RHEOLOGY AND THE CONTINUOUS BREADMAKING PROCESS

P. J. FRAZIER, N. W. R. DANIELS, and P. W. RUSSELL EGGITT, Spillers Limited, Research and Technology Centre, Station Road, Cambridge, CB1 2JN, England

ABSTRACT

Modern continuous breadmaking processes have evolved from a common aim—elimination of the lengthy conventional bulk fermentation needed to mature dough proteins. The various ways in which this has been achieved, based on mechanical development of the dough, are briefly traced and the rheological behavior of dough under intensive mixing conditions is discussed, with particular regard to 'optimum development.' Aspects considered include mixer speed and geometry, rates of mechanical work input and total work levels applied to the dough. Rheological methods for the control of mechanical development and dough consistency are also reviewed, and a new computing dough mixer for research into mechanical development is described. Finally, the different indications of 'optimum' development obtained from recording mixers and from the testing of rested doughs are discussed, and it is concluded that dough development is dependent on a complex relation between mechanical work and the action of chemical oxidizing and reducing agents.

The elimination of bulk fermentation from bread manufacturing processes by the use of mechanical means to mature the dough is not new. As early as 1926 Swanson and Working (1) described a 'no-time' dough method based on a pin mixer running at moderate speed (60 or 120 rpm) the action of which was sufficient to satisfactorily modify the gluten proteins without bulk fermentation. Although provision was included for power measurement, no attempt was apparently made to quantify dough development in terms of work input and with some flours overmixing occurred (2). The lack of guidance in respect of the degree of mechanical modification required and its control in mixers of different design, together with problems in handling the resulting doughs (3), probably explains why commercial adoption of mechanical dough development was so slow to follow.

Not until the experiments of J. C. Baker, 25 years later, culminating in the 'Do-maker' continuous breadmaking process (4,5), were the practical problems of high-speed developer design solved and accepted by the breadmaking industry. Neither the 'Do-maker' process nor the continuous sponge-and-dough 'Amflow' system (6,7), which followed 5 years later, made provision for automatic control of work input during dough development, although it was implied in the original 'Amflow' patent (8) that an energy input of 40 kJ kg^{-1} (0.4 HPmin/lb; 5 Whr/lb) should be used.

Further investigations into the factors involved in the production of bread from mechanically developed doughs were undertaken at the Flour Milling and Baking Research Association, Chorleywood, England. It was found that, irrespective of formulation, the best bread was produced when work expended on the dough fell between 37 and 46 kJ kg^{-1} (9). The outcome of this was the definition of a batch mechanical development process known as the 'Chorleywood Bread Process' (10–14) in which a mixer of sufficient power was employed to expend 40 kJ of energy per kg dough over a period of time preferably not exceeding 5 min (*i.e.*, an average rate of work input of 8 to 10 kJ $kg^{-1}min^{-1}$).

Following these observations, a number of alternative methods of batch mechanical development were introduced including the 'Brimec' process (15,16) in Australia, the 'Blanchard Batter Process' (17,18) in the U.K., and North American adaptations to produce high-volume bread (19–21), as well as modified continuous systems allowing sufficient work input to be achieved (22,23). Meanwhile other workers turned their attention to ways of decreasing the energy requirements for mechanical dough development. In 1960 Henika and Zenner (24,25) shortened fermentation time by adding cysteine to conventionally mixed doughs together with oxidizing agents. At Chorleywood, Axford and Elton (9) showed that mechanical work input for optimum dough development could be reduced by addition of sodium metabisulfite to doughs. Cysteine in particular, was then used in combination with oxidizing agents, to produce mechanically developed dough either by low-power batch mixing (26–29) or by reduced-power continuous Do-maker or Amflow processes (30). Ascorbic acid, in the absence of atmospheric oxygen, also reduced power requirements (31–33) and collectively these methods have become known as 'chemical dough development' (34,35) although 'chemically accelerated mechanical development' may be more appropriate (36).

It will be evident from the foregoing that the evolution of modern short-time batch and continuous breadmaking processes has been largely an achievement of bakery technology and engineering. Considerations of dough rheological behavior are rarely discussed even though changes in dough structure and physical properties are an integral part of dough development. It is the purpose of this article to review and relate studies of dough rheology to mechanical development and to outline how such studies may aid future progress.

RHEOLOGY OF MECHANICAL DOUGH DEVELOPMENT

Conventional dough rheological techniques may be conveniently divided into two groups: first, mixing studies in which various torque-recording instruments such as the farinograph or mixograph are used to monitor changes in dough consistency during mixing; and second, studies in which doughs that have been mixed and allowed a rest period for structural relaxation, are then tested by various means, often involving simple load-extension measurements. Both groups of techniques are applicable to the study of mechanically developed doughs but, perhaps not surprisingly in view of the significance of mixing, the former group has been preferred by the majority of workers. There is, however, some disagreement over interpretation of mixing curves in terms of 'optimum development' which the results of tests on rested doughs may help to resolve.

Mixing Studies

When water is added to flour and mixed, a progression of changes takes place. The flour particles are hydrated. The mass becomes gradually more coherent, losing its wet and lumpy appearance. Eventually, a smooth, apparently homogenous dough is produced which stiffens, as mixing proceeds, until a point of maximum consistency (minimum mobility) is reached, when the torque on the mixer drive shaft or the power consumption of the motor is greatest. Finally, if mixing is continued, the consistency of the dough decreases (*i.e.*, mobility increases, torque or power decrease). This decrease is usually progressive, generally called 'breakdown' or 'rheodestruction,' and eventually results in an extremely sticky but very cohesive dough, capable of being drawn out into long strands. In practice, for a given mixer design and speed of mixing, the time taken for doughs to reach maximum consistency and the rate of decrease in consistency thereafter depend very much on the type of flour used. Figure 1 shows the behavior of six flours of differing strength in the Brabender Farinograph. Decreasing flour strength generally results in more rapid arrival at, and departure from, peak consistency.

If a given flour is examined in several different mixers and a graphical record made of torque on the final drive shaft or electrical power consumption [preferably with suitable correction being made for losses in the motor, gearbox, etc., when under load (37)] then the types of curve obtained will depend on a number of factors, including the mixer design (*i.e.*, how the shape of the blades and the pattern of their movement varies the shear rate conditions throughout the dough) and the speed of rotation. In addition, the degree of damping on the recorder will greatly influence the appearance of the curve. Since the differences in action, speed and recorder damping between two conventional laboratory mixers, the farinograph and mixograph, are sufficient to produce markedly different traces and lead to discussions as to which is the more useful (38), it will be apparent that the variety of results obtainable from the range of commercial mixers used for mechanical dough development could be very considerable.

To illustrate the effect of speed on mixing curves, Fig. 2 shows the result of attaching a standard 300-g farinograph bowl to a computing dough mixer (Spillers 'Compudomixer,' see later) in the authors' laboratory, programmed to maintain constant drive shaft speeds of 60, 120, 180, 240, 300, 360, 480, and 600 rpm. The electronic chart recorder was adjusted to be approximately equivalent to the kymograph chart of the farinograph (although giving a rectilinear rather than curvilinear graph). The flour used was commercially milled from a strong (U.S. Northern Springs) grist and water added was several per cent below

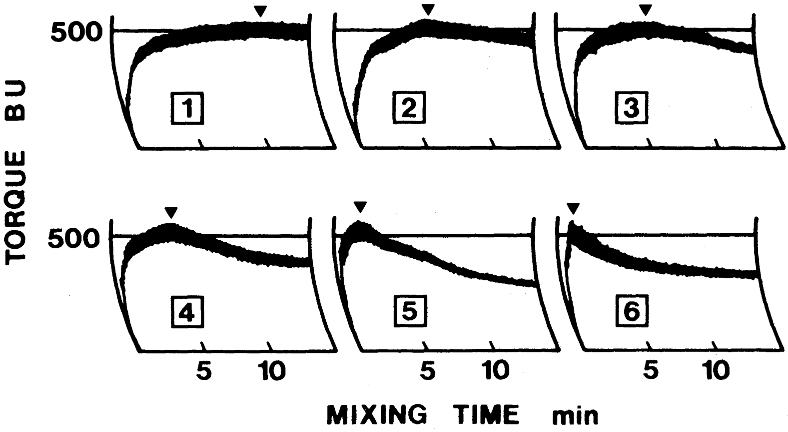

Fig. 1. Farinograms showing flours of decreasing strength from 1 (strongest) to 6 (weakest).

farinograph absorption at 500 BU, to allow easier handling after gross overworking. The torque calibration in kgf m can be converted to Brabender Units by multiplying by 1,000 (*i.e.*, 1 kgf m = 1,000 BU). At 60 rpm the curve was very similar to a standard farinograph trace. Maximum torque was reached just before 3 min mixing and, on the full original graph, the torque then decreased slowly up to 60 min. Mixing at higher speeds produced higher torque readings, as would be expected, but in addition the shape of the curves progressively changed. At 120 rpm the curve was very flat between 'arrival' at the 1.0 kgf m line after 1 min and 'departure' after 4 min. On increasing speed to 180 rpm the previous 'departure' appeared to have moved up to become a peak after 2 min, while the previous 'arrival' appeared more like a shoulder. The peak and shoulder then occurred progressively closer together at higher torque values and at shorter times as speed was further increased, until, by 480 rpm, a single peak was predominant with only a slight broadening of the trace where a shoulder would be expected.

Throughout each of these mixings the mechanical work input was continuously displayed and Fig. 3 shows the mean torque replotted against work input for each mixing speed. It can be seen that the work expended on the dough, from commencement of mixing until peak torque, increased progressively from 8 to 60 kJ kg^{-1} as the speed increased from 60 to 600 rpm. Reference back to Fig. 2 provides the explanation for this result. Although peak torque occurred at progressively shorter times, these changes were not sufficient to compensate for the considerable increase in the rate of work input (proportional to speed × torque) as speed and resistance to mixing increased.

The question that must be asked, therefore, is what constitutes 'optimum' mechanical dough development for breadmaking, and does this necessarily correspond with the point of minimum mobility (peak torque), under whatever mixing conditions are employed, irrespective of work input?

The literature is fairly evenly divided on this topic. Bohn and Bailey (39) in

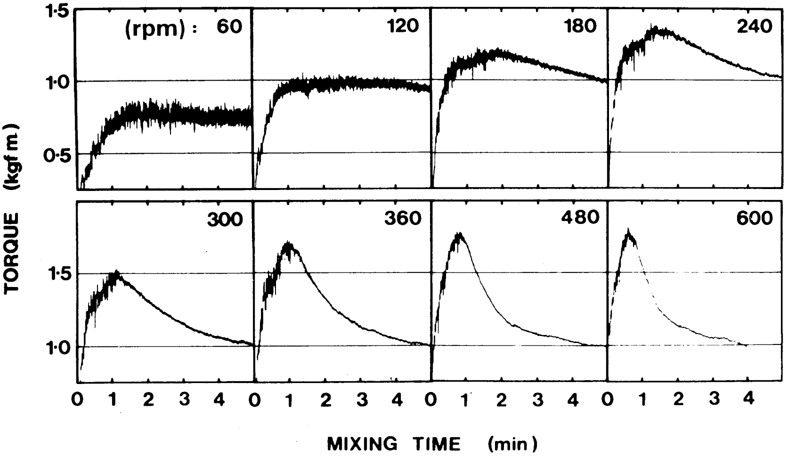

Fig. 2. Effect of mixer speeds from 60 to 600 rpm on the appearance of torque *vs.* time recordings.

1936, before the advent of successful mechanical development processes, were of the opinion that the maximum reading on the farinograph curve was about optimum as far as (conventional) baking quality was concerned, and that overmixing (which the method of Swanson and Working involved) could not be substituted for fermentation. Dalby (40) in 1960, using an electronically damped ammeter in the circuit of a bar mixer, took maximum amperage as the optimum mixing time. Similarly, Fortmann *et al.* (41), in 1964, using a recording wattmeter judged optimum gas retention and optimum bread to occur around the power peak, and found that the work required to reach this varied with the impeller shape. Marston (16), working with the Brimec mixer, found optimum development as shown by peak power consumption to occur at higher work levels as speed increased and suggested that there was a critical rate of work input. Jelaca and Hlynka (42), in 1971, using a GRL mixer with work input meter, found the peak consistency of a control dough to occur at about twice the work level recommended for the Chorleywood Bread Process, while Kilborn and Tipples (43), in an extensive study of factors affecting the Chorleywood method of mechanical development, regarded peak consistency as optimum development, qualified by the need for a 'critical minimum speed.' Most recently Hoseney and Finney (38) concluded that the function of mixing was to develop a dough to the point of minimum mobility regardless of speed or additives.

The possibility that peak torque may not be a measure of optimum dough development was discussed by Malloch (44) in 1938 using a novel recording

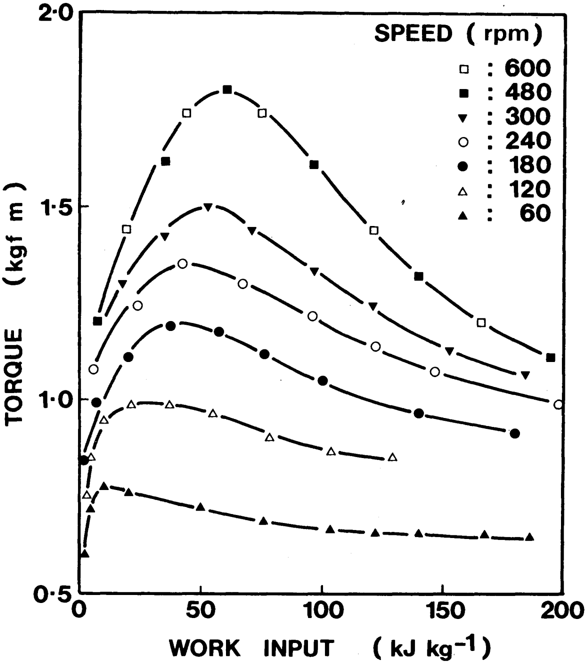

Fig. 3. Mean torque values from Fig. 2 replotted against work input for various mixer speeds (60 to 600 rpm).

mixer with helical pins to reduce the jerky action that the intermittent passing of straight pins through the dough produced. He observed, some time after the maximum of the torque trace, a discontinuity or 'break' in the curve which was related to the colloidal properties of the gluten. With the advent of mechanical development Chamberlain *et al.* (9–12) found that the optimum mechanical work input for the Chorleywood Bread Process was largely constant and independent of flour mixing strength, while Zentner (45) demonstrated that the consistency of a dough mechanically developed to produce good bread corresponded to a dough of identical composition which had been extensively broken down in the farinograph. Gracza (46), in 1964, studying the rate of energy consumption in mixing doughs from air-classified flour fractions, found a great variation in farinograph peak torque characteristics and after carrying out baking tests concluded that the relation between the peak torque of mixing curves and optimum mixing requirements was of a rather dubious nature. In 1966, Gross *et al.* (47), using a Brabender Do-corder at 210 rpm to study the effect of enzyme preparations on mixing energy requirements, found that the torque curves rose to a peak, fell slightly, and rose to a second peak before dropping more rapidly. They considered the second peak as a reference point for calculating mixing energy. Two years later, Conn and Kichline (48) operating the farinograph at 40° C to correspond with continuous dough temperatures, obtained two curve peaks over a range of speeds. They related the first peak to flour hydration and the second considerably later peak to gluten development. Tanaka and Tipples (49) also obtained either a 'double rise' or two peaks in farinograms under certain conditions, particularly with flours of low protein content. Most recently D'Appolonia *et al.* (50), in comparing farinograph, mixograph, and rheograph peak time, continuous unit peak time, and continuous unit optimum development speed, found that although the various correlation coefficients were significant they generally accounted for less than 50% of the total variability. Up to the present time, therefore, mixing studies have not clearly resolved the question of what constitutes optimum mechanical dough development.

Tests on Rested Doughs

The recommended level of mechanical work input (40 kJ kg^{-1}) for the Chorleywood Bread Process has been described as strikingly critical (9) and suggesting that certain well-defined processes have to occur to render the dough capable of producing its best bread. In an attempt to establish whether these processes could be defined in terms of the viscous or elastic behavior of the dough, Heaps *et al.* (51) in 1965 applied the 'work technique' of Muller *et al.* (52,53) to mechanically-developed doughs. The work technique involved experimental determination of the total and the recoverable (elastic) stress work performed when dough was stretched on the Brabender Extensigraph. The irrecoverable (viscous) component of stress work was then obtained by difference. Doughs were mixed in a farinograph at 60 rpm to work levels between 10 and 110 kJ kg^{-1} and 150-g pieces were moulded, pegged into extensigraph cradles, and allowed to rest for 45 min at 30° C in humified cabinets before being stretched. Heaps found that both the viscous and elastic components of stress work increased with mixing work input and that both attained a maximum value at the same level of mixing work input. This appeared to provide a measurable basis for the term 'dough development.' For the untreated flour used maximum development occurred around 100 kJ kg^{-1}. It was noted particularly that this level of work input, required to develop the dough until the viscous and elastic stress work components were at a maximum, was not coincident with the Chorleywood optimum development of 40 kJ kg^{-1}. One possible reason considered was that the rather low rate of work input (average: 4.0 kJ $kg^{-1}min^{-1}$) could be responsible for the discrepancy. In a later paper (54) a variable-speed Brabender Do-corder was used, allowing a much faster rate of mechanical work input to be obtained (45.0 kJ $kg^{-1}min^{-1}$), but the stress work component maxima were further displaced from the Chorleywood optimum (see Fig. 4) and occurred at about 250 kJ kg^{-1}. However, the results confirmed that both the viscous and elastic stress work components passed through a maximum at the same work level.

The extensigraph work technique suffers from two disadvantages: first, it is laborious and very time-consuming; second, it can only be applied to doughs and not to the isolated glutens. Moreover, since the viscous and elastic components have been shown to be qualitatively similar in their indication of dough development, then for this purpose it is not essential to employ techniques that separate them. Heaps *et al.* (55), therefore, proposed a simple stress relaxation test for monitoring dough development. The method, which has been described in more detail by Frazier *et al.* (56), consists of moulding 10.0-g pieces of dough (or gluten) into spherical balls, and allowing them to rest for 45 min at 30°C before compression on an Instron Universal Testing machine to a predetermined load. The dough is then allowed to relax at constant deformation to a lower load

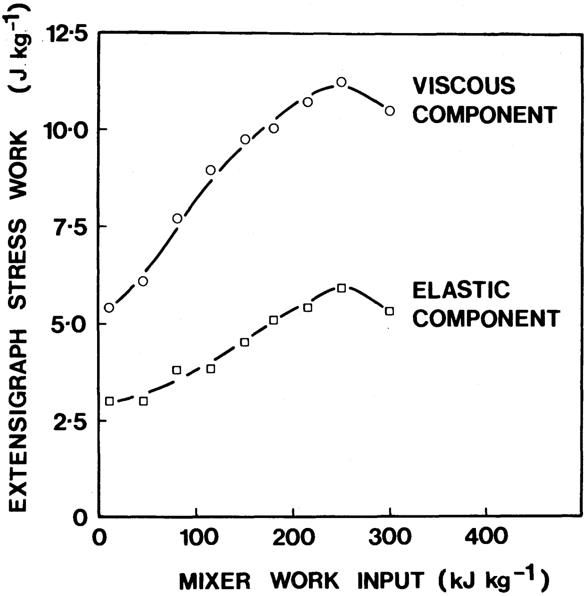

Fig. 4. Effect of mixing work input on extensigraph viscous and elastic stress work components (8 cm nonrecoverable and 5 cm recoverable extension, respectively) (54).

limit and the relaxation time determined. Load limits found most practicable from consideration of machine performance and experimental time for a very wide variety of dough samples were: for doughs 180–80 gf and for glutens 90–60 gf. Figure 5 shows that good correlation was obtained between total (*i.e.*, viscous plus elastic) stress work and relaxation time as an indication of the extent of mechanical development (55).

Using the compressive stress relaxation technique, Webb *et al.* (57) examined the mechanical development of doughs from a variety of Buhler-milled flours of widely differing protein content. Some examples from their results are shown in Fig. 6. Development was carried out at a constant rate of work input of 20 kJ $kg^{-1}min^{-1}$ and with the majority of flours relaxation time increased to a maximum as work increased. The rate of this increase and the maximum relaxation time attained, varied with the flour protein quantity and quality. The level of work input at which these maxima were reached ranged between 170 kJ kg^{-1} and 310 kJ kg^{-1}, though for most of the flours examined the maximum occurred around 210 kJ kg^{-1} (Fig. 6). Some flour samples, however, notably the American Soft White (8.2% protein) and the English Hybrid 46 (9.8% protein), did not appear to respond at all to mechanical development insofar as dough relaxation time either remained approximately constant or fell with increasing work input.

These results from tests on mixed and rested doughs, indicating optimum mechanical development to occur at work levels around 200 kJ kg^{-1}, appear clearly at variance with the results from recording mixers described earlier, where peak torque occurred around 50 kJ kg^{-1}. An attempt to reconcile this apparent

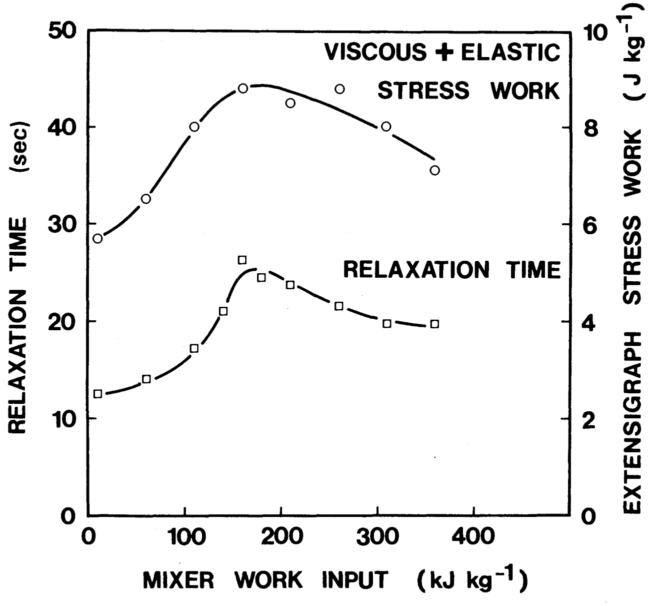

Fig. 5. Comparison between Instron compressive stress relaxation time (180–80 gf) and extensigraph total stress work (viscous plus elastic at 10 cm extension) parameters as an indication of the extent of mechanical dough development (55).

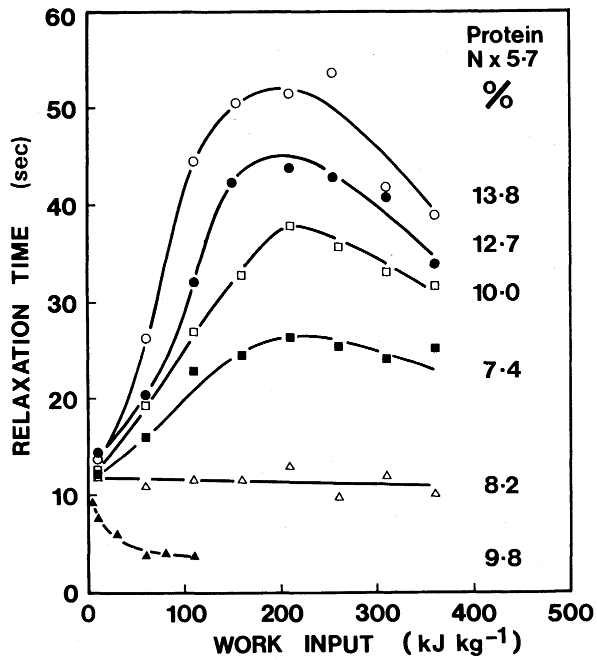

Fig. 6. Mechanical development of doughs from flours differing in protein quality and quantity (relaxation times from 180–80 gf) (57). Key: ○ Russian; ● No. 2 Manitoba; □ Hungarian; ■ French; △ American Soft White; ▲ English Hybrid 46.

discrepancy will be made and the meaning of mechanical development discussed in the concluding section of this paper.

Effect of Rate of Work Input on Dough Development

A fully-developed, mature dough may be produced either by yeast fermentation involving, among other factors, gentle mechanical action over several hours, or by vigorous mechanical mixing occupying less than a minute in a continuous developer. Both systems give good quality bread and their comparison illustrates the diversity of rates of work input acceptable to the breadmaking process.

To examine the effect of work rate on dough development in more detail, Heaps *et al.* (54) mixed doughs at a variety of constant rates of work input and then tested the rested doughs by the extensigraph work technique. They found that the stress work components increased at a particular work level as the rate of mechanical work input increased. Thus, for a given amount of energy expended, the degree of development of the dough structure could be increased by mixing at a higher rate of work input. (In other words, high-power mixing made more efficient use of energy in developing dough.) Whereas early indications were obtained that an optimum rate of work input may exist at 35 kJ $\mathrm{kg^{-1}min^{-1}}$, this was not confirmed by further work using a modified Do-corder with a higher power capability.[1]

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[1] Webb, T., personal communication.

The effects of work rate on dough development are currently being reappraised by the present authors, using the new Compudomixer (described later). An example of the results obtained is shown in Fig. 7. Doughs from an unbleached, untreated, strong flour (100% U.S. Northern Springs) were developed in air at a series of constant rates of work input from 2.0 to 60.0 kJ $kg^{-1}min^{-1}$, moulded, rested for 45 min at 30° C and tested by the compressive stress relaxation method (55,56). Data were then fed into an Atlas 2 Computer programmed to produce a contour map output showing relaxation time (in 5-sec intervals) as a function of work rate and work level. It can be seen that increasing the work rate resulted both in a progressively higher peak development and a displacement of the peak development to higher work levels. This may be clarified by a more conventional plot of relaxation time *vs.* work input (Fig. 8) showing a family of curves derived from horizontal cross sections through the contour plot at the selected work rates shown. The large change in magnitude of peak development with work rate (from 29 sec at 2.0 kJ $kg^{-1}min^{-1}$ to 72 sec at 40 kJ $kg^{-1}min^{-1}$) is clearly evident. It is also apparent that increasing the work rate enabled doughs to be mixed to a higher work level before breakdown. Alternatively, if vertical cross sections are taken through the contour plot at

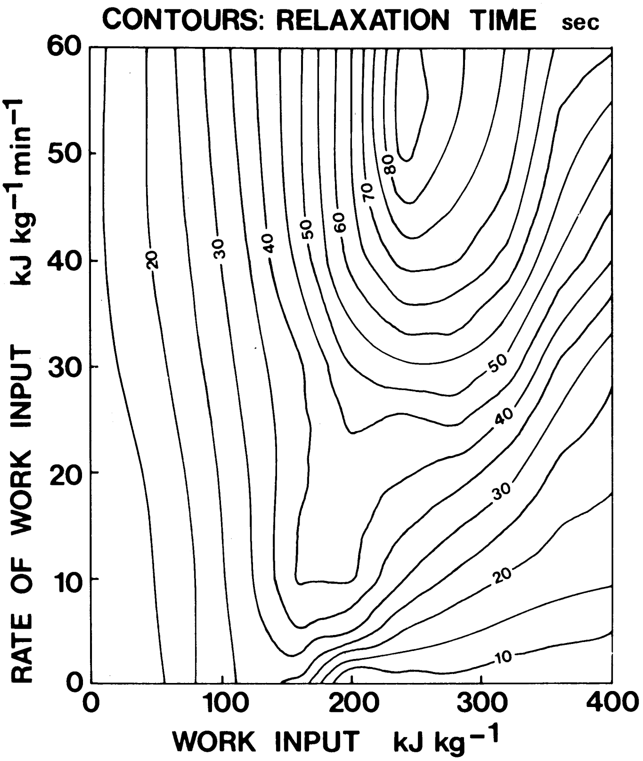

Fig. 7. Computer generated contour plot showing the effect of rate of work input and level of work input on dough development as indicated by relaxation time contours (5-sec intervals).

selected work levels (Fig. 9) it can be seen that relaxation time is almost linearly related to the rate of work input. No optimum rate has been found in the range so far examined (up to 60 kJ $kg^{-1}min^{-1}$, or approximately equivalent to mixing in a farinograph bowl at 500 rpm) although it is assumed that an upper limit of development must exist. It is also evident that work rate has much more influence on relaxation time near peak development. On the lower slopes of the development curves (*e.g.*, 40–100 kJ kg^{-1}) the effect of rate is much less noticeable. It may seem unexpected that relaxation times for the highest work level in Fig. 9 (250 kJ kg^{-1}) fall below those for the 100 and 40 kJ kg^{-1} levels at low rates of work input (below 10 kJ $kg^{-1}min^{-1}$). However, by reference back to the contour map (Fig. 7), it can be seen that this falloff in relaxation time is due to dough breakdown, since at low work rates a work level of 250 kJ kg^{-1} is well beyond peak development.

When a soft flour (100% English) was examined, the results were qualitatively similar to those presented above, but the maximum relaxation times reached were very much less, ranging from 14 sec at 2.0 kJ $kg^{-1}min^{-1}$ to 25 sec at 60 kJ $kg^{-1}min^{-1}$.

In practical bakery terms, the effect of rate of work input has been stressed

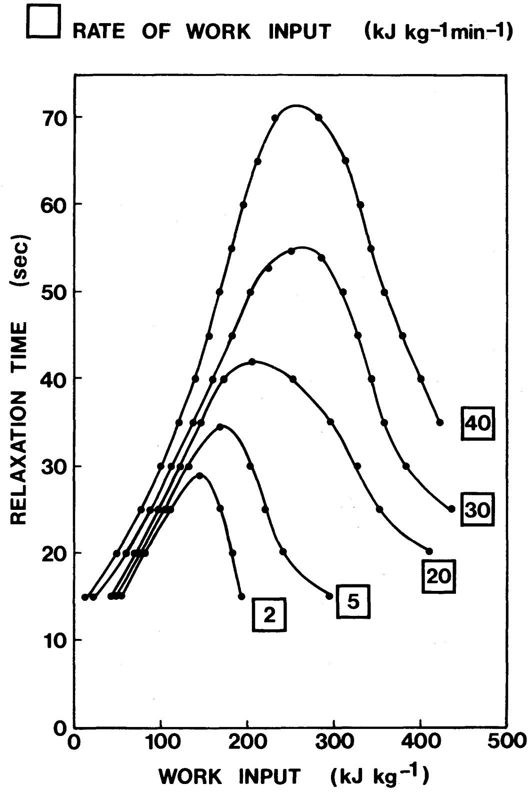

Fig. 8. Curves derived from horizontal sections through the contour plot (Fig. 7) showing dough development at selected rates of work input from 2.0 to 40.0 kJ $kg^{-1}min^{-1}$.

particularly in the Brimec Process (16,29,58). The above results also help to explain the 'critical minimum speed' of mixing observed by Kilborn and Tipples (43). Since the average rate of work input is dependent on the speed of rotation of the mixer, then below a certain speed dough may not be sufficiently developed to produce good bread even when mixed to the maximum development as indicated by peak relaxation time. For example, from Fig. 8, if 35 sec were the minimum relaxation time for a good loaf, then mixing at or below 5 kJ $kg^{-1}min^{-1}$ would not produce good bread even at the peak development. However, mixing at speeds which gave a rate above 20 kJ $kg^{-1}min^{-1}$ would enable doughs to be developed to a relaxation time above 35 sec. (In practice, the work levels and relaxation times involved would be very different due to the presence of chemical improvers.) Changing the mixer design, of course, would introduce a different pattern of shear (and consequently a different torque at a given speed) so that the average rate of work input would be changed. In order to attain the same minimum average rate of work input, therefore, different mixers would require different minimum speeds (43).

The implications of mixing commercially at a constant rate of work input have been discussed by Kilborn and Tipples (59). Constant power mixing ensures that maximum utilization is made of the mechanical capabilities of the mixer

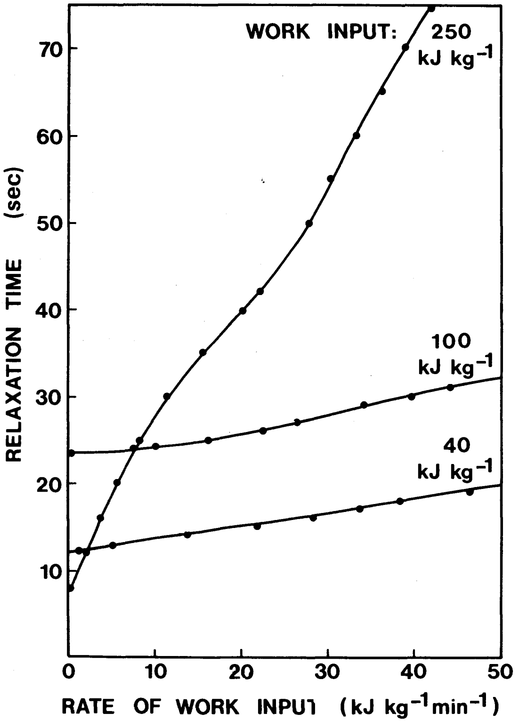

Fig. 9. Curves derived from vertical sections through the contour plot (Fig. 7) showing the relation between relaxation time and rate of work input at selected work levels (40, 100, 250 kJ kg^{-1}).

throughout the whole of the mixing period and not just when the dough is at its maximum consistency. Time saved would depend on the mixing characteristics of the flour and the speed at which the mixer was normally run. Perhaps more important, however, is the fact that mixing times would always be constant (for a given work input) thereby allowing finer control of subsequent processes.

CONTROL METHODS FOR MECHANICAL DEVELOPMENT

Laboratory Methods

The advent of continuous dough processing and batch mechanical development placed new demands on laboratories concerned with flour quality assessment and led to the adaptation of conventional farinograph and extensigraph techniques in an attempt to predict flour behavior under these new conditions. Thus, Trum and Snyder (60), shortening the dough rest period from 90 min to 5 min before stretching on the extensigraph found considerable differences between some flours which otherwise appeared identical after the conventional 90-min rest period. A flour was regarded to be of suitable strength for continuous processing if the 5 min value of 10 E/R was in the range 1.0–1.5 providing $R > 750$ BU. A similar short rest (10 min) extensigraph test was used in studies of the Chorleywood Bread Process (61). A farinograph technique in which mixing was carried out at 38° C was described by Trum and Rose (62), who found that flours with a satisfactory conventional (30° C) farinogram may exhibit weak characteristics at 38° C and not perform well in continuous mixing processes. The relation between conventional farinograph mixing curves and mechanical development has been discussed in detail by Tanaka and Tipples (49) and D'Appolonia *et al.* (50). (See also: **Mixing Studies** above.)

The growth of mechanical development also resulted in the design of a number of small-scale dough developers for laboratory bread production and flour evaluation (63–67). In addition, new Brabender mixers were introduced which are more suitable than the Farinograph for examining mechanical dough development—the Do-corder (47,68) (or Plastograph), and very recently the Resistograph (69).

Where work is to be controlled, some form of recording wattmeter or integrating watt-hour meter in the motor supply circuit is required, such as that described by Kilborn and Dempster (70). Alternatively, electronic measurement of torque and speed on the final drive shaft and integration of their product over time is needed. This approach is potentially more accurate since it is not influenced by power losses in the motor and gearbox and is used in the 'Compudomixer' described below. Whichever method is employed, examination of the mixing behavior of doughs is facilitated by the use of electronic recording mixers. Suitable modifications of the farinograph and other mixers for electronic torque recording have been described thoroughly by Voisey *et al.* (71–79).

Commercial Systems

The Chorleywood Bread Process was the first breadmaking system in which an effective rheological parameter, the work expended on the dough, was used directly as a means of controlling the process. Suitable control system designs for a number of mixers, based on measurement of electrical power consumption with watt-hour meters, have been described in detail by the process originators

(80) and further description is not warranted here.

Another aspect of bakery control is the problem of maintaining optimum water addition in batch or continuous mixers as the flour absorption changes during the course of a working shift. The water addition required for a given consistency could, of course, be determined by conventional laboratory rheological methods, but in recent years attempts have been made to extract automatically during a mixing rheological measurements which are related to the consistency of the dough and to use these measurements to control the metering of one of the ingredients, usually water. One such method (81) involves following the time required for the input of a given amount of energy at constant mixing speed. If the dough is too stiff, the motor consumes energy at a greater rate and, therefore, uses up the given amount of energy in a shorter time. However, this method has the disadvantage that it can only be used to control subsequent mixes and, therefore, is unable to compensate for random consistency variations.

An improved system, developed by Morison (82), allows dough consistency correction to be made to the same mixing that provided the rheological information. The principle is illustrated in Fig. 10. As the mixing proceeds, consistency is assessed by measuring the quantity of energy consumed during a predetermined period, the 'assessment time,' which is shorter than the total mixing time. This energy measurement is compared electronically with the final desired consistency setting and the difference is used to compute automatically a small water addition. The added water is blended into the dough to give the final corrected consistency just before mixing is completed, in the usual way, on reaching the correct total work input. Clearly, if the assessment indicated the dough to be too slack, water could not be removed. Therefore, all doughs are

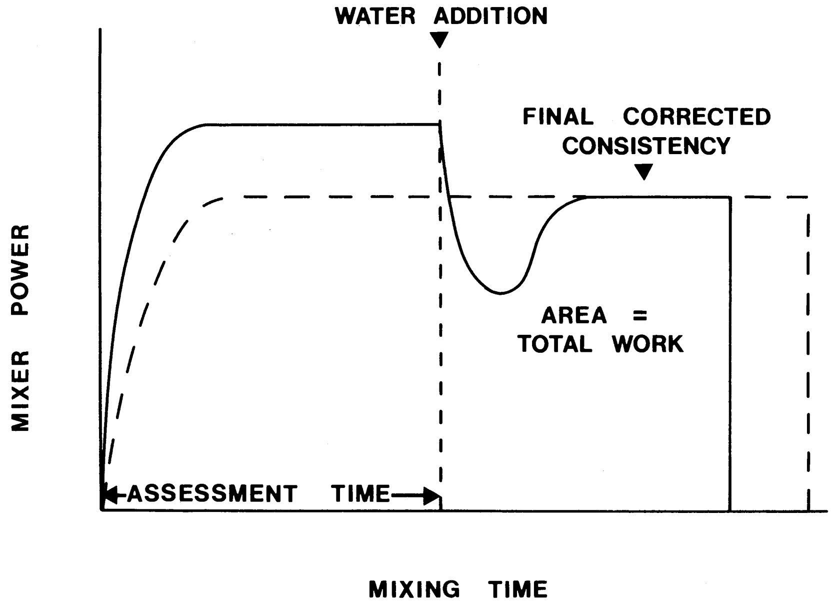

Fig. 10. Principle of Spillers Dough Consistency Control (82).

initially made too stiff by deliberately reducing the initial water content by a small amount (about 3%). Within these limits (±3%), determined by the maximum amount of water that can be successfully blended into the dough, the consistency control will correct both positive and negative deviations.

A NEW COMPUTING DOUGH MIXER ('COMPUDOMIXER') FOR RESEARCH INTO MECHANICAL DOUGH DEVELOPMENT

The sensitivity of dough development to work rate, as discussed in section on **Effect of Rate of Work Input on Dough Development**, clearly makes it desirable for constant rates of work input to be employed for research purposes whenever possible, so that the development of a given dough may be defined both in terms of the level of work applied and the rate of input. By manually varying the speed

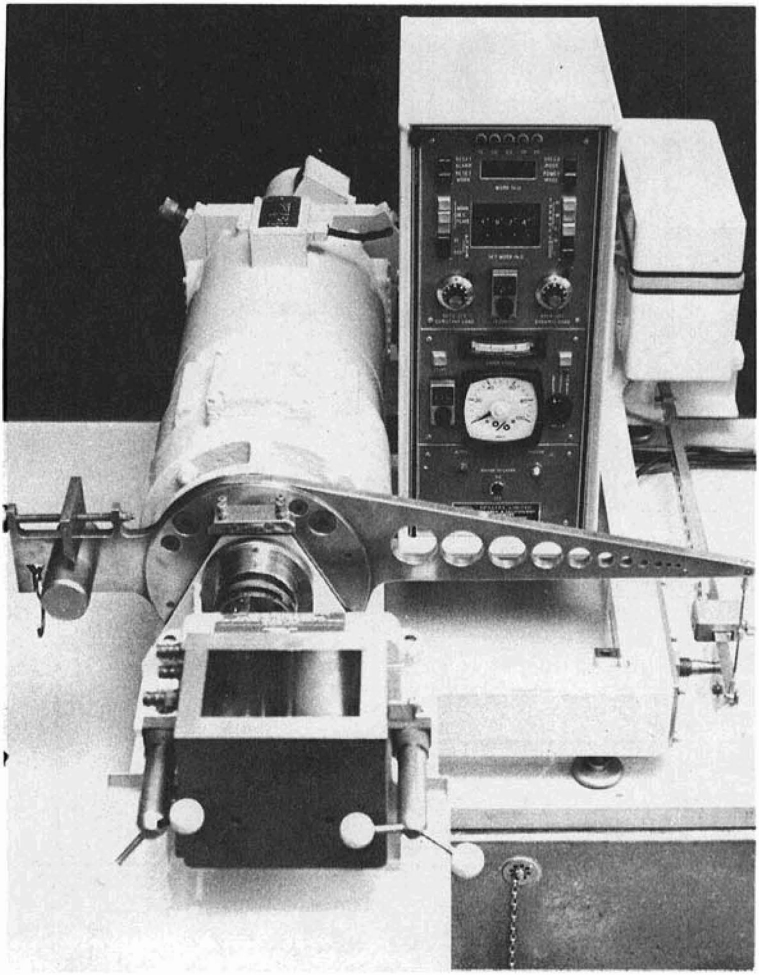

Fig. 11. Spillers research 'Compudomixer' (computing dough mixer).

of a Brabender Do-corder according to the torque displayed approximations to constant power mixing have been achieved (54,56,57) but quite large errors were inevitable, particularly during the early stages of mixing when torque values changed rapidly. A modified GRL Mixer for use at a constant rate of work input has been described (59). However, this design, in relying on measurement of electrical power consumption as the control parameter, is inherently more susceptible to error than a direct torque recording instrument owing to losses in the motor, gearbox, etc. (37). Although detailed modifications to a Brabender Farinograph to permit electronic torque recording have also been published (71–79), the basic instrument is not sufficiently powerful to provide the range of speeds and rates of work input ideally required for a research dough mixer. It was accordingly decided by the present authors to design and construct a completely new machine. The following account summarizes the main features. (Full details will be published elsewhere.)

The Spillers 'Compudomixer,' illustrated in Fig. 11, is powered by a 2-HP, dc industrial motor and concentric gearbox suspended at either end in bearings and free to rotate. The drive shaft may be coupled to a standard 300-g farinograph bowl (as illustrated) or to any other design of mixing chamber that may be desired. Torque on the final drive shaft is transmitted via a system of levers to a moving-coil electromagnetic force balance measuring system. Speed is monitored by a dc tachogenerator mounted on the motor drive shaft. Signals from the tachogenerator and the torque transducer are fed into the control system which utilizes both analogue and digital logic as shown in the simplified block diagram in Fig. 12 (for constant power mode). Controls and monitoring

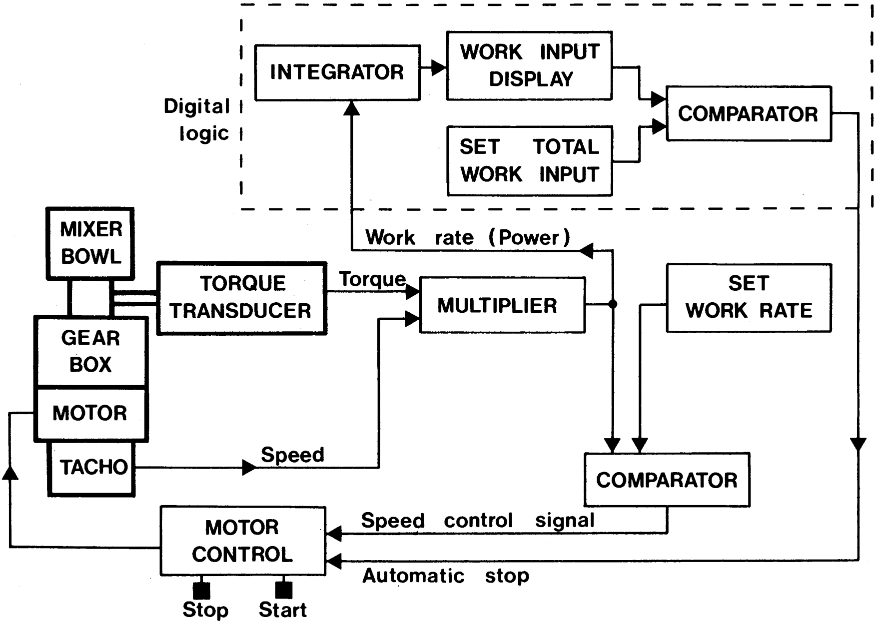

Fig. 12. Simplified block diagram of the 'Compudomixer' in constant power mode.

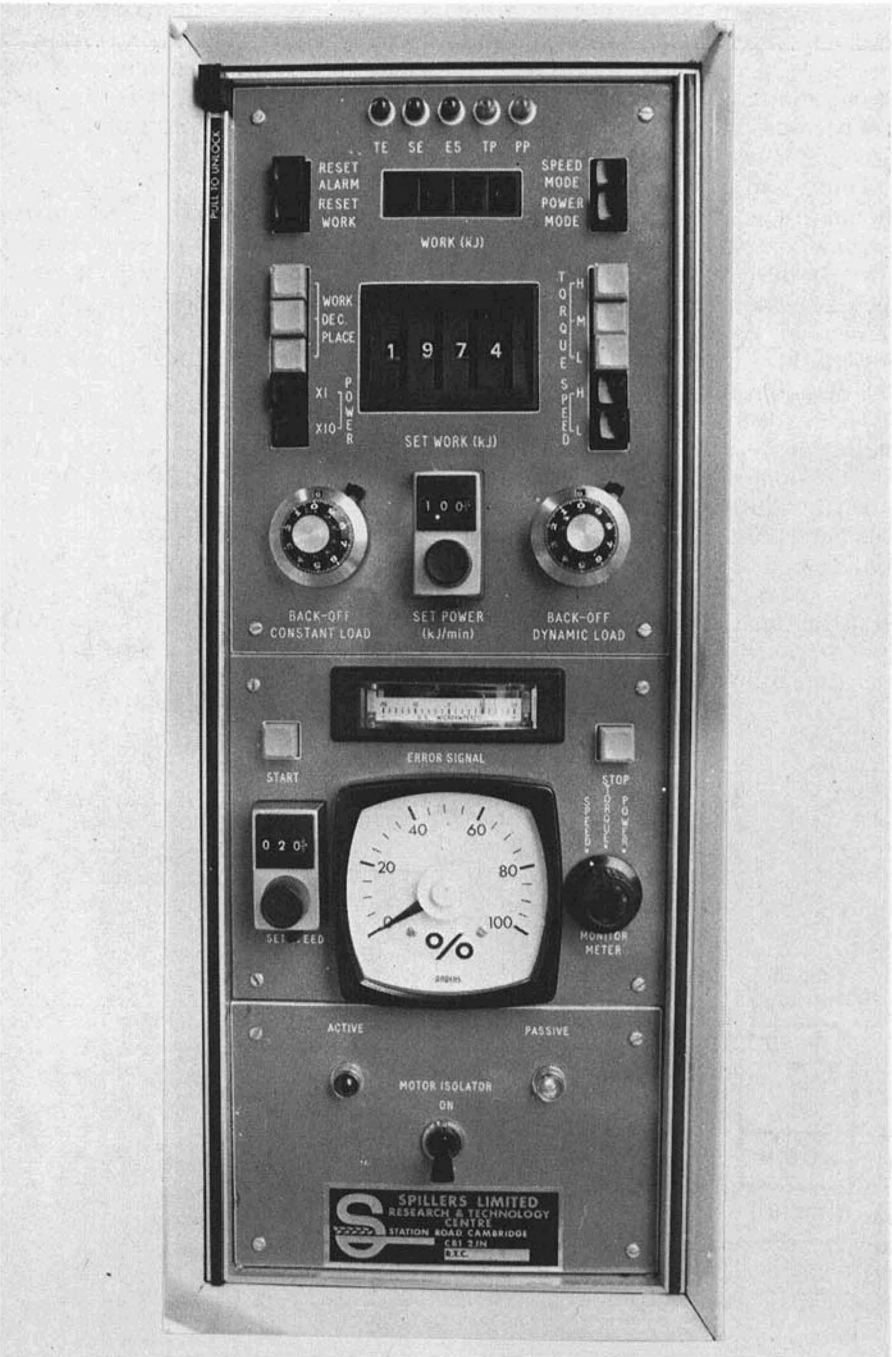

Fig. 13. Control panel of the 'Compudomixer.'

displays are shown in close-up in Fig. 13. Work done is indicated continuously on the upper digital display and the work input required is set by digital switches below. Push-button switches are provided for selection of different torque, speed and power ranges. The mixer may be run in either constant speed or constant power mode with either speed or power being selected on the digital readout potentiometers ('set speed' and 'set power'). A meter (lower center) is provided for monitoring torque, speed or power as a percentage of full scale for the range selected. Provision is also made for recording torque, speed, and power on separate electronic chart recorders. Electronic compensation may be made for any small constant or speed dependent torque resulting from the mixing bowl itself, so that only the true work done on the dough is measured. An alarm is provided which sounds if either torque or speed become limiting, or if errors occur from other causes, and which also marks the completion of mixing.

Tests on performance accuracy gave the following (summarized) results which serve also to indicate the wide dynamic range over which the mixer may be used with confidence:

Torque: within 0.5% of indicated value between 0.01 and 4.10 kgf m
Speed: within 0.25% of indicated value between 50 and 600 rpm
Power: dependent on torque value, but generally within 1.0% of indicated value between 1.00 and 100 kJ min^{-1}
Work: dependent on power accuracy, but generally within 1.0% of indicated value. (Range obtainable 0.001–9999 kJ)

The precision of mixer control is illustrated by Fig. 14 which shows a typical simultaneous record of torque, speed, and power obtained during dough development at a constant rate of work input of 20 kJ $\text{kg}^{-1}\text{min}^{-1}$ after a short initial premix at constant speed (20 rpm). The electronic chart recorder was run at 5.0 cm min^{-1}, rather than the normal farinograph chart speed of 1.0 cm min^{-1}, to permit analysis of the mixing action. It can be seen that not only was the constant power control able to allow for the gradual change in consistency of the dough, but also that the computing control system was sufficiently precise even to compensate for rapid changes in torque arising from the pattern of dough movement in the mixing bowl.

CONCLUSION

The principles underlying determination of the so-called 'optimum' mechanical dough development, either by the use of recording mixers or by the testing of rested doughs, have been discussed earlier (see **Mixing Studies** and **Tests on Rested Doughs**). Using the new 'Compudomixer' in the constant-speed mode, Fig. 15 compares the results obtained for identical doughs by these two approaches. At a given speed, the discrepancy between the work level at which peak torque occurred and that at which peak relaxation time occurred, is clearly seen. How can this be resolved?

It is recognized that development of a dough probably involves the breakage and reformation of cross-links in the gluten protein (9) until a suitably cross-linked network (83,84) or optimum molecular-weight (85) is obtained. Thus, it seems likely that tests on rested doughs provide a measurement of mechanical development in terms of protein structure, particularly since the changes in relaxation time observed following mechanical development appear to be permanent. For example, Heaps *et al.* (55) found that curves of relaxation time *vs.* work input for isolated gluten, after a 24-hr rest period, indicated the same optimum work level as tests on the dough after a 45-min rest period.

On the other hand, torque curves are very much dependent on the mixing action actively occurring during mechanical dough development (see **Mixing Studies**). If mixing is stopped beyond the peak and restarted after a time, the torque curve may again pass through a peak (45). It would appear, therefore, that any change in dough structure contributing to the torque peak must be of a temporary nature. An additional factor contributing to dough consistency is the

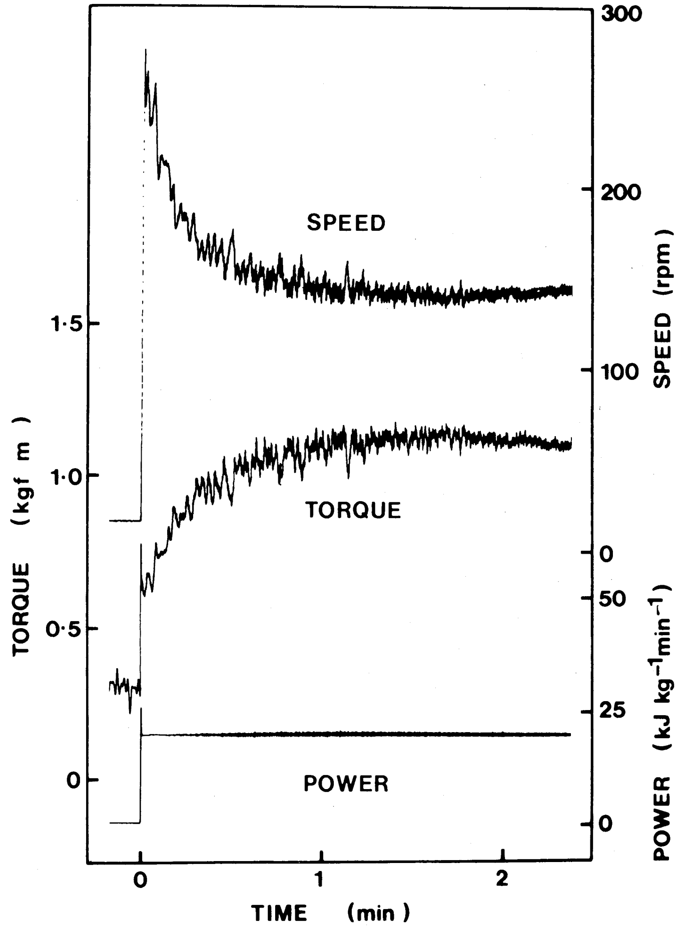

Fig. 14. Simultaneous record of torque, speed, and power during mechanical dough development in the 'Compudomixer' at a constant rate of work input of 20.0 kJ $kg^{-1}min^{-1}$.

release of bound water which may occur during mixing. This aspect of dough mixing has been reviewed recently by Daniels (86). Direct rheological evidence for an increase in free water on mixing was obtained by Webb *et al.* (87). Replotted in Fig. 16 their data suggest that this increase in free water could result in a considerable decrease in consistency as mixing proceeds.

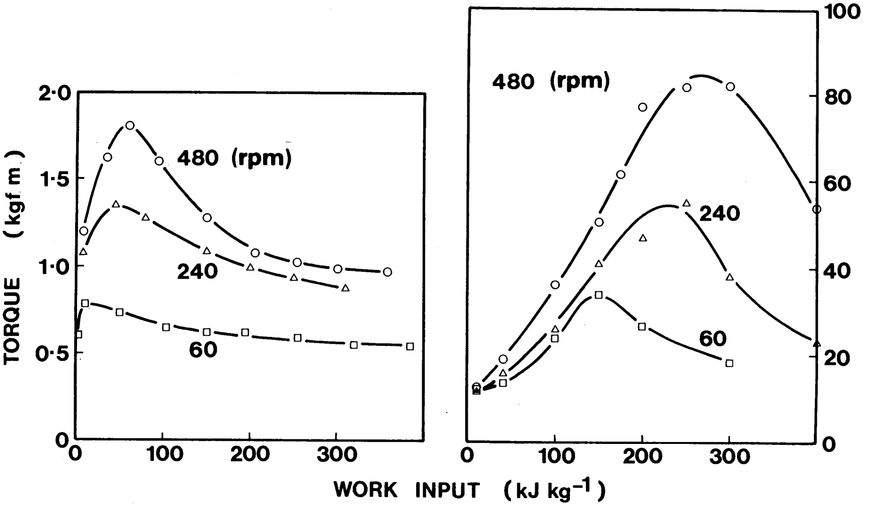

Fig. 15. Mechanical development of doughs at three constant speeds (60, 240, 480 rpm) showing comparison between mean torque *vs.* work input and relaxation time *vs.* work input.

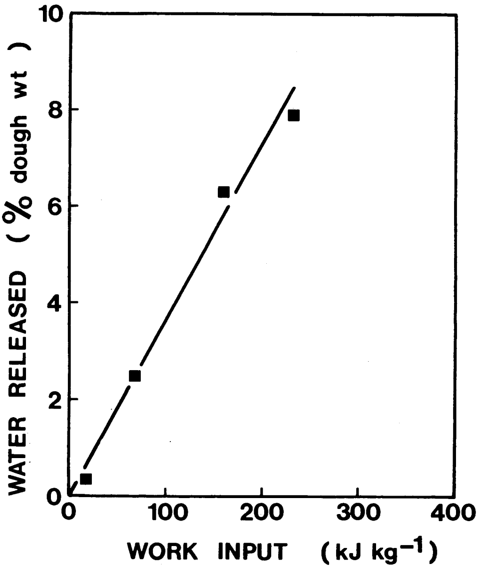

Fig. 16. Release of bound water during mechanical development of doughs (86,87).

Consideration of dough stickiness provides further insight into the changes occurring during mechanical development. Stickiness is known to increase slightly after the conventional torque peak, which may be related as suggested in Fig. 16, to the release of bound water. However, when doughs are mixed beyond the relaxation time peak a marked change in characteristics occurs. The dough becomes *extremely* sticky and can be drawn out into long strands in a similar way to dough that has been partially broken down by proteolytic enzymes. Structural breakdown is obviously occurring here, confirming the irreversible nature of true peak development.

Moreover, with some designs of recording mixer (44,69), and with the Do-corder under certain conditions (47–49), a second peak or inflection has been obtained in the torque curve. This may occur at work levels nearer to, or possibly coincident with, those indicated as optimum by tests on rested doughs. In the present authors' experience, using a modified Do-corder and farinograph bowl at a constant rate of work input, a marginal change in torque trace amplitude and slope is sometimes observed at work levels known to be in the region of the relaxation time maximum.

Whatever interpretation is placed on results from these two approaches with regard to dough structure, the final arbiter remains the baking test: how are these development curves correlated with loaf volume and quality? Working with mechanically developed doughs containing lipoxygenase-active soya flour, yeast, hard fat, and salt, but no other additives or improvers, the best loaves, both in terms of volume and texture, were obtained not at a work level corresponding to the torque peak (around 50 kJ kg^{-1}) but at a work input close to the relaxation

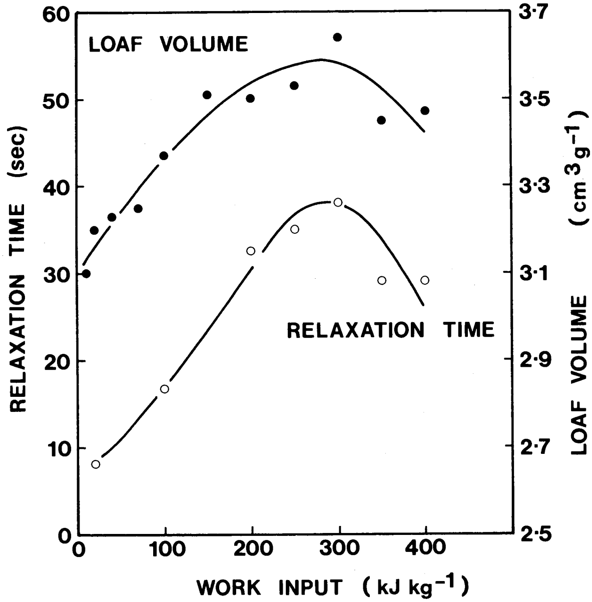

Fig. 17. Dependence of relaxation time and loaf specific volume on mechanical work input during dough mixing (88).

time peak at 300 kJ kg^{-1} (see Fig. 17) (56,88). While it is not suggested that such mixing would be commercially feasible, the results provide a significant pointer to the correlation of baking results with dough rheological measurements in mechanical development processes.

The action of commercial dough additives on dough development is complex. Preliminary investigations with a range of oxidizing and reducing agents have shown wide variation in their effect on the position of peak development, defined by relaxation time measurement (89), as well as their expected effects on the magnitude of relaxation times. In addition, the presence or absence of atmospheric oxygen during mixing appears fundamental to the dough development process (56,89), whether or not other oxidants are present.

Clearly, much more work has to be done before the changes in dough physical properties brought about by the combined effects of mechanical development and chemical action can be understood and explained. To the baking industry, such an understanding would be of considerable value.

Acknowledgments

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