"UNMIXING" — THE DISORIENTATION OF DEVELOPED BREAD DOUGHS BY SLOW SPEED MIXING[1]

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ABSTRACT

"Unmixing" is the apparent reverse of dough development brought about when a dough mixed to peak consistency at high speed is mixed for a further period of time well below the minimum speed required for optimum development. The dough changes in appearance and character and assumes the properties of a dough that is undermixed. Bread baked from such "unmixed" dough is similar to bread baked from undermixed dough. The "unmixed" dough may be redeveloped to peak consistency by speeding up the mixer and the remixed dough produces bread of the same quality as that made from the initial developed dough. The "unmix"/remix cycle may be repeated several times. The deleterious effects of "unmixing" in terms of lower loaf volume, poorer external appearance and crumb texture are more pronounced with slower "unmix" speed and longer "unmixing" time.

Previous studies (1, 2) have stressed the importance of both energy and mixing speed or intensity in dough development for baking methods which depend on adequate mixing (mechanical development) for the achievement of maximum potential loaf volume. The object of this paper is to report on the marked deterioration in dough and bread properties caused when a developed dough is mixed for a further period of time considerably below the "critical speed" (1) for that flour.

The term "unmixing" has been coined to describe this phenomenon.

MATERIALS AND METHODS

The flours used in this study were straight-grade flours milled on an Allis-Chalmers laboratory mill. Table I lists analytical and other data.

Baking

The GRL-Chorleywood method described previously (2) was used except that oxidation level was lowered to 37.5 ppm ascorbic acid + 30 ppm potassium bromate unless otherwise noted. Mixing was carried out in a variable speed GRL-200 mixer (3). Mixing times and speeds were as shown. Energy curves were obtained from a recorder trace of watts against time. Energy input values were net figures obtained by correcting gross energy values for mixer mechanical efficiency (4). All work reported in this study was carried out at maximum water absorption consistent with satisfactory handling properties or machinability at time of panning. These values were determined for doughs developed to peak consistency at 160 rpm.

EXPERIMENTAL AND RESULTS

Demonstration of the Phenomenon of "Unmixing"

The phenomenon of "unmixing" is well illustrated using flour A. This flour was fairly strong and the quality of bread produced was very sensitive to mixing

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speed and degree of dough development; it performed poorly under conditions of slow-speed mixing or mixing to suboptimum energy input levels.

When mixed at 160 rpm dough from flour A developed into a shiny elastic mass with the characteristic ability to form thin sheets when stretched. If mixing was interrupted before optimum development was achieved, the dough had less sheen and the ability to form thin sheets diminished in proportion to the degree of undermixing. Grossly undermixed dough was short and lacked cohesiveness and had virtually no ability to stretch and form sheets. The dough did not have a smooth, continuous surface, but was rough in appearance.

When dough was developed to peak consistency at 160 rpm, the mixer was slowed down to 37 rpm and mixing continued further for 4 min; the dough changed in character and showed all the outward characteristics of being grossly undermixed. It appeared that the development process had been reversed and the dough pushed backwards to an undermixed state. The term "unmixing" has been given to this phenomenon.

A mixing curve, of the type shown in this paper, indicates the amount of energy being used by the mixer in maintaining a constant speed of the pins against the resistance provided by the dough. The higher the mixing speed the greater is the resistance offered to the pins by a dough of a given consistency or viscosity, and the higher the energy curve will be. Although at a constant mixing speed a change in curve height relates directly to a change in dough consistency, a change in mixer speed during mixing is marked by an immediate corresponding change in curve height.

In the mixing curves shown in Fig. 1 the change of mixing speed from 160 to 37 rpm was marked by an immediate drop in curve height. The "unmixing" curve showed a further reduction in height with time which indicated a decrease in dough consistency with increasing "unmix" time, and band width also decreased. The "unmixing" curve, in fact, looked like the reverse of a "normal" development curve where dough consistency increases to a maximum.

Bread baked from the "unmixed" dough was low in volume and had other poor loaf characteristics as shown in Figs. 2 and 3 and Table II. When the "unmixed" dough was immediately remixed at 160 rpm, a second development curve was obtained. The remixed, redeveloped dough had the same characteristics as the dough initially developed at 160 rpm and the ability to

TABLE I
Analytical and Farinograph Data for Flours Used in This Study

Source	A	B	C	D	E	F
Protein, %	13.3	13.8	14.1	13.3	10.6	10.2
Ash, %	0.40	0.42	0.39	0.38	0.41	0.43
Color, Kent-Jones units	−0.3	0.5	−0.2	−0.1	0.1	0.0
Damaged starch Farrand units	22	32	22	20	17	19
Gassing power, mm	310	385	295	275	355	415
Farinograph absorption, %	61.8	65.0	63.1	61.3	56.4	57.8
Farinograph dough development time, min	6.50	4.50	5.00	7.75	1.75	1.50
Baking absorption, %	66	65	65	66	59	61

produce bread of high volume and good crumb properties was regained. The "unmixing"/remixing cycle was repeated twice more (Figs. 1 - 3 and Table II). For each successive remix at 160 rpm, less energy and shorter time was required to achieve peak development. While some increase in stickiness could be observed in the redeveloped doughs directly from the mixer as the sequence was repeated more times, these doughs all handled satisfactorily at panning and produced bread of high volume. Slight deterioration in external appearance and crumb texture was observed, but this deterioration was not as marked as when the dough was mixed well past peak development at 160 rpm at an energy level equivalent to the total energy imparted during the initial mix to peak and three subsequent high-speed remixes (see Table II).

Flour B had significantly shorter mixing requirements than flour A and did much better when mixed at lower speeds and at work levels considerably less than that necessary for peak dough development. The effect of "unmixing" was less marked and loaf volume and other bread characteristics did not deteriorate to the same extent as with flour A after 4 min of unmixing at 37 rpm. Table III shows dough mixing and bread data for flour B when it was subjected to the same sequence of repeated development and "unmixing" as described above with flour A. In this case there was a greater deterioration in loaf properties in the bread baked from the redeveloped doughs with increasing numbers of repetitions of the cycle. At the same time the quality of the bread baked from the "unmixed" doughs showed a significant improvement from the second to the third "unmix" which may have been partly due to the effect of fermentation. This sample also did not stand up well to overmixing; loaf volume decreased by 175 cc when the dough was mixed at 160 rpm to an energy input level equivalent to the total energy imparted during the sequence of initial mixing plus three "unmix"/remix operations.

Although most of the results presented in this paper were obtained using flour A, the phenomenon of marked deterioration in bread quality, caused by the further mixing of developed doughs at slow speed, has been observed for all flours tested. Table IV lists data for four flours chosen to represent a range in protein content and mixing requirements. Flour C was milled from a sample of "Napayo," the most recently licensed Canadian hard red spring wheat variety. Flour D was from the cultivar CT 450, which was dropped from

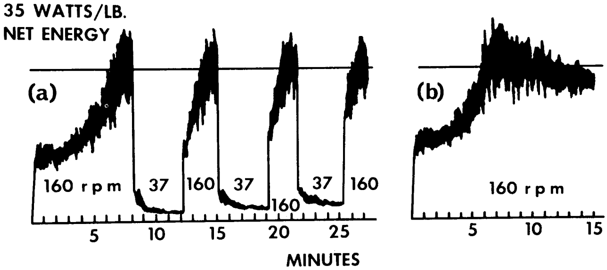

Fig. 1. Energy curves for the mixing of doughs from flour A. a) Dough mixed to peak at 160 rpm then subjected to three "unmix"/remix operations. Each "unmix" for 4 min at 37 rpm; each "remix" to peak consistency at 160 rpm. b) Dough overmixed at 160 rpm.

extracts were concentrated under reduced pressure in a rotary evaporator to remove ethanol. All extracts were lyophilized.

The HOAc and $HgCl_2$ extracts were further fractionated by dissolving or dispersing them in 0.7% acetic acid-70% ethanol and adjusting the pH to 6.6 with 2N NaOH (10). After cooling to 4° C., the precipitated glutenins were removed by centrifugation, and recoveries were determined gravimetrically after ethanol removal and lyophilization.

Other Analytical Methods

Nitrogen recoveries were determined by a modification of an automated Kjeldahl procedure (18). SDS-PAGE was performed on 5% polyacrylamide gels using a pH 8.9 0.125M *tris*-borate buffer containing 0.1% SDS, as described by Koenig et al. (19). Further experimental details and application of the method to wheat proteins were described previously (15,16). Reagent-grade chemicals and deionized water were used in all studies.

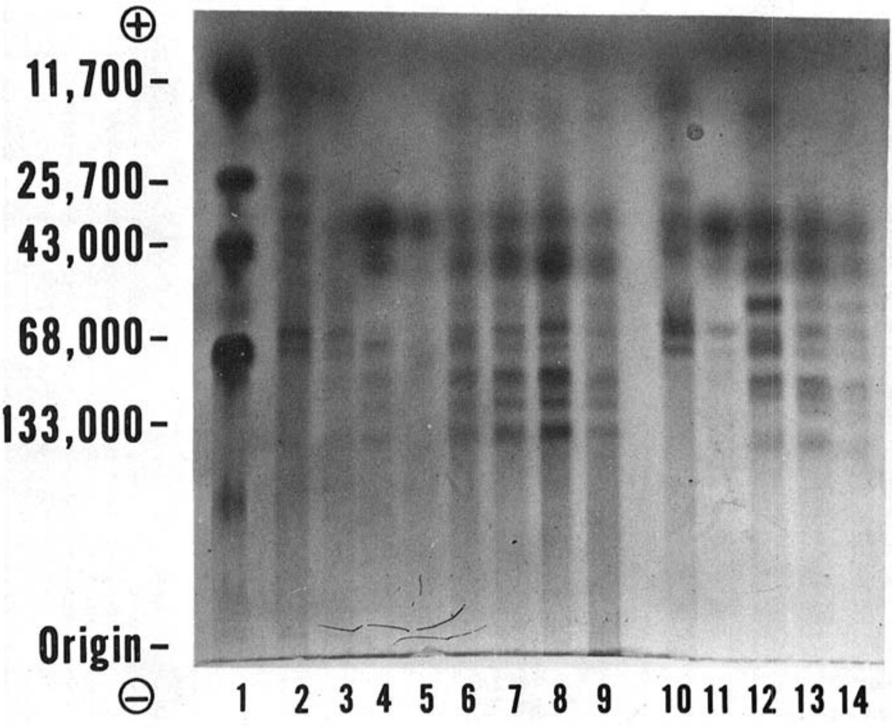

Fig. 1. Sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE) patterns of subunits of all proteins extracted from wheat varieties Ponca and Chinese Spring. SDS-PAGE was performed on 5% gels using 0.125M *tris*-borate, pH 8.9. (1) Standard proteins; (2–9) Ponca flour extracts from two extractions each with (2–3) NaCl, (4–5) EtOH, (6–7) HOAc, and (8–9) $HgCl_2$; (10–14) Chinese Spring flour extracts with (10) NaCl, (11) EtOH, (12) HOAc, (13) $HgCl_2$, and (14) 2-mercaptoethanol (ME). Each Chinese Spring pattern is of two combined extracts with each solvent. Scale on the left indicates molecular weight.

TABLE II
Effect of Repeated "Unmix"/Remix Operations on Bread Properties for Flour A

	Mix to Peak at 160 rpm	1st "Unmix" 4 min at 37 rpm	1st Remix to Peak at 160 rpm	2nd "Unmix" 4 min at 37 rpm	2nd Remix to Peak at 160 rpm	3rd "Unmix" 4 min at 37 rpm	3rd Remix to Peak at 160 rpm	Overmix at 160 rpm
Loaf volume, cc	990	570	965	570	935	580	920	960
External appearance	8.8	5.0	8.0	4.0-old	8.0	4.0-old	7.8	7.5
Crumb texture	6.8-o[a]	3.5c-o	6.5-o	2.0c-o	6.5-o	2.0c-o	6.5-o	5.5vo
Crumb color	9.0	3.5yg	9.5	3.0yg	9.0	3.5yg	8.8	9.0
Net Whr/lb for 160 rpm mixing stage	3.00		1.30		1.15		0.99	7.00
Min mix at 160 rpm mixing stage	8.2		2.9		2.4		1.7	15.2

[a]c = coarse; o = open; vo = very open; yg = yellow grey.

TABLE III
Effect of Repeated "Unmix"/Remix Operations on Bread Properties for Flour B

	Mix to Peak at 160 rpm	1st "Unmix" 4 min at 37 rpm	1st Remix to Peak at 160 rpm	2nd "Unmix" 4 min at 37 rpm	2nd Remix to Peak at 160 rpm	3rd "Unmix" 4 min at 37 rpm	3rd Remix to Peak at 160 rpm	Overmix at 160 rpm
Loaf volume, cc	990	710	970	680	930	760 (770)[a]	845 (880)	815
External appearance	8.0	6.0	8.0	5.0	7.8	6.5 (6.5)	7.5 (7.5)	7.2
Crumb texture	6.2-o[b]	5.5c-o	6.0-o	5.0c-o	5.5-o	5.8-o (6.0)	5.8vo (6.0-o)	6.5
Crumb color	8.0	5.0yd	8.5	4.5yg	8.0	6.0yd (7.0)	7.8 (8.0)	7.0
Net Whr/lb for mixing stage	2.1		1.26		0.84		0.50	5.0
Min mix at 160 rpm	4.5		2.1		1.9		1.2	8.9

[a]Figures in parentheses are data for mixes with reduced oxidation (37.5 ppm ascorbic + 15 ppm bromate).
[b]c = coarse; o = open; vo = very open; y = yellow; d = dull; g = grey.

TABLE IV

Effect of "Unmixing" for 4 min at 37 rpm on Bread Properties of Doughs Developed at 160 rpm from Four Flours

	Flour C		Flour D		Flour E		Flour F	
	Mix to Peak at 160 rpm	+ "Unmix" 4 min at 37 rpm	Mix to Peak at 160 rpm	+ "Unmix" 4 min at 37 rpm	Mix to Peak at 160 rpm	+ "Unmix" 4 min at 37 rpm	Mix to Peak at 160 rpm	+ "Unmix" 4 min at 37 rpm
Loaf volume, cc	1065	695	1045	570	825	660	765	610
Appearance	8.0	5.8	8.0	5.0-old	7.2	5.8	7.2	5.0
Crumb texture	6.8-o[a]	4.5c-o	7.0	2.5c-vo	6.2-o	5.5c-o	6.8	5.5c-o
Crumb color	8.0	5.8yd	9.0	4.5yg	7.0	4.5yg	9.0d	5.5yg
Net energy, Whr/lb	1.89		2.61		2.11		2.10	
Mixing time, min	4.25		7.9		4.6		5.0	

[a]o = open; c = coarse; vo = very open; y = yellow; d = dull; g = grey.

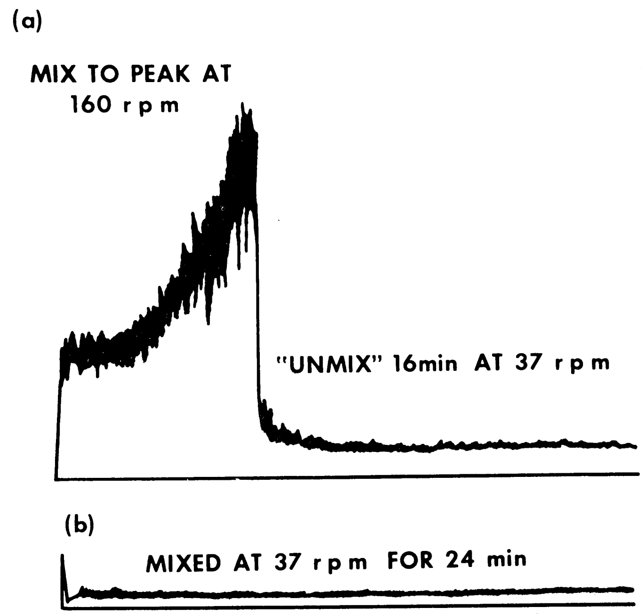

Fig. 4. Energy curves for doughs mixed from flour A. a) Mix to peak at 160 rpm followed by 16 min "unmix" at 37 rpm. b) Dough mixed 24 min at 37 rpm.

advanced quality tests due to undesirably long mixing characteristics. Flours E and F are 50/50 blends of spring and soft white winter wheat flours. The deterioration in bread quality caused by "unmixing" and illustrated in Table IV was most pronounced for the strongest flour (D), and least pronounced for the two blends of lower protein content.

Effect of Duration of "Unmixing" at 37 rpm

Using flour A, doughs were mixed to peak development at 160 rpm, then "unmixed" at 37 rpm for 1, 2, 4, 8 and 16 min. For comparison, one dough was mixed for 24 min at 37 rpm with no prior development. Mixing curves are shown in Fig. 4. Bread quality of the loaves baked from the "unmixed" doughs deteriorated progressively with increasing "unmixing" time as shown in Fig. 5 and Table V. Loaf volume reached a minimum value after 8 min of "unmixing," but appearance and crumb texture were even poorer for the 16-min-"unmix" bread. This latter loaf was identical in all respects to the loaf baked from dough mixed 24 min at 37 rpm, thus reinforcing the idea that the "unmixing" changed the developed dough into a physical state equivalent to that of a grossly undermixed dough. When the "unmixed" doughs were remixed to peak at 160 rpm, bread quality returned in each case to the same level. However, the time and energy level required to reachieve peak consistency increased with increasing "unmix" time as shown in Table V. This suggested that the longer the "unmixing" time the further back towards gross undermixing the dough was pushed, necessitating more mixing to redevelop it to peak consistency.

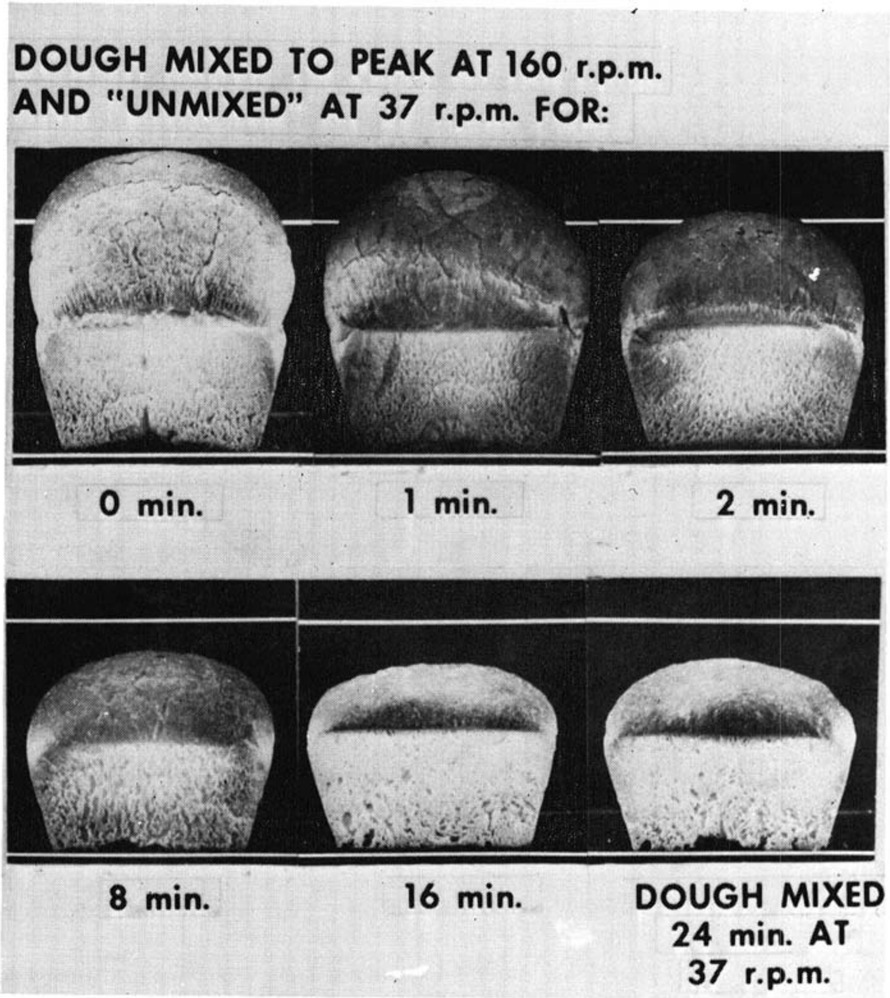

Fig. 5. External appearance of loaves baked from flour A showing the effect of increasing "unmixing" time.

Effect of Speed of "Unmixing"

Doughs from flour A were mixed to peak consistency at 160 rpm then "unmixed" for 4 min at 55, 85 and 105 rpm. "Unmixing" and remixing curves are shown in Fig. 6 and may be compared with the curves for the 37 rpm "unmix" shown in Fig. 1. Bread data are shown in Table VI. The slower the speed of "unmixing" the further the dough was apparently pushed back towards a state of being grossly undermixed. Bread properties of the loaf baked from dough mixed to peak consistency at 105 rpm were almost identical to those of a loaf baked from dough mixed to peak consistency at 105 rpm. This again confirmed that a

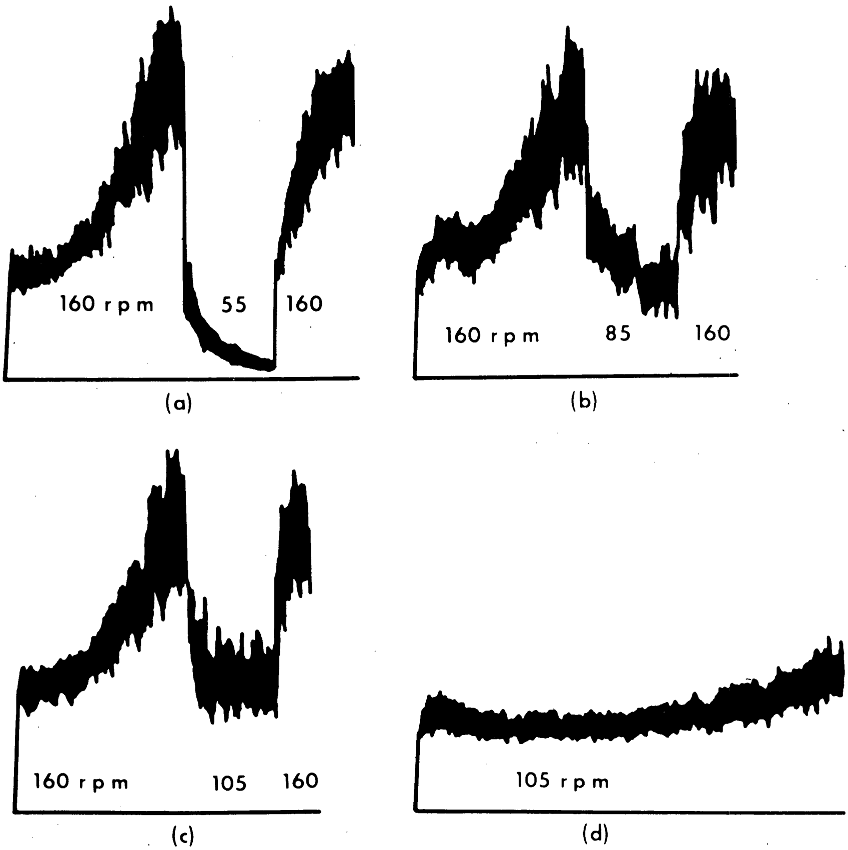

Fig. 6. Mixing curves for doughs from flour A mixed to peak at 160 rpm then "unmixed" 4 min at various speeds: a) 55 rpm; b) 85 rpm; c) 105 rpm; then remixed to peak at 160 rpm. Mixing curve d) is for dough mixed to peak at 105 rpm.

dough developed at high speed then "unmixed" at a lower speed has the properties of a dough mixed only at the lower speed. The loaves obtained after remixing of the "unmixed" doughs were all very similar to the original loaf of "maximum" quality. The amount of mixing required to redevelop the unmixed doughs increased with decreasing "unmixing" speed again indicating that the further back towards gross undermixing the dough is taken, the more mixing is required to return it to a state of optimum development.

That the relative effect of "unmixing" at a given speed appears to be related to "critical speed" (1) is illustrated by Fig. 7 which is a plot of loaf volume against "unmixing" speed. This graph indicates a possible method of determining critical speed by extrapolation of the loaf volumes of loaves from doughs "unmixed" at various speeds. In this case the critical speed for flour A under these conditions appears to be around 115 rpm. There would be two main advantages in determining critical speed by high-speed development followed by "unmixing" as opposed to mixing to peak energy level at various speeds. First, the time taken to

TABLE V
Effect of Duration of "Unmixing" on Bread Properties for Flour A

	Dough Mixed to Peak at 160 rpm Followed by "Unmixing" at 37 rpm for:						Dough mixed 24 min at 37 rpm
	0	1 min	2 min	4 min	8 min	16 min	
Loaf volume, cc	990	840	660	570	500	505	500
External appearance	8.2	7.5	6.2	5.0-old	4.2-old	1.5-old	1.5-old
Crumb texture	6.2-o[a]	6.5-o	5.0c-o	3.5c-o	2.0c-o	1.0c-vo	1.0c-vo
Crumb color	8.8	7.0	4.8yg	3.5yg	2.5yg	2.0yg	2.0yg
Accumulative total net energy, Whr/lb	3.00	3.10	3.19	3.28	3.48	3.89	0.73
Total mixing time, min	8.2	9.2	10.2	12.2	16.2	24.2	24.0
	Above "Unmixed" Doughs Remixed to Peak at 160 rpm						
Loaf volume, cc		1000	975	965	995		
External appearance		7.8	7.8	8.0	8.0		
Crumb texture		6.5-o	6.5-o	6.5-o	6.5-o		
Crumb color		9.5	9.5	9.5	9.2		
Net energy Whr/lb for remix		0.60	0.78	1.30	1.77		
Min mix for remix		1.5	1.7	2.9	4.2		

[a]c = coarse; o = open; vo = very open; yg = yellow grey.

TABLE VI
Effect of Speed of "Unmixing" on Bread Properties of Flour A

	Dough Mixed to Peak at 160 rpm then "Unmixed" 4 min at:			Dough Mixed to Peak at 105 rpm (19.5 min, 3.03 Whr/lb)
	55 rpm	85 rpm	105 rpm	
Loaf volume, cc	610	740	880	850
External appearance	5.0	6.8	8.0	7.0
Crumb texture	4.0c-o[a]	5.8-o	6.8-o	6.0-o
Crumb color	3.5yg	6.0yd	8.5	7.2

[a]c = coarse; o = open; y = yellow; d = dull; g = grey.

impart the necessary energy levels at slow speeds may be excessive and second, loaf volumes tend to be rather variable when mixing is carried out at or just below critical speed.

Effect of "Unmixing" on Underdeveloped and Overdeveloped Doughs

The experiments on "unmixing" described so far have all been with doughs developed to peak consistency. In order to determine the effect of unmixing on doughs mixed at high speed, a stage either short of or past peak consistency, flour A was used to mix doughs to 50% (undermix) and 150% (overmix) of the energy input level required for peak development. Mixer speed was then slowed to 37 rpm for 4 min. Mixing curves and bread are shown in Figs. 8 and 9. In both cases bread from the "unmixed" doughs was similar to that obtained from the

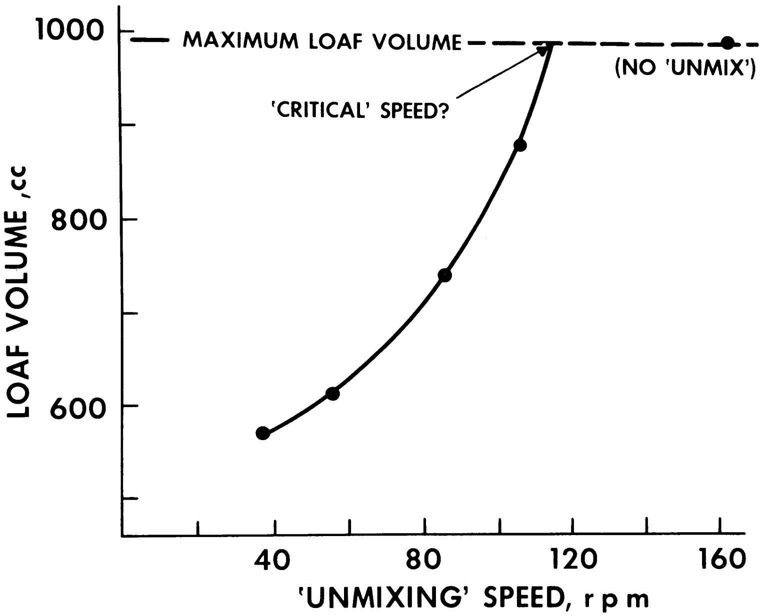

Fig. 7. Effect of "unmixing" speed on loaf volume of bread baked from flour A. Doughs mixed to peak consistency at 160 rpm then "unmixed" 4 min.

"unmixed" peak-consistency dough, except that crumb texture was slightly poorer in the bread from the "unmixed" 50%-peak-energy sample. The greater the amount of mixing given in the initial stage, the less mixing required to remix the "unmixed" dough to peak consistency.

DISCUSSION

Based on a consideration of dough appearance and mixing curve shape, dough mixing may be conveniently divided into three stages. The first stage is the bringing of dough ingredients into intimate contact and the achievement of a homogeneous mass.

A second stage, which overlaps the first, is suggested by the curve shape in the early part of mixing. In the initial-development curve shown in Fig. 1, following the initial rise of the curve during the first 0.5 min of mixing, dough consistency levels off before picking up again (after about 3 min for this example) and increasing to a peak or maximum value. This "lag phase," which is of longer duration for "stronger" flours and at slower speeds (e.g., see Fig. 6, curve d) may well be related to the hydration requirements of the flour. Although Bernardin and Kasarda (5) have strikingly demonstrated on videotape the immediate and almost explosive formation of protein fibrils when flour particles or endosperm sections are wetted on a microscope slide, it is probable that under the conditions of relatively limited water availability that exist in dough, the attainment of an equilibrium of water distribution between the various water-absorbing components of dough is time-dependent.

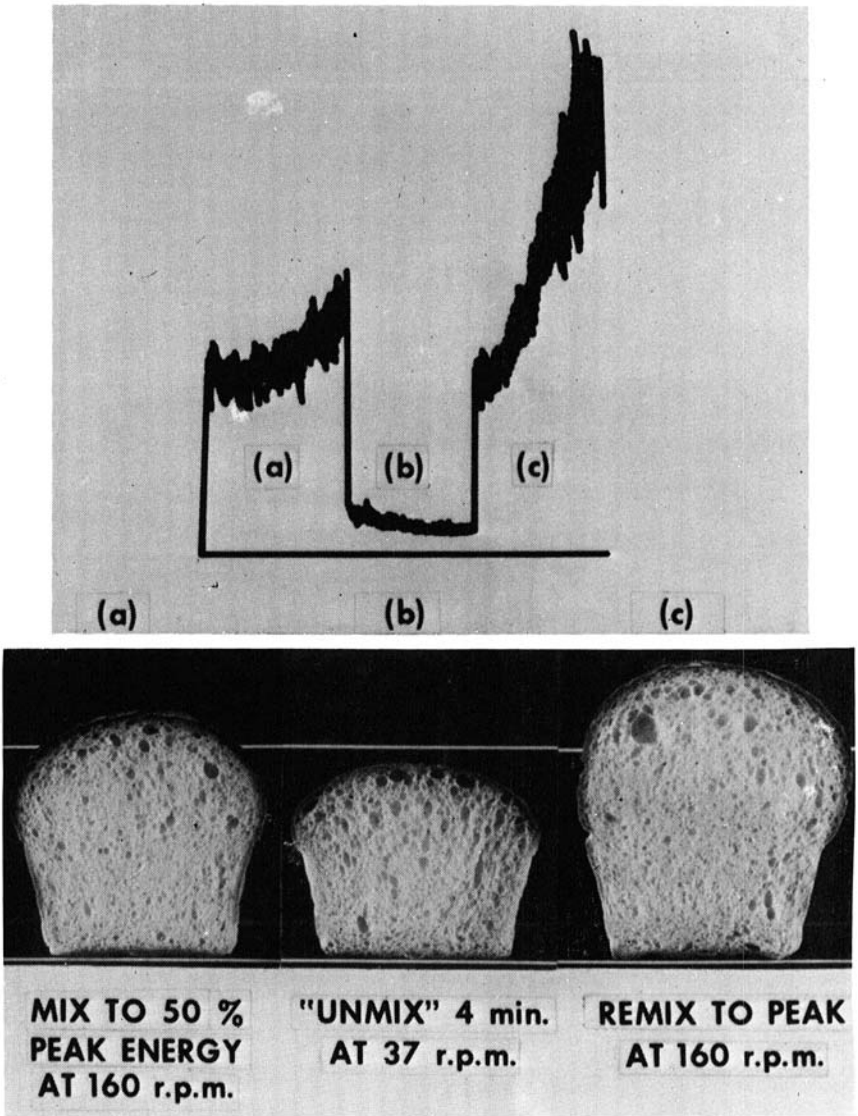

Fig. 8. Mixing curves and bread for doughs mixed from flour A. a) Mixed at 160 rpm to 50% of the net energy required for peak development, then b) "unmixed" 4 min at 37 rpm, and c) remixed at 160 rpm to peak.

The occurrence of the "lag phase" in mixing suggests that hydration must proceed to a sufficient extent before the dough becomes cohesive enough to respond to further stretching and development. Energy imparted during the second stage of mixing appears to be of little or no benefit in terms of dough development. The shorter time and lower energy requirements for remixing

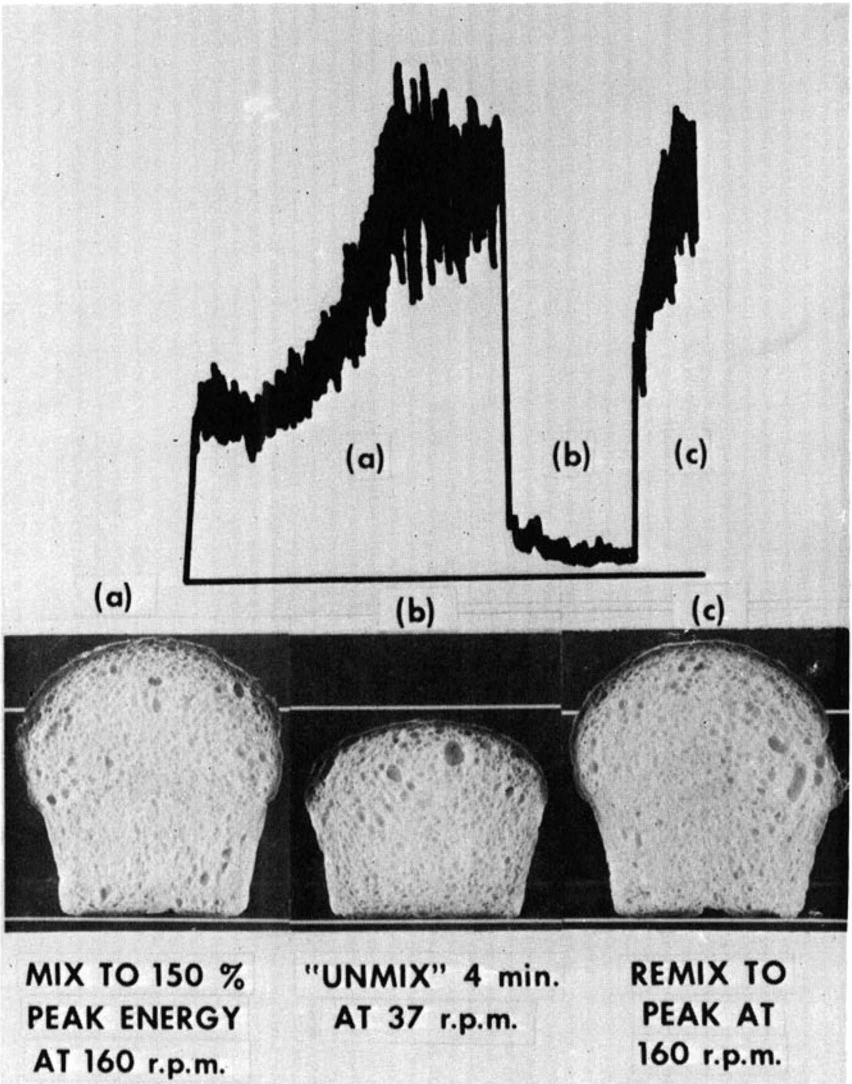

Fig. 9. Mixing curves and bread for doughs mixed from flour A. a) Mixed at 160 rpm to 150% of energy required for peak development, then b) "unmixed" 4 min at 37 rpm, and c) remixed at 160 rpm to peak.

"unmixed" doughs may be partly accounted for by the fact that hydration only affects initial mixing and is not a factor in subsequent processing.

The third stage of mixing is dough development. Once sufficient cohesiveness is attained, the dough responds to further physical working provided that it is deformed at a faster rate than it is able to relax. If mixing speed is too low the dough will not respond regardless of how long it is mixed (see curve b in Fig. 4).

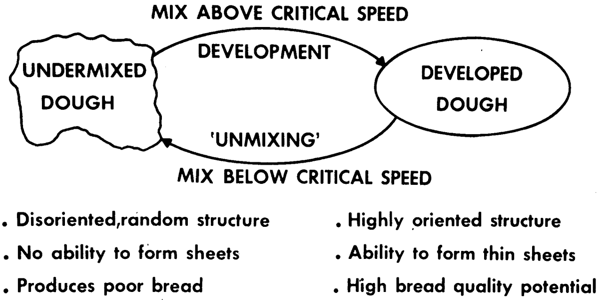

Fig. 10. Proposed relation between dough development and "unmixing."

The fibrillar nature of dough protein has recently been clearly demonstrated and discussed by Bernardin and Kasarda (6). While a degree of lateral interaction may exist between protein fibrils to form sheets early in mixing, it is evident that the sheet-forming potential of an undermixed dough is not adequate for sufficient gas to be retained to produce a large-volume, fine-texture loaf. Mixing provides an opportunity for interchange of interfibrillar attractive forces. Mixing at a sufficiently high speed also stretches the fibrils, thus increasing the probability of maximum lateral surface contact and adhesion between fibrils. This, in turn, would enhance the ability of a dough to form thin sheets of bonded (6) fibrils capable of expanding and holding gas without rupture.

Mixing of a dough above critical speed is considered to promote the formation of a highly oriented structure having a characteristic ability to form thin, gas-retentive sheets. However, if a developed dough is "unmixed" at well below critical speed, it appears that a disorientation of the dough structure occurs. Without the high stress necessary for optimum stretching and lateral adhesion between fibrils, mixing instead may favor a random interchange of adhesive forces between fibrils. This would allow the formation of a more randomized, less highly oriented structure with diminished expansion and gas-retention properties. Such disorientation is more pronounced at slower speeds where the stress is lower and the opportunity for lateral alignment of fibrils is reduced. Disorientation does not appear to occur to any great extent when the developed dough is merely rested for an equivalent (short) period of time because mixing is necessary to provide opportunities for randomized bond-interchange.

Although we have tended to discuss dough development in terms of dough being in an "optimum" or "suboptimum" state from the mixer, the "makeup" stages of rounding, resting (intermediate proof), and sheeting and moulding are obviously important in determining the final structure prior to proofing and baking.

In a straight-dough process the interactions between initial mixing, oxidation level, total fermentation effect, and subsequent manipulation (punching, etc.) are very complex. During fermentation the expansion caused by gas production, conceivably, has a mechanical effect analogous to extremely slow-speed mixing. Therefore, it is possible that a certain degree of "unmixing" occurs during fermentation. The very intense and efficient dough development action of sheeting rolls (7) may be enough to reorient the gluten fibrils sufficiently during makeup to ensure that the dough, when panned, is in a suitable condition to expand and retain gas during proofing and baking.

The postulated relation between developed and undermixed dough is summed up in Fig. 10. Although it has been shown that development appears to be reversible even when the dough is taken slightly past peak consistency (see Fig. 9), however, once a dough is overmixed beyond a certain stage of breakdown and stickiness, the process would not be reversible without some subsequent recovery period and further processing.

While it is not suggested that "unmixing" has any great practical significance (except, perhaps, as a warning that a developed dough should not be unduly abused), the phenomenon is considered as another piece in the total puzzle concerning what changes are occurring during dough development. It may also prove to be useful as the basis of a convenient method for predicting critical-speed requirements of experimental flours.

Acknowledgments

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