INFLUENCE OF TEMPERATURE, SPEED OF MIXING, AND SALT ON SOME RHEOLOGICAL PROPERTIES OF DOUGH IN THE FARINOGRAPH[1]

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ABSTRACT

The relations between temperature and dough mobility in the farinograph, and also between temperature and absorption were found to be approximately linear. There is a change of 0.047 in mobility (12 B.U. at consistency of 500) and 0.52% in absorption per 1°C. The activation energy of dough mobility is of the order of 4 kcal. per mol. Dough development time was found to increase by 0.39 minutes per 1°C. fall.

At constant maximum dough consistency, a higher speed of mixing, 44 to 154 r.p.m., gave a higher apparent consistency or farinograph absorption. The logarithm (or square root) of mixing speed vs. consistency gave a linear function. For constant consistency or absorption the reciprocal of mixing speed was linearly related to dough development time. Dough consistency and development time are also linearly related with speed held constant.

When dough consistency was 500 B.U., 1% salt in dough produced a decrease in absorption of 2.3%; 2% salt produced a decrease of 3%. Similarly at 60% absorption, 1% salt decreased consistency by 70 and 2% salt by 90 B.U. At 500 B.U. the increase in dough development time was about 0.5 minute for each 1% salt in the flour studied.

In a recent paper (14) the writer described a simple relationship between dough mobility and farinograph absorption. This suggested a new approach for a more basic re-examination of the effect of the

[1]Manuscript received June 8, 1961. Paper No. 209 of the Grain Research Laboratory, Board of Grain Commissioners for Canada, Winnipeg 2, Manitoba, Canada.

more important variables on the properties and behavior in the farinograph.

The following survey of literature will review the main references dealing successively with the effect of temperature, speed of mixing, and salt on the physical properties of dough.

Studies on the relation between temperature and dough properties have not been many. Skovholt and Bailey (19) noted that the change in consistency per 1°C. was dependent on the range of consistency. Moore and Herman (18) and more recently Bayfield and Stone (3) studied the effect of temperature and absorption on a variety of practical farinogram indices.

Earlier studies of the effect of mixing have followed several directions. Bohn and Bailey (5), for example, varied the duration of mixing and studied the resulting changes in dough properties. Stamberg and Bailey (20) and Swanson and Bayfield (21) varied the speed of dough mixers and studied the optimum mixing requirements of doughs for breadmaking. Aitken, Fisher, and Anderson (1) used the farinograph at two speeds to study the development time and other farinogram properties. At the present time a variable-speed research model of the farinograph has become available. It has been used in the present study for a more systematic investigation of the effect of speed of mixing on the properties of dough in the farinograph.

Common salt is added to dough primarily to enhance the taste of bread. At the same time, the added salt has a variety of other effects including a marked effect on the physical properties of dough. In the extensigraph test the addition of salt increases both the resistance to extension and the extensibility of doughs (11). This strengthening effect is also indicated in stress relaxation experiments (12,13,15). Bohn and Bailey (6) reported that sodium chloride markedly increased stress readings in their plastometer. The Simon "research" water absorption meter, however, showed no response to the presence of salt (4). The farinograph shows a pronounced decrease in consistency upon the addition of salt to dough (4,18).

The present paper describes the results of experiments on the effect of temperature, speed of mixing, and salt on dough mobility and absorption, and on dough development time in the farinograph, and discusses some of the more fundamental as well as practical aspects of this study.

Materials and Methods

The flour used in this study was unbleached, improver-free, straight

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grade, and commercially milled from a blend of Canadian hard red spring wheat. The protein content was 13.2% and ash 0.46% on a 14% moisture basis. At a consistency of 500 B.U. the farinograph absorption was 64.5% and the dough development time was 7.5 minutes.

The farinograph, a variable-speed model equipped with a small stainless-steel-clad bowl, was normally operated at 62.9 r.p.m. and at a temperature of 30°C. For the temperature study, the temperature was varied from 15 to 40°C. by controlling the temperature of a circulating water bath. In each instance the temperature of the dough in the farinograph bowl was measured at the end of mixing. For the mixing speed experiments the farinograph speed was varied according to requirements. The speed was checked by actual count of the r.p.m. of the drive to the bowl.

The constant flour weight procedure was used to obtain farinograms, but the amount of water added was varied so as to give a range of dough consistencies at maximum from 400 to 600 B.U. In the experiments with salt, enough water was added as part of the doughing liquid to give 0 to 3% salt, flour basis. Dough mobility was obtained as the reciprocal of maximum dough consistency and was therefore minimum mobility for each dough. Dough development time was taken as the midpoint of the range from the first indication of leveling off to the first indication of the falling off of the farinogram. Both the top and the bottom of the curve were taken into consideration.

Experimental Results

I. Effect of Temperature

For convenience in presentation, the experimental results have been divided into three major sections. The first section deals with the effect on dough properties of temperature, the second with the effect of the speed of mixing in the farinograph, and the last with the effect of salt.

Effect of Temperature on Dough Mobility and Absorption. The initial aim of this part of the investigation was to obtain data on the effect of temperature on the relation between dough mobility and absorption. An equally important objective was to investigate the simpler and more fundamental aspects of the temperature effect on the rheological properties of dough.

Figure 1 summarizes the data in the form of minimum mobility vs. absorption curves for temperatures of 15 to 40°C. in 5° intervals. The main effect of increasing temperature is to displace the absorption vs. mobility curves downward, along the absorption axis. These are the primary data from which a variety of information can be extracted. Specific aspects will be discussed in the following subsections.

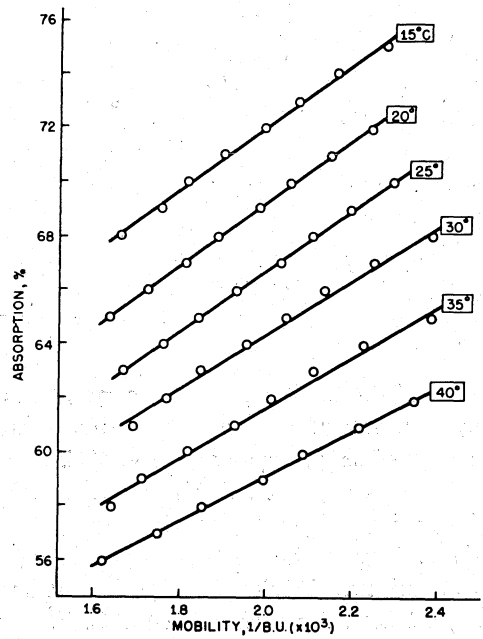

Fig. 1. Relation between dough mobility in the farinograph, and absorption, for different temperatures.

It has been pointed out in a previous paper (14) that the intercept of absorption vs. mobility curves may be interpreted as "bound" water; the remainder of the total water added is water of mobility, i.e., water associated with conferring the property of mobility to dough, broadly analogous to the action of a lubricant.

From an examination of the intercepts on the ordinate in Fig. 1, it may be inferred that as the temperature of the dough increases the amount of "bound" water decreases. Complementary with this, the amount of mobility water for a fixed absorption increases with increasing temperature. This interpretation helps to provide a reasonable mechanism of how the mobility of the dough increases with increasing temperature.

Effect of Temperature on Dough Mobility. Figure 2 shows a plot of temperature against minimum dough mobility for specified levels of absorption in a series of doughs. The graphs are linear, parallel, and equally spaced for equal increments of absorption. This provides a

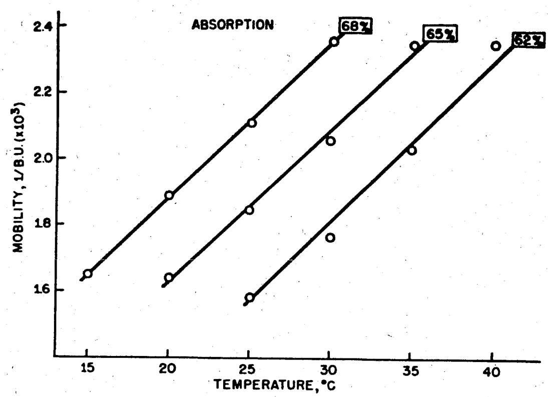

Fig. 2. Effect of temperature on dough mobility in the farinograph for different levels of absorption.

further illustration of the usefulness of the concept of dough mobility.

From this graph practical data can be readily obtained. For example, at an absorption of 65%, for a change of 1°C. there is a change of 0.047 in terms of dough mobility. In the more familiar terms of consistency the relation is more complex; the change in consistency per degree differs, depending on the range of consistency (19). In the range around 500 B.U. maximum consistency, the present data give a change of approximately 12 B.U. for a change of 1°C. in temperature. This value is somewhat lower than that indicated by Skovholt and Bailey (19), who give a change of 12 units in the range of 340 B.U. consistency and a change of 40 units in the range of 670 B.U. per 1°C. change in temperature for their flour and instrument.

Effect of Temperature on Farinograph Absorption. Figure 3 summarizes the relation between temperature and absorption for a given minimum mobility or maximum consistency. Here the relationship is also conveniently simple. The graphs are linear, equally spaced if plotted at equal intervals of mobility (rather than consistency), but the lines are not parallel.

In terms of practical indices, for a mobility of 2×10^{-3} (consistency of 500 B.U.), there is a change of 0.52% in absorption for a change of 1°C. in temperature for the flour used in this study.

Energy of Activation of Dough Mobility. The foregoing primary data on the effect of temperature on dough properties can be used to obtain an activation energy of dough mobility. This is analogous to the energy of activation of viscous flow (2) of water, for example. It turns out that the magnitude of the activation energy is quite interesting, as will be seen presently.

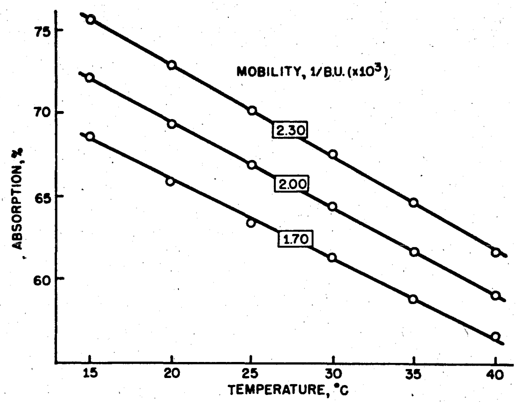

Fig. 3. Effect of temperature on absorption for different levels of mobility.

Before attempting to evaluate activation energies it is necessary to show that the plot of the reciprocal of absolute temperature (1/T) against the logarithm of the property under study is linear. Such a

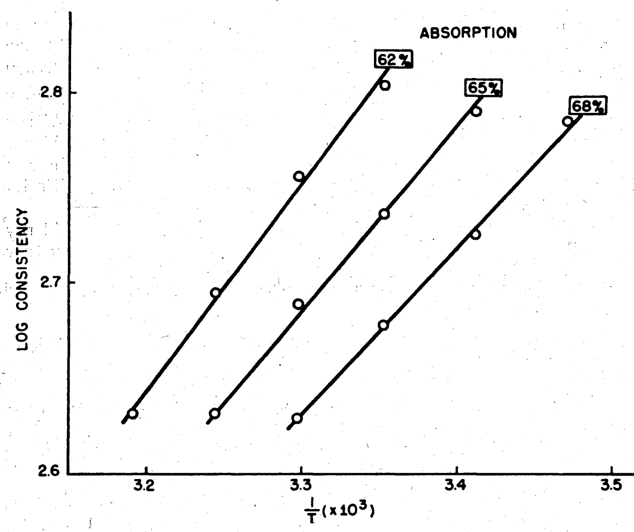

Fig. 4. Arrhenius plot for dough consistency for different levels of absorption.

plot is shown in Fig. 4, for 62, 65, and 68% absorption. The ordinate is log consistency. Mobility can also be used, with the only difference that the result will differ in sign.

The activation energies were calculated according to standard physicochemical procedures (2) using the formula

$$\log \frac{C_1}{C_2} = \frac{E}{2.3\ R} \left[\frac{T_2 - T_1}{T_2 T_1}\right]$$

where C_1 and C_2 are consistencies at temperatures T_1 and T_2.

Table I lists the activation energies for dough at three levels of absorption, together with some other data for comparison. The activation energy of dough mobility decreases with increasing water content of dough. The magnitude of the activation of energy of dough mobility is of the same general order as that of viscous flow of water or other fluids. It is lower than that for natural rubber and very much lower than that for polymethylmethacrylate systems.

TABLE I
ENERGIES OF ACTIVATION FOR DOUGH MOBILITY AND FOR VISCOUS FLOW OF OTHER MATERIALS

MATERIAL	ACTIVATION ENERGY	REFERENCE
	kcal/mol	
Dough:		
62% absorption	5.0	Present study
65% absorption	4.4	Present study
68% absorption	3.0	Present study
Water	4.0	Present study[a]
Tetrachloroethane	3.0	Alfrey (2)
Tetrabromomethane	3.7	Alfrey (2)
Paraffins	6.7	Treloar (22)
Natural rubber	8.1–10.2	Treloar (22)
Polymethylmethacrylate:		
No plasticizer	75	Alfrey (2)
30% plasticizer	52	Alfrey (2)

[a] Calculated from viscosity data for water as given in *Handbook of Chemistry and Physics* (ref. 16).

Two suggestions arise from a consideration of the magnitude of the activation energies of dough mobility. The first is that water plays a major role in dough mobility. This suggestion has already been made from independent consideration of other data (14). A second suggestion is that if the mixing process involves a larger particle size or rheological unit of dough with a consequently smaller total surface area or shear surface in dough, a low activation energy of dough mobility would be expected. Again, this idea is supported by consideration of independent data (7,9).

Effect of Temperature on Dough Development Time. Another common farinogram index is dough development time. Unfortunately, dough development time can at best be read to 0.25 minute, and the results by contrast lack the high precision obtainable with absorption vs. mobility measurements. Nor have we been as successful in relating dough development time to the more basic aspects of dough rheology. Nevertheless, the results should be of interest in understanding the rheology of dough in the farinograph.

Figure 5 shows that dough development is directly related to water content or absorption of dough, and that this relationship is different for each temperature. The change in dough development time per percentage unit of absorption can be readily evaluated. For the flour studied there is a change of 0.57, 0.31, and 0.17 minutes of dough development time per percentage unit of absorption at temperature levels of 25, 30, and 35°C. The influence of temperature in this instance is not large.

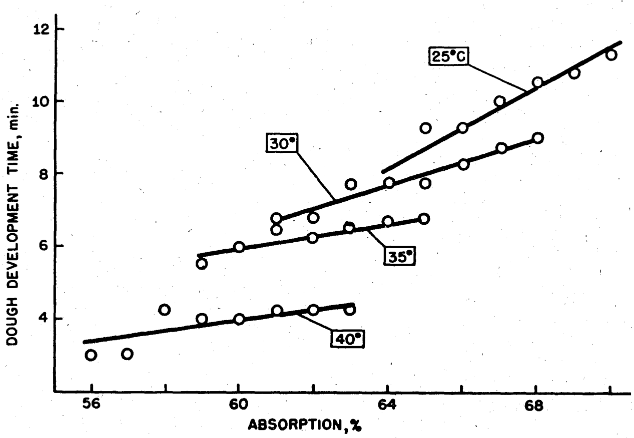

Fig. 5. Relation between dough development time and absorption for different temperatures.

Figure 6 shows the effect of temperature on the relation between dough development time and consistency. The relationship is linear. Here, a useful index is the change in dough development time per 20 B.U. of consistency. For the flour studied at temperature levels at 25, 30, and 35°C. there was a change of 0.5, 0.26, and 0.14 minutes in dough development time for each 20 units change in dough consistency. Again, the effect of temperature on this index is not large.

Finally, Fig. 7 represents the relations between dough development time and temperature for different levels of consistency. For the flour studied, and at a dough consistency level of 500 B.U., the change in dough development time for each degree was found to be 0.40 minutes.

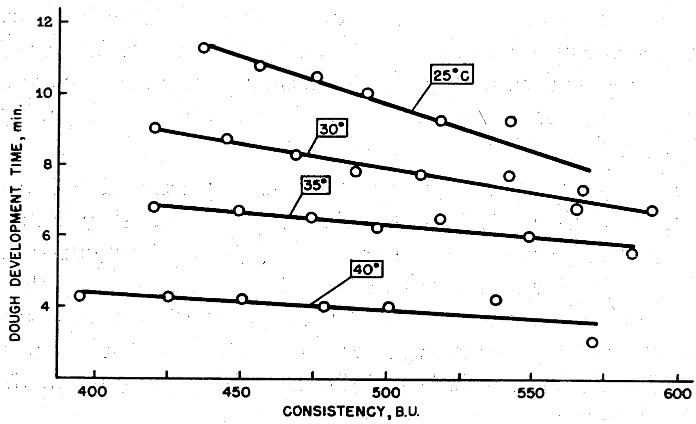

Fig. 6. Relation between dough development time and consistency for different temperatures.

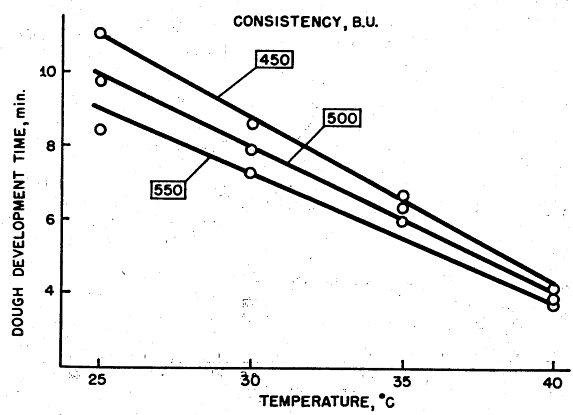

Fig. 7. Effect of temperature on dough development time for different dough consistency levels.

This is an appreciable change and indicates the importance of proper temperature control.

II. Effect of Mixing Speed

Effect of Farinograph Speed on Dough Mobility and Absorption. Another important factor that determines the behavior of dough in the farinograph is mixing speed. Figure 8 summarizes the data on the effect of farinograph speed on absorption vs. mobility curves for a range of speeds from 44 to 154 r.p.m. The general effect of increase in speed is to displace the absorption vs. mobility curves upward along the absorption axis (ordinate). More specifically, it may be noted that for a constant consistency (equal water content), a higher speed of mixing will lower the mobility (increase consistency). Complementary with this, with consistency constant, the higher the speed, the higher the farinograph absorption.

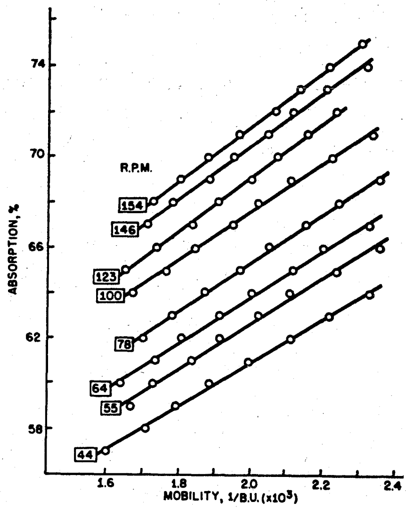

Fig. 8. Relation between dough mobility and absorption for different mixing speeds in the farinograph.

As has been pointed out previously, the intercept of these curves on the ordinate may be interpreted as "bound" water; the remainder of the total water added is water of mobility. According to this concept it may be inferred from Fig. 8 that as the speed of mixing increases the amount of bound water (intercept) increases, and complementary with this the amount of water of mobility decreases.

A reasonable explanation, in terms of a physical process that can be readily visualized, may be suggested for the decrease of mobility water with increased speed of mixing. At higher speeds the particles of dough slip past one another as a result of the high shearing force instead of by lubrication between the particles. To maintain a constant consistency the need for water of mobility thus decreases.

Effect of Farinograph Speed (Rate of Shear) on Dough Consistency or Mobility. A widely used relationship between the rate of shear and shear stress in rheological systems is the so-called power law (10,17), according to which the shear rate and shear stress are related exponentially. Although dough is quite a complex system, it also appears to be governed by the power law.

Figure 9 shows a plot of the logarithm of mixing speed (shear rate) against farinograph consistency. It should be noted that for a given absorption the change in consistency is an apparent change which results from an increase in the speed of mixing. Rheologically it may be regarded as a measure of shear stress. It is seen from the graph that for a given absorption the relation between the logarithm of shear rate (mixing speed) and shear stress (consistency) is linear. In other words, dough during mixing obeys the power law. Dough mobility can be used instead of dough consistency, with the only difference that the slope of the curves will be negative.

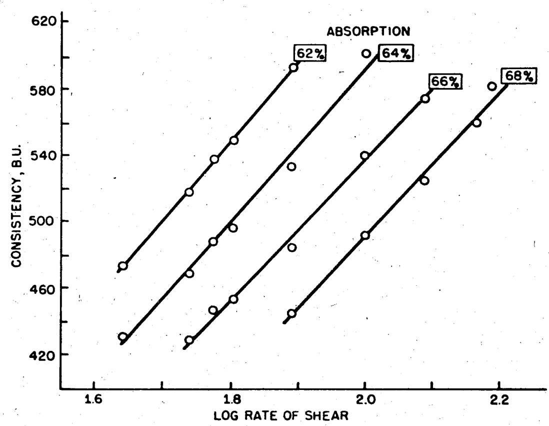

Fig. 9. Relation between the logarithm of mixing speed (shear rate) and farinograph consistency, with absorption held constant.

The slope of curves such as those shown in Fig. 9 may be of practical interest for evaluating the change in consistency corresponding to known differences in speed of a given mixer.

Effect of Speed (Rate of Shear) on Farinograph Absorption. A complementary aspect to that described in the preceding section is the relation between the rate of shear and absorption, with dough mobility or consistency held constant. Figure 10 shows a plot of the data. The relationship is linear if the logarithm of speed is used, and the lines are equally spaced if plotted at equal intervals of dough mobility rather than consistency. However, consistency is used here as it is obtained as a direct measurement.

Although the ordinate in Fig. 10 is farinograph absorption, it is related to dough mobility or consistency. Hence farinograph absorption may be regarded as a function of shear stress. Thus Figs. 9 and 10 are fundamentally related.

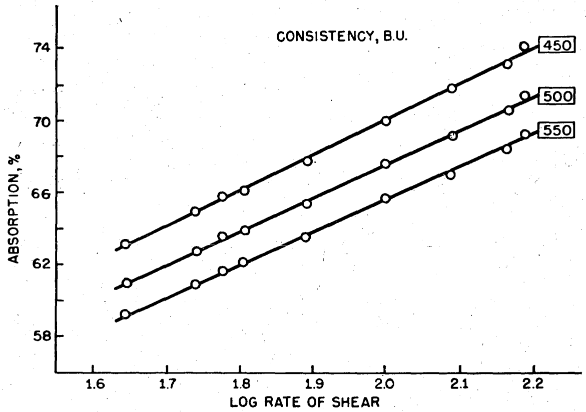

Fig. 10. Relation between the logarithm of mixing speed (shear rate) and farinograph absorption, with dough consistency held constant.

Again, curves such as those in Fig. 10 have a practical implication as well. One can calculate the change in farinograph absorption that corresponds to specified differences in mixing speed.

Relationship between the Square Root of Farinograph Speed and Dough Consistency. Another relationship between shear rate and shear stress has been proposed by Casson (8). Figure 11 shows the results plotted in this manner. Again, the result shows a linear relation between the square root of the rate of shear and consistency.

It appears that for dough the square root may be used interchangeably with the logarithmic relationship. Since neither relation has a

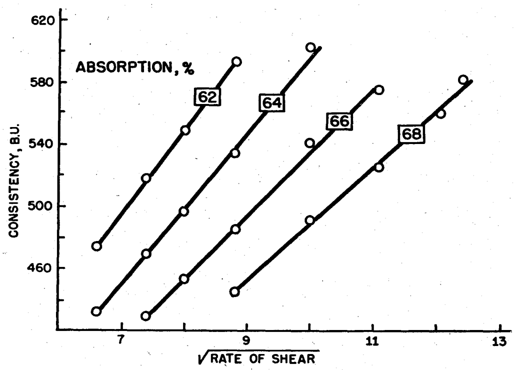

Fig. 11. Relation between square root of farinograph speed and dough consistency, with absorption held constant.

completely worked out scientific background, one cannot choose between them at this stage.

Effect of Farinograph Speed on Dough Development Time. This last section deals with experimental data on the effect of farinograph speed on dough development time. One of the more effective ways of presenting these data is to plot the reciprocal of speed against development time. Figures 12 and 13 summarize the data.

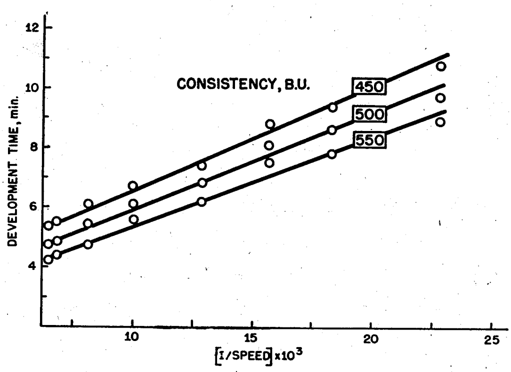

Fig. 12. Relation between farinograph speed and dough development time, with consistency held constant.

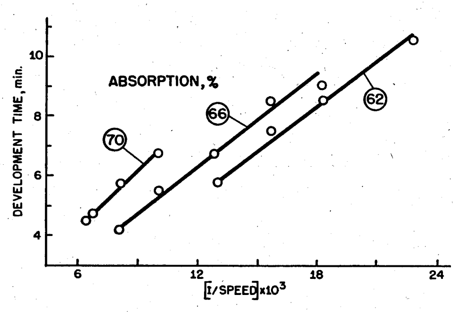

Fig. 13. Relation between farinograph speed and dough development time, with absorption held constant.

Figure 12 shows that, for constant consistency, the reciprocal of mixing speed (rate of shear) is linearly related to dough development time. Figure 13 shows a similar relation although over a more limited range, for the condition of constant absorption.

Another way of expressing these relationships is to say that the product of development time and speed is a constant. Hence if we obtain this constant for given conditions we can readily calculate the development time for any desired speed of the mixer.

A final graph, Fig. 14, shows the relation between dough consistency and development time with speed held constant. The relationship is linear and thus one can calculate the change in development time corresponding to a given change in dough consistency.

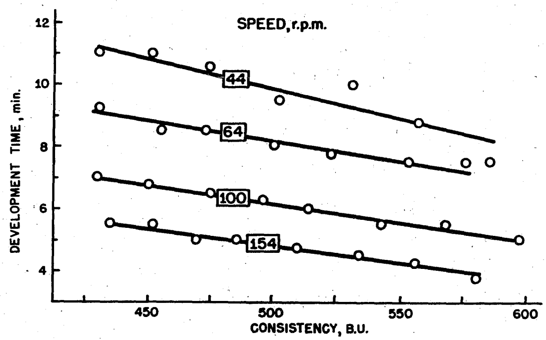

Fig. 14. Relation between dough consistency and dough development time, with farinograph speed held constant.

III. Effect of Salt

Effect of Salt on Absorption-Mobility Relationship in Dough. Another important common factor that influences dough properties is the added salt. Figure 15 summarizes the absorption-mobility curves for salt concentrations from 0 to 3% (flour basis). The general effect

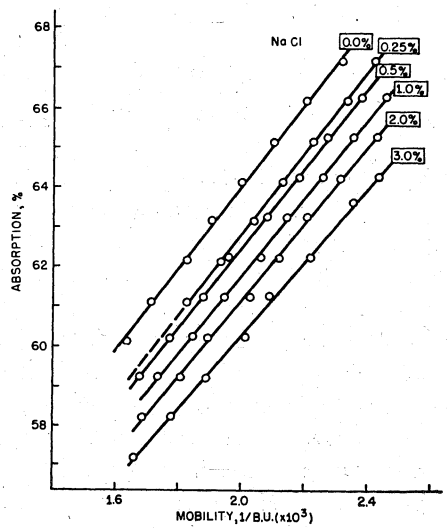

Fig. 15. Effect of salt on absorption-mobility relation.

of the salt is quite pronounced; salt tends to displace the curves downward on the absorption axis, i.e., it tends to decrease the absorption.

Once again, it is of interest to consider the intercepts of the graphs from the point of view of "bound" water. As the salt content of dough increases, the amount of "bound" water decreases. Complementary with this, the amount of mobility water for a fixed absorption must therefore increase, thus increasing the mobility of dough. This interpretation helps to provide a reasonable picture, in terms of a physical process, of how the mobility of the dough increases with increasing salt.

A further examination of the relation between the salt concentration in dough and water of mobility is shown in Fig. 16. The water of mobility was calculated as the intercept of the regression equations corresponding to the lines shown in Fig. 15. The results show that if consistency is held constant at 500 B.U. for example, the water of mobility decreases linearly with increase in the concentration of salt.

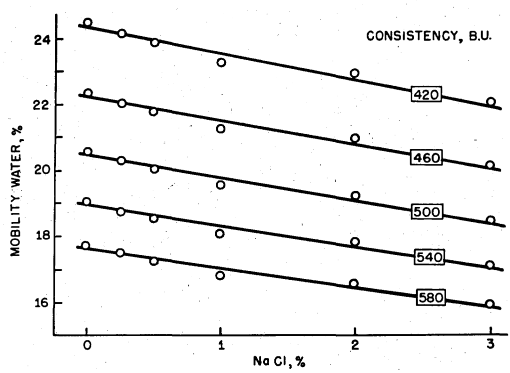

Fig. 16. Effect of salt on water of mobility with dough consistency held constant.

Effect of Salt on Farinograph Absorption and Dough Consistency. From a practical point of view the most important questions are, first, how large an effect does the salt have on absorption if consistency is maintained constant, and second, how large an effect does the salt have on dough consistency if absorption is maintained constant. Answers to these questions are presented graphically in Figs. 17 and 18.

Figure 17 (and the data on which it is based) shows, for example, that if dough consistency is held constant at 500 B.U. the effect of the first 0.25% salt is to decrease the absorption by 1.2% for the flour studied. The effect of subsequent increments is somewhat less and tends to become linearly related to salt concentration. For 1% salt the decrease in absorption is 2.3%, and for 2% salt the decrease is 3.0%.

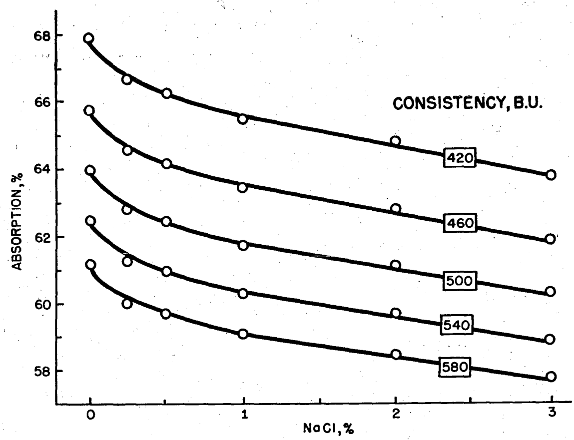

Fig. 17. Effect of salt on absorption with dough consistency held constant.

Similarly, Fig. 18 (and the data on which it is based) shows that for the flour studied the effect of the addition of the first 0.25% salt decreased the dough consistency by 40 B.U. for 60% absorption. The decrease was smaller at higher absorptions. At the 60% absorption level, salt concentrations of 1 and 2% gave a decrease in consistency of 70 and 90 B.U., respectively.

Effect of Salt on Dough Development Time. Another common farinogram index is dough development time. Unfortunately, dough development time can at best be read to 0.25 minute. Since the range of

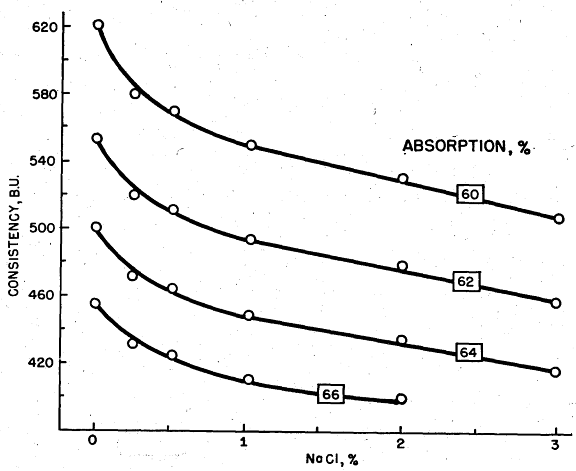

Fig. 18. Effect of salt on dough consistency, with absorption held constant.

dough development times is also somewhat small, the results, by contrast with absorption-mobility data, show a lower order of precision. Nevertheless the results are of interest.

Figure 19 shows the effect of salt on dough development time, first, with the condition that absorption is held constant, and second, that consistency is held constant. The general effect of salt is to increase dough development time. For constant absorption the effect of salt is to increase dough development time by about 1 minute for each 1% salt. At a constant consistency of 500 B.U. the effect of salt is to increase dough development time by about a half-minute for each 1% salt for the flour studied.

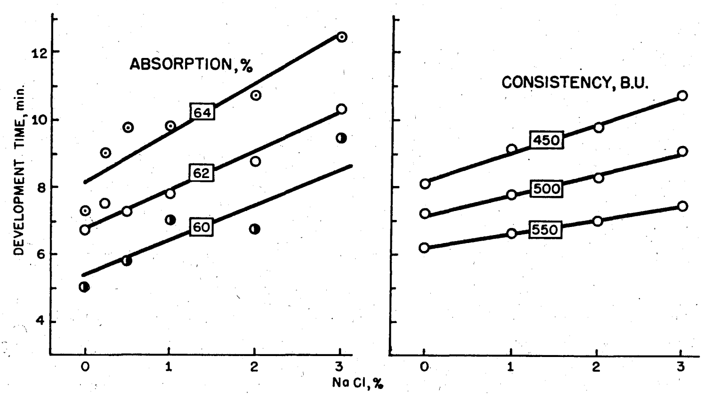

Fig. 19. Effect of salt on dough development time: left, with absorption constant; right, with consistency held constant.

Concluding Comment

The farinograph is a complex instrument and rheologists, given a choice, would select an instrument of simpler design that would give more readily interpretable results. Similarly, dough is a complex mixture of materials, and chemists and rheologists would prefer a simpler and a better chemically defined system. Nevertheless, the cereal chemist must accept dough as a basic material for his studies. Moreover, the farinograph is a widely known and well-established instrument used for assessing flour quality. With small modifications it is also now widely used in other industries under the name of plastometer.

The results presented in this paper indicate that in spite of the complexity of the farinograph and of the dough system, some progress can be made. The emphasis has been primarily on examining some of the more fundamental relationships in both their basic and practical aspects. The values that have been obtained should be considered as illustrative. A detailed study of flours varying widely in quality, and a further application of the more promising findings reported here, will remain a task for future research.

Acknowledgment

The writer gratefully acknowledges the able technical assistance of E. J. Zebrowski and F. D. Kuzina.

Literature Cited

1. AITKEN, T. R., FISHER, M. H., and ANDERSON, J. A. Effect of protein content and grade on farinograms, extensograms, and alveograms. Cereal Chem. **21**: 465–488 (1944).
2. ALFREY, T., JR. Mechanical behavior of high polymers. Interscience: New York (1948).
3. BAYFIELD, E. G., and STONE, C. D. Effects of absorption and temperature upon flour-water farinograms. Cereal Chem. **37**: 233–240 (1960).
4. BENNETT, RUTH, and COPPOCK, J. B. M. Dough consistency measurement of water absorption on the Brabender farinograph and Simon "research" water absorption meter. Trans. Am. Assoc. Cereal Chemists **11**: 172–182 (1953).
5. BOHN, L. J., and BAILEY, C. H. Effect of mixing on the physical properties of doughs. Cereal Chem. **13**: 560–575 (1936).
6. BOHN, L. J., and BAILEY, C. H. Effect of fermentation, certain dough ingredients, and proteases upon the physical properties of flour doughs. Cereal Chem. **14**: 335–348 (1937).
7. BUSHUK, W., and HLYNKA, I. The bromate reaction in dough. III. Effect of continuous mixing and flour particle size. Cereal Chem. **38**: 178–186 (1961).
8. CASSON, N. *In* Rheology of disperse systems, chap. 5, ed. by C. C. Mill. Pergamm Press: London (1959). (Cited by G. W. Scott Blair in: Recent advances in laboratory techniques; rheology. Laboratory Practice **9** (11): 733–776; 1960.)
9. DEMPSTER, C. J., and HLYNKA, I. Some effects of the mixing process on the physical properties of dough. Cereal Chem. **35**: 483–488 (1958).
10. DODGE, D. W. Fluid systems. Ind. Eng. Chem. **51**: 839–840 (1959).
11. FISHER, M. H., AITKEN, T. R., and ANDERSON, J. A. Effect of mixing, salt, and consistency on extensograms. Cereal Chem. **26**: 81–97 (1949).
12. GROGG, B., and MELMS, D. A method for analyzing extensograms of dough. Cereal Chem. **33**: 310–314 (1956).
13. GROGG, B., and MELMS, D. A modification of the extensograph for the study of externally applied stress in wheat dough. Cereal Chem. **35**: 189–195 (1958).
14. HLYNKA, I. Dough mobility and absorption. Cereal Chem. **36**: 378–385 (1959).
15. HLYNKA, I., and ANDERSON, J. A. Relaxation of tension in stretched dough. Can. J. Technol. **30**: 198–210 (1952).
16. HODGMAN, C. D., ED. Handbook of chemistry and physics (41st ed.). Chemical Rubber Pub. Co.: Cleveland, Ohio (1960).
17. MOONEY, M., and BLACK, S. A. A generalized fluidity power law and laws of extrusion. J. Colloid Sci. **7**: 204–217 (1952).
18. MOORE, C. L., and HERMAN, R. S. The effect of certain ingredients and variations in manipulations on the farinograph curve. Cereal Chem. **19**: 568–587 (1942).
19. SKOVHOLT, O., and BAILEY, C. H. The effect of temperature and of the inclusion of dry skim milk upon the properties of doughs as measured with the farinograph. Cereal Chem. **9**: 523–530 (1932).
20. STAMBERG, O. E., and BAILEY, C. H. Relationship of mixing speed to dough development. Cereal Chem. **15**: 739–748 (1938).
21. SWANSON, E. C., and BAYFIELD, E. G. The effect of mixing speed and dry milk solids on bread volume. Cereal Chem. **22**: 214–224 (1945).
22. TRELOAR, L. R. G. The physics of rubber elasticity. Clarendon Press: Oxford (1949).