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An Improved Method for Measurement of Gel Strength and Data on Starch Gels

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A method is described for the measurement of gel strength that involves essentially the determination of the shearing force required to fracture gels. Weight is applied to standard disks embedded in the gels. A standardization of the method is outlined. Several applications are given to illustrate the precision of the method and its use in studies of starches of various kinds. No exact correlation between gel strength and the granular size or the amylose or amylopectin contents of starches was found.

I. Introduction

This paper deals with a method for the measurement of gel strength. It was developed during the course of an investigation of the paste-wall of electric dry cells. The paste-wall of most dry cells consists of starch-flour gels. Therefore, attention is primarily given to gels prepared with these materials. The method, however, may be used in determining the strength of all types of gels whether they are of the reversible (gelatin) or irreversible (starch) type.

Many methods have been proposed for the measurement of gel strength. Of these, mention may be made of the ASTM [1][1] and Fuchs [2] penetrometers, the Bloom [3] gelometer, the Tarr-Baker [4, 5] gel tester, the Brimhall-Hixon [6] rigidometer, the Sheppard [7, 8] torsion dynamometer, the Rosinger-Vetter [9] static-loading membrane method, and the Saare-Martens [10] disk method. All of these have specific advantages. However, as stated by Kerr [11], different characteristics of a gel may be measured by the various methods, depending on the point of view. They may give an indication of the rigidity, elasticity, plastic viscosity, or the resistance of gels to some force such as cutting action or torsional force. Some of these properties may be related to gel strength. For precise measurements on starches, the methods that involve the surface of the gel are less suitable than the others because starch gels form hard "surface skins" on standing.

[1] Figures in brackets indicate the literature references at the end of this paper.

Of the various procedures, the Saare-Martens disk method appeared to be the best suited to starches and to give data that are a true indication of their strength. However, preliminary tests showed that it could be used only with gels containing a small amount of starch, and that the precision was low. The Saare-Martens method involves the fracture of a gel by an embedded disk. The gel and disk are placed on a stationary platform over one pan of an analytical balance, and lead shot is added at a known rate to the other pan. However, because of the deformability of the gels, the pan to which the lead shot is added frequently touches the balance rest before a fracture of the gel occurs. This was prevented in the present work by using an adjustable platform instead of a stationary one. Use of mercury was also found superior to lead shot because the latter could not be added at a steady or consistent rate. By using an adjustable platform it was also possible to obtain an indication of the rigidity of gels by determining the rate of change of height of the adjustable platform. The method described in this report, therefore, gives two properties of gels: the strength of the gel and an indication of its deformability.

II. Description of the Method

A schematic diagram of the apparatus is shown in figure 1. A brass disk is suspended in the gel by a brass wire connected to the center of the top surface of the disk. The upper end of the wire is bent so that it may be fastened to a hook,

L, suspended from the beam of an analytical balance. A beaker, A, containing the gel and disk is placed on an adjustable platform, B, with scale C, over one pan of the balance. Mercury is then added from a burette, E, supported by a stand, F, at a constant flow-rate to a beaker, G, on the other pan of the balance. The beaker is tared with a weight, H. A burette constructed on the principle of the Mariotte flask is used so that mercury is delivered at a constant rate regardless of the amount of mercury in the burette. Different flow-rates were made possible by the use of various sizes of capillary tubes, M, which were attached with rubber tubing to the bulb of the burette. The capillary tubes were calibrated by weighing the mercury delivered in a given time. At the beginning, the space above the mercury is evacuated, and as mercury is withdrawn, a partial pressure is maintained over the mercury. As mercury is added to beaker G, the height of the adjustable platform, B, is changed by a screw, D, so that the pointer, J, of the balance is always kept at the zero mark. The scale readings on scale C, are read at intervals of 1 minute, timed with a stopwatch, until the end point is reached. The end point is determined to the nearest quarter of a minute.

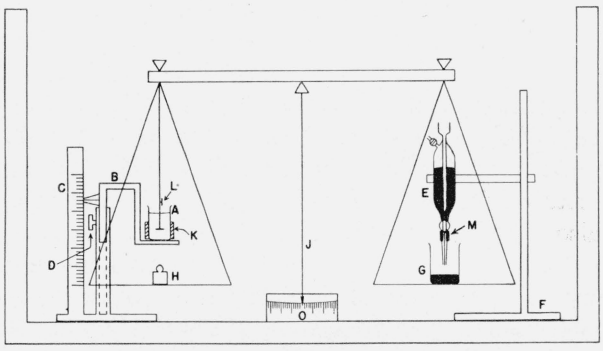

FIGURE 1.—*Schematic diagram of equipment for the measurement of gel strengths.*

For many of the concentrated gels, so much mercury was required to pull disks from the gels that beaker A would be raised from the platform before a fracture of the gel occurred. Therefore, the beaker was placed in a lead mold, K, weighing 1,500 g made to fit snugly the circumference of the beakers. Copper strips fused into the lead mold protruded up and over the rim of the beaker.

Saare and Martens and others have defined gel strength as the weight of mercury required to produce a fracture in the gel divided by the area of the disk. It will be shown later that this definition must be modified and is suitable only for comparisons. The rate of change in height of the adjustable platform gives an indication of the resistance of gels to deformation.

The precise moment the first fracture of the gel occurs is not always easy to detect. Therefore, the weight of mercury was recorded as the value after the disk was pulled from the gel. In those cases where the time of fracture was noted, it was observed that the disks were pulled from the gels within a few seconds for dilute gels and within ½ to 2 minutes for the more concentrated gels. These time intervals introduce only small errors in the determination of gel strength. Furthermore, the true end point may be determined from a plot of the scale readings of the adjustable platform as a function of time as will be discussed later. The disks sometime separate suddenly from the gels with considerable jarring of the balance. Therefore, cork pads were placed under the balance pan to protect the beams and knife edges of the balance against injury.

To illustrate the method, a number of gels were made under identical conditions. A known weight of sample was added to a known weight of distilled water of pH 6.1 to 6.6 in a Pyrex beaker. The beaker was then placed in a boiling-water bath (98° C) and the paste heated for 15 minutes with constant stirring. The paste was then poured into a beaker of standard dimensions to a designated mark. A brass disk having a thickness of 1 mm and a diameter of 1.9 cm (¾ in.) was immediately inserted into the hot gel to a depth of 3.8 cm (2 in) and the hook of the supporting wire hung over a temporary rod resting on the top edge of the bottle. The temporary rod was removed before the wire of the disk was engaged with the wire extending from the beam of the balance. The disk was centered in the gel, a necessary precaution, by a simple mechanical device. It consisted of a circular piece of aluminum (1/64 in. thick) with holes for the wire and hook supporting the disk. It rested loosely on top of the beaker. Ten milliliters of liquid petrolatum was then poured over the surface of the gel to prevent the formation of "surface

skins." Prior to the measurements, the gels were aged for 24 hr in a constant-temperature water bath controlled at 25 $\pm 0.02°$ C.

In table 1 data are given for various gels. Here, for illustration, gel strength is defined in the customary manner as the load in grams divided by the area of the disk in square centimeters. Actually, the surface of shear, as will be discussed later, is given by a column of starch, having a circumference equal to that of the disk and a height approximately the depth of immersion. A flow rate of 16 g of mercury per minute was used in these measurements. The gel strengths may be calculated either from the final weight of mercury or the flow-rate, and the minutes required to reach the end point. Both values are given in the table, and the agreement is good. The reproducibility of the method is high, and the gel strength may be determined with a precision of better than 0.5 percent. The limitations of the method lie more in the reproducibility with which gels can be prepared than in errors inherent in the method.

TABLE 1.—*Gel strength of various starches and wheat flour at 25° C*

Sample [a]	Weight of sample	Weight of water	Weight of dry sample per 100 ml	Weight of mercury	Time of end point	Weight of mercury from end point	Gel strength
	g	*g*	*g*	*g*	*minute*	*g*	*g/cm²*
Cornstarch	3.211	145.9	1.9	0	-------	-------	0
	5.600	140.0	3.3	13	1.00	16	5
	6.422	144.7	3.8	22	1.25	20	8
	9.633	134.7	5.7	161	10.00	160	56
	10.00	141.3	5.9	177	11.00	176	62
	12.84	138.4	7.6	291	18.50	296	102
	15.00	138.0	8.8	362	23.00	368	127
	20.00	134.7	11.8	592	37.25	596	208
Wheat starch	5.000	142.3	2.9	0	-------	-------	0
	6.527	143.7	3.8	21	1.25	20	7
	10.00	141.3	5.8	141	9.00	144	49
	13.05	138.2	7.6	251	16.00	256	88
	15.00	138.0	8.7	294	20.25	324	103
	20.00	134.7	11.6	463	29.00	464	162
Wheat flour	6.393	143.7	3.8	4	0.25	4	1
	10.00	141.3	5.9	40	2.50	40	14
	12.79	138.4	7.6	77	5.00	80	27
	15.00	138.0	8.9	113	7.00	112	40
	20.00	134.7	11.8	170	10.00	160	60
Waxy cornstarch	11.20	140.0	6.6	0	-------	-------	0
	12.95	138.3	7.6	0	-------	-------	0
	20.00	134.7	11.7	0	-------	-------	0
Gum gluten	10.00	141.3	6.4	0	-------	-------	0
	15.00	138.0	9.7	0	-------	-------	0
	20.00	134.5	12.9	0	-------	-------	0
Maine potato starch	13.11	138.1	7.6	70	4.25	68	25
Idaho potato starch	13.11	138.1	7.6	12	1.00	16	4
Sweetpotato starch	12.49	138.7	7.6	88	5.25	84	32

[a] Source (Co.) and moisture content of samples: cornstarch, Buffalo, 12.8%; wheat starch, A21 General Mills, 14.2%; wheat flour, Pillsbury XXXX, 12.4% waxy cornstarch, National Starch, 13.5%; gum gluten, Keever Starch, 4.5%; Maine potato starch, American Maize, 14.6%; Idaho potato starch, American Maize, 14.6%; and sweetpotato starch, Laurel Starch, 10.3%.

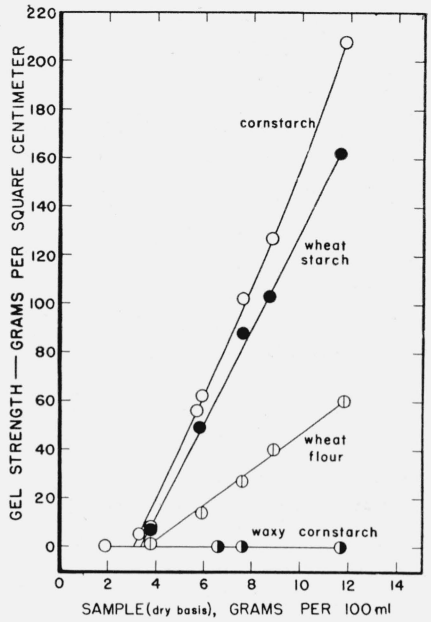

FIGURE 2.—*Gel strength of some starch and flour samples at 25° C.*

Comparisons of the gel strengths of the samples on the dry basis are shown in figure 2. The moisture contents of the samples were determined as recommended by Sair and Fetzer [12] by heating 2 to 5 g of the sample in a vacuum oven for 48 to 72 hr at 135° C to constant weight. Dilute pastes of waxy cornstarch and gum gluten do not form gels. Only a fraction of a minute was required to pull disks from them, and they were listed as having no gel strength. As will be shown later, more concentrated pastes of waxy cornstarch form gels. Wheat flour has less strength than wheat starch. It contains about 30 percent of gluten, which does not contribute to gel strength. The method also makes possible the determination of the minimum percentage of starch for gel formation. Pastes containing less than about 4 percent of dry wheat flour, wheat starch, or cornstarch do not gel. For illustration, data are given in table 2 showing the effect of temperature on the strength of cornstarch gels. The gel strength of cornstarch is lowered by an increase in temperature and by additions of either NH_4Cl

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TABLE 2.—*Effect of salts and temperature on the strength of cornstarch gels*

Salt	Weight of starch	Weight of water	Weight of dry starch per 100 ml	Weight of mercury	Gel strength[a] (aqueous paste)	Gel strength (salt paste)
	g	*g*	*g/ml*	*g*	*g/cm²*	*g/cm²*
40 g NH_4Cl	10	115.3	5.9	51	62	18
40 g NH_4Cl	20	108.6	11.8	440	208	154
40 g $ZnCl_2$	10	127.6	5.9	6	62	2
41 g $ZnCl_2$	20	120.9	11.8	290	208	102
Temperature, °C					Gel strength,[a] 25° C	Gel strength, 54° C
54	10	141.3	5.9	26	62	9
54	15	138.0	8.8	250	127	88
54	20	134.7	11.8	445	208	156

[a] Data obtained from table 1.

or $ZnCl_2$, the effect being more marked for dilute gels.[2] The data presented are not extensive, as it is beyond the scope of this paper to investigate all possible variations on the characteristics of starch gels. Only sufficient data have been included to illustrate the possibilities of the method described in this paper.

In table 3, the scale readings for a cornstarch gel

TABLE 3.—*Scale readings of the adjustable platform for cornstarch gel containing 11.8 g of dry starch per 100 ml*

Minutes	Scale reading	Minutes	Scale reading	Minutes	Scale reading
0	[a] 2.141	13	2.092	26	2.048
1	2.138	14	2.090	27	2.040
2	2.133	15	2.086	28	2.032
3	2.128	16	2.083	29	2.025
4	2.123	17	2.079	30	2.018
5	2.119	18	2.078	31	2.002
6	2.116	19	2.076	32	1.988
7	2.112	20	2.072	33	1.979
8	2.108	21	2.068	34	1.968
9	2.104	22	2.066	35	1.955
10	2.101	23	2.063	36	1.938
11	2.098	24	2.058	37	1.907
12	2.096	25	2.055	37.25	1.858

[a] A 0.02 scale reading equals 1.0 mm.

(11.8 g of dry starch per 100 ml) are given for illustration. In figure 3, the scale readings are shown plotted with respect to time for gels containing 20 g of starch in 148 ml of paste. The

[2] These variables were chosen here because of their importance in dry cells. A temperature of 54° C was used because dry cells during the war were shipped to the tropics, where the temperature in some cases reached as high as 54° C.

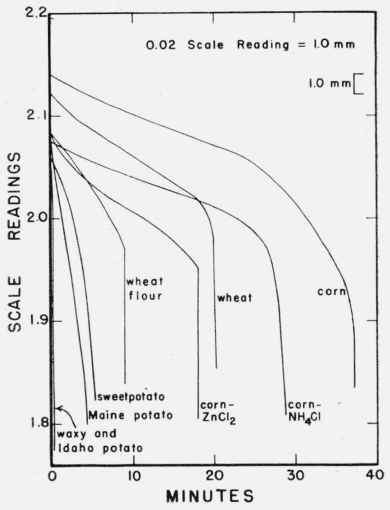

FIGURE 3.—*Scale readings of the adjustable platform as a function of time, showing the deformability of different gels under various conditions.*

slope differs for each sample. A large slope up to the break in the curve (large departure from vertical axis) means that the gel is more easily deformed. It will also be noted that the end point for cornstarch gel is approached gradually, whereas the addition of $ZnCl_2$ causes the gel to break sharply. A more accurate value of the end point may be obtained from these plots by extending the two distinct sections of the curves until they intersect. In general, the value of gel strength obtained from these end points agrees closely with that found from the weight of mercury and given in table 1. In table 4, the values of the slopes are

TABLE 4.—*Rate of change of the platform height for various gels*

Sample [a]	*d* (scale reading)/*dt*		Gel strength
	Number/min	*mm/min*	*g/cm²*
Cornstarch	[b] 0.003	0.15	208
Wheat starch	.004	.20	162
Wheat flour	.010	.50	60
Sweet potato starch	04	2.0	32
Maine potato starch	.05	2.5	25
Idaho potato starch	.4	20	4
Waxy cornstarch	[c] .9	[c] 45	0
Cornstarch NH_4Cl	.003	0.15	154
Cornstarch $ZnCl_2$	.006	.30	102
Cornstarch at 54° C	.004	.20	156

[a] All gels contained 20 g of undried starch per 148 ml of paste except the ones made with potato starches, which contained 12.94 to 13.11 g per 148 ml of paste.

[b] A value of 0.02 on the scale equalled 1.0 mm.

[c] Estimated value; the slope may be infinite as the gel strength was practically zero.

given for the various samples plotted in figure 3. It may be seen that gels having the same strength do not always have the same slope, or the same resistance to deformation.

III. Standardization of the Method

In the foregoing, certain variables were assigned arbitrary values. Obviously, the rate at which the mercury is added, the diameter of the disk, the depth of disk immersion, the time of heating and aging of the gels, and the heating container must be standardized.

In table 5 data are given for various flow-rates obtained with a disk having a diameter of 1.9 cm and embedded 3.8 cm in the gels. Higher values of gel strength are obtained by using higher flow-rates, because the gels have not had sufficient time between successive additions of mercury to adjust to the strains imposed on them. A higher flow-rate, although requiring less time for each measurement, makes less accurate the reading of the scale of the adjustable platform and introduces a larger end-point error. Usually, the stopcock of the burette cannot be closed at the instant the disk is pulled from the gel. Therefore, some mercury is delivered after the disk has been separated from the gel. Experience has shown that the stopcock can be closed within 2 to 3 seconds after the disk has been pulled from the gel. This is equivalent to an error of 0.5 to 0.8 g in total weight of mercury for a flow-rate of 16 g of mercury per minute. Corresponding end-point errors for other flow-rates are given in the last column of table 5. A flow-rate of 16 or 17.1 g of mercury per minute was found to be the most convenient, and either may be used as the standard. The former was used for all data already presented; the latter value is used for all subsequent data.

TABLE 5.—*The effect of flow-rate of mercury on the measurement of gel strength*

Flow-rate	Weight of mercury required to pull disks from gels	Gel strength	End-point error
A, 8.8 G OF DRY CORNSTARCH PER 100 ML OF PASTE			
Minute	*g*	*g/cm²*	*g*
8.0	340	119	0.3 to 0.4
16.0	362	127	.5 to .8
17.1	364	128	.6 to .9
43.0	386	135	1.4 to 2.2
92	428	150	3.1 to 4.6
170	452	159	5.7 to 8.5
B, 5.9 G OF DRY CORNSTARCH PER 100 ML OF PASTE			
7.0	159	56	0.2 to 0.4
16.0	177	62	.5 to .8
17.1	178	63	.6 to .9
43.0	204	72	1.4 to 2.2

Data are given in table 6 showing the effect of heating time on the pastes. As no change was observed in gel strength after 15 minutes, this time of heating was chosen as standard.

TABLE 6.—*Effect of time of heating of gels on the measurement of gel strength*

Sample	Weight of dry sample per 100 ml of paste	Time of heating	Weight of mercury required to pull disk from gels	Gel strength
	g	*Minute*	*g*	*g/cm²*
Cornstarch	5.7	6	44.5	16
	5.7	15	161	57
	5.7	30	172	60
	11.8	4	473	166
	11.8	6	588	206
	11.8	10	594	208
	11.8	15	592	208
	11.8	30	588	206
Wheat starch	5.8	6	22	8
	5.8	15	141	49
	5.8	30	139	48

Data obtained with different sizes of disks embedded various depths in Amaizo cornstarch gels are given in table 7. It was found that the concentrated pastes could not be prepared in beakers and then transferred to other containers. Therefore, the procedure of preparing the gels was changed. The pastes were prepared and heated in standard Pyrex 150-ml beakers (diameter=5.2 cm), disks were inserted to a known depth, and tests of the strengths made of the gels in the standard beakers. Metal containers had the disadvantage of being either expensive or easily corroded.

The weight of mercury required to fracture the gels approaches a constant value with an increase in the depth of immersion and more rapidly the smaller the diameter of the disk. It would be convenient, therefore, to have some means by which data obtained with different sizes of disks embedded various depths may be correlated. For rigid materials, like concrete or steel, the

TABLE 7.—*Data showing the effects of the diameter of the disk and the depth of immersion of the disk on the load required to fracture Amaizo cornstarch gels at 25° C*

Weight of starch	Weight of water	Weight of dry starch per 100 ml [a]	Height, in cm											
			1			2			3			4		
			Diameter, in cm											
			1.9	0.95	0.64	1.9	0.95	0.64	1.9	0.95	0.64	1.9	0.95	0.64
g	*g*	*g*	*g*	*g*	*g*	*g*	*g*	*g*	*g*	*g*	*g*	*g*	*g*	*g*
5	104.5	4.1	5	0	0	9	0	0	10	5	0	19	6	0
7	103.2	5.7	17	10	5	42	15	10	48	20	11	84	24	12
10	101.2	8.2	50	21	14	103	40	24	143	50	28	178	60	28
12	99.8	9.7	85	41	24	166	63	37	223	88	42	292	95	44
15	97.8	12.1	148	67	38	267	108	63	360	131	70	471	140	75
18	95.8	14.7	217	103	61	395	156	89	555	197	105	673	213	108
20	94.5	16.2	260	127	75	493	210	110	678	243	127	827	268	129
25	91.2	20.3	377	185	112	743	296	162	989	364	183	----	399	197
30	87.8	24.4	540	258	151	999	420	229	----	505	256	----	550	261
35	84.5	28.5	690	328	200	----	537	291	----	649	326	----	714	340
40	81.2	32.5	904	428	257	----	693	376	----	822	423	----	915	445
45	77.8	36.5	----	571	371	----	930	510	----	----	587	----	----	610
50	74.5	40.6	----	723	462	----	----	642	----	----	751	----	----	807
55	71.2	44.7	----	----	560	----	----	----	----	----	----	----	----	----

[a] Moisture content of Amaizo cornstarch=12.4 percent.

surface of shear would be given by a column having a circumference equal to that of the disk and a height equal to the depth of penetration of the disk. For gels, however, the column is not a true cylinder but is somewhat conical with a height empirically found in this work to be proportional to the radius of the disk. Therefore, gel strength is given by

$$\text{Gel strength}=\frac{\text{load}}{(2\pi r)(kr)}\ g/cm^2, \qquad (1)$$

where k is the proportionality constant, and kr would be the effective height of the surface of shear. Only when $k=0.5$ is the area of the surface of shear equal to that of the disk. Hence only for this special case may gel strength be defined in the customary manner as the load divided by area of the disk. The data of table 7 show that the weight varies exponentially with the depth and more rapidly the smaller the diameter of the disk. Therefore, the proportionality constant, k, varies exponentially, and its variation may be expressed by

$$k=0.5[1-e^{-\alpha(h/r)^n}], \qquad (2)$$

where h is the depth of immersion and α and n are empirical constants. For plastic materials, n is equal to 2. Values of α and n were chosen to give the best fit with the experimental data. They were found to be, respectively, 0.24 and 1.1. Consequently, for correlation of data, gel strength may be calculated by the equation

$$\text{Gel strength}=\frac{\text{load}}{\pi r^2(1-e^{-0.24(h/r)^{1.1}})}\ g/cm^2. \qquad (3)$$

Values calculated by this equation are independent of the diameter of the disks or their depth of immersion, but are for a designated flow-rate, in this case 17.1 g of mercury per minute. In table 8, data are given for the gel strength of cornstarch calculated by eq 3. As contrasted with the data of table 7, these data show the validity of the generalized equation. The fit is best in the intermediate range of concentration, is fair for dilute gels where the value of the load is low, and fair for the most concentrated gel where in each case the precision of the method is less. It was found that this equation with the same numerical constants also applied to other varieties of starches. For the sake of brevity these data are not included.

For convenience, instead of using various sizes of disks and depths of immersions, standard values of the diameter of the disk and its depth of immersion may be chosen. Then the quantity in the parenthesis of eq 3 is a constant. A diameter of 0.95 cm (⅜ in.) and a depth of immersion of 2 cm were chosen as standard because of experimental convenience. Larger diameters or greater depths require longer time for the individual experiments, and smaller diameters or smaller depths decrease the precision of the method.

Briefly, therefore, a flow-rate of 17.1 g of mercury per minute, a disk diameter of 0.95 cm, a depth of immersion of 2 cm, a Pyrex glass heating container, a heating period of 15 minutes, and an aging period of 1 day were chosen as the standard conditions. Tests indicated that the strength of gels showed significant changes only after 4 or 5 days of storage.

IV. Applications of the Method

A few applications of the method follow. Various starches may be characterized by their gel

TABLE 8.—*Gel strength of Amaizo cornstarch at 25° C. calculated by the equation*

$$\text{Gel strength} = \frac{\text{load}}{\pi r^2 \left[1 - e^{-0.24(h/r)1.1}\right]} \text{ g/cm}^2$$

Weight of dry starch per 100 ml	Height, in cm												Average	Δ[b]
	1			2			3			4				
	Diameter, in cm													
	1.9	0.95	0.64	1.9	0.95	0.64	1.9	0.95	0.64	1.9	0.95	0.64		
g	*g*	*g*	*g*	*g*	*g*	*g*	*g*	*g*	*g*	*g*	*g*	*g*	*g*	
4.1	8	0	0	8	0	0	6	8	0	10	8	0	4	4
5.7	27	33	27	35	30	38	29	33	37	43	32	38	38	5
8.1	78	70	77	86	80	90	88	84	94	91	82	90	84	6
9.7	133	137	132	139	128	139	137	147	141	149	145	142	137	5
12.1	232	224	210	224	220	237	221	219	234	240	214	242	226	9
14.7	340	345	337	331	318	335	341	330	352	343	339	348	338	7
16.2	408	425	414	413	428	414	416	407	426	[a](422)	416	415	417	6
20.3	591	619	618	622	604	610	[a](607)	610	613	-------	610	634	613	8
24.4	857	864	833	[a](837)	857	863	-------	845	858	-------	842	840	850	10
28.5	1,082	1,098	1,104	-------	1,095	1,096	-------	1,086	1,092	-------	1,092	1,095	1,093	5
32.5	[a](1,418)	1,433	1,418	-------	1,413	1,416	-------	[a](1,375)	1,417	-------	[a](1,414)	1,416	1,413	9
36.5	-------	1,912	2,047	-------	[a](1,897)	1,921	-------	-------	1,967	-------	-------	1,994	1,956	46
40.6	-------	[a](2,421)	2,549	-------	-------	[a](2,417)	-------	-------	(2,516)	-------	-------	[a](2,589)	2,498	64
44.7	-------	-------	[a](3,090)	-------	-------	-------	-------	-------	-------	-------	-------	-------	3,090	-------

[a] Values in parentheses are less precise than the other values.

[b] Arithematical mean deviation; refers to the limits with which the equation reproduces the experimental data and not to the experimental precision.

strength. The amounts of mercury required to pull disks from various starches are given in table 9. The gel strengths of the various starches as calculated by eq 3 are shown plotted in figure 4 as a function of grams of dry starch per 100 ml of paste. The minimum concentration for gel formation differs for the various starches.

TABLE 9.—*Gel strength of various starches at 25° C*

Weight of starch	Weight of water	Weight of mercury							
		Corn	Wheat	Arrowroot	Rice	Cassava	Waxy corn	Defatted corn	Defatted wheat
g	*g*	*g*	*g*	*g*	*g*	*g*	*g*	*g*	*g*
5	104.5	0	0	4	0	0	0	10	------
7	103.2	11	------	------	0	0	0	53	49
10	101.2	22	12	52	9	0	0	150	138
12	99.8	50	------	------	------	------	0	235	215
15	97.8	119	71	80	34	14	0	435	350
20	94.5	264	234	123	85	63	26	625	512
25	91.2	363	372	169	137	76	53	------	750
30	87.8	493	585	256	208	130	92	------	975
37	83.2	661	826	477	330	197	146	------	------
45	77.8	825	------	884	528	293	228	------	------
55	71.2	------	------	------	947	418	322	------	------

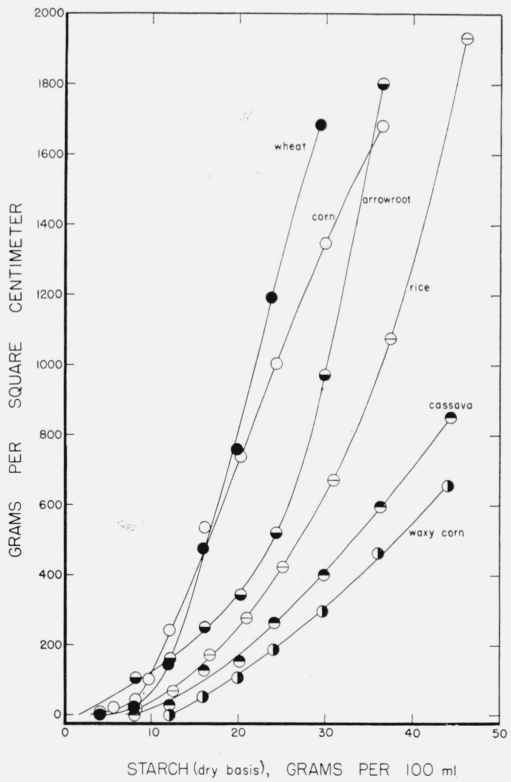

FIGURE 4.—*Gel strength at 25° C of different varieties of starch as a function of concentration*

In figure 5, the scale readings of the various starches are plotted as functions of time (in each case 20 g of starch per 94.5 g of water). This plot shows the difference in the resistance the various starches offer to deformation. In figures 6 and 7 the scale readings are shown plotted with respect to time for various concentrations, respectively, of cornstarch and arrowroot starch. Both types of starch approach the end points rather sharply at all concentrations.

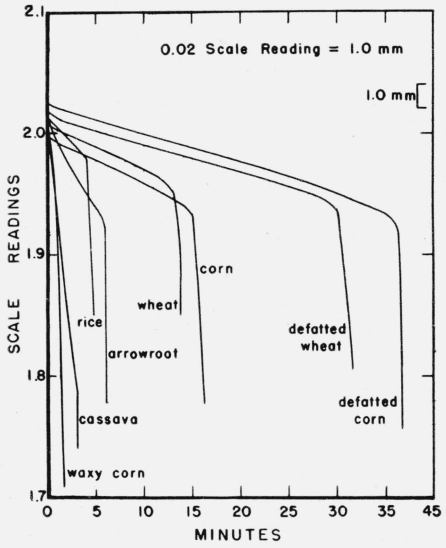

FIGURE 5.—*Scale readings of the adjustable platform as a function of time showing the deformability of different varieties of starch of the same concentration.*

Starches of various types have quite different strengths. There is no exact correlation between gel strength and grain size of the various starches. Rice has the smallest grain size, arrowroot the largest, and the grain size of the other starches is intermediate between these two [13]. Bates, French, and Rundle [14] have shown that wheat, corn, rice, cassava, and waxy-corn starches contain, respectively, 24, 21, 17, 17, and 0 percent of amylose, the straight-chained polymer fraction of starch and the gel-forming constituent. Thus wheat with the highest percentage of amylose has the highest gel strength, and waxy cornstarch with the lowest percentage of amylose has the lowest gel strength. However, the gel strength of rice and cassava starches differ although they both contain 17 percent of amylose. The length of the amylose chain differs in these two types of starch. In any case the relation between gel

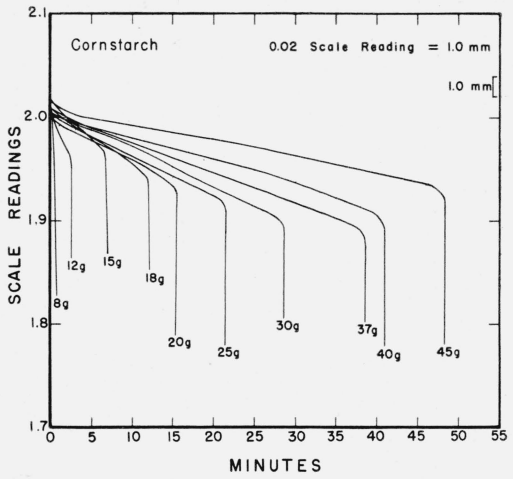

FIGURE 6.—*Scale readings (deformability) of cornstarch gels of various concentrations.*

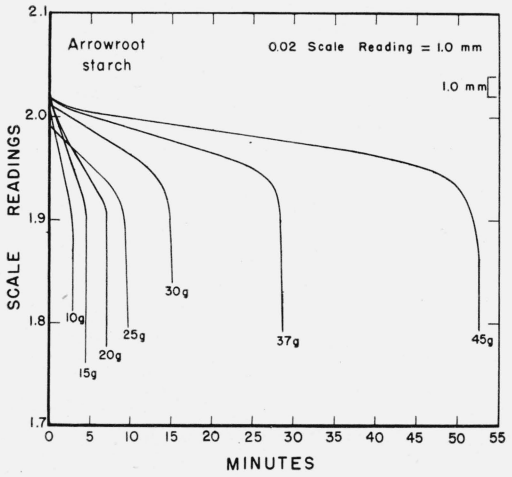

FIGURE 7.—*Scale readings (deformability) of arrowroot-starch gels of various concentrations.*

strength and granular structure is complex. This is even more apparent when it is realized that different varieties of the same type of starch show different gel strengths. In figure 8, a comparison is given of Amaizo and Buffalo cornstarch. These two brands of cornstarch give gels of different strength when they are prepared under identical conditions.

It is well known that fats (oleic, palmitic, linoleic, and linolenic acids) are adsorbed on the surface of the granules of corn and wheat starches. The method described here may be used to see what effect these adsorbed fats have on gel strength. To this end corn and wheat starches were defatted by the methanol method of Schoch [15]

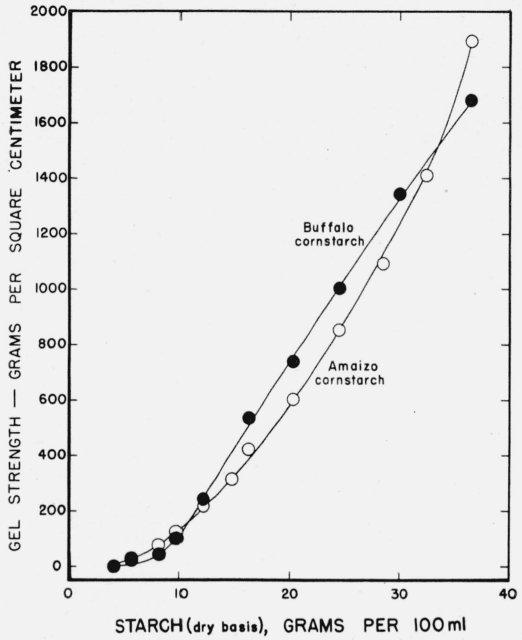

FIGURE 8.—*Comparison of the gel strength of different brands of cornstarch at 25° C.*

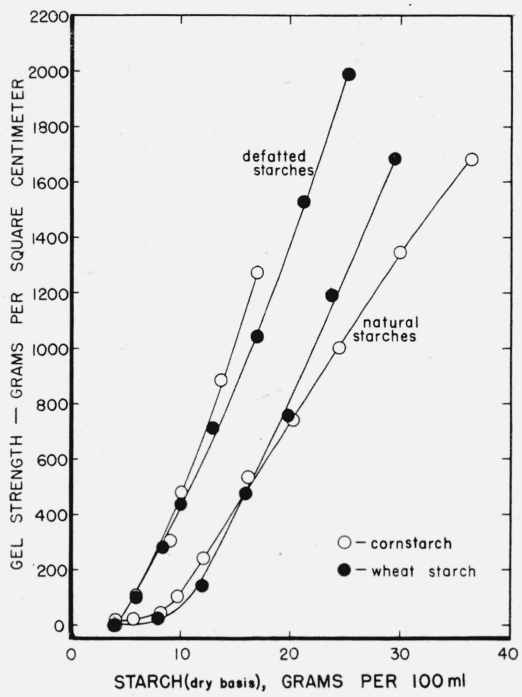

FIGURE 9.—*Comparison of the gel strength at 25° C of natural and defatted starches.*

and gels made with the defatted starches. The data are given in the last 2 columns of table 9. Comparisons of the gel strengths of natural and defatted corn and wheat starches are given in figure 9. The gel strength of each is increased when the fats adsorbed on the starch granules are removed. The granules can then come into closer contact, and there is no fatty film between them. As a consequence, the strength of the gel is increased.

Only sufficient applications have been given to illustrate the precision of the method. It could be used in the study of the modifications of starches for adhesives, of detailed studies of the paste wall of dry cells, of the preparations of starches for foods, and in many other ways. The method is convenient, entails little equipment, and has a precision of better than 0.5 percent. The limitations of the method lie more in the reproducibility with which gels can be prepared than in errors inherent in the method.

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