DOUGH STRENGTH AS MEASURED BY DOUGH PROFILING AND THE EXTENSIGRAPH

by

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DOUGH STRENGTH AS MEASURED BY DOUGH PROFILING AND THE EXTENSIGRAPH

BY

LINDA SCHLICHTING

A Thesis/Practicum submitted to the Faculty of Graduate Studies of the University of Manitoba in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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ABSTRACT

The potential of the dough profiling technique to measure dough strength was evaluated. When secondary data analysis was conducted on a set of bread wheat lines, it indicated that several dough profiling parameters were highly correlated with extensigraph properties. Relaxation degree correlated with extensigraph maximum resistance to extension ($r = 0.87$) and relaxation ratio with extensigraph ratio at 45 min rest time ($r = -0.82$). Tension work was correlated with mixograph peak height ($r = 0.82$). Canonical correlation analysis indicated that relaxation ratio and relaxation index were found to be important in the prediction of extensigraph maximum resistance to extension and ratio of maximum resistance to extensibility.

In the experimental study, four flours with widely varying dough properties were evaluated using the farinograph, extensigraph and the dough profiling method. Extensigraph data were obtained using a 150 g sample size, as well as a 70 g sample size. Extensigraph properties of maximum resistance to extension, area and ratio of maximum resistance to extensibility were well correlated for the 70 g and 150 g sample sizes at all rest times. Pearson correlation coefficients were 0.82 - 0.88 for maximum resistance to extension, 0.88 - 0.93 for area and 0.70 - 0.75 for ratio. Extensibility values for the two sample sizes were not correlated.

Large differences in extensigraph properties were evident between the four base flours. The CWES doughs had the highest values for maximum resistance to extension, area and ratio at all rest times, followed by the CWRS and CPS doughs. The SWS dough had the lowest values for maximum resistance to extension, area and ratio at all rest times.

Dough profiling parameters discriminated among the four base flours. Compression work values were highest for CWES (51 N.mm) and CWRS (54 N.mm) doughs and lowest for the SWS (32 N.mm) dough. Tension work values were lowest for the CWES (100 N.mm) and CWRS (115 N.mm) doughs and highest for the SWS dough (198 N.mm). Relaxation ratio values were highest for the CWES dough (0.30) and lowest for the SWS dough (0.12), while relaxation index values were highest for the SWS dough (-0.16) and lowest for the CWES dough (-0.29).

Two of the dough profiling relaxation parameters, relaxation degree and relaxation ratio were highly correlated with extensigraph maximum resistance to extension. Pearson correlation coefficients between relaxation ratio and maximum resistance to extension at 45, 90 and 135 min rest times were 0.89, 0.87, and 0.85, respectively. Tension work of the first cycle was also correlated with maximum resistance to extension. Pearson correlation coefficients between tension work and maximum resistance to extension at 45, 90 and 135 min rest times were -0.76, -0.78, and -0.77, respectively. Extensigraph area and ratio were also highly correlated with the relaxation ratio at all three rest periods ($r > 0.81$). Dough profiling compression parameters compression peak force and compression work were correlated with extensigraph extensibility at 90 and 135 min rest time ($r = -0.70$ - -0.82).

The R-square variable selection procedure was used to generate regression models to predict extensigraph parameters. The regression models for maximum resistance to extension , area and ratio all had R^2 values > 0.88 and were dominated by relaxation and tension variables. Two relaxation variables, relaxation ratio and relaxation degree were common to all models.

The dough profiling method appears to be a useful and reproducible method to measure dough strength. It requires further investigation.

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For my dad

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Chapter 1

INTRODUCTION

The rheological properties of wheat flour dough govern its behaviour during mixing, processing, handling and baking and influence end product quality (Bloksma, 1990). Determination of the rheological properties of doughs is becoming more important for several reasons. Increased automation in the bakery and consumer demand for a variety of products make subjective evaluations of dough properties inadequate for consistent quality production (Menjivar, 1990). Description of dough behaviour with meaningful parameters will allow the prediction of dough behaviour under different experimental conditions (Faubion and Faridi, 1986). Ultimately, knowledge of the rheological properties of dough will provide essential information on the structure and chemistry of dough, which will make new product or process development possible (MacRitchie, 1980). Therefore, rheological testing is important to wheat breeding programs and to milling and baking industries.

Traditional physical dough testing instruments have been used extensively for evaluation of dough properties such as strength, stability and extensibility. These instruments have not been successful for fully describing dough quality or for predicting dough handling properties and end product quality. New methods of dough testing that would provide rapid, reliable estimates of dough properties would benefit breeding programs and industry. New texture testing methods might also bridge the gap between empirical tests, those that measure properties that are hard to define, but provide useful information to breeders and bakers, and fundamental tests, which measure clearly defined properties but do not provide practical information (Rasper, 1994).

Texture Profile Analysis (TPA) has been used extensively for assessing textural properties of food products. The advantage of the TPA technique is that it offers a multi-dimensional texture characterization (Szczesniak, 1985). The use of TPA to study dough rheological properties has received little attention. Although the TPA does not provide fundamental data, the parameters obtained from the curve have a fundamental basis (Szczesniak, 1963).

A modified form of TPA, called dough profiling, was used to study the rheological properties of wheat flour doughs to characterize dough stickiness by Wang et al (1996). It would be useful to determine whether dough profiling could be used to characterize other important dough properties and possibly provide a rapid quality test to supplement or replace current physical tests. Dough profiling may prove to be the method that is the most useful for routine quality control testing because it is easy to do and provides information on several textural properties with a single test.

The general objective of this study was to determine the usefulness of dough profiling parameters for dough rheological measurements. This thesis is divided into two sections. The objective of the first section was to determine the relationships between dough profiling parameters and standard physical dough testing results through analysis of rheological data and dough profiling values of bread wheat flours. The objective of the second section of this thesis was to test the hypothesis that dough profiling parameters could be used to measure dough strength, as determined by the extensigraph.

Chapter 2

REVIEW OF LITERATURE

INTRODUCTION

Physical dough testing instruments like the mixograph, farinograph and extensigraph have typically been applied to measure strength in wheat flour and dough quality testing. Although they do not provide fundamental data, these tests have provided practical information when assessing flour quality and baking performance. Due to the time and sample size requirements of these tests, researchers have looked for simpler, quicker and more accurate tests. Texture profile analysis is a useful instrumental technique that describes the texture of many food products. Recently, Wang et al (1996) successfully predicted dough stickiness using a modified TPA. It is possible that the dough profiling technique can be used to measure other dough rheological properties like dough strength.

QUALITY TESTING

Quality testing plays an important role in the cereals industry. Wheat quality assessment is particularly important for wheat breeding programs, in marketing, processing and quality control (Weipert and Pomeranz, 1986). Quality testing must reflect the end use of the wheat, as properties essential to one product may be undesirable for another. However, in wheat breeding programs, wheats are often selected because they can be used for a variety of products and have tolerance to several mixing, processing and baking conditions (Lukow, 1991). Wheat quality assessment includes many types of tests that measure properties of wheat flour and dough, which are important to the quality of the baked product (Khattack et al, 1974). Wheat quality cannot be measured by a single test (Branlard et al, 1992). Quality testing has played a significant role in wheat breeding programs which aim not only to develop high quality wheats for domestic use, but also for Canada's large export market (Fowler and De La Roche, 1975). In a typical wheat breeding program, it takes many years to fully develop and assess the quality of a cultivar. Large numbers of samples need to be evaluated and quick quality tests are essential to identify those cultivars with the best quality (Lukow, 1991). Cereal laboratories involved in wheat breeding programs are always looking for new procedures to assess quality that meet the criteria of rapidness, simplicity and small sample requirements (Gras and O'Brien, 1992).

Quality tests used for early generation testing include protein content, flour yield and mixograph values, and for advanced generation testing include, in addition, the farinograph, extensigraph, amylograph, sedimentation value, damaged starch content and falling number tests. In early generation testing, only 60-100 g of seed is available, therefore quality testing at this stage is limited to tests that require small sample sizes. Lines which exhibit desirable qualities will proceed to late generation testing. In later generation screening, availability of larger sample sizes allow more in-depth analysis of the breadmaking potential of the new lines (Lukow, 1991). At this stage, more physical, chemical and baking quality tests are performed.

The mixograph is one of the most important quality tests for early generation screening (Lukow, 1991). Dough strength, as measured by mixograph peak height and mixograph development time, is the most important characteristic in bread wheat quality evaluation (Lukow, 1991).

DOUGH STRENGTH

The ultimate goal of quality testing is to identify flours with good breadmaking potential. One of the essential criteria is to assess dough strength, a critical factor in the breadmaking process. The strength of the dough will determine how the dough will behave during the handling and processing stages, and strength is particularly important during the fermentation and processing stages when the dough is subjected to many stresses. The dough must have sufficient elasticity to expand and retain gas during fermentation (Bloksma, 1990). Breadmaking potential, or baking strength, is primarily assessed by the ability of the dough to produce large loaf volume and good crumb structure in the baked product (Williams et al, 1988).

Dough strength should be assessed in terms of the end-use of the flour being evaluated (Williams et al, 1988). Those qualities that characterize strength for breadmaking will not be the same as those that characterize good cake or biscuit flour (Williams et al, 1988). However, the term strength, as used in the literature, has generally been applied to describe flours used for breadmaking (Preston and Hoseney, 1991).

A term often encountered in the literature is 'flour strength', which is used interchangeably with dough strength. In the strictest sense, the term flour strength can only be applied to the mixing process. The term flour strength, as used in this thesis, refers to the characteristics of a flour during the mixing process.

The fundamental rheological properties of elasticity and viscosity are reflected in dough strength. The viscoelastic properties of wheat flour doughs are primarily due to the protein component (Faubion and Hoseney, 1990). Although the protein content is important, protein quality, or the inherent properties of protein are also important to dough strength and breadmaking potential. Upon mixing with water, the proteins in wheat flour combine to form gluten, a cohesive, extensible and rubbery mass that contributes the functional properties of wheat flour doughs. Gluten is composed of two major groups of proteins, the gliadins, which contribute the viscous component, and glutenins, which contribute the elastic component to dough (Kaufmann et al, 1986). The differences in glutenin subunit composition may be responsible for the observed differences in dough strength (Wrigley, 1994).

Strength, as used in the literature, is really the composite of characteristics of wheat flour that relate to its potential for breadmaking. These characteristics are evaluated by physical dough testing instruments as well as the baking test. Characteristics of a flour with high potential for breadmaking include high water absorption, a medium to long mixing time, tolerance to mixing, good loaf volume potential and good crumb texture and colour. Wheats that have these characteristics are generally referred to as strong (Tipples et al, 1982).

PHYSICAL DOUGH TESTING INSTRUMENTS

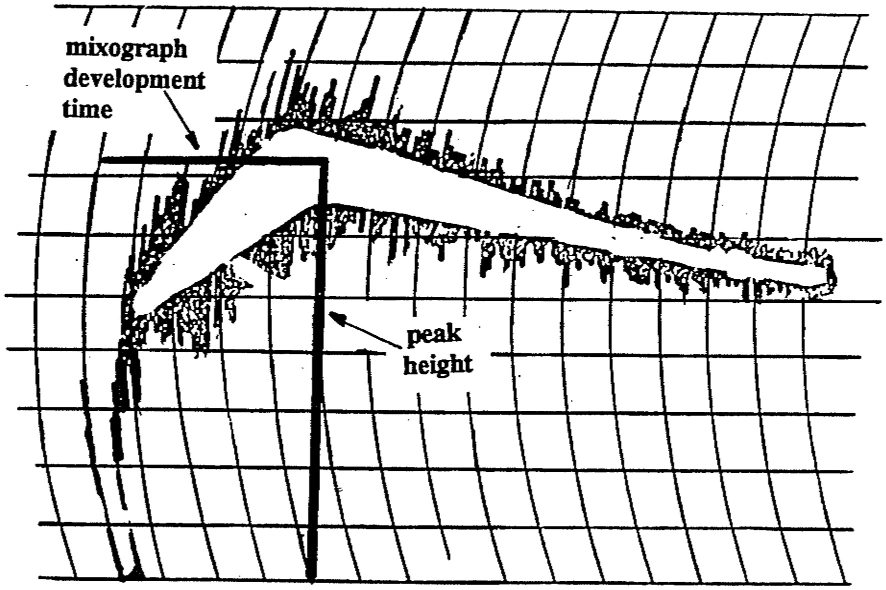
Dough rheological properties have traditionally been measured with recording dough mixers like the mixograph and farinograph, and load-extension instruments such as the extensigraph and alveograph. Information derived from the curves that these instrument produce has been used to describe dough properties like strength, stability and extensibility. Although these instruments do not provide fundamental rheological data, they have been successfully applied as quality control and research tools and provide valuable information for predicting dough behaviour in the bakery.

Mixograph

The mixograph is a high speed recording dough mixer that has been widely used for wheat quality evaluation (Kunerth and D'Applonia, 1985). The present day mixograph is a modified version of the original model developed by Swanson and Working in 1926 (Shogren, 1990). Finney and Shogren (1972) developed a 10 g mixograph, which was subsequently modified by Finney (1989) to require only 5 g of flour. Recently, Rath et al (1990) developed a mixograph requiring only 2 g of flour, which has been applied for early generation testing in wheat breeding programs (Gras and O'Brien, 1992).

The mixograph has been used extensively for early generation screening in wheat breeding programs. Several mixograph parameters have been used to measure dough strength, including mixograph development time, mixograph peak height and area under the curve (Shuey, 1975). A typical mixograph curve is shown in Figure 1. Mixograph development time, or peak time, is the time to the maximum height of the curve in min. Mixograph peak height is the height of the curve at peak time. Area under the curve can be measured as total area or area under the curve to peak time. Computerized data collection has made it possible to measure other curve parameters like total energy to peak, band width at peak and total band energy (Navickis et al, 1990).

Many studies have correlated various mixograph parameters with baking quality (Johnson et al, 1943; Finney and Shogren, 1972; Fowler and De La Roche, 1975; Rubenthaler and King, 1986; Branlard et al, 1991). The most useful parameters for predicting loaf volume have been mixograph development time and mixograph peak height (Finney and Shogren, 1972; Lukow, 1991). The mixograph remains a useful instrument in assessing flour strength, particularly in early generation screening, when only small sample sizes are available.



Time (minutes)

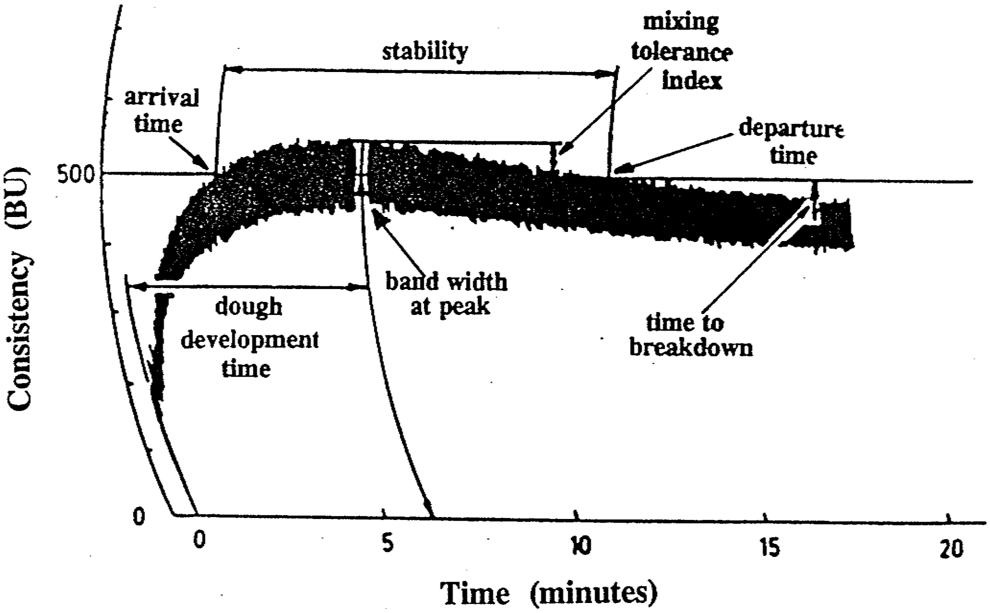
Adapted from Kunerth and D'Appolonia (1985)

Figure 1. A typical mixograph curve.

Farinograph

The farinograph is used to measure the physical properties of dough during mixing. This widely used instrument is a recording dough mixer that mixes water and flour into a dough and measures the dough's resistance to mixing at a constant temperature (Bloksma, 1990). It is used to determine flour water absorption and mixing time that is required to achieve optimum dough development. The farinograph has also been used to evaluate dough strength (Preston and Kilborn, 1990). A typical farinograph curve is shown in Figure 2. Several farinogram characteristics are thought to reflect dough strength, including water absorption, dough development time, stability, mixing tolerance index, time to breakdown and departure time (Shuey, 1990; Bloksma and Bushuk, 1988). Water absorption is the amount of water required by a given weight of flour to obtain a dough of desired consistency (usually curve is centred on the 500 BU line). Dough development time or peak time is the time in minutes, from the onset of mixing to the point at which the dough reaches maximum consistency. Stability is the time in minutes, between the point at which the curve first intercepts the 500 BU line and the point at which the curve drops below the 500 BU line. Stability indicates flour tolerance to mixing. Departure time is the time at which top of the curve drops below the 500 BU line. Time to breakdown is the time in minutes, from the onset of mixing to the time at which the dough consistency has decreased by 30 BU from the peak time. This value indicates flour stability to mixing. Mixing tolerance index is the difference in BU, between the top of the curve at peak and the top of the curve 5 minutes after peak. This value is an indicator of flour tolerance to mixing.

These characteristics have been used to classify flours according to properties suitable for a particular end use (Preston and Kilborn, 1990; Bloksma and Bushuk, 1988; Tipples et al, 1982).



Adapted from Bloksma (1971)

Figure 2. A typical farinograph curve.

Weak flours are characterized by low water absorption, short dough development times and high mixing tolerance index values. Medium flours have intermediate water absorption values, dough development times and mixing tolerance index values. Strong flours are characterized by high water absorption, long dough development times, low mixing tolerance index values and high time to breakdown values. Very strong wheat flours exhibit very long mixing times and very low mixing tolerance index values.

Several researchers have correlated farinograph parameters and baking quality parameters (Branlard et al, 1991; Fowler and De La Roche, 1975; Orth et al, 1972; Baker et al, 1971). The most useful parameters for predicting loaf volume included farinograph dough development time, stability and mixing tolerance index. Orth et al (1972) found that loaf volume was significantly correlated ($p<0.01$) with farinograph dough development time ($r = 0.64$) and mixing tolerance index ($r = -0.79$) for 26 spring wheat cultivars. Fowler and De La Roche (1975) studied the relationships between wheat quality tests and breadmaking potential using 23 common wheat cultivars. Loaf volume was significantly correlated ($p=0.05$) with farinograph water absorption ($r = 0.50$), arrival time ($r = 0.46$), stability ($r = 0.55$), departure time ($r = 0.61$) and mixing tolerance index ($r = -0.72$). Branlard et al (1991) found that loaf volume and crumb score were significantly correlated with farinograph dough development time and stability for 40 winter wheat cultivars, however, no correlation was found between farinograph absorption and loaf volume.

Factors affecting the farinograph curve characteristics

An excellent review of the factors affecting farinograph curves has been provided by

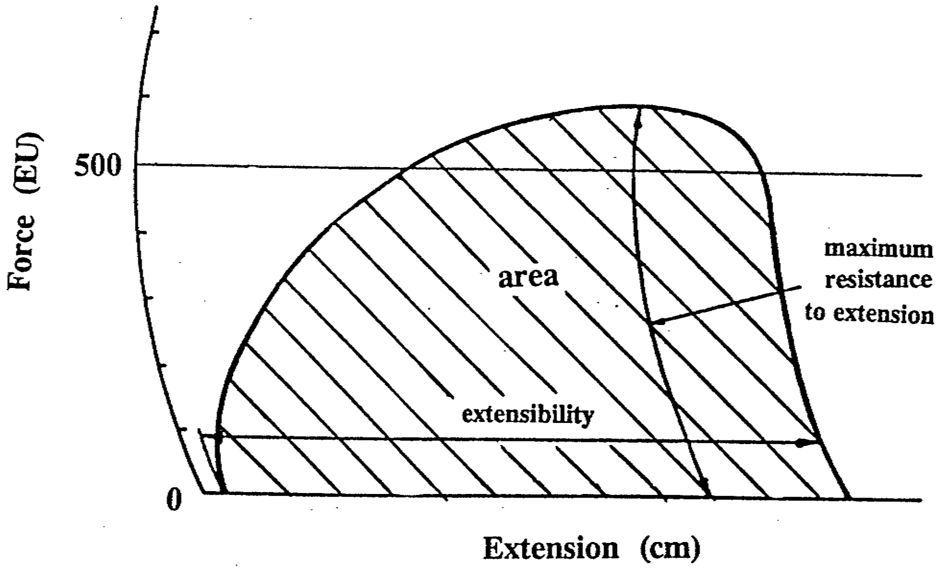
D'Appolonia (1990). Factors affecting the farinograph curve can be grouped into two categories: flour characteristics and operating conditions. The most important factors related to flour characteristics are water absorption, protein content, flour quality and added ingredients. Determination of exact water absorption is critical, as addition of more or less water will significantly affect the curve characteristics (Kunerth and D'Appolonia, 1985). Increases in protein content to 12% will increase water absorption and peak height of the curve. Holas and Tipples (1978) studied the effects of milling streams on farinograph characteristics and found that both development time and stability were highest for the break flours and decreased with decreasing flour quality. Although the farinograph has most often been used to test flour-water doughs, the effects of ingredients used in the bread formula have been investigated. The addition of yeast and nonfat dry milk decrease stability, but nonfat dry milk increases absorption and arrival time. Salt and sodium stearoyl lactylate (SSL) increase dough development time and stability, however, SSL decreases arrival time and salt increases arrival time. Addition of sugar decreases stability but increases arrival time, while addition of malt decreases absorption, dough development time and stability (D'Appolonia, 1990).

The most important factors related to operating conditions include temperature and operating procedures. Constant temperature must be maintained in the farinograph water jacket as absorption, dough development time and stability decrease with increasing temperature (Bayfield and Stone, 1960). Operating procedures can also significantly affect the curve characteristics. The two most commonly used methods for running a flour-water curve are the constant flour-weight method and the constant dough-weight method. Curve characteristics vary depending on which method is used, particularly for flours with high or low absorptions (Shuey, 1990a). The lever and balance system must be properly calibrated as farinograph water absorption determinations are very sensitive to the operation of the balance system (Shuey, 1990a). Curve characteristics, particularly dough development time, stability and tolerance, are affected when different bowls are used on the same farinograph and consistently weaker curves are produced when using the 50 g bowl compared with the 300 g bowl (Shuey, 1990a).

Extensigraph

The extensigraph is a load-extension instrument that imitates the conditions under which a dough is fermented and processed in the baking industry. The extensigraph has commonly been applied to study the effects of dough additives and dough processing stages (Sietz et al, 1991) and to evaluate dough strength (Preston and Hoseney, 1991). A typical extensigram is shown in Figure 3. Several extensigraph parameters have traditionally been used to measure dough strength including maximum resistance to extension, which is the maximum height of the of the extensigraph curve in extensigraph units (EU), area under the curve, which is the area in cm^2 above the baseline bordered by the curve, and the ratio of maximum resistance to extensibility (Preston and Hoseney, 1991). Extensibility measures the ability of the dough to stretch without breaking and is defined as the total length of the curve in cm.

These measurements have been used to classify doughs according to strength (Preston and Hoseney, 1991) and end use properties (Munz and Brabender, 1941). Weak doughs are characterized by small extensigraph area (< 80 cm^2) and low maximum resistance values, but generally exhibit good extensibility (Tipples et al, 1982). Doughs with medium strength have medium values for area (80-100 cm^2) and medium resistance to extension.



Adapted from Bloksma (1971)

Figure 3. A typical extensigraph curve.

Strong doughs are characterized by large area under the curve (120-200 cm^2) and high maximum resistance to extension. Very strong doughs are characterized by very large area values and very high maximum resistance to extension values.

Doughs with high ratio values have low extensibility and are often classified as 'bucky', while doughs with low ratio values have high extensibility and are classified as ‘extensible’ or ‘pliable’ (Preston and Hoseney, 1991). In the bakery, neither bucky or extensible doughs are desirable as extensible doughs tend to ‘flow’ during the fermentation stage and do not maintain the required shape while bucky doughs resist moulding and sheeting and become tight during the fermentation stage (Spies, 1990; Shuey, 1975).

Several researchers have correlated extensigraph parameters and baking quality parameters (Campbell et al, 1987; Preston et al, 1982; Baker et al, 1971). The most useful parameters for predicting loaf volume included extensigraph maximum resistance to extension and area. Baker et al (1971) found that loaf volume was significantly correlated ($p<0.05$) with extensigraph maximum resistance to extension and area ($r = 0.56$ and 0.62, respectively) for a set of spring wheat cultivars. Preston et al (1982) found that loaf volume was most highly correlated with extensigraph extensibility and area, however, no significant correlations were found between loaf volume and extensigraph maximum resistance to extension. Campbell et al (1987) found that loaf volume was significantly correlated ($p<0.01$) with extensigraph maximum resistance to extension and extensibility ($r = 0.53$ and 0.43, respectively), for 71 wheats of diverse quality.

The extensigraph has also been used to monitor the effects of oxidizing agents and to develop rapid physico-chemical tests of dough strength and to evaluate gluten components. One of the most useful applications of the extensigraph has been to assess the effects of slow-acting oxidizing agents such as potassium bromate on dough strength. Recently, the extensigraph has been used to develop enzyme preparations that can be used to replace potassium bromate in the bread formula (Amano Enzyme USA Co, 1994). The extensigraph has been used to develop physicochemical tests such as the SDS-sedimentation test (Axford et al, 1978), the residue protein test (Orth and O'Brien, 1976), and antibody-based enzyme-immunoassy tests (Andrews et al, 1993) to determine dough strength. Williams et al (1988) investigated the usefulness of Near Infrared Reflectance to determine wheat strength as measured by the farinograph and the extensigraph. Other applications of the extensigraph include attempts to identify the components of flour protein, particularly the separation of glutenin proteins, to determine the subunits that affect dough strength (Gupta et al, 1992; Fullington et al, 1987).

Factors affecting extensigraph curve characteristics

A review of the factors affecting extensigraph curves has been provided by Preston and Hoseney (1991). Factors affecting the extensigraph curve can be grouped into two categories: flour characteristics and operating conditions. The most important factors related to flour characteristics are protein content, milling conditions and added ingredients. Generally, increases in flour protein content result in higher maximum resistance to extension, larger extensigraph area, and greater extensibility (Preston and Hoseney, 1991). Preston et al (1982) and Holas and Tipples (1978) studied the effects of milling streams on extensigraph properties and found that maximum resistance to extension and area were highest for the break flours and decreased with decreasing flour quality. Orth and Mander (1979) found that maximum resistance to extension decreased as flour extraction rate increased. In standard extensigraph procedures, 2% salt (based on flour weight) is added to decrease dough stickiness during testing (Preston and Hoseney, 1991). Fisher et al (1949) examined the effects of salt concentration in flour-water-salt doughs and found that as salt concentration increased, maximum resistance to extension and extensibility increased. Casutt et al (1984) demonstrated that maximum resistance to extension, area and extensibility increased with increasing salt concentration for full-formula doughs.

The most important factors related to operating conditions include the mixing procedure and water absorption. The two most common methods for obtaining extensigraph data are American Association of Cereal Chemists Method 54-10 (AACC, 1983) and the International Association for Cereal Chemistry Standard No.114 (ICC, 1980). Extensigram characteristics will vary depending on which procedure is followed as the AACC method optimizes mixing while the ICC procedure optimizes work input and oxidation (Preston and Hoseney, 1991). Fisher et al (1949) demonstrated that decreasing water absorption results in increased maximum resistance to extension.

Limitations

There are many advantages associated with the use of these instruments. Many of the parameters obtained from the curves produced by these instruments have been correlated with bread quality. They are generally inexpensive and rapid to implement (Menjivar, 1990). They can be used for predictive purposes in flour quality control when an experienced operator is performing the test (Spies, 1990), and can be used to determine flour acceptability specifications (Bloksma, 1972). However, consistent correlations have not been established between quality measures and final baking performance of flours. The large sample size requirements and time to conduct the tests make them impractical for routine use in quality control and wheat breeding programs. The deformations imposed during testing are large, which results in changes in the mechanical properties of the dough due to the test itself (Faubion et al, 1985). Empirical instruments used to measure dough extensional rates subject doughs to much higher rates than those occurring under normal fermentation and oven-rise conditions (Bloksma, 1972). According to Weipert (1992), these instruments test dough at a very specific point in the process and provide a measure of the textural properties of the sample only at that point. They do not provide fundamental rheological data, which limits their use in process design and product development (Faubion et al, 1985). None the less, physical dough testing instruments have provided useful information for wheat breeders and bakers and remain as standard testing methods in wheat quality and in quality control applications.

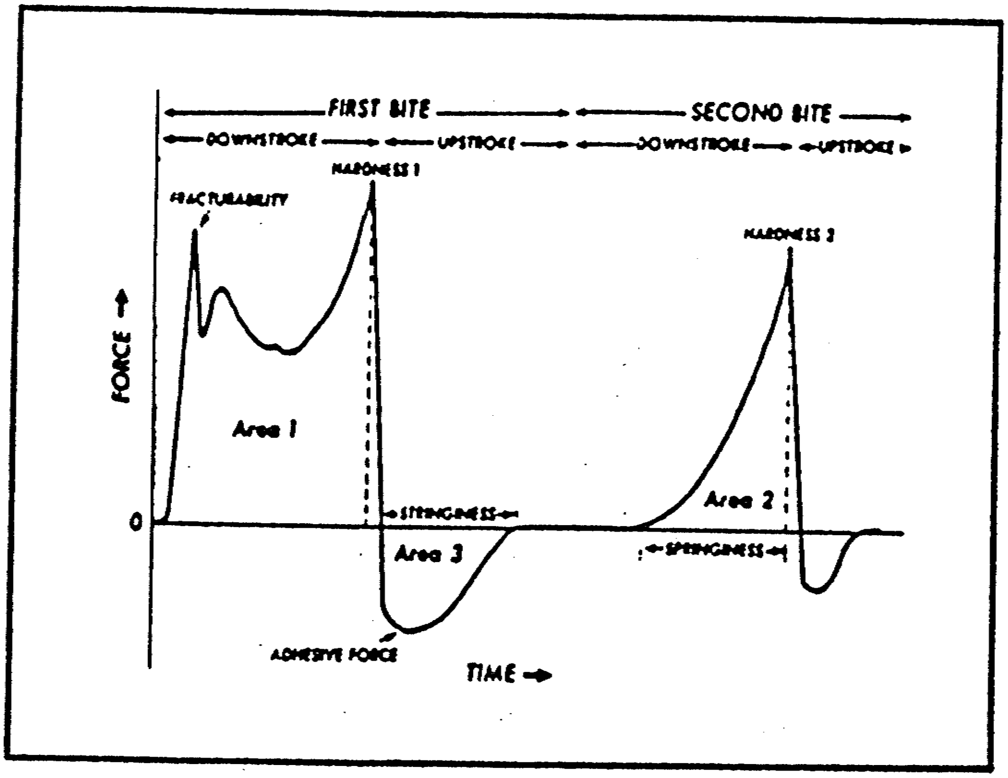
TEXTURE PROFILE ANALYSIS

Texture profile analysis is an instrumental technique designed to measure well-defined sensory properties of foods (Friedmann et al, 1963). Texture Profile Analysis (TPA) describes the textural characteristics of a food product and attempts to quantify a number of textural parameters from a single test. TPA gives a profile of food texture which includes all or most of the textural parameters that are important to that food product (Szczesniak, 1975).

TPA was developed by a group of researchers at the General Foods Corporation in the early 1960's. The method was developed using the Texturometer which consisted of a plate and plunger driven by a motor, and a strip-chart recorder, which traced the force-time interactions of the food sample. During the test, the sample is subjected to a series of compression and tension phases, while the chart recorder is monitoring the response of the sample to compression and tension. Several parameters that characterize the textural properties of the food can be extracted from the recording. The original parameters identified by Friedmann et al (1963) are: hardness, cohesiveness, springiness, adhesiveness, brittleness, chewiness and gumminess.

Bourne (1966) was the first to apply TPA to the Instron Universal Testing Machine (UTM), an instrument commonly used in the textile, plastics and rubber industry (Voisey and DeMan, 1976). One advantage of using the UTM is that it moves only linearly which results in the same surface area of the test fixture being in contact with the sample at every point throughout the test (Bourne, 1976). Additionally, the crosshead and the chart paper are driven by the same motor, so the UTM TPA curve is both a force-time and a force-distance curve (Bourne, 1968). Since work is a force-distance integral, the UTM TPA reliably measures work. Since Bourne (1966) applied the Instron to texture evaluation, this type of machine has replaced the texturometer as the most commonly used instrument for conducting texture profile analysis (Breene, 1975).

A typical UTM TPA curve is shown in Figure 4. Several additional parameters from those defined by Szczesniak can be extracted from the curve. Fracturability is the force at the first significant break in the curve, and is not relevant for all food products. Hardness is the peak force during the first compression cycle. Cohesiveness is the ratio of the compression area of the first cycle to the second cycle. Adhesiveness is the area under the curve and represents the force required to pull the plunger from the sample. Springiness represents the height the sample recovers between the end of the first bite and the start of the second bite. Gumminess is the product of hardness x cohesiveness. Chewiness is the product of gumminess x springiness.



From Bourne (1978)

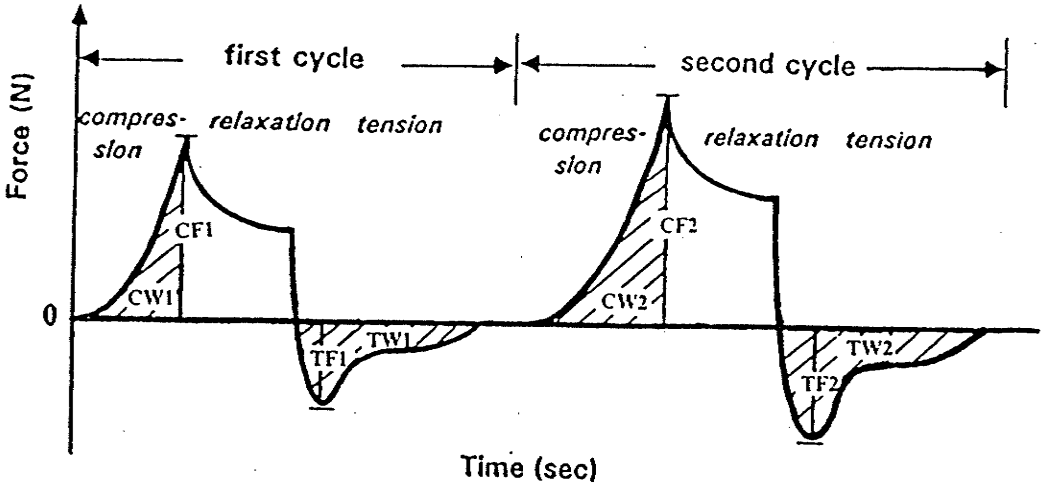
Figure 4. A generalized texture profile analysis curve from the Instron Universal Testing Machine.

Texture profile analysis has been applied to many different food products, including fruits, vegetables, meat products, snack foods and pasta (Breene, 1975; Bourne, 1978). A variation of the traditional texture profile analysis has also been used to study bread crumb firmness and bread staling (Redlinger, 1985). Several researchers have indicated that the Instron, or similar instrument, can be applied to study dough properties (Spies, 1990; Faubion and Faridi, 1985; Szczesniak and Hall, 1975), and recently, TPA has been used to characterize dough stickiness (Chen and Hoseney, 1992; Dhaliwal et al, 1990; Atkins, 1989). Few researchers have applied TPA for studying other dough properties.

Sirivicha and Kramer (1980) used the farinograph and a shear-press, which yields a 'texturegram' curve similar to a TPA curve, to determine the rheological properties of doughs made from all-purpose flour, hard wheat flour and soy fortified wheat flour. Several parameters were obtained from the texturegram including compression peak height, tension peak height, compression area, tension area, and ratio of compression area of the first cycle to the second cycle, and ratio of tension area of the first cycle to the second cycle. In addition to the typical parameters extracted from farinograph curve, band width at arrival time, band width at mixing tolerance index and band width at twenty minute drop were evaluated. High correlations were found between most texturegram parameters and band width at arrival time, band width at peak, band width at mixing tolerance index and band width at 20 min drop ($r = 0.817 - 0.982$). High correlations were also found between the farinograph 20 min drop values and compression area, ratio of compression area of the first cycle to the second cycle, compression peak height and tension peak height ($r = 0.882 - 0.941$). Based on the high correlations between the farinograph parameters and the texturegram parameters, these researchers concluded that the farinograph and the shear-press provided the same information on the rheological properties of dough.

Ram and Nigam (1983) applied TPA to study the properties of dough, glutenin, gliadin and residue protein from several varieties of Indian wheats. Hardness and compression area values of the doughs increased with increasing flour strength. The amount of residue protein, and the ratio of residue protein to gliadin and glutenin were highly positively correlated with hardness and compression area of the first cycle and the second cycle ($r = 0.907 - 0.952$). The amount of residue protein was highly negatively correlated with adhesiveness ($r = -0.819$). Hardness and compression area values of the glutenin fraction increased with increasing flour strength, however, no increase in hardness and compression area values was seen for the gliadin or residue protein fractions with increasing flour strength. The adhesive portion of the curve was present only when testing the gliadin portion of the gluten. In related work, high positive correlations were found between amount of residue protein and farinograph dough development time ($r = 0.884$) and stability ($r = 0.932$) (Ram and Nigam, 1979).

Recently, Wang et al (1996) applied a modified texture profile analysis, or dough profile, to characterize dough stickiness. In the dough profiling method, the sample is first compressed, then held (or relaxed) for a specified amount of time, followed by a tension phase during which the sample is extended until completely broken. A generalized dough profiling curve is shown in Figure 5. The key modification in the dough profiling method is the incorporation of a relaxation period between the compression and tension phases. Three parameters could be extracted from the relaxation portion of the curve including relaxation degree, relaxation index and relaxation ratio. A test cell designed specifically for use with doughs, allowed the use of a small amount of sample (14 g).



Adapted from Wang et al (1996)

Figure 5. A generalized dough profiling curve.

CONCLUSION

Identification of the quality characteristics of wheat flours and doughs is essential in wheat breeding programs, quality control and research. Strength has been targeted as an important characteristic of flour and dough because of its relationship to end product quality. Traditional physical dough testing methods have been useful for characterizing flour and dough strength, but are of limited usefulness in some applications as they often require large sample sizes and a long time to run each test. Texture profile analysis is a method developed to characterize textural properties of foods, and has been applied to a range of products. Dough profiling, a recently developed modification of the traditional TPA, can be used to measure dough characteristics and may provide useful information in the study of dough rheological properties.

Chapter 3

COMPARISON OF DOUGH PROFILING WITH TRADITIONAL MEASURES OF DOUGH STRENGTH

INTRODUCTION

Identification of flour and dough strength is essential in wheat breeding programs, quality control and research because of its relationship to end product quality. Wheat breeding programs in particular, need testing methods which are rapid, reliable and simple to conduct. Traditional physical dough testing instruments like the mixograph, farinograph and extensigraph have been used to evaluate strength, but often require large sample sizes and a long time to conduct the tests. Texture profile analysis (TPA) is an instrumental technique designed to measure the textural properties of foods (Friedman et al, 1963). Dough profiling, a recent modification of the traditional TPA (Wang et al, 1996) has been successfully applied to characterize dough stickiness, and may provide useful information on other dough rheological properties including strength.

This chapter describes secondary data analysis conducted on comprehensive results obtained from a quality study with the principal objective of exploring the relationships between parameters obtained by the dough profiling method and parameters obtained from traditional physical dough testing methods.

The specific objectives of this analysis were:

1. To determine the relationship between dough profiling parameters and standard physical dough testing parameters.

2. To identify the dough profiling parameter or combination of parameters that best measure flour or dough strength.
3. To determine the usefulness of the dough profiling method to determine dough strength.

MATERIALS AND METHODS

Materials

A data set consisting of comprehensive test results collected on 10 bread wheat lines grown in two locations (Glenlea, MB and Swift Current, SK) in 1992 was examined. The ten bread wheat lines included Canada Western Red Spring (CWRS) and Canada Prairie Spring (CPS) wheat lines (Hussain and Lukow, 1994). Samples were grown in a complete randomized block design, with two replications at each location. Wheats were milled into straight grade flours on a Bühler pneumatic laboratory mill (Bühler Bros., Inc., Uzwil, Switzerland). All flours were stored in air-tight containers at 4°C during the study but allowed to equilibrate to room temperature at least one day prior to conducting the tests.

Methods

The ten wheat lines were analysed for physical, chemical and baking characteristics. Protein content and moisture content (14% moisture basis) were determined using the Dickey-John Near Infrared Analyser (Dickey-John Corp., Auburn, IL) according to AACC method 39-11 AACC (1991). A computerized 50 g farinograph (Pon et al, 1989) was used to determine flour mixing characteristics using AACC standard method 54-21 (constant flour-weight method) (AACC, 1983). Farinograph dough development time and mixing tolerance index were taken directly from the farinogram. Extensigraph data were obtained by AACC method 54-10 (AACC, 1983) with the following modification: the Grain Research Laboratory (GRL) mixer was used to mix the doughs and all doughs were mixed for a standard time of 3 minutes. Measurements of maximum resistance to extension and extensibility were taken directly from the extensigram. The ratio of maximum resistance to extensibility was also calculated. Mixograph data were obtained using a 10 g electronic recording mixograph (Voisey et al, 1966) using a constant absorption of 60%. Mixograph development time and peak height were taken directly from the mixogram. All tests were conducted in duplicate. Baking data were obtained using the AACC straight dough method with 10 ppm bromate (AACC, 1983). Loaf volume determinations were made in duplicate using a rapeseed displacement volumeter (National Manufacturing Co., Lincoln, NB).

Samples were evaluated using a modified texture profile analysis, which included a 45 second rest period between the compression and tension phases according to the method developed by Wang et al (1996). Doughs made using 35 g flour (14% m.b.) and distilled water equal to farinograph water absorption less 3% were mixed in a 35 g mixograph to 1.2 times the mixograph development time. Doughs were profiled using a Lloyd Materials Testing Machine (Model 1000R) (Lloyd Instruments Ltd., Fareham, England) equipped with a 100N load cell and a specially designed testing cell for doughs (Wang et al, 1996). The related software package (RControl) was programmed to control the movement of the crosshead and performed data acquisition. Compression work, tension work, tension peak force values were taken directly from the profiling curve. Relaxation degree, relaxation index, relaxation ratio were determined using the relaxation model developed by Wang et al (1996). Cohesiveness was calculated as the ratio of compression work of the second cycle to compression work of the first cycle. Dough profiling tests were conducted in duplicate. A detailed description of the dough profiling curve and the test procedure appears in the Methods section in Chapter 4.

Statistical Analysis

Data were analysed using the Statistical Analysis System (SAS Institute Inc., Cary, NC). Pearson correlation coefficients (SAS, 1990) were generated to examine the relationships between the traditional physical, chemical and baking tests and the parameters obtained from the dough profiling curve. Although many of the physical, chemical and baking test parameters were highly correlated with dough profiling parameters, of the measures of flour and dough strength, the extensigraph parameters were the most highly correlated with dough profiling parameters. Extensigraph parameters that were highly correlated with profiling parameters were further explored using the SAS Canonical Correlation procedure (SAS, 1990).

RESULTS AND DISCUSSION

Relationship between selected dough profiling parameters and physical and baking data

The relationships between dough profiling parameters and the physical and baking data were examined using Pearson correlation coefficients. Correlations between selected dough profiling parameters and extensigraph properties are shown in Table 1. The dough profiling relaxation parameters, R1, K1 and M1 had the highest correlations with extensigraph parameters maximum resistance to extension and ratio of maximum resistance to extensibility. Two of the dough profiling relaxation parameters, relaxation degree (R1) and relaxation index (K1), were highly correlated with extensigraph maximum resistance to extension (Table 1). The r values for correlations between relaxation degree (R1) and maximum resistance to extension at 45 and 135 min rest time were 0.87 and 0.89, respectively. The r values for correlations between relaxation index (K1) and maximum resistance to extension at 45 and 135 min rest time were 0.82 and 0.83, respectively. Two relaxation parameters, relaxation degree (R1) and relaxation ratio (M1), were highly correlated with extensigraph ratio values. The r values for correlations between relaxation degree (R1) and ratio of maximum resistance to extensibility at 45 and 135 min rest time were -0.87 and -0.83, respectively. The r values for correlations between relaxation ratio (M1) and ratio at 45 and 135 min rest time were -0.82 and -0.81, respectively.

Three of the compression and tension parameters were highly correlated with extensigraph properties. Compression work (CW1) and cohesiveness (CC) were highly correlated with ratio of maximum resistance to extensibility (Table 1). The r values for correlations between CC and

Table 1. Matrix of Pearson Correlation Coefficients[1] Between Selected Dough Profiling Parameters and Extensigraph Parameters.

Dough Profiling Parameters[3]	Extensigraph Parameters[2]					
	RM1	E1	R/E1	RM2	E2	R/E2
CW1	.54	-.60	-.75**	.58	-.67	-.75**
TW1	-.11	.72**	.44	-.20	.73**	.47
TW2	-.39	.72**	.67	-.45	.76**	.68
R1	.87***	-.20	-.87***	.89***	-.31	-.83***
R2	.87***	.02	-.77***	.88***	-.11	-.75**
M1	.54	-.62	-.82***	.59	-.66	-.81***
M2	.57	-.52	-.81***	.63	-.59	-.83***
K1	.82***	-.18	-.77***	.83***	-.33	-.75**
K2	.74**	.21	-.46	.67	.05	-.44
CC	-.61	.50	.81***	-.68	.59	.83***

[1] Statistically significant at **P=0.001, ***P=0.0001

[2] RM1 = maximum resistance to extension at 45 min (BU); E1 = extensibility at 45 min (cm); R/E1 = ratio of maximum resistance to extensibility at 45 min; RM2 = maximum resistance to extension at 135 min (BU); E2 = extensibility at 135 min (cm); R/E2 = ratio of maximum resistance to extensibility at 135 min.

[3] CW1 = compression work of the first cycle; TW1 = tension work of the first cycle (N.mm); TW2 = tension work of the second cycle (N.mm); R1 = relaxation degree of the first cycle; R2 = relaxation degree of the second cycle; K1 = relaxation index of the first cycle; K2 = relaxation index of the second cycle; M1 = relaxation ratio of the first cycle; M2 = relaxation ratio of the second cycle.

ratio at 45 and 135 min rest time were 0.81 and 0.83, respectively. Tension work of the first cycle (TW1) and second cycle (TW2) were correlated with extensigraph extensibility (r = 0.72 - 0.76) (Table 1).

Correlations between selected dough profiling parameters and protein, mixograph, farinograph and baking data are shown in Table 2. The dough profiling tension parameters were better correlated with mixograph parameters and baking data, than with farinograph parameters. Two of the profiling tension parameters, tension peak force (TF1) and tension work of the second cycle (TW2) were highly correlated with mixograph peak height (Table 2). The r values for correlations between mixograph peak height and TF1 and TW1 were -0.85 and 0.82, respectively. Relaxation degree (R1) and relaxation ratio (M1) were correlated with mixograph development time (r = 0.74 and 0.72, respectively). Tension work of the first cycle (TW1) was highly correlated with flour protein content (r = 0.82). Loaf volume was correlated with tension work of the first cycle (TW1) and second cycle (TW2) (r = 0.78 and 0.76, respectively). None of the dough profiling parameters were highly correlated with farinograph properties (Table 2).

In general, the highest correlations were seen between the dough profiling relaxation parameters and extensigraph maximum resistance to extension as well as ratio of maximum resistance to extensibility. Dough profiling tension parameters were most highly correlated with flour protein, mixograph peak height and loaf volume. The relationship between the dough profiling relaxation parameters and extensigraph parameters was further explored using canonical correlation analysis (SAS, 1990).

Table 2. Matrix of Pearson Correlation Coefficients[1] for Selected Dough Profiling Parameters and Mixograph, Farinograph and Baking Parameters.

	Quality Parameters					
Dough Profiling Parameters[5]	Mixograph[2]			Farinograph[3]		Baking[4]
	Protein	PKH	MDT	DDT	MTI	LV
TF1	-.70**	-.85***	.26	-.60	-.14	-.72**
TW1	.82***	.71**	-.17	.63	.18	.78**
TW2	.79***	.82***	-.37	.66	.28	.76**
R1	-.17	-.33	.74**	-.24	-.49	-.20
R2	.06	-.10	.74**	-.01	-.57	.01
K1	-.61	-.59	.45	-.36	-.47	-.62
K2	-.53	-.52	.52	-.24	-.54	-.52
M1	-.18	-.45	.72**	-.39	-.37	-.22
M2	.29	-.13	.59	-.18	-.20	.18

[1] Statistically significant at **P=0.001,***P=0.0001.

[2] PKH = mixograph peak height (N.mm); MDT = mixograph development time (min).

[3] DDT = farinograph dough development time (min); MTI = mixing tolerance index (BU).

[4] LV = loaf volume (cc).

[5] TF1 = tension peak force of the first cycle (N); TW1 = tension work of the first cycle (N.mm); TW2 = tension work of the second cycle (N.mm); R1 = relaxation degree of the first cycle; R2 = relaxation degree of the second cycle; K1 = relaxation index of the first cycle; K2 = relaxation index of the second cycle; M1 = relaxation ratio of the first cycle; M2 = relaxation ratio of the second cycle.

Canonical correlation analysis

Canonical correlation is a statistical technique for analysing the relationship between 2 sets of variables, each of which may contain several variables (SAS, 1990). The CANCORR procedure generates a canonical variable from each set of variables, maximizing the correlation between the two canonical variables. Additional canonical variables with the next highest canonical correlation, but uncorrelated with the previous variables, are generated until the number of pairs of canonical variables is equivalent to the number of variables in the smaller group. The CANCORR procedure also generates standardized canonical coefficients which indicate the loading contribution of each of the original variables to the canonical variables. Canonical redundancy analysis examines how well the original variables can be predicted from their own canonical variables as well as from the opposite canonical variables.

The CANCORR procedure is useful for determining the important variables from a large set of variables but requires a large sample size in order to make definite conclusions about the predictive ability of the variables. Since the sample size in the present work was small (n=40), canonical correlation analysis was used to explore the relationships between the many parameters obtained from the dough profiling method and the extensigraph test.

When conducting canonical correlation analysis, results can be confounded if the sets contain highly inter-correlated parameters. Therefore it is essential to include only the variables which are not highly correlated with each other. Many of the relaxation parameters correlated with each other as did the extensigraph parameters. The correlations among the relaxation parameters and among the extensigraph parameters are shown in Tables 3-4. Relaxation degree (R1) and relaxation index (K1) of the first cycle were highly correlated with the second cycle values (R2 and K2).

Table 3. Matrix of Pearson Correlation Coefficients between Dough Profiling Relaxation Parameters of the First Cycle and Dough Profiling Relaxation Parameters of the Second Cycle.

Relaxation Parameters of the Second Cycle[2]	Relaxation Parameters of the First Cycle[1]		
	R1	K1	M1
R2	0.94	0.67	0.78
K2	0.80	0.94	0.68
M2	0.62	0.26	0.77

[1] R1 = relaxation degree of the first cycle; K1 = relaxation index of the first cycle; M1 = relaxation ratio of the first cycle.

[2] R2 = relaxation degree of the second cycle; K2 = relaxation index of the second cycle; M2 = relaxation ratio of the second cycle.

Table 4. Matrix of Pearson Correlation Coefficients between Extensigraph Parameters at 45 min Rest Time and Extensigraph Parameters at 135 min Rest Time.

Extensigraph Parameters at 135 min rest time[2]	Extensigraph Parameters at 45 min rest time[1]		
	RM1	E1	RM/E1
RM2	0.98	NS	-0.84
E2	-0.09	0.89	0.49
RM/E2	-0.75	0.43	0.93

[1] RM1 = maximum resistance to extension at 45 min rest time; E1 = extensibility at 45 min rest time; RM/E1 = ratio of maximum resistance to extensibility at 45 min ret time.

[2] RM2 = maximum resistance to extension at 135 min rest time; E2 = extensibility at 135 min rest time; RM/E2 = ratio of maximum resistance to extensibility at 135 min rest time.

The r values for correlations between R1 and R2, and K1 and K2 were 0.94 and 0.94, respectively (Table 3). Extensibility, maximum resistance to extension and ratio of maximum resistance to extensibility at 45 min rest time were highly correlated with measures at 135 min rest time. The r values for correlations between maximum resistance to extension at 45 and 135 min rest time, extensibility at 45 and 135 min rest time, and ratio of maximum resistance to extensibility at 45 and 135 min rest time were 0.98, 0.89 and 0.93 respectively (Table 4). Because of this, relaxation parameters from the first cycle, R1, K1 and M1 and extensigraph parameters at 45 min, E1, RM1 and R/E1 were chosen to construct the canonical variables.

The results of the canonical correlation analysis permit the identification of the most important relationships between the two sets of original variables. The first pair of canonical variables were very highly correlated (r = 0.92) (Table 5, Figure 6). The first relaxation canonical variable, V1, was heavily weighted for R1 (0.82) (Table 6). RM1 had the highest loading contribution for the first extensigraph canonical variable, W1 (0.73) (Table 7). The second pair of canonical variables was also highly correlated (r = 0.82) (Table 5, Figure 7). The second relaxation canonical variable, V2, was a weighted difference of R1 (1.67) and K1 (-1.7) (Table 6), while RM1 had the highest loading contribution for the second extensigraph variable, W2 (0.75) (Table 7). The first and second canonical variable pairs resulted in a cumulative explanation of 98% of the variation in the data (Table 5). R1 and K1 appear to be the most important original variables for the relaxation canonical variables, while RM1 is important for the extensigraph canonical variables.

The correlations between the original variables and their canonical variables, and the opposite canonical variables are presented in Tables 8-11. As expected, R1 was highly correlated

Table 5. Correlations Between the Canonical Variables.

Canonical Variable Set	Canonical Correlation	Cumulative Variance Explained by the Canonical Variable Set	Pr > F
1	0.92	0.71	0.0001
2	0.82	0.98	0.0001
3	0.32	1.00	0.05

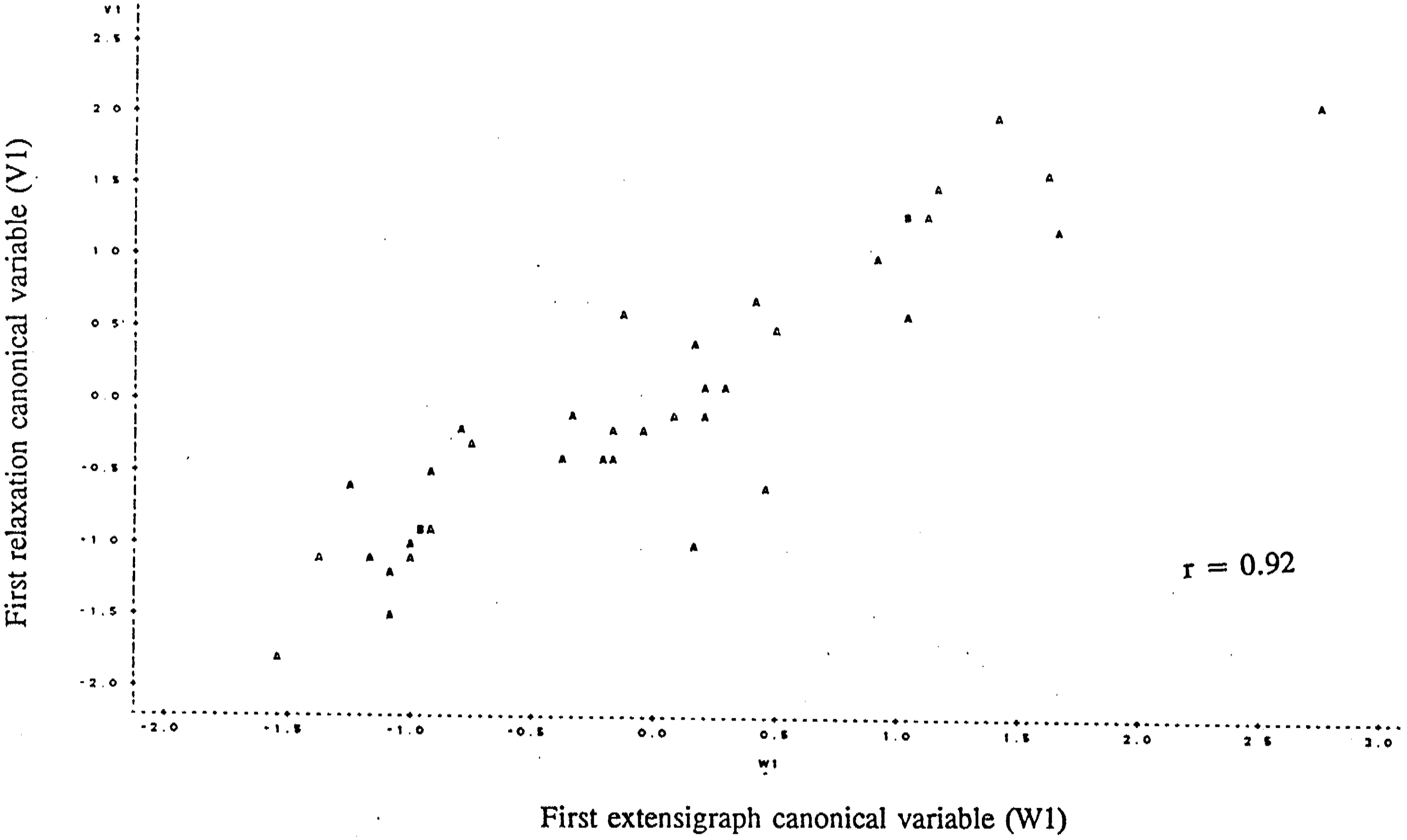


Figure 6. Plot of the first relaxation canonical variable (V1) versus the first extensigraph canonical variable (W1) for 10 wheat lines grown at 2 locations (n=40).

Table 6. Standardized Canonical Coefficients for the Relaxation Variables.

Original Relaxation Variables[1]	Relaxation Canonical Variables		
	V1	V2	V3
R1	0.82	1.67	-2.17
K1	0.01	-1.7	0.17
M1	0.18	-0.37	2.20

[1] R1 = relaxation degree of the first cycle; K1 = relaxation index of the first cycle; M1 = relaxation ratio of the first cycle.

Table 7. Standardized Canonical Coefficients for the Extensigraph Variables.

Original Extensigraph Variables[1]	Extensigraph Canonical Variables		
	W1	W2	W3
E1	-0.14	0.65	-1.82
RM1	0.73	0.75	2.83
R/E1	-0.29	0.60	3.30

[1] E1 = extensibility at 45 min (cm); RM1 = maximum resistance to extension at 45 min (cm); R/E1 = ratio of maximum resistance to extensibility at 45 min.

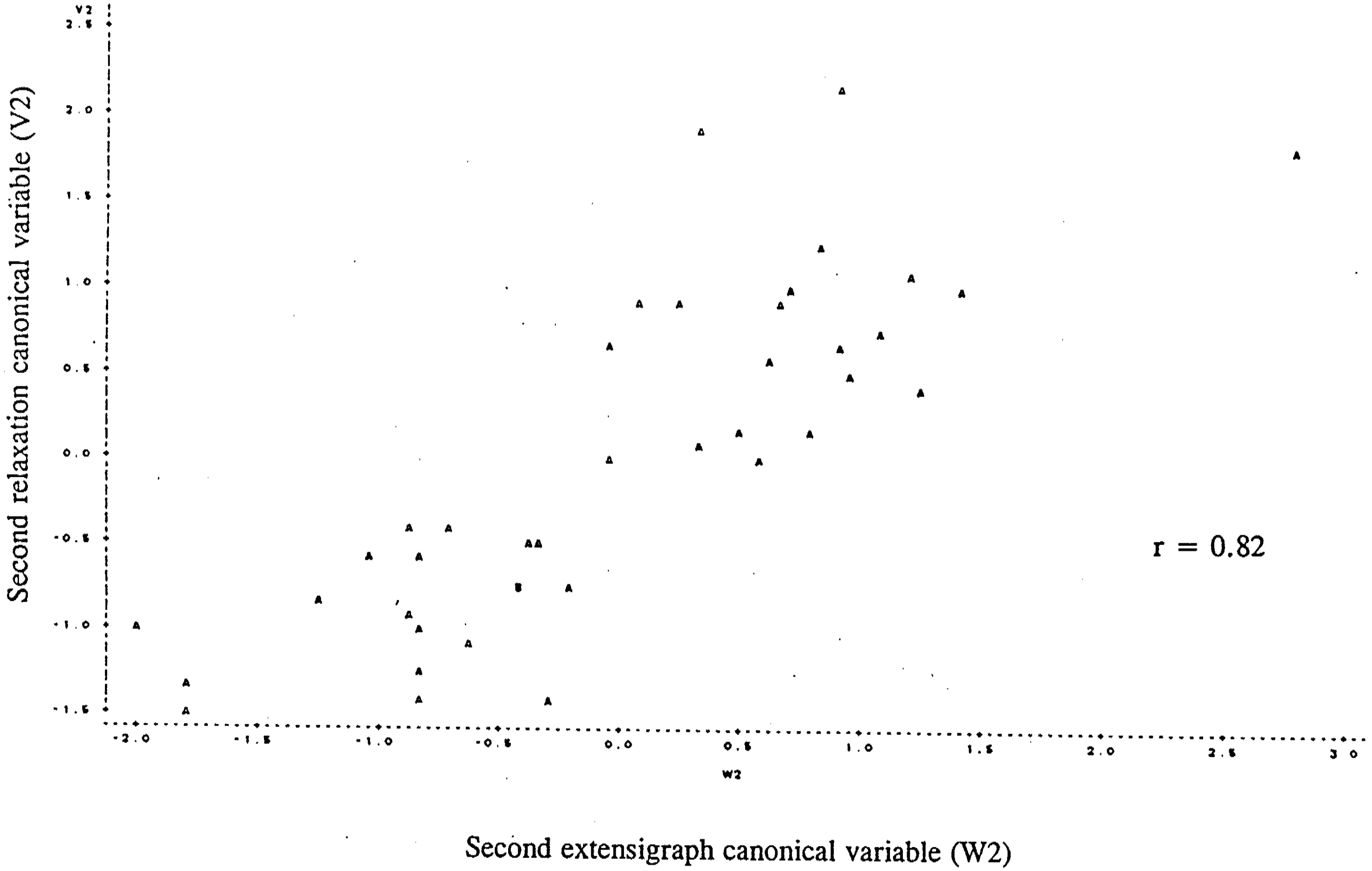


Figure 7. Plot of the second relaxation canonical variable (V2) versus the second extensigraph canonical variable (W2) for 10 wheat lines grown at 2 locations (n=40).

Table 8. Correlations between the Original Relaxation Variables and Their Canonical Variables.

Original Relaxation Variables[1]	Relaxation Canonical Variables		
	V1	V2	V3
R1	0.99	-0.001	-0.08
K1	0.78	-0.60	-0.16
M1	0.92	0.05	0.38

[1] R1 = relaxation degree of the first cycle; K1 = relaxation index of the first cycle; M1 = relaxation ratio of the first cycle.

Table 9. Correlations between the Original Extensigraph Variables and Their Canonical Variables.

Original Extensigraph Variables[1]	Extensigraph Canonical Variables		
	W1	W2	W3
E1	-0.23	0.95	-0.19
RM1	0.96	0.29	0.03
R/E1	-0.95	0.28	0.17

[1] E1 = extensibility at 45 min (cm); RM1 = maximum resistance to extension at 45 min (cm); R/E1 = ratio of maximum resistance to extensibility.

Table 10. Correlations between the Original Relaxation Variables and Extensigraph Canonical Variables.

Original Relaxation Variables[1]	Extensigraph Canonical Variables		
	W1	W2	W3
R1	0.91	-0.001	-0.03
K1	0.72	-0.49	-0.05
M1	0.84	0.04	0.13

[1] R1 = relaxation degree of the first cycle; K1 = relaxation index of the first cycle; M1 = relaxation ratio of the first cycle.

Table 11. Correlations between the Original Extensigraph Variables and Relaxation Canonical Variables.

Original Extensigraph Variables[1]	Relaxation Canonical Variables		
	V1	V2	V3
E1	-0.21	0.78	-0.06
RM1	0.88	0.24	0.01
R/E1	-0.87	0.23	0.06

[1] E1 = extensibility at 45 min (cm); RM1 = maximum resistance to extension at 45 min (cm); R/E1 = ratio of maximum resistance to extensibility at 45 min.

(r = 0.99) with the first relaxation canonical variable V1, since V1 was heavily weighted for R1 (Table 8). M1 was also highly correlated to V1 (r = 0.92), likely because of the high correlation between R1 and M1. Both RM1 and R/E1 were highly correlated with the first extensigraph canonical variable W1 (r = 0.96 and -0.95, respectively) (Table 9), likely because of the correlation between RM1 and R/E1. The second extensigraph canonical variable W2 was highly correlated with E1 (r = 0.95) (Table 9). As expected, the first extensigraph canonical variable W1 was highly correlated with R1 (r = 0.91) and M1 (r = 0.84) (Table 10). The first relaxation canonical variable V1 was highly correlated with RM1 (r = 0.88) and R/E1 (r = -0.87) (Table 11).

Canonical redundancy analysis is presented in Tables 12-13. Seventy-seven percent of the variation in relaxation variables was explained by the first two extensigraph canonical variables (Table 12). Seventy-six percent of the variation in the extensigraph variables was explained by the first two relaxation canonical variables (Table 13).

The squared multiple correlations (Tables 14-15) indicated that the second canonical variable of the extensigraph data good predictive power for R1 (R^2 = 0.83), and fairly good predictive power for M1 (R^2 = 0.71) (Table 14). The second relaxation canonical variable has good predictive power for RM1 (R^2 = 0.82) and R/E1 (R^2 = 0.80), but less predictive power for E1 (R^2 = 0.65) (Table 15). The second relaxation canonical variable was a weighted difference of R1 and K1, indicating that both of these parameters are necessary in predicting maximum resistance to extension and ratio of maximum resistance to extensibility.

Canonical correlation analysis indicated very strong relationships between the dough profiling relaxation parameters and extensigraph parameters. The second relaxation canonical

Table 12. Standardized Variance of the Relaxation Variables Explained by the Relaxation Canonical Variables and by the Extensigraph Canonical Variables.

Canonical Variable Set	Relaxation Canonical Variables		Extensigraph Canonical Variables	
	Proportion	Cumulative	Proportion	Cumulative
1	0.82	0.82	0.69	0.69
2	0.12	0.94	0.08	0.77
3	0.06	1.00	0.006	0.77

Table 13. Standardized Variance of the Extensigraph Variables Explained by the Extensigraph Canonical Variables and by the Relaxation Canonical Variables.

Canonical Variable Set	Extensigraph Canonical Variables		Relaxation Canonical Variables	
	Proportion	Cumulative	Proportion	Cumulative
1	0.62	0.62	0.52	0.52
2	0.36	0.98	0.24	0.76
3	0.02	1.00	0.002	0.76

Table 14. R^2 Values between the Relaxation Variables and the Extensigraph Canonical Variables.

Original Relaxation Variables[1]	Extensigraph Canonical Variables		
	1	2	3
R1	0.83	0.83	0.83
K1	0.51	0.76	0.76
M1	0.71	0.71	0.73

[1] R1 = relaxation degree of the first cycle; K1 = relaxation index of the first cycle; M1 = relaxation ratio of the first cycle.

Table 15. R^2 Values between the Extensigraph Variables and the Relaxation Canonical Variables.

Original Extensigraph Variables[1]	Relaxation Canonical Variables		
	1	2	3
E1	0.04	0.65	0.66
RM1	0.77	0.82	0.82
R/E1	0.75	0.80	0.80

[1] E1 = extensibility at 45 min (cm); RM1 = maximum resistance to extension at 45 min (cm); R/E1 = ratio of maximum resistance to extensibility at 45 min.

variable had good predictive power for both maximum resistance to extension and the ratio of maximum resistance to extensibility. The second relaxation canonical variable was a weighted difference of relaxation degree (R1) and relaxation index (K1), indicating that both are important in characterizing maximum resistance to extension and ratio of maximum resistance to extensibility.

The secondary data analysis presented in this chapter was conducted to determine the relationship between dough profiling parameters and parameters obtained from standard physical dough tests, and to identify the parameters that best measure dough strength. Although many of the dough profiling parameters were highly correlated with physical dough testing and baking parameters, the dough profiling relaxation parameters were most highly correlated with the extensigraph parameters. The canonical correlation analysis indicated the usefulness of dough profiling for predicting extensigraph properties, although the sample size in this data set is not large enough to draw definite conclusions. The strong relationships between the dough profiling relaxation parameters and extensigraph parameters indicate that the dough profiling method appears to measure similar properties to the extensigraph and may be useful in replacing the traditional extensigraph test.

Chapter 4

USE OF DOUGH PROFILING TO MEASURE DOUGH STRENGTH

INTRODUCTION

The secondary data analysis described in the previous chapter indicated some strong relationships between a number of dough profiling and extensigraph parameters. The following experiment was designed to investigate the potential of the dough profiling method for evaluating flour mixing strength as determined by the farinograph, and dough strength as determined by the extensigraph. The use of a small-scale extensigraph procedure was also investigated.

Four flours with widely differing dough properties were chosen to complete this experiment. These flours were used to prepare fifteen blends, and these were used to prepare doughs that were tested with the extensigraph and the Lloyd Materials Testing Machine (LMTM) using the dough profiling method. Correlation coefficients were generated between extensigraph and dough profiling parameters, and regression models were developed to explain extensigraph parameters.

The specific objectives of this study were:

1. To compare dough profiling values for weak to very strong wheat flours and their blends with selected traditional flour or dough strength measures.
2. To determine the validity of a small-scale extensigraph procedure to measure extensigraph properties.
3. To identify the dough profiling parameter or combination of parameters that best account for the variance in extensigraph properties.

MATERIALS AND METHODS

Materials

Four straight grade flours, milled from Canada Western Extra Strong Red Spring (CWES), Canada Western Red Spring (CWRS), Canada Prairie Spring (CPS) and Canada Western Soft White Spring (SWS) wheats were obtained from the Canadian International Grains Institute (CIGI), Winnipeg, Manitoba. These flours had been milled on a small-scale commercial mill at CIGI and stored at 4°C until used. Sodium chloride was obtained from Sigma Chemical Company (St. Louis, MO).

Blended flours were prepared with CWES flour using increasing percentages of CWRS, CPS and SWS flours; and with CWRS flour using increasing percentages of CPS and SWS flours, as shown in Table 16. Flours were blended in two lots; a total of 5000 g for each blend in the first lot and 2000 g for each blend in the second lot. The flours from the first lot were used to determine flour water absorption, farinograph mixing characteristics and the standard extensigraph test values. Flours from the second lot were used for the small-scale extensigraph testing and dough profiling. Flours were weighed (according to the percentage of the total blend weight) (Table 16) and blended for 5 minutes at low speed in a 5 L Hobart mixer (model N-50) using the wire whisk attachment. The bowl was covered with aluminum foil to prevent loss of flour during mixing. Blended flours were allowed to stand for 1-2 minutes prior to bagging to allow flour dust to settle. Approximately 200 g of the blended flour was placed in a polyethylene bag and stored at 4°C. The remainder of the blended flour was placed in air-tight plastic containers and kept at room temperature for immediate use. All samples were allowed to equilibrate to room temperature at least one day prior to testing.

Table 16. Experimental Design showing the Percentages of Flours used for Each Blend.

Sample	CWES (%)	CWRS (%)	CPS (%)	SWS (%)
1	100	--	--	--
2	75	25	--	--
3	50	50	--	--
4	25	75	--	--
5	--	100	--	--
6	75	--	25	--
7	50	--	50	--
8	25	--	75	--
9	--	--	100	--
10	75	--	--	25
11	50	--	--	50
12	25	--	--	75
13	--	--	--	100
14	--	75	25	--
15	--	50	50	--
16	--	25	75	--
17	--	75	--	25
18	--	50	--	50
19	--	25	--	75

Methods

Moisture and protein determination

Flour moisture was determined following AACC method 44-15A (AACC, 1983). Flour protein was determined following AACC method 46-12 (Kjeldahl protein, N X 5.7) (AACC, 1983) with the titanium dioxide modification described by Williams (1973).

Farinograph

A computerized 50 g farinograph (Pon et al, 1989) was used to determine flour water absorption and mixing characteristics using AACC method 54-21 (constant flour weight method) (AACC, 1983) for all flours and blends. Doughs were mixed at high speed; 62 rpm on the slow paddle and 93 rpm on the fast paddle. The computer allowed rapid determination of water absorption, dough development time, stability, arrival time, departure time, time to breakdown, mixing tolerance index and band width at peak. A description of these characteristics is given in Table 17. Curves were evaluated visually which resulted in an adjustment in dough development time and mixing tolerance index values for the CWES/CWRS 75:25 blend. One farinogram was obtained for each flour and blend. A detailed procedure is given in Appendix 1.

Extensigraph

Extensigraph tests were conducted as described in AACC method 54-10 (AACC, 1983) using the Brabender extensigraph (C. W. Brabender Instruments, Inc, Hackensack, NJ). The extensigraph was calibrated with 500 E.U. equal to a 500 g load. For small-scale testing, in

Table 17. Farinograph characteristics[a].

Parameter	Evaluation	Units
Water absorption	the amount of water required by a given weight of flour to obtain a dough of desired consistency (usually curve is centred on 500-BU line)	%
Dough development time	the time from the first addition of water to the development of the dough's maximum consistency	minutes
Stability	difference in time between the point at which the top of the curve intercepts the 500-BU line and the point at which the top of the curve drops below the 500-BU line	minutes
Arrival time	time at which the top of the curve first intercepts the 500-BU line	minutes
Departure time	time at which the top of the curve drops below the 500-BU line	minutes
Time to breakdown	time from the start of mixing to the time at which the dough consistency has decreased 30 BU from the peak time	minutes
Mixing tolerance index	the difference between the top of the curve at peak and the top of the curve 5 minutes after peak	BU
Band width at peak	width of the curve at peak time	BU

[a] Shuey (1990)

which a 70 g dough piece was used, an 80 g weight was attached to the cradle area. One farinogram was generated for each flour and blend prior to the extensigraph test. Dough development times from these curves were used as a guide for mixing to peak.

Dough preparation and test piece scaling for extensigraph testing

Dough for the 150 g test pieces was prepared in the large farinograph bowl using 300 g flour (at 14% moisture basis), distilled water equal to flour water absorption less 2% (to compensate for the effect of the salt) and 2% salt (based on flour weight). Doughs were mixed to optimum development or for a maximum of 10 minutes. Two 150 g pieces were scaled off, rounded, moulded, clamped in the dough holders and allowed to rest in the humidifying cabinet. These can be considered replicates according to the standard method (AACC, 1983).

The 70 g doughs were prepared in a similar way, but using the small farinograph bowl and 50 g flour (at 14% moisture basis), and a 70 g piece was scaled off. Doughs were prepared a second time to obtain replicates.

Extensigraph test procedure

Doughs were stretched after 45, 90 and 135 min rest time. Measurements of maximum resistance to extension and extensibility were taken directly from the extensigram. Area under the extensigraph curve was measured using a polar planimeter and was reported as the mean of three readings. The ratio of maximum resistance to extensibility was also calculated. A description of these characteristics is given in Table 18. The detailed procedure is given in Appendix 2.

Table 18. Extensigraph characteristics[a].

Parameter	Evaluation	Unit
Maximum resistance to extension	maximum height of the curve	EU
Extensibility	the total length of the curve	cm
Area	area under the curve	cm^2
Ratio	ratio of maximum resistance to extensibility	-

[a] Preston and Hoseney (1991)

Dough profiling

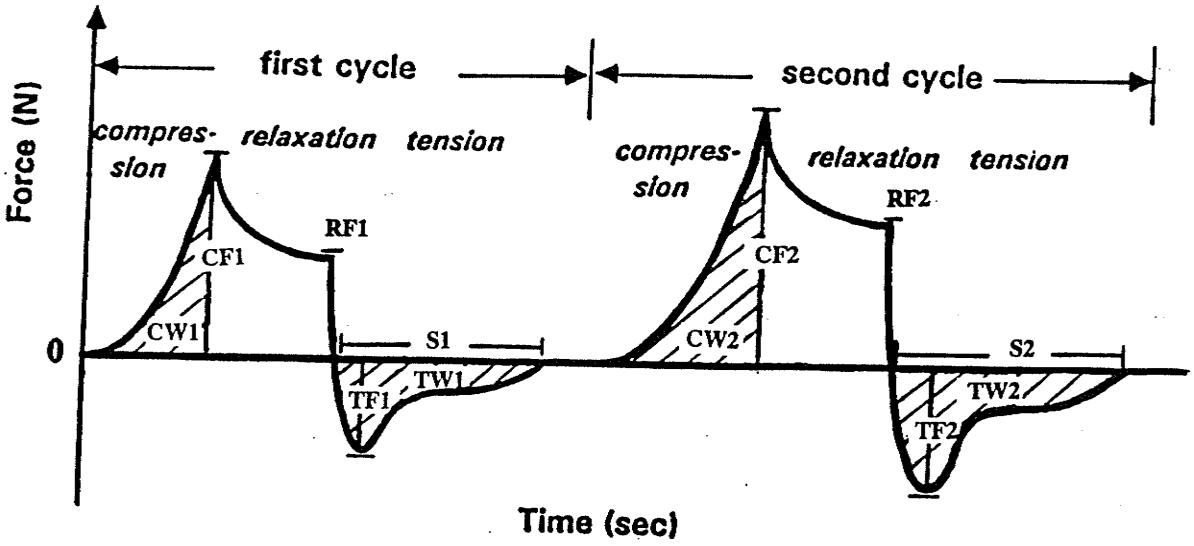
A Lloyd Materials Testing Machine (LMTM) (Model 1000R) equipped with a 100N load cell, and with the dough profiling test cell designed by Wang et al (1996), was used to conduct a modified texture profile analysis, dough profiling, which consisted of two cycles of compression-relaxation-tension. A typical dough profiling curve is shown in Figure 8. The related computer software (RControl) was programmed to control the movement of the crosshead and performed data acquisition. Data was used directly from the curve or calculated to determine several dough profiling parameters (Table 19). Dough profiling data was collected following the method outlined by Wang et al (1996). A detailed description of the dough profiling method is given in Appendix 3.

Dough preparation for profiling

Doughs were prepared using 35 g flour (14% moisture basis), distilled water equal to flour water absorption less 2% (to compensate for the effect of the salt), and 2% salt (based on flour weight). Doughs were mixed at 90 rpm in a 35 g mixograph to mixograph development time. Two mixograph curves were obtained for all flours and blends in order to determine mixograph development time. The mean MDT was used as guide for mixing dough to peak. All tests were conducted at a room temperature of 23±1°C and a relative humidity of 50±3%. A detailed description of the mixograph procedure appears in Appendix 4.

Sample preparation for profiling

The sample was placed in the test cell designed for dough profiling . The test cell consisted of a slotted ring, an upper plate and a lower plate, 4 flat pins and a stand (Figure 9).



Adapted from Wang et al (1996)

Figure 8. A typical dough profiling curve with two cycles of compression-relaxation-tension.

Table 19. Dough Profiling Parameter Definitions.

Mode	Parameter	Method of Measurement	Units
Compression	Compression peak force CF1 and CF2[a]	Force at peak compression	N
	Compression work CW1 and CW2[a]	Area under the peak from onset of compression to peak compression	N.mm
Tension	Tension peak force TF1 and TF2[a]	Force at peak tension	N
	Tension work TW1 and TW2[a]	Area of the peak beneath the baseline (from onset of tension to sample break)	N.mm
	Stringiness S1 and S2[a]	Distance from onset of tension to sample break	mm
Relaxation	Relaxation end force RF1 and RF2[a]	Force at the end of relaxation	N
	Relaxation degree R1 and R2[a]	1 less the ratio of force at the end of relaxation to force at the onset of relaxation	-
	Relaxation index K1 and K2[a]	Slope for the linear portion of the relaxation curve (0.5 sec to 45 sec)	-
	Relaxation ratio M1 and M2[a]	Ratio of the projected relaxation force at 1 second to compression peak force	-
Composite parameters	Cohesiveness CC	CC=CW2/CW1	N
	Gumminess GC	GC=CF1*CW2/CW1	N
	Tension work ratio CT	CT=TW2/TW1	N
	Tension force X work ratio GT	GT=TF1*TW2/TW1	N
	Average compression force AC1 and AC2[a]	AC=CW/compression time	N
	Average tension force AT1 and AT2[a]	AT=TW/S	N

[a] 1 = first cycle, 2 = second cycle.

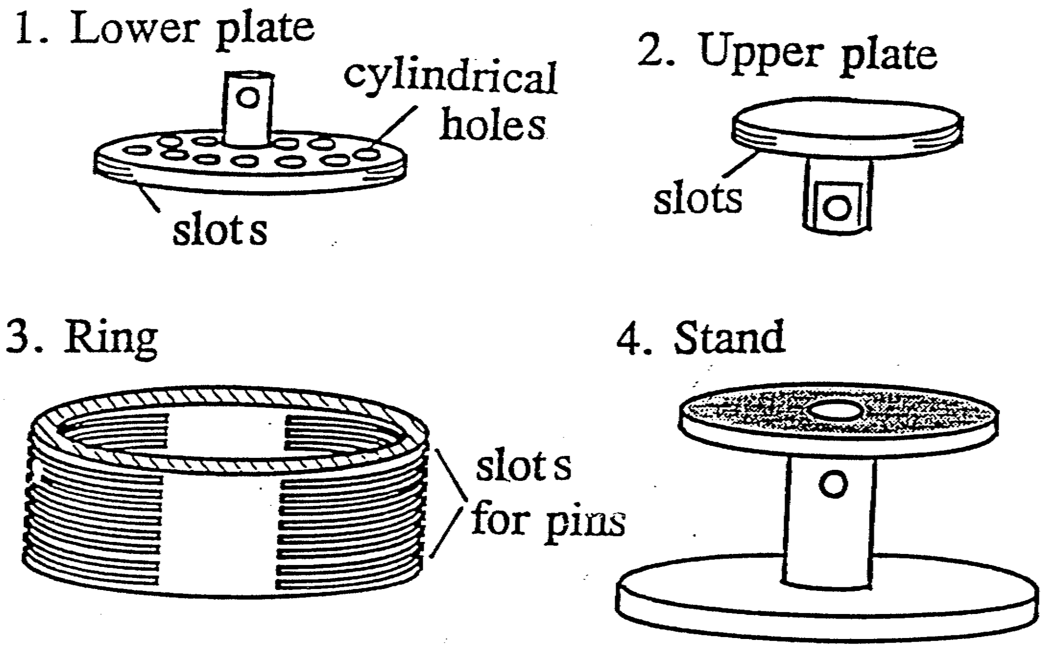


Figure 9. Components of the dough profiling test cell.

The test cell design allows for the preparation of samples varying in height from 1.6 mm to 29.6 mm (Appendix 5). The upper plate was positioned in the centre of the ring using a guide, fastened with two flat pins, placed on a balance and tared. Immediately after mixing, a sample of the dough was scaled off and fixed onto the entire surface area of the upper plate. The weight of the sample represented a fixed percent of the total dough weight, and varied slightly since flour moisture and farinograph water absorption determined the total dough weight (Appendix 6). The lower plate was used to compress the sample to 7.2 mm and released for a few seconds before being fixed in place with two flat pins. The entire cell was inverted and fixed to the stand with a cylindrical pin. The stand was then fastened to the Lloyd base plate and the crosshead was lowered and a cylindrical pin inserted through the upper plate and load cell adaptor. The flat pins were removed to release the ring and the load and extension were zeroed.

Dough profiling test

Instrumental settings used were a compression speed of 100 mm/min, a compression level of 50%, a tension speed of 500 mm/min, and a sample height of 7.2 mm. Relaxation time for both cycles was set at 45 seconds for all samples. All tests were performed in duplicate. Parameters measured from the dough profiling curve are listed in Table 19.

Doughs were subjected to two cycles of compression-relaxation-tension. The primary compression parameters CF1, CF2, CW1 and CW2, tension parameters TF1, TF2, TW1 and TW2, stringiness values S1 and S2 and relaxation parameters RF1 and RF2 were measured directly from the dough profiling curve. Parameters RF1 and RF2 are in addition to those measured by Wang et al (1996). Secondary parameters cohesiveness (CC), gumminess (GC), tension work ratio (CT), tension work times tension work ratio (GT), average compression force of the first and second cycle (AC1, AC2) and average tension force of the first and second cycle (AT1, AT2) were calculated from the primary parameters.

The relaxation degree parameters R1 and R2 were measured using the following formula:

$$R = 1 - F(t_{45})/F(t_o)$$

where R is the relaxation degree, $F(t_{45})$ is the end relaxation force, and $F(t_o)$ is the compression peak force (initial relaxation force). Relaxation ratio of the first and second cycle (M1, M2) and relaxation index of the first and second cycle (K1, K2) were determined using the relaxation formula:

$$F(t)/F(t_o) = M\, t^k$$

where F(t) is compression force from 0.5 to 45 seconds, $F(t_o)$ is compression force at the onset of relaxation (or peak compression force), M is the ratio of relaxation force at 1 second to compression peak force and K is the relaxation index.

RESULTS AND DISCUSSION

Moisture and protein content of the base flours

Moisture content of the four base flours ranged from 11.4% for CWES to 14.3% for CWRS (Table 20). The four base flours had protein contents ranging from 10.2% for SWS to 11.4% for CWRS (14% moisture basis) (Table 20). The protein content of the CWRS flour was relatively low for this class, although this allowed more valid comparisons between the flours.

Table 20. Moisture and Protein Contents for the Four Base Flours.

Flour	Moisture	Protein[1]
CWES	11.4	11.3
CWRS	14.3	11.4
CPS	11.9	10.9
SWS	11.9	10.2

[1] 14% moisture basis, N X 5.7.

Farinograph Properties

Farinograph properties of the base flours

Farinograph properties were determined for each of the base flours and the blends. Farinograms and farinograph data for the CWES, CWRS, CPS and SWS flours are presented in Figure 10 and Table 21, respectively. Values in Table 21 for time to breakdown, and for departure time for the CWES flour are default values, and would have been longer, except the computer was programmed to record the mixing curve for a maximum of 20 minutes.

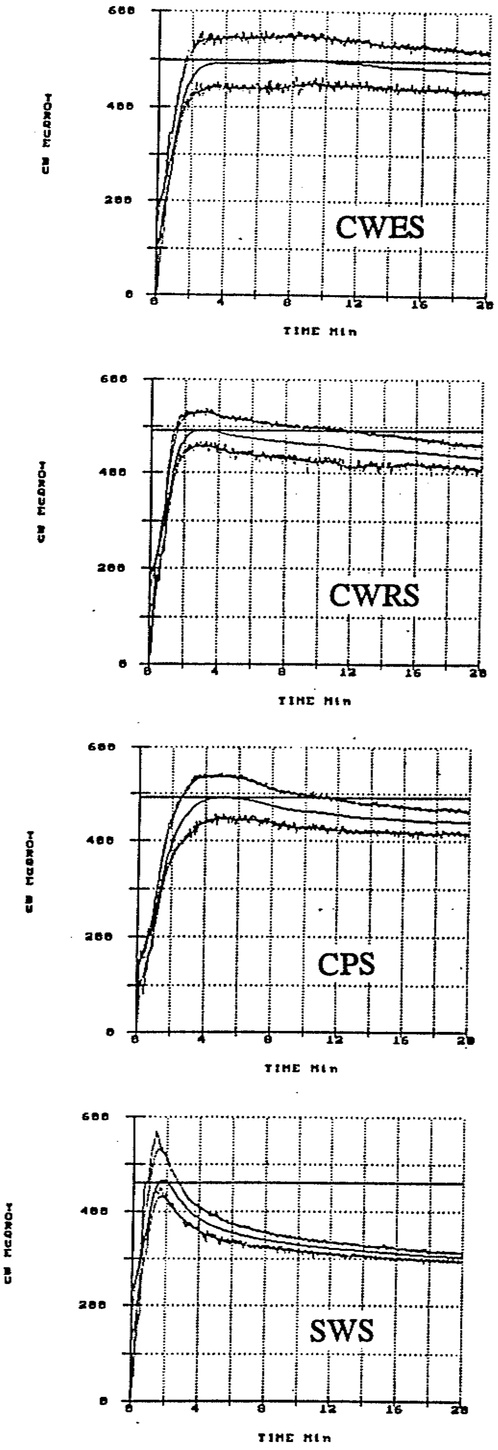


Figure 10. Farinograph curves for the four base flours.

Table 21. Farinograph properties[1] of CWES, CWRS, CPS and SWS flours.

Sample	ABS	DDT	MTI	STA	DEP	TBD	BWP
CWES	58.3	8.5	18	18.2	20.0	20.0	101.4
CWRS	62.1	3.2	28	10.0	11.6	9.4	71.3
CPS	58.8	5.0	40	8.7	11.3	10.5	89.6
SWS	50.6	2.1	142	1.8	2.8	2.7	81.3

[1] ABS = water absorption (%); STA = stability (min); DEP = departure time (min); TBD = time to breakdown (min); DDT = dough development time (min); MTI = mixing tolerance index (BU); BWP = band width at peak (BU).

The water absorption value was highest for the CWRS flour, 62.1%, and lowest for the SWS flour, 50.6%. CWES and CPS flours had intermediate water absorption values of 58.3% and 58.8% respectively. The CWES flour showed the longest dough development time, 8.5 min, while the SWS flour exhibited the shortest development time, 2.1 min. Dough development times were intermediate for the CPS flour and the CWRS flour, 5.0 and 3.2 min respectively. Stability, mixing tolerance (low MTI value) and departure time were highest for the CWES flour and decreased with flours generally considered to be decreasing in strength. The time to breakdown was in excess of 20 minutes for the CWES flour and very short, 2.7 min, for the SWS flour. Band width at peak was highest for the CWES flour and lowest for the SWS flour. Time to breakdown and band width at peak values were lower for the CWRS flour than for the CPS flour, which is not typical of the CWRS wheat class.

Large differences in dough mixing properties were evident between the four base flours. The CWES flour had the highest values and the SWS flour the lowest values for all measurements. The CPS flour had higher values for dough development time, time to breakdown and band width at peak than the CWRS flour.

Farinograph properties of the blends

Farinograph curves for the CWES flour were altered by the addition of CWRS, CPS and SWS flours (Figure 11); and for the CWRS flour by the addition of CPS and SWS (Figure 12). Properties of the blends are presented in Tables 22-26.

The effects of varying the amount of CWES flours in blends with CWRS, CPS and SWS flours are presented in Tables 22-24. Addition of 50% CWRS flour to CWES flour resulted in

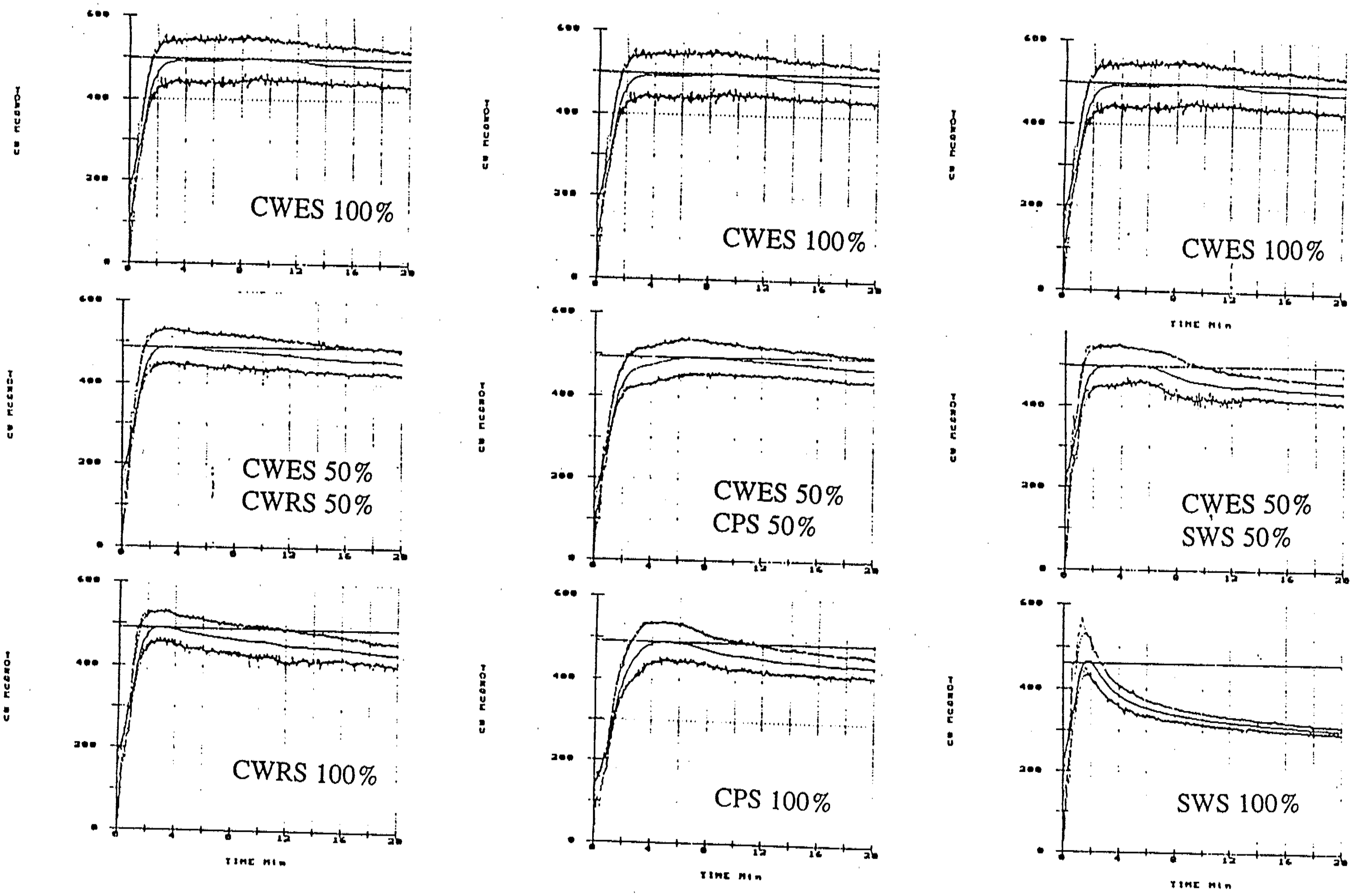


Figure 11. Farinograph curves for CWES flour in blends with CWRS, CPS and SWS flours.

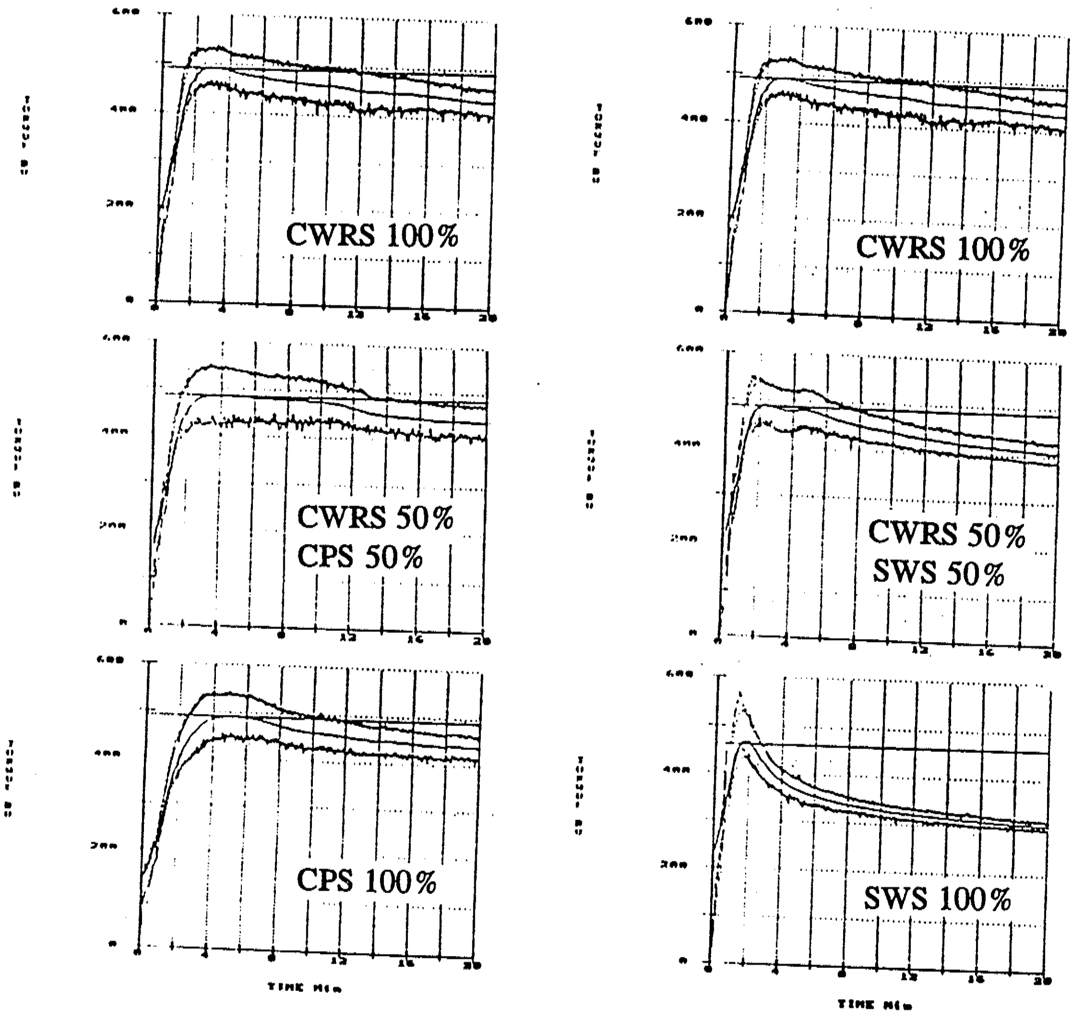


Figure 12. Farinograph curves for CWRS flour in blends with CPS and SWS flours.

Table 22 Farinograph properties[1] of CWES and CWRS flours and blends.

Sample	ABS	DDT	MTI	STA	DEP	TBD	BWP
CWES	58.3	8.5	18	18.2	20.0	20.0	101.4
ES75HS25	59.2	8.0	15	18.1	20.0	20.0	90.7
ES50HS50	59.9	3.5	15	16.3	18.1	16.6	84.1
ES25HS75	61.0	3.1	20	13.4	15.1	12.6	77.6
CWRS	62.1	3.2	28	10.0	11.6	9.4	71.3

[1] ABS = water absorption (%); STA = stability (min); DEP = departure time (min); TBD = time to breakdown (min); DDT = dough development time (min); MTI = mixing tolerance index (BU); BWP = band width at peak (BU).

Table 23. Farinograph properties[1] of CWES and CPS flours and blends.

Sample	ABS	DDT	MTI	STA	DEP	TBD	BWP
CWES	58.3	8.5	18	18.2	20.0	20.0	101.4
ES75CP25	59.3	8.5	18	17.7	20.0	20.0	87.6
ES50CP50	59.3	6.7	17	17.5	20.0	20.0	85.5
ES25CP75	58.8	5.3	21	10.9	13.5	13.3	92.1
CPS	58.8	5.0	40	8.7	11.3	10.5	89.6

[1] ABS = water absorption (%); STA = stability (min); DEP = departure time (min); TBD = time to breakdown (min); DDT = dough development time (min); MTI = mixing tolerance index (BU); BWP = band width at peak (BU).

Table 24 Farinograph properties[1] of CWES and SWS flours and blends.

Sample	ABS	DDT	MTI	STA	DEP	TBD	BWP
CWES	58.3	8.5	18	18.2	20.0	20.0	101.4
ES75SW25	56.9	6.6	18	18.2	20.0	20.0	96.1
ES50SW50	55.5	3.9	39	8.4	9.8	8.4	96.0
ES25SW75	53.0	2.1	90	3.7	4.9	4.7	96.7
SWS	50.6	2.1	142	1.8	2.8	2.7	81.3

[1] ABS = water absorption (%); STA = stability (min); DEP = departure time (min); TBD = time to breakdown (min); DDT = dough development time (min); MTI = mixing tolerance index (BU); BWP = band width at peak (BU).

Table 25. Farinograph properties[1] of CWRS and CPS flours and blends.

Sample	ABS	DDT	MTI	STA	DEP	TBD	BWP
CWRS	62.1	3.2	28	10.0	11.6	9.4	71.3
HS75CP25	59.8	3.3	20	13.1	14.7	13.2	107.3
HS50CP50	59.4	3.7	18	13.1	14.9	13.3	117.0
HS25CP75	59.5	3.7	32	8.5	10.2	10.0	89.6
CPS	58.8	5.0	40	8.7	11.3	10.5	89.6

[1] ABS = water absorption (%); STA = stability (min); DEP = departure time (min); TBD = time to breakdown (min); DDT = dough development time (min); MTI = mixing tolerance index (BU); BWP = band width at peak (BU).

Table 26. Farinograph properties[1] of CWRS and SWS flours and blends.

Sample	ABS	DDT	MTI	STA	DEP	TBD	BWP
CWRS	62.1	3.2	28	10.0	11.6	9.4	71.3
HS75SW25	58.7	2.3	29	8.1	9.5	9.3	81.6
HS50SW50	55.4	2.1	46	6.4	7.7	7.5	91.3
HS25SW75	53.6	2.1	95	3.2	4.4	4.1	96.1
SWS	50.6	2.1	142	1.8	2.8	2.7	81.3

[1] ABS = water absorption (%); STA = stability (min); DEP = departure time (min); TBD = time to breakdown (min); DDT = dough development time (min); MTI = mixing tolerance index (BU); BWP = band width at peak (BU).

a substantial decrease in dough development time, stability, time to breakdown and departure time (Figure 11). Dough development time remained long for the CWES/CPS blends until 50% CPS was incorporated into the blend (Table 23). Stability, mixing tolerance index, departure time and time to breakdown did not appear to be affected until at least 75% CPS flour was incorporated into the blend (Figure 11) (Table 23). This has significant implications for the baking industry as flour tolerance to overmixing is important but long mix times are undesirable. Dough development time for the CWES/SWS blends was affected by the addition of 25% SWS flour to the CWES flour, however, stability, departure time, time to breakdown and mixing tolerance index were not affected until the SWS flour was blended at the 50% level (Figure 11) (Table 24).

Effects of varying the amount of CWRS flour in blends with CPS and SWS flours are shown in Tables 25-26. Dough development time remained short for CWRS/CPS blends with the incorporation of 75% CPS flour. At 25% and 50% levels, addition of CPS flour appeared to have a beneficial effect on mixing tolerance index, stability, departure time and time to breakdown (Table 25). This appeared to be an additive effect of the addition of CPS flour to the CWRS flour, as the CPS flour had higher values for departure time and time to breakdown than the CWRS flour. At the 75% level, there was a large decrease in stability, departure time and time to breakdown and an increase in mixing tolerance index. Dough development time, stability and departure time values decreased with the addition of 25% SWS flour to CWRS flour, however, time to breakdown and mixing tolerance index were not significantly affected until 50% SWS was incorporated into the blend (Table 26).

As the amount of the flour generally considered to be stronger was increased in the blend, dough development time, stability, time to breakdown and departure time increased and mixing tolerance index decreased. For CWES/CWRS, CWES/SWS and CWRS/SWS blends the magnitude of the change was not significant until 50% of the weaker flour was incorporated. Up to 75% of the CPS flour could be blended with CWES flour without major effects on farinograph properties. The relationship of band width at peak values to increasing amounts of stronger flours was not as consistent as the relationship of the other farinograph parameters. These results indicate that both CWES and CWRS flours can be used to improve mixing strength of weaker flours.

Extensigraph properties

Comparison of the standard extensigraph method with a small-scale method

Extensigraph data were obtained using the standard 150 g test piece and a 70 g test piece for the four base flours and blends after 45, 90 and 135 min rest periods. The 70 g dough pieces were used because maximum resistance exceeded 1000 extensigraph units (EU) for the CWES flour and for the blends containing a high proportion of CWES flour for the 150 g sample size at all rest times.

Correlations between the two methods

The relationship between the 70 g and 150 g sample sizes was examined and correlation coefficients are given in Table 27. In spite of the fact that for the 150 g dough pieces several of the samples exceeded the 1000 EU maximum, correlations between the two sample sizes were high. Maximum resistance to extension for the 70 g sample size was highly correlated with maximum resistance for the 150 g sample size at 45, 90 and 135 min rest time (r = 0.82 - 0.88).

Table 27. Pearson Correlation Coefficients[1] between Extensigraph Parameters at 45, 90 and 135 min Rest Time for 70 g and 150 g Sample Sizes[e].

Rest time (min)	Maximum resistance[a]	Area[a]	Ratio[b]	Extensibility
45	.88	.93	.75	.60[c]
90	.83	.89	.72	NS[d]
135	.82	.88	.70	NS

[a] Statistically significant at P = 0.0001.
[b] Statistically significant at P = 0.001.
[c] Statistically significant at P = 0.01.
[d] NS = Not significant.
[e] n=30

Area for the 70 g sample size was highly correlated with area for 150 g sample size at all rest times (r = 0.88 - 0.93). Ratio values at all rest times for the two sample sizes were not as highly correlated (r = 0.70 - 0.75). Extensibility values were not highly correlated for the two sample sizes except at 45 minutes (r = 0.60), possibly due to the difficulty in fastening the smaller dough pieces in the dough holders. The CWES flour and blends with a high proportion of CWES flour were very elastic and had to be stretched slightly in order to fasten the pins through the dough. This could increase the variability in sample break during stretching. Modifications to the dough holders would resolve this difficulty. Oliver (1979) used a 75 g dough piece for extensigraph testing but no modification to the dough holders was reported.

Although the correlations were somewhat lower than expected, the results indicate that use of a 70 g sample provides comparable results to that of the standard method in which a 150 g dough piece is used. Higher correlations between small scale and large scale extensigraph testing methods were reported by Oliver (1979). The lower correlations observed in the current work are probably due to differences in the methods used to prepare the dough between the current work and that of Oliver (1979). In addition, Oliver (1979) used samples from one wheat class, whereas this data contained samples from four wheat classes with widely differing properties.

Correlations among extensigraph parameters

Correlations were generated among extensigraph parameters and results for the 70 g sample size are listed in Table 28. Determination of the area under the extensigraph curve requires the use of a planimeter and is a time-consuming and tedious task. In recent years, the ratio of maximum resistance to extensibility has been used to replace the area measurement (Spies, 1990).

Table 28. Matrix of Pearson Correlation Coefficients[1] describing Relationships Among Extensigraph Parameters using 70 g Sample Size.

Parameter[2]	RM1	E1	A1	R1	RM2	E2	A2	R2	RM3	E3	A3	R3
RM1	1.00											
E1		1.00										
A1	0.98		1.00									
R1	0.97		0.92	1.00								
RM2	0.99		0.99	0.94	1.00							
E2						1.00						
A2	0.96		0.98	0.88	0.98		1.00					
R2	0.98		0.96	0.97	0.98		0.93	1.00				
RM3	0.98		0.98	0.92	0.99		0.98	0.96	1.00			
E3						0.82				1.00		
A3	0.95		0.98	0.87	0.98		0.98	0.94	0.99		1.00	
R3	0.99		0.97	0.96	0.99		0.97	0.98	0.99		0.95	1.00

[1] Only statistically significant (0.0001 level) values are given.

[2] RM1 = maximum resistance to extension at 45 min (EU); E1 = extensibility at 45 min (cm); A1 = area under extensigram at 45 min (cm^2); R1 = ratio of maximum resistance to extensibility at 45 min; RM2 = maximum resistance to extension at 90 minutes (EU); E2 = extensibility at 90 minutes (cm); A2 = area under the extensigram at 90 minutes (cm^2); R2 = ratio of maximum resistance to extensibility at 90 min; RM3 = maximum resistance to extension at 135 min (EU); E3 = extensibility at 135 min (cm); A3 = area under the extensigram at 135 min (cm^2); R3 = ratio of maximum resistance to extensibility at 135 min.

Area and ratio values were highly correlated at all rest times, r = 0.92, r = 0.93, r = 0.95 at 45, 90 and 135 min rest time, respectively. These high correlations indicate that use of the ratio as a substitute for the area measure appears to be appropriate, however, a word of caution should be noted. Ratio values could be quite similar for doughs which are both elastic and extensible, and doughs which are inelastic and inextensible, a condition which could occur when testing the effects of additives. Therefore, the ratio value should be reported in conjunction with area under the extensigram and vice versa to provide a more complete characterization of extensigraph properties.

Maximum resistance, area and ratio at 45 min rest time were highly correlated with maximum resistance, area and ratio at 90 and 135 min rest time ($r > 0.96$). For the purpose of evaluating dough strength, there appears to be no advantage to obtaining a curve at 90 and 135 min.

Maximum resistance to extension at 45, 90 and 135 min rest time was highly correlated ($p=0.0001$) to area and ratio measures at 45, 90 and 135 min ($r = 0.87 - 0.99$) for the 70 g sample size. Extensibility at 90 min and 135 min were highly correlated for the 70 g sample size ($r = 0.82$).

Extensigraph properties of the base flours

Extensigrams and extensigraph properties for the 70 g test of the four base flours at 45, 90 and 135 min rest times are shown in Figures 13-15 and Table 29, respectively. Maximum resistance to extension, area and ratio values were highest for the CWES flour and lowest for the SWS flour at all rest times. The CWRS and CPS flours had intermediate values for maximum resistance, area and ratio, with the CWRS flour having higher values than the CPS flour at all rest times (Figure 16). As expected, increases in maximum resistance were observed from 45 min

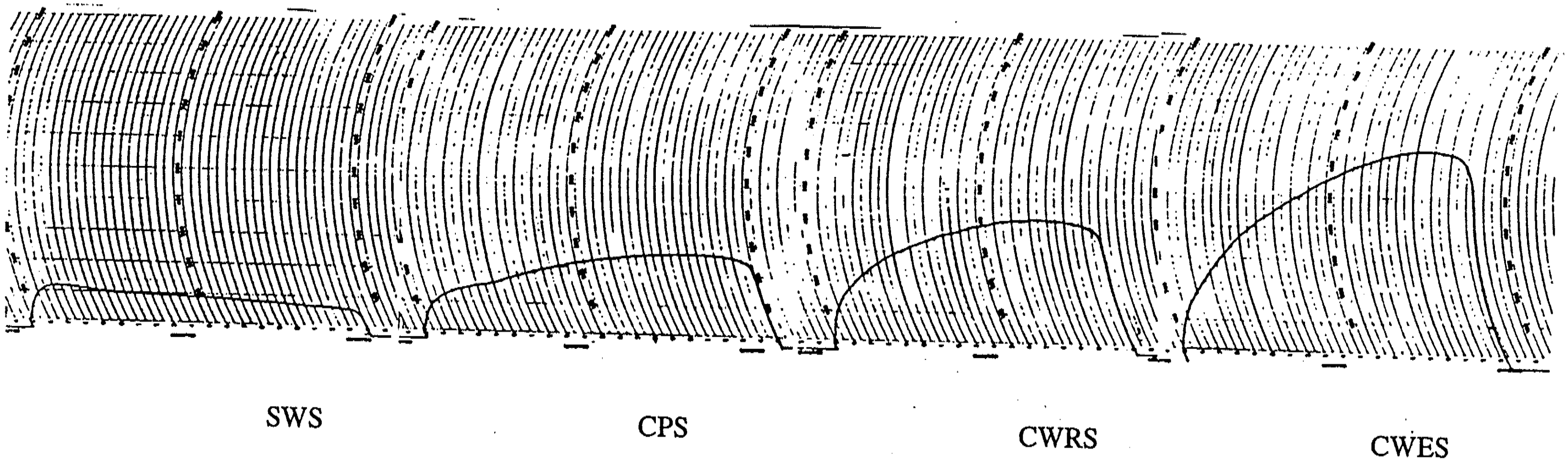


Figure 13. Extensigraph curves for the four base flours at 45 min rest time.

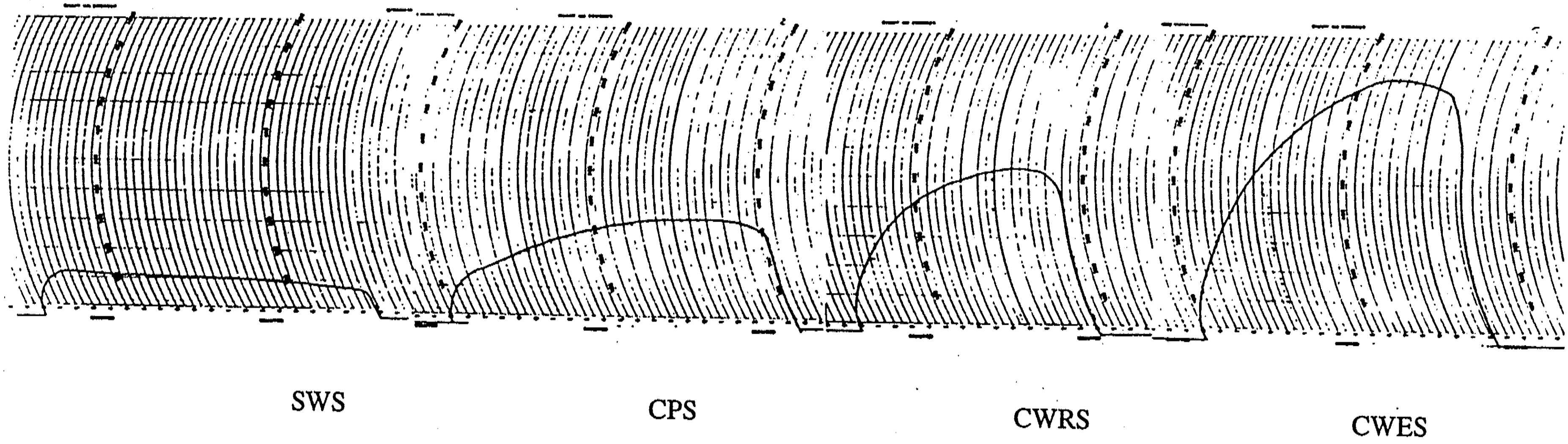
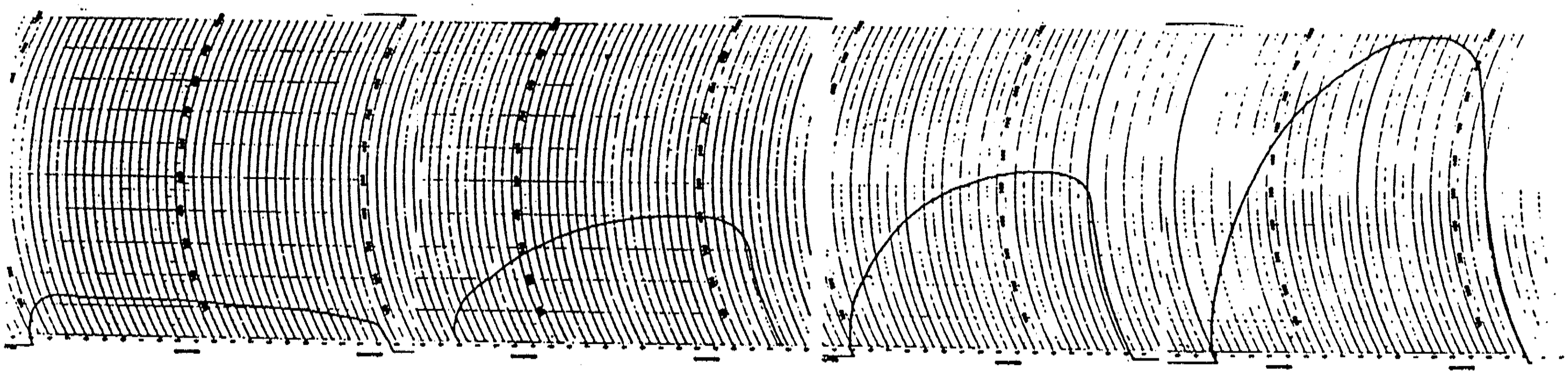


Figure 14. Extensigraph curves for the four base flours at 90 min rest time.



SWS CPS CWRS CWES

Figure 15. Extensigraph curves for the four base flours at 135 min rest time.

Table 29. Sample Means[1] of Extensigraph Properties[2] for the Four Base Flours.

Sample	RM1	E1	A1	R1	RM2	E2	A2	R2	RM3	E3	A3	R3
CWES	655	19.3	161.2	34.0	910	15.4	173.0	60.6	995	15.8	198.7	63.6
CWRS	420	15.5	89.4	27.4	555	13.0	96.5	43.3	545	14.8	109.2	36.8
CPS	275	19.0	69.9	14.5	360	18.9	89.0	19.3	410	16.8	91.9	24.6
SWS	125	18.3	26.7	6.9	125	19.4	32.7	6.5	130	19.4	33.9	6.7

[1] Means are the average of 2 replicates.

[2] RM1 = maximum resistance to extension at 45 min (EU); E1 = extensibility at 45 min (cm); A1 = area under the extensigram at 45 min (cm^2); R1 = ratio of maximum resistance to extensibility at 45 min; RM2 = maximum resistance to extension at 90 min (EU); E2 = extensibility at 90 min (cm); A2 = area under the extensigram at 90 min (cm^2); R2 = ration of maximum resistance to extensibility at 90 min; RM3 = maximum resistance to extension at 135 min (EU); E3 = extensibility at 135 min (cm); A3 = area under the extensigram at 135 min (cm^2); R3 = ration of maximum resistance to extensibility at 135 min.

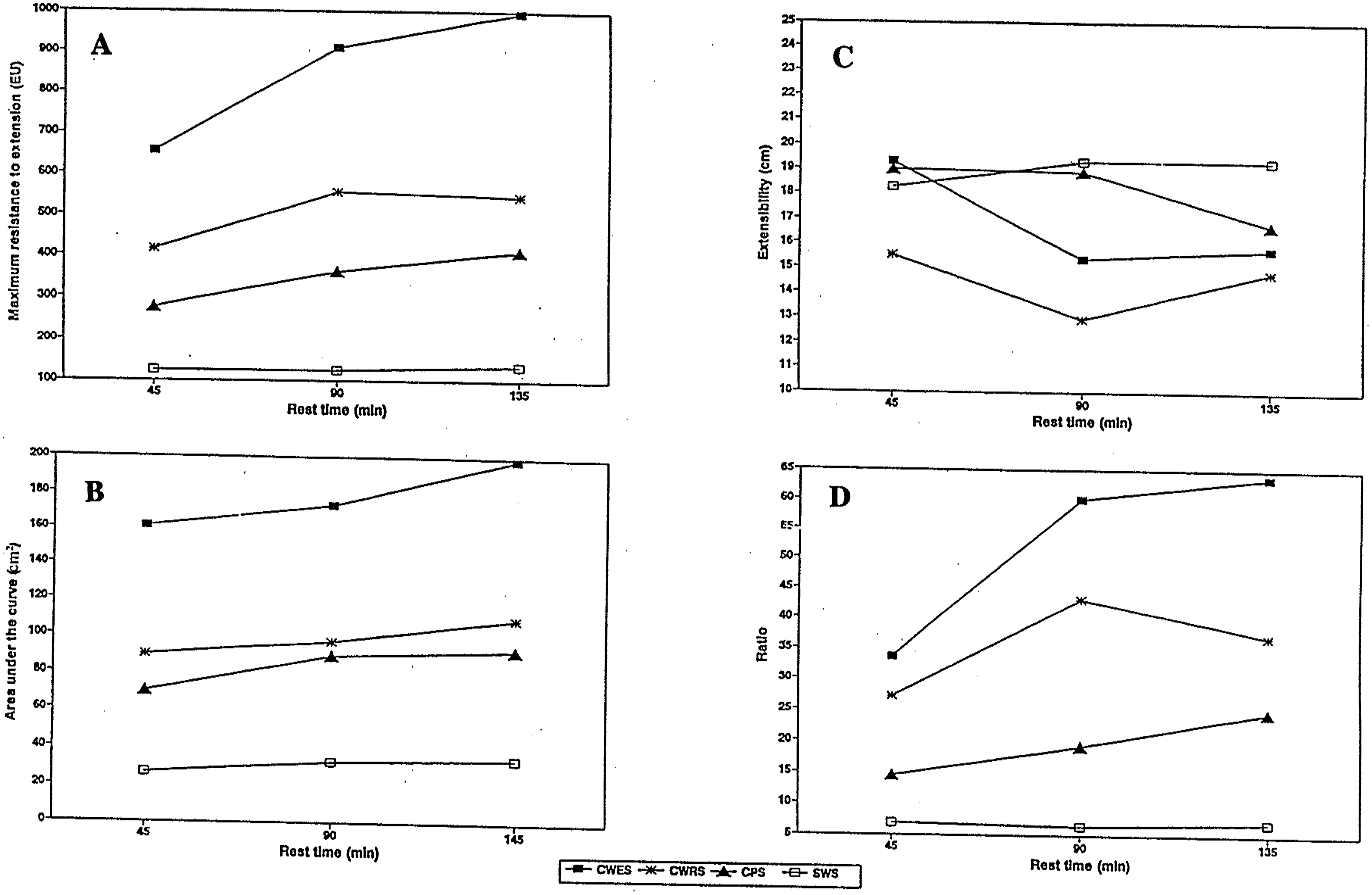


Figure 16. Extensigraph properties of the four base flours. A, Maximum resistance to extension (EU); B, Area under the curve (cm^2); C, Extensibility (cm); D, Ratio of maximum resistance to extensibility.

to 90 min for all four base flours. Extensibility values for the CWES, CPS and SWS flours were similar at 45 min rest time, while the CWRS flour had a lower extensibility. Extensibility decreased for the CWES and CWRS flours at 90 min rest time and increased at 135 min rest time. Extensibility decreased for the CPS flour at 90 and 135 minutes and increased for the SWS flour (Figure 16).

Large differences in extensigraph properties were evident between the four base flours. The CWES flour had the highest values for maximum resistance to extension, area and ratio measures at all rest times, but intermediate values for extensibility at all rest times. The CWRS flour had the next highest values for maximum resistance, area and ratio at all rest times, but the lowest extensibility values at all rest times. The CPS flour had the next highest values for maximum resistance, area and ratio, with intermediate extensibility values, while the SWS flour had the lowest values for maximum resistance, area and ratio at all rest times, and the highest values for extensibility.

Extensigraph properties of the blends

The effects of varying the amount of CWES flour in blends with CWRS, CPS and SWS flours; and CWRS flour in blends with CPS and SWS flours on maximum resistance to extension are shown in Figures 17-18. Increasing levels of CWES resulted in increased maximum resistance to extension for all blends with the largest increases evident with addition of CWES flour to CPS and SWS flours. Increased maximum resistance was also observed when CWES was added to CWRS but the increases were minimal until at least 50% CWES was incorporated into the blend.

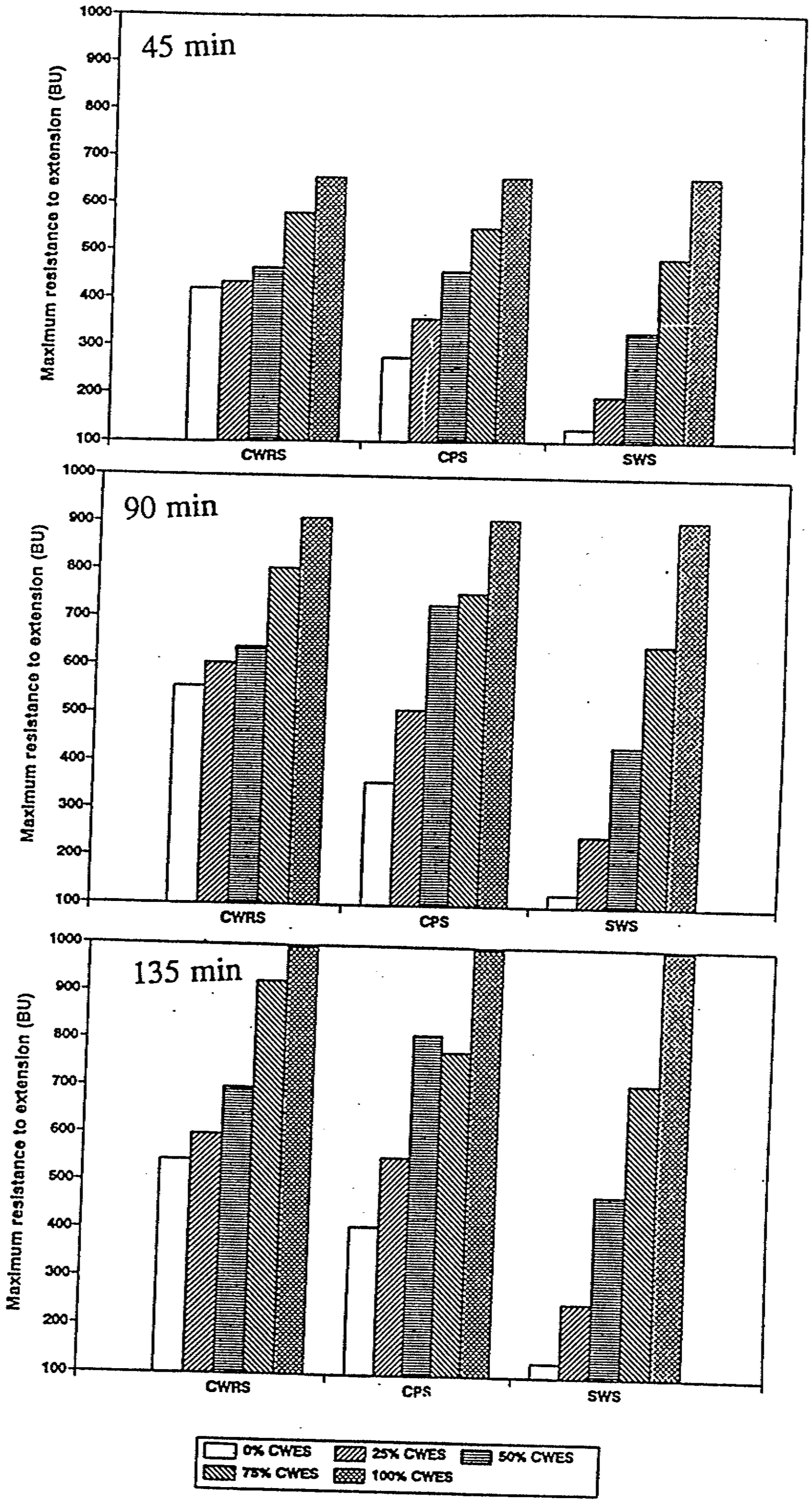


Figure 17. Effect of level of CWES flour in blends with CWRS, CPS and SWS flours on maximum resistance to extension at 45, 90 and 135 min rest time.

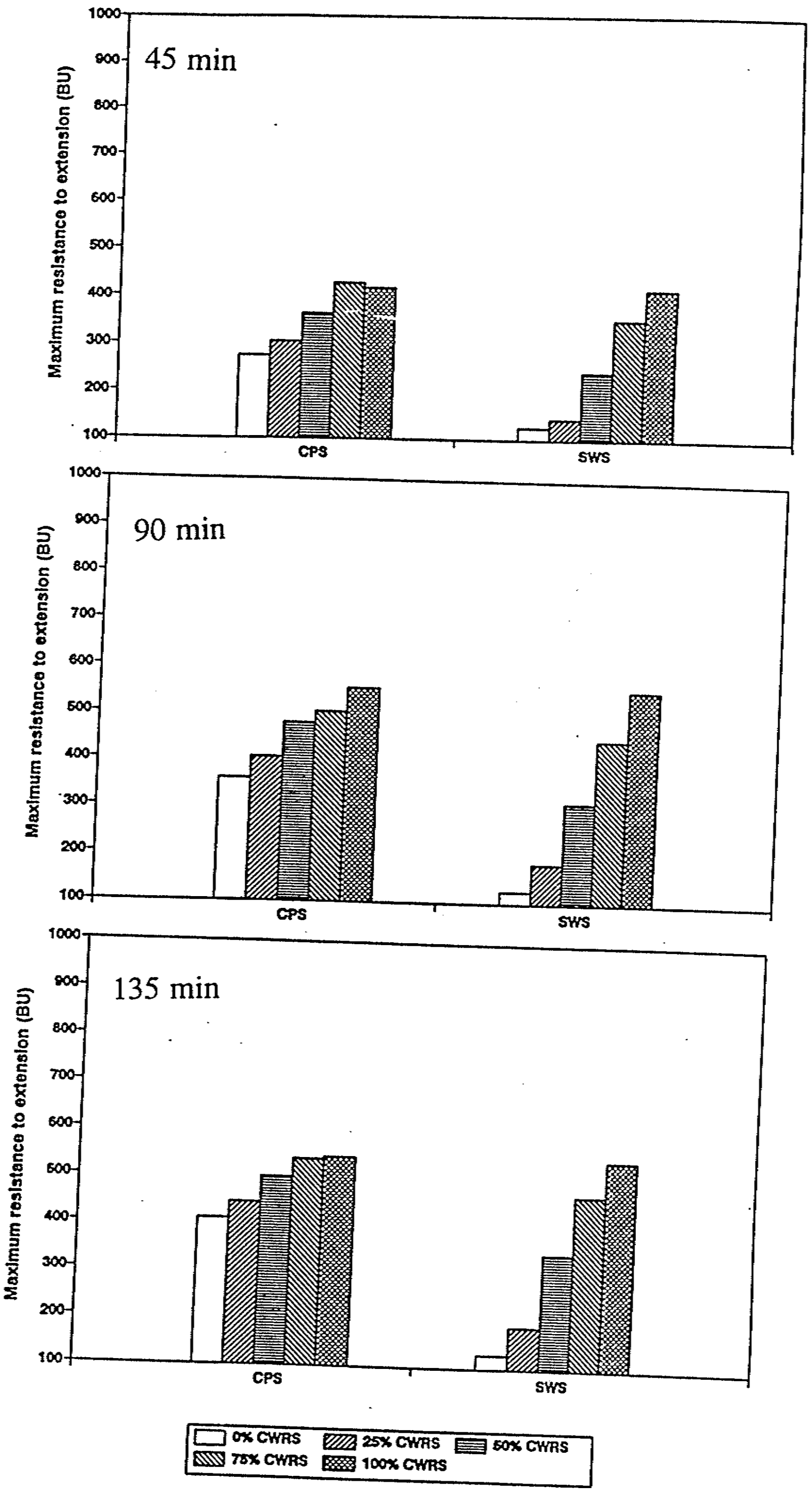


Figure 18. Effect of level of CWRS flour in blends with CPS and SWS flours on maximum resistance to extension at 45, 90 and 135 min rest time.

Addition of CWRS flours to CPS and SWS flours also resulted in increased maximum resistance, although the magnitude of the effect was much more pronounced with the addition of CWES flour, especially in blends with the CPS flour (Figure 18).

The effects of varying the amounts of CWES flour in blends with CWRS, CPS and SWS flours; and CWRS flour in blends with CPS and SWS flours on area under the extensigram are shown in Figures 19-20. Results were similar to those for maximum resistance to extension; an increase in area with increasing amounts of CWES flour and CWRS flour, with the largest increases when CWES was blended with CPS and SWS flours.

The effects of varying the amount of CWES flour in blends with CWRS, CPS and SWS flours; and CWRS flour in blends with CPS and SWS flours on ratio of maximum resistance to extensibility are shown in Figures 21-22. As observed for maximum resistance and area values, increasing levels of CWES flour blended with CWRS, CPS and SWS flours resulted in an increase in the ratio of maximum resistance to extensibility. The high ratio value for the CWRS flour at 45 and 90 minutes is likely due to the lower extensibility for the CWRS flour at these rest times (Figure 16).

The effects of varying the amount of CWES flour in blends with CWRS, CPS and SWS flours; and the CWRS flour in blends with the CPS and SWS flours on extensibility are shown in Figures 23-24. Increasing levels of the CWES flour in blends with the CWRS flour increased extensibility of the blends, while increasing levels of the CWES flour in blends with the CPS and SWS flours resulted in decreased extensibility (Figure 23). Increasing levels of the CWRS flour in blends with CPS and SWS flours resulted in a decrease in extensibility (Figure 24).

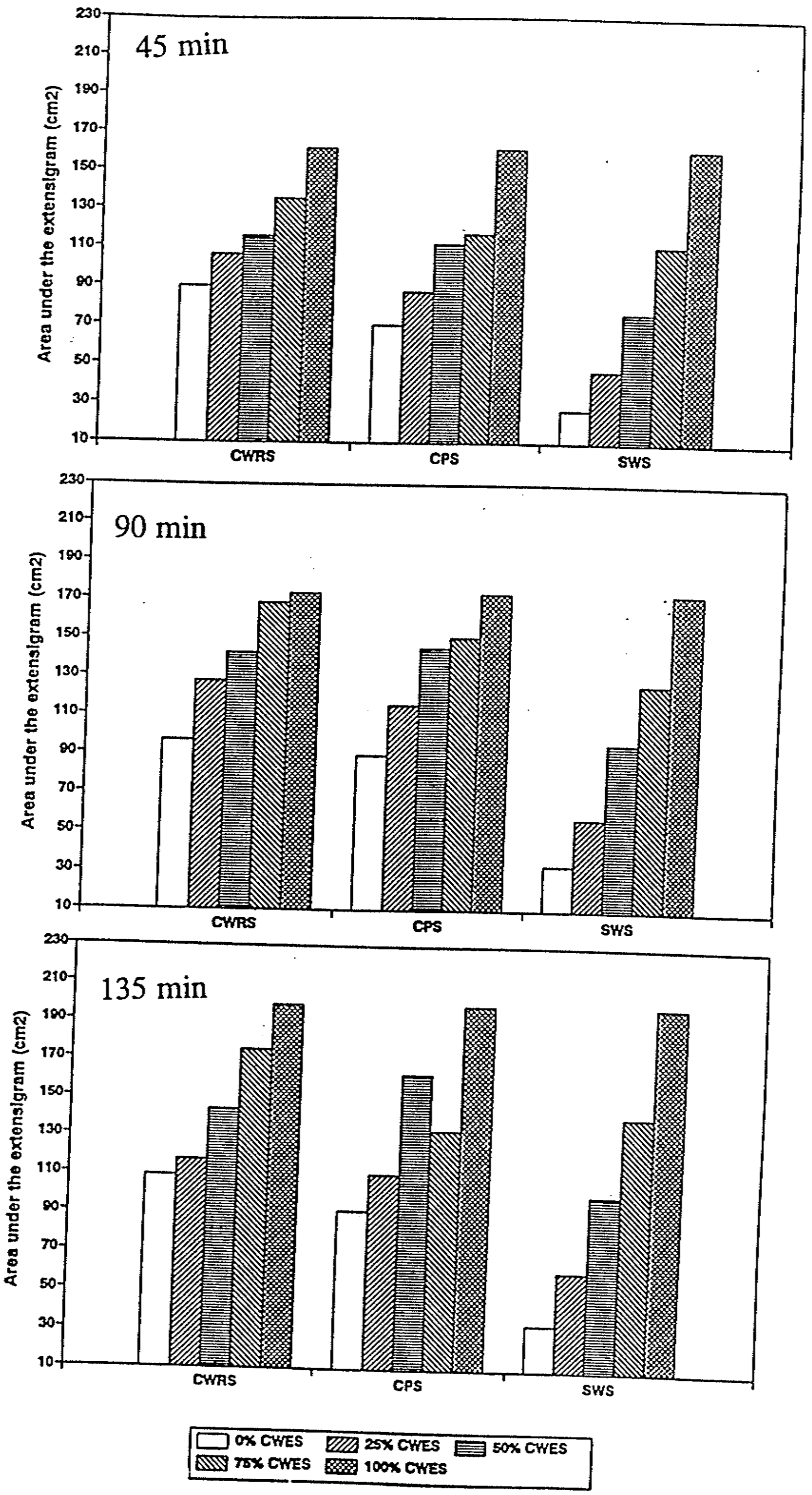


Figure 19. Effect of level of CWES flour in blends with CWRS, CPS and SWS flours on area under the extensigram at 45, 90 and 135 min rest time.

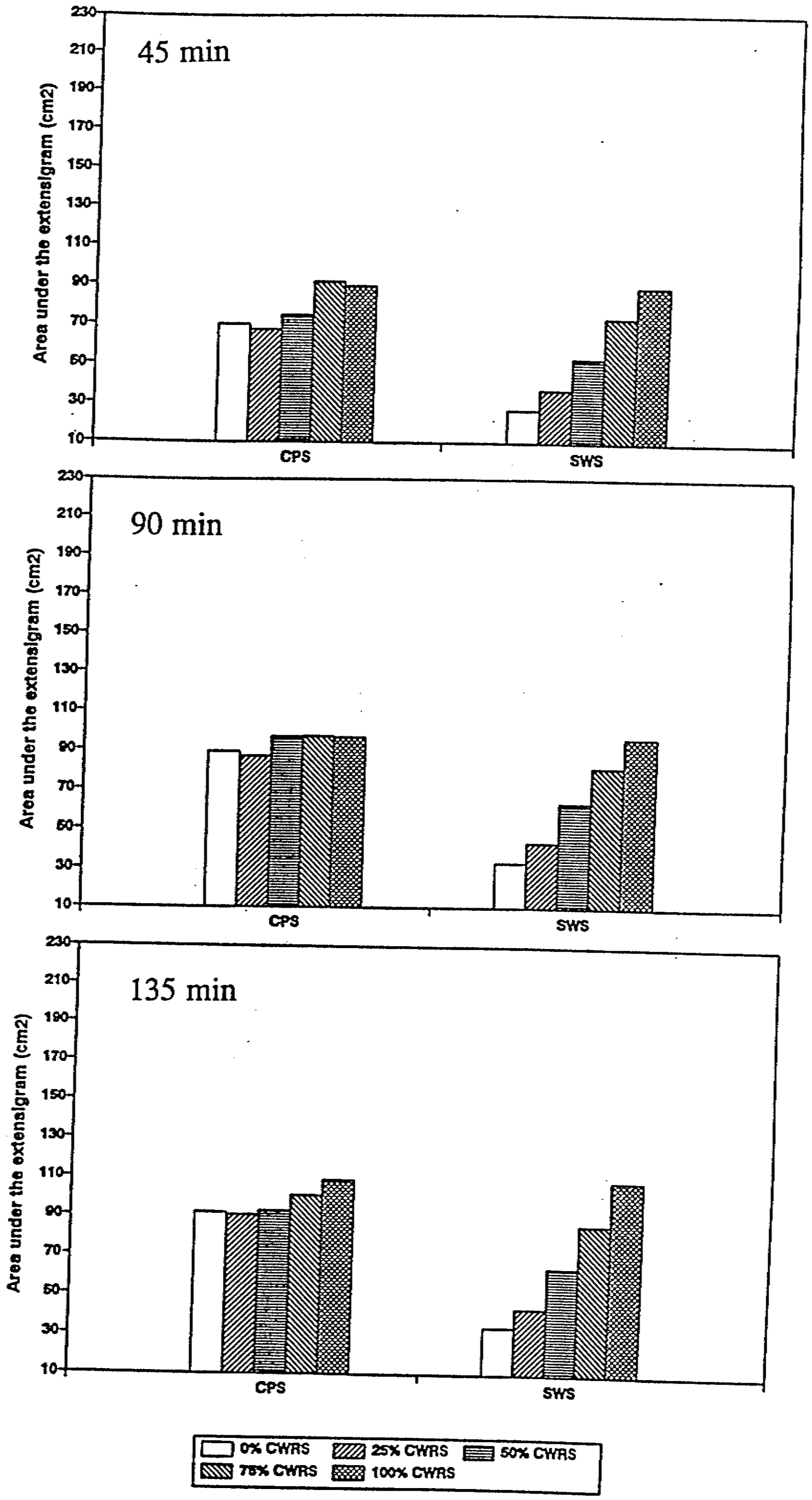


Figure 20. Effect of level of CWRS flour in blends with CPS and SWS flours on area under the extensigram at 45, 90 and 135 min rest time.

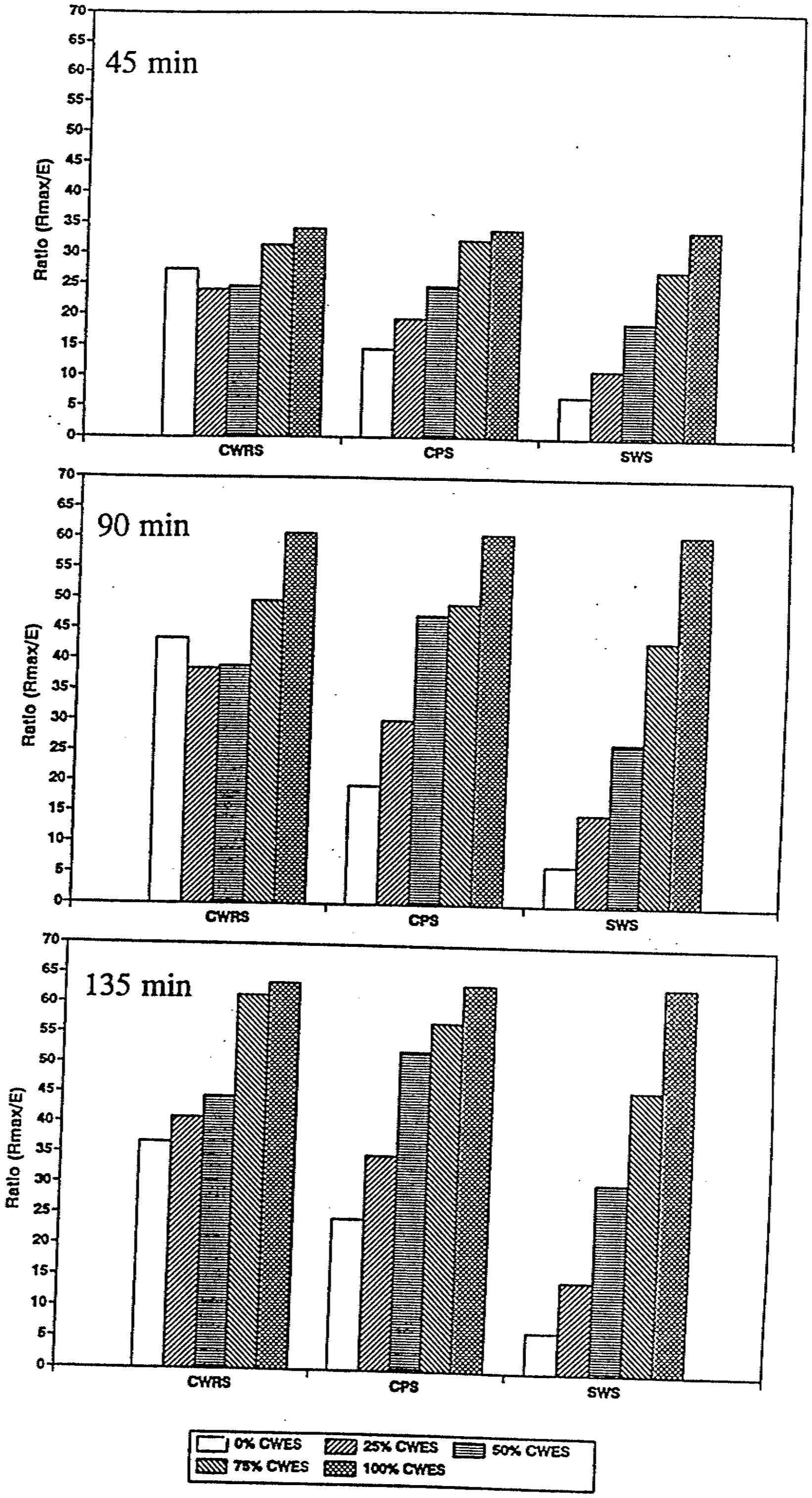


Figure 21. Effect of level of CWES flour in blends with CWRS, CPS and SWS flours on ratio of ratio of maximum resistance to extensibility at 45, 90 and 135 min rest time.

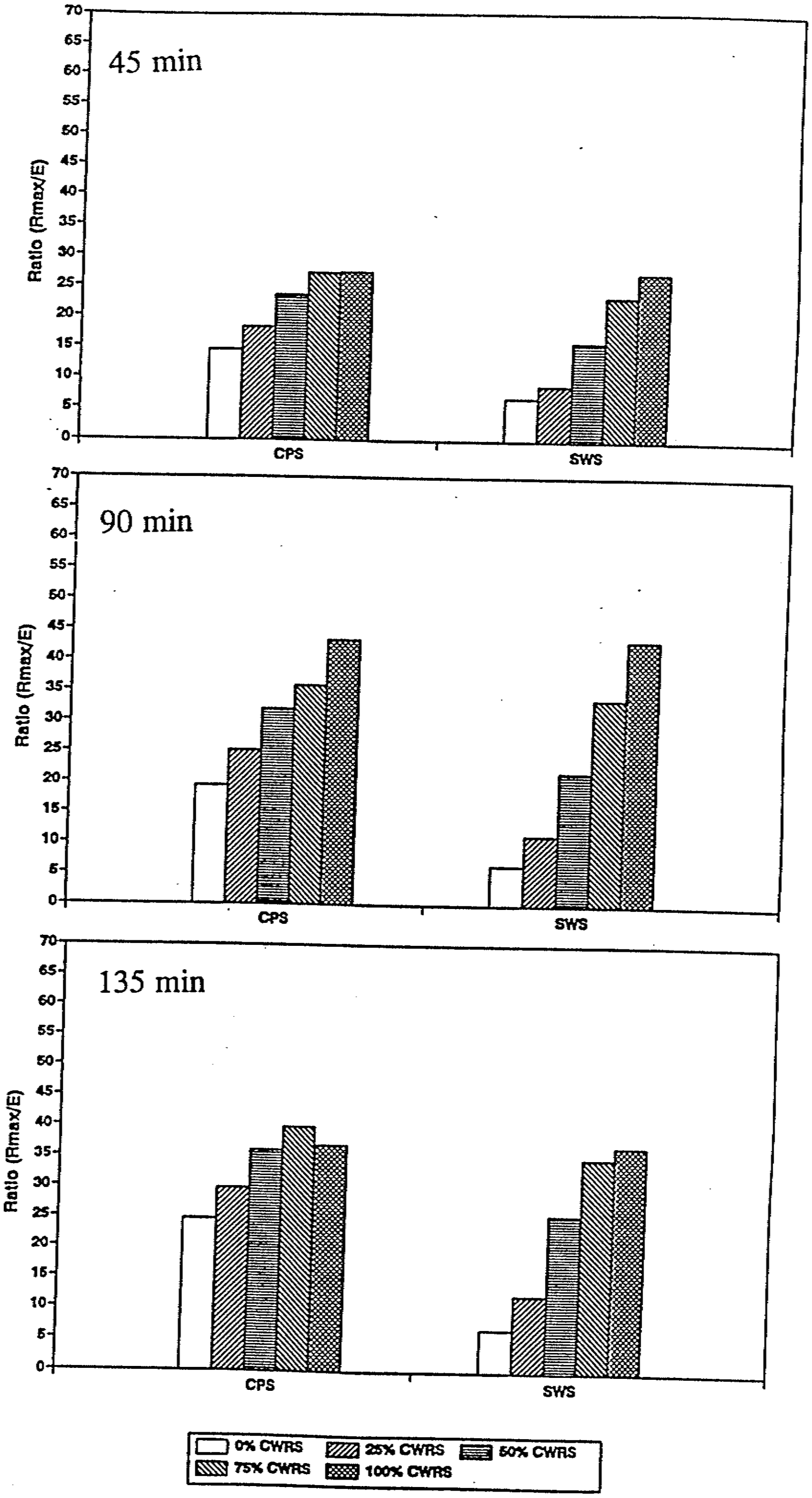


Figure 22. Effect of level of CWRS flour in blends with CPS and SWS flours on ratio of maximum resistance to extensibility at 45, 90 and 135 min rest time.

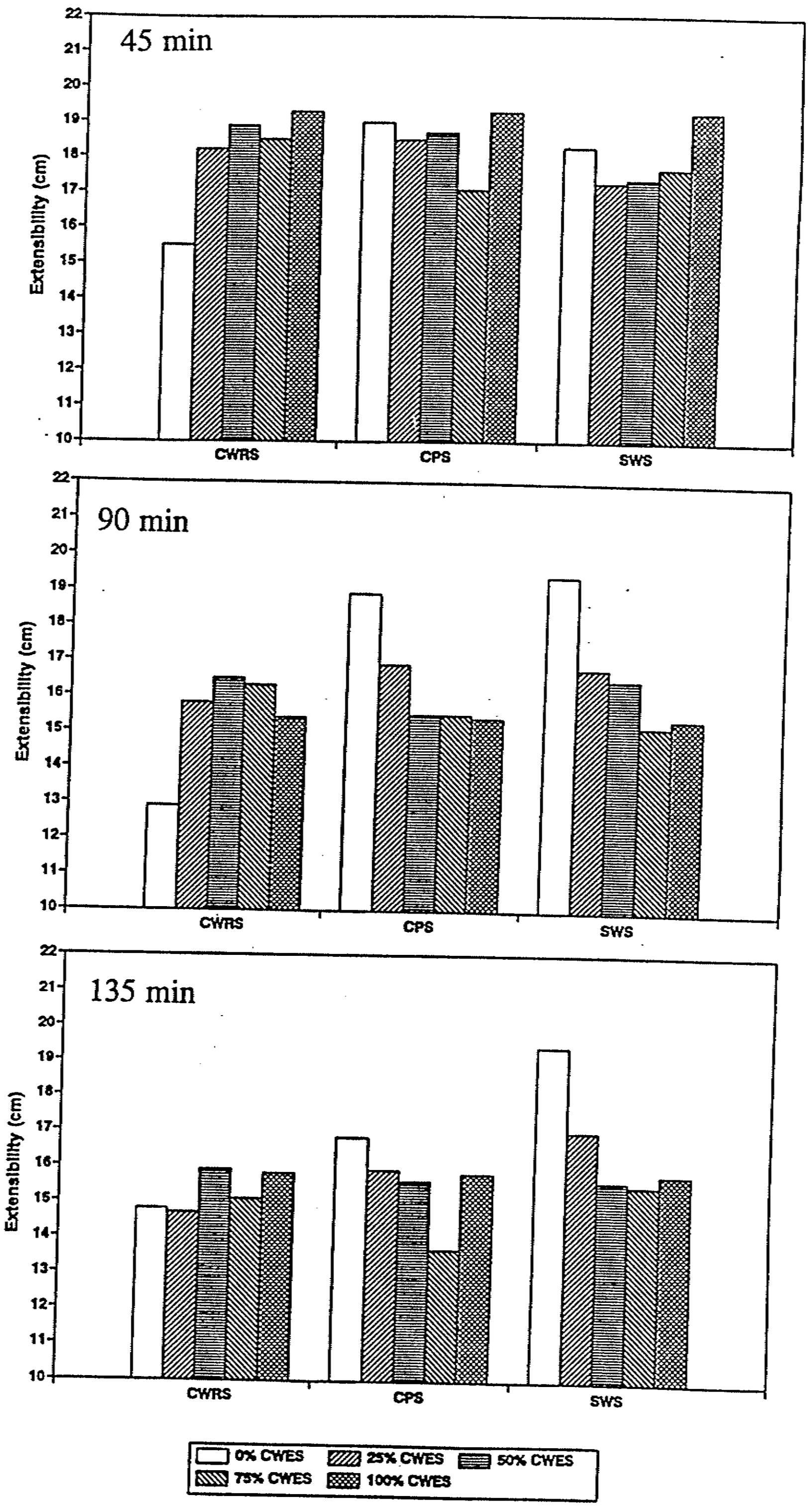


Figure 23. Effect of level of CWES flour in blends with CWRS, CPS and SWS flours on extensibility at 45, 90 and 135 min rest time.

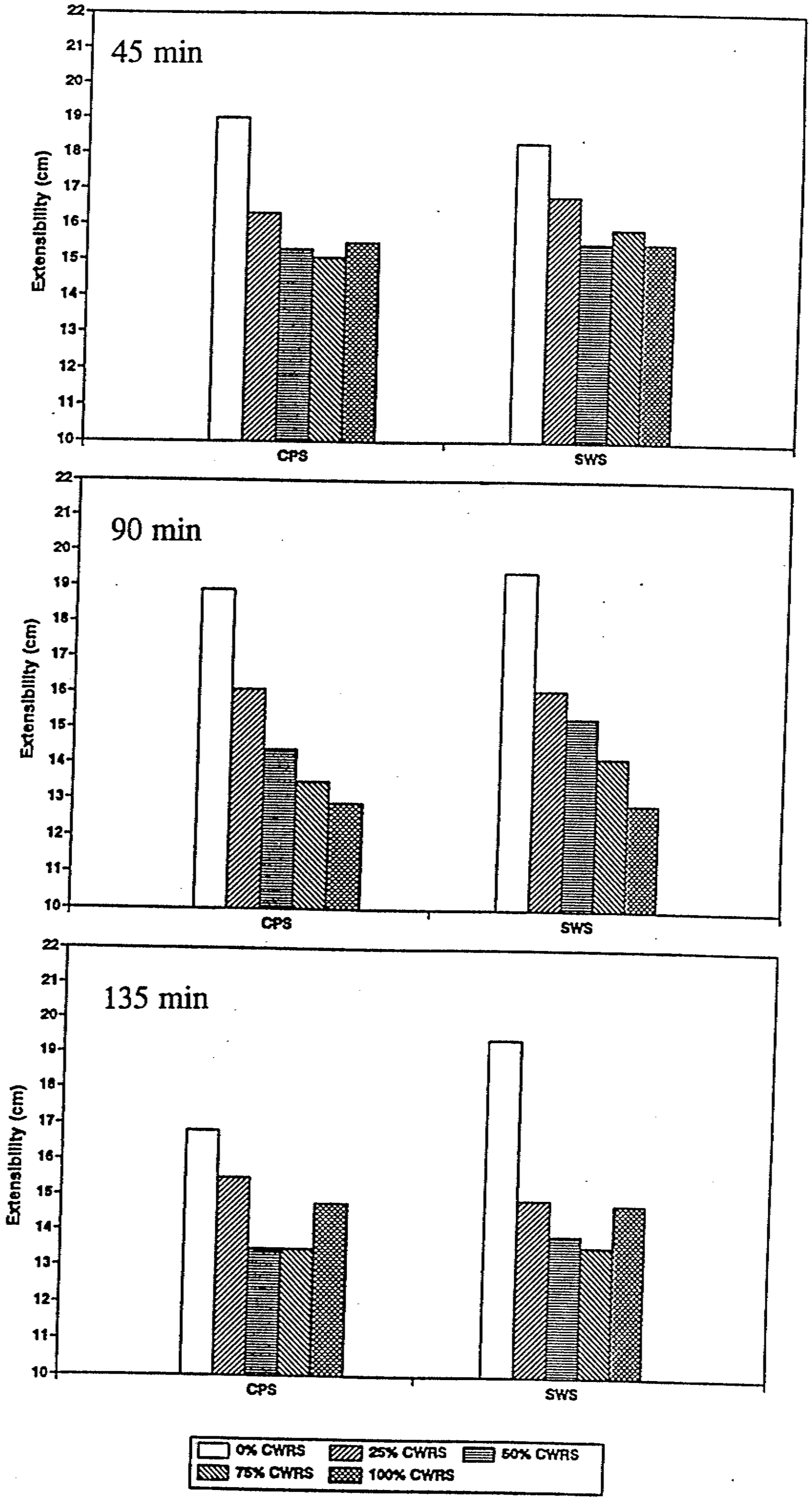


Figure 24. Effect of level of CWRS flour in blends with CPS and SWS flours on extensibility at 45, 90 and 135 min rest time.

As the amount of flour generally considered to be stronger increased in the blend, maximum resistance to extension, area and ratio values increased. The effects of blending the CWES flour with CPS and SWS flours were much more pronounced than for the CWRS flour. These results indicate that the CWES flour can be used to improve the strength of weaker flours.

Reproducibility of the extensigraph data

Coefficients of variation (CV) for extensigraph parameters were less than 8% for all but one property, the ratio of maximum resistance to extensibility at 90 min rest time, which had a CV of 11% (Figure 25). Results are for duplicate, separately prepared, scaled and tested dough pieces. Merritt and Bailey (1945) and Aitkens et al (1944) also reported that reproducibility of the extensigraph test was good if a standard procedure was followed.

Dough profiling properties

The dough profiling method was applied to each of the four base flours and blends. Results of the dough profiling tests provide information on the behaviour of doughs under compression, tension and during relaxation measured during two test cycles. Twenty-six parameters were measured or calculated from the dough profiling curve.

Correlations among the dough profiling parameters

Pearson correlation coefficients, generated among the dough profiling parameters, showed that some were highly correlated with each other (Appendix 7). Compression parameters CF and CW were highly correlated for both first and second cycles, but tension parameters TF and TW

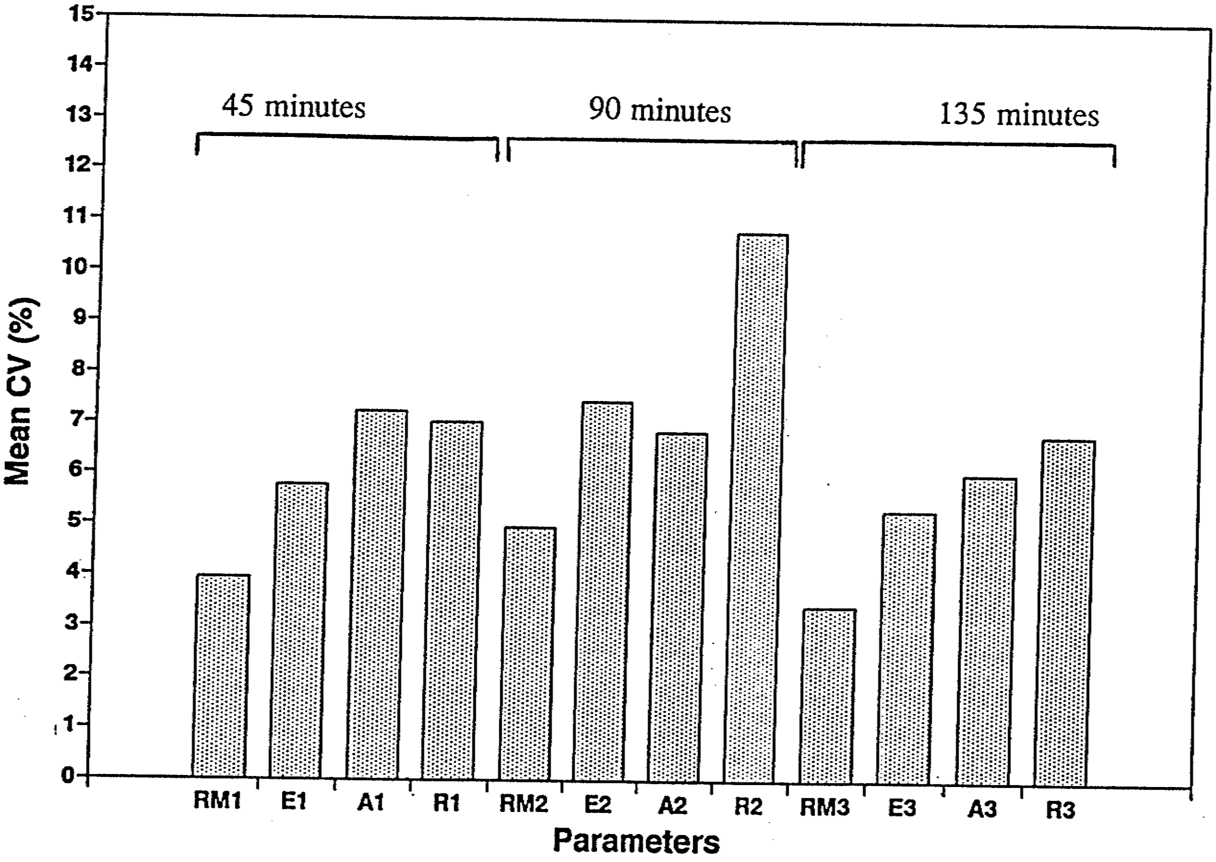


Figure 25. Mean coefficients of variation for the extensigraph parameters.

were not significantly correlated for either cycle. Compression parameters were highly correlated with relaxation end force (RF) and relaxation degree (R) for the first cycle. Tension work (TW) was highly correlated with relaxation ratio (M1) for the first cycle. Relaxation end force (RF), relaxation degree (R), and relaxation ratio (M) were highly correlated for both cycles. Relaxation index (K) was highly correlated with relaxation end force (RF) and relaxation degree (R) for the second cycle. All second cycle parameters were highly correlated with corresponding first cycle parameters except for the compression work and tension work.

Dough profiling properties of the base flours

Selected dough profiling properties of the CWES, CWRS, CPS and SWS flours are shown in Figure 26 and Table 30. Compression peak force (Figure 26A), the maximum force recorded during rapid compression of dough sample, and compression work values (Figure 26B), which integrate force over the compression period, were highest for the CWES and CWRS doughs. Peak compression force values were lower for the CPS flour and lower still for the SWS doughs. Differences between stronger (CWES and CWRS), medium (CPS), and weaker (SWS) types of doughs were even more evident with the compression work values. The compression work value for the CWES dough was 51 N.mm and for the SWS dough was 32 N.mm. Although large differences were seen between the CWES and CWRS doughs in comparison with the CPS doughs and SWS doughs, the compression peak force values and the compression work values did not differentiate between the CWES and CWRS doughs. Tension peak force values (Figure 26C) were similar for all four base flours (23 to 26N) while tension work area (Figure 26D) was highest for the SWS dough (198 N.mm) and lowest for the CWES dough (100 N.mm). Tension

Figure 26. Selected dough profiling properties for the four base flours. A, Compression peak force (N); B, Compression work (N.mm); C, Tension peak force (N); D, Tension work (N.mm); E, Relaxation ratio; F, Relaxation end force (N); G, Relaxation degree; H, Relaxation index.

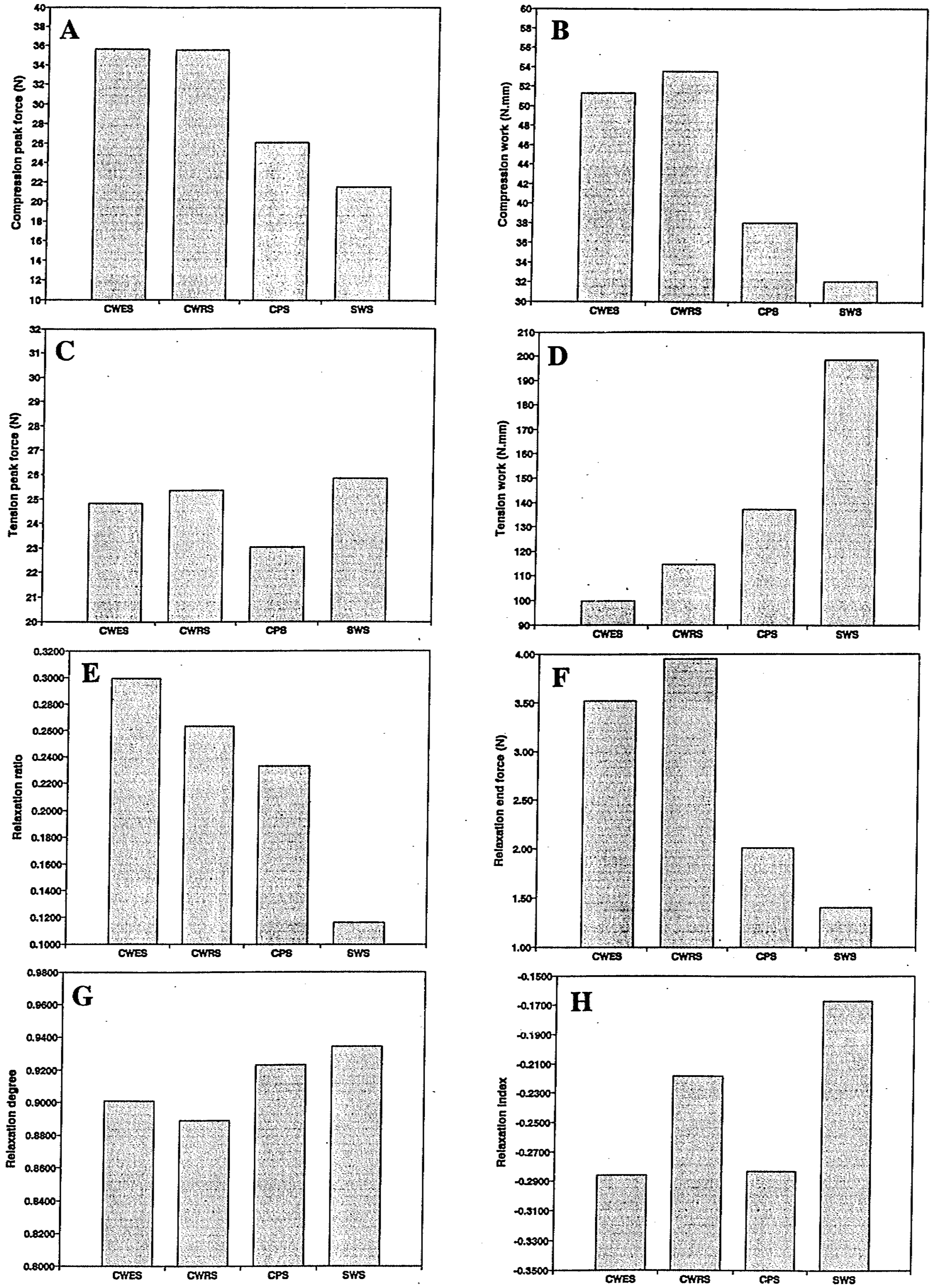

A
Compression peak force (N)
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
CWES
CWRS
CPS
SWS
B
Compression work (N.mm)
60
58
56
54
52
50
48
46
44
42
40
38
36
34
32
30
CWES
CWRS
CPS
SWS
C
Tension peak force (N)
32
31
30
29
28
27
26
25
24
23
22
21
20
CWES
CWRS
CPS
SWS
D
Tension work (N.mm)
210
200
190
180
170
160
150
140
130
120
110
100
90
CWES
CWRS
CPS
SWS
E
Relaxation ratio
0.3200
0.3000
0.2800
0.2600
0.2400
0.2200
0.2000
0.1800
0.1600
0.1400
0.1200
0.1000
CWES
CWRS
CPS
SWS
F
Relaxation end force (N)
4.00
3.50
3.00
2.50
2.00
1.50
1.00
CWES
CWRS
CPS
SWS
G
Relaxation degree
0.9800
0.9600
0.9400
0.9200
0.9000
0.8800
0.8600
0.8400
0.8200
0.8000
CWES
CWRS
CPS
SWS
H
Relaxation Index
-0.1500
-0.1700
-0.1900
-0.2100
-0.2300
-0.2500
-0.2700
-0.2900
-0.3100
-0.3300
-0.3500
CWES
CWRS
CPS
SWS

Table 30. Sample Means[1] for Selected Dough Profiling Parameters of the First Cycle for the Four Base Flours.

Sample	CF1	CW1	TF1	TW1	RF1	R1	M1	K1
CWES	36	51	25	100	3.5	0.90	0.30	-0.29
CWRS	36	54	25	115	3.9	0.89	0.26	-0.22
CPS	26	38	23	137	2.0	0.92	0.23	-0.28
SWS	22	32	26	198	1.4	0.94	0.12	-0.17

[1] Means are average of two values.

[2] CF1=Compression peak force (N); CW1=Compression work (N.mm); TF1=Tension peak force (N); TW1=Tension work (N.mm); RF1= Relaxation end force (N); R1=Relaxation degree; M1=Relaxation ratio; K1=Relaxation index.

peak force is a measure of dough resistance to rapid extension. Tension work measures the dough resistance under prolonged conditions of extension. The tension peak force values did not discriminate between the doughs indicating that under rapid extension, the doughs have similar resistance. The tension work values showed large differences between the four base flour doughs. The high tension work value for the SWS dough indicated the increased tendency of the SWS dough to flow under conditions of prolonged extension.

Measurements taken from the relaxation portion of the profiling curve represented either force at a specific time (relaxation degree and relaxation end force), or changes in force registered over the relaxation period (relaxation index and relaxation ratio). The relaxation ratio values (Figure 26E), the ratio of projected compression force at the beginning of the relaxation curve to the compression peak force, were highest for the CWES and CWRS doughs (M1 = 0.30 and 0.26 respectively). M1 values were lower for the CPS dough (0.23), and lower still for the SWS dough (0.12). Relaxation end force (RF) values (Figure 26F), compression force at the end of the relaxation period, were highly correlated with compression peak force and offered no additional useful information.

Relaxation degree (Figure 26G), a measure of the extent of dough relaxation, was highest for the SWS dough (0.94), lower for the CPS dough (0.92) and lowest for the CWES and CWRS doughs (0.90 and 0.89 respectively). Relaxation index (Figure 26H), a measure of the rate of dough relaxation, was also highest for the SWS dough (-0.17), and lowest for the CWES and CPS doughs (-0.29). The CWRS dough had an intermediate K1 value of -0.22.

The relaxation ratio (M) and the relaxation index (K) appeared to discriminate well among the base flour doughs. These parameters can be interpreted as representing elasticity (M), and viscosity (K). M and K are related to the dough relaxation rate, a characteristic of dough viscoelasticity. The relaxation index (K) approaches zero and relaxation ratio (M) approaches one with greater dough strength, or when elasticity predominates over viscosity. The opposite is true for weaker doughs, where the dough is more viscous than elastic. Although these characteristics of dough are sometimes considered to be simply the inverse of each other, these data indicate that this may not necessarily be true. The CWRS dough had relatively high levels of both M and K.

Dough profiling properties of the blends

The effects of varying the amount of CWES flour in blends with CWRS, CPS and SWS flours on compression, tension and relaxation properties are shown in Figures 27-28. Addition of increasing levels of CWES flour to CWRS flour resulted in a decrease in peak compression force and compression work (Figure 27). Compression peak force and compression work values increased with increasing levels of the CWES flour in blends with CPS and SWS flours (Figure 27). Tension work values decreased with increasing levels of the CWES flour in blends with CWRS, CPS and SWS flours (Figure 27). Results for the tension peak force values were not as consistent, likely because they failed to discriminate among the four base flours. Relaxation degree decreased with increased levels of the CWES flour in blends with CPS and SWS flours. Relaxation ratio values increased with increasing levels of the CWES flour in blends with CPS and SWS flours (Figure 28). Increasing levels of CWES flour in blends with CWRS flour does not increase strength, however, there is a decrease in the ability of the dough to flow, as shown by the difference in tension work values.

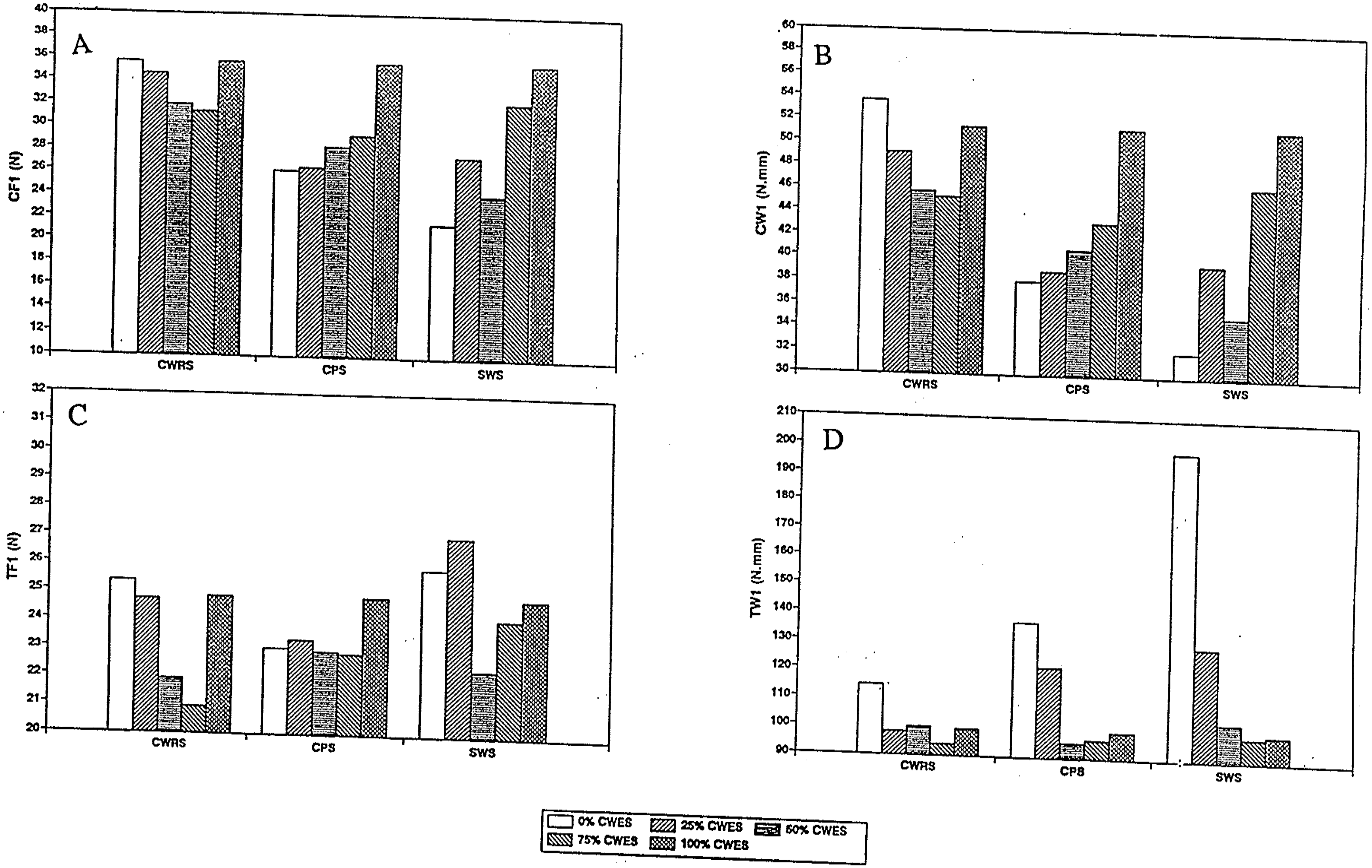


Figure 27. Effect of level of CWES flour in blends with CWRS, CPS and SWS flours on A, Compression peak force; B, Compression work; C, Tension peak force; D, Tension work

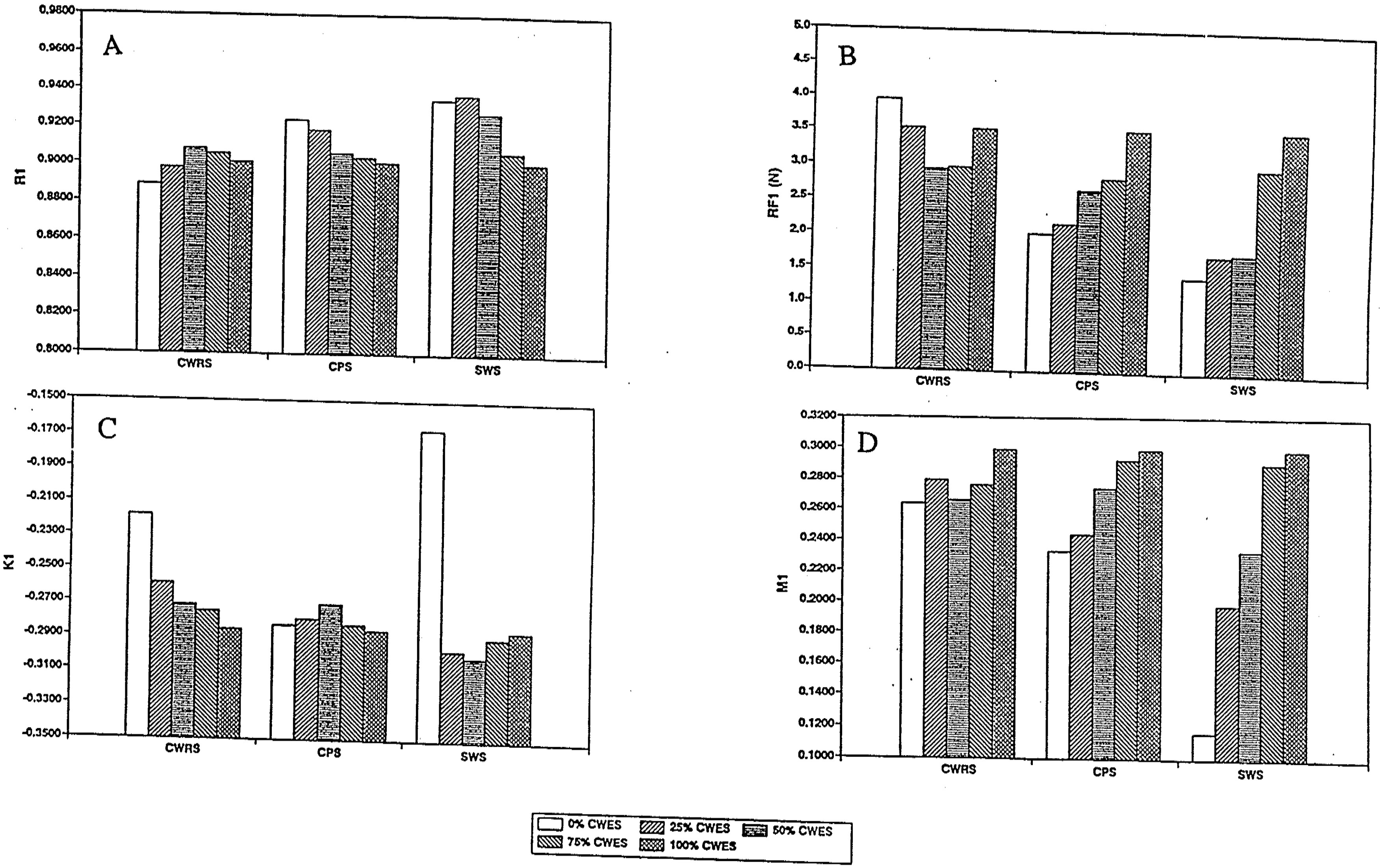


Figure 28. Effect of level of CWES flour in blends with CWRS, CPS and SWS flours on A, Relaxation degree; B, Relaxation end force; C, Relaxation index; D, Relaxation ratio.

The effects of increasing levels of CWRS flour in blends with CPS and SWS flour on compression, tension and relaxation parameters are shown in Figures 29-30. Compression peak force and compression work values increased with increasing level of CWRS flour in blends with CPS and SWS flours (Figure 29). Tension work values decreased for CWRS/CPS and CWRS/SWS blends as the amount on CWRS flour in the blend increased. Tension peak force values increased with increasing levels of CWRS flour in blends with CPS flour, while addition of increasing levels of CWRS flour in blends with SWS flour appeared to have an additive effect on tension peak force values. Relaxation ratio, relaxation index and relaxation end force values decreased as the amount of CWRS flour in blends with CPS and SWS flours, although the effect was much more pronounced for the CWRS/SWS blends (Figure 30).

In general, increasing proportions of the CWES and CWRS flour in blends with CPS and SWS resulted in increased values for compression parameters and decreased values for tension parameters. Increasing levels of the stronger flour resulted in increasing relaxation end force and relaxation ratio values, and a decrease in relaxation degree values. The effect was more pronounced in CWES/SWS and CWRS/SWS blends.

Reproducibility of the dough profiling data

Low coefficients of variation indicated a high level of reproducibility for many of the dough profile parameters. The mean coefficients of variation (CV) for dough profiling parameters of the first cycle, except stringiness (S1), were less than 8%, and for second cycle parameters, were less than 15% (Figure 31). The lowest CV's for both cycles were for the relaxation parameters.

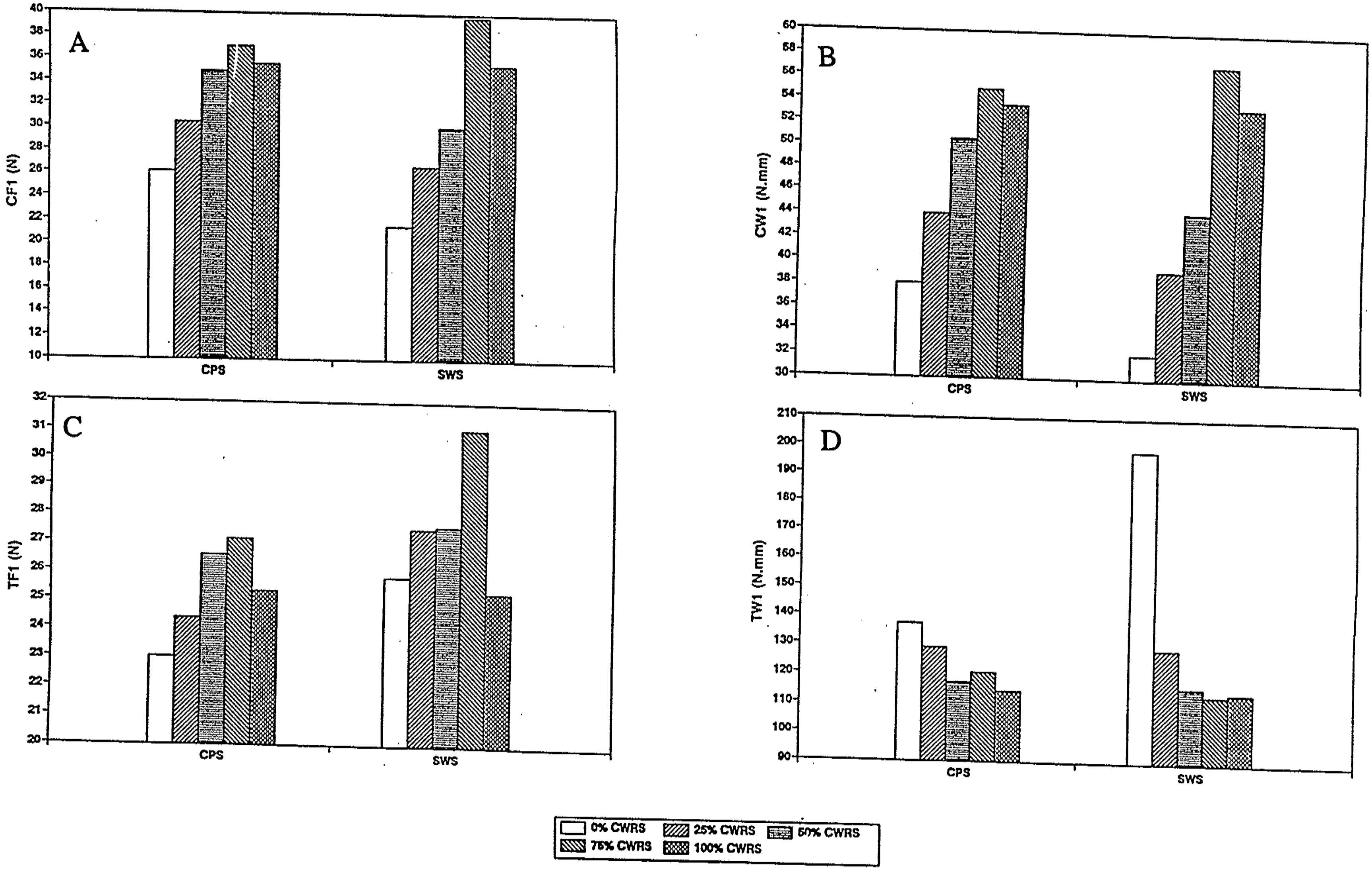


Figure 29. Effect of level of CWRS flour in blends with CPS and SWS flours on A, Compression peak force; B, Compression work; C, Tension peak force; D, Tension work.

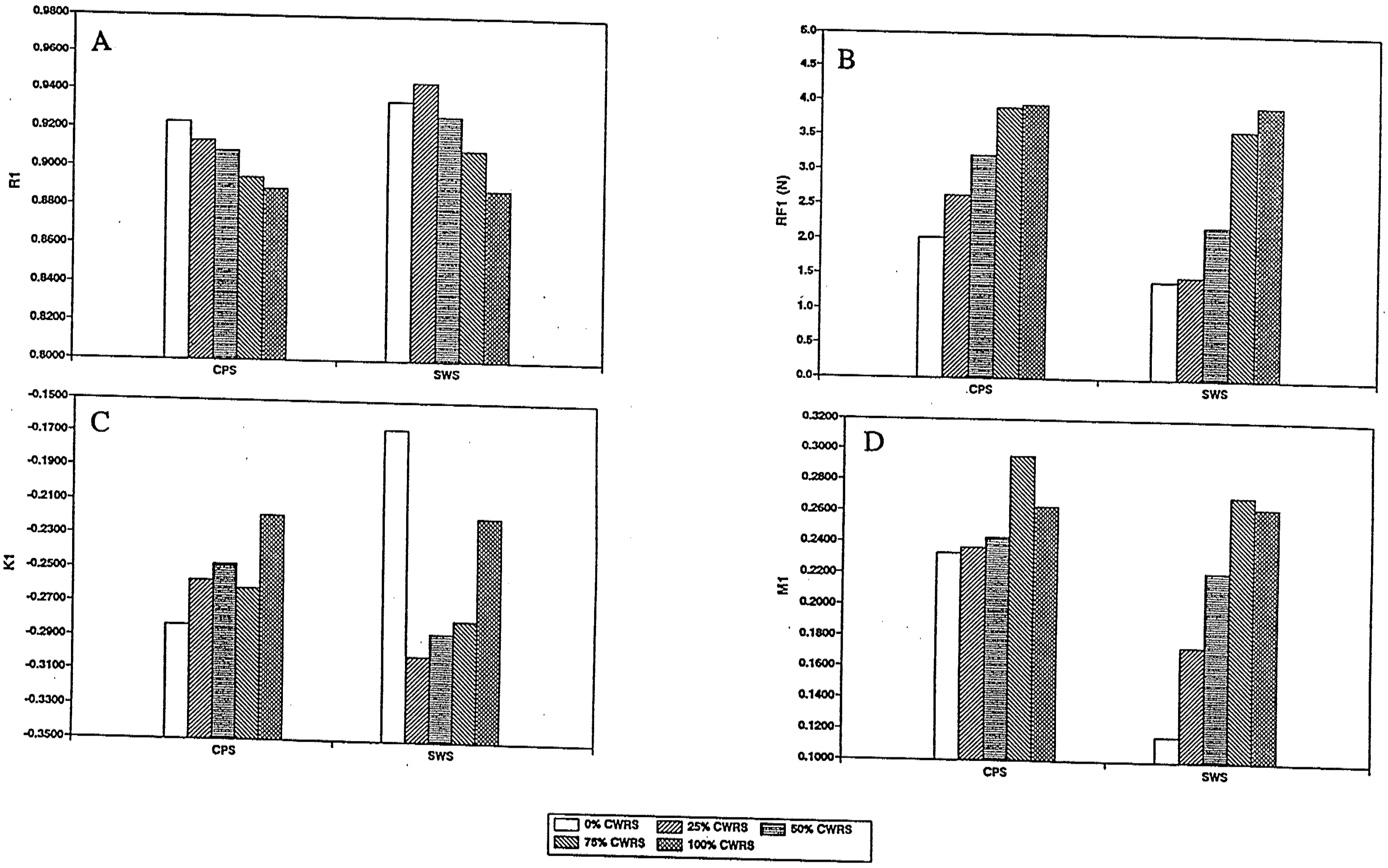


Figure 30. Effect of level of CWRS flour in blends with CPS and SWS flours on A, Relaxation degree; B, Relaxation end force; C, Relaxation index; D, Relaxation ratio.

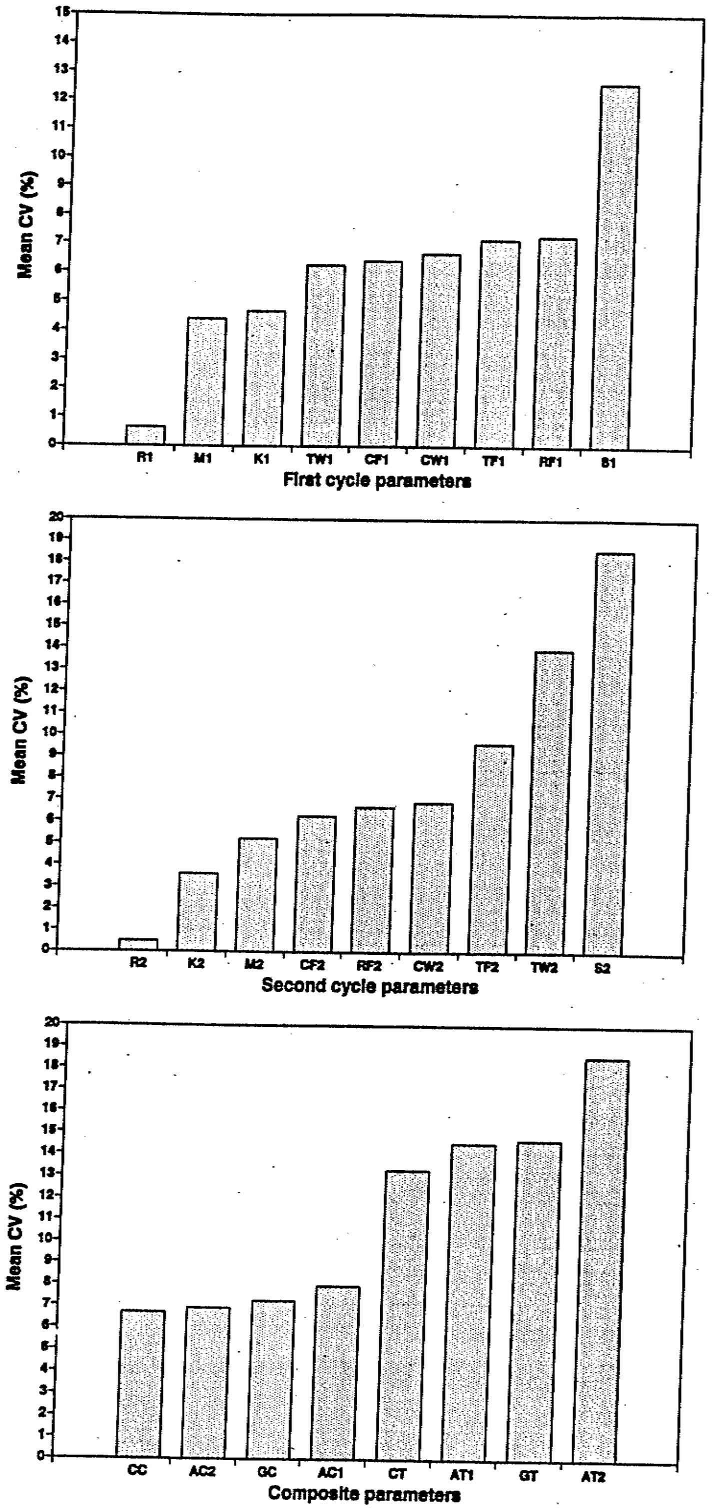


Figure 31. Mean coefficients of variation for the dough profiling parameters.

Standard errors, and therefore CV's, were higher for the second cycle values probably because of the manipulation of the dough during the first cycle. The four compression based composite parameters, cohesiveness (CC), gumminess (GC), average compression force of the first cycle (AC1) and of the second cycle (AC2), had CV's of 6-8 %. The four tension-related secondary parameters were less reproducible: CV's for tension work ratio (CT), tension work ratio times tension peak force of the first cycle (GT), average tension force of the first cycle (AT1) and of the second cycle (AT2) were from 13-18% (Figure 31). The greater variance associated with these measures is a consequence of variability in the stringiness values. Exact end points for this portion of the curve were difficult to establish. These results confirm those observed by Wang et al (1996). The overall low CV's indicate that dough profiling is a highly reproducible method.

Relationship of dough profiling parameters with extensigraph properties

The analysis of the wheat lines presented in Chapter 3 indicated high correlations between certain extensigraph measurements and dough profiling parameters. This study was designed to examine the correlations further and to determine which dough profiling parameters might be used to give a rapid estimate of dough strength. The relationship of dough profiling parameters to extensigraph measurements was examined using Pearson correlation coefficients (Tables 31-36).

The dough profiling relaxation parameters showed the best correlations with extensigraph parameters, followed by tension parameters and then compression parameters. Several parameters were well correlated with maximum resistance to extension at all rest times. Two of the profiling relaxation parameters relaxation degree (R1) and relaxation ratio (M1) were highly correlated with maximum resistance to extension (Table 31). The r values for correlations between relaxation

Table 31. Matrix of Pearson Correlation Coefficients[1] describing Relationships between First Cycle Relaxation Parameters and Extensigraph Parameters.

Extensigraph Parameter (70g)[2]	Relaxation Parameter[3]			
	R1	M1	K1	RF1
RM1	-0.81***	0.89***	-0.20	0.71**
E1	0.02	0.06	-0.06	-0.24
A1	-0.75**	0.85***	-0.25	0.63*
R1	-0.88***	0.92***	-0.16	0.81***
RM2	-0.77***	0.87***	-0.23	0.65*
E2	0.58*	-0.59*	0.17	-0.73**
A2	-0.70**	0.82***	-0.27	0.54
R2	-0.84***	0.89***	-0.18	0.75**
RM3	-0.73**	0.85***	-0.25	0.60*
E3	0.52	-0.66*	0.37	-0.62*
A3	-0.69*	0.81***	-0.26	0.55
R3	-0.77**	0.88***	-0.25	0.66*

[1] Statistically significant at *P=0.01, **P=0.001, ***P=0.0001.

[2] RM1 = maximum resistance to extension at 45 min (EU); E1 = extensibility at 45 min (cm); A1 = area under the extensigram at 45 min (cm^2); R1 = ratio of maximum resistance to extensibility at 45 min; RM2 = maximum resistance to extension at 90 min (EU); E2 = extensibility at 90 min (cm); A2 = area under the extensigram at 90 min (cm^2); R2 = ratio of maximum resistance to extensibility at 90 min; RM3 = maximum resistance to extension at 135 min (EU); E3 = extensibility at 135 min (cm); A3 = area under the extensigram at 135 min (cm^2); R3 = ratio of maximum resistance to extensibility at 135 min.

[3] R1 = relaxation degree of the first cycle; M1 = relaxation ratio of the first cycle; K1 = relaxation index of the first cycle; RF1 = relaxation end force of the first cycle (N).

Table 32. Matrix of Pearson Correlation Coefficients[1] describing Relationships between Second Cycle Relaxation Parameters and Extensigraph Parameters.

Extensigraph Parameter (70g)[2]	Relaxation Parameter[3]			
	R2	M2	K2	RF2
RM1	-0.68*	0.79***	0.28	0.51
E1	0.06	0.18	-0.36	-0.29
A1	-0.62*	0.75**	0.21	0.44
R1	-0.74**	0.80***	0.40	0.63*
RM2	-0.64*	0.74**	0.28	0.45
E2	0.48	-0.28	-0.55	-0.61*
A2	-0.60*	0.74**	0.22	0.38
R2	-0.68*	0.73**	0.34	0.53
RM3	-0.60*	0.72**	0.23	0.40
E3	0.56	-0.40	-0.62*	-0.61*
A3	-0.58*	0.71**	0.19	0.36
R3	-0.64*	0.74**	0.29	0.46

[1] Statistically significant at *P=0.01, **P=0.001, ***P=0.0001.

[2] RM1 = maximum resistance to extension at 45 min (EU); E1 = extensibility at 45 min (cm); A1 = area under the extensigram at 45 min (cm^2); R1 = ratio of maximum resistance to extensibility at 45 min; RM2 = maximum resistance to extension at 90 min (EU); E2 = extensibility at 90 min (cm); A2 = area under the extensigram at 90 min (cm^2); R2 = ratio of maximum resistance to extensibility at 90 min; RM3 = maximum resistance to extension at 135 min (EU); E3 = extensibility at 135 min (cm); A3 = area under the extensigram at 135 min (cm^2); R3 = ratio of maximum resistance to extensibility at 135 min.

[3] R2 = relaxation degree of the second cycle; M2 = relaxation ratio of the second cycle; K2 = relaxation index of the second cycle; RF2 = relaxation end force of the second cycle (N).

Table 33. Matrix of Pearson Correlation Coefficients[1] describing Relationships between Dough Profiling Tension Parameters and Extensigraph Parameters.

Extensigraph Parameter (70g)[2]	Tension Parameter[3]			
	TF1	TW1	TF2	TW2
RM1	0.46	-0.76**	0.21	0.17
E1	0.73**	-0.05	0.48	0.25
A1	0.52	-0.76**	0.28	0.15
R1	0.32	-0.76***	0.10	0.15
RM2	0.51	-0.78***	0.30	0.12
E2	0.42	0.57	0.27	0.29
A2	0.63*	-0.77***	0.39	0.14
R2	0.38	-0.78***	0.19	0.09
RM3	0.54	-0.77***	0.34	0.13
E3	0.26	0.65*	0.07	0.18
A3	0.59	-0.74**	0.37	0.13
R3	0.47	-0.79***	0.29	0.13

[1] Statistically significant at *P=0.01, **P=0.001, ***P=0.0001.

[2] RM1 = maximum resistance to extension at 45 min (EU); E1 = extensibility at 45 min (cm); A1 = area under the extensigram at 45 min (cm^2); R1 = ratio of maximum resistance to extensibility at 45 min; RM2 = maximum resistance to extension at 90 min (EU); E2 = extensibility at 90 min (cm); A2 = area under the extensigram at 90 min (cm^2); R2 = ratio of maximum resistance to extensibility at 90 min; RM3 = maximum resistance to extension at 135 min (EU); E3 = extensibility at 135 min (cm); A3 = area under the extensigram at 135 min (cm^2); R3 = ratio of maximum resistance to extensibility at 135 min.

[3] TF1 = tension peak force of the first cycle (N); TW1 = tension work of the first cycle (N.mm); TF2 = tension peak force of the second cycle (N.mm); TW2 = tension work of the second cycle (N.mm).

Table 34. Matrix of Pearson Correlation Coefficients[1] describing Relationships between Compression-based Composite Parameters and Extensigraph Parameters.

Extensigraph Parameter (70g)[2]	Composite Parameter[3]			
	CC	GC	AC1	AC2
RM1	-0.77***	-0.46	0.40	-0.50
E1	0.14	-0.48*	-0.50	-0.54
A1	-0.71**	-0.47*	0.32	-0.53
R1	-0.84***	-0.38	0.54	-0.41
RM2	-0.74**	-0.51*	0.33	-0.56
E2	0.68*	-0.20	-0.79***	-0.22
A2	-0.67*	-0.56*	0.21	-0.63*
R2	-0.80***	-0.43	0.46	-0.47
RM3	-0.71**	-0.54*	0.29	-0.59*
E3	0.67*	-0.10	-0.67*	-0.09
A3	-0.67*	-0.54*	0.23	-0.61*
R3	-0.77***	-0.50*	0.37	-0.55

[1] Statistically significant at *P=0.01, **P=0.001, ***P=0.0001.

[2] RM1 = maximum resistance to extension at 45 min (EU); E1 = extensibility at 45 min (cm); A1 = area under the extensigram at 45 min (cm^2); R1 = ratio of maximum resistance to extensibility at 45 min; RM2 = maximum resistance to extension at 90 min (EU); E2 = extensibility at 90 min (cm); A2 = area under the extensigram at 90 min (cm^2); R2 = ratio of maximum resistance to extensibility at 90 min; RM3 = maximum resistance to extension at 135 min (EU); E3 = extensibility at 135 min (cm); A3 = area under the extensigram at 135 min (cm^2); R3 = ratio of maximum resistance to extensibility at 135 min.

[3] CC = cohesiveness (N); GC = gumminess (N); AC1 = average compression force of the first cycle (N); AC2 = average compression force of the second cycle (N).

Table 35. Matrix of Pearson Correlation Coefficients[1] describing Relationships between Tension-based Composite Parameters and Extensigraph Parameters.

Extensigraph Parameter (70g)[2]	Composite Parameter[3]			
	CT	GT	AT1	AT2
RM1	0.79***	-0.66*	0.75**	0.18
E1	0.35	-0.04	-0.18	-0.66*
A1	0.78***	-0.61*	0.69*	0.07
R1	0.76**	-0.69**	0.82***	0.35
RM2	0.77***	-0.61*	0.70**	0.12
E2	-0.15	0.35	-0.72**	-0.71**
A2	0.79***	-0.57	0.59*	-0.00
R2	0.73**	-0.63*	0.79***	0.25
RM3	0.77***	-0.59*	0.68*	0.08
E3	-0.29	0.44	-0.57	-0.59*
A3	0.76**	-0.56	0.64*	0.03
R3	0.78***	-0.63*	0.72**	0.15

[1] Statistically significant at *P=0.01, **P=0.001, ***P=0.0001.

[2] RM1 = maximum resistance to extension at 45 min (EU); E1 = extensibility at 45 min (cm); A1 = area under the extensigram at 45 min (cm^2); R1 = ratio of maximum resistance to extensibility at 45 min; RM2 = maximum resistance to extension at 90 min (EU); E2 = extensibility at 90 min (cm); A2 = area under the extensigram at 90 min (cm^2); R2 = ratio of maximum resistance to extensibility at 90 min; RM3 = maximum resistance to extension at 135 min (EU); E3 = extensibility at 135 min (cm); A3 = area under the extensigram at 135 min (cm^2); R3 = ratio of maximum resistance to extensibility at 135 min.

[3] CT = tension work ratio (N); GT = tension wok ratio times tension peak force of the first cycle (N); AT1 = average tension force of the first cycle (N); AT2 = average tension force of the second cycle.

Table 36. Matrix of Pearson Correlation Coefficients[1] describing Relationships between Dough Profiling Compression Parameters and Extensigraph Parameters.

Extensigraph Parameter (70g)[2]	Compression Parameter[3]			
	CF1	CW1	CF2	CW2
RM1	0.54	0.52	0.03	-0.50
E1	-0.42	-0.46	-0.42	-0.54
A1	0.46	0.43	-0.01	-0.53
R1	0.66*	0.65*	0.12	-0.41
RM2	0.47	0.44	-0.04	-0.56
E2	-0.80***	-0.82***	-0.49	-0.22
A2	0.35	0.32	-0.14	-0.63*
R2	0.58*	0.57	0.07	-0.47
RM3	0.42	0.40	-0.09	-0.59*
E3	-0.70**	-0.71**	-0.31	-0.09
A3	0.37	0.34	-0.11	-0.61*
R3	0.49	0.47	-0.05	-0.55

[1] Statistically significant at *P=0.01, **P=0.001, ***P=0.0001.

[2] RM1 = maximum resistance to extension at 45 min (EU); E1 = extensibility at 45 min (cm); A1 = area under the extensigram at 45 min (cm^2); R1 = ratio of maximum resistance to extensibility at 45 min; RM2 = maximum resistance to extension at 90 min (EU); E2 = extensibility at 90 min (cm); A2 = area under the extensigram at 90 min (cm^2); R2 = ratio of maximum resistance to extensibility at 90 min; RM3 = maximum resistance to extension at 135 min (EU); E3 = extensibility at 135 min (cm); A3 = area under the extensigram at 135 min (cm^2); R3 = ratio of maximum resistance to extensibility at 135 min.

[3] CF1 = compression peak force of the first cycle (N); CW1 = compression work of the first cycle (N.mm); CF2 = compression peak force of the second cycle (N); CW2 = compression work of the second cycle (N).

ratio and maximum resistance to extension at 45, 90 and 135 min rest time were 0.89, 0.87 and 0.85, respectively. Relaxation ratio of the second cycle (M2) was also correlated with maximum resistance to extension at 45, 90 and 135 min rest time (r = 0.79, 0.74 and 0.72, respectively) (Table 32). Tension work of the first cycle (TW1) was also correlated with maximum resistance to extension (Table 33). The r values for correlations between tension work and maximum resistance to extension at 45, 90 and 135 minutes were -0.76, -0.78 and -0.77, respectively.

Extensigraph area and ratio were also highly correlated with relaxation ratio (M1) for all three rest periods (r > 0.81) (Table 31). Since the maximum resistance to extension, area and ratio were so highly correlated for this data set, this result would follow.

The compression based composite parameter cohesiveness (CC) was highly correlated with the ratio of maximum resistance to extensibility (Table 34). The r values for correlations between CC and ratio at 45, 90 and 135 min rest time were -0.84, -0.80 and -0.77 respectively. The tension based composite parameter tension work ratio (CT) was highly correlated with extensigraph area values (Table 35). The r values for correlations between CT and area at 45, 90 and 135 min rest time were 0.78, 0.79 and 0.76 respectively. Extensigraph extensibility was correlated with compression peak force (CF1) and compression work (CW1) at 90 and 135 minutes (r = -0.70 - -0.82) (Table 36).

The high correlation coefficients indicated that dough profiling relaxation and tension parameters were better indicators of dough strength than compression parameters. The relaxation parameters can give an excellent indication of dough strength as measured by extensigraph maximum resistance to extension, area and ratio. The compression parameters are a good indicator of extensibility.

Model Building

The high correlations between certain dough profiling parameters and extensigraph values described in the previous section suggested that some parameters could be useful for predictive purposes. These parameters were used to generate regression models to predict various extensigraph parameters.

Several dough profiling parameters were eliminated prior to the R-square selection procedure. Stringiness values and three composite parameters based on tension measurements, GT, AT1 and AT2, were eliminated due to their overall higher CV's. Compression based composite parameters GC, AC1 and AC2 were eliminated because they were not highly correlated with extensigraph parameters.

The R-square variable selection method (SAS, 1991) was used to develop regression models for extensigraph parameters. The R-square method uses the Mallows C(*p*) statistic criterion which measures the total mean squared error for a subset model containing *p* independent variables (SAS, 1991). C(*p*) values that are larger than *p* indicate that important variables have been excluded, while C(*p*) values less than *p* indicate that the model contains too many variables. Models where C(*p*) is close *p* indicate that bias is small. For each of the extensigraph parameters, the four 'best' models, or those with the smallest error mean square, were generated.

Regression models for maximum resistance to extension are shown in Table 37. Relaxation ratio (M1) explained 75% of the variation in maximum resistance to extension but the large C(*p*) value (60) clearly indicated that important variables had been omitted from the model (Figure 32). A seven variable model appeared to be the best choice since this was the point where C(*p*) was close to *p* (Figure 32) and inclusion of additional variables did not substantially improve

Table 37. Models for Determining Extensigraph Maximum Resistance to Extension Based on Dough Profiling Parameters.

Number of variables in the model	R-square	C(p)	Variables in the model[1]
1	0.75	60	M1
2	0.81	39	TF1 M1
3	0.86	23	TW1 R1 K2
4	0.89	13	TW1 R1 K2 CT
5	0.90	10	M1 K1 TW2 K2 CT
6	0.91	9	RF1 TF1 M1 CF2 RF2 R2
7*	**0.92**	**7**	**TF1 CW1 M1 K1 CF2 RF2 R2**
7	0.92	8	TF1 M1 K1 CF2 RF2 R2 CC
7	0.92	8	TF1 TW1 M1 K1 R1 M2 K2
7	0.92	9	CF1 TF1 M1 K1 CF2 RF2 R2
18	0.95	19	CF1 RF1 TF1 CW1 TW1 R1 M1 K1 CF2 RF2 TF2 CW2 TW2 R2 M2 K2 CC CT

[1] CF1 = compression peak force of the first cycle (N); TF1 = tension peak force of the first cycle (N); CW1 = compression work of the first cycle (N.mm); TW1 = tension work of the first cycle (N.mm); R1 = relaxation degree of the first cycle; M1 = relaxation ratio of the first cycle; K1 = relaxation index of the first cycle; RF1 = relaxation end force of the first cycle (N); CF2 = compression peak force of the second cycle (N); TF2 = tension peak force of the second cycle (N); CW2 = compression work of the second cycle (N.mm); TW2 = tension work of the second cycle (N.mm); R2 = relaxation degree of the second cycle; M2 = relaxation ratio of the second cycle; K2 = relaxation index of the second cycle; RF2 = relaxation end force of the second cycle (N); CC = cohesiveness (N); CT = tension work ratio (N).

* Best model.

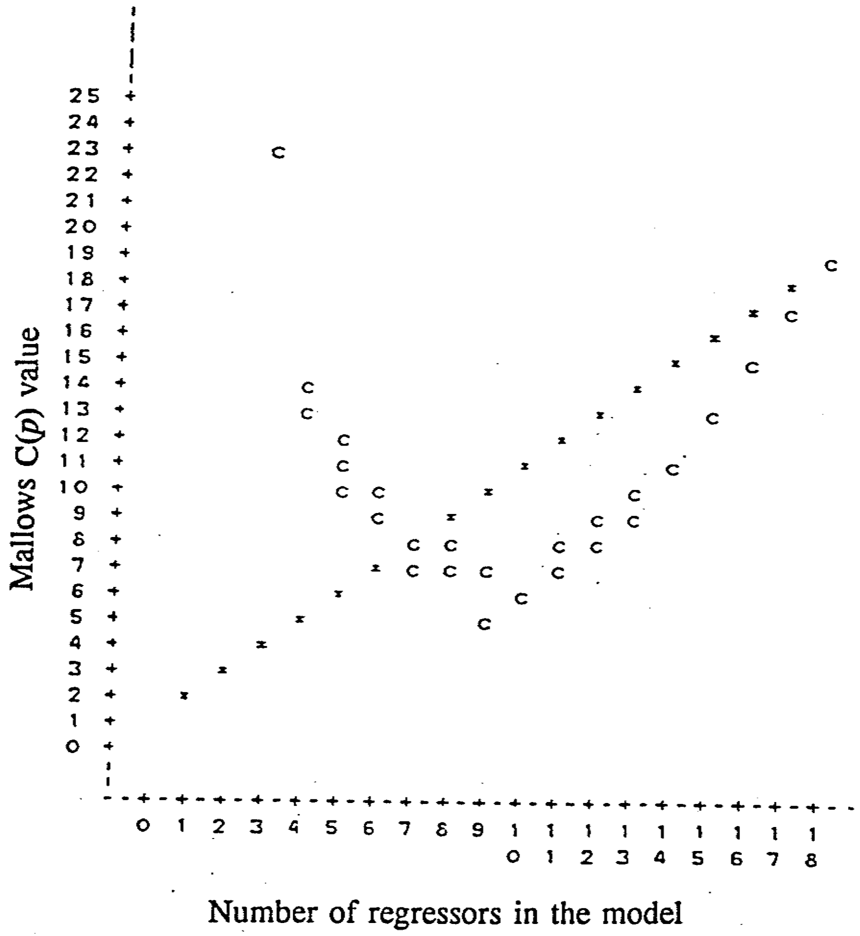


Figure 32. Plot of Mallow's C(*p*) statistic versus the number of variables in the model for determining extensigraph maximum resistance to extension from dough profiling parameters.

the R-square value. Each of the four 'best' seven variable models explained 92% of the variation in maximum resistance to extension and were dominated by relaxation parameters. Four variables appeared in all four 'best' models, three relaxation, M1, K1 and R2, and one tension, TF1. All four models included parameters from the first and second cycle of the dough profiling curve, indicating that both cycles are necessary for characterizing dough strength. In addition, the C(*p*) values for all four 'best' models were very similar, indicating that multicollinearity allows for interchange of variables without seriously affecting the fit of the model. When 18 variables were in the model, 95% of the variation in the dependant variable was explained.

Regression models for extensigraph area are shown in Table 38. A six variable model was appeared to be the best choice (Table 38) (Figure 33). All four 'best' models were dominated by relaxation parameters and contained parameters from both cycles of the dough profiling curve. Two variables, M1 and TF1, were common to all four models. One model was chosen above the others because of the slightly higher R-square and lower C(*p*) values associated with it. This model included four relaxation parameters, M1, RF1, RF2 and R2, one tension parameter, TF1, and one compression parameter, CF2.

Regression models for ratio of maximum resistance to extensibility are shown in Table 39. Results were similar to those observed for maximum resistance and area (Figure 34). Each of the four six variable models included at least 3 relaxation variables and parameters from both cycles of the dough profiling curve. The model with five relaxation variables, M1, K1, R2, M2, K2 and one tension variable, TW1 was selected because the other three 'best' models included the tension parameter TW2 which had a higher degree of variability associated with it.

Table 38. Models for Determining Extensigraph Area Based on Dough Profiling Parameters.

Number of variables in the model	R-square	C(p)	Variables in the model[1]
1	0.68	52	M1
2	0.78	28	TF1 M1
3	0.82	18	TF1 M1 K2
4	0.85	12	TF1 M1 K2 CC
5	0.86	10	TW1 R1 TF2 K2 CT
6*	**0.89**	**6**	**RF1 TF1 M1 CF2 RF2 R2**
6	0.88	8	RF1 TF1 M1 R2 M2 K2
6	0.88	8	CF1 TF1 M1 R2 M2 K2
6	0.88	8	RF1 TF1 M1 CF2 RF2 CW2
18	0.93	19	CF1 RF1 TF1 CW1 TW1 R1 M1 K1 CF2 RF2 TF2 CW2 TW2 R2 M2 K2 CC CT

[1] CF1 = compression peak force of the first cycle (N); TF1 = tension peak force of the first cycle (N); CW1 = compression work of the first cycle (N.mm); TW1 = tension work of the first cycle (N.mm); R1 = relaxation degree of the first cycle; M1 = relaxation ratio of the first cycle; K1 = relaxation index of the first cycle; RF1 = relaxation end force of the first cycle (N); CF2 = compression peak force of the second cycle (N); TF2 = tension peak force of the second cycle (N); CW2 = compression work of the second cycle (N.mm); TW2 = tension work of the second cycle (N.mm); R2 = relaxation degree of the second cycle; M2 = relaxation ratio of the second cycle; K2 = relaxation index of the second cycle; RF2 = relaxation end force of the second cycle (N); CC = cohesiveness (N); CT = tension work ratio (N).

* Best model.

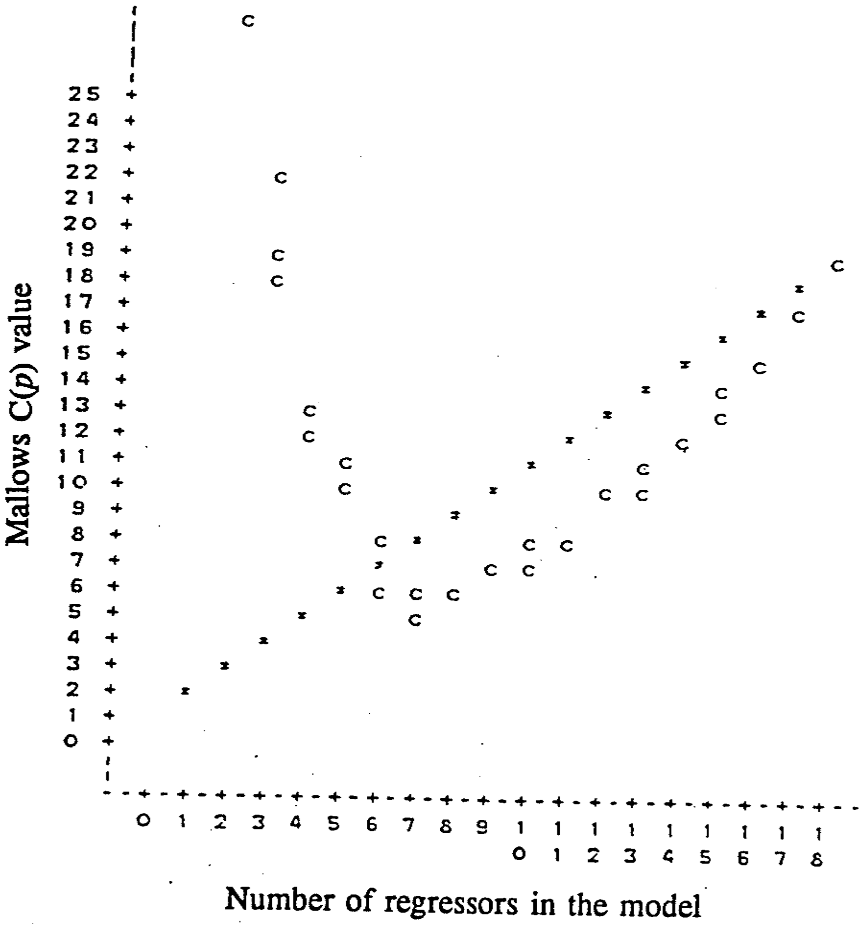


Figure 33. Plot of Mallow's C(p) statistic versus the number of variables in the model for determining extensigraph area from dough profiling parameters.

Table 39. Models for Determining Extensigraph Ratio of Maximum Resistance to Extensibility Based on Dough Profiling Parameters.

Number of variables in the model	R-square	C(p)	Variable in the model[1]
1	0.77	25	M1
2	0.81	16	M1 K1
3	0.85	9	TW1 R1 K2
4	0.86	6	TW1 R1 K2 CT
5	0.87	6	CW1 TW1 R1 K2 CT
6*	**0.88**	**6**	**TW1 M1 K1 R2 M2 K2**
6	0.88	6	RF1 CW1 R1 TW2 K2 CT
6	0.88	6	CW1 M1 K1 TW2 K2 CT
6	0.88	6	M1 K1 TW2 R2 K2 CT
18	0.92	19	CF1 RF1 TF1 CW1 TW1 R1 M1 K1 CF2 RF2 TF2 CW2 TW2 R2 M2 K2 CC CT

[1] CF1 = compression peak force of the first cycle (N); TF1 = tension peak force of the first cycle (N); CW1 = compression work of the first cycle (N.mm); TW1 = tension work of the first cycle (N.mm); R1 = relaxation degree of the first cycle; M1 = relaxation ratio of the first cycle; K1 = relaxation index of the first cycle; RF1 = relaxation end force of the first cycle (N); CF2 = compression peak force of the second cycle (N); TF2 = tension peak force of the second cycle (N); CW2 = compression work of the second cycle (N.mm); TW2 = tension work of the second cycle (N.mm); R2 = relaxation degree of the second cycle; M2 = relaxation ratio of the second cycle; K2 = relaxation index of the second cycle; RF2 = relaxation end force of the second cycle (N); CC = cohesiveness (N); CT = tension work ratio (N).

* Best model.

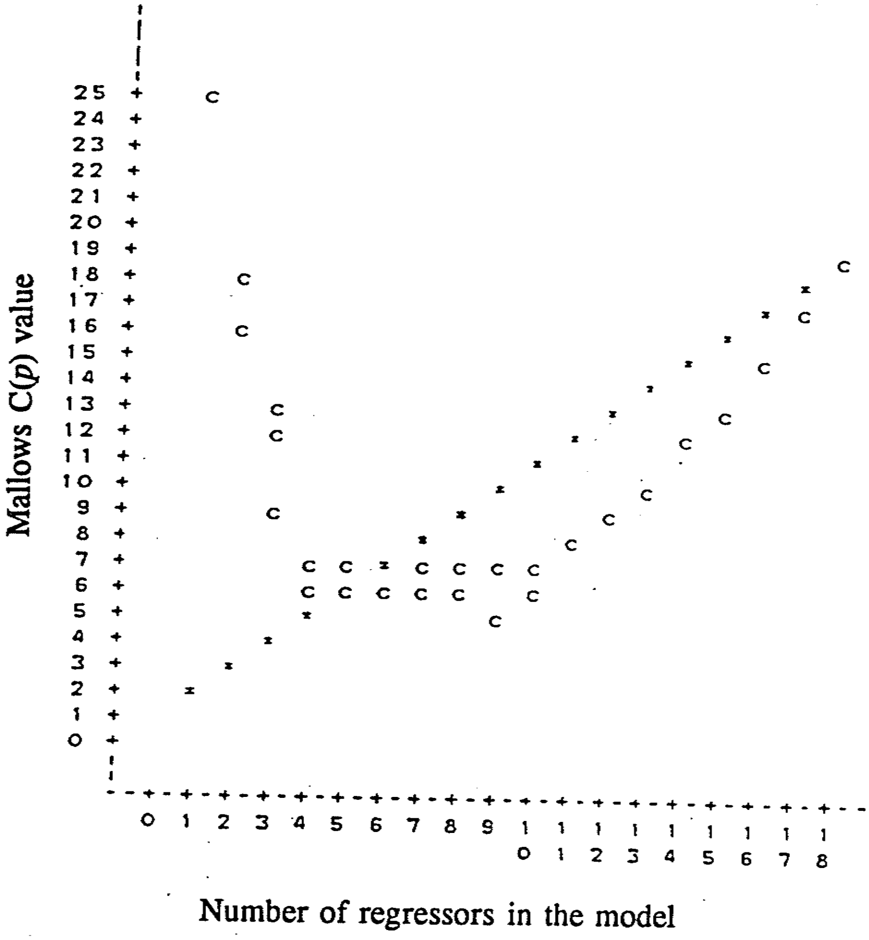


Figure 34. Plot of Mallow's C(*p*) statistic versus the number of variables in the model for determining extensigraph ratio of maximum resistance to extensibility from dough profiling parameters.

Extensibility is not considered to be a measure of dough strength but the R-square selection method was applied to determine the dough profiling variables considered most important for the prediction of extensibility (Table 40). A model with all 18 variables explained only 74% of the variation in extensibility. A four variable model appeared to be the best choice based on the C(*p*) criterion (Figure 35), although the corresponding R-square value was low (0.58). All four best models were dominated by compression or compression-based parameters. Extensibility was highly negatively correlated with CF1 and CW1 (Table 36) and therefore it seems likely that as the force required to compress the dough decreases, extensibility increases.

In general, the regression models for maximum resistance to extension, area and ratio were dominated by relaxation and tension variables. Two relaxation variables, M1 and R2 were common to the selected models for maximum resistance, area and ratio. The models for maximum resistance, area and ratio were similar, likely because maximum resistance to extension, area and ratio were highly correlated for this data set.

Table 40. Models for Determining Extensigraph Extensibility Based on Dough Profiling Parameters.

Number of variables in the model	R-square	C(p)	Variables in the model[1]
1	0.30	18	TF1
2	0.39	13	TF1 K2
3	0.50	7	TF2 K2 CT
4*	**0.58**	**3**	**CF1 M1 CF2 CW2**
4	0.56	4	CW1 M1 CF2 CW2
4	0.56	5	M1 CF2 CW2 CC
4	0.55	5	CF1 TF1 CF2 CW2
18	0.74	19	CF1 RF1 TF1 CW1 TW1 R1 M1 K1 CF2 RF2 TF2 CW2 TW2 R2 M2 K2 CC CT

[1] CF1 = compression peak force of the first cycle (N); TF1 = tension peak force of the first cycle (N); CW1 = compression work of the first cycle (N.mm); TW1 = tension work of the first cycle (N.mm); R1 = relaxation degree of the first cycle; M1 = relaxation ratio of the first cycle; K1 = relaxation index of the first cycle; RF1 = relaxation end force of the first cycle (N); CF2 = compression peak force of the second cycle (N); TF2 = tension peak force of the second cycle (N); CW2 = compression work of the second cycle (N.mm); TW2 = tension work of the second cycle (N.mm); R2 = relaxation degree of the second cycle; M2 = relaxation ratio of the second cycle; K2 = relaxation index of the second cycle; RF2 = relaxation end force of the second cycle (N); CC = cohesiveness (N); CT = tension work ratio (N).

* Best model.

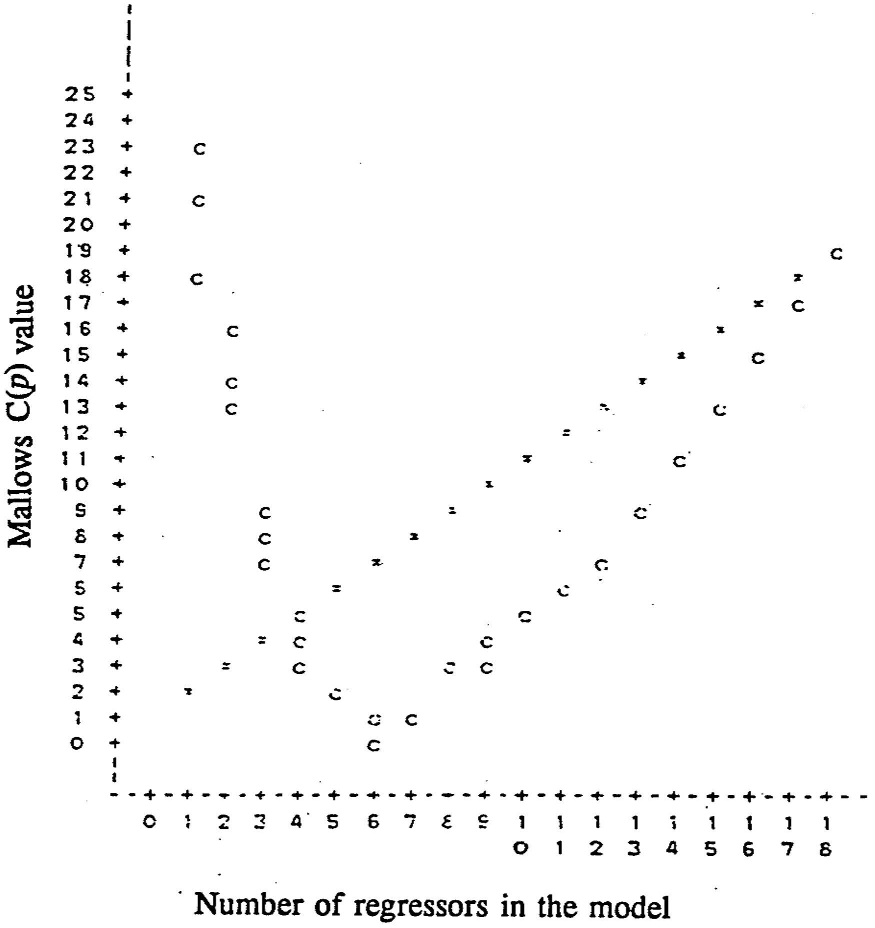


Figure 35. Plot of Mallow's C(p) statistic versus the number of variables in the model for determining extensigraph extensibility from dough profiling parameters.

Chapter 5

GENERAL DISCUSSION

The principal objective of the first part of this work was to determine the relationships between dough profiling parameters and standard physical dough testing parameters through the analysis of rheological data and dough profiling values of a set of bread wheat flours. The high correlations between the dough profiling parameters, particularly the relaxation parameters, and extensigraph parameters indicated that it would be useful to investigate the potential of the dough profiling method to measure dough strength. The principal objective of the second part of this work was to test the hypothesis that dough profiling parameters could be used to measure dough strength, as determined by the extensigraph. In order to allow evaluation of the dough profiling method for measuring dough strength, the method of dough preparation was carefully controlled. Doughs for the extensigraph testing were mixed to peak development time in the farinograph, which allowed comparison of optimally mixed doughs. Doughs for the dough profiling tests included 2% salt (based on flour weight), to ensure that the dough formula was identical for the two tests.

Dough strength reflects the fundamental rheological properties of elasticity and viscosity and both the viscous and elastic components are important for baking quality (Abdelrahman and Spies, 1986). However, measurements of the rheological properties of wheat flour doughs have been mostly empirical in nature due to the time and effort required to obtain fundamental data (Weipert, 1990). The extensigraph has been a widely used instrument for determining the visco-elastic properties of doughs and properties measured more closely approach actual fundamental properties than do those of any other quality testing instrument. When tested with the extensigraph, doughs for breadmaking should have relatively high resistance to extension and good extensibility. These measurements represent elastic and viscous elements respectively. Two dough profiling parameters, relaxation ratio (M) and relaxation index (K), appear to measure dough viscoelasticity. The relaxation index (K) appears to be closely related to dough viscosity while the relaxation ratio (M) appears closely related to dough elasticity. The relaxation index approaches zero and the relaxation ratio approaches one with greater dough strength, while K approaches one and M approaches zero for weaker doughs.

In this study, as shown in Table 41, the CWES dough showed high resistance to extension but had low extensibility relative to resistance, while dough profiling results showed that the CWES dough had a low K value, but a high M value. The CWRS dough showed moderately high maximum resistance to extension and moderately high extensibility and had an intermediate K value and an intermediate M value. The CPS dough showed moderately low maximum resistance relative to extensibility, but had a high K value and an intermediate M value. The SWS dough lacked resistance to extension but had high extensibility and a high K value and a low M value.

The dough profiling relaxation ratio (M) values are parallel to the extensigraph maximum resistance values. For very weak flours (SWS) and very strong flours (CWES), the relaxation values (K) appears to indicate extensigraph extensibility. However, extensigraph extensibility measures both the ability of the dough to extend and resist breaking. It combines both flow characteristics and cohesive properties of the flour. Relaxation index values (K) measure the tendency of the dough to flow under compression and measures only the flow properties of the dough. We hypothesize that the relaxation index is a better indicator of fundamental viscosity than extensigraph extensibility.

It is the balance between the viscous and elastic components, as well as their extent, that characterize a good flour for bread making. A hypothetical representation of the extensigraph properties for CWES, CWRS, CPS and SWS flours is shown in Table 42. The CWES flours have a high resistance to extension, but coupled with the relatively low extensibility, do not produce good loaf volumes because the elastic component is predominant. CWRS flours are well known for their excellent baking quality. The balance between the viscous and elastic components allows dough to expand and retain gas during the bread making process and yet flow to allow the dough to fill the pan. The CPS flour, though having balanced characteristics, has lower levels of both components resulting in normally poorer bread making performance than CWRS flour. The SWS flour is very low in the elastic component, which results in doughs collapsing and limits their ability to retain gas, characteristics that are essential for good loaf volume production.

CWES flours have commonly been used as blending flours with weaker flours, such as CPS flour, to improve dough strength. The CWES doughs exhibit high resistance to extension but lack extensibility. The extensigraph curves for the base flours and blends were re-examined to determine which blend most closely approximated the extensigraph curves obtained for CWRS dough. The extensigraph curve for the CWRS dough at 90 min was nearly super-imposable with that for the CWES/SWS 75/25 blend at 90 min (Figure 36). Perhaps this is an indication that CWES should be blended with weaker wheats like the SWS, as the additional viscous component is essential for obtaining a proper balance of the viscoelastic properties.

Both the extensigraph and the dough profiling technique yield empirical measurements, but are measuring similar underlying fundamental properties. It would be interesting to be able to relate these methods to fundamental tests of elasticity and viscosity.

Table 41. Indicators of Elasticity and Viscosity for the Four Base Flours.

Dough	Indicators of elasticity		Indicators of viscosity	
	Extensigraph maximum resistance to extension (EU)	Dough profiling relaxation ratio (M)	Extensigraph extensibility (cm)	Dough profiling relaxation index (K)
CWES	655	0.30	19.3	-0.29
CWRS	420	0.26	15.5	-0.22
CPS	275	0.24	19.0	-0.29
SWS	125	0.12	18.3	-0.17

Table 42. Hypothetical Representation of the Balance Between Maximum Resistance to Extension and Extensibility.

Dough	Maximum resistance to extension	Extensibility
CWES	****	*
CWRS	***	**
CPS	**	*
SWS	*	***

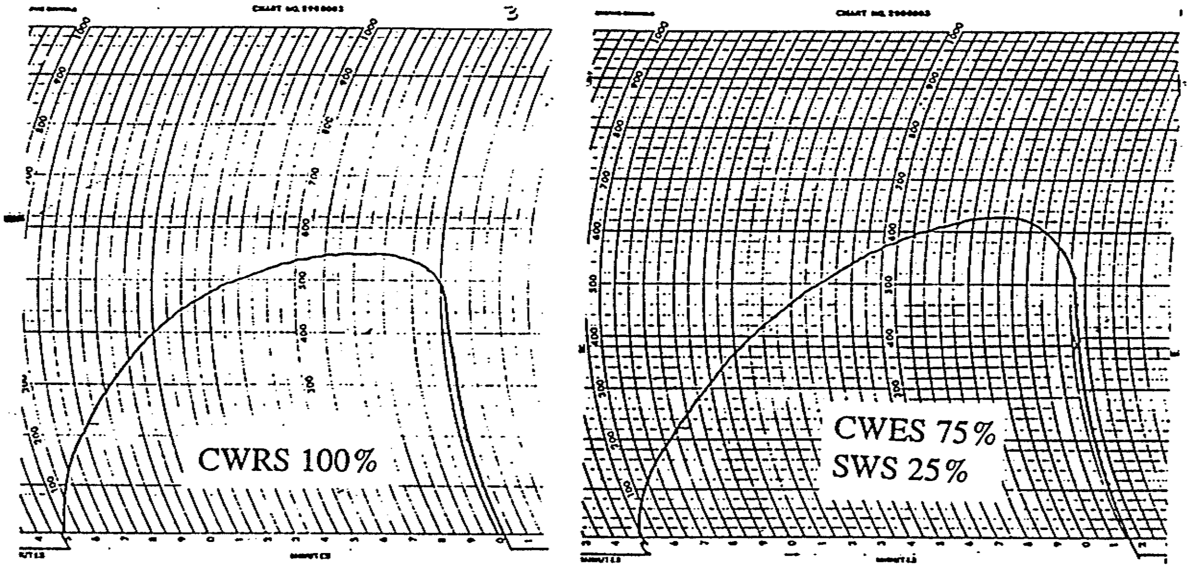


Figure 36. Extensigraph curves for the CWRS dough and the CWES/SWS 75/25 blend at 90 minutes.

Chapter 6

CONCLUSIONS

The purpose of this study was to evaluate the potential usefulness of dough profiling to measure dough strength. Quality testing is important in wheat breeding programs to identify properties of wheat flour and dough and quality control applications. Instruments such as the mixograph, farinograph and extensigraph have been developed to measure the physical properties of dough at various stages of the bread making process. These instruments have not been adequate to fully characterize dough properties. In addition, the tests are often time-consuming to conduct and require large sample sizes, which make them impractical for routine use in quality control and in wheat breeding programs. Texture profile analysis has been successfully applied to characterize the textural properties of many food products. One advantage associated with texture profile analysis is that it provides a multi-point measure of many of the properties which are important to that food product.

Secondary data analysis was conducted on a set of bread wheat lines to determine the relationship of dough profiling parameters and traditional quality test parameters. High correlations were found between dough profiling relaxation parameters and extensigraph parameters. Dough profiling tension parameters were correlated with mixograph parameters. Canonical correlation analysis was used to further examine the relationship between dough profiling parameters and extensigraph parameters. The dough profiling parameters relaxation degree and relaxation index were found to be important in the prediction of extensigraph maximum resistance to extension and ratio of maximum resistance to extensibility.

In the experimental study conducted using CWES, CWRS, CPS and SWS flours, extensigraph data were obtained using a 150 g sample, as well as a 70 g sample. High correlations between the values obtained for the 70 g sample size and 150 g sample size indicate that the small-scale extensigraph procedure provides comparable results to that of the standard method.

Large differences in extensigraph properties were evident between the four base flours. The CWES flour had the highest values for maximum resistance to extension, area and ratio but intermediate values for extensibility at all rest times. The CWRS flours had the next highest values for maximum resistance to extension, area and ratio, but the lowest extensibility at all rest times. The CPS flour had the next highest values for maximum resistance to extension, area and ratio, and intermediate values for extensibility at all rest times. The SWS flour had the lowest values for maximum resistance to extension, area and ratio and the highest values for extensibility at all rest times. As the amount of the stronger flour was increased in the blend, maximum resistance to extension, area and ratio values increased.

Large differences in dough profiling properties were evident between the four base flours. Compression values were highest for the CWES and CWRS doughs and lowest for the SWS doughs. Tension work values were lowest for the CWES and CWRS doughs and highest for the SWS doughs. Relaxation ratio values were highest for the CWES doughs and lowest for the SWS doughs, while relaxation index and relaxation degree values were highest for the SWS doughs and lowest for the CWES and CWRS doughs. Increasing proportions of the CWES and CWRS flours in blends with CPS and SWS flours resulted in increasing values for compression parameters and relaxation ratio values, and decreasing values for tension parameters, and relaxation index values.

Dough profiling relaxation parameters were highly correlated with extensigraph maximum resistance to extension, area and ratio of maximum resistance to extensibility. Dough profiling compression parameters were correlated with extensigraph extensibility.

The high correlations between dough profiling relaxation parameters and extensigraph parameters suggested that some parameters could be useful for predictive purposes. Regression models were developed to predict extensigraph parameters. The best regression models for maximum resistance to extension, area and ratio of maximum resistance to extensibility all had R^2 values > 0.88. The models were dominated by relaxation and tension parameters and two relaxation variables, relaxation ratio and relaxation degree were common to all models.

Chapter 7

RECOMMENDATIONS FOR FUTURE RESEARCH

1. The dough profiling method has been shown to discriminate between doughs differing widely in strength. The flour samples used in this study represented a wide range of properties and wheat classes and it would be useful to determine whether the method is as effective for differentiating between doughs prepared with flours from the same wheat class.

2. This study has demonstrated the potential for the application of dough profiling to study dough rheological properties. Quality testing and quality control are two areas in which dough profiling has potential for routine use as it fulfils the criteria necessary for rapid screening. To further investigate its usefulness in both quality testing and quality control, samples should be profiled and subjected to the baking test to determine if dough profiling is more useful in predicting baking quality than traditional physical dough testing methods.

3. Dough profiling is an empirical testing method and does not describe the fundamental rheological properties of elasticity and viscosity. It would be worthwhile to investigate the relationship between data obtained with the dough profiling method and that determined by a fundamental rheological testing method.

4. The dough profiling technique is a rapid method that could be used to evaluate the effects of additives such as oxidizing agents and enzymes on dough properties.

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APPENDIX I

FARINOGRAPH CONSTANT FLOUR WEIGHT PROCEDURE.

Preparation

1. Calculate amount of flour based on moisture content.
2. Turn water bath to 'on' position, temperature should be 30±0.1°C.
3. Clean farinograph bowl and blades with distilled water and dry thoroughly.
4. Enter sample numbers and estimated water absorption into acquisition computer.

Farinograph titration

1. Switch farinograph to computer mode.
2. Fill 30 ml self-leveling buret with distilled water.
3. Weigh 50 g flour (14% mb) and add to mixing bowl.
4. Calibrate chart pen. 500 on gauge=500 units on the chart paper.
5. Select the farinograph channel on the selector module.
6. Press both buttons on the farinograph simultaneously to start the mixer.
7. Immediately begin titrating distilled water in the front right corner of the bowl to the expected flour absorption. Quickly scrape the sides of the bowl with a plastic scraper starting at the right front corner and moving counterclockwise. Cover mixing bowl with the plastic cover to prevent evaporation.
8. Observe the curve. If the curve includes the 500-BU line, water absorption can be adjusted; when curve is centred below the 500-BU line, subtract 0.4 ml for every 20 BU for hard wheat flours; when curve is centred above 500-BU line, add 0.4 ml for every 20 BU for hard wheat flours. (For soft wheat flours, adjust 0.3 ml for every 20 BU). If curve is not centred on the 500 BU line, stop the test and adjust the water absorption on the acquisition computer.
9. Switch to manual mode and clean farinograph bowl and blades.

Farinograph curve

1. Repeat above procedure except add all the titrating water within 30 seconds of opening the buret stopcock.
2. Farinograph automatically shuts off after 20 minutes.

Cleaning farinograph bowl and blades

1. Add approximately 15 ml of 0.5% salt solution and approximately 30 ml bulk flour to the

farinograph bowl.

2. Switch to manual mode and lift chart pen from paper.
3. Run the farinograph for approximately 2 minutes and take out approximately half of the dough. Scrape the sides of the farinograph bowl.
4. Run the farinograph for another 1½-2 minutes. Take out the remaining dough.
5. Scrape off adhering dough with plastic. Clean farinograph blades, back and bowl with a damp cloth.
6. Rinse the blades and bowl with distilled water and dry well.

Reference method: AACC Method 54-21, 1983

APPENDIX II

EXTENSIGRAPH PROCEDURE.

150 g Sample Size

Preparation

Evening prior to testing:

1. Weigh 300 g flour (14% mb) and place in labelled air-tight containers.
2. Calculate amount of water based on farinograph water absorption.
3. Prepare 4% salt solution by dissolving 40 g NaCl into 1000 ml distilled water (150 ml delivers 6 g salt).

Morning of testing:

1. Turn extensigraph waterbath and farinograph waterbath switches to 'on' position; should be at 30±0.1°C.
2. Place approximately 80 ml distilled water in extensigraph trays and place in humidity cabinets.
3. Have scale, dusting flour and a knife ready.
4. Clean farinograph blades and bowl with distilled water and dry thoroughly.
5. Calibrate farinograph by adjusting the balance weights so the scale head pointer shows zero while the farinograph is running at high speed with the mixing bowl empty.
6. Calibrate extensigraph by placing dough holder and clamps plus 150 g weight on the extensigraph balance arm. Adjust position of pen to the zero line.
7. Rinse burets with distilled water.

Dough preparation

1. Fill 250 ml buret with 4% salt solution; fill 50 ml buret with distilled water and level.
2. Place 300 g flour (14% mb) in the large farinograph bowl.
3. Set chart paper on either 0 or 5 minute mark (to facilitate ease of curve interpretation).
4. Position the buret with the salt solution in the right front corner of the farinograph bowl.
5. Start farinograph and chart paper simultaneously.
6. Start stop watch and immediately titrate 150 ml salt solution and enough distilled water to equal farinograph water absorption. Quickly scrape the sides of the bowl with a plastic scraper starting at the right front corner and moving counterclockwise. Cover mixing bowl with plastic cover to prevent evaporation.
7. At 1 minute, stop the farinograph and chart paper. Rest for 5 minutes.

8. After 5 minutes, start farinograph and chart paper simultaneously.
9. Mix dough to optimum development.

Test piece preparation

1. Remove dough from the mixing bowl and round in hands 7 times.
2. Scale off 150±0.05 g dough, round and mould into a cylindrical test piece.
3. Clamp piece into dough holders which have been lightly sprinkled with flour. Place in extensigraph humidified cabinet.
4. Repeat steps 2-3 with remaining dough.

Extensigraph test

1. Set extensigraph chart paper at either 0 or 5 cm mark and label with sample name and rest period.
2. After a 45 minute rest period, remove dough holder from cabinet and place on balance arm of the extensigraph.
3. Start the hook and stretch the dough piece until it breaks. Return hook to 'start' position.
4. Re-round and re-mould the dough, clamp into dough holders and return test piece to the humidifying cabinet for additional 45 minute rest period.
5. Repeat steps 2-4 after 90 and 135 minutes rest time.

70 g Sample Size

Use of the 70 g sample size required the following modifications:

1. Prepare 8% salt solution by dissolving 80 g NaCl into 1000 ml distilled water (12.5 ml delivers 1 g salt).
2. Weigh 50 g flour (14% mb) into the small (50 g) farinograph bowl.
3. Fill one 25 ml buret with 8% salt solution and one 25 ml buret with distilled water and level.
4. Titrate 12.5 ml of 8% salt solution.
5. Scale off 70 g dough and weight the extensigraph balance arm with 80 g.

NOTE: When changing the mixing bowls, several adjustments to the farinograph are required:

1. The linkage between the dynamometer lever arm at the top of the machine and the scale head lever arm below the base plate should be positioned toward the back of the machine (closest to the scale head) when the large bowl is used. This linkage should be in the position closest to the operator when the small bowl is used.

2. To adjust the position of the scale head pointer, the smaller of the two balance weights should be removed when using the small bowl.
3. To adjust band width, the dynamometer lever arm should be raised until the scale head pointer indicates 1000. When released, the pointer should drop to 100 within 0.6 to 0.8 seconds.

Reference method: AACC Method 54-10 (1983)

APPENDIX III

DOUGH PROFILING PROCEDURE.

Preparation

Evening prior to testing:

1. Calculate flour weight based on moisture content.
2. Calculate amount of water based on farinograph water absorption.
3. Calculate sample weight based on total dough weight.
4. Prepare 4% salt solution by dissolving 40 g NaCl into 1000 ml distilled water (17.5 ml delivers 0.7 g salt)

Morning of testing:

1. Program Materials Testing Machine for appropriate test settings. Conduct imitation test to ensure that proper settings have been selected.
2. Calibrate mixograph.
3. Assemble test cell for required sample height by positioning the wide slotted ring around the upper plate of the profiling cell. Place on scale and tare.

Dough preparation

1. Set timer to mixograph dough development time (MDT).
2. Weigh 35 g flour (14% mb) into 35 g mixograph bowl. Make well in flour.
3. Add appropriate amount of distilled water to flour well.
4. Use automatic dispenser to dispense 17.5 ml of 4% salt solution to flour well.
5. Immediately place bowl on mixograph platform, fix pins, lower mixing head and start chart paper.
6. When pen reaches horizontal line, start timer and mix dough to MDT.

Test piece preparation

1. Remove approximate portion of the dough and place on upper plate. Scale off until required amount of dough is achieved.
2. Fix dough to entire surface area of upper plate.
3. Place lower plate on the sample. Compress to preselected height and release for three seconds (to prevent stored energy). Position pins.
4. Invert cell, place on stand and secure with the cylindrical pin.

Dough profiling test

1. Place stand and test cell on MTM base plate.

2. Lower MTM crosshead to allow adapter to be attached to the upper plate with cylindrical pin.
3. Secure stand on base plate.
4. Gently remove flat pins (start with lower plate pins) to release the slotted ring.
5. Zero load and extension readings.
6. Perform test and save data.

Reference method: Wang et al, 1996

APPENDIX IV

MIXOGRAPH PROCEDURE.

35 g Bowl

Preparation

1. Calculate amount of flour based on moisture content.
2. Calculate amount of water based on farinograph water absorption.
3. Power 'on' mixograph at least 20 minutes prior to use.
4. Calibrate mixograph. Adjust 'zero' knob until pen reaches zero line. Attach a 500 g weight and adjust 'sensitivity' knob until pen reaches 50-unit line. Remove weight and readjust 'zero' knob if necessary.

Mixograph curve

1. Weigh 35 g flour (14% mb) and place in 35 g mixing bowl. Make well in the flour using small spoon.
2. Add appropriate amount of distilled water to well in flour.
3. Immediately place bowl on mixograph platform, fix pins in place, lower mixograph head and start chart paper.
4. When pen reaches horizontal line on chart paper, start timer and record mixogram for 15 minutes.

Cleaning

1. Fill mixograph bowl with warm water and allow to stand.
2. Clean mixograph pins thoroughly with damp towel and dry.
3. Clean mixograph bowl. Place in container filled with distilled water at room temperature for at least 5 minutes (to allow bowl to reach room temperature).
4. Dry bowl thoroughly prior to next sample.

Reference method: AACC Method 54-40A (1983)

APPENDIX V

Positioning of the Upper and Lower Plates within the Ring to Obtain a Range of Sample Heights.

Sample height (mm)	Positioning of the ring	Positioning of the upper and lower plates
	N1-N2[a]	n3+n4[b]
1.6	2	2
3.1	3	3
4.6	4	4
7.2	3	2
8.7	4	3
10.2	5	4
12.8	4	2
14.3	5	3
15.8	6	4
18.4	5	2
19.9	6	3
21.4	7	4
24.0	6	2
25.5	7	3
29.6	7	2

[a] Difference between slots on the ring.

[b] Difference between slots on the upper and lower plates.

APPENDIX VI

Sample Weights used for Dough Profiling Tests.

Sample	Flour Moisture (%)	Flour Weight (g)	FAB[1]	Total water (g)	Total dough weight[2] (g)	Sample weight for profiling[3] (g)
CWES	11.4	33.97	61.4	20.79	54.76	13.7
ES75HS25	11.8	34.13	62.2	21.07	55.20	13.8
ES50HS50	12.6	34.44	62.0	21.00	55.44	13.9
ES25HS75	13.3	34.72	62.0	21.00	55.72	13.9
CWRS	14.3	35.12	62.0	21.00	56.12	14.0
ES75CP25	11.5	34.01	62.4	21.14	55.15	13.8
ES50CP50	11.7	34.09	62.2	21.07	55.16	13.8
ES25CP75	11.8	34.13	61.8	20.93	55.06	13.8
CPS	11.9	34.17	61.6	20.86	55.03	13.8
ES75SW25	11.4	33.97	60.4	20.44	54.41	13.6
ES50SW50	11.7	34.09	58.2	19.67	53.76	13.4
ES25SW75	11.8	34.13	55.8	18.83	52.96	13.2
SWS	11.9	34.17	54.4	18.34	52.51	13.1
HS75CP25	13.5	34.80	61.0	20.65	55.45	13.9
HS50CP50	13.1	34.64	61.0	20.65	55.29	13.8
HS25CP75	12.6	34.44	61.2	20.72	55.16	13.8
HS75SW25	13.5	34.80	59.6	20.16	54.96	13.7
HS50SW50	12.9	34.56	57.4	19.39	53.95	13.5
HS25SW75	12.4	34.36	56.2	18.97	53.33	13.3

[1] FAB=Farinograph water absorption (%).

[2] Total dough weight=Flour weight + Total water.

[3] Sample weight for profiling=25% X Total dough weight.

APPENDIX VII

Pearson Correlation Coefficients Among the Dough Profiling Parameters

Table A-1. Matrix of Pearson Correlation Coefficients[1] Among Dough Profiling Parameters of the First Cycle.

First Cycle Parameter[2]	CF1	RF1	TF1	S1	CW1	TW1	R1	M1	K1
CF1	1.000								
RF1	0.93***	1.000							
TF1	-0.39	-0.11	1.000						
S1	-0.71**	-0.70**	-0.11	1.000					
CW1	0.99***	0.93***	-0.41	-0.69*	1.000				
TW1	-0.49	-0.53	-0.32	0.92***	-0.46	1.000			
R1	-0.74**	-0.94***	-0.19	0.65*	-0.75**	0.56	1.000		
M1	0.70**	0.80***	0.25	-0.89***	0.68*	-0.85***	-0.84***	1.000	
K1	-0.05	0.10	-0.08	0.58*	-0.02	0.64*	-0.16	-0.38	1.000

[1] Statistically significant at *P=0.01, **P=0.001, ***P=0.0001.

[2] CF1 = compression peak force (N); RF1 = relaxation end force (N); TF1 = tension peak force (N); CW1 = compression work (N.mm); TW1 = tension work (N.mm); S1 = stringiness (mm); R1 = relaxation degree; K1 = relaxation index; M1 = relaxation ratio.

Table A-2. Matrix of Pearson Correlation Coefficients[1] Among Dough Profiling Parameters of the Second Cycle.

Second Cycle Parameter[2]	CF2	RF2	TF2	S2	CW2	TW2	R2	M2	K2
CF2	1.000								
RF2	0.57	1.000							
TF2	-0.62*	-0.24	1.000						
S2	-0.40	-0.32	0.12	1.000					
CW2	0.75**	0.06	-0.47	-0.41	1.000				
TW2	-0.13	0.27	-0.04	0.71**	-0.41	1.000			
R2	-0.24	-0.92***	-0.03	0.22	0.29	-0.36	1.000		
M2	0.16	0.75**	0.06	-0.14	-0.32	0.27	-0.85***	1.000	
K2	0.16	0.76***	0.09	-0.28	-0.16	0.26	-0.78***	0.39	1.000

[1] Statistically significant at *P=0.01, **P=0.001, ***P=0.0001.

[2] CF2 = compression peak force (N); RF2 = relaxation end force (N); TF2 = tension peak force (N); CW2 = compression work (N.mm); TW2 = tension work (N.mm); S2 = springiness (mm); R2 = relaxation degree; K2 = relaxation index; M2 = relaxation ratio.

Table A-3. Matrix of Pearson Correlation Coefficients[1] Among Composite Dough Profiling Parameters.

Composite Parameter[2]	CC	GC	CT	GT	AC1	AC2	AT1	AT2
CC	1.000							
GC	0.344	1.000						
CT	-0.76**	-0.56	1.000					
GT	0.82***	0.29	-0.90***	1.000				
AC1	-0.77***	0.22	0.34	-0.62*	1.000			
AC2	0.38	0.98***	-0.62*	0.35	0.19	1.000		
AT1	-0.89***	-0.05	0.64*	-0.74**	0.81***	-0.08	1.000	
AT2	-0.53	0.25	0.09	-0.33	0.71**	0.27	0.60*	1.000

[1] Statistically significant at *P=0.01, **P=0.001, ***P=0.0001.

[2] CC = cohesiveness (N); GC = gumminess (N); CT = tension work ratio (N); GT = tension work ratio times tension peak force of the first cycle (N); AC1 = average compression force of the first cycle (N); AC2 = average compression force of the second cycle (N); AT1 = average tension force of the first cycle

Table A-4. Matrix of Pearson Correlation Coefficients[1] Between First Cycle Parameters and Second Cycle Parameters.

Second Cycle Parameters[3]	First Cycle Parameters[2]								
	CF1	RF1	TF1	S1	CW1	TW1	R1	M1	K1
CF2	0.68*	0.48	-0.68*	-0.35	0.67*	-0.09	-0.21	0.23	-0.12
RF2	0.84***	0.87***	-0.13	-0.69**	0.84***	-0.45	-0.81***	0.72**	-0.00
TF2	-0.44	-0.26	0.73**	-0.13	-0.45	-0.30	0.009	0.15	-0.28
S2	-0.37	-0.19	0.31	0.61*	-0.37	0.54	0.03	-0.30	0.61*
CW2	0.14	-0.11	-0.73**	0.06	0.15	0.25	0.36	-0.27	-0.20
TW2	0.13	-0.29	0.17	0.19	0.12	0.33	-0.37	0.09	0.56
R2	-0.69**	-0.83***	-0.19	0.70**	-0.69**	0.54	0.86***	-0.80***	0.01
M2	0.55	0.69**	0.41	-0.66*	0.53	-0.61*	-0.77***	0.81***	-0.16
K2	0.55	0.63*	-0.06	-0.55	0.56	-0.37	-0.64*	0.54	0.03

[1] Statistically significant at *P=0.01, **P=0.001, ***P=0.0001.

[2] CF1 = compression peak force (N); RF1 = relaxation end force (N); TF1 = tension peak force (N); CW1 = compression work (N.mm); TW1 = tension work (N.mm); S1 = stringiness (mm); R1 = relaxation degree; K1 = relaxation index; M1 = relaxation ratio.

[3] CF2 = compression peak force (N); RF2 = relaxation end force (N); TF2 = tension peak force (N); CW2 = compression work (N.mm); TW2 = tension work (N.mm); S2 = springiness (mm); R2 = relaxation degree; K2 = relaxation index; M2 = relaxation ratio.

Table A-5. Matrix of Pearson Correlation Coefficients[1] Between First Cycle Parameters and Composite Parameters.

Composite Parameters[3]	First Cycle Parameters[2]								
	CF1	RF1	TF1	S1	CW1	TW1	R1	M1	K1
CC	-0.85***	-0.92***	-0.04	0.74**	-0.84***	0.63*	0.89***	-0.82***	-0.01
GC	0.18	-0.10	-0.71**	-0.004	0.17	0.17	0.35	-0.22	-0.27
CT	0.48	0.67*	0.46	-0.52	0.45	-0.48	-0.79***	0.75**	0.04
GT	-0.71**	-0.80***	-0.03	0.51	-0.69**	0.36	0.79***	-0.71**	-0.10
AC1	0.95***	0.84***	-0.53	-0.60*	0.95***	-0.38	-0.62*	0.59*	-0.04
AC2	0.13	-0.12	-0.73**	0.06	0.15	0.25	0.36	-0.28	-0.20
AT1	0.90***	0.91***	-0.10	-0.79***	0.89***	-0.61*	-0.82***	0.80***	-0.09
AT2	0.70**	0.58*	-0.45	-0.51	0.73**	-0.25	-0.41	0.36	-0.05

[1] Statistically significant at *P=0.01, **P=0.001, ***P=0.0001.

[2] CF1 = compression peak force (N); RF1 = relaxation end force (N); TF1 = tension peak force (N); CW1 = compression work (N.mm); TW1 = tension work (N.mm); S1 = stringiness (mm); R1 = relaxation degree; K1 = relaxation index; M1 = relaxation ratio.

[3] CC = cohesiveness (N); GC = gumminess (N); CT = tension work ratio (N); GT = tension work ratio times tension peak force of the first cycle (N); AC1 = average compression force of the first cycle (N); AC2 = average compression force of the second cycle (N); AT1 = average tension force of the first cycle.

Table A-6. Matrix of Pearson Correlation Coefficients[1] Between Second Cycle Parameters and Composite Parameters.

Composite Parameters[3]	Second Cycle Parameters[2]								
	CF2	RF2	TF2	S2	CW2	TW2	R2	M2	K2
CC	-0.22	-0.76**	0.09	0.19	0.38	-0.29	0.81***	-0.69**	-0.64*
GC	0.79***	0.09	-0.45	-0.41	0.98***	-0.41	0.26	-0.28	-0.16
CT	-0.07	0.55	0.21	0.29	-0.62*	0.65*	-0.71**	0.70**	0.46
GT	-0.23	-0.69**	0.11	-0.19	0.35	-0.67*	0.73**	-0.59*	-0.58*
AC1	0.67*	0.74**	-0.60*	-0.38	0.19	0.08	-0.56	0.43	0.48
AC2	0.75**	0.06	-0.47	-0.41	1.00***	-0.41	0.29	-0.32	-0.16
AT1	0.50	0.77***	-0.21	-0.30	-0.08	0.17	-0.72**	0.65*	0.50
AT2	0.54	0.70**	-0.50	-0.67*	0.27	-0.02	-0.58*	0.36	0.57

[1] Statistically significant at *P=0.01, **P=0.001, ***P=0.0001.

[2] CF2 = compression peak force (N); RF2 = relaxation end force (N); TF2 = tension peak force (N); CW2 = compression work (N.mm); TW2 = tension work (N.mm); S2 = springiness (mm); R2 = relaxation degree; K2 = relaxation index; M2 = relaxation ratio.

[3] CC = cohesiveness (N); GC = gumminess (N); CT = tension work ratio (N); GT = tension work ratio times tension peak force of the first cycle (N); AC1 = average compression force of the first cycle (N); AC2 = average compression force of the second cycle (N); AT1 = average tension force of the first cycle.