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Flow Behavior of Wheat Flour-Water Dough Using a Capillary Rheometer. II. Effects of Water, Protein, Mix, and Rest Time[1,2]

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ABSTRACT

Doughs made with various combinations of water, protein, and mix and rest times were extruded at ambient temperature through a capillary of known geometry. The flow behavior of the doughs was described by a power law model. The consistency coefficient decreased with increasing water content in the doughs, but it increased with increasing protein content. Mix and rest times did not show a significant effect on the consistency coefficient. The flow behavior indices were not affected by water, protein, mix time, or rest time over the ranges studied. The consistency coefficients were predicted within reasonable accuracy by a quadratic model including only water and protein as independent variables. The quantification of flow properties could be used for quality control using automated process control in bakeries of the future.

The best known application of dough rheology is in determining the baking quality of flour (Muller 1968). Quality of the finished product is thought to be largely dependent on dough rheology. This has led researchers to investigate rheological properties of doughs in detail and to report the outcomes in a large number of publications (Udy 1953, Dempster and Hlynka 1958, Bayfield and Stone 1960, Glucklich and Shelef 1962, Hlynka 1962, Bloksma 1968, Funt et al 1968, Lerchenthal and Funt 1968, Navickis et al 1982, Faubion et al 1985, Abdelrahman and Spies 1986, Dreese et al 1988, Refai et al 1988, and Preston 1989). These studies evaluated the effect of mixing time, temperature, water, and several additives on the storage modulus, loss modulus, loss tangent, elasticity, and plasticity of doughs. In general, these studies were related to quality of flour and dough performance in baking, but the information cannot be applied to engineering calculations. In automated bakeries of the future, it is envisioned that the use of off-line or laboratory instrumentation will not be possible (Faubion and Faridi 1986). Rather, on-line sensors will assess the difference in the dough's mechanical properties, and a control system will order the necessary adjustments. Flour uniformity, dough consistency, and flow properties of dough are the characteristics that appear to be important for designing automatic control systems for the bakeries of the future. At present, not much information is available on the flow behavior of dough. Some literature exists on flow characteristics of flour-water and other food suspensions (Kitterman and Rubenthaler 1971, Doublier 1981, Doublier et al 1987, Vergnes and Villemarie 1987, Alloncle et al 1989, Steffe et al 1989), but the information is not applicable to doughs. Sharma (1990) studied flow characterization of dough itself, as opposed to flour-water suspensions, using the capillary technique, which proved to be successful in handling highly viscous doughs. The flow behavior of flour-water dough with a fixed composition (fixed amount of water and flour) was described. In reality, doughs can be made from flours with varying amounts of proteins, and with different amounts of water, depending on the desired final characteristics of the finished product. It is important to know how the flow behavior is affected by changes in water or protein content. Therefore, this study evaluated the effects of changing water content

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in doughs made from flours of different protein content. The influences of mix time and rest time on flow properties were also studied because of their known effects on dough performance.

MATERIALS AND METHODS

The capillary extrusion rheometer, as described by Sharma and Hanna (1992), was used to obtain necessary data on the flow rate and the pressure drop through the capillary. A brass capillary tube with a 3.2-mm inside diameter and a 49.7-mm length was used. The dough was extruded in the shear rate range of 3–600 sec^{-1}. Bakery flour and vital wheat gluten were obtained from ConAgra (Omaha, NE) and Ogilvie Mills, Inc. (Minnetonka, MN), respectively. The moisture contents of flour and gluten were determined to be 12.6 and 7.8% (wet basis), respectively, using the standard method of drying 3 g of flour at 130°C for 1 hr in a convection oven (method 44-15a, AACC 1983). The protein contents of flour and gluten were determined to be 14.3 and 69.3%, respectively, from the Kjeldahl nitrogen, using a protein conversion factor of 5.73 (method 46-11, AACC 1983). To obtain a flour with a higher protein content, bakery flour and gluten were mixed in a model 310 Hobart mixer (Hobart Corp., Troy, OH) using the appropriate amount of each after considering their individual moisture and protein contents. Flours with final protein contents of 20, 30, and 40% were prepared in this manner. The moisture content of final mixed flour (gluten and bakery flour) was determined using the standard method 44-15A (AACC 1983).

TABLE I
Rheological Data for Doughs Made from Flour with 14 and 20% Protein Using Different Water Contents, Mix Times, and Rest Times

Sample: Protein (%)	Water (%)	Mix Time (min)	Rest Time (min)	Plunger Speed (mm/min)	Force (N)	Pressure (kPa)	Shear Stress (kPa)	Shear Rate (1/s)
14	45	3	15	10	3,303	2,900	47	59
				20	3,842	3,370	54	117
				50	4,851	4,250	69	293
				100	6,223	5,460	88	586
20	45	2	0	10	3,881	3,420	55	59
				20	5,096	4,490	72	117
				50	6,635	5,850	94	293
				100	8,565	7,550	122	586
20	40	3	15	10	11,182	9,860	159	59
				20	13,612	12,000	194	117
				50	18,620	16,420	265	293
				100	23,912	21,080	340	586

TABLE II
Rheological Data for Doughs Made from Flour with 30% Protein Using Different Water Contents, Mix Times, and Rest Times

Sample: Protein (%)	Water (%)	Mix Time (min)	Rest Time (min)	Plunger Speed (mm/min)	Force (N)	Pressure (kPa)	Shear Stress (kPa)	Shear Rate (1/s)
30	40	2	30	5	8,212	7,240	117	29
				10	10,535	9,290	150	59
				20	10,868	9,580	155	117
				50	20,217	17,830	288	293
30	40	2	0	5	8,193	7,220	117	29
				10	11,025	9,720	157	59
				20	14,631	12,900	208	117
				50	17,287	15,240	246	293
30	45	4	30	10	4,018	3,540	57	58
				20	4,802	4,230	68	117
				50	6,899	6,080	98	293
				100	8,526	7,520	121	586

Water was added to the flour to attain final moisture contents of 40, 45, and 50% (wet basis) in the dough. These moisture contents in the dough were computed considering the moisture of the flour and the added water.

Mix times of 2, 3, and 4 min were used with the above three amounts of water to make the doughs in a Pin Mixer (National Manufacturing Co., Lincoln, NE). After the doughs were made, they were allowed to rest in plastic bags for 0, 15, and 30 min and then extruded.

A 1/3 fraction of a 3^4 factorial experiment was combined with axial and center points to form a central composite design to study the effects of protein and water concentrations and the effects of mix and rest times. With each combination of the four factors, dough was extruded with four different plunger speeds to obtain four values of shear stress and shear rate. Response surface regression analysis was used to develop the statistical model to predict the flow parameters of the flour-water dough as a function of the independent parameters studied.

Apparent shear rate was calculated as

$$\dot{\gamma} = 4Q/\pi r^3,$$

where $\dot{\gamma}$ = apparent shear rate (sec^{-1}), Q = volumetric flow rate (m^3/sec), and r = capillary radius (m).

Shear stress at the wall of the capillary tube was calculated as

$$\tau_w = \Delta P r/2L,$$

where τ_w = shear stress at wall (Pa), ΔP = pressure drop down the capillary (Pa), r = radius of capillary (m), and L = length of capillary (m). The Rabinowitsch correction factor was obtained

TABLE III
Rheological Data for Doughs Made from Flour with 40 and 50% Protein Using Different Water Contents, Mix Times, and Rest Times

Sample: Protein (%)	Water (%)	Mix Time (min)	Rest Time (min)	Plunger Speed (mm/min)	Force (N)	Pressure (kPa)	Shear Stress (kPa)	Shear Rate (1/s)
40	50	4	0	10	3,121	2,740	44	59
				20	3,935	3,450	56	117
				50	5,204	4,560	74	293
				100	7,879	6,910	111	586
40	50	2	0	10	2,421	2,120	34	59
				20	3,175	2,790	45	117
				50	4,444	3,900	63	293
				100	6,007	5,270	85	586
50	45	3	15	10	9,614	8,430	136	59
				20	10,819	9,490	153	117
				50	13,975	12,260	198	293
				100	15,935	13,980	226	586

TABLE IV
Sample Regression Constants for the Relationship $\log \dot{\gamma} = a + b \log \tau$ and the Correction Factor

Protein (%)	Mix Time (min)	Rest Time (min)	Moisture (%)	a	b	R^2	Correction Factor
14	3	15	45	−15.57	3.72	0.99	1.68
20	2	0	40	−11.75	2.65	0.99	1.41
20	2	15	40	−13.73	3.06	0.97	1.51
20	3	30	50	−5.78	1.94	0.98	1.23
30	2	30	40	−10.70	2.42	0.89	1.36
30	3	15	45	−10.87	2.65	0.94	1.41
30	4	30	45	−12.25	2.95	0.99	1.49
40	2	15	45	−9.98	2.41	0.99	1.35
40	2	30	50	−12.30	3.05	0.99	1.51
40	3	30	50	−10.90	2.82	0.97	1.46

from the slope of the straight line resulting from the plot of log shear rate versus log shear stress. Finally, corrected shear rates were obtained by multiplying the apparent shear rate by the Rabinowitsch correction factor. The end corrections were not applied because the doughs were extruded through only one capillary. The flow curves were obtained by plotting log shear stress versus log shear rate (corrected), which gave a comparative idea of flow parameters of doughs.

TABLE V
Regression Constants for the Relationship $\log \tau = a + b \log \dot{\gamma}$ for Some Doughs

Protein (%)	Mix Time (min)	Rest Time (min)	Moisture %	a	b	R^2
14	3	15	45	4.13	0.27	0.99
20	2	0	40	4.39	0.38	0.99
20	2	15	40	4.45	0.31	0.97
20	3	30	50	2.97	0.51	0.98
30	2	30	40	4.46	0.37	0.89
30	3	15	45	4.10	0.35	0.94
30	4	30	45	4.10	0.34	0.99
40	2	15	45	4.09	0.41	0.99
40	2	30	50	4.00	0.32	0.97
40	3	30	50	3.83	0.34	0.97

RESULTS AND DISCUSSION

The complete data on forces, pressure drops across the capillary, shear stresses, and shear rates generated while extruding different doughs are presented elsewhere (Sharma 1990), but some representative data are shown in Tables I–III. The shear rate and shear stress data had a power-law relationship with a coefficient of determination greater than 0.9, as shown in Table IV. Plots of the logarithmic shear stresses and the corrected logarithmic shear rates were linear, as suggested by the regression constants in Table V. This suggested that the flow behaviors of dough made with various combinations of protein concentrations, water levels, mix times, and rest times were satisfactorily described by a two-parameter power-law model over the range of shear rates studied. Representative flow curves for some of the doughs are shown in Figures

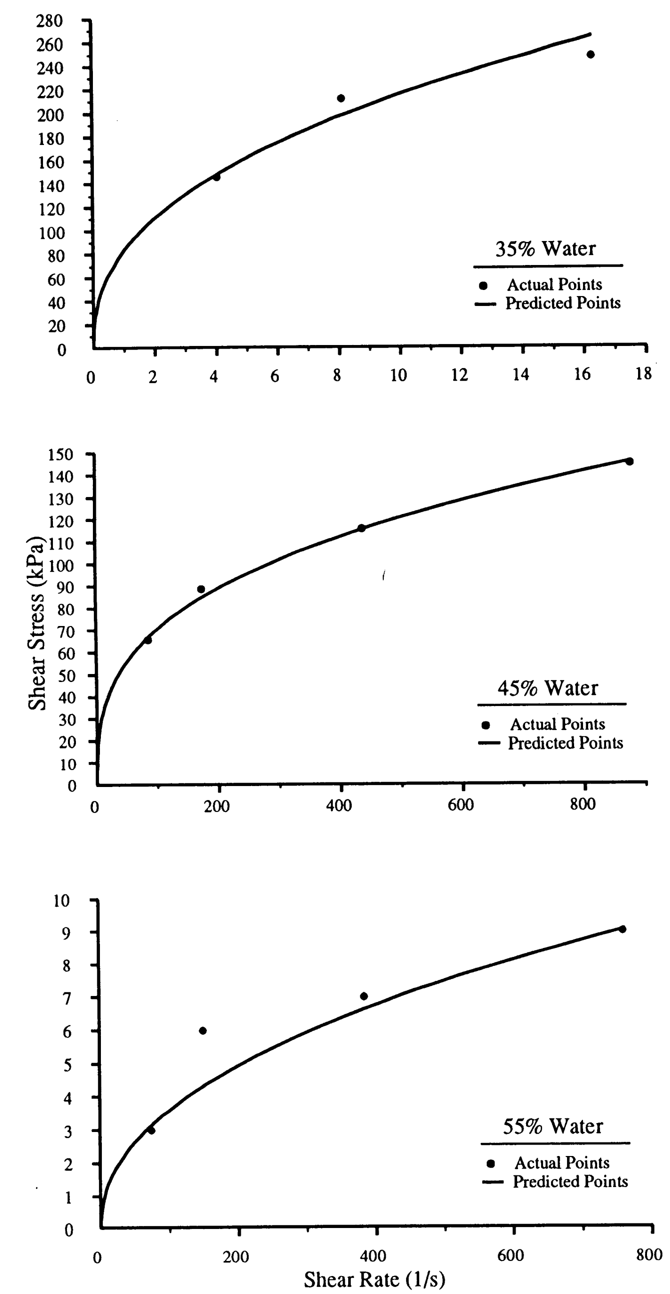

Fig. 1. Flow curves for dough made from 30% protein flour mixed with 35, 45, and 55% water for 3 min and rested for 15 min.

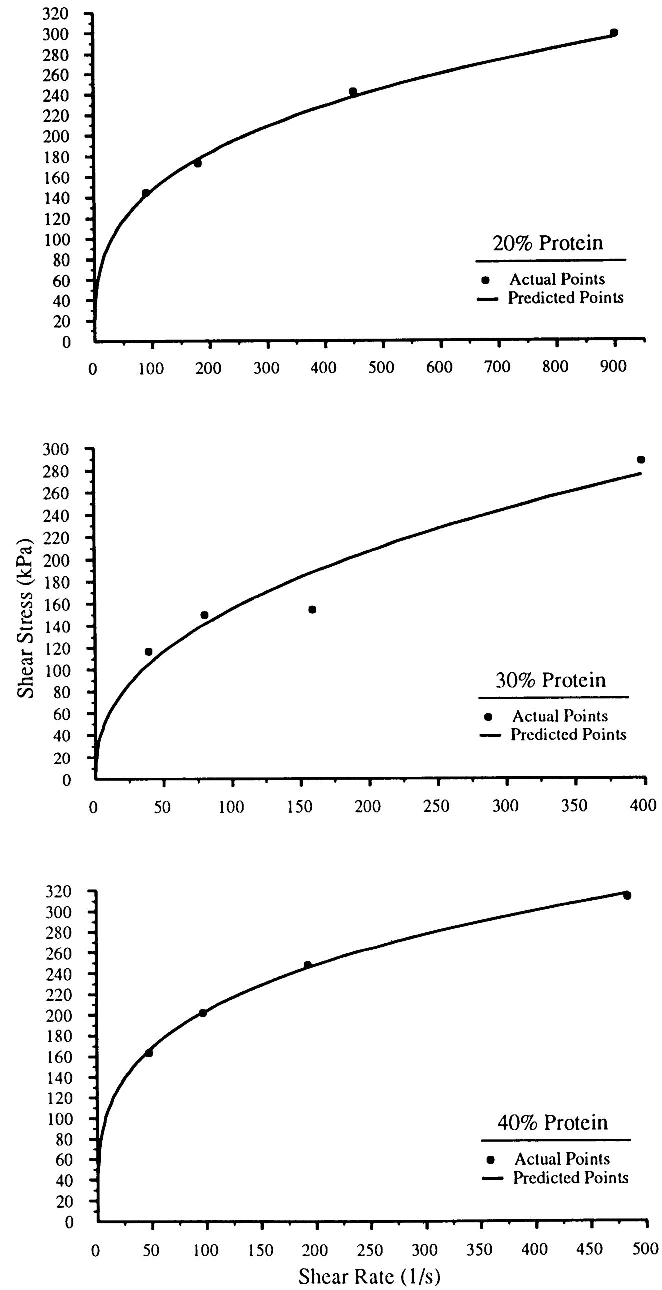

Fig. 2. Flow curves for dough made from 20, 30, and 40% protein flour mixed with 40% water for 2 min and rested for 30 min.

1 and 2. Results of the response surface regression analyses revealed that none of the independent parameters had a significant effect on the flow behavior index, *n*, with probability values of 0.3908, 0.9906, 0.8024, and 0.2310 for protein, mix time, rest time, and water, respectively. Based on this information, it was not possible to develop an adequate model for predicting the flow behavior index.

Because the range of consistency coefficients (*m*) was very wide (700–89,000 Pa-sec^n) for doughs made with water concentrations ranging from 35–55%, a logarithmic transformation of *m* values, denoted by *ln*(*m*), was used to obtain homogeneity of variability. Regression analysis revealed that the transformed consistency coefficients were mainly affected by water and protein concentration, and that mix and rest times did not have a significant effect on the parameter *ln*(*m*). The response surface for the variable *ln*(*m*) is shown in Figure 3. The quadratic model

$$ln(m) = 11.5372 - 0.1212\,P + 0.1963\,W + 0.001\,P^2 + 0.0021\,PW - 0.0054\,W^2,$$

where *P* is percent protein and *W* is percent water in the dough, adequately related the independent parameters to the consistency coefficients. As the protein concentration increased from 20 to 40%, the value of the consistency coefficient more than doubled, as seen in Table VI. It is well known that the viscous and elastic properties of dough are primarily derived from the gluten phase in the dough. Elastic and viscoelastic polymers generally are long-chain molecules with occasional cross-links between them (Bloksma 1971). By analogy, the viscoelasticity of gluten and dough should be due to a network of protein molecules. The rheological properties of such a network greatly depend on the number and strength of the cross-links between the protein molecules. Reasonably, increasing the amount of gluten (in doughs used in this study) would increase the number of cross-links between the protein molecules. The result, as seen in Table VI, would be a stronger dough with higher consistency coefficients.

Table VI also shows that the consistency coefficients for the doughs decreased with increasing amounts of water. A similar observation was made by Jao et al (1978) with soy melt, for which the consistency coefficient decreased from 1,105,646 units to 288,260 units as the moisture increased from 22 to 35%. Such a response was expected because increasing the amount of water increases the flowability of the dough as exemplified by a smaller consistency coefficient. Using a farinograph, it was also found that the maximum consistency decreased with increasing water content. On the average it decreased by 30 BU per milliliter of water per 100 g of flour.

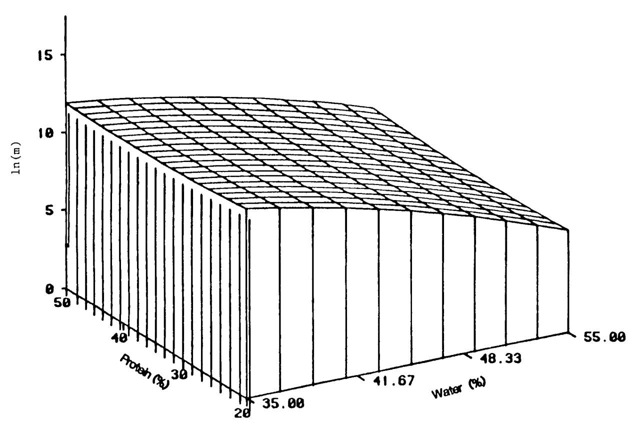

Fig. 3. Response surface for the variable *ln*(*m*), the logarithmic transformation of consistency coefficients.

TABLE VI
Consistency Coefficients (*m*) for Doughs Obtained with Different Amounts of Protein and Water with 2 min Mix Time and Zero Rest Time

Protein (%)	Moisture (%)	*m* (Pa-s^n)
20	40	24,570
20	45	12,428
20	50	3,077
30	40	35,432
40	40	60,940

Mechanical work, such as mixing, causes formation as well as disruption of bonds in the gluten complex. Accordingly, the resistance of dough to deformation increases or decreases. Overmixing dough ruptures bonds, effecting a low consistency coefficient. For example, dough made from flour with 20% protein and 40% water, rested for 0 min, and mixed for 2 and 4 min, had consistency coefficients of 24,570 and 34,451 Pa-sec^n, respectively (Sharma 1990). Increasing the mix time from 2 to 4 min was conducive to the formation of the bonds in the gluten complex. This much time was used in uniform distribution and mixing of water and hydration of gluten, thereby developing bonds. Hence a higher consistency coefficient was observed with the higher mix time. Because the range of mix times used in this study was very small, it is difficult to speculate on the transition mix time that would have resulted in a decrease in the consistency coefficient. However, it would be expected that longer mix times would cause the dough to lose its elasticity. Such an overmixed dough would be highly extensible and sticky and would acquire a liquid-type characteristic with increased flowability and a lower consistency coefficient. A similar phenomenon has been observed with the farinograph, in which prolonged mixing resulted in a drop in the maximum consistency line. This indicates increased mobility or decreased consistency. It is clear from our study that the protein content of the flour and the water content of the dough have a direct influence on the flow properties. We have quantified that effect, which should be helpful in designing dough pumping systems. Also, precise adjustments in the formulation can be made to achieve a desired consistency in dough for quality control purposes.

CONCLUSIONS

1. Flour-water doughs with higher protein and lower water contents were more viscous, as indicated by higher consistency coefficients.
2. Doughs made with various combinations of water and protein and mix times and rest times had highly non-Newtonian pseudoplastic flow behavior indices around 0.3 in the shear rate range of 3–600 sec^{-1}.
3. The consistency coefficients of flour-water doughs made with various combinations of protein and water contents and mix times and rest times were significantly affected by protein and water contents in the dough but were statistically unaffected in the range of mix and rest times studied.
4. The flow behavior indices were not significantly affected by protein content, water content, mix time, or rest time over the ranges studied.
5. A quadratic model was found adequate to relate the log-transformed consistency coefficient to protein and water content.

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Viscoelastograph Measures and Total Organic Matter Test: Suitability in Evaluating Textural Characteristics of Cooked Pasta

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Cereal Chem. 70(1):67–72

ABSTRACT

Two sets of Italian durum wheats were used to make spaghetti: 54 samples dried at low temperature (50°C) and 64 samples dried at high temperature (90°C). Cooking quality was evaluated using sensory judgment (SJ), total organic matter (TOM), and viscoelastograph parameters. SJ was expressed by its components (stickiness, bulkiness, and firmness) and by an overall score. Factor analysis was applied as a clustering tool to assess similar behavior of variables. Four factors were useful in describing the relationships among variables for each temperature considered. At 50°C the first factor was related to viscoelastograph parameters, the second grouped SJ, stickiness, bulkiness, and TOM, whereas firmness was linked to a different factor. At 90°C firmness was associated with stickiness, bulkiness, and SJ on the second factor, whereas TOM shifted to another factor. Multiple regressions were calculated to evaluate the relative worths of stickiness, bulkiness, and firmness on SJ and TOM as well as their relationships with viscoelastograph measures when different drying temperatures were applied. At low temperature, stickiness was the most important SJ component and TOM was a suitable method in estimating SJ. At high temperature, firmness played a more important role and viscoelastograph consistency was used to complement the TOM test.

Textural characteristics of cooked pasta are of primary importance in defining pasta quality. Among the characteristics, firmness, compressibility, elasticity, and surface stickiness have received the greatest attention, and different objective methods have been used to measure these parameters (Matsuo and Irvine 1969, 1971, 1974; Feillet et al 1977; Voisey et al 1978a,b; D'Egidio et al 1982; Dexter et al 1983, 1985). Matsuo and Irvine (1969, 1971) developed a Grain Research Laboratory (GRL) tenderness testing apparatus to measure tenderness, compressibility, and recovery of cooked pasta. Voisey and Larmond (1973) studied the relations between sensory parameters and instrumental measures obtained from Instron and Ottawa measuring systems. Subsequently, Matsuo and Irvine (1974) reported the good relationships of GRL apparatus readings with the sensory evaluations obtained by Voisey and Larmond (1973). Dexter et al (1983) adapted the GRL tester to measure cooked spaghetti stickiness, and then Dexter et al (1985) found their instrumental measures well related to the total organic matter (TOM) test of D'Egidio et al (1982). Feillet et al (1977) applied the viscoelastograph to the determination of viscoelastic properties of cooked

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