RHEOLOGY AND THE CONVENTIONAL BREAD AND BISCUIT-MAKING PROCESS

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ABSTRACT

In this introductory paper, rheological methods and their relevance to the conventional bread- and biscuit-making process are outlined. After a brief historical introduction, a critical evaluation of both empirical and fundamental testing methods is presented. Finally, three aspects of the relation between rheology and baking receive attention. First, the statistical relation between dough tests and bread characteristics are considered. Shown is that the improvement in methodology over the past 35 years is reflected in improved correlation which is, however, still poor. Second, the meaning is explored of flour-water absorption and the relation between farinograph absorption on one hand, and protein and moisture content, starch damage, and α-amylase activity on the other, are discussed. Third, the concept of flour strength is considered. It is suggested that this is largely a reflection of the degree of cross linkage of the gluten-protein complex in the developed dough. It is suggested that much is known about the rheology of dough *per se* and also its relation to dough structure. However, when applied to bakery technology, the direct usefulness of dough rheology is very limited.

Rheology has been defined as the science of deformation of matter (1,2,3). A rheologist studies that deformation in relation to force and time.

There are two basic types of measurement; the fundamental and the empirical. In the former, all test results are returned in terms of basic physical quantities such as stress, strain, or rate of strain. Such results are easily understandable since the basic units are readily available as standards. Within the experimental error the results are also independent of instrument or operator. Conversely, they may be very difficult to obtain experimentally or to derive mathematically. Empirical tests are usually easy to perform. There is no underlying physical theory and the operator requires no knowledge of physics. However, the results are only of use if *either* they are correlated with material performance (*e.g.*, baking) *or* with material structure (*e.g.*, the dough-protein network).

The general advantages and disadvantages of the two kinds of measurement have been discussed before (3). Following they will be considered with specific reference to flour dough.

Instrumentation and Rheological Concepts

Rheological studies before 1900.—The early development of dough and gluten rheology has been considered by Bailey (4) in 1940 and Muller (5) in 1964. From the earliest times writers such as Plinius the Elder (6), Müller (7), Beccari (8), and Fourcroy (9) were well aware of the rheological difference between flour doughs, and after 1728 (when Beccari described gluten isolation) between glutens of different origin.

The first physical testing instrument was the Aleurometer developed by Boland in 1836 (10) (Fig. 1). It measured the volume expansion of gluten when heated in an oil bath and was clearly an extension of the baking test. The instrument was in use for about 80 years (11). In 1886, Jago (12), described the first truly rheological dough-testing instrument, a simple extrusion instrument without temperature control or standardized dough mixing and moulding which must have been very inaccurate (Fig. 2). Hogarth (13), a Scottish miller, patented the first recording dough mixer in 1889. This was followed in 1901 by Kosutany's load extension instrument (14). Apparently based on a machine used for testing the tensile strength of textile fibers, it stretched a dumbbell-shaped piece of dough until it ruptured. Kosutany conducted several thousand tests between 1901 and 1907 mainly to assess the "strength" of central European wheats.

Clearly, by the turn of the century dough rheology was established. Kosutany already attempted fundamental measurements but all other methods were

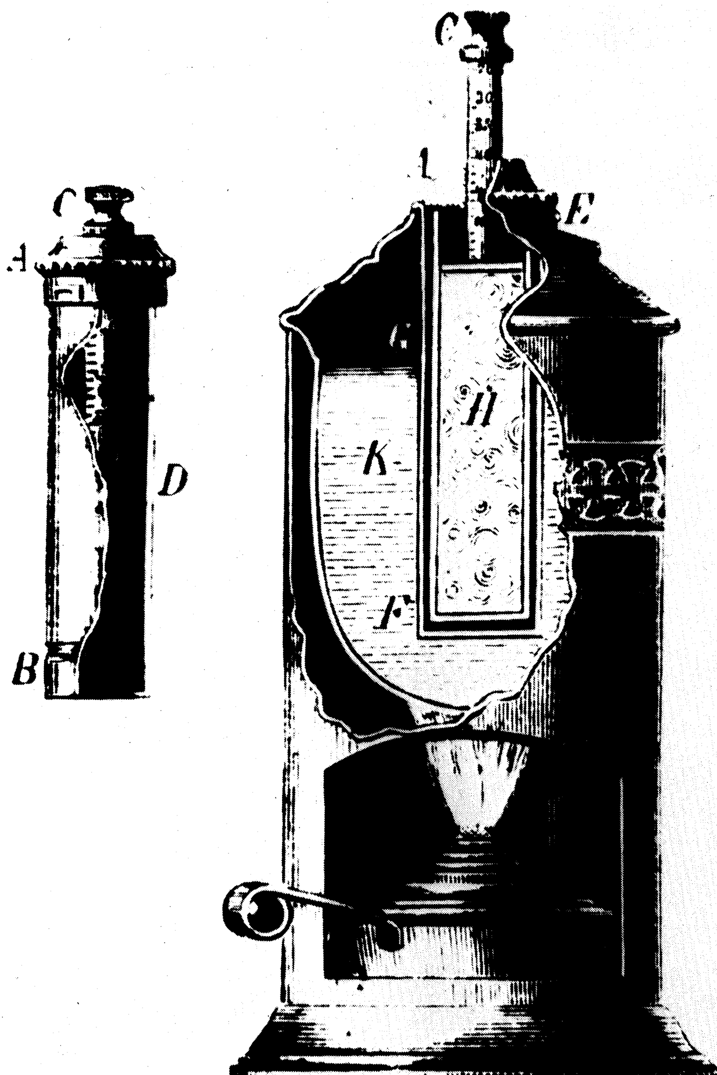

Fig. 1. Boland's Aleurometer (5).

empirical. Scientifically, viscoelastic measurement was not understood, so even Kosutany's method was fundamentally unsound.

As regards general application, neither chemistry nor rheology was used in the mill or bakery. Voller (15) wrote in 1882, "For ordinary mills, science has at present little to offer worthy of serious consideration."

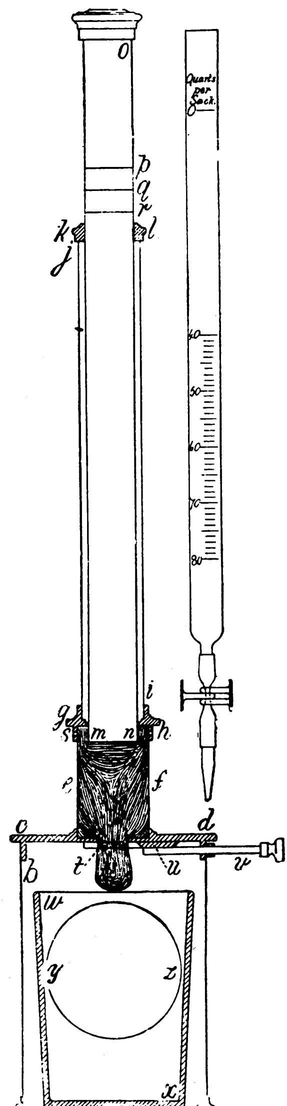

Fig. 2. Jago's Viscometer (12).

Empirical Studies

There are very many empirical testing instruments and comprehensive reviews have been written by Bailey (4) in 1940, Muller (16) in 1962, and Bloksma (17) in 1971. However, some basic considerations on the various groups are not out of place.

Recording Dough Mixers

All recording dough mixers are, in essence, empirical instruments and for non-Newtonian materials, it is impossible to obtain fundamental rheological information from them.

There are two types of recording systems, the mechanical and the electrical. The mechanical or dynamometer type measures torque (work) at the paddles (Farinograph) or at the pins (Swanson Mixograph), while the electrical type takes its measurement at the input (Fig. 3). Thus any motor or gearbox changes during the test (temperature, oil viscosity etc.) will interfere with the electrical, but not with the mechanical measurement. For this reason the mechanical measurement is always more accurate. In order to reduce variables during electrical recording, the mixer is usually allowed to run for some considerable time to "settle down." This is not necessary with the dynamometer type. The advantage of the electrical system is greater flexibility. Not only can the recorder be fitted to any type of mixing unit, large or small, continuous or batch, but the signal can also be differentiated or integrated. Dimensionally watt-hour meter readings are equivalent to the dynamometer reading obtained with, for instance, the Farinograph.

Extrusion Devices

Following Jago's "Viscometer," similar devices were developed by which doughs were extruded from a cup through one or more orifices. The necessary pressure was exerted mechanically or pneumatically. For various reasons (3) all extrusion devices using an orifice rather than a capillary tube give empirical results, not only with a material as complex as dough, but even with a simple Newtonian liquid. For reliable work, the instrument should be used with a water jacket and a standardized dough-handling procedure (18,19).

Penetrometers

In this test, either a graduated rod is dropped into the dough from a given height, or a plunger slowly forced into it. The latter method appears to be popular in the USSR and some neighboring countries (20,21,22).

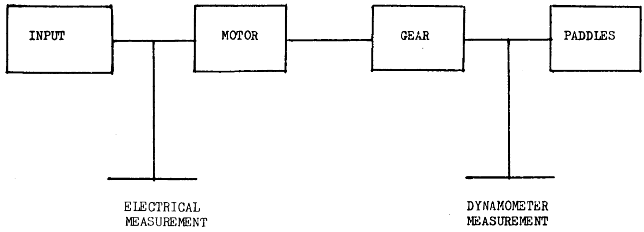

Fig. 3. Mechanical and electrical measurement with recording mixers.

Wolarowich and Churaev (23) in the USSR, and Pendleton (24) in the U.S., have determined the relative viscosity of some stiff materials by this method. Their reasoning can, however, only be applied if the material under test is Newtonian, and dough is not.

For both extrusion devices and penetrometers, mathematical equations have been very useful, mainly to determine flour-water absorption. They are, however, empirically based and have no basic physical significance.

Load Extension Instruments

Kosutany's work with the first load-extension instrument gave rise to devices which form two natural groups: 1) those stretching gluten or dough pneumatically (*e.g.*, Hankoczy's gluten tester, Chopin Alveograph), and 2) those working on purely mechanical principles (*e.g.*, Brabender Extensograph[1], Halton Extensometer). With the last three instruments which are commercially available, a curve is drawn which generally shows greater height and area with a strong flour dough than with a soft one. The curves have been evaluated in various ways (17,25). It is best not to use misleading terminology such as resistance, energy, viscoelastic ratio, strength, stability, elasticity, relaxation, etc. The curves are empirical, and they are best described in geometrical terms such as height, length, and area. There is no general agreement as to how the dough should be mixed, moulded, or rested before the test. Just as old wives' tales, having no rational basis, are passed on from generation to generation, so methods of dough testing are transmitted until they are ultimately frozen in some standard method without any good reason (26). How many dough rheologists know why when using the Brabender Extensograph, each dough piece is moulded and tested three times rather than once only as with other systems? (27, Method 54—10). The procedure is, in fact, based on a now forgotten German test baking procedure, and totally irrelevant to modern conditions.

The relaxation method (27, Method 54—11) was suggested by Dempster *et al.* (28) in 1952 and is based on the work of Andrews *et al.* (29) with polyisobutylene. The advantage is that an attempt is made to determine the dynamic rather than the static behavior of dough. However, it is not always appreciated that the method is empirical and does not give results in basic physical quantities. The relaxation constant and asymptotic load (30) are mathematical expressions and do not reflect physical concepts. The "short method" (27, Method 54—11) should be used with caution (31). The effectiveness of empirical load extension instruments in fundamental work is considered in a later section.

Miscellaneous Instruments

These include a multitude of instruments. Often based on ingenious ideas, they have usually not been correlated with material performance and their usefulness is then debatable. Some of the more acceptable devices include the Amylo-Viscograph used for measuring starch paste viscosity (32), the oven rise recorder, a modern version of Bolands Aleurometer (10), the centrifuge used for determining flour-water absorption (33), and the Brabender Maturograph (34).

[1]The Brabender load extension instrument is for patent reasons sometimes referred to as the Extensograph or the Extensigraph. In this paper the latter spelling has been used unless reference has been made to literature where the former spelling is employed.

Fundamental Studies

Stress-strain and viscosity determinations.—Kosutany (14) obtained stress-strain measurements on dough as early as 1901. He stretched at constant rate dumbbell-shaped pieces of dough, supported by corks and securely clamped at the ends, and obtained load-extension diagrams on a recorder. From these he obtained the maximum extending force P, the tensile stress (force per unit area of cross section) and the strain (fractional extension). Hence, single stress-strain values at P were obtained. He did not control temperature or rate of strain, nor did he obtain stress-strain curves, but single values only. This method was taken up again by Rada (35) in 1956 who designed the Neolaborograph. His assumption that the first part of the curve shows perfectly elastic behavior and the second part perfectly viscous behavior is erroneous. The two phenomena are coincidental in the test.

More recent attempts at obtaining tensile stress-strain data are those of Hlynka and Barth (36) who used the Chopin Alveograph, Muller *et al.* (25), and Přihoda and Bushuk (37), who used the Brabender Extensograph. Tschoegl *et al.* (38) used an instrument of their own design which stretched dough rings, and Rasper *et al.* (39) stretched dough rings on the Instron tester.

The last-mentioned two teams used an interesting method of evaluation originally developed by Smith and Frederik (40). Using data obtained in simple tension, the results were interpreted in terms of a so-called isochronal constant strain rate modulus, and an exponent n characterizing the time dependence of the modulus. If $n = -1$ a purely viscous response, if $n = 0$, a purely elastic one was indicated. Using the improvers potassium bromate, azodicarbonamide, and ascorbic acid Rasper *et al.* showed that on treatment the dough showed an increasing tendency to resemble an elastic material. This finding is not inconsistent with the work reported by Muller (41) who applied the rubber-elasticity theory to gluten.

Quite a number of experiments using viscometers on dough have also been carried out through the years. The latest is that of Launay and Buré (42) who used the Haake Rotovisco as a cone and plate viscometer. Earlier workers used the falling ball or the capillary tube method.

The basic objection to stress-strain and viscosity measurements on dough or batter (and, indeed, cake and bread crumb) is this: the former methods are applicable to solids measurements, the latter to liquids measurements. They are not generally interpretable when applied to viscoelastic materials. It is true that certain techniques exist which allow both viscous and elastic constants to be derived from stress-strain data. These, however, usually assume linear response and are not, as a rule, applicable to dough, batter, bread or cake crumb, except sometimes over a very narrow range of conditions (see below). It appears that Eyring's approach using hyperbolic functions has not been applied to dough.

On deformation of a viscoelastic material, both the viscous and the elastic component normally express themselves together. It is, however, possible to separate them by carefully designed methods. Of these, the following three have been applied to dough with some success.

Loading—Unloading Experiments

Following the work of Kosutany in Hungary, and that of Weinberg (43) (Fig. 4) in the USSR in 1912, Schofield and Scott-Blair (44) published 3 papers between 1932 and 1933. They used several methods, but the most important was that using the mercury bath extensometer (Fig. 5). Here a dough cylinder was extended under a given load and then allowed to contract after unloading. Both creep compliance and relaxation could be measured in this way. The tests were further developed by Reiner and coworkers (45,46,47) and Fig. 6 shows the model proposed by Lerchenthal and Muller (48) in 1967. It consists of twelve components, most of which are nonlinear. The model is, indeed, somewhat formidable. However, for normal purposes it is adequate to describe dough as a Burgers model (3).

Bloksma (49,50) used a somewhat different approach. He designed a cone and plate viscometer fitted with a circular knife to trim the sample *in situ* and minimize evaporation. Shear stresses from 140 − 37,200 dynes/cm^2 were reported.

Occasionally attempts have been made to use empirical instruments for fundamental tests (51,52). These exercises tend to be very laborious. They often throw light on the relevant instrument particularly in relation to the factors involved in calibration, but the data obtained on the dough itself can be achieved more easily in other ways.

Relaxation Studies

In 1932, Schofield and Scott-Blair had recognized the importance of relaxation studies. In considering theoretically any viscoelastic system the effective contribution of the viscous and elastic component depend on the type of model assumed (*i.e.*, Maxwell, Kelvin Voigt, Burgers) Schofield and Scott-Blair (44) originally assumed Maxwell's behavior, but in 1933 they introduced an additional expression, alpha, into the Maxwell equation to allow for the elastic

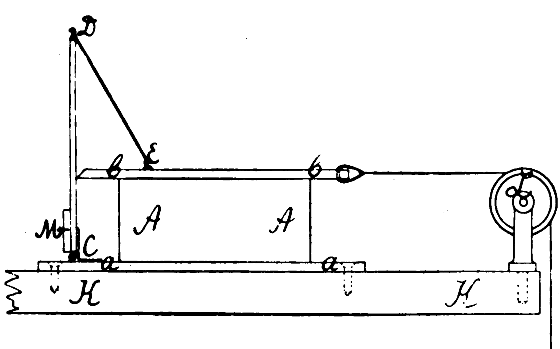

Fig. 4. The Weinberg shear plate instrument (43).

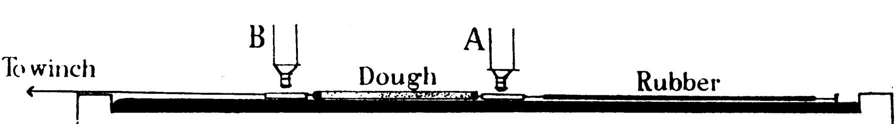

Fig. 5. The Mercury bath extensometer of Schofield and Scott-Blair (44).

aftereffect and elastic hysteresis.

Twenty years later, Hlynka and coworkers (53) specially built a relaxometer, but in only one instance (54) did they attempt to obtain fundamental values. Basing their work on the findings of Gross (55), they stated as a working hypothesis that dough behavior was not represented by a single Maxwell element but by a parallel array of Maxwell elements. Neglecting α and summing over i terms they obtained the appropriate differential equation.

Hlynka and coworkers also made an attempt to evaluate their results for the distribution of activation energies and so introduced thermodynamic concepts.

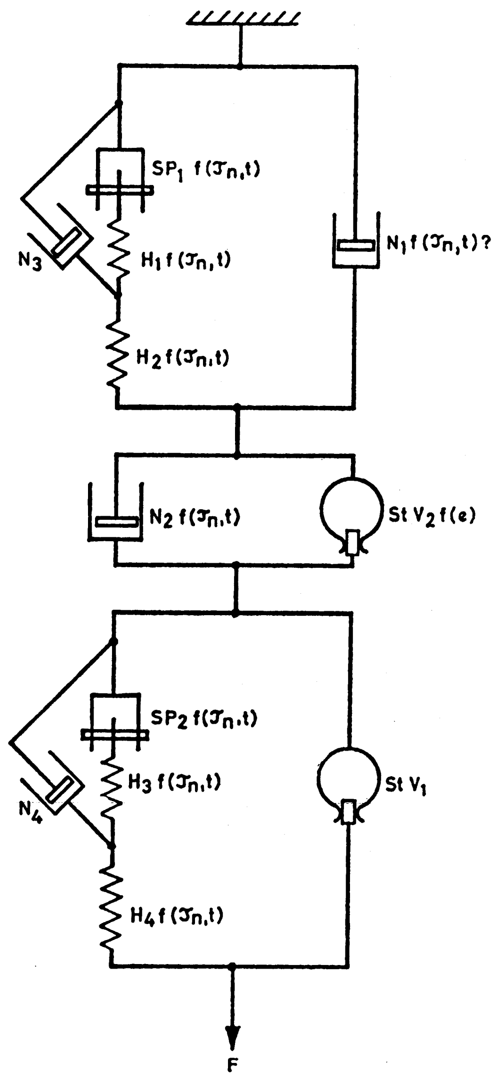

Fig. 6. A rheological model of wheat flour dough (48).

Shelef and Busso (47) analyzed relaxation behavior by straightening out the relaxation curve, in probability *vs.* log coordinates. In 1959, Grogg and Melms (56) had used a similar analysis of relaxation measurements using the Brabender Extensograph. While their theoretical approach was interesting (central limit theorem) the extensigraph was not sensitive enough for such work (16). Other methods of stress relaxation analysis are given by Mohsenin (57).

Nowicki used a tensometer to determine both loading-unloading and relaxation curves on dough. His instrumental arrangement is not clear, but the work gives a useful review and lists recent Russian work in the area. The work of Nikolayew and Rebinder is of particular interest (58).

Dynamic Measurements

Viscoelastic properties can be analyzed by studying either Lissajou's figures or the phase shift between stress and strain curves obtained in forced oscillations.

Shimizu and Akiyoshi (59) used an adapted viscometer for obtaining Lissajou's figures whereas Muller (60) used phase shift measurements with the Weissenberg Rheogoniometer. He was not successful in determining normal pressures because in rotation experiments the dough tended to roll out of the gap between the cone and plate.

Slater (61) used resonance studies and damping curves have also been obtained with the Ultra-Viscoson from decaying free oscillations. Hibberd and Wallace (62), and Smith *et al.* (63), found linear behavior only at very low amplitudes and for this reason it does not appear that dynamic measurements throw much light on bread-baking performance where relatively large tensile deformations take place.

Table I gives some rheological parameters of dough at zero stress as determined by Glücklich and Shelef (46). Summaries of rheological data collected from the general literature are given by Bloksma (17), Muller *et al.* (64), and Sherman (65). However, there are several kinds of moduli, and several kinds of stress, and such tables are often confusing.

TABLE I
Rheological Parameters of Dough at Zero Stress (46)

Parameter	Dough Made from Bread Wheat	Dough Made from Durum Wheat
Bulk modulus dyn/cm^2	1.4×10^7	...
Shear modulus dyn/cm^2	4.2×10^5	9×10^5
Poisson's ratio	0.5	...
Newtonian viscosity (from creep compliance − time study) [poise (P)]	18×10^6	36×10^5
Relaxation time (sec)	43	40
Modulus of delayed elasticity dyn/cm^2	2.7×10^5	9×10^5
Retardation time (sec)	9	20
Solid coefficient of viscosity (associated with retarded elastic compliance) (P)	2.4×10^6	18×10^6

RHEOLOGY AND BAKING

Statistical Aspects

In 1939, Markley and Bailey (66) reported the statistical correlation between the baking test and some analytical characteristics of flour including Farinograph water absorption. Using 23 flour samples of the 1933 crop, and the AACC baking test supplement D, they obtained the standard deviations (SD) and coefficients of variability (CV) given in Table II.

TABLE II
Statistical Constants 23 Flour Samples, 1933 Crop (66)

	Mean	SD	CV
C Loaf vol 2 min mix (cc)	598.3	79.0	13.2
K Loaf vol 5 min mix (cc)	522.4	54.1	10.4
M Farinograph absorption at 550 FU (%)	58.8	2.4	4.1
J Flour protein (%) ($N \times 5.7$)	14.0	1.3	9.3
G Diastatic activity (Blish & Sandsted)	253.5	28.9	11.4

The statistical constants are given in Table III.

It is apparent from these studies that the correlation coefficient relating Farinograph absorption with protein content was low. The relation between Farinograph absorption and loaf volume was not significant.

In 1940 Geddes *et al.* (67) evaluated 333 samples of Western Canadian hard red spring (HRS) wheat. Some of their data connecting loaf volume with flour protein and the farinogram are given in Table IV.

It was concluded that there was a significant negative correlation between weakening area and loaf volume, but the correlation was less pronounced than between volume and dough development angle or protein content. On the whole, protein content gave a better prediction of loaf volume than farinograph data.

In 1959, Fuchs (68) reported correlation coefficients between gluten, dough, and baking tests. Significance levels have been added here for convenience. Fuchs' definitions were:

Baking tests (69)	
Loaf volume	Recalculated per 100 g flour
Shape	For tinned bread or oven bottom bread, ratio of height to diameter
Farinogram	
Water absorption	Corrected for 15% moisture
Development	From start to peak of farinogram in minutes
Consistency	From start to point at which upper part of band touches the 500 FU line in minutes
Softening	Difference in FU between 500 and midline of curve after 15 min
Valorimeter figure	Standard designation
Extensigram	
Extensibility	Third curve baseline in mm
Resistance	Height of curve in extensigraph units after 5 cm
R/E	Extensibility : Resistance
Energy	Third curve in cm^2

Table V shows the correlation between baking test data and farinogram and extensogram data.

TABLE III
Correlation Coefficients
(Those Above 5% Significance Level Are Underlined) (66)

	M	J	G
C	+.35	<u>+.82</u>	+.01
K	+.08	+.33	−.19
M	...	<u>+.49</u>	<u>+.48</u>

TABLE IV
Correlation Coefficients of 333 Samples of Western Canadian HRS Wheat
(r at 5% Significance Level = +.138) (67)

	Farinograph Absorption %	Loaf Volume cc	Dough development angle	Weakening area	Mean Band Width
Flour protein (N × 5.7)	−.173	+.903	−.735	−.652	+.222
Loaf volume (cc)	...	...	−.699	−.619	+.167
Dough development angle	...	...	...	+.830	−.354
Weakening area	...	...	...	...	−.549

TABLE V
Correlation Between Baking Test and Farinogram and Extensogram (68)

Relation Between	Not considering	Tinned bread	Oven bottom bread	Significance	
Farinogram—baking test					
Water absorption/vol	...	+0.44	+0.52	1%	1%
Water absorption/wt	...	+0.48	+0.58	1%	1%
Development/vol	...	+0.74	+0.43	1%	1%
Consistency/vol	...	+0.69	+0.25	1%	NS
Development/shape	...	+0.09	−0.10	NS	NS
Consistency/shape	...	+0.18	+0.39	NS	5%
Softening/shape	...	−0.08	−0.47	NS	1%
Valorimeter figure/vol	...	+0.53	+0.43	1%	1%
Valorimeter figure/wt	...	+0.31	+0.24	NS	NS
Development/shape	Consistency	−0.13	−0.91	NS	1%
Consistency/shape	Development	+0.19	+0.93	NS	1%
Extensogram—baking test					
Extensibility/vol	...	+0.68	+0.19	1%	NS
Extensibility/vol	Resistance	+0.69	+0.19	1%	NS
Resistance/vol	...	−0.20	−0.25	NS	NS
Resistance/vol	Extensibility	−0.24	−0.27	NS	NS
Energy/vol	...	+0.58	−0.05	1%	NS
Resistance/shape	...	+0.52	+0.58	1%	1%
Extensibility/shape	...	−0.33	0.57	5%	1%
R/E/shape	...	+0.41	+0.58	5%	1%

If the highly significant results are summarized (1% significance level) the following Table VI can be constructed.

It would appear that the farinogram is a better criterion of flour quality than the extensogram if the flour is sound, untreated, and milled to an ash content of 0.70% on a Bühler mill.

Basically, the usefulness of dough rheology to the baker hinges on correlation. From the three statistical analyses given (66,67,68) it is apparent that methodology in cereal science has improved greatly. As a result, correlations have also improved. However, all correlation coefficients but two in Table VI are far removed from the ideal figure of 1.00 although the flours were experimentally milled to a uniform ash content. The coefficients for commercially milled flours would be worse. It is now unlikely that correlation can be further improved by better methods. Low correlation is due to the complexity of both dough rheology and the baking process.

Flour-Water Absorption

It has been known since very ancient times that different wheat flours may have different water absorptions: "*Sic ait optimum frumentum esse, quod in subactu congium aquae capiat*"—(Plinius, book 18, chap. 10) (6).

What is the basis of flour-water absorption?

Dill and Alsberg (70) found a remarkable constancy in the moisture content of various glutens (ca. 67–69%) when washed out with tap water. Nevertheless, Finney (71) had shown that water absorption was strongly influenced by variety. Hence, Greer and Stewart (72) concluded that a factor other than gluten was effective. This, they assumed to be, damaged starch and they postulated the regression equation,

$$y = 2.74\ x + 3.30\ z + 37.51$$

Where y = water absorption % (Halton Absorption Meter), x = flour nitrogen content %, and z = reducing sugar as percentage of flour taken. The last-mentioned was taken as an approximate indication of starch damage (reducing sugar divided by 0.37). (*Note*: Water uptake is about 70% for protein, 40% for starch, and 200% for damaged starch). Farrand (73) developed these concepts

TABLE VI
Highly-Significant Correlation (1% Significance Level)
Between Baking Test and Farinogram and Extensogram (68)

	Loaf Weight	Volume	Shape
Farinogram			
Water absorption	+ 0.58		
Development		+ 0.74	− 0.91
Consistency		+ 0.69	+ 0.93
Softening			− 0.47
Valorimeter figure		+ 0.53	
Extensogram			
Extensibility		+ 0.68	− 0.57
Resistance			+ 0.58
R/E			+ 0.58
Energy		+ 0.58	

further and suggested that starch damage and also α-amylase activity were of primary importance in relation to flour-water absorption (Farinograph). In 1969, he (74) proposed an absorption equation connecting Farinograph absorption, protein and moisture content, starch damage, and α-amylase activity. It is to Farrand's merit to have shown how very complex is such an apparently simple property as water absorption. The factors governing the effect of heat during baking on the flour-water system are little known. Is it any wonder that the correlation coefficient between water absorption and the weight of tinned bread is only + 0.48 (Table V)?

In 1969, Farrand stressed that gluten quality did not enter into his equation. By 1972, he (75) went so far as to conclude, "gluten quality is a term that most technologists claim to understand but none seem able to explain." To some extent this view had been held by Webb *et al.* (76) in 1971.

Gluten quality is based on the degree of cross linkage of the gluten protein complex. It is thus, basically a "solids" concept apparent in extension tests. It is only marginally expressed in viscosity measurements perhaps because it is swamped by other factors. For this reason studies on *e.g.*, the improver effect is conducted with load extension instruments and not with empirical viscometers such as extrusion devices or recording dough mixers. In fact, the Brabender Extensograph was designed when it became apparent that the Farinograph did not respond to improvers such as bromate, persulfate and nitrogen trichloride (Agene). Why this is so is difficult to explain because both the Farinograph and Extensigraph are empirical instruments and little is known about their action.

Flour Strength

Jago (12) had defined flour strength as the measure of the capacity of a flour to produce a bold, large-volumed and well-risen loaf.

Some subsequent workers have preferred to define flour strength in relation to load extension curves obtained from dough. This excludes from the definition the fermentation system, starch gelatinization factors, and the baker's manipulative skill.

It is generally agreed that "strength" in this rheological sense depends on the quantity and quality of the wheat protein, mainly the gluten.

Protein quantity is usually expressed as Kjeldahl nitrogen multiplied by 5.7. Since the amino acid composition of flour protein varies, this factor has been the subject of debate. It has, on occasion, been suggested that either a different factor should be used, or the factor be avoided altogether by directly reporting the nitrogen determined. There is an enormous amount of statistical data connecting protein content with loaf characteristics (see *e.g.*, 77).

Gluten quality appears to be based on its molecular structure. Highly-kinked, cross linked, long-chain protein molecules, or their aggregates are thought to provide the necessary elasticity while viscous flow appears to be due to water, lipid, and the rate of reversible bond interchange in the connected structure. For the various detailed hypotheses connecting dough and gluten rheology with molecular structure the relevant literature should be consulted (41,50,78,79,80). The author is not aware of any work connecting detailed protein structure with the characteristics of the baked product.

Bread and Biscuit (Cookie) Manufacture

What is the relevance of dough rheology to the manufacturing process?

First, it is of importance in dough mixing. The mixing process consists initially of a distribution of the dough components, but this *per se* does not result in a dough. The author well remembers mixing flour and snow in the correct proportion on the roof of the Grain Research Laboratory in Winnipeg on a very cold winter's day. On subsequent melting in the laboratory, a soft porridge without any coherence resulted. This was, however, quickly turned into a dough on further mixing. So, the second stage in normal dough mixing is the formation of a coherent viscoelastic dough structure that ultimately gives good bread. To some extent, the effects of mechanical treatment, chemical treatment, and fermentation are interchangeable. Good dough can be made by mixing up to 30 min at 15 kJ/kg followed by fermentation. Alternatively, fermentation can be reduced if cysteine or bisulfite as well as bromate or ascorbate is added during mixing. Finally, if the energy input is increased to 40 kJ/kg fermentation can be reduced without the use of chemicals (17).

Second, dough rheology is important in dough handling such as rolling, sheeting, folding, or cutting. Hlynka (81) has given a qualitative assessment of these factors, and his paper should be consulted. There appears to be little quantitative work available. There is a rather unsatisfactory Russian paper (82) on the rheology of short biscuit dough. The instrument used is not described and the final model for the dough is not given because of "the specialized nature of the problem." However, the author points (probably quite correctly) to the importance of plasticity and elastic aftereffect in short dough. Both could be of importance in dough rolling and change of shape of biscuit dough pieces after shaping.

An interesting study is that by Pelshenke (83) of the action of the shaping unit in the manufacture of croissants. The effect of working is quite apparent.

Third, dough rheology is important in relation to the expansion of the gas cells during fermentations and baking. Here the interesting approach of Matsumoto and coworker (84,85) should be cited. Assuming a Maxwell model for dough, they calculated that viscosity and strain rate determined the tension on the dough membranes surrounding the gas bubbles.

In conclusion, it is apparent that much is known about the rheology of dough. Rheology has also told us much about dough structure. However, except in the field of dough mixing, useful applications of that knowledge to bakery technology are few and far between.

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