Effect of Granule Size of Substituted Starches on the Rheological Character of Composite Doughs

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ABSTRACT

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An attempt was made to evaluate the direct effect that particle size of substituted starch in composite dough has on the dough's rheological character. Tensile stress-strain data were measured at four different extension rates on doughs supplemented with starches of distinctly different size characteristics (rice, cassava, wheat, potato and yam—*Dioscorea rotundata* Poir.). Parameters derived from these data were compared with those of doughs prepared from wheat flour/glass powder mixtures. The latter were obtained by mixing wheat flour with glass powder composed of spherical particles in three well-defined size fractions. The particle sizes in these fractions covered approximately the same ranges as those of the starches used in this study. Because of the relatively high uniformity in the water-binding capacity of the fractions, the measured differences between the supplemented doughs could be related directly to the particle size of the substituting glass powder. Although the limited number of data did not allow any conclusive fundamental relationship to be established, particle size was clearly shown to have an effect. Starch-supplemented doughs and those mixed from flour/glass powder mixtures differed in their responses to the particle size of the substitute. This observation indicated that differences in water-binding capacity and some other properties of starches of different plant origins might play a more pronounced role in the development of the physical quality of composite dough than does granule size.

Although the role of starch in dough and baked goods has been well recognized (Hoseney et al 1978, Medcalf and Gilles 1968, Stamberg 1939, Sandsted 1961), the contribution of this major component of wheat flour to the rheological properties of dough still remains a rather unexplored area of study. A deeper interest in the role of starch in dough emerged with the advent of composite flours, when the compatibility of nonwheat starches with wheat flour starch became the subject of many investigations (D'Appolonia and Gilles 1971, Jongh 1961, Lii and Lineback 1977, Rasper et al 1974, Sollars and Rubenthaler 1971). Some of these focused on the relationship between the chemical and physical properties of various starches and their dough-making potential in composite doughs. From analogy with other food systems (Parkinson et al 1970, Sherman 1970), granule size may be expected to contribute significantly to the development of the rheological character of a system in which starch represents the predominant part.

To evaluate this contribution and separate it from other factors is a difficult task. Although some earlier published results show that starch granule size affects the viscoelastic character of dough (Gracza and Greenberg 1963, Ponte et al 1963), no direct conclusions about granule size can be drawn without minimizing or eliminating other factors that depend on the type or size of the starch granule. In studies using starches of different plant origin, differences in hydration capacity, amylolytic susceptibility, and surface interactions with other macromolecules of the system have to be taken into consideration. Some of these factors may vary with the size of the granule, even within the same botanical species (Kulp 1973).

To eliminate interference from factors other than starch granule

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size, mixtures of wheat flour and glass powder fractions of well-defined size characteristics were used in this study. Glass powder was assumed to behave in dough as a chemically inert material. Doughs prepared from these mixtures were subjected to the same rheological tests as were doughs prepared from mixtures of wheat flour and starches varying distinctly in size characteristics, and the results were compared.

MATERIALS AND METHODS

Wheat Flour and Starches

Wheat flour was a commercially milled untreated strong flour (12.82% protein on 14% mb). Starches (potato, wheat, rice, and cassava) were commercial nondefatted thick boiling starches. Potato, wheat, and rice starches were supplied by BDH Chemicals; cassava starch was a product of A. E. Staley Mfg. Co., Decatur, IL. Yam starch was prepared under laboratory conditions (Banks and Greenwood 1975) from tubers of *Dioscorea rotundata* Poir, cv. Puna, grown in Ghana.

Glass Powder

Glass powder size 3,000 (average size, 25 μm), was supplied by Potter's Industries Ltd., (La Prerrie, Quebec). It was fractionated into three size fractions by elutriation in air using an Infrasizer (Haultian 1961) at the Department of Physics and Metallurgy, University of Toronto, Ontario.

Particle Size Analysis of Starches and Glass Powder

Particle size characteristics of starches were determined with a Coulter counter with model M attachment using a 200-μm aperture tube for yam, potato, wheat, and cassava starches and a 100-μm aperture tube for rice starch. The size distribution characteristics of glass powder fractions were obtained from visual analysis of scanning electron micrographs of the individual fractions. The particle size distribution data were evaluated according to Irani and Callis (1963). The specific surface area of starches and glass powder fractions was calculated according to Hellman and Melvin (1950).

Scanning Electron Microscopy (SEM) of Starches, Glass Powder, and Dough

Starches and glass powder were prepared for SEM by coating with a thin layer of carbon (2–5 μm) followed by approximately 20–30 μm of gold. They were examined by means of an ETEC Autoscan at accelerating voltages of 10–20 kV and tilt of 45°.

Starch Damage

An enzymatic method was applied for this test following the standard AACC procedure (1969).

Starch, Flour, and Glass Powder Density

Absolute densities of starches and glass powder required for the calculation of the size distribution data were determined by the xylene replacement method (Schoch and Leach 1964). Bulk densities of flour and flour mixtures were determined with a Scott paint volumeter.

Preparation of Composite Flours

Wheat flour/starch mixtures were prepared by replacing wheat flour dry solids with an equal weight of starch dry solids. With wheat flour/glass powder mixtures, the replacement was on a volume basis because of a considerable difference in the densities of these two materials.

Water Absorption and Retention

Besides farinograph absorption (AACC 1969), water absorption of wheat flour, wheat flour substitutes, and composite mixtures was determined directly using the Baumann capillary apparatus (Baumann 1967). Water retention of these materials was measured as described by Sollars (1973).

Dough Preparation

Wheat flour and flour/starch mixtures were made into dough by mixing with water to maximum development consistency in a 300-g stainless steel farinograph mixing bowl. The constant flour dough method (AACC 1969) was used with addition of 1.5% NaCl. The doughs were prepared in two series: in one, all doughs had the same water content (56.8%) but different maximum development consistencies; in the other, they had different water content and the same maximum development consistency (73.5 kg. cm). Because the doughs were mixed in a farinograph with a strain-gauge recording system, the consistency was reported in units of torque.

The wheat flour/glass powder doughs were mixed in a standard Brabender farinograph with 50-g stainless steel mixing bowl. Again, the two series of doughs were prepared from each mixture.

Testing Doughs for Tensile Properties

Doughs were tested in simple tensile mode at four extension rates ($\lambda = 0.44, 0.22, 0.12$, and $0.04\ s^{-1}$), using the method described by Rasper (1975). The stress-strain curves obtained with a special crosshead attachment for the Instron Universal Tester were evaluated in terms of constant strain rate isochronal modulus, $F(t^*)$, for an arbitrarily chosen time of extension ($t^* = 0.1$ min). They were also evaluated in terms of the exponent n, which, under the conditions of the test, should indicate the balance between the elastic and viscous response of the tested material. For the evaluation of stress-strain curves in terms of these two parameters, a procedure described in detail by Tschoegl et al (1970) was applied. For an easier comparison of the stress-strain relationships, each

TABLE I
Starch Granule Size Characteristics

Origin of Starch	Geometric Mean (μm)	Geometric Standard Deviation	Density ($g.ml^{-1}$)	Approximate Number of Granules in 1 g of Starch (10^{-8})	Approximate Specific Surface Area of Starch Granules ($cm^2.g^{-1}$)
Rice	6.82	1.30	1.497	39.28	6,792
Cassava	16.75	1.76	1.528	2.65	4,427
Potato	24.46	1.95	1.583	0.85	3,898
Yam (*Dioscorea rotundata* Poir.)	34.35	1.57	1.508	0.39	2,189
	Size Classes (μm)			**Approximate Number of Granules in 1 g Starch (%)**	**Approximate Specific Surface Area of Classes ($cm^2.g^{-1}$)**
Wheat	<7.5	···	···	1.83	3,026
	7.5–15	···	···	0.19	418
	>15	···	···	0.38	772
Wheat Total	···	···	1.536	2.40	4,216

family of four stress-strain curves obtained at four extension rates was transformed into a deformation curve for an arbitrarily chosen value of stress (Prihoda and Bushuk 1971).

Stress Relaxation Tests

The Instron Universal Tester with the same crosshead attachment as used in the stress-strain studies was used for stress relaxation tests with crosshead speed set to 50 $cm.min^{-1}$. The crosshead was stopped when a tensile load of 10 g was reached; the dough was allowed to relax at the same deformation and the decay of the tensile load was recorded. In addition to tests performed after reaching a constant tensile load, tests were also run after the same elongation (120%) was reached by all doughs. In both cases, relaxation time was defined as the time required for 36.7% relaxation of the maximum load at the beginning of the relaxation period.

Measuring Ultimate Properties

The ultimate properties of the tested doughs were evaluated graphically in the form of "failure envelopes" resulting from a double logarithmic plot of break stress values, σ_b, against break strain, $(\lambda - 1)_b$, measured at four extension rates (Smith 1963).

RESULTS AND DISCUSSION

Particle Size, Water Absorption, and Retention Capacities of the Tested Materials

Particle size characteristics of starches used as partial substitutes for wheat flour in the tested composite mixtures are summarized in Table I. The SEM micrographs of these starches are presented in Fig. 1.

The particle size distribution curves of the three size fractions of glass powder separated by elutriation are shown in Fig. 2. Fraction A ($M_g = 12.59 \pm 1.41$ μm) and fraction C ($M_g = 48.09 \pm 1.11$ μm) were both characterized by a very narrow particle size distribution range. The medium fraction (B) had a bimodal size distribution with peak values of 12.3 and 29.5 μm. The ideally spherical shape of the particles and the differences between the fractions with respect to their particle size distribution are evident from SEM micrographs (Fig. 3).

Because the physical quality of dough largely depends on the amount of water and its distribution in the form of bound and free water (Bushuk 1966), the water absorption and retention capacities of the substitutes were evaluated before rheological testing of the composite mixtures was started.

Although the starches used in this study differed noticeably in their water absorption and retention capacities, no unambiguous relationship was found between the measured values and the specific surface area of the individual starches (Table II). The varying degree of starch damage might have a considerable effect on these measurements.

In spite of a significant difference in the surface area of the individual glass powder fractions, their water absorption values covered a narrow range, which was more or less within the range of experimental error (Table III). Particle size had a more distinct effect on the water retention values; the finest fraction was characterized by the lowest water retention capacity under the conditions of the test. This relationship indicated that water retained by this type of material after centrifuging was primarily held by capillary forces in the interspace between the spherical

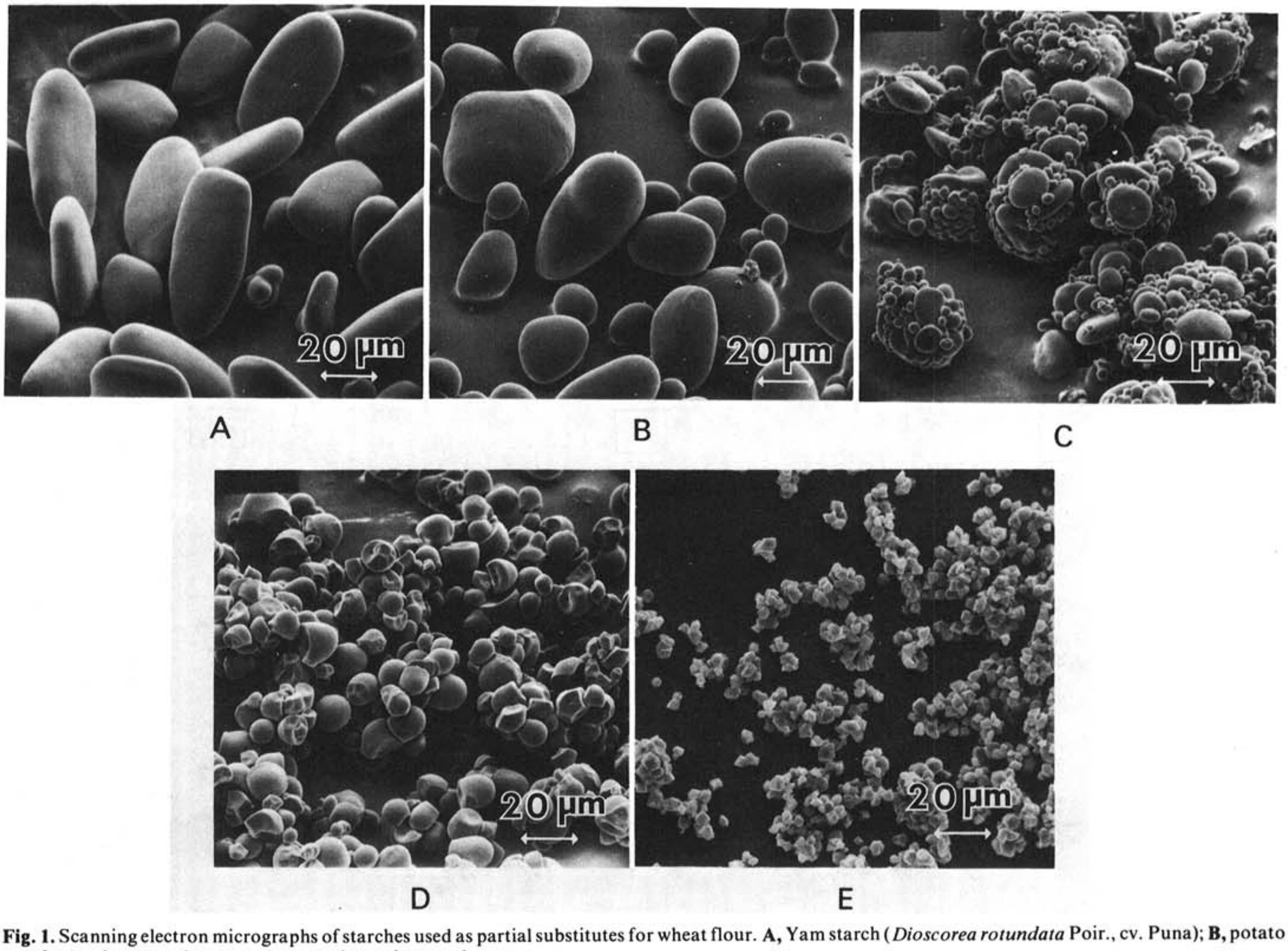

Fig. 1. Scanning electron micrographs of starches used as partial substitutes for wheat flour. **A,** Yam starch (*Dioscorea rotundata* Poir., cv. Puna); **B,** potato starch; **C,** wheat starch; **D,** cassava starch; **E,** rice starch.

particles. Finer particles formed a more compact mass, and less water was retained.

The way that the water absorption and retention capacities of flour/starch mixtures responded to increasing concentrations of added starch is demonstrated by the curves shown in Fig. 4. As expected, replacing flour with starch resulted in a lower water-binding capacity of the mixture compared with that of the original flour. This reduction was observed unless the replacement exceeded approximately 30%. Beyond this point, the water absorption and retention values displayed a tendency to increase with increasing concentration of starch in the mixture. The order in which individual starches affected the water-binding capacity of the test mixtures was not identical to that in which pure starches were ranked for water-binding potential.

The water absorption values of flour/glass powder mixtures correlated positively with the absorption values of the glass powder fractions in the respective mixtures (Table III). No such correlation was found for water retention values, however.

TABLE II
Water Absorption and Retention Characteristics[a] and Degree of Physical Damage[a] of Undefatted Starches Used in the Preparation of Wheat Flour/Starch Mixtures

Starch	Approximate Specific Surface Area of Granules ($cm^2.g^{-1}$)	Damage (%)	Water Absorption (%)	Water Retention (%)
Rice	6.8×10^3	1.03	92.0	87.6
Cassava	4.4×10^3	0.31	81.8	79.3
Wheat	4.2×10^3	3.38	99.2	87.5
Potato	3.9×10^3	0.41	109.7	102.1
Yam (*Dioscorea rotundata* Poir.)	2.2×10^3	0.58	126.2	104.9

[a]Dry solids basis.

TABLE III
Water Absorption and Retention Characteristics of Fractionated Glass Powder and Wheat Flour/Glass Powder Mixtures

Sample	Glass Powder Size Fraction[a]	Water Absorption (%)	Water Retention (%)	Loose Bulk Density[b] ($g.ml^{-1}$)
Glass powder	Small	29.0	25.9	1.3338
	Medium	31.5	27.4	1.4483
	Large	30.0	30.4	1.5243
Wheat flour + 20% glass powder	Small	87.0	60.5	0.8195
	Medium	90.4	57.7	0.7796
	Large	89.6	56.6	0.8236
Wheat flour + 10% glass powder	Small	96.7	66.8	0.7682
	Medium	103.0	68.6	0.7570
	Large	101.3	68.7	0.7789

[a]Size ranges of fractions, in micrometers: small, < 30; medium, 5–40; large, 30–60.
[b]The loose bulk density of flour was 0.6811 $g.ml^{-1}$.

Farinograph Characteristics

The relationship between farinograph absorption and starch concentration in flour or flour/starch mixture has been recognized since the early days of farinograph studies (Markley 1938, Stamberg 1939). Farinograph absorption decreases with increasing starch content in dough until a minimum is reached. Beyond this minimum, further addition of starch results in a progressive increase in farinograph absorption. This behavior has been attributed to changes in both the actual absorption capacity and the rheological character of the system. The increase in farinograph absorption at high starch content in dough has been described as a rheological phenomenon resulting from both the increase in surface area of the dispersed starch phase and the dilution of the

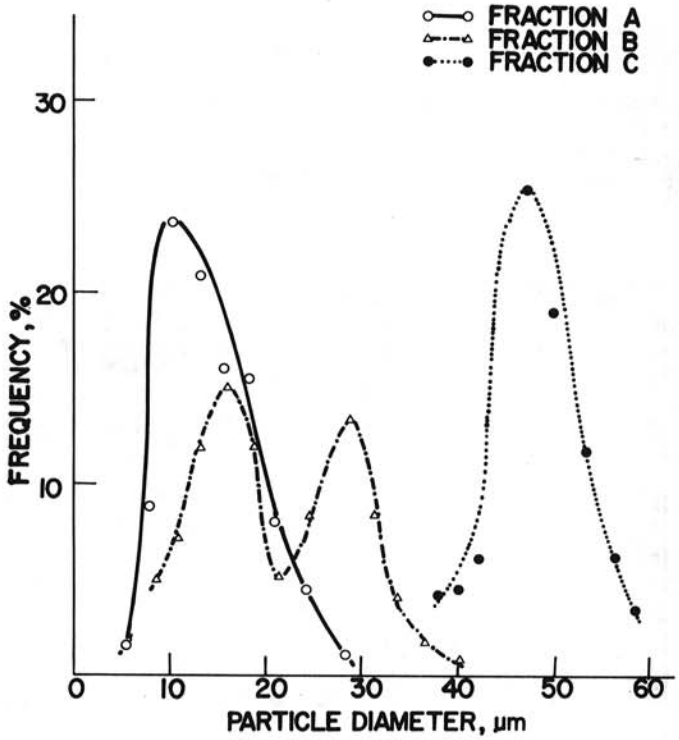

Fig. 2. Particle size distribution characteristics of glass powder fractions prepared by elutriation in air.

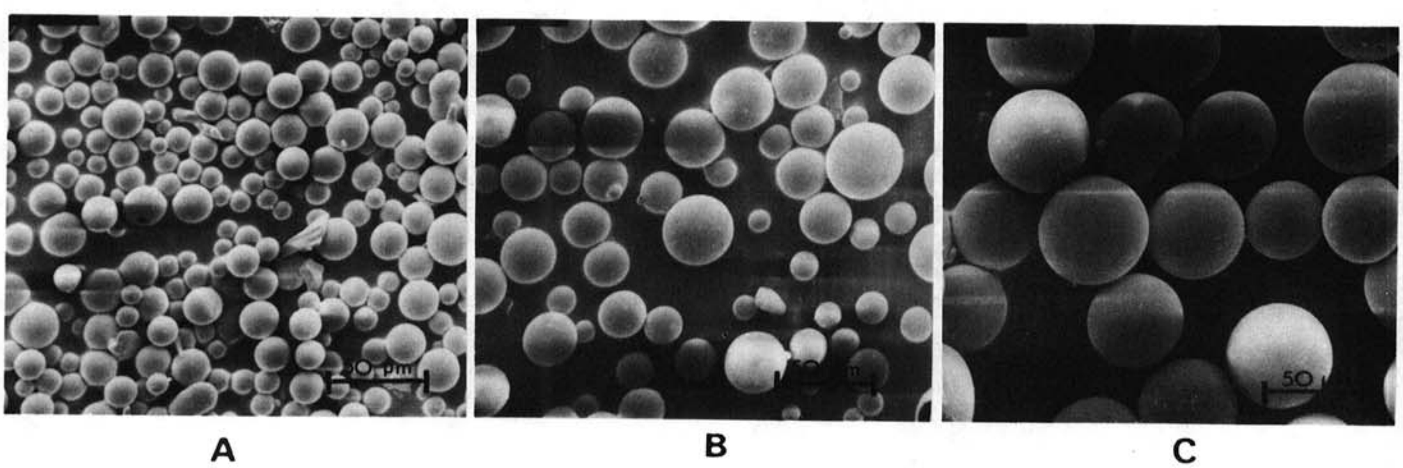

Fig. 3. Scanning electron micrographs of glass powder fractions prepared by elutriation in air.

continuous gluten phase. The part played by the surface area of the starch phase was evidenced by the finding that the critical dilution of gluten at which the minimum occurs is dependent on the average diameter of the starch granules in the mixture (Stamberg 1939).

Figure 5 shows the changes in farinograph absorption of tested flour/starch mixtures with increasing concentration of added starch in doughs mixed to 500 BU maximum development consistency without NaCl. With mixtures containing wheat and potato starch, farinograph absorption decreased steadily and no minimum was reached even at replacement levels of 40% (7.69% protein in the mixture). With mixtures containing cassava starch, the trend in the absorption vs starch concentration relationship reversed when the concentration of added starch exceeded approximately 30% (8.97% protein in the mixture), whereas the addition of rice starch resulted in an increased farinograph absorption even at the lowest replacement level (10% added starch).

The pattern established for unsalted mixtures changed when the same mixtures were mixed into doughs containing 1.5% NaCl. (The doughs were later used for testing in simple tensile mode.) With the exception of flour/rice starch mixtures, doughs mixed to a constant consistency of 73.5 kg.cm showed steadily decreasing farinograph absorption with increasing concentration of starch, and no inflection point appeared on any of the curves shown in Fig. 6, top. Under these conditions, the magnitude of the changes in farinograph absorption caused by added starch was closely related to the specific surface area of the added starch granules.

When the doughs were prepared with constant water content, the changes (Fig. 6, bottom) in maximum development consistency showed a trend similar to the changes in farinograph absorption

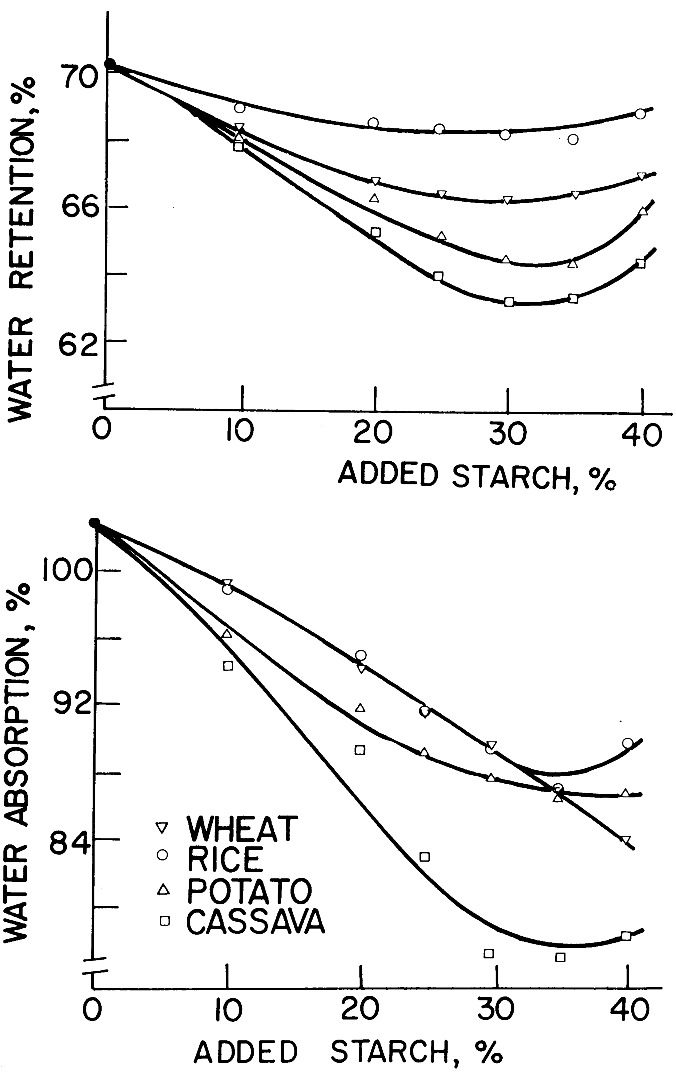

Fig. 4. Water-binding capacities of composite flour/starch mixtures.

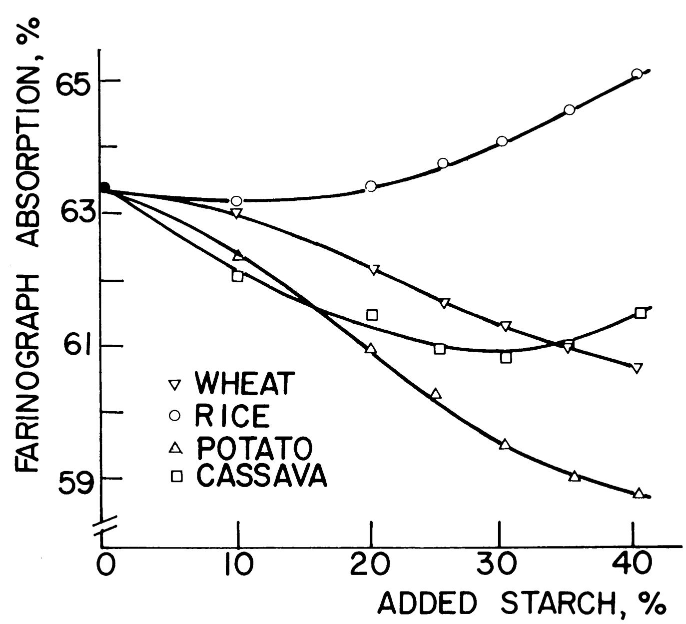

Fig. 5. Relationship between the farinograph absorption and added starch concentration of the composite mixtures. All doughs mixed, without NaCl, to 500 BU maximum development consistency.

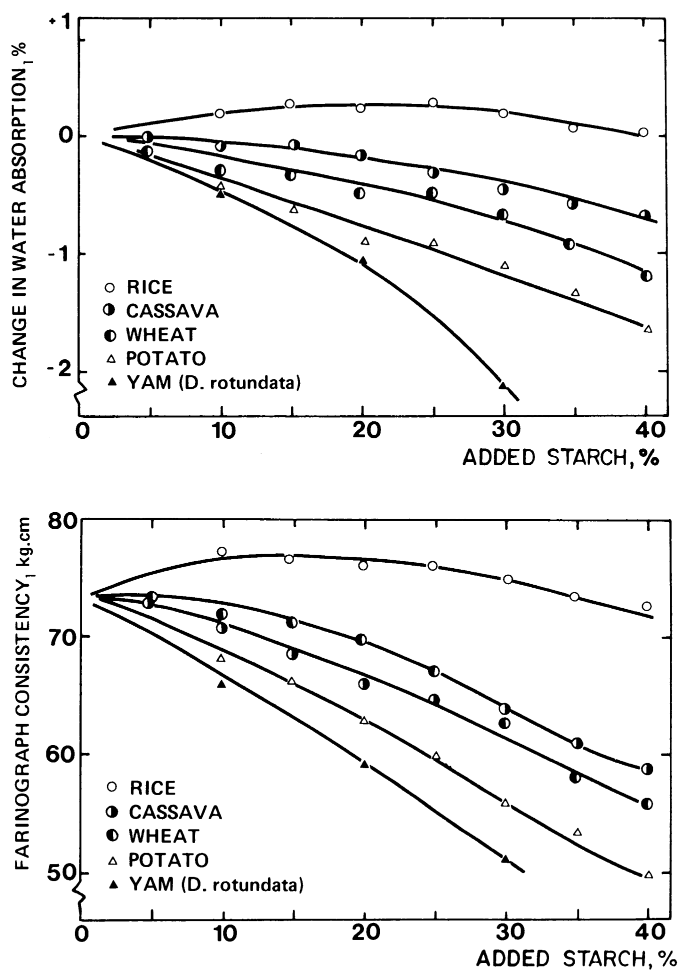

Fig. 6. Top, changes in farinograph absorption with increasing concentration of starch in composite mixtures. All doughs mixed to the same maximum development consistency (torque = 73.5 kg.cm) and containing 1.5% NaCl. **Bottom,** changes in the maximum development consistency with increasing concentration of starch in composite mixtures. All doughs prepared with constant water content (56.8%) and containing 1.5% NaCl.

under conditions of constant consistency. This was in agreement with the well-established fact that farinograph absorption is dependent not only on the water-binding capacity but also on the inherent rheological nature of the tested material, so that a separation of these two contributions is practically impossible.

Evaluation of Stress-Strain Relationships

To save space, only stress-strain curves obtained for doughs prepared from wheat flour/glass powder mixtures are presented as examples of four curve families that were further used for transformation into parameters more suitable for comparing the rheological quality of the individual doughs (Fig. 7).

Transformation of Tensile Stress-Strain Curves into Deformation Curves

Each family of four stress-strain curves, from four extension rates, was transformed into deformation curves for two arbitrarily chosen values of true stress, $\lambda\sigma$, (4.0 and 6.4 $kg.cm^{-1}.s^{-2}$ for flour and flour/starch mixtures; 7.9 and 12.6 $kg.cm^{-1}.s^{-2}$ for flour/glass powder mixtures).

The distribution of the deformation curves for flour/starch doughs prepared under the conditions of constant water content, ie, varying maximum development consistency (Fig. 8), seemed to be indirectly but closely related to the corresponding farinograph consistencies of the individual doughs. However, when the doughs were mixed to the same maximum development consistency (Fig. 9), the deformation curves of all supplemented doughs appeared almost identical, regardless of the adjustments of the water content, unless the concentration of added starch reached approximately 30%. Above this point, a distinct separation of the curves was observed. Doughs supplemented with rice starch were closest to the control, whereas doughs supplemented with potato starch differed from it most markedly and had the lowest deformations at the chosen values of true stress.

Unlike flour/starch mixtures, the mixtures supplemented with glass powder fractions yielded deformation curves following the same pattern regardless of the method of dough preparation (Figs. 10 and 11). Under conditions of both constant water content in the dough and constant maximum development consistency, dough containing the coarsest fraction required the least deformation to develop the arbitrarily chosen values of true stress. Dough containing the finest glass particles was characterized by the highest deformations.

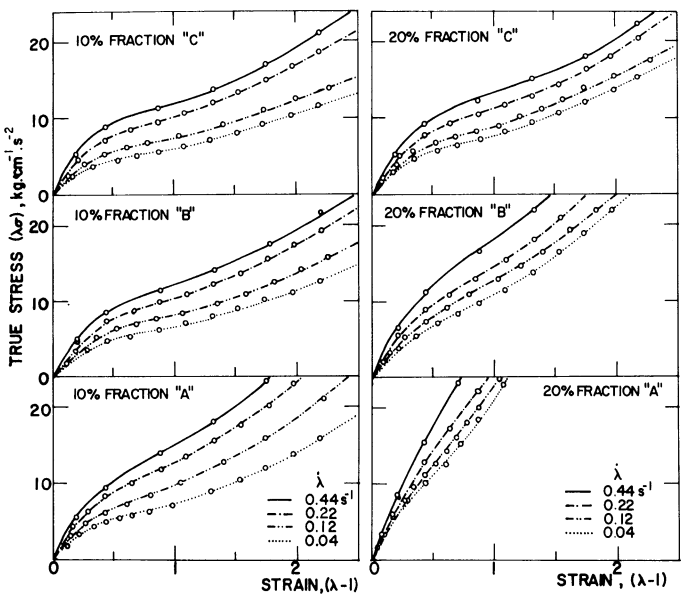

Fig. 7. Stress-strain curves of flour/glass powder doughs obtained at four extension rates ($\dot{\lambda}$). All doughs mixed to constant maximum development consistency (torque = 73.5 kg.cm).

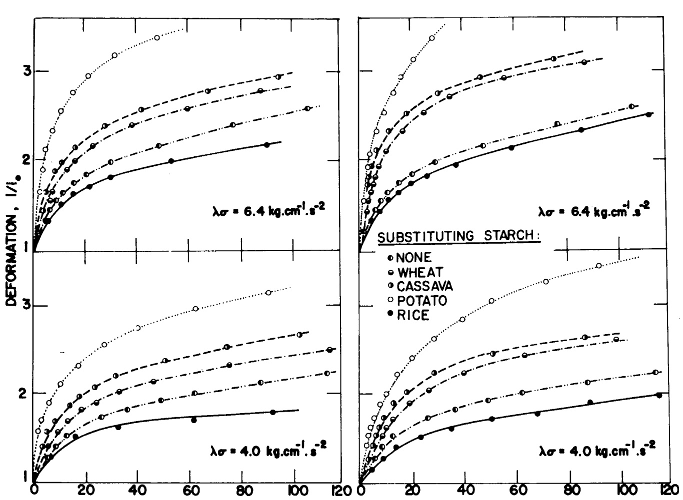

Fig. 8. Deformation curves of starch-supplemented doughs derived from their stress-strain curves obtained at four extension rates. All doughs prepared with constant water content (56.8%). **Left,** 30% replacement level; **right,** 40% replacement level.

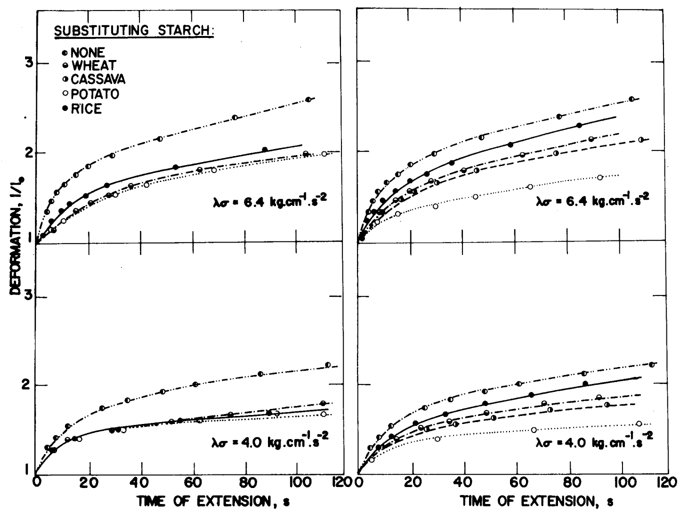

Fig. 9. Deformation curves of starch-supplemented doughs derived from their stress-strain curves obtained at four extension rates. All doughs mixed to constant maximum development consistency (torque = 73.5 kg.cm). **Left,** 30% replacement level; **right,** 40% replacement level.

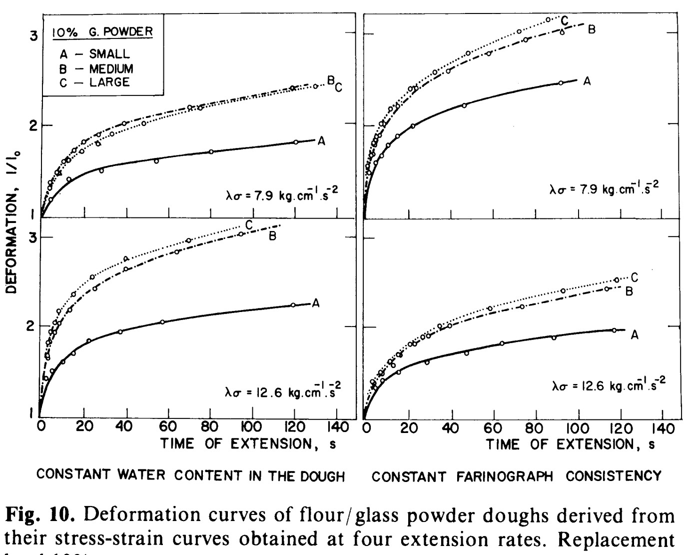

Fig. 10. Deformation curves of flour/glass powder doughs derived from their stress-strain curves obtained at four extension rates. Replacement level 10%.

Evaluation of the Stress-Strain Curves in Terms of Constant Strain Rate Isochronal Modulus F(0.1 min)

The constant strain rate isochronal modulus indicates the stress-strain relationship of the test material at an arbitrarily chosen time of extension. Because the modulus is dependent on the water content of the dough (Tschoegl et al 1970), any changes affecting the water-binding capacity of the system can be expected to be reflected in the value of this rheological parameter.

When the water content of the composite doughs prepared from flour/starch mixtures was adjusted to obtain doughs of the same maximum development consistency, the moduli of the tested doughs remained more or less unchanged until the concentration of added starch in the mixtures reached about 25% (Fig. 12, top). This observation was in agreement with the nature of the deformation curves obtained under the same test conditions. At higher starch concentrations, the moduli increased, and the magnitude of increase for each dough was negatively correlated with the corresponding change in farinograph absorption; dough with the lowest farinograph absorption had the highest modulus and vice versa. However, the relationship between the isochronal modulus and farinograph absorption was more ambiguous when the water content in all doughs was adjusted to the same level (Fig. 12, bottom). Except for the rather exceptional behavior of doughs supplemented with yam starch, the modulus at the lowest supplementation levels (up to 10% added starch) increased slightly. This trend continued for doughs containing rice starch, whereas the moduli of other doughs started to decrease as the concentration of added starch exceeded 10%. Another inflection point appeared on the curve for dough containing cassava starch when added starch reached approximately 30%.

The relationship between the rheological characteristics and the isochronal modulus was even less conclusive when the results obtained with flour/glass powder mixtures were evaluated. The inverse relationship between the isochronal moduli of starch-

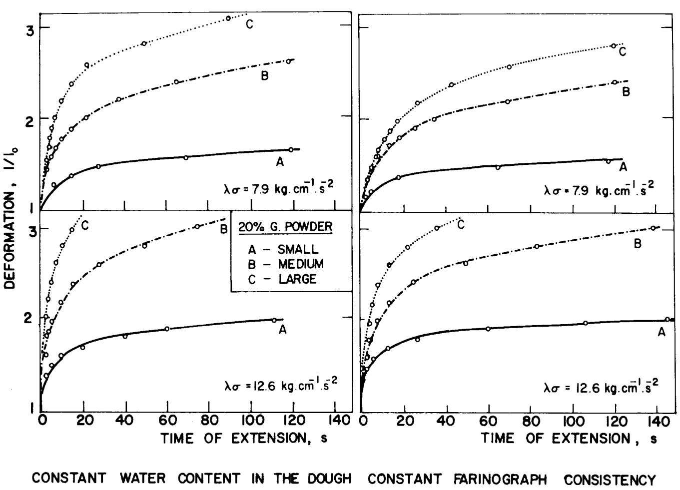

Fig. 11. Deformation curves of flour/glass powder doughs derived from their stress-strain curves obtained at four extension rates. Replacement level 20%.

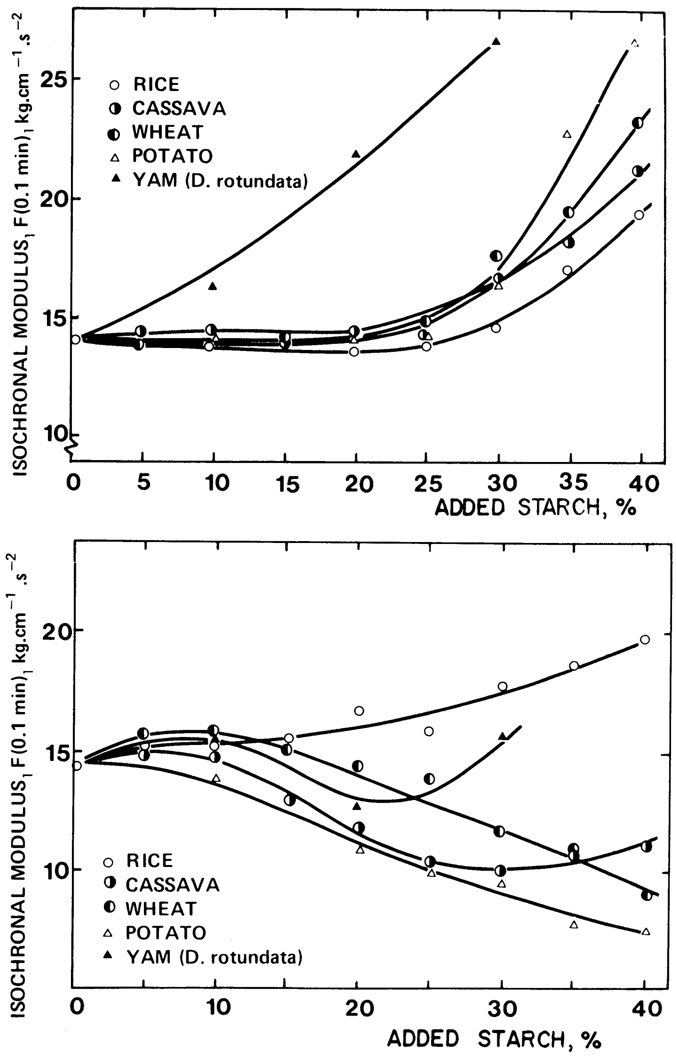

Fig. 12. Changes in isochronal modulus F(0.1 min) with increasing concentration of starch in starch-supplemented doughs prepared by two methods: **top,** dough mixed to constant maximum development consistency; **bottom,** dough prepared with constant water content.

TABLE IV
Rheological Characteristics of Doughs Prepared from Mixtures of Wheat Flour and Fractionated Glass Powder: Doughs Mixed to Same Maximum Development Consistency (520 BU)[a]

Flour/Glass Powder Mixture: Percent Glass in Mixture	Glass Fraction	Farinograph Absorption[b] (%)	Arrival Time[b] (min)	Isochronal Modulus[c] ($kg.cm^{-1}.s^{-2}$)	Exponent *n*	Relaxation Time: Constant Stress[d] (sec)	Relaxation Time: Constant Strain[e] (sec)
10%	Small	66.3	5.5	16.3	−0.32	...	...
	Medium	65.7	4.5	13.9	−0.35	...	...
	Large	64.9	3.0	13.2	−0.37	...	...
20%	Small	61.6	2.5	27.5	−0.17	7.1	7.0
	Medium	59.0	2.5	17.8	−0.295	4.6	6.6
	Large	57.5	2.0	15.2	−0.32	4.0	4.2

[a] With varying amounts of water.
[b] Based on maximum development consistency of 520 BU.
[c] F(0.1 min).
[d] All doughs stretched to reach tensile load of 10 g.
[e] All doughs stretched to 120% elongation.

supplemented doughs and the adjustments in water content required to reach the same maximum development consistency was not found with flour/glass powder doughs. The highest value of isochronal modulus among doughs mixed to the same maximum development consistency was that of dough containing the finest fraction, in spite of its highest water content (Table IV). However, the differences in the water content of these doughs were small enough to attribute the differences in the modulus primarily to the particle size effect of the substituting material. This conclusion was further supported by the similarity in the responses of doughs mixed to the same maximum development consistency and those prepared with constant water content (Table V).

To eliminate the effect of varying water content, the stress-strain relationship was evaluated in terms of a parameter largely independent of the water content of the test material. Tschoegl et al (1970) found such a parameter in the exponent n, which characterizes the time dependence of the time-dependent modulus, F(t), as expressed by the following equation:

$$F(t) = F(t^*) (t/t^*)^n$$

Using this expression, the exponent n may serve as an indicator of the viscoelastic nature of the material; a limit value of 0 would signify a purely elastic material, whereas a purely viscous material would be characterized by the value of −1. Any value between the two limits indicates that the material is both viscous and elastic, and any change in the balance between the viscous and elastic response should be reflected in a shift of the exponent toward one of the limit values. Rasper (1974) has shown that the exponent can be used as a sensitive indicator of the strengthening effect of oxidizing agents in wheat dough.

The measured values of the exponent n for doughs supplemented with starch are summarized in Tables VI and VII.

Evaluation of these data indicates that, with the type of test material used in this study, the exponent n failed to be an indicator of differences in the elastic response. Table VI shows a shift of the exponent toward 0 as the starch content in the doughs increases, with the exception of doughs containing rice starch. According to the formula presented above, this shift should indicate a move closer to the elastic end of the viscoelastic continuum. The doughs, however, did not show any sign of greater elasticity. They would be more appropriately described as "firmer" or more plastic. Doughs with higher starch content are "firmer" than are more tenacious doughs that are richer in protein, even if they are both mixed to the same farinograph consistency. A closer examination of the data of Table VI indicates that the changes in exponent n were directly related to changes in farinograph absorption of the composite mixtures as the concentration of the added starch increased. The same similarity in the response to increasing starch concentration and type of starch became evident when the data of Table VII were compared with curves of Fig. 6, bottom. The dependence of the exponent n on the amount of water in the dough was further confirmed by tests on doughs supplemented with wheat starch and prepared with varying amounts of water (Table VIII).

Like starch-supplemented doughs, the flour/glass powder doughs had exponents n that did not appear to be a true reflection of their viscoelastic character. Unlike starch-supplemented doughs, however, dough containing the substitute with the finest particle size was characterized by the highest value of this exponent regardless of the method of dough preparation (Tables IV and V).

Because wheat dough does not strictly follow the Maxwellian model, characterization of the stress relaxation process by only one value of relaxation time instead of by a relaxation time spectrum may lead to erroneous conclusions (Cunningham and Hlynka 1954). Such data should be considered of only relative value. Relaxation times given in Tables IV and V show a consistent pattern of shorter relaxation times for doughs containing the coarsest glass powder.

TABLE V
Rheological Characteristics of Doughs Prepared from Mixtures of Wheat Flour and Fractionated Glass Powder: Doughs with Same Water Content (61.6)

Flour/Glass Powder Mixture						Relaxation Time	
Percent Glass in Mixture	Glass Fraction	Farinograph Consistency (BU)	Peak Time (min)	Isochronal Modulus[a] ($kg.cm^{-1}.s^{-2}$)	Exponent n	Constant[b] Stress (sec)	Constant[c] Strain (sec)
10%	Small	740	4.0	29.5	−0.24	5.3	5.4
	Medium	710	3.5	26.6	−0.31	4.0	3.5
	Large	670	2.5	18.8	−0.31	3.8	3.5
20%	Small	520	2.5	27.5	−0.17	7.1	7.0
	Medium	470	2.0	14.8	−0.27	4.8	5.6
	Large	410	2.0	10.0	−0.34	4.9	4.6

[a] F(0.1 min).
[b] All doughs stretched to reach tensile load of 10 g.
[c] All doughs stretched to 120% elongation.

TABLE VI
Effect of Increased Concentration of Starches of Different Plant Origin on the Exponent n: Doughs with Constant Farinograph Consistency (73.5 kg.cm)

Concentration of Added Starch (%)	Origin of Starch				
	Rice	Cassava	Wheat	Potatoes	Yam (*D. rotundata*)
0	−0.315	−0.315	−0.315	−0.315	−0.315
5	···	−0.315	−0.300	···	···
10	−0.290	−0.327	−0.315	−0.320	−0.275
15	···	−0.340	−0.315	···	···
20	−0.300	−0.340	−0.300	−0.315	−0.185
25	−0.307	−0.335	−0.305	−0.298	···
30	−0.312	−0.305	−0.300	−0.290	−0.170
35	−0.340	−0.290	−0.275	−0.285	···
40	−0.337	−0.310	−0.255	−0.272	···

TABLE VII
Effect of Increased Concentration of Starches of Different Plant Origin on the Exponent n: Doughs with Constant Water Content (56.8%)

Concentration of Added Starch (%)	Origin of Starch				
	Rice	Cassava	Wheat	Potatoes	Yam (*D. rotundata*)
0	−0.315	−0.315	−0.315	−0.315	−0.315
5	···	−0.315	−0.315	···	···
10	−0.295	−0.300	−0.300	−0.310	−0.310
15	···	−0.305	−0.315	···	···
20	−0.312	−0.320	−0.320	−0.320	−0.322
25	−0.320	−0.320	−0.320	−0.300	···
30	−0.314	−0.325	−0.330	−0.350	−0.221
35	−0.337	−0.335	−0.350	−0.380	···
40	−0.340	−0.360	−0.350	−0.420	···

TABLE VIII
Effect of Changing Water Content on Measured Rheological Characteristics of Doughs Prepared from Wheat Flour/Wheat Starch Mixtures

Added Starch in Mixture (%)	Water Content (%)	Farinograph Consistency (kg.cm)	Isochronal Modulus[a] ($kg.cm^{-1}.s^{-2}$)	Exponent n
35	50.5	71.0	21.0	−0.275
	51.4	69.0	18.6	−0.295
	52.2	67.0	17.8	−0.305
	53.0	65.0	15.8	−0.310
	56.8	58.0	10.7	−0.350
40	49.9	71.0	32.8	−0.255
	50.8	68.5	22.3	−0.265
	53.7	64.0	18.8	−0.280
	56.8	58.0	8.9	−0.340
	...	...	...	...

[a]F(0.1 min).

Ultimate Properties of Tested Doughs

The break stress values, σ_b, and break strain values, $(\lambda - 1)_b$, evaluated in the form of failure envelopes, are presented in Figs. 13–15.

Flour/starch doughs of constant maximum development consistency yielded two distinctly different patterns of failure envelopes (Fig. 13). Doughs containing starch granules with the extreme granule size characteristics (the finest in rice starch and the coarsest in yam starch) produced separate segments of failure envelopes for each flour replacement level. With increasing starch concentration, a marked decrease in break strain but relatively smaller change in break stress resulted. With all other doughs, the points resulting from a double logarithmic plot of break stress vs break strain fell on one line, forming one failure envelope for each series of doughs. The envelopes indicated a distinct decrease in both break stress and break strain with increasing starch concentration.

Doughs of constant water content yielded distinctly separated envelopes for each replacement level without offering any conclusive pattern with respect to the particle size of the substituting starch (Fig. 14).

Flour/glass powder mixtures also yielded separate envelopes for each dough, but the effect of particle size became more evident (Fig. 15). For both series of doughs, break stress noticeably decreased with increasing particle size, and break strain values increased.

CONCLUSIONS

In experiments with starch-supplemented doughs, separation of the direct rheological effect of granule size from factors depending on the type of substituting starch appeared to be a rather difficult task. The use of glass powder instead of starch in composite mixtures made this separation easy enough to permit certain conclusions. Although the parameters derived from the tensile stress-strain curves failed to truly indicate changes in the balance between the viscous and elastic response, the effect of the particle size of the substituting phase on the physical quality of dough became quite evident. The dissimilarities in dough's rheological responses to the particle size of added glass powder on the one hand and to the type of the substituting starch on the other support the conclusion that factors not necessarily directly related to the specific surface area of the granules, factors such as the water-binding capacity of the starch, may play a more pronounced role in the development of the rheological character of dough than does the particle size of the dispersed phase.

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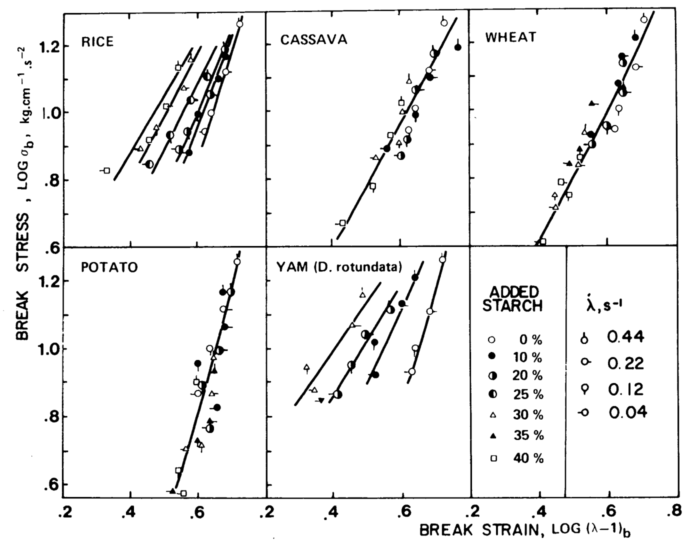

Fig. 13. Failure envelopes of starch-supplemented doughs mixed to the same maximum development consistency (torque = 73.5 kg.cm) and containing 1.5% NaCl.

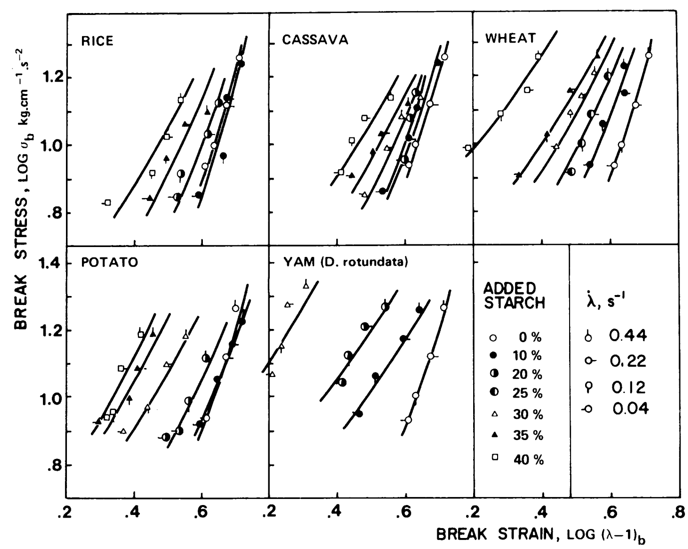

Fig. 14. Failure envelopes of starch-supplemented doughs prepared with constant water content (56.8%) and containing 1.5% NaCl.

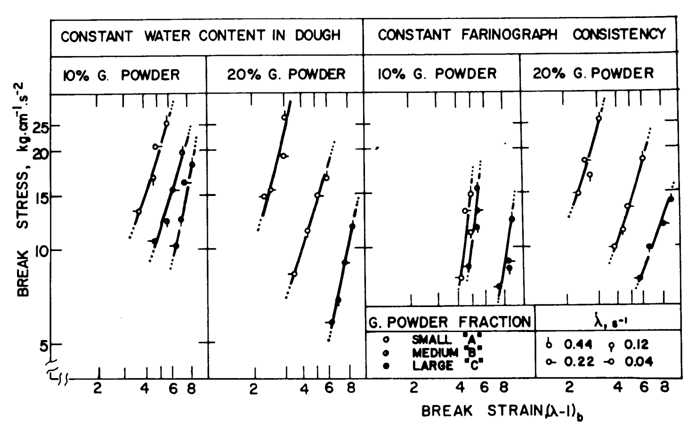

Fig. 15. Failure envelopes of flour/glass powder doughs.

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