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The Effects of Selected Sugars on The Rheological Properties of Rehydrated Vital Gluten[1]

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Solutions of four common sugars, sucrose, maltose, glucose, and fructose were individually mixed with rehydrated vital gluten. The mixtures were then subjected to a standard baking test and to rheological examination. In both instances the addition of sugar significantly altered stress-strain relationships. The viscosity and extensibility of all the mixtures containing sugar were greater than that of the pure gluten. This suggests that the sugars had peptized the gluten and inhibited its thermal coagulation during baking. Significant differences between the action of individual sugars could not be ascertained, however.

A Maxwell model for visoelastic behavior was found to fit the rheological data quite well within experimental limits. Meaningful comparisons between experimentally measured coefficients for viscosity and shear moduli and literature values were difficult because of differences in purity and sources of the gluten. However, the measured elastic moduli were an order of magnitude greater than those reported earlier for gluten in wheat flour doughs. This was attributed to a higher purity of the test gluten and to a better testing technique than had been used heretofore.

When flour is mixed with water in the right proportion a dough is formed. If the dough is then gently kneaded in the hand beneath a slowly flowing stream of water, the starch fraction can be washed away. The remaining portion is a typically ductile, tenacious, and elastic mass called wet gluten.

Gluten is composed primarily of hydrated, insoluble proteins of flour with some entangled starch, lipids, and mineral salts. The amount of these constituents varies with the manipulation in washing, the kind of water used and the characteristics of the flour. Not only do flours of higher total protein content yield larger quantities of gluten, but also the ratio of gluten to nongluten protein is usually larger as the total flour protein content increases. The wet gluten may vary in color, texture, elasticity, extensibility, tensile strength, the volume obtained when baked, and other properties (Bloksma, 1971).

When gluten obtained by the washing technique is shaped into a ball, placed in an oven and baked, it increases in volume several fold. A high oven temperature converts the water to steam and coagulates the protein. The pressure of the expanding gas coupled with the ability of the gluten to stretch and retain gas is responsible for the expansion of the gluten as it bakes. Once the gluten is inflated, the pressure of the steam maintains its volume until heat has had time to set the protein. If the gluten is removed from the oven before it has set, the steam condenses and the inflated gluten will collapse (Dimler, 1963).

The elasticity of gluten is attributed to the coiled and folded protein molecules (peptide chains), while the plastic flow can be explained as imperfect rigidity, due to slipping in the protein molecular arrangement. It has been proposed (Grosskreutz, 1961) that gluten forms a polyplatelet sheet structure (Figure 1) during the hydration period and that these platelets consist of coiled polypeptide chains with their hydrophilic side chains oriented outwards and their
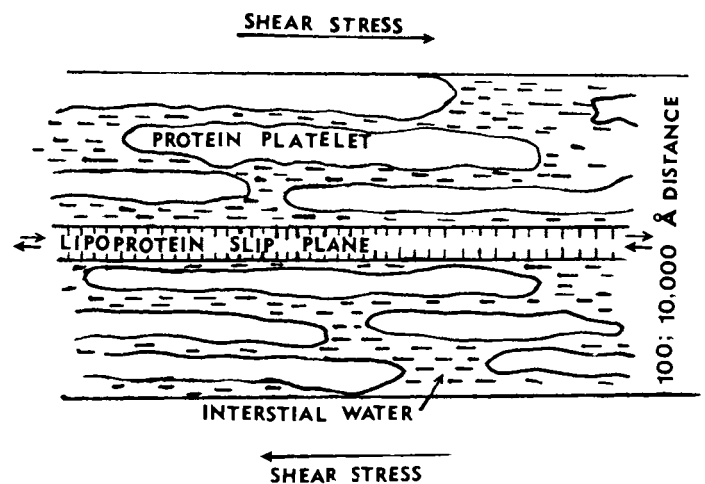
Figure 1. Model of gluten sheet structure proposed by Grosskreutz (1961)

hydrophobic side chains oriented inwards. A small proportion of lipo-protein complex which consists of two or more protein chains bound by phospholipid material present in the form of bimolecular leaflets is also formed. Phospholipids cause gluten to be soft and plastic. The linkage between the lipid and the protein is a salt-like bond between the acidic group of the phospholipid and the basic protein groups. These lipo-protein leaflets occur at random among the protein platelets and interfere with the orderly bonding between the protein platelets. According to Grosskreutz (1961), there is a random weakness throughout the protein structure wherever the phospholipid filling occurs. Therefore an applied stress to the gluten structure will result in the slipping along the interfaces of phospholipid layers before the rupture strength of the interprotein bonds is reached. This gives the plasticflow properties, so important in the gluten complex.

X-ray scattering curves showed the characteristic pattern of platelet structure of gluten, as recorded on photographic films. Electron micrographs taken of surface replicas of freeze-dried stretched gluten confirmed the X-ray finding. It can be seen that too much of the lipid filling would result in a runny gluten, while too little would

give hard and short gluten. The importance of this proposed structure can be seen and it takes little imagination to realize how easily and inevitably the "vitality" of the gluten can be lost in the drying process. Figure 1 is a hypothetical scheme showing a possible structure for a gluten sheet made up of protein platelets and lipoproteins in the appropriate concentration (Grosskreutz, 1961).

Vital gluten is used extensively as an ingredient in yeast-raised baked goods, particularly bread. The effect of introducing gluten into a bread mix is not only to increase the protein content of the finished loaf of bread, but to produce greater volume and better crumb texture. Moreover, the dough yields are increased because there is a greater absorption of water, and the finished loaf has a longer shelf life because of the finer grain and softer texture.

Gluten can be used in macaroni products to give an improved resistance to breakage in the extruded product. An increase in the protein content of spaghetti from 10.8% to 12.7% protein by the addition of "vital" gluten has been reported to increase the breaking strength by 10%. If too much gluten is added, the product becomes too tough (Carlson, 1958, Kasarda, 1971).

Gluten has natural film-making tendencies (Dimler, 1963, Krull, 1971) as exhibited in the film between bubbles in a dough and in bread crumb. Clear pieces of film can be prepared from wheat gluten. Gluten films become brittle and lack the resistance to water that is required for many types of applications. Film properties need to be improved if they are to provide a basis for wheat utilization.

EFFECTS OF SUGAR ON GLUTEN

Gluten is a food constituent that requires hydration for its development. Gluten properties may be markedly changed in the presence of other materials (Barham, 1951, Baxter, 1958). Early work showed that the physical condition of a flour-water dough was noticeably affected by the presence of sucrose. As the concentration of the sugar in the dough increased, dough viscosity decreased. The observed effect of sucrose on the development of gluten has been attributed to the competition for water. In their study, Baxter and Hester (1958) found that the addition of sucrose to soft wheat flour at levels of 15% or 30% of the weight of the flour increased the time required to develop dough in a mixograph. Dough formation was prevented when sucrose was added at the 60 and 120% levels.

Similar results were found by Meiske and co-workers (1960) when the effects of various sugars on the formation of gluten were investigated. The concentrations of sugar used were in increments of 5% based on the flour weight. At the critical levels of 55-65% for fructose, glucose and sucrose, 45% for maltose, and 35-45% for beta-lactose, the amount of gluten recovered by the "washing out" technique was reduced.

RHEOLOGICAL STUDIES OF DOUGH AND GLUTEN

Many of the peculiar rheological properties of doughs were described by Schofield and Scott Blair (1932-1937), some 40 years ago. Generally the results of such tests were interpreted empirically in terms of protein quality. Rarely were measurements made directly on isolated gluten (Heaps, 1968).

Schofield and Scott Blair measured the stress exerted on a small dough cylinder of known radius to produce a permanent elongation of dough. Based on the average readings of the curves, rheological properties of dough were calculated following the formulation of a Maxwell element.

In subsequent studies, Schofield and Scott Blair measured the viscosity and shearing stress on cylinders of unyeasted dough. The dough samples were hung vertically by their upper ends and allowed to extend under the action of gravity (Schofield and Scott Blair, 1932). The deformations were recorded by marking a millimeter scale on the surface of the dough cylinder. They found that viscosity was equal to the product of the rigidity modulus and the relaxation time.

A Jolly balance was used by Udy (1958) to measure the force required to elongate a gluten sample. A linear relationship was found between the stretching force and the relative length for the gluten samples. The gluten became more resistant to stretching after resting.

Halton (1949) determined the modulus and viscosity of doughs from different flours. They found that satisfactory bread dough could be characterized by a high viscosity/modulus quotient (Bloksma, 1971).

Schofield and Scott Blair were the first to establish that flour dough exhibits Maxwellian characteristics, i.e., the viscous flow would be superimposed upon the elasticity. The work of Schofield and Scott Blair further indicated that the "purified" gluten might closely simulate a Maxwell element (Glucklich and Shelef, 1962).

The most common methods of measuring dough properties are static measurements such as creep and stress-relaxation or stress and strain relationships which involve some type of elongation. A wide variety of rheological instruments have been used to assess the quality of wheat flour doughs. Many investigators have obtained data using instruments such as Brabender Farinographs, Extensographs or Chopin Alveographs (Bloksma, 1971). A Farinograph measures the resistance to mixing or the power that is needed for mixing a dough at constant speed. The Brabender Extensograph and the Chopin Alveograph measure the extent to which a properly developed gluten can be extended.

THIS STUDY

The baking performance of flour in any food product is the cumulative product of numerous chemical and physical interactions between the various constituents of the flour and other constituents of the food mixture. These relationships are further complicated by the unsteady state, nonisothermal conditions of baking. No complete characterization of the phenomena has yet been developed. However, studies have provided substantial information concerning the structure of dough prior to the baking process. For example, gluten, the insoluble proteins of grain flour, is known to be responsible for the unique cohesive-elastic properties of dough. This permits wheat flour doughs to be distinguished from those made from other cereal grains (Udy, 1953; Wall, 1971).

While the characteristics of gluten give it a structure-forming role in bakery products, these properties may be altered by the addition of other ingredients to the dough. For example, sugar is frequently added to provide a tenderizing effect in addition to its utilization as a sweetener and as a substrate for yeast. Several studies of the gross effects that sugars have on doughs and gluten have been reported (Barham et al., 1951), (Baxter, et al., 1958), (Meiske, et al., 1960), but very little has been reported which details the effects that sugars have on the rheological properties of gluten. Yet it is the variations in rheological behavior of different wheat flour doughs that has long been recognized as a quality characteristic by the baking industry (Udy, 1953). Therefore, the objectives of this study were to evaluate the effects of four common sugars, sucrose, glucose, fructose, and maltose, on the rheological properties of rehydrated vital gluten. Since a standard baking test had been used to evaluate the quality of crude gluten, the gluten-sugar mixtures used in this study were also subjected to a baking test to provide additional information about the effects of the sugars.

MATERIALS AND METHODS

A commercial vital gluten (sample R) was supplied by General Mills Chemicals, Inc. The gluten was obtained from unbleached flour derived from hard red winter wheat. Salt was added during the washing operation to "toughen" the gluten for handling. The gluten was flash dried. Four sugars: sucrose (Baker's Reagent Grade), maltose (Pfanstiehl Laboratories, Inc.), glucose (CPC, Cerelose), and fructose (Pfanstiehl Laboratories, Inc.) were used. The amount of sugars is expressed as a ratio of sugar to gluten (dry basis). Ratios of sugar to gluten at two different levels, 0.5: 1 and 0.25 : 1, were used. The sugars were dissolved in the water present in the final mixture. Solution of the sugars before addition to the gluten eliminated any effects of the rates of solution of various sugars on the hydration of the gluten.

A series of Teflon mixers (rod-like) was used to mix the samples at known rpm. However, the shearing action in this type of mixing failed to give a homogeneous mass of gluten. Propeller-type mixing rods were also tried, but they, too, did not give satisfactory results. Consequently, a standard procedure for mixing the samples for three minutes by hand manipulation was used for all gluten on which data are reported. Although hand mixing introduced the possibility of greater variability than mechanical mixing, it was the only method tried that yielded the necessary homogeneity.

Five grams of vital gluten were reconstituted with 6.5 ml. of water or sugar solutions of each of the four different sugars at two different ratios. The gluten masses were mixed individually at room temperature. They were then rested for a period of four hours before the baking or testing of rheological properties with the Instron Universal Testing Machine. Gluten mixed with distilled water served as the control.

Quadruplicate gluten balls, each prepared the same way for each sugar level, were baked in a vacuum oven (Hot-Pack) at 130-140°C. The vacuum pump was turned on after the gluten balls had been in the oven for ten minutes. The pressure was maintained at 15 inches of mercury vacuum for 30 minutes, after which it was allowed to rise to 28 inches of mercury vacuum. The gluten balls required three hours of baking at these conditions before the structure set. They were weighed before and after the baking. The baked volume was measured by a standard rapeseed displacement method.

During the development of a satisfactory method of baking, gluten balls with sugar solutions were baked in a home-type gas convection oven. They were baked at 232°C for 15 minutes and then at 149°C for 35 minutes. A microwave oven (Radarange) was used according to the recommendation of the manual for baking popovers. A combination of the affect of regular electric convection and microwave energy (915 megacycles/sec) of a G.E. Versatronic oven (Model J856)'was also used according to the recommendation for baking popovers. Variations of length of time and degree of heat of oven were tried.

MEASUREMENTS OF RHEOLOGICAL PROPERTIES

Total elongation and resistance to deformation of gluten mixed with various sugar solutions or water were measured with an Instron Universal Testing Machine, Model TM (Instron Corporation, 2500 Washington Ave., Canton, Mass.). The rheological properties — apparent viscosity, modulus, stress, and strain-were calculated from the curves obtained. By use of the Instrom and a special holder, a sample of gluten was stretched until ruptured, and a curve of load vs elongation was recorded. From these records, resistance to deformation (stress) and extensibility (strain) were read.

In order to perform the tensile test on the gluten mixtures, a special sample holder was required. Basically, the holder had to absorb the compressive forces of the Instron grips and at the same time prevent the gluten sample from slipping during elongation. It consisted of two identical sections machined from aluminum rod stock 1/2 inch O.D. The critical dimensions are shown in the sectional view in Figure 2.

For testing, the gluten sample was placed in the upper section of the holder and was forced with a brass rod through the central restriction until approximately half was in each the upper and lower section. In theory, the reduction in cross section in the central portion prevents the gluten sample from slipping while the aluminum rods absorb the compression forces of the Instron grips. Testing conditions were: testing machine, Instron Model TM; load cell, ABC; full scale range, 50 lbs; sensitivity, normal; cross-head travel, 0.5 in./min/; Chart drive, 2 in./min.; gage length, 1/4 in.; temp. = 23°C. The machine was calibrated before the testing.

To ascertain whether there is a significant difference between the sugars on gluten balls, a comparison between means were carried out by use of Student's t test.
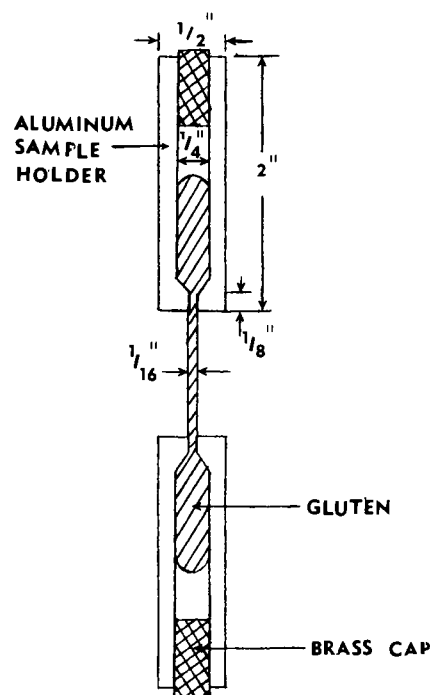

Figure 2. Sectional view of gluten specimen holder with strained gluten

RHEOLOGICAL STUDIES: MAXWELL MODEL

In order to deal quantitatively with the deformation of viscoelastic materials, mathematical models are needed to represent the observed stress-time behavior of the real material. The Maxwell Model was one of the first and simplest mathematical models used to describe the behavior of viscoelastic materials. It assumes that deformation (elongation) under stress will be analogous to that of an ideal Hookean spring and Newtonian dashpot coupled in series (Hanks, 1970). The Maxwell Model was found to be sufficient for these systems within the error limits of the experiment. A mathematical model could be set up to calculate the rheological parameters based on the curves obtained from the Instron Universal Testing Machine.

MATHEMATICAL MODEL FOR MAXWELL APPROXIMATION

If a force F is applied to the ends of the model, then the total deformation (γ_T) will be the sum of the elastic deformation of the spring (γ_e) and the viscous deformation of the dashpot (γ_v).

$$\gamma_T = \gamma_e + \gamma_v \tag{1}$$

Similarly the deformation with respect to time can be written as a differential equation.

$$\frac{d\gamma_T}{dt} = \frac{d\gamma_e}{dt} + \frac{d\gamma_v}{dt} \tag{2}$$

The deformation of a Hookean spring is defined as

$$\gamma_e = \frac{\tau}{G} \tag{3}$$

where τ is the shear stress in the spring, and G is the shear modulus of the spring.

The derivative of (γe) with respect to time, therefore can be written as

$$\frac{d\gamma_e}{dt} = \frac{1}{G} \frac{d\tau}{dt} \tag{4}$$

since G is constant and only τ and γe are time dependent. Correspondingly, the behavior of an ideal Newtonian dashpot is described mathematically as

$$\frac{d\gamma_v}{dt} = \frac{\tau}{\mu} \tag{5}$$

where τ is again the shear stress and μ is the viscosity of the Newtonian fluid in poise.

If equations (4) and (5) are substituted into equation (2), a complete differential equation for deformation with respect to time is obtained.

$$\frac{d\gamma_T}{dt} = \frac{1}{G} \frac{d\tau}{dt} + \frac{\tau}{\mu} \tag{6}$$

By using an Instron, it is possible to actually elongate the sample so that the strain rate $\frac{(d\gamma_T)}{dt}$ is constant. If this is the case, equation (6) can be rewritten as

$$\frac{d\tau}{d\gamma} + \frac{G}{\mu} \tau = GC' \tag{7}$$

where C^1 = constant = $\frac{d\gamma_T}{dt}$ Equation (7) is immediately recognizable as a linear first order differential equation, the solution of which is

$$\tau e^{\int \frac{G}{\mu} dt} = \int GC' e^{\int \frac{G}{\mu} dt} dt + C'' \tag{8}$$

and C'' is the constant or integration.

After performing the necessary integration and noting the boundary condition at time zero;

$$t = 0; \tau = 0$$

the constant C'' is shown to be equal to - C'. Thus equation (8) can be written in the following manner for any time t.

$$\tau e^{\frac{(G)t}{\mu}} = \mu C' e^{\frac{(G)t}{\mu}} - \mu C' \tag{9}$$

Solving equation (9) for τ, the shear stress, and substituting $d\gamma T$ for C', a final working equation is obtained for stress as a function of time.

$$\tau = \mu \frac{d\gamma T}{dt} (1 - e^{-(\frac{G}{\mu})t}) \tag{10}$$

Equation (10) predicts that for a constant strain rate the shear stress τ will be constant after a sufficient long time, t, i.e.

$$\tau = \mu \frac{d\gamma T}{dt} = \text{Constant; for constant } \frac{d\gamma T}{dt}$$

and t, large.

Thus, if τ and $\frac{d\gamma T}{dt}$ are known, the viscosity μ can be easily calculated. Moreover, it is a relatively simple procedure to calculate G, the shear modulus, from the slope of the stress-strain curve. Thus, if μ, G, and dt are known or can be measured, then the state of stress as a function of time can be predicted at will. This would be an invaluable tool if indeed mixtures of vital gluten behaved in this manner.

DISCUSSION AND RESULTS

Comparison of Glucose, Fructose, Sucrose, and Maltose in Baking

Figure 3 shows the effect of various sugars on the expansion of gluten when heated. All the sugars caused an increase in the volume of baked gluten balls. Moreover, if the baked gluten balls containing the same level of sugar are considered as one group, then the average volumes of 325 ml. and 210 ml. for weight ratios of 0.5 : 1 and 0.25 : 1 respectively, were found to be significantly different (P < 0.01) from those gluten balls containing no sugar, 83 ml. (Table 1).

Analysis of the effect of the individual sugars on the volume of gluten balls showed no significant difference at the higher sugar level. At the lower level, no significant difference was found between sucrose, glucose, and fructose, but maltose caused the volume of the gluten balls to be smaller than those containing the other sugars, the difference being significant at P< 0.05. None of the sugars at the test levels of addition had a deletrious effect on the volume of gluten balls.
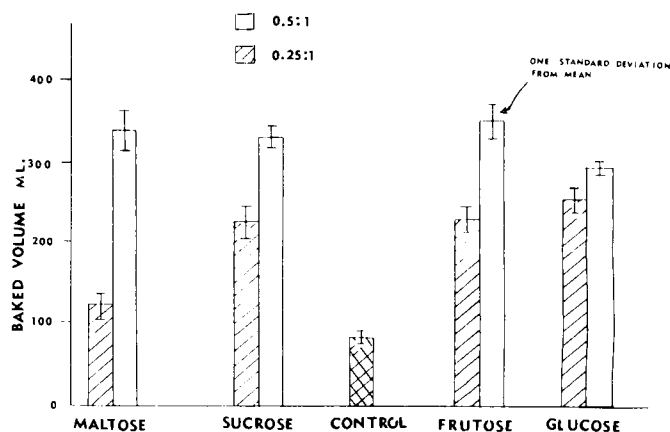

Figure 3. The effect of the experimental sugars on the volume of gluten balls after baking. The control contained only water

TABLE 1

MEAN VALUES OF THE VOLUME OF BAKED GLUTEN BALLS
MIXED WITH DIFFERENT SUGARS

Sugar to gluten ratio	Sugar	Wet weight (gm.)	Dry weight (gm.)	Volume (ml.) mean ± S.D.
0.5 : 1	maltose	11.80	6.51	333.0 ± 22.78**
0.5 : 1	sucrose	11.82	6.65	325.0 ± 12.90**
0.5 : 1	fructose	11.75	6.32	350.0 ± 21.60**
0.5 : 1	glucose	11.55	6.30	293.8 ± 11.08**
0.25 : 1	maltose	11.30	5.90	133.5 ± 17.76*
0.25 : 1	sucrose	11.48	5.90	225.0 ± 19.15**
0.25 : 1	fructose	11.30	5.60	230.0 ± 17.20**
0.25 : 1	glucose	11.08	5.41	258.0 ± 17.28**
control	none	10.75	4.80	82.9 ± 3.87

*significantly different from control, $P \pm 0.05$
**significantly different from control, $P \pm 0.01$

These findings were different from those reported by Meiske et al. (1960) who found there was no effect on the volume of their gluten balls when mixed with different sugars. The discrepancies in results may have been caused by the difference in the methods used in the two studies. Sugars were in solution before the water was mixed with gluten in this study. In the Meiske study, the dry sugar was mixed with the flour before water was added to develop the gluten. Any effect of the sugar on gluten development must, therefore, have been influenced by the rate at which it entered solution. Furthermore, most of the sugar was undoubtedly removed during subsequent washing of the dough to remove the starch and, as a consequence, was not present when the gluten was baked. Recognizing the last probability, Meiske et al., conducted another series of experiments in which they replaced the sugars washed from the gluten. But the gluten was now already hydrated. Thus, when the sugar was again added in the dry form, they observed that in the case of lactose, the sugar did not dissolve.

The present study appears to support the suggestion of Baxter and Hester (1958) that sugars decrease the development of gluten by competing for the water needed for hydration. To do this, the sugar must be in solution rather than in the solid form.

CRUST COLOR

A difference in crust color was observed among the baked gluten balls. The crust color of gluten balls made with sucrose was the lightest of all the sugars used. Sucrose is a nonreducing sugar, and therefore would not be expected to produce as much Maillard reaction during baking. The crust color of gluten balls made with the lower ratio of glucose to gluten was slightly lighter than that of those made with fructose and maltose. Browning occurred before the structure of gluten balls was set during baking. Increasing sugar concentrations caused more pronounced browning.

CRUSHING TEST

A crushing test was not performed on the baked bluten balls as a measure of tenderizing effect of sugar on gluten. Such tests were judged not to be a valid measure of tenderizing action because:
(1) with greater expansion of balls, walls were thinner, and
(2) high degree of browning suggested that some decomposition of gluten had occurred in those containing sugars.
Browning in the present study was reduced by use of a vacuum

oven, but was nevertheless great. This fact leads one to question the significance of the data on crushing reported by others on gluten balls baked in ordinary convection ovens. Use of a temperature sufficiently low to prevent browning also prevents the setting of the gluten structure.

RHEOLOGICAL STUDIES

In early studies of viscoelastic properties, dough was characterized in terms of a simple Maxwell Model. However, Hlynka and coworkers (1957) clearly showed that dough possesses complete viscoelastic properties that can only be represented by a generalized Maxwell Model; an infinite number of Maxwell elements connected in parallel. Consequently, gluten cannot be completely described by a single relaxation time and stress-relaxation modulus, but by distribution functions of them.
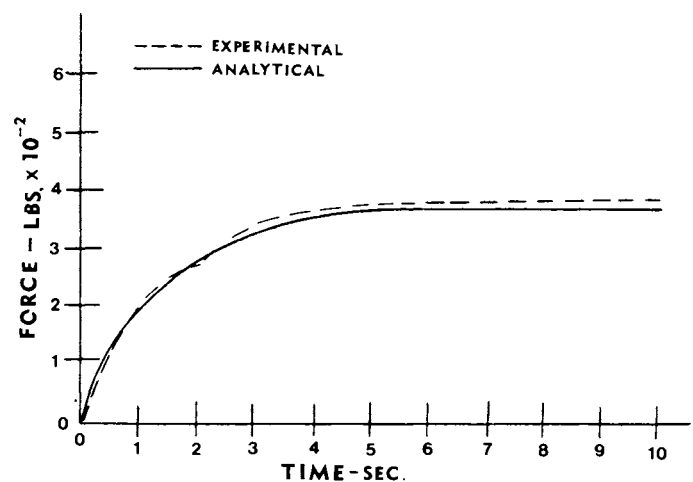

Figure 4. Comparison of the instron trace and the analytical curve based on a Maxwell Model

Figure 4 shows a typical recorded curve and an analytical curve plotted from averaged data for the gluten used in this study.
(1) Analytical curves are from averaged data; therefore there will be some natural scatter of data around the analytical curves.
(2) Analytical curves were based on a hypothetic Maxwell Model of the system. It is not expected that the actual data would follow this idealized model, as other researchers have demonstrated.
The mean values for elongation of the unbaked gluten are shown in Table 2. The data presented show that small quantities of different sugars do affect the extensibilities and expansion properties of gluten. In all cases, the gluten samples could be stretched from 10-20 times their initial length before rupture. This capacity to extend under stress without rupture is a desired property in mixtures for baking because it prevents escape of gas before or during heating.
An examination of the resultant curves showed that as the height of the curves increased, total elongation decreased. These changes in the shape of the curve suggest a softening of the gluten mixed with sugar solution. In general, the greater the height of the stress-strain curve, the better the baking qualities of the gluten. In other words, the load developed during stretching was indicative of the quality of the gluten.

TABLE 2

MEAN VALUES OF TOTAL ELONGATION

Sugar to gluten ratio	Sugar	Elongation (in/in) mean ± S.D.	Number of samples
0.5 : 1	maltose	2.18 ± .22	10
0.5 : 1	sucrose	4.44 ± .63	10
0.5 : 1	fructose	2.76 ± .67	9
0.5 : 1	glucose	4.27 ± .77	8
0.5 : 1	water	3.15 ± .62	7
0.25 : 1	maltose	4.42 ± .92	10
0.25 : 1	sucrose	4.13 ± .52	9
0.25 : 1	fructose	3.67 ± .80	10
0.25 : 1	glucose	4.17 ± .80	10
0.25 : 1	water	2.91 ± .48	6

Certain problems occurred in applying extensibility measurements to gluten. Prior to testing in the Instron Universal Testing Machine, the gluten was rested for a period of four hours after hydration. This was found to be necessary to permit the gluten to rehydrate and develop as evenly as possible. Even after resting, however, the samples were not in an entirely homogeneous state of stress. Once the test was underway, there was also a tendency for a weaker section to undergo greater deformation. As the deformation continued, the material eventually ruptured in the weak section. Uneven contraction of this kind is called "necking". It is induced as a result of nonuniformity of the stresses throughout the sample. This necking or reduction in the cross sectional area of the sample is gradual, not abrupt, but even so the sample does not remain in the state of pure tension. Radial and tangential stresses exist in the necked region which tend to invalidate the test. Others (Hibberd, 1966, Holmes, 1966) also found that the consistency of gluten is such that it is almost impossible to maintain constant sample geometry.

Average values of rheological parameters calculated from the results and based on the rheological considerations of the Maxwell Model are shown in Table 3. The mean of the values obtained on the 10 samples was considered representative of the gluten mixed with each of the respective sugar solutions.

The relative magnitude of the apparent viscosity obtained for the different sugars and gluten mixtures was essentially the same. The range was 9.8×10^6 to 17.5×10^6 dyne/cm^2. The apparent viscosity

of gluten with water, 8.92×10^6 dyne/cm^2, is comparable to the range found by Bloksma (1971) for dough in a survey of values reported in the literature. Most of these lay between 10^4 and 10^6 kg. m.$^{-1}$ sec.$^{-1}$ with some as low as 10^2kg. m.$^{-1}$ sec.$^{-1}$.

The range of shear moduli of dough reported by Schofield, Scott Blair, and Halton (1971) were 1×10^4 to 11×10^4 dyne/cm^2, while Glucklich and Shelef (1962) reported values ranging from 0.7×10^4 to 2×10^4 dyne/cm^2 and 9×10^5 dyne/cm^2. The values for gluten alone were given in the literature as 1×10^3 x to 8×10^3 dyne/cm^2 and $>6 \times 10^3$ dyne/cm^2 by Bloksma (1971). Obviously, this material property is quite variable. It is not surprising that the moduli values obtained in this work are in significant disagreement with those reported by earlier investigators. This may have been due to differences in testing and treatment of the gluten and the reaction time allowed. The reaction times that is, between mixing and test period (sample stretching) are varied. It is well known that the history of a visoelastic test specimen is an important factor. Also the materials used in the various studies were quite different. The earlier investigators used dough as the testing material, whereas reconstituted vital gluten was used in this study. The properties of this vital gluten could be radically different because the gluten had been extracted by
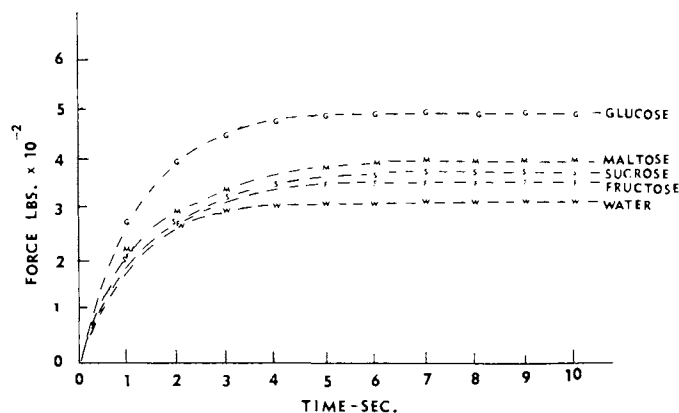

Figure 5. Load-time history for gluten mixtures with low sugar concentrations 0.25 to 1.0

TABLE 3

AVERAGED NUMERICAL VALUES OF RHEOLOGICAL PARAMETERS CALCULATED FROM INSTRON CURVES

Sugar to gluten ratio	Sugar	Maximum stress (τ) (psi)	Elasticity (E) (dyne/cm^2)	Apparent viscosity (poise)	Shear modulus (G) (dyne/cm^2)
0.5 : 1	maltose	2.54×10^{-1}	4.92×10^7	17.5×10^6	16.4×10^6
0.5 : 1	sucrose	2.18×10^{-1}	2.65×10^7	15.1×10^6	8.85×10^6
0.5 : 1	fructose	2.26×10^{-1}	2.76×10^7	15.6×10^6	9.18×10^6
0.5 : 1	glucose	2.46×10^{-1}	3.25×10^7	17.0×10^6	10.80×10^6
0.0 : 1	control (water)	1.28×10^{-1}	2.94×10^7	8.86×10^6	9.86×10^6
0.25 : 1	maltose	1.68×10^{-1}	1.93×10^7	11.86×10^6	6.43×10^6
0.25 : 1	sucrose	1.51×10^{-1}	2.33×10^7	10.40×10^6	7.77×10^6
0.25 : 1	fructose	1.42×10^{-1}	2.92×10^7	9.82×10^6	9.74×10^6
0.25 : 1	glucose	2.03×10^{-1}	3.40×10^7	14.00×10^6	11.30×10^6
0.00 : 1	control (water)	1.29×10^{-1}	2.95×10^7	8.92×10^6	9.83×10^6

a salt solution and flash dried. Oxidation of the protein might have occurred during the drying process. Also, a far greater amount of occluded starch granules in the earlier studies may have "diluted" the testing material. Any of these factors could explain the discrepancies in the results, but no attempt was made at this time to resolve the differences.

The general shapes of the stress-strain curves were quite similar when different sugars were used at a low ratio (Figure 5). However, differences between the curves obtained with various sugars at the higher concentration were more pronounced (Figure 6). The maximum shear modulus, G, is about the same even at the higher sugar concentrations. When the effect of sugar solutions of equal concentration by weight were compared with respect to gluten extensibility, it appeared that the type of sugar had no effect.
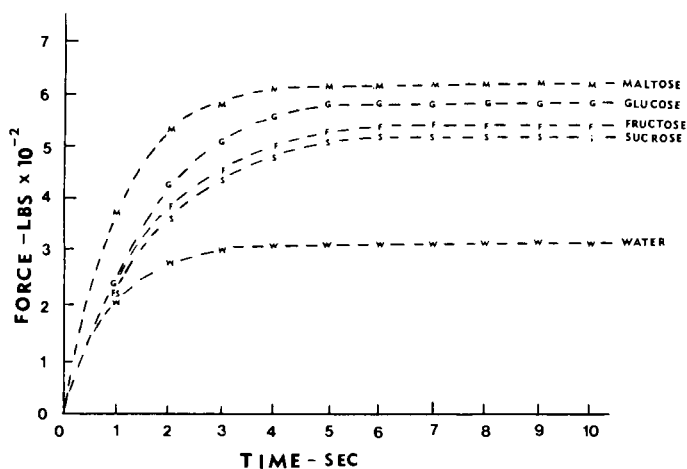

Figure 6. Load-time history for gluten materials with high sugar concentrations 0.50 to 1.0

CONCLUSIONS

The presence of dissolved sugar in the water used to reconstitute the dried vital gluten produced an increase in the volume of experimental gluten balls when baked. The crust color of gluten balls was dark brown when reducing sugars were used, indicating the interaction of carbohydrate and gluten in a typical Maillard reaction. Browning was reduced when a vacuum oven was used. Under the experimental conditions, no significant difference in the volumes of the baked gluten balls could be attributed to a specific kind of sugar. Thus, there was no apparent difference in the effect of different sugars. The findings did indicate that sugars had a peptizing action and inhibited heat coagulation of the gluten.

The viscoelastic properties of vital gluten were significantly changed by the various selected sugars at the levels studied. The apparent viscosity of gluten mixed with sugar solutions was higher than that for gluten mixed with water. The average values for the 0.5 : 1 sugar to gluten ratio were twice those of the control which contained only water and gluten.

A comparison with literature data was not possible because of the complexity and uncertainty in the rheological behavior of gluten. The levels of the results and their interpretation depend on the method used. In the present study greater rigidity and resistance to extension were found when the samples of gluten prepared with sugar solutions rather than water were subjected to stretching forces. The presence of sugar had a significant effect on the stress-strain behavior of gluten. There is generally a correlation between the re-

sistance to deformation (heights) and extensibility (elongation) of the curves. There is also a correlation between the apparent viscosity of prepared gluten and the volume of baked gluten balls except with those samples containing maltose. In contrast to data reported for wheat flour doughs obtained from dough testing machines, the values obtained in this study were much higher and more comparable to rubber-like materials.

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