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A STUDY OF SOME PHYSICAL PROPERTIES OF FLOUR DOUGHS IN RELATION TO THEIR BREAD-MAKING QUALITIES

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INTRODUCTION

Attempts to measure the physical properties of flour doughs were made by Kosutány (4) as early as 1907. This author pulled out a cylinder of flour dough at a constant rate, and measured the stress build-up.[2] Although not clearly distinguishing between viscous and elastic properties, the author's interpretation of his data points clearly to a number of the conclusions reached in the present work.

It is curious that this valuable work, in which Kosutány came so near to separating and measuring specific physical properties, should have lain fallow for so many years. From 1907 to 1932 work on the physical properties of flour doughs was confined almost entirely to the production of instruments measuring a complex mixture of properties, which, although in some cases of real value in the bread-making industry, threw little or no light on the physical nature of the problem. In 1932–33 three papers were published by Schofield and Scott Blair (8), in which certain of the physical properties of doughs were separated and independently measured. For the sake of convenience these papers will be referred to as I, II, and III.

In paper I it was emphasized that flour dough belongs to a group of materials in which a high degree of plasticity is combined with considerable elasticity. When under stress the relative amounts of plastic (non-

[1] By mutual agreement the authors' names are in alphabetical order and no seniority is implied.

[2] Terzaghi (9) develops very similar ideas. The constant which he calls "degree of elasticity" (p. 79) is closely connected with relaxation time (vide infra). Terzaghi's work refers to soils and clays, but their behavior is in some ways strikingly similar to that of flour doughs. See also a recent paper by M. P. Wolarowitsch and K. I. Samarina (10) dealing with some physical properties of flour doughs.

recoverable) and elastic (recoverable) deformation depend on the time of duration of the stress. An extended significance was given to Maxwell's relaxation time, so that the equation

$$t_r = \eta/n$$

in which t_r = relaxation time, η = viscosity, and n = shear (rigidity) modulus,[3] could be applied to a material such as flour dough, in which neither η nor n is a constant.

It was found that η and t_r decrease with increasing stress and increase with increasing deformation. Fall in viscosity with increasing stress is a phenomenon well known in many colloidal systems, and has been called "structural viscosity" (6). Increase in viscosity with increasing strain is a common characteristic of metals, and is called "work-hardening."

In paper II, these two properties were more fully studied by observing the rate of shear of cylinders of dough hung vertically, and allowed to elongate under the action of gravity (the method of rheograms).

The Maxwell equation could only be tested satisfactorily after the most suitable value of modulus to use in calculating viscosities from relaxation times was known. Experiments to decide this point were described in paper III, and agreement was found to be as satisfactory as could be expected when the best value for the modulus was used. These experiments also made it clear that dough shows two other properties characteristic of metals, namely, elastic hysteresis and elastic after-effect.

The former causes the rigidity modulus to fall slowly as stress is raised, and also as stress is lowered, but at the point at which the sign of dS/dt changes,[4] the modulus increases abruptly. The latter means that elastic deformations are not recovered instantly, so that unless time is given for slow recovery to take place, certain deformations will be regarded as permanent which are in reality recoverable. This would lead to considerable errors in determining viscosity and modulus (see experimental section). In view of the partial understanding which this treatment had already given, it seemed advisable to investigate further the relationship between these fundamental physical properties, and those qualities of the dough which are of importance in the bread-making industry. For this purpose the Physics Department of the Rothamsted Experimental Station and the Research Association of British Flour Millers decided to coöperate in the further study of the problem.

[3] Note that for flour doughs, Poisson's ratio being 0.5, we can assume the rigidity modulus to be equal to one-third of Young's modulus. The shearing stress likewise is one-third of the loading stress. In the present paper, the term "rigidity modulus" is often abbreviated to "modulus," since no other modulus is discussed.

[4] Where S is shearing stress and t the time.

The general principles have now been elucidated, and although much detail requires yet to be filled in, the present paper gives a description of the conclusions to date.

EXPERIMENTAL

By far the most serious difficulties that have been encountered were those associated with the reproducibility of measurements on different test pieces from the same dough. In papers I, II, and III accurate replication on different test pieces was not attempted, and although the phenomena described could be repeatedly observed, it was realized that no fully satisfactory technique existed for such replication. In the course of the present investigation much time has been spent in developing such a technique, and the method finally adopted has proved on the whole to be satisfactory.

TABLE 1

The effect of mixing on the viscosity and modulus of the dough

TIME OF MIXING	TIME OF RESTING AFTER MIXING	VISCOSITY*	MODULUS*
minutes	*minutes*		
3	0	6.38×10^6	4.29×10^4
	30	4.92×10^6	3.94×10^4
	60	4.04×10^6	3.73×10^4
12	0	2.92×10^6	3.02×10^4
	30	3.55×10^6	3.41×10^4
	60	3.51×10^6	3.50×10^4

* All data for viscosities (η) and moduli (n) in this paper are given in C.G.S. units, but it must be borne in mind that they refer only to arbitrary fixed conditions of stress and strain.

It is necessary to make as homogeneous a dough as possible, and it has been found that machine mixing of the flour and water gives the most satisfactory results. The longer the time of mixing, the more homogeneous is the finished dough, but excessive mixing has a very marked effect on the dough's physical properties.

From the data in table 1 it can be seen that excessive mixing considerably lowers the viscosity and modulus of the dough, but that these increase again on resting. Such treatment, however, permanently lowers the tensile strength of the dough.

It will be shown later that the general tendency on aging a dough is for the viscosity and modulus both to fall. It is only after prolonged mixing that the opposite effect more than compensates for this fall, producing a net rise in both properties. Thus it appears in table 1 that after 3 minutes mixing, the effect of standing is the opposite of that produced by 12 minutes mixing.

The sample of dough is transferred from the mixer to a "gun," consisting of a hollow metal cylinder, 5 cm. long and 2.5 cm. in diameter, fitted with a plunger. To the bottom of the cylinder is fitted a solid piece of metal drilled with a hole 3.5 cm. long and 0.5 cm. in diameter. This first gun, into which the dough can be placed by means of a spatula, thus avoiding handling it, is too big to fit conveniently on to the apparatus, and therefore the extended dough cylinder is squeezed straight into a second smaller gun 15 cm. long and 1 cm. in diameter, which is fitted with an end piece similar to that of the first gun. The dough is forced from this second gun straight on to the surface of a bath of mercury.

Statistical analysis[5] showed that there was no greater error in comparing test pieces from different doughs than in comparing pieces from the same dough. It thus appeared that the chief source of error lay in the method of preparation of the test pieces. It was found that the force applied to the guns very largely affected the physical properties of the prepared dough cylinder. A system of pulleys and weights was therefore used for manipulation of the guns, and, provided that the weights were small, we found very little alteration of the properties of the doughs. The importance of a carefully standardized use of these guns cannot be too strongly emphasized.

During extrusion the dough cylinder swells, this swelling being in general greater for good than for poor quality flours. The exact connection, however, is not clearly understood.

The dough cylinders have been examined by the two general methods described in papers I, II, and III, namely (a) rheograms, and (b) the mercury trough extensimeter, but the technique of the latter method has been extended and developed.

(*a*) *The rheogram method.* This method has been further developed and has now reached a stage at which the results are excellently reproducible, and, although not free from errors, it provides the most satisfactory way at present available for separating the effects of work-hardening (rise in viscosity with rising strain) and structural viscosity (fall in viscosity with rising stress).

In most doughs these two properties appear, under the conditions of the rheogram experiments, approximately to cancel out. Without committing ourselves to any assessment of the degree of accuracy of individual samples, an examination of the data obtained from a study of some sixty doughs made from a series of twenty different flours, leads to the conclusion that certain flours tend to show higher or lower degrees of work-

[5] Our best thanks are due to Mr. F. Yates of the Rothamsted Experimental Station Statistical Department for doing this analysis.

hardening than others, and that this property generally persists when different amounts of water and times of aging are used. Such differences do not, however, correlate directly with flour quality, and we conclude that weakness in a flour due to an unsuitable degree of work-hardening is the exception rather than the rule.

Certain practical difficulties are encountered in using the rheogram technique in the case of sticky doughs, and doughs of poor tensile strength. Moreover, both viscosity and rigidity modulus can be calculated from a single test on the extensimeter (*vide infra*); therefore the rheogram method was not employed further in this investigation.

(*b*) *The extensimeter.* This instrument, which is an improved model of the extensimeter described in papers I and III, is shown diagrammatically in figure 1.

A dough cylinder A, about 10 cm. long by 0.7 cm. in diameter, made as described above, is floated on a mercury bath. The ends of this cylinder are connected by means of cork "chairs" and cotton threads to two small scales B, which are observed through low-power microscopes, C. The

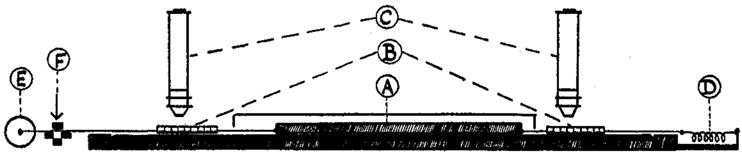

FIG. 1. The mercury bath extensimeter

smallest divisions on the scales are 0.013 cm. in length, and readings to one-tenth of this can be estimated with a fair degree of accuracy. To one scale is fastened a steel spring D, the other end of which is securely attached to the framework of the apparatus; the other scale is connected by cotton to a small winch (E), which can be wound either by hand or by a small motor.

During experiments the dough is protected by a cover, the felt lining of which is damped to provide a humid atmosphere to prevent drying out of the dough surface.

When the winch (E) is wound up, the dough and scales are moved to the left, and this extends the spring D. The dough is therefore subjected to a stress, the value of which is proportional to the extension of the spring, and inversely proportional to the cross section of the dough cylinder. The spring is calibrated by noting the extension caused by hanging weights of various sizes from it when placed in a vertical position. The diameter and initial length of the dough cylinder are measured with calipers.

In order to measure viscosity, which is defined (see paper I) as the ratio of shearing stress to velocity gradient (i.e., rate of change of non-recoverable strain), we can either fix the rate of change of strain and measure the stress, or fix the stress and measure the rate of change of strain. The latter has in practice been found to be by far the simpler method to use, and has been the basis for most of the experiments described in this paper.

Before doing an experiment, the necessary deflection of the spring to give the desired stress is first calculated from a knowledge of the constant for the spring and the cross section of the dough cylinder. The winch is then rapidly wound up until the shift in the scale attached to the spring corresponds to this required stress. For ordinary purposes we worked with an arbitrary tensile stress of 1500 dynes per square centimeter (shearing stress 500 dynes per square centimeter).

Under stress the dough cylinder extends, and for five minutes this extension is taken up by slowly winding the winch so that the deflection of the right-hand scale is kept constant. By this means the stress is kept almost constant, the rise in stress with slight thinning of the dough cylinder not being generally great enough to introduce any serious error, especially when relative, rather than absolute, viscosities of doughs are required.

By measuring the extension at minute intervals it would appear that the mean viscosity for each minute could be determined, and from this an indication of the amount of work-hardening (i.e., change in viscosity with strain) assessed. This is not, however, practicable, since elastic after-effect is taking place during the whole process (see introduction).

The stress is released at the end of the five minutes and the dough allowed to relax until no further change in length takes place (this takes about three to five minutes). The difference in the length of the dough cylinder before any stress is applied to it and at the end of relaxation gives a measure of the non-recoverable strain caused by the stress acting for five minutes.[6] From this a mean viscosity can be determined by dividing the non-recoverable strain per unit time into the stress. This is free from errors due to elastic after-effect.

The amount of recoverable or elastic deformation is obtained by noting the change in length of the dough cylinder between the time of releasing the stress and the end of relaxation. The value of the shear modulus which is given by the ratio

$$\frac{\text{change in shearing stress}}{\text{change in recoverable strain}}$$

[6] Strictly speaking, the strains should be calculated from $\log_e l/l_0$, as in the rheogram calculation, but for the small strains used the method described here is adequate.

is a *mean* value for a change in stress from 500 to 0 dynes,[7] the modulus falling progressively during the lowering of the stress due to elastic hysteresis (see introduction).

Effect of temperature

Experiments have shown that the viscosity of a typical dough falls by about 10 per cent per degree Centigrade rise in temperature and the modulus by about 5 per cent. This makes it desirable to exercise careful control over the temperature. The extensimeter is not easily thermostated, and, moreover, the processes of dough preparation should also be carried out at a constant temperature. It would thus be best to carry out all measurements in a constant temperature room.[8]

Although a suitable constant temperature room has now been built, the fact that it was not available for the earlier work meant that we could only make direct comparison between results obtained over periods during which laboratory temperature did not fluctuate very widely, and in consequence we have had to forego making as full use of our data as we should otherwise have been able to do. Further, since the viscosity falls about twice as fast (with rise in temperature) as does the modulus, it is clear that the all-important[9] viscosity modulus ratio (relaxation time) is higher, the lower the temperature. This supports the view held by some bakers that dough should be fermented and put into the oven at as low a temperature as is consistent with the satisfactory working of the yeast.

The temperature coefficients also vary with the age of the dough, and it is thus clear that the temperature at which it is aged plays an important part in defining its physical properties at any given time, and hence in determining the quality of the resulting bread. Further experiments are needed to explore this field.

WATER ABSORPTION

When determining the value of a flour in the bakehouse the first step is to turn it into dough by mixing with water and other ingredients. The baker does not use a constant ratio of flour to water for all samples, otherwise some of his doughs would be too soft and sticky, while others would be too tough, extremes of condition which not only cause serious difficulties in the handling of the doughs, but which do not result in bread representative of the value of the flour. In view of this, the baker varies the

[7] The stress is never allowed to fall quite to zero, owing to the necessity for keeping the cotton taut, but the final stress is very small, and is the same in all experiments.

[8] Care must be exercised to ensure proper ventilation and so prevent the danger of mercury poisoning (see Stock (9)).

[9] See later, under the section headed "general considerations."

amount of water he adds to each flour so that his doughs are easy to handle and in general bake into as good quality bread as his various flours are capable of making.

We are therefore faced with the problem of determining the significance of this optimum amount of water, or "water absorption" as it is called in the bakehouse, and also with the necessity of determining some method whereby it could be fixed. In assessing water absorption the baker relies on his sense of touch, and one of the impressions which helps in his judgment of correct absorption is the extent to which the dough sticks to his hands.[10]

It appeared to us that the baker made up his doughs so that the stickiness was just short of being a trouble, and on this assumption we based our

TABLE 2

Effect of water content on viscosity and modulus of flour doughs

FLOUR	WATER CONTENT				
	− 1 gal.	− ½ gal.	Normal	+ ½ gal.	+ 1 gal.
No. 1 Manitoba:					
Viscosity ($\times 10^6$)	10.0	7.5	5.8	4.8	4.1
Modulus ($\times 10^4$)	4.1	3.6	3.1	2.6	2.1
Barusso Plate:					
Viscosity ($\times 10^6$)	15.0	8.3	5.7	4.4	3.5
Modulus ($\times 10^4$)	4.6	4.0	3.4	2.8	2.2
Australian:					
Viscosity ($\times 10^6$)	7.5	4.8	3.5	2.8	2.3
Modulus ($\times 10^4$)	5.5	4.6	3.6	2.6	1.6

Normal absorptions: No. 1 Manitoba, 15.6 gals. per sack; Barusso Plate, 15.3 gals. per sack; Australian, 14.0 gals. per sack.

first attempt to connect water absorption with a physical property, so that by the measurement of the latter we could fix the former.

Measurements of stickiness were made by measuring the force required to overcome the adhesion of a metal weight to the surface of a dough. The method used was a modification of those proposed by Kachinski (3) and others (1, 2, 5, 7) for measuring the stickiness of soils. It has, however, not been possible to make the measurements reproducible enough to use as a means of assessing water absorption.

The connection between water content and two other physical properties, namely, viscosity and rigidity modulus, was next investigated.

For this a series of flours was obtained, and from each flour several doughs were made containing different amounts of water. The data

[10] For experiments on the psychological aspect of stickiness, see Zigler (12).

obtained by measuring the viscosities and moduli of the doughs made from three of these flours, a No. 1 Manitoba, a Barusso Plate, and an Australian are given in table 2.

Each flour was examined at the absorption chosen in the bakehouse which we have called "normal," and at four other water contents $\pm\frac{1}{2}$ gallon and ± 1 gallon per 280-lb. sack of flour.[11] Each dough was fermented for four hours, at the end of which time samples were taken for viscosity and modulus measurements. In figure 2 curves are drawn showing the relationship between these two properties at each of the five water contents for each of the three flours.

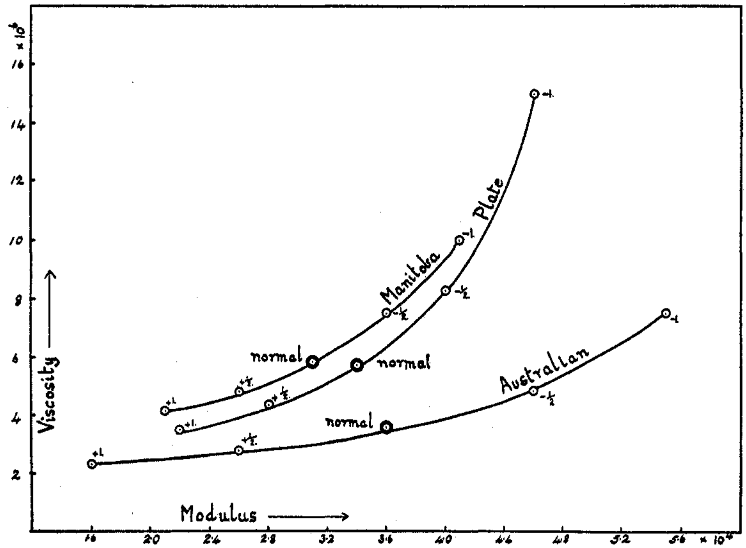

FIG. 2. The effect of water content of dough on the viscosity and modulus

An examination of these curves shows that with each flour both viscosity and modulus fell with increasing water content and vice versa. The relative effects on these two properties were not the same, and differed from flour to flour. The effects of a change of 2 gallons in water content on viscosity and modulus are given in table 3, the figures representing the difference in values for the driest and wettest doughs expressed as a percentage of the average.

These figures show that the effect both on viscosity and modulus was least in the case of the Manitoba, which is in keeping with the experience

[11] One gallon per sack = 3.57 per cent on the flour.

of the baker that this type of flour has a much greater tolerance to changing water content than any other. The Plate flour differed from the Manitoba chiefly on account of the much greater effect of changing water content on viscosity, while in the case of the Australian both viscosity and modulus, and particularly the latter, were more markedly affected than in the case of the Manitoba. It is probable that a big upward change in viscosity with decreasing water content is of much less account in the bakehouse than a big increase in modulus, as the latter would make the doughs "dead" and lifeless (see later).

The three doughs of particular interest are the "normal" doughs, and it will be noticed that these doughs differed very considerably in viscosity, but only to a small extent in modulus. It is probable that the baker is unconsciously more influenced in choosing his water absorption by the moduli of his doughs than by their viscosities, and in consequence we may be able to use measurements of the former property as a means of determining correct water absorption. This point, however, needs much further investigation before it can be settled.

GENERAL CONSIDERATIONS

Although it is quite possible to make a dough from any flour whatsoever so that it shall have any desired viscosity or modulus (within wide limits), by using the appropriate amount of water, it is well known that a poor flour cannot by any such means be made to give a dough of satisfactory plastic and elastic properties. The reason for this is clearly seen from table 3. It is here apparent that if a "strong" flour dough (Manitoba) is compared with a "weak" (Australian) at the same viscosity, the modulus of the strong flour is much lower than that of the weak. If the comparison is made at the same modulus value, the strong flour has by far the greater viscosity. The intermediate Plate flour falls between the two extremes. This suggests that the relaxation time (η/n, see paper I) is of primary importance. This suggestion has been amply verified. It is, of course, clear that we cannot regard relaxation time as a constant of a dough, since it varies with both stress and deformation, but it has become increasingly evident during the course of this work that if doughs are compared under similar conditions of stress and strain, and if these conditions approximate as closely as possible to those obtained in the commercial dough, a comparison of relaxation times ("viscosity–modulus ratios") gives a primary measure of the differences in flour quality (although as is shown later, many other factors have to be taken into consideration as well). In paper I it is suggested that "the dough contains elastic elements which form a connected structure . . . (which elements) are not joined securely, but slide past one another whenever a sufficient stress is operative. The viscosity which has been determined is mainly governed by the behaviour of a plastic film by which the elastic elements are connected. It is quite possible that the elements are capable of complete elastic recovery, but there is at present no criterion for testing this. The time of relaxation is a characteristic of the connected structure as a whole and its value is as much determined by the elasticity of the elements as by the viscosity associated with their plastic junctions. . . . In relating these deductions to the known structure of the dough, one may safely identify the elastic elements with the protein part of the flour."

When a dough rises under the action of yeast, it is advantageous for as high a percentage as possible of the deformation to be elastic (recoverable). Non-recoverable deformations imply flow of the cell-walls, leading to their rupture, and collapse of the dough due to inability for it to hold its shape, resulting in a loaf having large and badly shaped holes, a poor volume, and bad over-all shape. Big elastic extension resulting from low modulus tends to produce a big rise when the dough is first placed in the oven, and hence big loaf volume.

TABLE 3

Effect of change in water content

	MANITOBA	PLATE	AUSTRALIAN
Viscosity	83	124	106
Modulus	64	70	105

The property by which an extended dough on release recovers a high percentage of its extension, is called by bakers "spring." It is clear that the extent to which the dough fails to return to its original length after such an extension will depend on how far the elastic elements have slipped past one another. This depends on the amount of friction between them, which, as we have seen, corresponds to the viscosity of the dough (as normally measured). The higher the viscosity, the less the slippage. But the amount of slippage depends not only on the viscosity, but also on the internal stress set up in the elastic elements. If we think of these as coiled springs, it is easy to see that the "lighter" the springs (i.e., the lower their moduli), the less stress will be built up for any given extension, and hence the less will be the slippage for a given viscosity. Thus a dough showing good "spring" will have a relatively high viscosity and low modulus, whereas a dough having bad spring will have a relatively low viscosity and high modulus.

It is now clear why the baker attaches so much importance to "spring" in his doughs. Good spring means a high viscosity modulus ratio (big relaxation time), and, as already stated, this is (other things being equal) the primary characteristic of a good flour.

It is pertinent to enquire as to the significance of the extent of the variation of viscosity and modulus with stress, strain, and stress history for different flours. Experiment has shown that even widely different flours show a very similar degree of elastic hysteresis, and no marked differences in their elastic after-effect behavior. As explained in paper III elastic after-effect is important in that unless attention is paid to eliminate its effect, it is liable to interfere seriously with the correct determination of viscosity.

TENSILE STRENGTH

In the bakehouse occasional doughs are encountered which "tear" badly during the baker's manipulation and during the rising of the doughs under the pressure of the gas generated inside them. Such doughs are said to be "short" and bake into unsatisfactory bread. Owing to the tearing, excessive gas leakage occurs which results in poor loaf volume, and the actual tearing gives the outside of the loaf a ragged appearance. In addition, the insides of such loaves easily crumble when pressed with the fingers. It thus appears that for such flours tensile strength is also a factor of major importance. This property is now being investigated.

AGING AND FERMENTATION OF DOUGHS

In the process of bread making the doughs are kept for some hours before baking into bread. Not only do their handling properties depend on the length of this period, but the type of bread also shows considerable variation.

In order to determine the changes with age in the physical properties of such doughs, and to find what connections exist between these changes and bakehouse behavior, a series of flours was obtained which had been previously examined by the baker. The doughs were made up with the same ingredients as had been used in the bakehouse and were kept at 27°C., samples being taken at hourly intervals for viscosity and modulus measurements, which were made at room temperature.

The data obtained on four of these flours, a No. 1 Manitoba, a No. 3 Manitoba, a Barusso Plate, and a South Australian, are given in table 4, and curves drawn from these data are given in figures 3, 4, and 5.

It will be noticed that no data are given for freshly made doughs. This is because of the difficulty of obtaining reproducible measurements on them. Rapid changes take place during this initial period and are probably connected with the rate of absorption of water by the flour. After one-half to one hour these effects disappear, and the physical properties then change in a normal and regular fashion.

In the case of the above four flours, the changes in physical properties were almost linear functions of time.

TABLE 4

Effect of fermentation on viscosity, modulus, and the η/n ratio

FLOUR	TIME IN HOURS	VISCOSITY × 10^6	MODULUS × 10^4	η/n RATIO
No. 1 Manitoba	1.23	3.97	3.16	126
	2.12	3.82	3.02	126
	3.05	3.79	3.21	118
	4.93	3.32	2.99	111
	6.00	3.27	3.21	102
	6.93	3.25	3.09	105
No. 3 Manitoba	1.10	3.25	2.61	124
	2.03	2.84	2.37	120
	3.08	2.68	2.53	105
	5.02	1.88	2.18	86
	6.07	2.04	2.18	93
	7.03	1.83	2.03	90
Barusso Plate	1.18	3.33	3.53	94
	2.03	3.46	3.47	100
	3.13	2.83	3.23	87
	5.02	2.56	3.08	83
	6.00	2.45	2.76	89
	7.07	2.07	2.39	89
Australian	1.07	2.52	3.21	78
	2.05	2.18	2.92	74
	3.00	1.97	2.82	70
	5.00	1.39	2.32	60
	6.13	1.00	2.06	48
	7.00	0.76	1.58	48

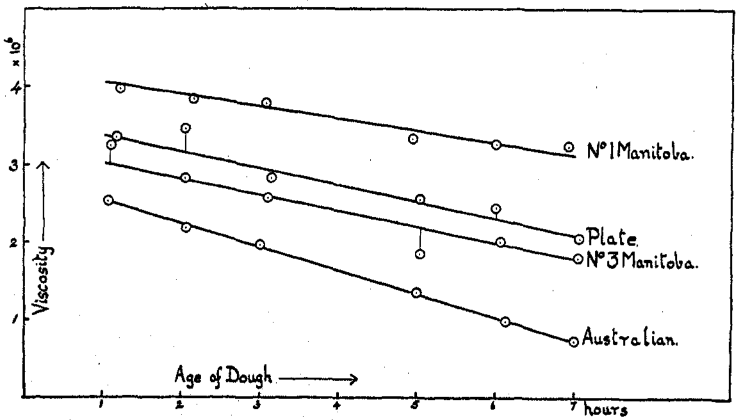

FIG. 3. The effect of age of the dough on the viscosity

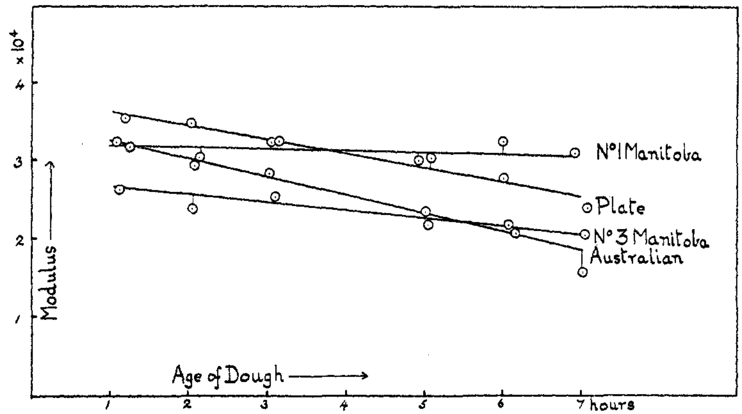

FIG. 4. The effect of age of the dough on the modulus

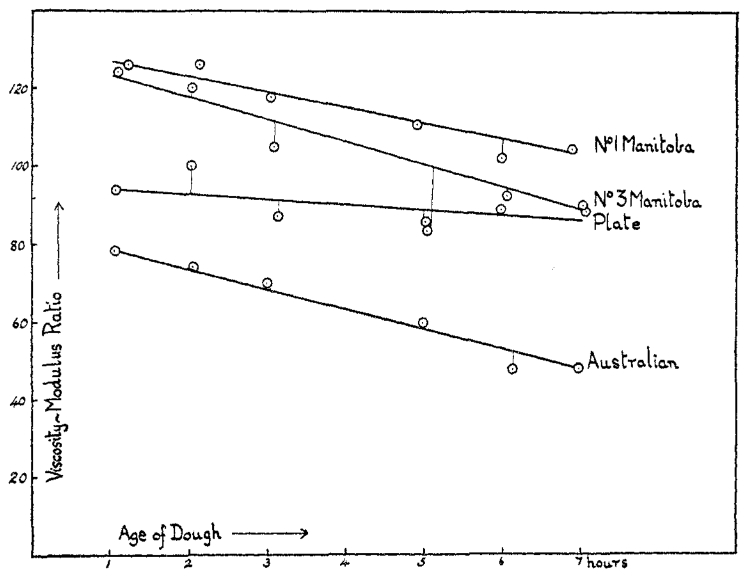

FIG. 5. The effect of age of the dough on the viscosity–modulus ratio

The data given in table 5 have been obtained from the curves (see figures 3, 4, and 5). An examination of the data shows that both viscosity and modulus fell with time of fermentation, and that in the case of each flour the viscosity fell more rapidly than the modulus, resulting in the ratio of these two properties also falling with increasing time.

In attempting to correlate these changes with the changes which took place in the handling properties of the doughs in the bakehouse, we were at once confronted with the fact that the baker reported that the No. 1 Manitoba dough improved in body and spring as fermentation progressed, that the Plate remained unchanged, and that the No. 3 Manitoba and Australian doughs became softer with increasing time.

TABLE 5

Change in physical properties with time

FLOUR	VISCOSITY AT		ACTUAL DECREASE	PERCENTAGE DECREASE
	1st hr.	7th hr.		
No. 1 Manitoba	4.05×10^6	3.17×10^6	0.88×10^6	22
No. 3 Manitoba	3.01×10^6	1.83×10^6	1.18×10^6	39
Plate	3.37×10^6	2.12×10^6	1.25×10^6	37
Australian	2.84×10^6	0.77×10^6	2.07×10^6	70
FLOUR	**MODULUS AT**		**ACTUAL DECREASE**	**PERCENTAGE DECREASE**
	1st hr.	7th hr.		
No. 1 Manitoba	3.19×10^4	3.05×10^4	0.14×10^4	4
No. 3 Manitoba	2.66×10^4	2.04×10^4	0.62×10^4	23
Plate	3.62×10^4	2.55×10^4	1.07×10^4	30
Australian	3.23×10^4	1.87×10^4	1.36×10^4	42
FLOUR	**VISCOSITY-MODULUS RATIO AT**		**ACTUAL DECREASE**	**PERCENTAGE DECREASE**
	1st hr.	7th hr.		
No. 1 Manitoba	127	104	23	18
No. 3 Manitoba	123	89	31	28
Plate	94	87	7	7
Australian	79	48	31	39

This improvement or toughening is associated by bakers with good quality. Several flours which have shown this response to fermentation in the bakehouse have been examined in the laboratory, and in every case both viscosity and modulus have been found to decrease with aging; in fact, no flour has yet been examined which showed a rise in either property during fermentation. It has been noticed, however, that those flours which have been reported as toughening in the bakehouse, were those which showed the smallest fall-off in physical properties when examined in the laboratory.

In the actual stretching of the dough during hand manipulation by the baker, dough does toughen,[12] but this happens with all flours, and in addition the effect disappears on resting. The toughening the baker speaks of in connection with good quality flours only, is considered by him to be due to the action of fermentation.

Careful tests have now been carried out in the bakehouse in which freshly made doughs were compared with fermented doughs made from the same Manitoba flour, which the baker considered had toughened. When the doughs were moulded side by side, one in each hand, and then allowed a few minutes to rest, it was reported by the baker that when tested by "feel" the older dough was very slightly the softer. It thus appears that bakers have been mistaken in their impressions that certain doughs toughen during fermentation.

When a series of replicate doughs is made from the same flour and allowed to ferment for varying times, it is found that with increasing time the volume and crumb quality of the bread at first improves, and then falls off. This improvement is considered by the baker to be due to what is called the "ripening" of the dough, the actual time to obtain maximum improvement varying with the amount of yeast, and with the type of flour used. "Strong" flours like Manitoba require much longer fermentation for optimum results than "weak" flours like English or Australian. Increasing the amount of yeast in the dough decreases the time of ripening.

Since viscosity, modulus, and relaxation time all fall consistently as the dough ages, it is difficult to explain the initial improvement in bread quality with time of fermentation in terms of the changes taking place in these physical properties.

The decrease in rigidity modulus with time is in itself desirable, but since it is the ratio of viscosity to modulus which is of primary importance in determining flour quality, the general result would be expected to be a fall-off, and not an improvement in bread quality. Also, if a fall in both of these physical properties were desirable, then a similar improvement in bread quality to that which takes place with fermentation could be brought about by using more water in the dough. This is not so, and even when the baker adds too much water to the flour, he still gets an improvement in bread quality with increasing fermentation time.

Although this improvement or "dough ripening" may be partly due to changes taking place in some physical property other than viscosity or modulus, it is possible to account for it on purely mechanical lines. Before a good loaf can be made, the necessary cell structure has to be built up in the dough, and this cell structure must be determined by the number and distribution of the yeast cells. Now normal bakehouse mixing is comparatively crude, and in consequence this distribution is probably anything

[12] See paper II, figure 6.

but uniform. Owing to the activity of the yeast, however, the dough swells, and this probably helps to spread the yeast cells. In addition, at various stages of fermentation, the baker knocks the gas out of the dough and moulds it up, thus again helping towards more uniform distribution. During fermentation the yeast cells multiply, and thus as time goes on the gas-producing centers increase in number.

If the above picture is correct, and it is the building up of the necessary cell structure which determines how much fermentation is required for any flour to give its best bread, then it should be possible to cut down this time by the use of more yeast and/or thorough mixing. That this is so is well known, and it has moreover been verified experimentally by us.

During fermentation we therefore have two processes going on side by side, an improvement due to the multiplication and better distribution of the yeast, and a falling-off in bread-making quality due to the decrease in value of viscosity and relaxation time. The improvement due to the yeast appears to be comparatively independent of the physical properties of the dough. With a good quality flour such as Manitoba, the fall-off in physical properties is so slight that good bread is produced over a large range of time, while on the other hand the fall-off in physical properties is so great with a poor quality flour like English, that the best bread is produced early, and is followed by a rapid fall-off in quality.

Returning to the data in table 5, the No. 1 Manitoba had the highest initial viscosity and showed the smallest decrease in this property with time. This flour also had the highest viscosity–modulus ratio either after one or after seven hours. This is all in keeping with the general quality of the flour as shown in the bakehouse, where it behaved as by far the best of the four.

The No. 3 Manitoba, however, had a much lower initial viscosity and a much greater fall in this property with time. This low viscosity was accompanied by a low modulus, so that the initial value of the ratio of these two was high, although it fell considerably with time. This flour was not up to standard for its grade, and although it produced bread of excellent volume (low modulus) the best loaf was "thrown" relatively early, and the later loaves had much poorer "crumbs," owing to the fall in viscosity.

The Plate flour had a much higher viscosity than the No. 3 Manitoba throughout the seven hours, but this was accompanied by a rather high modulus. The ratio was lower than that for the No. 3 Manitoba at the beginning of fermentation, but decreased very little, so that at the later times the two flours approached one another in this respect. The Plate was a very good sample for its grade and gave its best bread late. The bread was of good volume, and would probably have been better if the flour had been given more water at dough making. By increasing the water content, however, the viscosity would have been lowered, so that although the best bread would probably have had greater volume, it would have been made earlier, and might have had a poorer crumb structure.

The Australian flour with its low initial viscosity, low viscosity–modulus ratio, and considerable fall in both with time, would be expected to be much the poorest flour of the four, and this was found to be so in the bakehouse.

So far we have only dealt with doughs containing yeast. This ingredient is necessary to produce the gas which builds up dough structure, but has it any other function in bread-making?

Tests have been carried out in which the physical properties of doughs with and without yeast have been compared. The general results of these tests show that in small amounts such as are used in commercial bread-making, the effect of the yeast on the viscosity and modulus of the dough is probably not great enough to be of importance in the bakehouse. Very large amounts of yeast do affect viscosity, for example, in one case 8 per cent yeast lowered the viscosity from 3.6×10^6 to 2.9×10^6. The effect on the modulus and on the rate of change of either property with age of the dough was, however, insignificant.

CONCLUSIONS

1. Viscosity and rigidity modulus appear to be of major importance. The viscosity must be high enough to prevent undesirable flowing-out of the dough, but on the other hand the modulus must be low, to allow big elastic expansion under the relatively low pressure of gas inside a fermenting dough. The relaxation time (which is the ratio of these two properties) is perhaps the most important single criterion of quality.

2. The water content of a dough determines the magnitude of its viscosity and modulus, and it is desirable that variations in water content should have as small an effect on these properties as possible, thus helping towards making the flour more fool-proof in the bakehouse. Whether water absorption is important in other ways, apart from financial considerations to the baker, is not known.

3. The degree to which viscosity and modulus change during the aging of the dough is of the utmost importance. The fall in viscosity with time is probably a major factor in determining the fermentation tolerance of a flour, and not only is the absolute rate of fall of this property important, but equally so is its relative rate compared with the rate of fall of modulus, since this determines the fall in relaxation time.

4. Tensile strength is a major factor in determining the extensibility and gas-holding properties of a dough, and this is of the utmost importance, since a deficiency in these properties ruins the quality of a flour even when other factors are up to standard.

5. Stickiness is important in affecting the dough's handling properties; the dough must not be too sticky to work over that range of moisture best suited to its other properties, nor should excessive stickiness develop during fermentation.

6. It is realized that such properties as work-hardening, structural viscosity, elastic hysteresis, and elastic after-effect must play their parts in determining the behavior of dough in the bakehouse, but although their significance is not yet fully understood, it is certain that they are only of secondary importance in determining the relative values of different flour samples except perhaps in certain abnormal cases.

7. It is considered that measurements of the physical properties of doughs, as far as possible in absolute units and under standard reproducible conditions, should lead to a far better appreciation of flour quality than any number of empirical tests, and should afford a sound basis for the control of quality in flour.

SUMMARY

Methods described in earlier papers for measuring the viscosity and rigidity modulus of flour doughs have been extended and developed.

The physical properties of dough are markedly affected by excessive handling, either during the preparation of the dough itself or during the preparation of the test piece. The methods used have therefore to be carefully controlled.

Viscosity and modulus measured under standard conditions of stress and strain both decrease with increasing water content or with increasing age of the dough.

Good bread-making quality is associated with a relatively high viscosity and low modulus; the relaxation time, i.e., viscosity–modulus ratio, therefore appears to be the chief single criterion of quality.

Yeast in small amounts has little effect on viscosity or modulus, and its importance in bread-making appears to be entirely due to its gas-producing activities.

Tensile strength is a major factor in determining the extensibility and gas-holding properties of a dough, but work on this property is still at too early a stage to be discussed.

Stickiness is an independent property which can be roughly measured. Its principal importance lies in its effect on the handling properties of the dough.

The investigations have proceeded far enough to show definite relations between the physical properties of flour doughs and their bread-making qualities. It is suggested that it is along these lines that further insight into the nature of flour quality will be obtained.

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