Application of the Instron Tester for Investigation of Rheology of Corn Dough

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ABSTRACT

The expression for the deformation of a short cylinder of corn dough between parallel plates under constant load was derived and applied to the behavior of corn dough in the compression cell of the Instron Tester (model TM-M; tension cell, CTM). The results demonstrated that corn dough behaved as a Bingham plastic. When the mixing time is 15 min or more, the holding time 12 hr or more, and the moisture content carefully controlled, 5–7% precision can be obtained in the evaluation of the Bingham viscosity and yield values if the moisture content is 53% or more.

Corn dough results from the rehydration of lime-treated corn flour and is commonly used for the preparation of tortillas, a popular food in Mexico, Central America, and some southern regions of the United States. To make the flour, corn kernels are cooked in lime water, then ground and dried (Del Valle et al 1976). An alternate method was proposed by Molina et al (1977).

Corn tortillas are recognized as a good calorie source but a poor protein source (Del Valle and Perez-Villasenor 1974); their protein content is low and poor in quality (Cravioto et al 1945). Attempts to remedy this have been made by six methods: enrichment with soy flour (Cravioto and Cervantes 1965), amino acid supplementation (Bressani 1972), development of *opaque-2* corn (Bressani 1972), enrichment with whole soybeans (Del Valle and Perez-Villasenor 1974, Franz 1975), protein fortification with oilseed flours (Green et al 1976), and addition of whole cottonseed kernels and soybeans (Green et al 1977). To evaluate the suitability of these modifications in the commercial manufacture of flours and to evaluate the flours prepared from different varieties of corn to be used in tortillas, knowledge of the rheological properties of corn doughs is essential.

Current standard methodology for the study of these properties in wheat dough (Bloksma 1971, Shuey 1975) is not applicable to corn dough because flow behavior differs qualitatively. Therefore, we have investigated the possible use of the Instron Tester operated in the constant-load mode upon short cylinders of corn dough and have obtained an objective method for evaluating the rheological properties of corn doughs.

THEORY

In deriving an expression for the deformation of a short cylinder of dough between two parallel plates (Fig. 1) with the radius of the cylinder equal to that of the parallel plates, we assumed a Bingham model for the corn dough and applied the equations of motion expressed in cylindrical coordinates: r, θ, and z, for an incompressible uniform fluid (Bird et al 1960). Because of circular symmetry, the velocity in the angular direction (v_θ) is zero and, as long as the height of the cylinder is small compared to its radius, a good approximation is obtained by neglecting the velocity in the z direction (v_z) normal to the plates. Dienes and Klemm (1946) observed that these assumptions are valid if the radius of the dough cylinder is at least ten times larger than its height. We also assumed the absence of edge effects.

Thus, with v_θ and v_z equal to zero, only the equation of motion for the r component remains.

Considering the corn dough to be incompressible and assuming a steady-state flow, which is justified at the very slow flows in this study, and recognizing that the acceleration due to gravity in the r direction is zero, the equation of motion for the r component reduces to

$$\frac{\partial p}{\partial r} = \mu \left(\frac{\partial^2 v_r}{\partial r^2} + \frac{1}{r}\frac{\partial v_r}{\partial r} - \frac{1}{r^2} v_r + \frac{\partial^2 v_r}{\partial z^2}\right), \quad (1)$$

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where p = the pressure in the dough, v_r = the velocity in the radial direction, and μ = the coefficient of viscosity.

Because the flux into an element of volume is $r\,d\theta\,dz\,v_r$ and the flux out of the element is $(r + dr)\,d\theta\,dz\,(v_r + dv_r)$, we can conclude from their equality that

$$\frac{\partial v_r}{\partial r} = -\frac{v_r}{r} \quad (2)$$

and

$$\frac{\partial^2 v_r}{\partial r^2} = -\frac{1}{r}\frac{\partial v_r}{\partial r} + \frac{v_r}{r^2}. \quad (3)$$

When substituted in equation 1, this gives

$$\frac{\partial p}{\partial r} = \mu \frac{\partial^2 v_r}{\partial z^2}. \quad (4)$$

By integration of equation 4 with respect to z,

$$\frac{\partial v_r}{\partial z} = \frac{1}{\mu}\left(\frac{\partial p}{\partial r} z + f\right) \quad (5)$$

where f is the yield stress or the initial stress required before the flow occurs.

Figure 2 shows a vertical section of the disk being compressed. Because flow occurs only when $(\partial p/\partial r)z$ is greater than f in magnitude, a zone will extend to a distance of $f/-\partial p/\partial r$ on each side of the mid-plane (z = 0), in which no shear takes place, and the velocity profile takes the form shown in Fig. 2. Assuming no slippage at the plates, $v_r = 0$ at $z = h/2$, and therefore integration of equation 5 will yield:

$$v_r = \frac{1}{2\mu(\partial p/\partial r)}\left[\left(\frac{\partial p}{\partial r} z + f\right)^2 - \left(\frac{\partial p}{\partial r}\frac{h}{2} + f\right)^2\right] \quad (6)$$

and the area of the shaded zone swept out in time (dt) is

$$A = \frac{2}{\mu\,(\partial p/\partial r)^2}\left[-\frac{1}{3}\left(\frac{\partial p}{\partial r}\frac{h}{2} + f\right)^3 + \frac{f}{2}\left(\frac{\partial p}{\partial r}\frac{h}{2} + f\right)^2\right] dt. \quad (7)$$

Because the decrease in thickness of the disk in time (dt) is dh, the volume of material flowing into the shaded zone is $(-\pi r^2\,dh)$, and the shaded area equals $(-\frac{1}{2} r\,dh)$, which, when equated to the above expression for the same areas, gives

$$\frac{2\,dt}{\mu(\partial p/\partial r)^2}\left[-\frac{1}{3}\left(\frac{\partial p}{\partial r}\frac{h}{2} + f\right)^3 + \frac{f}{2}\left(\frac{\partial p}{\partial r}\frac{h}{2} + f\right)^2\right] = -\frac{1}{2} r\,dh \quad (8)$$

or

$$-\frac{\partial p}{\partial r}\left(1 - \frac{4f^3}{(\partial p/\partial r)^3 h^3}\right) = \frac{3f}{h} - \frac{6r\mu}{h^3}\frac{dh}{dt}. \quad (9)$$

The term $4f^3/(\partial p/\partial r)^3 h^3$ can be very small under appropriate experimental conditions and can be regarded as a constant k.

Considering $p = p°$, or atmospheric pressure when $r = R$, integration of equation 9 with respect to r yields

$$p = \frac{3f}{h(1-k)}(R-r) + \frac{6\mu}{2h^3(1-k)}(r^2 - R^2)\frac{dh}{dt} + p°. \qquad (10)$$

The integral of this pressure over the whole area of the disk equals the compressive force, F.

$$F + \int_0^R 2\pi r p° \, dr = \int_0^R 2\pi r p \, dr \qquad (11)$$

or

$$F = \frac{\pi f R^3}{h(1-k)} - \frac{3}{2}\frac{\mu\pi R^4}{h^3(1-k)}\frac{dh}{dt} \qquad (12)$$

If the experimental conditions are such that the assumptions are valid, this equation could be employed to describe the relationship between the compressive force and the height of the disk at fixed crosshead speed and would also allow for the evaluation of the parameters μ and f.

However, when a constant compressive force is applied to the disk of dough, the height of the disk decreases until a limiting height is reached below which the material cannot be compressed by the applied force. When h is equal to this limiting thickness (h_L), then $dh/dt = 0$. Inserting this condition in equation 8, it follows that

$$dp = -\frac{2f}{h_L}dr. \qquad (13)$$

Recalling that when $r = R$, $p = p°$, integration of equation 13 gives

$$p = \frac{2f}{h_L}(R-r) + p°. \qquad (14)$$

Substituting equation 14 in equation 11 and integrating yields:

$$F = \int_0^R \frac{4\pi f}{h_L}(Rr - r^2)\, dr = \frac{2\pi f R^3}{3h_L} \qquad (15)$$

or

$$f = \frac{3h_L F}{2\pi R^3} \qquad (16)$$

Assuming $(\partial p/\partial r)$ is independent of r in the term, $4f^3/(\partial p/\partial r)^3 h^3$ in equation 9, then

$$p = p° - \frac{\partial p}{\partial r}(R-r). \qquad (17)$$

Substituting equation 17 in equation 11, integrating, and rearranging yields:

$$-\frac{\partial p}{\partial r} = \frac{3F}{\pi R^3}. \qquad (18)$$

From equations 18 and 16, the expression

$$\frac{4f^3}{(\partial p/\partial r)^3 h^3} = 4\cdot\left(\frac{3h_L F}{2\pi R^3}\right)^3 \cdot \left(\frac{-\pi R^3}{3F}\right)^3 \cdot \frac{1}{h^3} = -\frac{1}{2}\left(\frac{h_L}{h}\right)^3. \qquad (19)$$

Substituting equations 19 and 16 in equation 12 and solving for dh/dt, we obtained:

$$\frac{dh}{dt} = -\frac{F h_L^3}{3\mu\pi R^4}\left[2\left(\frac{h}{h_L}\right)^3 - 3\left(\frac{h}{h_L}\right)^2 + 1\cdot\right] \qquad (20)$$

If we represent h/h_L by x and therefore dh/dt by $h_L\, dx/dt$ in equation 20 and rearrange the expression, we obtain:

$$\frac{F h_L^2}{3\mu\pi R^4}\, dt = \frac{dx}{(x-1)^2(2x+1)}. \qquad (21)$$

When $t = 0$, $h = h_o$ and $x = x_o = h_o/h_L$; therefore, upon integration of equation 21, we have:

$$\frac{-F h_L^2}{3\mu\pi R^4}\, t = \frac{1}{3}\left[\frac{1}{(x_o-1)} - \frac{1}{(x-1)}\right] + \frac{2}{9}\ln\frac{(2x+1)(x_o-1)}{(x-1)(2x_o+1)}. \qquad (22)$$

Substituting h_o/h_L for x_o and h/h_L for x in equation 22,

$$t = \frac{\mu\pi R^4}{F h_L^2}\left[\frac{h_L(h_o-h)}{(h-h_L)(h_o-h_L)} - \frac{2}{3}\ln\frac{(2h+h_L)(h_o-h_L)}{(h-h_L)(2h_o+h_L)}\right]. \qquad (23)$$

Equation 23 describes the relationship between the height of the disk of dough and the time when a constant load has been applied, if the assumptions employed in its derivation are valid. This equation would also provide a means of evaluating the parameters μ and f.

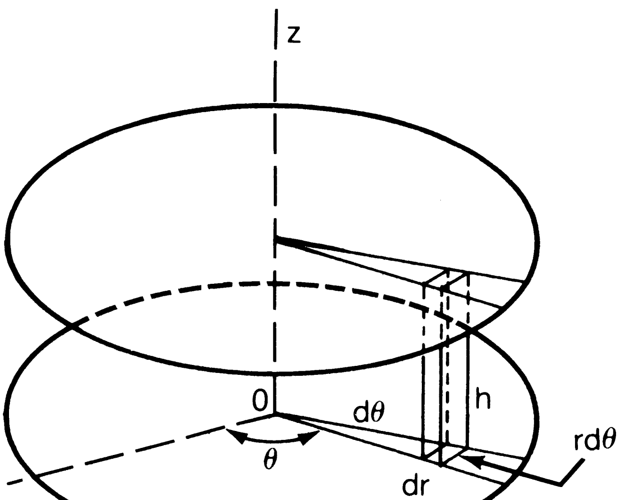

Fig. 1. Parallel plate assembly illustrating coordinate system (Dienes and Klemm 1946).

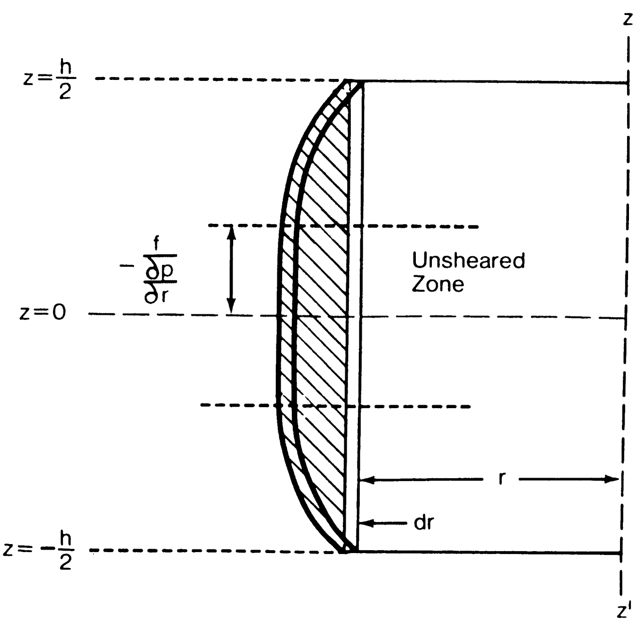

Fig. 2. Vertical section of disk of dough under compression (Scott 1931).

MATERIALS AND METHODS

Commercially limed corn flour (Masa Harina, Quaker Oats Co., Chicago, IL) was used to prepare the dough by mixing 150 g of flour in a Hobart mixer at 25 rpm for the specified time with the appropriate amount of water for each experiment. The dough was shaped into a sphere and placed into a closed container at room temperature (21.5°C) for the specified time to allow its moisture content to reach equilibrium. Before testing, the dough was cut into wedge-shaped sections, each of which was made into a small sphere that was flattened between two parallel plates to a preset height of 0.5 cm. A circle was then cut from the sheet with a stainless steel cutter to make a short cylinder 10 cm in diameter. Each dough cylinder was placed between two plastic sheets to facilitate cleanup and aligned with the circular plate of the compression cell of the Instron Tester (model TM-M; tension cell, CTM), which has the same diameter, and the instrument crosshead speed set at 0.05 cm/min and chart speed set at 10 cm/min.

Time zero was marked on the chart moving at constant speed when the instrument attained the preset load and the height read on the gauge-length dial. Subsequent points were recorded in the same fashion until the movement was practically stopped, usually 300–400 sec. The compression times were calculated from the marked distances on the chart paper and the known speed of the chart.

After the compression test, three pieces of the dough cylinder were analyzed for moisture content by being dried to constant weight in an air-circulation oven at 110°C.

From theoretical considerations already presented, equation 23 describes the deformation of a disk of dough with time under a constant load. This equation was fitted to the data with Deming's procedure (Deming 1944). The estimated parameters were the Bingham viscosity, μ, and the limiting thickness, h_L, from which the yield value, f, can be calculated by equation 16.

The χ^2 value for evaluating the fit is based on the estimated variances in the measure of h and t. When recording h from the gauge-length dial, the standard deviation of a reading is assumed to be 1/10 of the smallest marked dial division, 0.001 cm; thus, the corresponding variance is $(0.001)^2$ cm^2. When recording the time, the error introduced by making a mark manually on the moving chart was measured independently by running the chart at the speed employed in the test and marking on it intervals of equal length read from the gauge-length dial, the variance in these readings, $\sigma_t^2 = 0.823$, is assumed to be equal to the variance of t.

The magnitudes of the loads applied to the sample disks were chosen to produce a slow but detectable compression rate that could be easily followed and recorded. Excessively large loads would result in rapid compression rates that would be very hard to follow and, with too small a load, the error introduced in recording the time at which the thicknesses were reached would make the results meaningless.

RESULTS AND DISCUSSION

Compression at Constant Rate

Attempts were made to apply equation 12 to the characterization of the rheological properties of corn dough by operating the Instron Tester at constant crosshead speed. Although possible to fit the load and height data to the equation for a portion of each curve obtained at crosshead speeds of 0.5, 0.2, 0.1, and 0.05 cm/min, the values of μ and f showed significant dependence on the compression rate, indicating that the available crosshead rates were still too rapid to satisfy the assumptions involved in the derivation of equation 12. Perhaps if gears were available to secure appropriately slow rates, this dependence upon the compression rate would be eliminated, and equation 12 could be used to describe the rheology of corn dough.

Compression Under Constant Load

Figure 3 shows a typical Instron Tester chart obtained by the compression of corn dough under constant load. The instrument records the force applied, the height is marked manually as it is read on the gauge-length dial, and the time is calculated. A plot of the compression time against the height of the dough cylinder and the fitted equation 23 are shown in Fig. 4. χ^2 tests for significant lack of fit at the 5% probability level calculated by Deming's procedure (Deming 1944) indicated a satisfactory fit in all corn dough samples investigated. Therefore, the Bingham model adequately describes the consistency of the corn dough, and the assumptions involved in the derivation of equation 23 are valid under the conditions employed.

The Effect of Moisture Content

To investigate the effect of the moisture content of the corn dough on the rheological parameters and to determine the control necessary, replicate batches of 150 g of corn flour were mixed with 130–190 ml of water at 10-ml increments for 15 min and held for 18 hr at 21.5°C before analysis. The results are recorded in Table I. The lowest moisture level (~51%) indicated a significantly larger variance in the Bingham viscosity than the other moisture levels when evaluated by Bartlett's test, suggesting that corn doughs at

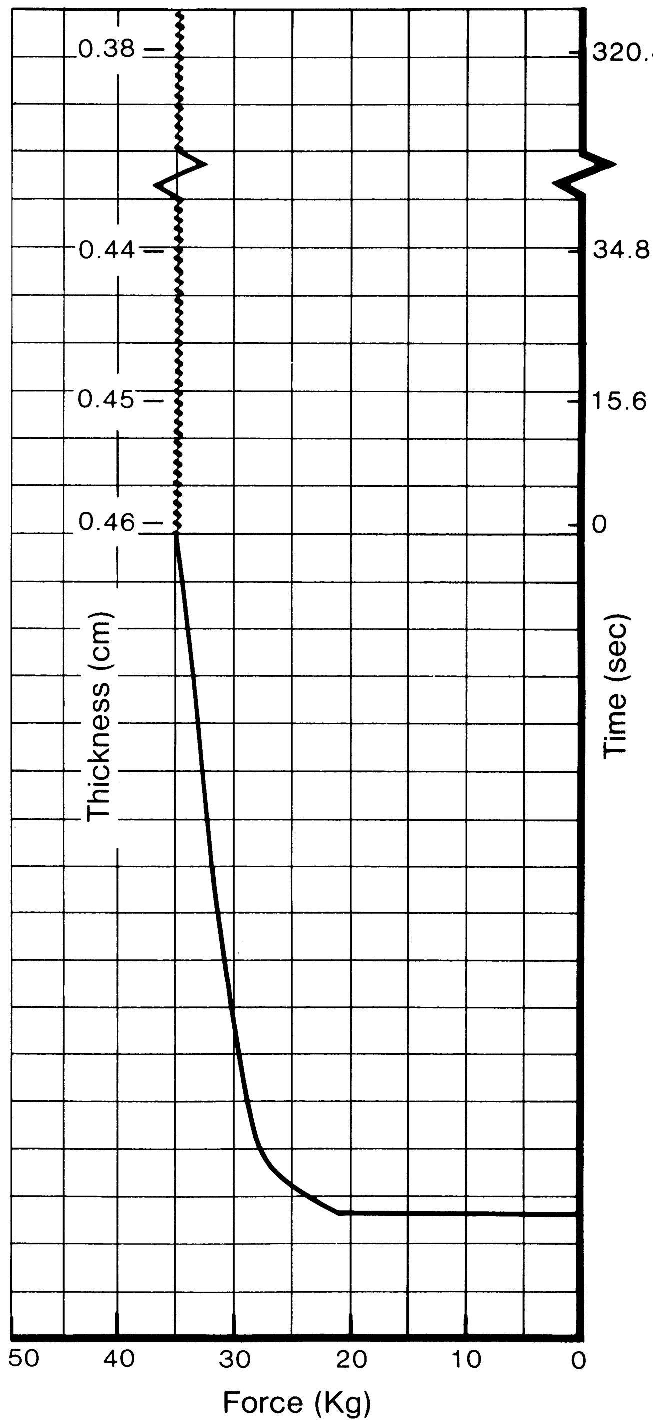

Fig. 3. Instron Tester chart showing the deformation of a disk of corn dough compressed under constant load.

TABLE I
Effect of Moisture Content on the Rheological Parameters of Corn Dough Evaluated by Compression Under Constant Load[a]

Number of Disks	Moisture Content (%)[b]	Force (kg)	Bingham Viscosity (μ) (dyne sec cm^{-2})	Limiting Height (h_L) (cm)[b]	Yield Value (f) (dyne cm^{-2})[b]
4	51.28 ± 0.14	39.5	302,800 ± 95,560	0.3601 ± 0.0047	64,690 ± 836
4	52.89 ± 0.14	32.5	180,100 ± 22,810	0.3406 ± 0.0237	50,340 ± 3,504
5	53.74 ± 0.04	25.2	154,100 ± 7,944	0.2996 ± 0.0182	34,330 ± 2,087
4	55.35 ± 0.09	15.0	80,460 ± 6,885	0.3715 ± 0.0081	25,340 ± 552
4	56.44 ± 0.11	11.8	49,020 ± 5,713	0.3702 ± 0.0086	19,870 ± 460
3	58.24 ± 0.15	10.0	43,900 ± 11,160	0.3982 ± 0.0013	18,110 ± 55
2	59.08 ± 0.01	10.0	33,040 ± 1,753	0.3423 ± 0.0026	15,600 ± 120

[a] Mixing time = 15 min; holding time = 18 hr; temperature = 21.5°C.
[b] Mean ± standard deviation between disks.

TABLE II
Estimated Contribution of the Precision of the Moisture Content to the Precision of the Predicted Rheological Parameters of Corn Dough at Selected Moisture Contents[a]

	Bingham Viscosity (μ)			Yield Value (f)		
	Predicted Value	Estimated Standard Error		Predicted Value	Estimated Standard Error	
Moisture Content (%)	$\left(\frac{\text{dyne sec}}{\text{cm}^2}\right)$	$\left(\frac{\text{dyne sec}}{\text{cm}^2}\right)$	(%)	(dyne cm^{-2})	(dyne cm^{-2})	(%)
52.89	187,200	11,080	5.92	50,390	2,879	5.71
55.35	82,850	6,183	7.46	24,870	819	3.29
58.24	35,900	428	1.19	17,680	708	4.00

[a] $S^2_M = 0.0414$.

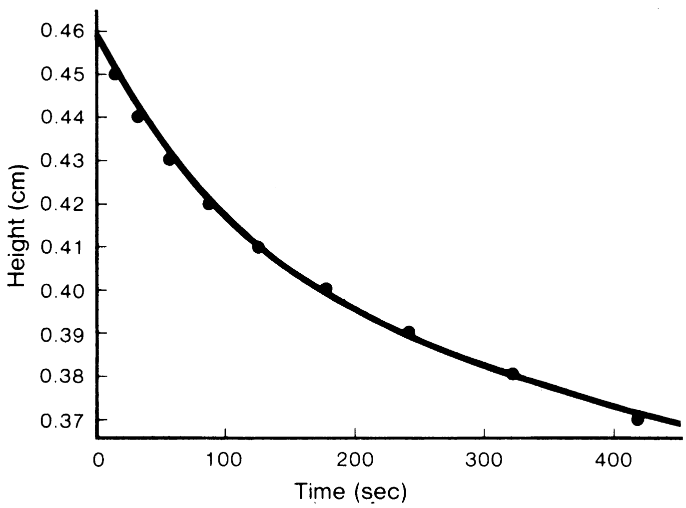

Fig. 4. Time versus deformation curve of a disk of corn dough when compressed under a constant load of 32 kg.

this level and below would not yield reproducible values. The balance of the data was subjected to regression analysis and indicated that the higher the moisture content, the lower the values of the parameters, as was expected. The following regression equations were obtained:

$$\mu = 1.6757 \times 10^7 - 5.7211 \times 10^5 \text{ M} + 4.8936 \times 10^3 \text{ M}^2$$

and

$$f = 24{,}412 - 4133.8\,(M - 55.46) + 221.19\,(M - 55.46)^4 \; (25) - 50.886\,(M - 55.46)^5,$$

where M = percent moisture content.

Analysis of variance of the moisture content indicated no significant difference between disks at the various moisture levels and an error variance within disks of 0.0414. The expected precision in the measurements of the parameters predicted by the regression equation and their variance at selected moisture levels is reported in Table II. Very precise control of the moisture content is indicated as necessary, especially at the lower moisture levels, in order to obtain reproducible values for the parameters.

Effect of Holding Time

To determine the holding time necessary for equilibration of the corn dough samples and the precision necessary to control it, a single batch of dough was prepared by combining 450 g of flour with 420 ml of water and mixing for 15 min. The dough was divided into three portions. One was analyzed immediately in replicate and the others stored in closed containers at 21.5°C for 12 and 24 hr, respectively, before analysis. The results are shown in Table III.

Analysis of variance of moisture content of the disks indicated no significant variation with holding time or between disks for the same holding time. In this study, the error variance within disks was 0.013. The statistical analysis of the rheological parameters shows, in the case of the Bingham viscosity, that, although the error variance at 0 hr is significantly larger than those at 12 and 24 hr, the precision of the measurements does not change significantly after 12 hr. The mean values for this parameter do not change significantly with time. In the case of the yield value, no significant difference was observed in the precision of its measurement with holding time. However, the mean yield value at 0 time was significantly smaller than those observed at the other holding times.

Therefore, since the data show that the values of μ and f and their variances are constant within experimental error for 12- and 24-hr holding times, 12-hr holding time appears to be sufficient for equilibration before these parameters are evaluated.

Effect of Mixing Time

The time employed for mixing the dough ingredients is also an important factor in the preparation of the dough for analysis. Not only will it influence the moisture distribution and contact with the flour, but it may influence the structure of the system, which would alter its consistency. To determine the time required to secure reproducible parameter values, four batches of dough were prepared from 150 g of flour and 140 ml of water by mixing for 4, 8, 12, and 16 min, respectively. The dough was stored in closed containers for 18 hr at 21.5°C and the rheology of the doughs investigated in replicate. The results are shown in Table IV.

Analysis of variance of the moisture content of the disks indicates a heterogeneity between disks with 4 min of mixing but a homogeneous distribution after 8 min of mixing. Statistical analysis of the yield values and Bingham viscosities indicates that, although the error variances are homogeneous with time of mixing for these parameters, the mean yield value is surprisingly low and the mean Bingham viscosity surprisingly high after 12 min of mixing, suggesting that uniformity in structure has not yet been obtained. Because previous experiments in which the dough was mixed for 15 min yielded reasonably uniform results in these parameters, at least 15 min of mixing time is recommended.

Precision in Parameter Evaluation

The precision of the measurement of the Bingham viscosity and yield value of a corn dough was estimated by comparing the standard deviation from a number of parameter measurements, all performed under the same conditions, with the standard errors in the parameters for each measurement calculated according to Deming (1944). He determines the error variance of the parameter as the product of the appropriate coefficients of variance obtained from the inverse matrix of the normal equations and the external variance. In this instance, the standard error in the limiting height (h_L), which is proportional to the yield value, was calculated because it is the parameter evaluated in equation 23. Table V

TABLE III
Effect of Holding Time on the Corn Dough in the Evaluation of its Rheological Parameters by Compression Under Constant Load[a]

Holding Time (hr)	Moisture[b] Content (%)	Bingham[b] Viscosity (μ) (dyne sec cm^{-2})	Limiting[b] Height (h_L) (cm)	Yield[b] Value (f) (dyne cm^{-2})
0	53.32 ± 0.05	206,800 ± 52,880	0.3174 ± 0.0121	43,640 ± 1,584
12	53.41 ± 0.08	182,800 ± 16,430	0.3456 ± 0.0049	47,470 ± 677
24	53.27 ± 0.14	180,800 ± 23,370	0.3595 ± 0.0087	49,400 ± 1,226

Analysis of Variance

Bingham Viscosity

Comparisons	*F*-Test for Homogeneity of Error: F	$F_{0.05}$	Significance[d]	t^1 Test for Equality of Means[c]: t^1	$t^1_{0.05}$	Significance[d]
0 hr vs 12 and 24 hr	6.84	4.75	S	0.91	3.13	NS
12 hr vs 24 hr	2.02	9.28	NS	0.14	3.18	NS

Yield Values[e]

Source	d.f.	s.s.	m.s.	F	$F_{0.05}$	Significance[d]
Total	11	8.219×10^7				
Holding time	2	6.879×10^7	3.439×10^7	23.09	4.25	VS
0 hr vs 12 and 24 hr	1	6.138×10^7	6.138×10^7	41.21	5.12	VS
12 hr vs 24 hr	1	7.411×10^6	7.411×10^6	4.98	5.12	NS
Error	9	1.340×10^7	1.489×10^6			

[a] Mixing time = 15 min; temperature = 21.5°C; force = 30.2 kg. Four disks per holding time were used.
[b] Mean ± standard deviation between disks.
[c] Steele and Torrie 1960.
[d] S = significant, NS = not significant, VS = very significant.
[e] d.f. = degrees of freedom, s.s. = sums of squares, m.s. = mean squares.

TABLE IV
Effect of Mixing Time on Corn Dough in the Evaluation of its Rheological Parameters by Compression Under Constant Load[a]

Mixing Time (min)	Moisture[b] Content (%)	Force (kg)	Bingham[b] Viscosity, μ (dyne sec cm^{-2})	Limiting[b] Height, h_L (cm)	Yield[b] Value, f (dyne cm^{-2})
4	51.97 ± 0.25	30.1	152,800 ± 26,010	0.3463 ± 0.0205	47,400 ± 2,803
8	52.14 ± 0.04	30.2	140,900 ± 12,870	0.3449 ± 0.0125	47,360 ± 1,715
12	52.19 ± 0.20	30.0	187,600 ± 27,470	0.3128 ± 0.0109	42,670 ± 1,493
16	52.30 ± 0.03	30.0	147,700 ± 15,080	0.3409 ± 0.0073	46,500 ± 993

Analysis of Variance[c]

Bingham Viscosity

Source	d.f.	s.s	m.s	F	$F_{0.05}$	Significance
Total	15	1.221 ± 10^{10}				
Mixing time	3	5.652 ± 10^9	1.884 ± 10^9	3.45	3.49	NS
4 min vs 8, 12, and 16 min	1	5.419 ± 10^7	5.419 ± 10^7	0.10	4.75	NS
8 min vs 12, and 16 min	1	1.570 ± 10^9	1.570 ± 10^9	2.87	4.75	NS
12 min vs 16 min	1	4.028×10^9	4.028×10^9	7.37	4.75	S
Error	12	6.557×10^9	5.464×10^8			

Yield Values

Source	d.f.	s.s.	m.s.	F	$F_{0.05}$	Significance
Total	15	1.028×10^8				
Mixing time	3	6.075×10^7	2.025×10^7	5.77	3.49	S
4 min vs 8, 12, and 16 min	1	1.073×10^7	1.073×10^7	3.06	4.75	NS
8 min vs 12 and 16 min	1	2.061×10^7	2.061×10^7	5.88	4.75	S
12 min vs 16 min	1	2.941×10^7	2.941×10^7	8.39	4.75	S
Error	12	4.205×10^7	3.504×10^6			

[a] Temperature = 21.5°C, holding time = 18 hr. Four disks were used per mixing time.
[b] Mean ± standard deviation between disks.
[c] d.f. = degrees of freedom, s.s. = sums of squares, m.s. = mean squares, S = significant, NS = not significant, VS = very significant.

TABLE V
Calculated Standard Error in the Bingham Viscosity and Limiting Height of Corn Dough Disks Compressed Under Constant Load[a]

Sample	Bingham Viscosity μ $\left(\frac{\text{dyne sec}}{\text{cm}^2}\right)$	Standard Error $\left(\frac{\text{dyne sec}}{\text{cm}^2}\right)$	Standard Error (%)	Limiting Height h_L (cm)	Standard Error (cm)	Standard Error (%)
1	159,700	8,846	5.54	0.3194	0.0026	081
2	164,900	4,658	2.82	0.3022	0.0015	0.50
3	148,300	7,190	4.85	0.2908	0.0023	0.79
4	151,500	10,327	6.82	0.3122	0.0032	1.04
5	146,100	6,209	4.25	0.2733	0.0020	0.73
Mean	154,100			0.2996		
Observed Standard Error	7,943			0.0182		
Percent Error	5.15			6.07		

[a]Force = 25.2 kg, temperature = 21.5°C, mixing time = 15 min, holding time = 18 hr.

indicates the calculated standard errors in the parameters as well as the mean, standard deviation, and percentage error in the observed values.

The results indicate that, for Bingham viscosity, the standard deviation of several measurements is within the range of the standard errors of the individual determinations. This suggests that the replication error is not significant and that the observed error is mainly the result of instrumental and observational variation within a determination. For the limiting height, the standard deviation of a group of determinations is significantly larger than the standard errors in individual determinations. Thus, there is a significant replication source of error added to the instrumental and observational variability. However, the magnitude of this error is small enough to consider the results reproducible. Therefore, the method with proper control of the moisture content, mixing time, and holding time will yield values for the Bingham viscosity and yield values of a corn dough with satisfactory precision ($\pm \sim 5\%$ and $\pm \sim 6\%$, respectively).

CONCLUSIONS

The Instron Tester in the constant-load mode can be used to evaluate the Bingham viscosity and yield values of corn dough when the mixing time is 15 min or more, the holding time 12 hr or more, and the moisture content carefully controlled (error variances of $\sim$0.0414). Our results demonstrate that corn dough behaves as a Bingham plastic and that its rheological characteristics can be evaluated with a precision of 5–7% at moisture contents of 53% or more.

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