be reported. Other factors that should be reported are listed in clause 11.

3.4 minimum and maximum radii of curvature, *R* and *R′*: The minimum, *R*, and maximum, *R′*, radii of curvature of the compression tool and the sample at the point of contact between them. It can be measured using a radius of curvature meter (see clause 5.2 and figure 5) or calculated (see clause 5.2 and figure 6).

3.5 point of inflection: A typical force-deformation curve is first concave up and then concave down (see figure 1). The point at which the rate of change of slope (second derivative) of the curve becomes zero is called the point of inflection. This point is designated as PI. The change in slope suggests that some type of failure is beginning. Therefore, when taking measurements for calculating apparent modulus of elasticity and other parameters, deformations should be less than the deformation at the point of inflection.

3.6 semi-major (a) and semi-minor (b) axes of the contact area: The dimensions of the elliptical contact area between the compression tool and the specimen can be calculated using the following formulas:

$$a=m\left[\frac{3F(\kappa_1+k_2)}{2}\left(\frac{1}{R_1}+\frac{1}{R'_1}+\frac{1}{R_2}+\frac{1}{R'_2}\right)^{-1}\right]^{1/3} \tag{5}$$

$$b=n\left[\frac{3F(\kappa_1+k_2)}{2}\left(\frac{1}{R_1}+\frac{1}{R'_1}+\frac{1}{R_2}+\frac{1}{R'_2}\right)^{-1}\right]^{1/3} \tag{6}$$

where c_1 and c_2 are determined from table 1 using the value of θ, F is the applied force and R_1 and R'_1 are the radii of curvature of the specimen at the point of contact with the compression device which has radii of curvature R_2 and R'_2. If the compression device is either spherical ($R_2=R'_2$) or flat ($R_2=R'_2$ and $[R_2]^{-1}=[R'_2]^{-1}=0$), cos θ is calculated from the formula:

$$\cos\theta=\frac{\left[\frac{1}{R_1}-\frac{1}{R'_1}\right]}{\left[\frac{1}{R_1}+\frac{1}{R'_1}+\frac{1}{R_2}+\frac{1}{R'_2}\right]} \tag{7}$$

For the more general case of contact between two convex surfaces whose principal planes of curvature do not coincide, the expression for cos θ is considerably more complicated (Mohsenin, 1986). Values of κ_1 and κ_2 are calculated from the material properties of the two surfaces in contact:

$$\kappa_1=\frac{1-\mu_1^2}{E_1} \quad \text{and} \quad \kappa_2=\frac{1-\mu_2^2}{E_2} \tag{8}$$

The *E*'s are the moduli of elasticity, respectively, of the specimen, E_1, and the loading tool, E_2, and μ_1 and μ_2 are respective Poisson's ratios. In most cases, E_2 will be much greater than E_1 and κ_2 can be assumed to be zero.

3.7 rupture point: The point on the force-deformation curve at which the loaded specimen shows a visible or invisible failure in the form of breaks or cracks. This point is detected by a continuous decrease of the load in the force-deformation diagram (see figure 1).

3.8 maximum contact stress: The maximum stress that occurs at the center of the surface of contact (the first point of contact between the compression tool and the sample). It is numerically equal to 1.5 times the average contact pressure and can be calculated from

$$S_{max}=\frac{1.5F}{\pi ab} \tag{9}$$

3.9 cell water potential: The chemical potential of water within the cells of the fruit or vegetable. It is dependent on the dissolved solids and the pressure of the water in the cells (see Nobel, 1974, for a more detailed explanation).

4 Apparatus

4.1 Testing machine. Any suitable testing machine capable of constant-rate-of-crosshead movement and comprising essentially the following:

4.1.1 A drive mechanism for imparting to the crosshead a constant velocity with respect to the base. The crosshead velocity shall also be repeatable with an accuracy of ± 1%.

4.1.2 A load indicating mechanism capable of showing the total compressive load carried by the test specimen. The mechanism shall be essentially free from inertia-lag at the specified site of testing and shall indicate the load with an accuracy of ± 1% of the maximum anticipated value of the load on the specimen. The accuracy of the testing machine shall be verified at least once a year in accordance with ASTM E4.

4.1.3 A suitable instrument capable of determining the change in distance between the point of loading and a fixed member of the base of the testing machine at any time during the test. It is desirable that this instrument automatically record the change of distance as a function of the load on the test specimen. The instrument shall be essentially free of inertia-lag at the specified rate of loading and shall conform to the requirements for a class B-2 extensometer as defined in ASTM E83. In the case of test specimens of food materials of convex shape the use of extensometers on the specimen is difficult and in most cases impractical. The second alternative shall be the use of an extensometer on the movable crosshead of the testing machine, sensing the true

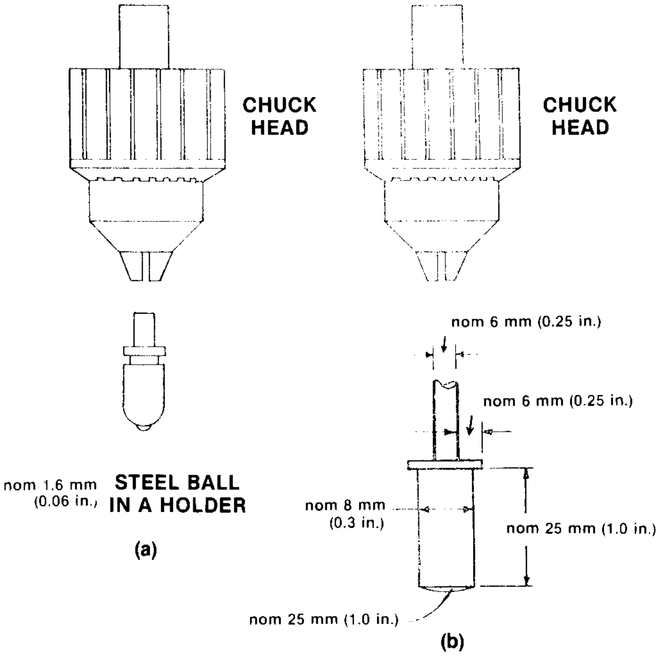

Figure 3 – Examples of compression tools with spherical ends; (a) nom 1.6 mm is diameter of steel ball; (b) nom 25 mm is diameter of curvature of the rounded tip on the plunger

displacement of the crosshead. The third alternative shall be the use of crosshead velocity as an indirect method of measuring deformation.

4.2 Compression tool. A compression tool with smooth and polished surface is used for applying the load to the specimen. The type of compression tool used for each test shall depend on the size of the specimen, the nature of the test, and the extent of information expected from that test. Either flat plate or spherical tools may be used for both soft and hard materials. Examples of suitable spherical compression tools are shown in figure 3. A plunger with end machined to a known radius without rounding the edge (see figure 3b) is suitable for soft materials such as fruits and vegetables, particularly those which exhibit a bioyield point.

4.2.1 The rounded tip of the plunger in figure 3b is the segment of a sphere with a diameter *d*. The radius of the circle of contact, a (calculated from equations 5 and 6 in clause 3.6), in this case is one-half of the diameter of the cylindrical portion of the compression tool when full contact is established. Knowing the magnitude of the desired deformation, the appropriate radius of the spherical tool can be computed from the equations. To obtain a distinct bioyield point on the recording chart in case of fruits and vegetables, it is desirable to bring the full diameter of the cylinder in contact with the specimen with as little deformation as possible. For example, if the skin of the fruit is removed and the tool in figure 3b is used, the full diameter of the cylindrical portion of the plunger will come in contact with the specimen at about 0.64 mm (0.025 in.) deformation.

4.2.2 The ratio of the radius of the circle of contact to the radius of the spherical indenter shall not be greater than 1:10.

4.2.3 The 8 mm (5/16 in.) diameter cylindrical plunger is recommended for use on fruits because this size corresponds to one of the two plungers of the Magness-Taylor fruit pressure tester commonly used for quality evaluation of such fruits as apples, pears, and peaches. If one of these plungers is used as the loading tool in conducting a compression test on fruits, it is recommended that the compression continue beyond and through the point of rupture. In this manner the force reading at the point of rupture can serve also as the Magness-Taylor pressure reading of the specimen.

4.3 Supporting the sample. A hardened metal plate with a smooth surface finish can be used as a supporting jig. For some loading geometries, it may be necessary to prepare samples in a specific manner, or it may be necessary to use a specially designed supporting jig. The geometry must be carefully controlled to ensure that significant deformation occurs only in the areas where the compression plate or tool makes contact with the specimen.

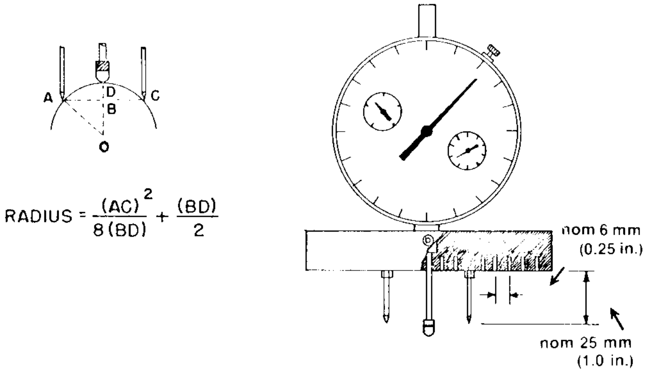

Figure 4 – Radius of curvature meter

4.3.1 Grains, seeds, and small hard specimens. Individual grains and seeds may be compressed between parallel plates (see figure 2a) made of hardened steel (Arnold and Roberts, 1969). Single plate loading (see figure 2b) can be achieved by mounting single or multiple specimens on the lower plate using a thin layer of quick hardening cement or glue to prevent movement during testing and to allow deformations on the bottom plate to be neglected (Arnold and Mohsenin, 1971). The flatter side of the grain should be lightly sanded before cementing. If grain specimens have been equilibrated for moisture contents higher than normal storage conditions, it is necessary to use a special glue that will harden in a high humidity atmosphere. Arnold and Roberts (1969) found identical results for glued samples (see equation of figure 2b) and for samples not glued (see equation of figure 2a).

4.3.2 Fruits, vegetables, and soft specimens. When single plate loading or spherical compression tools are used, it is essential that the specimens be supported so that the deformation at the support is negligible. For fruits such as apples or pears, the specimen can be cut in half. The deformation at the bottom plate will be negligible because the area of contact between the flat surface of the fruit half and the supporting plate will be many times greater than the area of contact between the compression tool and the fruit. If cutting the fruit is undesirable or impossible, parallel plate loading (see figure 2a) can be used.

5 Test specimens

5.1 Specimens can be tested in their natural form and size using the parallel plate-loading configuration. For larger convex-bodies such as fruits and vegetables, testing the specimen in its natural form permits taking several readings on the same specimen non-destructively. This would be in contrast with the case where the specimen is cut in the form of a segment of a sphere. If skin is sliced off at the point of compression, the details of test specimen with or without skin shall be given.

5.2 If only relative measurements of force and deformation are to be made, it is desirable to make measurements on shape, size, weight, color, and even such constituents as sugar and starch before testing the specimen. For more exact tests where equations given in clause 3.3 are expected to be used, in addition to the above data, the radii of curvature of the convex-shape specimen shall also be determined by either using a radius of curvature meter such as shown in figure 4 or by calculation as in figure 5. If the loading tool is rounded at the end, the radius of curvature of the tip shall also be specified.

6 Conditioning

The test specimen shall be conditioned for the desired temperature and relative humidity before testing. Fruits and vegetables normally require a

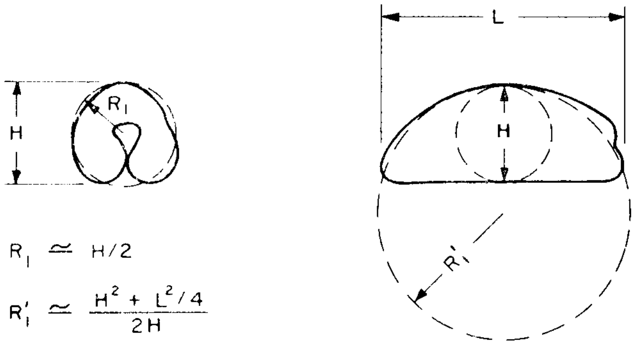

Figure 5 – Approximation of R_1 and R_1' for convex bodies

few hours to adjust their temperatures from field conditions to room temperature. Hard seeds and grains may have to be conditioned in an atmosphere of given relative humidity for several days if they are to be brought up to equilibrium moisture contents other than the ordinary storage conditions. In that case the conditioning chamber shall be brought into the testing room before testing so that moisture gains or losses of the specimen can be minimized.

7 Number of test specimens

Because of the large variance inherent in biological materials, each experiment shall be statistically designed with sufficient number of replications to result in an acceptable level of confidence insofar as significant differences are concerned. The variations due to shape, size, age, and cellular structure are normally such that at least a minimum of twenty specimens is required to be tested for each sample.

8 Speed of testing

8.1 Speed of testing shall be relative rate of motion of the compression tool during the test. Rate of motion of the driven compression tool when the machine is running idle may be used if it can be shown that the resulting speed of testing is within the limits of variations allowed. The recorder response shall be such that the rate of rise of force on the chart shall be at most 1/3 of the maximum theoretical rate of rise of the recorder pen.

8.2 The speed of testing shall be chosen on the basis of the sensitivity of the specimens to loading rate. For most hard fruits and vegetables a speed of 2.5 to 30 mm/min shall be specified as the standard speed. For specimens such as apples, the bioyield point is best observed at speeds below 10 mm/min. For seeds and grain, the speed of 1.25 mm/min ± 50% shall be specified.

9 Testing procedure

9.1 The test shall be conducted in a laboratory where the atmosphere is at a constant relative humidity and temperature. If possible, tests shall be conducted under laboratory conditions of 20 °C±5 °C and 50% relative humidity ±5%.

9.2 Moisture content can have a substantial effect on force-deformation characteristics. The moisture content of grains, seeds, and food products shall be measured. If possible, the water potential of fruits and vegetables should be measured. Uniaxial compression tests (compression of the ends of the cylinder in a direction parallel to the axis of the cylinder) have demonstrated that water potential has a substantial effect on force deformation behavior of fruits and vegetables (Murase *et al.*, 1980; Lin and Pitt, 1986).

9.3 The major, minor, and intermediate diameters of the specimen shall be measured to the nearest 10% of the respective dimension.

9.4 The specimen mass shall be measured and recorded together with observations of color and appearance.

9.5 If the apparent modulus of elasticity is to be calculated, the radius of curvature at the loading point shall be measured to the nearest 10%.

9.6 Information on variety, age, maturity, and the history of the material prior to testing shall be recorded.

9.7 Select the compression tool according to the requirements given in 4.3, and install the tool in the testing machine.

9.8 If the compression tool is one with a spherical end, the radius of the rounded end shall be recorded. Set the speed control at the desired rate and, if the machine records test information on a chart, calibrate the recording chart for load and displacement.

9.9 Place the specimen in the testing machine under the compression tool, taking care to align the center of the tool with the peak of the curvature of the test specimen.

9.10 When testing fruits and vegetables the specimen shall be cut in half and then placed on the supporting device, or it shall be placed on the supporting device without cutting (see clause 4.3.2). For specimens of seeds and grains which have been softened in an atmosphere of high relative humidity, a presetting arrangement can be devised to insure that the deformation of the whole specimen in comparison with the deformations at the points of first contact is negligible. This would involve loading the sample by means of a plate in contact with the upper surface of the seeds. The mass should be sufficient to deform the sample without causing objectionable mechanical damage at the points where the compression tool makes contact with the surface of the seeds.

9.11 Start the machine and record the complete force-deformation curve through the point of rupture.

9.11.1 When testing small, hard specimens such as grains, the deflections of most load cells cannot be considered negligible. For this reason either proof shall be given that the load cell deflection is negligible or the deflection shall be determined and deducted from the recorded deformation.

10 Calculations

10.1 Force and deformation to bioyield and to rupture. These values are read directly from the chart and recorded along with the type of compression tool used.

10.2 Point of inflection. Determine the point of inflection by using a straight edge on the force-deformation curve to locate the point where the slope of the curve begins to decrease.

10.3 Apparent modulus of elasticity. Calculate the apparent modulus of elasticity by using the appropriate equation in clause 3.3. The deformation should normally be less than the deformation at the point of inflection. Express the results in Pa (psi).

10.4 For each series of tests, calculate the mean and standard deviation.

11 Report

The report shall include the following:

- complete identification of the material tested including
  - source;
  - mass;
  - shape and size (as defined by major, minor, intermediate diameters);
  - specimen temperature or, if equilibrated, the room temperature;
  - whether the sample was modified in any way such as by removal of the skin;
- when mechanical properties are calculated and reported, the radii of curvature at the points of contact along with the force and deformation used for the mechanical properties;
- complete identification of the compression tool used including, *in the case of the spherical indenter,* the diameter of the cylindrical part of the tool and the radius of the spherical end;

Table 2 – Typical values of *E*, apparent modulus of elasticity, for compression tests of vegetables, fruits, and grains and seeds

Product	Method of loading (FIG)	Loading rate mm/min	*E*	Comments (assumptions, variety, moisture content, etc.)	Reference
Apple	2A	2.54	4.02 MPa	Yellow delicious apple stored at 1.1 °C, conditioned at 21.1 °C for one week and tested Oct. 22, 1969. Value calculated from their data assuming a Poisson's ratio of 0.22; determination made at a deformation equal to half the deformation at the point of inflection.	Arnold and Mohsenin, 1971
Apple	2C	2.54	3.03 MPa	Yellow delicious apple stored at 1.1 °C, conditioned at 21.1 °C for one week and tested Oct. 22, 1969. Value calculated from their data assuming a Poisson's ratio of 0.22; determination made at a deformation equal to half the deformation at the point of inflection; specimens supported by contact with the periphery of a cylindrical hole (diameter approximately half that of the apple diameter) in a hardwood support plate. Compression tool: 12.7 mm diameter spherical indenter.	Arnold and Mohsenin, 1971
Corn	2C	0.51	2030 MPa	Hybrid: (WF9MST×H71) (Oh43RF×B37RF). Single kernel glued to the bottom plate; Poisson's ratio of 0.4; moisture content 14.4% wet basis. Values determined for applied load of 2.26 kg; the spherical indenter had a radius of curvature of 0.838 mm; radii of curvature of corn kernels assumed to be infinite.	Shelef and Mohsenin, 1969
Peach	2A	33.0	$E_1 = 0.52$ MPa $E_2 = 0.97$ MPa	Poisson's ratio assumed to be 0.49; variety and maturity: E_1—Dixon clingstone with a Magness-Taylor pressure tester maturity of 4 lb; E_2—Fay Elberta Freestone with a Magness-Taylor maturity of 1 lb. Deformation of 0.152 mm.	Fridley, *et al.*, 1968
Pear	2B	33	$E_1 = 3.72$ MPa $E_2 = 9.65$ MPa	Poisson's ratio assumed to be 0.49. Variety and maturity: E_1—Bartlett with a Magness-Taylor pressure tester maturity of 12 to 18 lb; E_2—Winter Nelis with a Magness-Taylor maturity of 15 to 20 lb. Deformation of 0.152 mm.	Fridley, *et al.*, 1968
Potato	2D	50 to 500	0.75 to 1.53 MPa	Poisson's ratio of 0.48; Spunta variety (Northern Thailand); potatoes tested approximately four days after harvest; maximum deformation not specified; diameters of spherical indenters between 1.43 and 1.90 cm; *E* decreased with loading rate for rates between 100 and 500 mm/min.	Jindal and Techasena, 1985
Potato	2A	50	1.04 to 5.76 MPa	Poisson's ratio of 0.48; Spunta variety (Northern Thailand); maximum deformation not specified; storage temperatures of 5 to 30 °C; storage times up to 8 wks; *E* decreased with storage time. *E* was 5.76 MPa at the time the potatoes were placed in storage. Potatoes placed in storage approximately 4 days after harvest.	Jindal and Techasena, 1985
Soybean	2A	5.08	126 MPa	Poisson's ratio assumed to be 0.4; Variety: Ranson; deformation at which the calculation was made was not specified, but it was apparently the deformation at the rupture point. Sample dried at laboratory conditions of 25 °C, equilibrated at 0 °C for 4 or 5 days, and dried in a thin layer with air at 75 °C dry bulb and 20 °C dew point temperatures. Value of *E* at 13% m.c. predicted by a regression equation fitted to data for moistures between 2 and 26% wet basis. The equation was: $\ln(E) = 19.97 - 0.94(Ln(M) - 1.38)^2$	Misra and Young, 1981
Wheat[1)]	2A	6.6	930 to 3380 MPa	Poisson's ratio of 0.42; seven varieties of Australian wheats of representative hardness; wet basis moistures varied from 11.5 to 13%. Deformation equal to one half the deformation at the proportional limit.	Arnold and Roberts, 1969

[1)] It was assumed that the bottom surface of the kernel, containing the crease, made contact with the bottom plate at two points with radii R_2, R_2' equal to 0.5 times R_1, R_1'.

- — any special loading conditions, such as application of a small pre-test load of a specified value;
- — speed of testing (e.g. crosshead speed for a compression testing machine);
- — number of specimens tested;
- — date of test;
- — type of testing machine used;
- — mean and standard deviation *of all measurements taken*.

When possible, the following additional items should also be included:

- — additional information about the material tested including:
  - — previous history including time of storage prior to testing;
  - — date and time of the day samples were harvested;
  - — color and appearance;
  - — moisture content (or water potential) at the time of testing.
- — method of preparing the specimen for the test;
- — atmospheric conditions in the room where tests were conducted (e.g. relative humidity and temperature);
- — means and standard deviations of the force and deformation to both bioyield and rupture;
- — mean and standard deviation of the apparent modulus of elasticity.

12 Sample results

12.1 Table 2 gives values of E determined with this technique.

13 Sample calculation

Problem statement: A single Red Delicious apple was picked from a tree from an orchard on October 12, 1999. The apple weighed 183 grams and had major, minor, and intermediate diameters, respectively, of 8.0, 7.5, and 7.2 cm. It was subjected to a parallel plate compression test (figure 2a) on a servomechanical testing machine. Crosshead speed was 2.54 mm/min. Room temperature was 22°C. The upper (compression) plate and lower (support) plate were made of aluminum alloy. A radius of curvature meter (figure 4) was used to measure the radii of curvature of the apple at the points where the plates made contact with the apple. The prongs on the meter (refer to figure 4) were spaced 25.4 mm apart (AC=25.4 mm) and the values of BD were 2.49 and 1.96 mm for the point in contact with the upper (compression) plate and 2.337 and 2.108 mm for the point in contact with the lower (support) plate. When a force of 90 N was applied, the deformation was 4.56 mm. Calculate the apparent modulus of elasticity of the apple, the lengths of the semi-major and semi-minor axes of the elliptical area of contact between the upper plate and the apple, and the maximum contact stress at the center of the point of contact between the apple and the upper plate. Assume that the Poisson's ratio, μ of the apple is 0.25.

Solution: The radii of curvature of the apple at the point where the upper compression plate makes contact with the apple can be calculated using the equation given in figure 4:

$$R_U=\frac{(AC)^2}{8(BD)}+\frac{BD}{2}=\frac{0.0254m)^2}{8(0.00249m)}+\frac{0.00249m}{2}=0.0336m$$

Using this same equation, the value of R'_U is calculated as 0.04212m and the values of R_L and R'_L are calculated as 0.03568 and 0.03931 m, respectively. The value of cos θ for the point of contact between the upper compression plate and the apple is:

$$\cos\theta=\frac{\frac{1}{R_U}-\frac{1}{R'_U}}{\frac{1}{R_U}+\frac{1}{R'_U}+\frac{1}{R_{PU}}+\frac{1}{R'_{PU}}}$$

$$=\frac{\frac{1}{0.0336m}-\frac{1}{0.0421m}}{\frac{1}{0.0336m}+\frac{1}{0.0421m}+0.0+0.0}=0.1122$$

Note that $R_{PU}{}^{-1}$ and $R'_{PU}{}^{-1}$ are both equal to zero because R_{PU} and R'_{PU} are infinite. The value of cos θ for the point of contact with the lower supporting plate is calculated as 0.0463 using the same formula. Linear interpolation between $K=1.349$ corresponding to cos $\theta=0.0872$ (table 1) and $K=1.342$ corresponding to cos $\theta=0.1736$, gives $K_u=1.347$. Similarly, linear interpolation between $K=1.351$ corresponding to cos $\theta=0.0$ and $K=1.349$ corresponding to cos $\theta=0.0872$ gives $K_L=1.350$ when cos $\theta=0.0463$. The value of the apparent modulus of elasticity can be calculated from the equation 1 in clause 3.3:

$$E=\frac{0.338F(1-\mu^2)}{D^{3/2}}\left[K_U\left(\frac{1}{R_U}+\frac{1}{R'_U}\right)^{1/3}+K_L\left(\frac{1}{R_L}+\frac{1}{R'_L}\right)^{1/3}\right]^{3/2}$$

$$=\frac{0.338(90N)(1-0.25^2)}{(0.00456m)^{3/2}}\left[1.347\left(\frac{1}{0.0336m}+\frac{1}{0.0421m}\right)^{1/3}\right.$$

$$\left.+1.350\left(\frac{1}{0.0357m}+\frac{1}{0.0393m}\right)^{1/3}\right]^{3/2}$$

$$=2{,}960{,}000N/m^2=2.96\ \text{MPa}$$

The dimensions of the contact area can be calculated from the equations 5 and 6 in clause 3.6. The values of κ_1 and κ_2 must be calculated first using equations 8. The upper plate is aluminum alloy that has an elastic modulus, E, of approximately 70 GPa and a Poisson's ratio of approximately 0.25. The value of E for the apple was calculated above as 2.96 MPa and Poisson's ratio was given in the problem statement as 0.25. Therefore, the values of κ_1 and κ_2 are:

$$\kappa_1=\frac{1-\mu_1{}^2}{E_1}=\frac{1-0.25^2}{2.96\ \text{MPa}}=0.317\ \text{MPa}^{-1}\ \text{or}\ 3.17\times10^{-7}m^2/N$$

$$\text{and}\ \ \kappa_2=\frac{1-0.25^2}{70\ \text{GPa}}=0.0134\ \text{GPa}^{-1}$$

$$\text{or}\ \ 1.34\times10^{-11}m^2/N$$

The values of the semi-major and semi-minor diameters of the elliptical contact area where the upper plate compresses the apple can also be calculated from equations 5 and 6 in clause 3.6. The preceding calculation demonstrates that, when a hard plate compresses a soft material such as an apple, $\kappa_2 \gg \kappa_1$ and therefore κ_1 can be taken as 0. Beginning with the calculation of "a" and deferring until later the determination of c_1:

$$a=c_1\left[\frac{3F(\kappa_1+\kappa_2)}{2}\left(\frac{1}{R_{PU}}+\frac{1}{R'_{PU}}+\frac{1}{R_U}+\frac{1}{R'_U}\right)^{-1}\right]^{1/3}$$

$$=c_1\left[\frac{3(90\ \ N)(3.17\cdot10^{-7}+0.0)}{2}\left(0.0+0.0+\frac{1}{0.0336m}\right.\right.$$

$$\left.\left.+\frac{1}{0.0421m}\right)^{-1}\right]^{1/3}=c_1(0.00928\ \ m)$$

Note that the values inside the brackets in the equation above will be the same for the calculation of both a and b. The values of c_1 and c_2 are determined from Table I by interpolation. The value of c_1 corresponding to cos θ=0.0872 is 1.061 and the value of c_1 corresponding to cos θ=0.1736 is 1.128, giving a value for c_1 of 1.080 when cos θ=0.1122. Similarly, c_2 is interpolated between $c_2=0.944$ corresponding to cos θ=0.0872 and $c_2=0.893$ corresponding to cos θ=0.1736 giving a value for c_2 of 0.929 when cos $\theta=0.1122$.

The values of a and b are:

$$a=c_1(0.00928)=1.080(0.00928m)$$

$$=0.01002m\ \ \text{or}\ \ 10.02\ \ \text{mm}\ \ \text{and}\ \ b=c_2(0.00928)$$

$$=0.929(0.00928\text{m})=0.00862\ \ \text{or}\ \ 8.62\ \ \text{mm}.$$

The maximum contact stress at the upper plate can be calculated from equation 9 in clause 3.8:

$$S_{\max}=\frac{1.5\ \ F}{\pi ab}=\frac{1.5(90\ \ N)}{\pi(0.01002m)(0.00862m)}$$

$$=498{,}000N/m^2\ \ \text{or}\ \ 498\ \ \text{kPa}$$

Annex A
(informative)
Bibliography

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