Starch Damage and Alpha-Amylase as Bases for Mathematical Models Relating to Flour Water-Absorption

E. A. FARRAND, Ranks Hovis McDougall Limited, London, England

ABSTRACT

The relative amounts of water absorbed by the main components of flour are postulated as major factors contributing to the rheological properties of dough and to flour-quality attributes in terms of baking characteristics. Dough formation is considered as a problem of hydrating protein to form gluten, disaggregation of flour particles, and spreading the gluten over the starch to form a continuous matrix. Damaged starch is introduced in terms of arbitrarily measured absorption characteristics and consequent changes in surface area to be covered by the gluten. A relation is derived, expressing the optimum level of starch damage as a function of protein content. Absorption is finally expressed in terms of protein, moisture, and starch damage, the calibrating constants being obtained from a statistical evaluation of the Brabender farinograph absorption for reference flours at optimum starch damage. The mathematical model estimates flour water-absorption with precision similar to that of routine Brabender farinograph measurements, but has the advantage of giving additional information concerning the nature of the absorption. An ancillary equation is also described relating optimum levels of alpha-amylase to the level of starch damage, to ensure doughs with adequate gassing power and minimum rheological instability.

Studies of the measurement of flour water-absorption have been confined mainly to subjective assessment within a framework of test-bake operations and instrumentation procedures based on dough rheology.

Greer and Stewart (1) showed a significant correlation between analytical data for flour milled from English wheat and absorption, but the procedures were not suitable for commercial application. Farrand (2) reported a simple model to demonstrate that increase in starch damage was correlated with increase in absorption.

This paper makes a serious attempt to grapple with problems involved in using flour parameters to construct an absorption model sufficiently informative and reliable for commercial application in computerized control of quality-cost optimization in the flour-milling industry.

MATERIALS AND METHODS

Calculations were made with the Olivetti Programma 101 Desk Top Computer.

Methods

Rheological Absorption. Brabender Farinographs (Brabender OHG, Duisburg, W. Germany). The measurements were "as-is"; flour and water were used to point of minimum mobility at 600 B.U. Constant flour solids and constant dough weight techniques were not used, because in commercial practice variations in absorption are adjusted against a constant weight of flour as purchased.

Determinations. Protein, Kjeldahl N × 5.7. Moisture, 10 g. flour dried for 1.75 hr. in fan-ventilated oven at 127°C. Alpha-amylase and starch damage, Farrand units (2).

Mathematical Model. Relevant conditions appertaining to development of the mathematical model are:

1. Known variations in intrinsic properties of major flour components are replaced by a model system; e.g., variations in particle size and damage susceptibility of starch relating to a population of commercial flours are replaced by a model starch. Similarly, conventional gluten quality attributes are replaced by a model protein.

2. The level of starch damage measured is a statistical equivalent of a heterogeneous distribution of damage in the individual granules, resulting from mechanical abrasion under conventional conditions of commercial milling. The figure is expressed in arbitrary units related to the percentage of the starch that is damaged (Farrand, 2).

DEVELOPMENT OF A MATHEMATICAL MODEL FOR ABSORPTION

The reference flour (see table below) gave a farinograph absorption of 57.3% (16.0 gal. per sack) at starch damage D = 24 units.

Reference Flour, Basic Composition

Moisture, M, %	14.5
Protein, P, %	12.0
Starch, S, %	69.0
Unspecified components, U, %	4.5
Total, T, %	100.0

The unspecified components consisted of approx. 1.0% free fatty material, 0.5% ash, approx. 1.0% sugars, and approx. 2.0% pentosans, gums, etc. The role of these components in connection with the absorption problem was not known. The sugars and ash were partly soluble; the fatty material had only an adsorptive interfacial effect and no absorption; but the pentosans and gums were expected to contribute to the viscous component of the over-all absorption. For the purpose of developing the absorption model, the following assumptions were made:

1. Variation in protein content was accompanied by a corresponding change in starch content such that P + S = 81.
2. The unspecified components remained substantially constant and any absorption effects spread over the measured components.
3. The starch content (S) of any flour in terms of the reference flour was given by: S = 81.0 + 14.5 –M –P = 95.5 –M –P.
4. Gluten was formed from protein when protein absorbed twice its own weight of water.
5. Damaged starch (D) absorbed its own weight of water by definition.
6. Undamaged starch absorbed no water, but could adsorb up to 20% water before the vapor pressure approached that of water.
7. Free water was required to obtain conventional dough consistency in addition to the basic absorption and adsorptions.

Water absorption factors were as follows:

System Component	*Absorption Factor*	*Absorption Component*
Protein	2.0	2P
Damaged starch	1.0	S.D /100
Undamaged starch and free water associated with unspecified components	k	k[S – (S.D /100)]

where k was the water adsorbed by the undamaged starch, solution and/or

adsorption of the unspecified components and free water required for a reference dough consistency.

Therefore the total absorption by the flour solids was given by:

$$\text{Absorption} = 2P + (S.D/100) + k\,[S - (S.D/100)]$$

The absorption by 100 parts of flour at M% moisture:

$$A = \{2P + (S.D/100) + k\,[S - (S.D/100)]\} - M \qquad (1)$$

The value of k was found by substituting the reference flour figures in the above equation:

$$\left\{24 + \frac{69 \times 24}{100} + k\left(69 - \frac{69 \times 24}{100}\right)\right\} - 14.5 = 57.3$$

$$k = 0.60$$

Development of Basic Absorption Equation

A may now be expressed as follows by substituting k = 0.6 in equation 1:

$$A = 2P - M + S(0.6 + 0.004D)$$

To obtain an absorption equation in terms of the routine analytical data, protein, moisture, and damaged starch, it was necessary to eliminate S from the above equation. From the basic reference data,

$$S = 95.5 - M - P$$

Therefore, substituting for S:

$$A = 1.4P + 0.38D - [1.6M + 0.004D(M + P)] + 57.3 \qquad (2)$$

RELATION BETWEEN PROTEIN CONTENT AND STARCH DAMAGE

Assumed Functions of Gluten and Starch

The characteristics of a bread dough depended on the protein's hydrating to give sufficient gluten to form a continuous matrix, which completely covered the surface of the starch.

Practical absorption and baking tests indicated that the formation of insufficient gluten became highly significant with flours of approximately 7% protein content and 8% starch damaged.

Effect of Starch Damage on Covering Power of Gluten

The most efficient use of starch damage in terms of absorption was considered further.

Absorption of water increased the volume of the starch and thereby increased the surface area of the starch component of the flour. Consequently, more gluten was required to give an equivalent cover compared with undamaged starch. Any increase in the protein content of flour was accompanied by a corresponding decrease in the starch content, and was expressed P + S = 81. Therefore, if, for

example, a flour at 10% protein and 71% starch gave satisfactory results and the protein was increased to 11% with 70% starch, there was more protein covering less starch (assuming no physical change in the state of the starch) and, in terms of the functional use of protein, the extra protein was ineffective. However, if the level of damage in the 70% starch was increased so that the surface was equal to that of the 71%, the covering powers of the 10% and 11% levels of protein were equally efficient.

Therefore, a useful criterion for the optimum level of damaged starch was that which kept the surface area of the total starch component constant at an arbitrary level while the level of protein varied.

Relation between Protein and Starch at Constant Surface Area

The starch component of any flour made up from damaged and undamaged starch expressed in terms of D, the measured starch damage, was: Undamaged component, $S - (S.D/100)$; damaged component, $(S.D/100)$.

It was assumed that the undamaged component had surface unity and the damaged component, surface K_1. Then for any flour of varying protein content, since $S = 81 - P$:

$$(81 - P) - \frac{(81 - P)D}{100} + \frac{K_1 (81 - P)D}{100} = K_2$$

where K_2 was a secondary arbitrary constant in relation to unit surface for undamaged starch increased to K_1 for damaged starch; whence, $8{,}100 - 100P - 81D + D.P + K_1(81D - D.P) = K_2$

Accepting the experimental data on the limiting optimum covering power of protein, i.e., 7% protein, 8% starch damaged, 12% protein, 24% starch damaged, a solution of simultaneous equations in K_1 and K_2 was found: $K_1 = 1.48$; $K_2 = 7{,}690$. $K_1 = 1.48$ was the factor representing the increase in surface area compared with undamaged starch of unit surface area.

An independent approximation of K_1 can be made by considering the starch granules as a system of homogeneous spheres, and change in surface area resulting from doubling unit volume as $(3\sqrt{2})^2 = 1.58$.

This figure is a little greater than $K_1 = 1.48$, but the indications are that the model damaged starch has approximately 50% greater surface area compared with undamaged starch.

$K_2 = 7{,}690$ is an arbitrary constant relating to the surface conditions set out in the basic premises.

A relation between damaged starch and protein was established in terms of $K_1 = 1.48$ and $K_2 = 7{,}690$ in the original equation as follows:

$$8{,}100 - 100P - 81D + P.D + 120D - 1.48P.D = 7{,}690$$

whence, $D = (100P - 410)/(39 - 0.48P)$.

This relationship gave the optimum level of starch damage for any level of protein. The relationship was expressed as follows: let

$$(100P - 410)/(39 - 0.48P) = P^2/K_3$$

where K_3 is an arbitrary number that must be proved to be reasonably constant over the relevant range of protein content. Rearranging the equation:

$$K_3 = [P^2(39 - 0.48P)]/(100P - 410)$$

It was required to show that $\frac{\delta K_3}{\delta P} \sim$ zero:

$$\frac{\delta K_3}{\delta P} = \frac{78P - 1.44P^2}{100P - 410} - \frac{100\,(39P^2 - 0.48P^3)}{(100P - 410)^2}$$

Substitute P = 10, midpoint of the protein range, as follows:

$$\frac{\delta K_3}{\delta P} = \frac{780 - 144}{1{,}000 - 410} - \frac{390{,}000 - 48{,}000}{348{,}000}$$

$$= 1.07 - 0.98$$

$\therefore \frac{\delta K_3}{\delta P} \sim$ zero

$\therefore K_3$ was accepted as approximately constant.

The value of K_3 was found by substituting the reference protein P = 12 in the original equation:

$$K_3 = \frac{P^2\,(39 - 0.48P)}{100P - 410} = 6.05$$

Therefore an optimum level of starch damage for normal levels of protein was represented as $P^2/6$.

The validity of this simple relationship is set out in Table I.

TABLE I. RELATION BETWEEN OPTIMUM STARCH DAMAGE AND PROTEIN CONTENT

Protein (P)	Damaged Starch from $(100P - 410)/(39 - 0.48P)$	Damaged Starch from $P^2/6$
15	35	37
14	31	33
13	27	28
12	24	24
11	20	20
10	17	17
9	14	14
8	11	11
7	8	8

DEVELOPMENT AND MEANING OF A CONSISTENCY CORRECTION FACTOR

The basic equation gave the absorption in terms of protein, moisture, and starch damage. Estimated absorptions showed good agreement with farinograph absorptions for flours having characteristics similar to those of the reference flour. However, flour that differed markedly from the reference flour in terms of protein and starch damage often gave estimated absorptions that differed significantly from the farinograph absorptions.

The nature of the differences was investigated with many flours, including

Buhler-milled flours from single wheats, and the following information was obtained from an analysis of the results.

When the level of starch damage satisfied the optimum $P^2/6$ relationship, the deviations were significantly less, and appeared to be at a minimum.

When deviations occurred because the $P^2/6$ relationship was not satisfied, the magnitude of the deviation was also associated with the deviations in the protein content from the reference flour figure, 12%.

A consistency correcting factor satisfying these conditions was $(12/P) \cdot [(6D/P^2) - 1]$, i.e., proportional to the protein deviation from 12.0 multiplied by the deviation from optimum starch damage arranged so that the expression vanished when $D = P^2/6$ optimum starch damage.

$$\text{Consistency correction factor} = (12/P)\ [(6D/P^2) - 1] \qquad (3)$$

Equations 2 and 3 were added to complete the absorption model:

$$A = 1.4P + 0.38D - [1.6M + 0.004D(M + P)] + \frac{12}{P}\left(\frac{6D}{P^2} - 1\right) + 57.3 \qquad (4)$$

The consistency correction factor was investigated in relation to data obtained when a small (50-g.) bowl was calibrated against a standard (300-g.) bowl. This was done by measuring the absorption at 600 B.U. in the standard bowl and recording the consistency when the measured amount of water was added to flour in the small bowl. To eliminate any flour solids effects, all samples were tested at 14.5% moisture content.

It was found that, on average, flours that gave 600 B.U. on the standard bowl gave similar results at 500 B.U. on the 50-g. bowl. However, systematic deviations from 500 B.U. were associated with protein content and levels of starch damage. Figures for some characteristic groups are given in Table II. This table shows clearly that differences in consistency given by two bowls were associated with level of protein content and starch damage. However, the level of differences probably also was associated with the nature of the differences between bowls.

The working hypothesis is that calibration problems of this type are minimized when $(12/P)\ [(6D/P^2) - 1]$ ~zero.

Deviations of the consistency correction factor from zero were considered further. Two examples of Buhler-milled flour with poor baking properties (characterized by very small loaves) in relation to the analytical characteristics were:

	Protein %	*Damaged Starch* %	*Value of* $(12/P)\ [(6D/P^2) - 1]$
Western Australian, 1962-63	8.5	35	2.0
English: Opal 1963	9.0	40	2.4

These figures referred only to specific samples of these types of wheat that happened to give relatively high levels of starch damage. In each case the glutens were neither proteolytically active nor heat-damaged. However, when these flours were blended with Manitoban flour in such a way that the consistency correction factor was reduced to zero, excellent bread of normal volume was obtained. This drew attention to the limitations of interpreting the test bakes of flours from individual wheats in relation to grists.

The problem arose that if values of 2.0 for the consistency factor explained unsatisfactory results, at what level of the value would a significant deterioration in

TABLE II. COMPARISON OF 300- AND 50-g. FARINOGRAPH BOWLS AT CONSTANT ABSORPTION

(All flours at 14.5% moisture and absorption measured in standard bowl at 600 B.U.)

Protein	Flour Starch Damage	Protein %	Damaged Starch %	Deviation from 500 Units[a] B.U.
(Reference)		12.0	24	± 0
High	Below optimum	13.4	24	+15
		13.4	23	+10
		13.0	18	+10
		13.4	23	+20
Low	High	08.9	30	–20
		08.9	30	–10
		09.1	29	–30
Low	Low	07.8	07	+50
		06.5	09	+60
		07.5	08	+60
		07.6	04	+50

[a] In 50-g. bowl when given standard bowl absorption.

bread quality become detectable? The consistency factor being zero at optimum damaged starch (i.e., $D = [P^2/6]$), the problem posed was: how far can the level of starch damage be varied from optimum without prejudice to baking quality?

Let the consistency correction factor $= \frac{12}{P}\left(\frac{6D}{P^2} - 1\right) = K_4$

$$\therefore D = (P^2/6) + (K_4 P^3/72)$$

$\therefore$ the deviation from optimum starch damage $P^2/6$ in terms of the consistency correction factor K_4 is given by $\pm K_4 P^3/72$.

It had already been indicated that when $K_4 \sim 2.0$, significant depression of loaf volume occurred in relation to protein content. The value for K_4 at which significant deterioration in quality and depression in loaf volume first became detectable was difficult to assess. Empirical information obtained from laboratory test-baking and analysis of commercial data indicated a value of K_4 between 0.2 and 0.4, considering the fact that it was economically desirable to maximize flour absorption, and hence, starch damage and bread yield, with minimum prejudice to bread quality.

Table III shows a relation between protein content, optimum starch damage, and deviations in starch damage for $K_4 = \pm 0.2$ and $K_4 = \pm 0.4$, and may be helpful in understanding the nature of the problem.

Negative values of K_4 gave the levels of damage below optimum. However, low levels of starch damage in relation to protein content had no adverse effect on baking quality, provided the lower water absorptions predicted by the basic absorption equations were used. Low levels of absorption did, however, have a most serious adverse effect on bread yield. In addition, there were subtle and recognizable differences in loaf characteristics, mostly favorable, when high-protein flours were compared at low levels and optimum levels of starch damage with the appropriate water absorptions. However, there was no evidence, in terms of modern

baking, that these subtle differences had any very great commercial significance. Consequently, only maximum values for D are given in Table III.

TABLE III. CONDITIONS FOR MAXIMIZING LEVEL OF STARCH DAMAGE (D) IN RELATION TO PROTEIN CONTENT

		$K_4 = \pm 0.2$ $(P^3/72) \times \pm 0.2$		$K_4 = \pm 0.4$ $(P^3/72) \times \pm 0.4$	
Protein % P	Optimum D $P^2/6$	Variation in D	Maximum D	Variation in D	Maximum D
14.0	33	±8	41	±15	48
13.0	28	±6	34	±12	40
12.0	24	±5	29	±10	34
11.5	22	±4	26	± 8	30
11.0	20	±4	24	± 7	27
10.5	19	±3	22	± 6	25
10.0	17	±3	20	± 6	23
9.0	14	±2	16	± 4	18
8.0	11	±2	13	± 3	14

The table shows clearly that at high protein levels relatively large variations in damaged starch are permissable. It also indicates how the level of starch damage becomes more critical when the protein content falls to or below 11.0%. For example, solving the basic equation for starch damage D at 14.5% moisture and 57.3% absorption (16 gal. per sack) gave D ~28% for 11.0% protein and D ~30% for 10.5% protein. At the former level of protein the starch damage exceeds the optimum level by an amount that is barely permissible, and at the latter level by an amount that would be expected to result in a significant reduction in loaf volume.

The validity of the foregoing development of the interpretation of damaged starch measurements is also dependent on compliance with certain rules concerning permissible levels of alpha-amylase activity.

RELATION BETWEEN DAMAGED STARCH AND ALPHA-AMYLASE IN TERMS OF GASSING POWER AND DOUGH CONSISTENCY DECREASE DURING FERMENTATION

The stability of the damaged starch component of flour absorption in terms of consistency at 30°C. was dependent on both the level of starch damage and the level of alpha-amylase. The concept of damaged starch in arbitrary units was based on the premise that rate of attack of a measured excess of alpha-amylase under standardized conditions is proportional to the water absorbed by the starch. The breakdown of the starch by alpha-amylase was also time- and temperature-dependent, and the over-all effect was to reduce the water-holding capacity, which lowered the consistency. The problem was further complicated in the presence of nitrogen-solubilizing and gluten-softening enzymes (3), but these effects were relatively small in sound wheats.

Therefore, a study was made at different levels of damaged starch and alpha-amylase in relation to total gassing power (30°C. and 760 mm. pressure) for doughs prepared at constant consistency. The following relationships were established at suitable levels of statistical significance:

1. The higher the total gassing power, the greater the decrease in dough consistency for any arbitrary fermentation period.

2. Doughs at constant consistency, with a variable dough weight containing constant flour solids, gave increases in gassing power linearly related to the level of starch damaged.

3. At constant starch damage, increase in gassing power was linearly related to the logarithm of the malt dosage or fungal amylase dosage, or both.

4. These relationships were studied over the range 10 to 35 units starch damage and 0 to 2 lb. per sack of malt; i.e., <1 to 64 Farrand units alpha-amylase.

5. Total gas production could not be characterized simply in terms of alpha-amylase and starch damage, since it was also markedly influenced by yeast activity, level of nitrogen-solubilizing enzymes and/or addition of ammonium salts, level of naturally occurring sugars in the flour, level of vitamin B-1, rate of change of pH, method of estimation, i.e., constant solids, constant consistency, constant weight, etc.

6. The total gassing power of the reference flour at 24% starch damaged, 8 units alpha, was found to require 16 units of alpha when the starch damage was reduced to 19%.

7. The reference flour figure represented the empirically developed framework within which increased starch damage and levels of alpha had been introduced without prejudice to baking quality and absorption.

Development of Empirical Relationship

Gassing tests established the following empirical linear relationships:

Increase in gas production $\Delta G = k_1 + k_2 \log \text{malt dosage}$

$\Delta G = k_3 + k_4$ starch damage

$\therefore$ combining equations, adjusting constants, and putting malt dosage = alpha F units alpha-amylase and starch damage = D(% F units):

$$\log \text{alpha} = K_5 + K_6 D$$

Substituting, when alpha = 8, D = 24: alpha = 16, D = 19, we have

$$K_5 = 2.34$$

$$\therefore \quad \log \text{alpha} = 2.34 - 0.06D \tag{5}$$

Transforming eq. 5 to base 2 and approximating gave an exponential form expressed in integers:

$$\text{alpha} = 2^{[8 - (D/5)]} \tag{6}$$

The relationship includes no calibrating constants; consequently it cannot be used to predict total gassing power. It merely expressed a relation between alpha-amylase and starch damage for control of gassing power which, in the limit, kept constant that part of the total gassing power due to starch damage and alpha. A corollary was that it kept constant that part of decrease in dough consistency during fermentation which was due to alpha and damaged starch.

A summary of model equations is given in Table IV. The table includes simpli-

TABLE IV. SUMMARY OF ABSORPTION EQUATIONS

Symbols:

A = % Farinograph absorption

P = % Protein (N × 5.7)

M = % Moisture

D = % Starch damaged (Farrand arbitrary units)

alpha = Alpha-amylase (Farrand arbitrary units)

Main equation:

$$A = 1.4P + 0.38D - [1.6M + 0.004D\,(P + M)] + \frac{12}{P}\left(\frac{6D}{P^2} - 1\right) + 57.3 \quad \text{(Eq. 4)}$$

Subsidiary equations:

Approx. conditions for 16 gal. per sack (280 lb.) (57.3% absorption) at optimum starch damage $P^2/6$

i) $1.4P + 0.38D = 1.6M + (D/10)$, where $P + M \sim 25$

ii) $P^2 + 30.5P - 35M = 0$ Moisture known, solve for P

iii) $M = \frac{P^2 + 30.5P}{35}$ Protein known, solve for M

Optimum alpha equation:

$$\text{alpha} = 2^{[8 - D/5)]}$$

fied subsidiary equations giving the relationships for 16 gal. per sack (57.3%) at optimum starch damage.

RESULTS

Application of Absorption Model

A series of tests was carried out in which six Brabender Farinographs were used. It was shown that for a group of flours the error of the absorption estimated from the model in relation to a single farinograph was of the same order as the error between six farinographs when the same flour was used. (Standard deviations 0.45 and 0.35 respectively.)

The results for a series of flours representing a cross-section of baker's grade flour milled in the U.K. are given in Table V.

This table shows that for 31 samples the average farinograph absorption 57.54% differed from the estimated absorption by 0.2 units. The farinograph figures varied from 55.5 to 61.4, range 5.9; the model absorptions varied from 55.0 to 61.2, range 6.2.

The coefficient of correlation between the farinograph and model absorptions was 0.924***. The regression coefficient, with the farinograph as the independent variable, was 1.04, and the standard deviation of the estimate of the model absorption, 0.56. This figure included any error in the independent variable, and indicated that the error in the model absorption was of the same order as the error in a farinograph absorption.

Attention is drawn to the fact that the model absorption contains the combined errors of the separate protein, moisture, and starch damage determinations. While the error for the routine analytical techniques is known, the nature of the model is such that the error of calculation depends not only on the standard deviations of the three variables, but also on the actual level of each variable. For normal values of the variables, the error due to the process of calculations alone is estimated within a range of standard deviations 0.3 to 0.5. Consequently, there can never be

an over-all agreement between the farinograph and model absorptions better than the respective intrinsic errors will allow.

It is suggested that since the two absorptions are independent, an average will give an absorption with a correspondingly reduced error.

COMPARISON OF THE ABSORPTION MODEL WITH CONVENTIONAL MULTIPLE REGRESSION ANALYSIS

An independent approach to the same problem was by statistical analysis, multiple regression technique. The multiple regression equation written in conventional form (4), with variables and regression coefficients, is as follows:

$$A = K_{a.pmd} + R_{ap.md}P + R_{am.pd}M + R_{ad.pm}D$$

The symbolism is explained as follows: $K_{a.pmd}$ is the value of A if P, M, and D were held constant at their mean values. $R_{ap.md}$ measures the rate of increase in A with increasing P when M and D are held constant at their mean values; similarly for $R_{am.pd}$ and $R_{ad.pm}$.

The limitations of this procedure were:

1. The absorption was expressed as the *sum* of three variables. This meant that independence of the three variables was assumed. This was manifestly not true; as the protein content of flour increased, the starch content was correspondingly reduced, and changes in moisture content altered the levels of all constituents in the flour.

2. The rate of change of absorption due to change in protein as expressed by the coefficient was related to the average values for M and D; i.e., it was related to the average values for the range of flours selected.

3. The limitations in no way altered the validity of the level of statistical significance at which any relationship was established.

4. Within the above limitations the equation was used to predict absorptions from protein, moisture, and damaged starch data.

It should now be possible to understand more clearly the differences involved when absorption is calculated with the use of a model related to arbitrary differential absorptions of the flour components, and from an over-all statistical operation:

1. Model based on differential absorption of flour components: Assuming that the empirically derived flour component absorptions were valid in flour doughs: the procedure was independent of the population of flours being considered.

2. Statistical multiple regression procedure: Depending on the average characteristics of the population of flours examined, and assuming that parameters obtained for the flour components were independent.

Both techniques were applied to a set of data, presented in Table VI, which covered a very wide range of values for protein, moisture, and damaged starch. The samples were flours from break and reduction machines, and included air-classified high- and low-protein fractions before and after regrinding in a Kek mill. The background of the experimental data is not relevant, and interpretation must be confined to absorption data.

Multiple regression analysis gave:

$$A = 68.26 + 0.878P + 0.334D - 1.97M \qquad (7)$$

TABLE V. FARINOGRAPH AND MODEL ABSORPTIONS FOR U.K. BAKER'S GRADE-FLOURS

Ref. No.	Protein %	Moisture %	Starch Damaged %	Farinograph Absorption %	Model Eq. 4 Absorption %	Difference Farinograph minus Model
01	12.2	13.5	15	57.10	56.60	+0.50
02	11.8	14.3	20	57.10	56.30	+0.80
03	12.3	13.4	20	58.40	58.50	−0.10
04	11.8	14.6	22	56.30	56.50	−0.20
05	12.0	13.8	19	57.30	57.10	+0.20
06	12.0	13.9	15	56.30	55.70	+0.60
07	12.2	13.7	17	56.30	56.90	−0.50
08	12.3	13.0	16	57.50	57.80	−0.30
09	12.2	13.6	16	56.60	56.70	−0.10
10	11.9	13.4	16	57.60	56.70	+0.90
11	12.4	13.8	16	56.00	56.70	−0.70
12	12.5	13.9	14	56.60	56.00	+0.60
13	12.2	13.6	19	57.30	57.70	−0.40
14	11.4	14.1	24	57.80	57.50	+0.30
15	12.3	13.3	28	61.40	61.20	+0.20
16	12.3	13.8	24	58.50	59.00	−0.50
17	12.3	13.2	19	57.70	58.50	−0.80
18	12.7	13.3	20	57.90	59.10	−1.20
19	12.2	13.6	20	57.30	58.00	−0.70
20	12.1	13.8	20	57.00	57.50	−0.50
21	12.1	13.9	19	56.30	57.10	−0.80
22	12.6	13.9	30	60.30	61.10	−0.80
23	12.4	13.2	22	58.60	59.50	−0.90
24	11.9	14.4	16	55.50	55.00	+0.50
25	11.3	14.2	21	55.50	56.20	−0.70
26	11.4	13.7	23	57.30	57.90	−0.60
27	11.6	13.6	23	58.70	58.30	+0.40
28	11.8	13.6	24	58.30	58.80	−0.50
29	11.2	13.9	28	58.50	59.00	−0.50
30	13.3	13.8	22	59.20	59.60	−0.40
31	12.6	14.2	21	57.40	57.80	−0.40
Av.	....	....	....	57.54	57.75	−0.21

The regression coefficients exceeded 0.1% level of significance. Table VI gives three absorptions for each sample: 1) farinograph as measured, 2) calculated from model, and 3) calculated from multiple regression equations.

The coefficients of correlation were:

Farinograph *vs.* Absorption Model 0.9907***
Farinograph *vs.* Multiple Regression 0.9901***
Absorption Model *vs.* Multiple Regression . 0.9985***

The coefficients of the variables, protein, moisture, and damaged starch, in the absorption model and the regression equation were compared as follows:

	Model	Statistical
Protein, P,%	1.4	0.88
Starch damaged, D,%	0.38	0.33
Moisture, M,%	1.6	1.97

The coefficients show the change in absorption associated with unit change of the variable. While the coefficients were of similar magnitude, the differences were significant and stemmed from the different nature of the premises used in each case. The statistical calculation assumed that the independent variables P, D, and M were, in fact, independent. The model absorption equation 6 included interaction

TABLE VI. FARINOGRAPH, MODEL, AND STATISTICAL ABSORPTIONS FOR A WIDE RANGE OF FLOURS

Flour	Protein %	Moisture %	Damaged Starch %	Absorption: Farinograph: As found, Flour – Water, 600 B.U. %	Absorption: Model Eq. 4 Moisture – Protein – Damaged Starch %	Absorption: Statistical Eq. 7 Multiple Regression Equation %
I and II BMR						
Original	13.0	14.8	16	55.0	55.8	55.8
HP fraction	16.9	9.6	35	77.0	75.0	75.8
LP fraction	12.7	14.6	16	55.0	55.7	55.9
Kek mill	13.1	13.2	21	59.0	60.1	60.7
HP fraction	19.8	9.6	30	79.0	77.3	76.7
LP fraction	12.7	13.1	14	57.5	57.6	58.2
C ROLL						
Original	9.7	14.0	34	60.5	59.7	60.5
HP fraction	14.1	10.0	63	81.0	79.8	81.9
LP fraction	8.2	14.1	29	59.0	57.0	57.3
Kek mill	9.7	12.3	36	65.0	63.4	64.5
HP fraction	17.8	8.5	61	84.0	85.6	87.5
LP fraction	9.1	11.8	34	63.5	63.2	64.3
D ROLL						
Original	11.2	13.7	35	62.8	61.7	62.7
HP fraction	14.5	9.7	67	82.0	82.0	84.2
LP fraction	11.0	13.6	31	62.0	60.3	61.4
Kek mill	11.4	12.1	38	68.0	66.6	67.1
HP fraction	17.3	9.3	56	84.0	82.1	83.8
LP fraction	10.5	12.2	33	62.4	63.0	64.4
G ROLL						
Original	11.1	13.2	42	67.6	64.8	66.0
HP fraction	14.2	9.9	66	84.0	81.0	83.2
LP fraction	10.6	13.0	38	64.0	64.3	64.6
Kek mill	11.2	11.6	46	72.8	69.1	70.6
HP fraction	17.3	9.1	67	90.0	85.7	87.9
LP fraction	10.2	11.5	43	69.0	67.6	68.9
Average				69.34	68.27	69.33

and consistency correction factors which, if not included, would have tended to decrease the protein and damaged starch coefficients and increase the moisture coefficient. The operational difference between the coefficients was not, therefore, as great as might have appeared at first sight.

DISCUSSION

A major limitation of all methods measuring flour water absorption on the basis of dough rheology is the arbitrary nature of the calibration facilities and the meager information given concerning factors causing changes in absorption.

Notwithstanding the difficulties, a great deal of empirical knowledge concerning flour milling and baking must have been built around information based on rheological performance. Any mathematical model constructed from absorption characteristics of major flour components, and showing satisfactory correlation with rheological absorptions, should enlighten the situation in terms of function, control, and calibration.

If it can be accepted that significance of the foregoing absorption model has been satisfactorily established, then weight should be added to the validity of underlying principles used in the construction:

1) The method and meaning of starch damage in Farrand units;
2) The concept of mixing flour and water to form a dough as a problem in disaggregating flour particles and spreading gluten over a varying starch surface to form a continuous matrix;
3) The optimum level of starch damage expressed as a function of protein ($P^2/6$) and the relevance of the consistency correction factor as a flour quality attribute;
4) The use of protein as the variable controlling gluten quantity, but no specific parameter for gluten quality; and
5) Correlation between protein quantity and loaf volume is implicit, but at every protein level optimization of loaf volume and bread yield (absorption) is related to the optimum starch damage.

It is feasible to consider that the thinner the gluten film is spread, the higher the level of work required, and the lower the intrinsic stability of the system. Cross-linkages in the thinner film can be strengthened by increased oxidation. Alternatively, the gluten can be softened with reducing agents or enzymes (or both), when less work would be required to spread the gluten, and the film can be subsequently stabilized either by a slow-acting oxidizing agent or by delayed addition. The gluten-starch spreading hypothesis should therefore be applicable to both conventional and modern bread processes.

In terms of the absorption model, all sound glutens are similar in that by oxidation, reduction, or mixing (or all three) they can be brought to the same physical state. Against this background, flour absorption can be calibrated at any appropriate level, where the proportions absorbed by the protein and starch are flour properties, and the unaccounted-for or free-water-controlling consistency is related to the nature of the process. Consequently, flour parameters alone cannot provide a unique solution to all rheological problems associated with production. Similarly, conventional interpretation of rheological parameters in terms of gluten quality must be subject to corresponding limitations.

On the other hand, it does not necessarily follow that an approach through mathematical models, based on flour parameters, will impoverish the status of dough rheology. In fact, a comprehensive appreciation of both procedures should lead to more confident and profitable decision-making.

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