MIXOGRAM PARAMETERS AND THEIR RELATIONSHIP TO BREAD WHEAT QUALITY CHARACTERISTICS

by

Christina Wilhelmina Miles

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Supervisor: **Prof. M.T. Labuschagne**
Co-supervisors: **Dr. W.M. Otto**
Dr. A. van Biljon

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LIST OF ABBREVIATIONS

AA	Ascending angle from beginning until 1 min before peak time
AACC	American Association of Cereal Chemists
ANOVA	Analysis of variance
AP	Area under curve from beginning until peak time
Ar	Arlington
A-1	Area under curve from beginning until 1 min before peak time
A+2	Area under curve from beginning until 2 min after peak time
Be	Bethlehem
BFLY	Break flour yield
℃	Degrees Celsius
Bo	Bothaville
cm	Centimetre
cm^3	Cubic centimeter
CO_2	Carbon dioxide
CV	Coefficient of variation
C76	Flour colour expressed on a 76% flour yield basis (corrected flour colour)
DA	Descending angle from peak time until 2 min after peak time
df	Degrees of freedom
DIAM	Kernel diameter
FABS	Farinogram water-absorption
FCL	Flour colour
FLN	Falling number
FLY	Flour yield
FPC	Flour protein content
g	Gram(s)
G X E	Genotype-environment interaction
GPC	Grain protein content
h	Hour(s)
HI	Hardness index
HLM	Hectolitre mass

HMW	High molecular weight
HMW-GS	High molecular weight glutenin subunits
J	Joule
kDa	Kilodalton
kg ha^{-1}	Kilogram per hectare
kg hl^{-1}	Kilogram per hectolitre
KJ	Kent Jones
LMW	Low molecular weight
LMW-GS	Low molecular weight glutenin subunits
L	Alveogram dough distensibility
LFV	Loaf volume
LFV12%	Loaf volume expressed on a 12% protein basis (corrected loaf volume)
m	Meter
MABS	Mixogram water-absorption
MAX	Maximum
m.b.	Moisture basis
min	Minute(s)
MIN	Minimum
ml	Millilitre
mm	Millimetre
MMW	Medium molecular weight
N	Nitrogen
NaCl	Sodium chloride
ns	Not significant
p	Probability
P	Alveogram dough stability
PH	Peak height
P/L	Alveogram configuration ratio, dough stability/distensibility ratio
PT	Peak time
PW	Peakwidth
r^2	Correlation coefficient
R^2	Coefficient of determination
s	Seconds

SAGL	South African Grain Laboratory
SD	Standard deviation
SDS	Sodium dodecyl sulphate sedimentation volume
SDS-PAGE	Sodium dodecyl sulphate polyacrylamide gel electrophoresis
STRENGTH	Alveogram dough strength
TA	Total area under midline curve
TH	Tailheight
TKM	Thousand kernel mass
TQ	Torque
TW	Tailwidth
VK	Vitreous kernels
vs	Versus
WGC	Wet gluten content
W	Alveogram W-value
WTC	Wheat Technical Committee
W-1	Area under curve from beginning until 1 minute before peak time
W+2	Area under curve from beginning until 2 minutes after peak time

CHAPTER 1

INTRODUCTION

Bread wheat (*Triticum aestivum*) or common wheat is one of the principal cereal crops (Hoseney, 1994; Cornell and Hoveling, 1998) being cultivated worldwide (Posner and Hibbs, 1997). Its economical importance in agriculture is because of its nutritive value as well as its unique proteins (Finney *et al*., 1987), being the storage proteins that are formed in the endosperm during the grain-filling period (Payne *et al.*, 1983). These unique proteins allow wheat flour to be utilised as bread, pasta, noodles, breakfast cereals, fermented drinks as well as in the starch and the gluten industry (Posner and Hibbs, 1997; Rakszegi *et al*., 2005; Neacşu *et al.*, 2009). In many countries though, high yielding bread wheat, which exhibits poor bread making quality, is still grown, although the focus on wheat production is shifting more towards end-use quality requirements (Dobraszczyk and Schofield, 2002).

South Africa's wheat industry has set up certain end-use release criteria regarding grain, milling, rheological and baking characteristics, which a new bread wheat cultivar has to comply with before being commercially released. These criteria include primary and secondary requirements, where fixed deviations are allowed when a potential new cultivar is compared with a biological standard. Primary requirements are not flexible and include: hectolitre mass, falling number, protein content, flour yield, flour colour (on a 76% flour yield basis), mixogram peak time, farinogram water-absorption, loaf volume, alveogram dough strength and alveogram stability/distensibility (P/L)-values. Secondary requirements are flexible and include thousand kernel mass, break flour yield, farinogram dough development time, farinogram dough stability, alveogram P-value and alveogram L-value. Furthermore, only medium hard to hard red wheat cultivars are allowed to be submitted for commercial release (SAGL, 2010).

Large sample sizes are required to perform all these laboratory analyses, but sufficient seed is only available when breeding lines are in the advanced

breeding stages. In addition, many advanced breeding lines are discarded during these advanced phases due to unwanted rheological and baking quality characteristics. The constant need for an analysis method for selection of wheat quality during the early generations, where limited seed sample sizes are available, therefore exists. Laboratory analysis should be simple, quick, reliable, must use a small sample size, should have high correlations with end-use (functional) quality, it should distinguish between genotypes and it should be an effective predictor, independent of location and environmental conditions (O'Brien and Orth, 1977).

The mixograph has proven to adhere to all these requirements. The progress of a mixing process, as determined on a mixograph, is a useful tool for determining the functional properties of flour dough (Khatkar *et al*., 1996). The mixograph was developed during 1933 by Swanson and Working and was accepted in 1961 by the American Association of Cereal Chemists (AACC) as an official, effective tool for selection of required mixing behaviour of flour. Currently breeders mostly only concentrate on peak time (dough development time) of flour, which is usually determined manually on a printed mixogram. A computerised mixograph, which can measure 44 parameters on a single mixogram by using Mixsmart software, was introduced and found to be effective after being compared to the conventional mixograph (Gras *et al.*, 1990; Ohm and Chung, 1999).

Limited seed sample sizes are available during early generation quality testing. In addition, many new potential cultivars are discriminated against during the final evaluation stages regarding some of the fixed, primary requirements set by the South African industry. Hence, the need arose to investigate whether inter-relationships exist between mixogram parameters and the quality requirements set by this industry to assist breeders to discard breeding lines with unsatisfactory quality, before the final evaluation stages. The computerised mixograph also eliminates human interpretation error. The Mixsmart software draws a midline curve from the mixogram so that upper and lower envelopes result. The software analyses both the upper envelope as well as the midline curve (Walker and Walker, 1992; Dobraszczyk and

Schofield, 2002). The ascending and descending slopes as well as different heights and widths are measured at different times on the mixogram.

Other quality tests, which require small sample sizes, were found to be ineffective in predicting end-use quality e.g. the sodium dodecyl sulphate (SDS)-sedimentation volume test, falling number and sodium dodecyl sulphate polyacrylamide gel electrophoresis (SDS-PAGE), used to determine high molecular glutenin subunits. These tests were also time-consuming (Dobraszczyk and Schofield, 2002). Although the mixograph and SDS-sedimentation volume test can be applied to identify strong gluten quality (because neither is substantially affected by environmental changes in protein content), the SDS-sedimentation volume test fails to differentiate effectively between “strong” and “extra strong” wheat quality (Matsuo and Irvine, 1970; Quick and Donnelly, 1980).

Loaf volume, being the final evaluation of good bread making quality (gluten quality) is also time-consuming and requires large amounts of flour as well as highly trained labour (Neufeld and Walker, 1990; Khatkar *et al.*, 1996). Wikström and Bohlin (1996) stated that test baking can be effectively replaced by predictions made from a mixogram. Chung *et al*. (2001) also reported mixogram parameters to be useful selection tools for acceptable bread making quality, due to the high heritability of mixogram parameters. They also stated that the use of only one parameter (e.g. peak time, the most widely used parameter reported on in literature regarding mixograms), will not exhibit reliable baking potential of breeding lines.

Since very little has been reported on in literature about relationships between rheological characteristics and physical grain characteristics, it was decided to investigate the existence of possible relationships between rheological and physical grain characteristics as well. Therefore, to assist wheat breeders in discarding unwanted bread making quality wheat lines earlier in the breeding process, when sufficient seed is available for constructing a mixogram, the objectives of this research were to investigate the relationships between selected parameters supplied by Mixsmart software and:

- Eight grain characteristics of dry land wheat cultivars – hectolitre mass, kernel hardness, kernel weight, kernel diameter, vitreous kernels, grain protein content, falling number and flour protein content;
- Four milling characteristics of dry land wheat cultivars – break flour yield, flour yield, flour colour (as is) and flour colour on a 76% flour yield basis;
- Six rheological characteristics of dry land wheat cultivars – mixogram water-absorption, farinogram water-absorption, alveogram P-value, alveogram L-value, alveogram P/L-value and alveogram dough strength; and
- Two baking quality-related and two baking characteristics of dry land wheat cultivars – SDS-sedimentation volume, wet gluten content, loaf volume (as is) and loaf volume on a 12% flour protein content basis.

REFERENCES

Chung, O.K., Ohm, J.B., Caley, M.S. and Seabourn, B.W., 2001. Prediction of baking characteristics of hard winter wheat flours using computer-analysed mixograph parameters. Cereal Chemistry 78: 493-497.

Cornell, H.J. and Hoveling, A.W., 1998. Wheat: Chemistry and utilisation. 1st edition. Technomic Publishing, Basel, Switzerland.

Dobraszczyk, B.J. and Schofield, J.D., 2002. Rapid assessment and prediction of wheat and gluten baking quality with the 2-g direct drive mixograph using multivariate statistical analysis. Cereal Chemistry 79: 607-612.

Finney, K.F., Yamazaki, W.T., Youngs, V.L. and Rubenthaler, G.L., 1987. Quality of hard, soft and durum wheats. Pages 677-748 in: Wheat and wheat improvement. 2nd edition. E.G. Heyne, ed. American Society of Agronomy, Inc., Crop Science Society of America, Inc., Soil Science Society of America, Inc., USA.

Gras, P. W., Hibberd, G. E. and Walker, C. E. 1990. Electronic sensing and interpretation of dough properties using a 35-g mixograph. Cereal Foods World 35: 568-571.

Hoseney, R.C., 1994. Principles of cereal science and technology. 2nd edition. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA.

Matsuo, R. R. and Irvine, G. N., 1970. Effect of gluten on the cooking quality of spaghetti. Cereal Chemistry 47: 173-180.

Neacşu, A., Stanciu, G. and Sãulescu, N.N., 2009. Most suitable mixing parameters for use in breeding bread wheat for processing quality. Cereal Research Communications 37: 83-92.

Neufeld, K.J. and Walker, C.E., 1990. Evaluation of commercial wheat gluten using the mixograph. Cereal Foods World 35: 667-669.

Khatkar, B.S., Bell, A.E. and Schofield, J.D., 1996. A comparative study of the inter-relationships between mixograph parameters and bread making qualities of wheat flours and glutens. Journal of the Science of Food and Agriculture 72: 71-85.

O'Brien, L. and Orth, R.A., 1977. Effect of geographic location of growth on wheat milling yield, farinograph properties, flour protein and residue protein. Australian Journal of Agricultural Research 28: 5-9.

Ohm, J.B. and Chung, O.K., 1999. Gluten, pasting, and mixograph parameters of hard winter wheat flours in relation to bread making. Cereal Chemistry 76: 606-613.

Payne, P.I., Holt, L.M. and Lawrence, G.J., 1983. Detection of a novel HMW subunit of glutenin in some Japanese hexaploid wheats. Journal of Cereal Science 1: 3-8.

Posner, E.S. and Hibbs, A.N., 1997. Wheat flour milling. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA.

Quick, J.S. and Donnelly, B.J. 1980. A rapid test for estimating durum wheat gluten quality. Crop Science 20: 816-818.

Rakszegi, M., Békés, F., Láng, L., Tamás, L., Shewry, P.R. and Bedo, Z., 2005. Technological quality of transgenic wheat expressing an increased amount of a HMW glutenin subunit. Journal of Cereal Science 42: 15-23.

SAGL, 2010. Analysis procedure and evaluation norms for the classification of wheat breeders' lines for the RSA. September 2010 revision.

Walker, A.E. and Walker, C.E., 1992. Documentation and user's instructions for Mixsmart. National Manufacturing Division, TMCO, 507 J. Street, Lincoln, NE68508, USA.

Wikström, K. and Bohlin, L., 1996. Multivariate analysis as a tool to predict bread volume from mixogram parameters. Cereal Chemistry 73: 686-690.

CHAPTER 2

BREAD WHEAT QUALITY

Wheat quality means different things to different people, depending on the hands that are handling the wheat between the field and the table. Producers expect high grain yields, millers expect good milling quality and bakers expect flour suitable for the end-product they wish to supply to the consumer. Consumers classify quality according to what they see, feel, smell and taste (Kent, 1984; Morris and Rose, 1996; Cauvain, 2003). Therefore quality, regarding bread wheat, relates to the specific characteristics that wheat possess to make it suitable for the final product – bread production (Jones and Kosina, 2007).

Wheat genotype is one of the major contributors to differences in grain quality (Baenziger *et al*., 1992; Peterson *et al*., 1992; Jones and Kosina, 2007) and the two main interrelated role-players regarding quality, are protein content (quantity) and grain hardness (Pomeranz and Mattern, 1988; Bushuk, 1998). Wheat quality is a complex set of traits resulting from environmental as well as genetic attributes (Baenziger *et al*., 1992; Peterson *et al*., 1992; Jones and Kosina, 2007). Protein quality is mainly determined by the molecular structure of the proteins, which, in turn, control the protein-interaction during the bread making process (Bushuk, 1998).

Neacşu *et al.* (2009) stated that breeders are interested in parameters that are highly heritable and reproducible and that these parameters supply, among other things, information about dough mixing properties. Being important breeding objectives, dough-mixing properties inform us about improved bread making quality where homogeneous dough is formed when the gluten proteins form an elastic network during mixing. This network must have the ability to trap gas, which is the base of the bread making process (Wikström and Bohlin, 1996).

Various measurements can be done on whole grain, flour and dough to determine bread wheat quality but not many attempts have been made so far to predict whole kernel quality traits, milling, flour, dough and bread making quality from whole kernels or flour (Dowell *et al*., 2006). Figueroa *et al*. (2009) reported limited available research conducted on the relationships between grain and dough characteristics.

2.1 GRAIN CHARACTERISTICS

Kernel morphology determines the milling performance of a wheat cultivar. Kernels should be plump and uniform with a spherical shape (Fowler and Priestly, 1991). Uniform kernels are milled more evenly and result in higher flour yield and lower ash contents (Gaines *et al*., 1997). Shorter kernels, having narrow creases with a smooth surface and small or medium protruding embryos, are desirable. Kernels should also be sound without insect damage and a small, less dense brush is preferable. Regarding harder wheat types, kernels should be semi-translucent and contain sufficient protein (Berman *et al.*, 1996).

2.1.1 Hectolitre mass

Hectolitre mass or test weight, usually expressed as kilograms per hectolitre (kg hl^{-1}), is a measure of volume grain per unit, thus being a good indicator of grain-soundness (Czarnecki and Evans, 1986). Hectolitre mass is a primary criterion used in the wheat trade since it has a direct impact on the costs involved during grain-transportation (Bordes *et al*., 2008). Hectolitre mass is an important wheat grading factor (Donelson *et al*., 2002) and although some cultivars might have the ability to always have higher hectolitre mass than others grown under similar conditions, hectolitre mass is affected by growing conditions as well as genetic factors (Gaines *et al*., 1996a; Bordes *et al*., 2008). This was in agreement with Jalaluddin and Harrison (1989) and Koen (2006) who also stated that hectolitre mass is an indication of the packing efficiency and kernel density of a cultivar, where kernel density is influenced by environment and packing efficiency is a heritable trait. Well-filled, plump kernels result in higher hectolitre mass, because they pack more uniformly

compared to small, longer kernels which exhibit lower hectolitre mass because they pack more randomly (Dick and Matsuo, 1988).

When it rains on wheat that is ready to be harvested, lower hectolitre mass will occur due to the ripe grain absorbing the moisture, resulting in less dense kernels and the fact that wet kernels pack less efficiently than dry kernels. Lower hectolitre mass may also be the result of changes in the kernel shape or roughening of the bran coat, due to weathering (Carver, 1996). Other stress-factors like insufficient nutrition, drought, excessive soil moisture, too little sunlight, too low or too high temperatures, insect and weather damage, like frost and hail occurring during the grain-filling period of the plant, also result in lower hectolitre mass (Wrigley and Batey, 2003).

Posner and Hibbs (1997) stated that hectolitre mass can be an indication of expected flour yield to millers when a mixture of wheat varieties from the same environment are being considered for blending. However, when varying wheat varieties and classes from different localities are blended, hectolitre mass cannot be considered as a good indicator of expected flour yield from a given quantity of wheat. Gaines (1991) as well as Monsalve-Gonzalez and Pomeranz (1993) found positive correlations between hectolitre mass and flour yield, whereas Schuler *et al*. (1995) found no correlation with flour yield. Marshall *et al*. (1986) and Berman *et al*. (1996) found weak correlations between hectolitre mass and expected flour yield. Gaines (1991) found no correlation between hectolitre mass and flour protein content, whereas Schuler *et al*. (1995) and Preston *et al*. (1995) observed positive correlations between these two parameters. Dowell *et al*. (2008) reported negative correlations between hectolitre mass and protein content. Ohm *et al*. (1998) reported negative correlations between hectolitre mass, kernel density and percentage large kernels. Basset *et al*. (1989) and Ohm *et al*. (1998) reported a correlation between hectolitre mass and wheat kernel hardness.

A hectolitre mass of 74.00 kg hl^{-1} is required for bread making purposes (Nel *et al*., 1998; SAGL, 2010), but Koekemoer (2003) reported a hectolitre mass of 76.00 kg hl^{-1} and higher to be preferable. South African cultivar release

procedures allows a potential breeding line to exhibit a hectolitre mass of 1.8 units less than the hectolitre mass of the biological standard during the classification of potential breeding lines for commercial release as cultivars (SAGL, 2010).

2.1.2 Kernel hardness

Kernel hardness is the physical hardness or softness of the wheat endosperm (Bettge *et al*., 1995) and is determined by measuring a kernel's resistance to break into smaller pieces when a force is being applied to the kernel (Yamazaki and Donelson, 1983; Turnbull and Rahman, 2002). The importance of kernel hardness is that it affects the milling process as well as the amount of flour obtained from this process (Gaines *et al*., 1996b) in that, when milled, hard wheat breaks into large pieces, making the sieving process easier, compared to soft wheat that breaks into smaller pieces (Malouf *et al*., 1992). Flour cells consist of starch granules embedded in a protein matrix. Kernel texture (hardness or softness) results from the strength of this protein-starch bond. When soft wheat are being milled, the protein-starch bond breaks easily, resulting in no breakage of starch granules compared to hard wheat that breaks at the cell walls and not through the cell content, resulting in damaged starch granules (Hoseney, 1994). Higher water-absorption levels of hard wheat are the result of damaged starch (Bass, 1988; Bettge *et al*., 1995). Greenwell and Schofield (1986) found that starch from soft wheat contains a protein that is absent or present in low amounts in hard wheat. It seems that this protein covers the starch, resulting in a weaker protein-starch bond in soft wheat.

The general perception is that kernel texture is controlled by one major gene, and perhaps some minor genes with softness (*Ha*) being dominant (Baker and Dyck, 1975; Symes, 1965; 1969; Labuschagne and Van Vuuren, 2000). Yamazaki and Donelson (1983) reported two major and several minor genes to control kernel texture.

Doekes and Belderok (1976) located the gene for kernel texture on the short arm of chromosome 5D and it has been mapped close to loci coding for puroindoline proteins. The major components of the 15kDa protein band are puroindolines (Turnbull and Rahman, 2002). Puroindoline proteins *a* and *b* form the molecular-genetic basis of endosperm texture. Hard texture occurs when either one of the puroindolines are absent or altered by mutation and soft texture occurs when both puroindolines are functional (Morris, 2002).

Pomeranz and Mattern (1988) found that variation in hardness of wheat grown at different environments was mainly affected by genotype, which is contradictory to research done by Aucamp (2003) who reported environment to be the main factor influencing hardness of a cultivar. Genotype, harvest date and the location of the kernels on the wheat ear can also influence kernel hardness (Huebner and Gaines, 1992). Anjum and Walker (1991), Monsalve-Gonzalez and Pomeranz (1993) and Hazen and Ward (1997) reported kernel texture to be affected by genotype as well as environment, growing season, protein content, moisture, kernel size and bran. Czarnecki and Evans (1986) reported that kernel hardness decreases when harvesting is delayed.

Gaines (1991) reported that wheat grown in less humid areas exhibits plump, hard and large kernels, which are highly desirable for milling. Charles *et al*. (1996) reported that softer wheat textures occurred when wheat was grown in areas that are more humid.

It appears that grain, known to be soft, remains soft during its developmental time and grain, known to be hard, remains hard through its developmental time (Bechtel *et al*., 1996). Dhlaliwal *et al*. (1987) found that wheat that contains the 1B/1R translocation tends to be harder than wheat without this translocation.

Bergman *et al*. (1998) and Ohm *et al*. (1998) observed positive correlations between kernel hardness and flour yield. Bergman *et al*. (1998) reported a genetic correlation between kernel hardness and protein content, which they assumed to be as the result of the close linkage between the softness gene

(*Ha*) and the high protein yielding gene (*Pro 2*). Pomeranz *et al.* (1985) found no correlation between hardness and protein content. However, Huebner and Gaines (1992) and Lyon and Shelton (1999) found a correlation between hardness and protein content. Van Lill and Smith (1997) found that harder grain exhibited higher protein contents as well as higher flour yields.

Martinant *et al*. (1998) reported a strong relationship between grain hardness and mixogram midline parameters peak height, peakwidth, time X height and time X width, with time X being a time as selected by the operator. Kernel hardness plays a key role in wheat marketing regarding end-use quality as almost the whole worlds' wheat production and wheat trade are being classified as either hard or soft. In South Africa, wheat breeders are allowed to only submit medium hard to hard red wheat potential breeding lines, suitable for bread production, to be classified as cultivars suitable for bread production although hardness testing is not part of the classification process of new cultivars for commercial release in South Africa (SAGL, 2010).

2.1.3 Thousand kernel mass

Thousand kernel mass is the weight of a thousand sound, whole kernels (Posner and Hibbs, 1997) indicating kernel size and density, being highly influenced by genotype. Plumper kernels contain more endosperm and therefore have higher thousand kernel mass (Bhatt, 1972; Monsalve-Gonzalez and Pomeranz, 1993; Bordes *et al*., 2008).

Posner and Hibbs (1997) indicated that thousand kernel mass is a more reliable indicator to millers of expected flour yield than hectolitre mass as they found a strong correlation between thousand kernel mass and flour yield. Thousand kernel mass correlates with flowering date (Huebner and Gaines, 1992), because a short grain-filling period resulted in poorly developed kernels and thus low thousand kernel mass. Czarnecki and Evans (1986) found that thousand kernel mass was lower when harvesting was delayed. Thousand kernel mass decreased when high temperatures occurred continuously during the maturation of the crop (Gibson *et al*., 1998).

Jalaluddin and Harrison (1989) reported a high correlation between thousand kernel mass and grain yield as well as between thousand kernel mass and hectolitre mass, although kernel mass is associated with kernel density and kernel density is a component of hectolitre mass. Löffler and Busch (1982) found a correlation between thousand kernel mass and protein content per kernel but Pomeranz *et al*. (1985) found no correlation between these two characteristics. In South Africa, a tolerance of ±4 units is allowed for thousand kernel mass during classification of a new cultivar when comparing the potential breeding line with the biological standard (SAGL, 2010).

2.1.4 Kernel diameter

Differences in kernel size within a cultivar can be the result of environmental influences (Posner and Hibbs, 1997). Marshall *et al*. (1986) found that kernel size correlates with flour yield within a cultivar but not between cultivars. Dowell *et al*. (2008) reported positive correlations between kernel size and hectolitre mass as well as between kernel size and thousand kernel mass. Tsilo *et al*. (2010) also reported positive correlations between kernel diameter and test weight. They also reported that smaller kernels were negatively associated with flour brightness.

2.1.5 Vitreous kernels

Wheat endosperm differs in texture (hardness) as well as in appearance. Halved kernels can appear either floury or vitreous. Vitreous wheat has a glass-like appearance (Hoseney, 1994; Posner and Hibbs, 1997). Vitreousness is caused by a shortage of air spaces in a kernel during the final drying of the crop in the field when protein shrinking occurs but remains intact (Dobraszczyk, 1994). Floury kernels are the result of less dense grain due to the formation of air spaces, which are formed during grain drying when protein shrinking and rupturing occurs (Barlow *et al*., 1973; Hoseney, 1994).

Confusion between kernel hardness and vitreousness often occur. Czarnecki and Evans (1986) found that a delay in harvest affects the amount of vitreousness in wheat and Pomeranz and Williams (1990) found that

vitreousness occurs in all wheat cultivars because of conditions during the maturing of the wheat. They reported that high temperatures and sufficient nitrogen availability cause vitreousness in wheat. Environmental conditions therefore play a large role in whether vitreousness will occur or not.

Vitreousness, kernel hardness and high protein content are sometimes used in the same context, since Dexter *et al*. (1988) found that vitreous durum wheat contained higher protein contents and exhibited harder textures. Soft wheat cultivars, grown under perfect conditions, can also be vitreous but the texture remains soft (Hoseney, 1994).

2.1.6 Protein content

According to their solubility, four protein-types, namely albumins, globulins, prolamins and glutelins were originally classified by Osborne (1907). Gluten, the storage protein in wheat, mainly located in the endosperm (Shewry, 2003) and known for having an influence on functional properties of wheat as determined on a mixograph, farinograph, alveograph, SDS-sedimentation volumes and loaf volumes (Finney and Shogren, 1972; Finney *et al*., 1987; Koekemoer *et al*., 1999; Branlard *et al*., 2001; Rakszegi et al., 2005) can vary within and between genotypes regarding their proportions, structures and properties (Veraverbeke and Delcour, 2002; Shewry, 2003).

Protein content alone, especially where no big differences occur in protein content, is not a good loaf volume predictor, but when combined with certain mixogram parameters, loaf volume can be predicted more accurately (Dobraszczyk and Schofield, 2002). Protein content (quantity) as well as protein quality (composition) determines wheat flour quality (Graybosch *et al*., 1996; Wieser *et al*., 1998; DuPont and Altenbach, 2003) and stable flour composition and quality are desired traits in wheat quality despite the environmental influence (DuPont *et al*., 2007). Protein content is strongly affected by environment and less affected by genotype (Hoseney, 1994), which confirms that, depending on environmental conditions, wheat grain protein content can vary between 6% and 25% as affected by nitrogen

availability (Blackman and Payne, 1987). Total protein as well as the amount of each different protein is mainly determined by genotype.

Nitrogen fertiliser as well as temperature affects the ratio of HMW-GS to low molecular weight glutenin subunits (LMW-GS), the amount of HMW-GS per grain as well as the HMW-GS proportion per unit of flour protein. Higher growing temperatures result in a shorter duration but a higher rate of HMW-GS accumulation (DuPont *et al*., 2007). Nitrogen fertiliser after anthesis, results in a higher rate of HMW-GS accumulation, a higher amount per grain as well as a higher relative amount compared to sulfur-rich gluten proteins such as LMW-GS (Wieser et al.,1998; DuPont *et al*., 2006; 2007). Synthesis of HMW-GS occurs in such a way that each subunit proportion remains constant under a range of growing conditions (DuPont *et al*., 2007). Saint Pierre *et al*. (2008) reported that gliadins increase more than glutenins as flour protein increases when being fertilised with nitrogen.

Hoseney (1994) and Wieser *et al*. (2006) reported that the gluten complex consists of monomeric gliadin, which is responsible for dough-viscosity and extensibility, and polymeric glutenin, which is responsible for dough strength and elasticity. According to Singh *et al*. (1990), flour quality depends on a specific balance between gliadin and glutenin.

Bietz and Wall (1972) and Bushuk (1998) reported that the molecular structure and interactions of the different proteins are the cause of the viscoelastic properties of dough. Glutenin proteins have disulphide bonds that link to individual glutenin polypeptides (subunits). Bread wheat is hexaploid, meaning it has three genomes, namely A, B and D. Payne *et al*. (1987) reported several HMW-GS on chromosome 1A (null, 1 and 2*), 1B (6+8, 7, 7+8, 7+9, 17+18, 14+15) and 1D (2+12, 5+10, 3+12, 4+12, 2+11). Payne *et al*. (1987) and Hoseney (1994) reported HMW-GS 5 being associated with good bread making quality and HMW-GS 2 being associated with poor bread making quality. Uthayakumaran *et al*. (2002) reported that HMW-GS pair 5+10 makes a bigger contribution to dough properties when compared to HMW-GS pair 17+18 and HMW-GS 1 makes the smallest contribution. Marchylo *et al*.

(1992) reported the presence of HMW-GS 7 to result in greater dough strength properties.

Wieser *et al*. (1998) reported the existence of three main groups of gluten proteins and within each group, two or three different protein types can be distinguished. The HMW group that includes the *x*- and *y*-type of HMW-GS, a medium molecular weight group (MMW) is also a sulphur-poor group and it includes the ω5 and ω1, 2-type gliadins. The LMW group, which is also a sulphur-rich group, includes the LMW-GS as well as the α- and γ-gliadins. Wieser and Kieffer (2001) reported that the *x*-type HMW-GS includes subunits 1 to 7 and the *y*-type HMW-GS includes subunits 8 to 12 and the contribution of the *x*-type subunits to dough handling properties are more important than the contribution of the *y*-types.

Gliadins can be divided into α-, ß-, γ - and ω-gliadins. Most of the ω-gliadins do not have disulphide bonds and are therefore also called sulphur-poor prolamins (Shewry *et al*., 1986). Uthayakumaran *et al*. (2001; 2002) reported that higher amounts of gliadin fractions resulted in shorter mixing times, lower peak resistance and lower maximum resistance to extension as well as lower loaf volumes, but with the incorporation of a HMW-GS, a higher resistance to breakdown and extensibility occurred. All cultivars of hexaploid wheat have six HMW subunit genes, but only three, four or five subunits are expressed. Each subunit accounts for more or less 2% of the total grain protein content, and therefore gene expression variation causes different amounts of HMW-GS protein. Therefore, the polymeric structure of glutenin protein relates directly to the different glutenin subunits' contribution to the molecular properties of dough and is therefore recognised as one of the main determinants of physical dough handling properties (MacRitchie, 1999; Don *et al*., 2003).

Uthayakumaran *et al*. (2002) observed a strong correlation between the variation in structure and relative amounts of HMW glutenin and dough strength. Dough extensibility is affected when an alteration in LMW glutenin and gliadin composition occurs. Dough strength and peak time both relate to the amount and type of HMW proteins. Weak dough is obtained when some of

the subunits are absent. Dough strength and loaf volume potential may not always be strongly associated (Hoseney, 1994). Weegels *et al*. (1996) reported that the size distribution of polymeric glutenin appears to be the most important characteristic when dough strength is considered. The amount of albumins and globulins (physiologically active proteins) are higher at lower protein contents when expressed as a percentage of the total protein. Their total amounts increase as the amount of protein increases in a specific sample, but their increase is slower than gluten (storage protein) increase, because as more protein is produced, less protein is required for physiological functions. Thus, more is available as storage protein for functional properties, that is for dough formation with the ability to retain gas and produce aerated baked products like bread (Hoseney, 1994). Singh *et al*. (1990) also reported a strong negative correlation between relative quantity of albumin/globulin and flour protein content, although the absolute quantity of glutenin was strongly correlated with quality attributes, e.g. extensibility, farinograph dough development time and dough breakdown characteristics.

Huebner *et al*. (1997) reported that genotype and environment as well as their interaction, have major effects on flour protein composition and therefore potential loaf volumes. During classification of a potential new cultivar in South Africa, the protein content of the potential breeding line must not be less than 1% lower than that of the biological standard (SAGL, 2010).

2.1.7 Falling number

Pre-harvest sprouting has little impact on milling characteristics, but it is detrimental to bread quality, because the germination process leads to a high level of α-amylase activity resulting in unacceptable bread due to sticky crumb-texture, which causes a build-up on slicer blades and therefore bread cannot be cut effectively with mechanical slicers. Sprouting damage also causes a more open coarse crumb structure. Loaf volume is sometimes not affected by sprouting damage, but higher loaf volumes could be obtained due to more rapid gas production during the fermentation process (Edwards *et al*., 1989).

Falling number is an indirect measurement of α-amylase activity in samples to determine if pre-harvest sprouting has occurred or not (Hagberg, 1960; Kaldy and Rubenthaler, 1987; Posner and Hibbs, 1997). Falling number is the time, in seconds (s), it takes a viscometer stirrer to fall through a hot aqueous flour gel after it was stirred for 60 s (Kaldy and Rubenthaler, 1987; Posner and Hibbs, 1997). High concentrations of α-amylase break starch down and result in excessive sugars, which in turn result in bread with sticky crumbs and poor texture. The sticky crumb also causes problems during mechanical cutting of the bread that is unwanted by the industry (Chamberlain *et al*., 1981; Posner and Hibbs, 1997). Dowell *et al*. (2008) reported that flours exhibiting low falling numbers, also exhibited a decrease in their water-absorbing capacity, which might have an effect on loaf volume.

An acceptable falling number for bread production is between 200 s and 350 s. Falling numbers below 150 s result in sticky bread and falling numbers above 350 s result in bread with a dry crumb and diminished loaf volumes (Perten, 1964).

The Hagberg falling number test was incorporated within the South African wheat grading system in June 1998 (Anonymous, 2001) and in classification of potential new cultivars in South Africa, falling numbers should be higher than 250 s and it should not be more than 15% lower, when compared to the biological standard (SAGL, 2010).

2.2 MILLING CHARACTERISTICS

Millers are challenged to provide uniform and stable flour quality, suitable for specific end-products. Morris (1992) reported that wheat cultivars with intermediate flour quality characteristics are recommended when wheat belonging to different hardness classes is blended.

2.2.1 Break flour yield

Break flour is the total weight of flour, expressed as a percentage, obtained from the break rollers on a Bühler-mill during the milling process. The break

rollers open the kernel and separate the endosperm and germ from the bran (Bass, 1988).

Gaines (1991) reported a negative correlation between break flour yield and flour protein content for red wheat cultivars. Rogers *et al*. (1993) and Labuschagne *et al*. (1997) reported softer wheat to yield higher volumes of break flour and that softer wheat usually exhibits lower protein contents as well. Kosmolak and Dyck (1981) found a positive correlation between break flour yield and larger kernels. Gaines (1991) reported that less break flour was obtained from cultivars with higher test weights. During the classification of cultivars in South Africa, a potential breeding line is allowed to differ by ±5% for break flour yield when compared to the biological standard (SAGL, 2010).

2.2.2 Flour yield

Flour yield (flour extraction rate) is the percentage of flour obtained from a given amount of wheat. Flour yield is important because genotypes yielding higher volumes of flour are more profitable to millers (Bass, 1988). Conditioning (tempering) of wheat prior to milling is necessary in order to limit bran contamination of flour and to ensure easier separation of endosperm and bran (Marais and D'Appolonia, 1981).

Steve *et al*. (1995) reported flour yield as a complex trait affected by factors influencing the ease of endosperm-bran separation. Such factors include kernel hardness, endosperm-bran adherence, kernel plumpness and the endosperm-bran ratio. Pumphrey and Rubenthaler (1983) reported poor growing conditions resulting in shriveled kernels that lead to lower endosperm-bran ratios and therefore lower flour yields.

Ohm et al. (1998) observed positive correlations between flour yield, kernel hardness, hectolitre mass and kernel density. Labuschagne *et al*. (1997) reported softer wheat to deliver lower flour yields.

Souza *et al*. (1993) observed a correlation between flour yield and flour protein content. Van Lill and Smith (1997) found that genotype as well as environment had an effect on flour yield and Bergman *et al*. (1998) found that genotype has a significant effect on flour yield. During the classification of a new cultivar in South Africa, flour yield of a potential breeding line should not be more than 1.5% lower compared to the biological standard (SAGL, 2010).

2.2.3 Flour colour

Flour colour is a determination of the colour of the flour depending on the specific end-product. Flour colour is controlled by two independent factors, namely yellowness and brightness. Carotenoid pigments influence yellowness while the milling process itself (Oliver et al., 1993) influences flour-brightness. Flour colour can be determined by measuring reflectance with a light source in the green band of the light spectrum, where in this case, whiteness or yellowness is ignored and the concentration is on the influence of the bran in the flour (Mailhot and Patton, 1988).

Genotype, environment, genotype-environment interaction or the milling process itself can cause variance in flour colour. A darker flour colour may be the result of frost damage, immature kernels, black point (Bass, 1988) or bran contamination, influenced by the reduction phase during the milling process (Posner and Hibbs, 1997).

Southern African cultivars released since 1965 were found to be 46% brighter than cultivars released before then (Van Lill and Purchase, 1995). Posner and Hibbs (1997) found a strong correlation between brightness, ash content and flour yield. Li and Posner (1989) observed a linear relationship between flour colour and flour yield. Flour colour of a potential breeding line is allowed to be only 1 KJ (Kent Jones) unit higher compared to the biological standard (SAGL, 2010).

2.3 RHEOLOGICAL CHARACTERISTICS

Rheology refers to deformation of dough, made possible by the unique wheat protein, gluten, which forms viscoelastic dough when combined with water. The mixograph, farinograph and alveograph supply information regarding rheological behaviour of dough that is of utmost importance when flour is evaluated for a specific end-product (Walker and Hazelton, 1996).

2.3.1 Mixogram characteristics

The mixograph is an instrument that performs certain rheological measurements during dough mixing (Walker and Hazelton, 1996; Wikström and Bohlin, 1996; Bordes *et al*., 2008); it has been utilised for decades to classify wheat, for prediction of end-product quality, to study the effect of various additives being used in baking processes and for prediction of water-absorption in various dough processing systems (Lang *et al*., 1992; Van Lill and Purchase, 1995; Khatkar *et al*., 1996; Lukow, 1997; Ponte and Ingelin, 1997; Dobraszczyk and Schofield, 2002). The moving pins of the mixograph stretch the dough between fixed pins and the resulting resistance is registered, as a curve, the mixogram.

The mixogram gives information on optimum dough development time (peak time), dough strength (peak height), dough development (ascending part), tolerance to over-mixing (descending part) and dough stability (slopes or angles created by the two arms) of the mixogram (Walker and Hazelton, 1996; Walker *et al*. 1997). Van Lill (1992) and Hoseney (1994) reported that peak time is largely genetically determined. Gras and O'Brien (1992) reported medium to high heritability for peak time and medium heritability for mixing tolerance. With loaf volume being the ultimate test for bread making quality, it was found that when peak times were higher than three minutes combined with protein content above 13%, loaf volume stayed the same (Finney and Shogren, 1972). In 1994, Hoseney reported peak time to be influenced by protein content and peak time control as being associated with the glutenin fraction of the flour. He noticed that flour containing less than 12% protein

takes longer to reach a peak and when protein content was higher than 12%, peak time was not affected. As peak time increases, dough extensibility decreases and dough stability, elasticity and mixing tolerance increase. Flour containing protein content above 12% also exhibits more acceptable mixing tolerance.

Peak time, peak height and curve-width are determined by protein quality and protein quantity as well as the water-absorption of the specific flour (Walker and Hazelton, 1996; Lukow, 1997). Neacşu *et al*. (2009) stated that some parameters are indicative of more than one mixing property, for example the slope of the ascending part of the curve depends on both mixing requirements and dough strength, end-width is indicative of both dough extensibility and stability and the areas below and within the curve are an integration of basic mixing property aspects. The descending slope is largely determined by wheat variety, environment and flour protein content. The angle between the two slopes as well as curve-width after peak time, are indicative of the dough's tolerance to mixing. Soft wheat containing lower protein content levels exhibits a low tolerance to mixing, because it breaks down quickly after the peak time has been reached. Stronger flour containing higher protein content levels results in curves with long peak times and usually exhibits a tolerance to over-mixing. These curves are higher and may appear less tolerant, due to the smaller included angle developed between the ascending and descending slopes (Walker and Hazelton, 1996). Khatkar *et al*. (1996) reported that dough strength can be observed from peak times, peak heights and work input requirement, as it is a function of peak time and peak height as well as the overall shape of a mixogram.

Neacşu *et al*. (2009) indicated five parameters to be effective for selecting processing quality in breeding programmes and they are descriptive of all basic rheological aspects of mixing properties. These parameters exhibit lower correlations between themselves and they are the initial slope (indicative of water-absorption), peak time (indicative of mixing requirement), peak height (indicative of dough strength), end-width (indicative of extensibility) and breakdown (indicative of stability). These parameters

explained 91% of the variance observed in loaf volume. Wikström and Bohlin (1996) also reported five mixogram parameters namely build-up (which refers to the phase after initial build-up up to the maximum height at the top of the curve), peak time, initial width, area below the mixogram curve and peak height to be effective, when combined with protein content, in predicting loaf volume. These parameters explained 92.8% of the variance in loaf volume. They also reported midline peak time exhibiting highly negative correlations with the descending slope and it can be explained by the strong negative correlation between midline peak time and midline peak height. Midline peak height, midline peakwidth, midline time X height and midline time X width are related to grain hardness and there was a strong relationship between them and bread making quality. They also concluded that high values obtained for mixogram parameters build-up, area below the peak and peak height are indicative of strong dough, that peak time relates to build-up and water-absorption, and if low values are obtained for build-up, low loaf volumes will occur. Increasing values for area below the peak and peak height combined with decreasing values for peak time, will give higher loaf volumes.

Mixogram peak time was the only mixogram parameter reported to breeders from 1966 to 1986, but it has become clear that peak height and not peak time is the parameter that predicts bread making quality more effectively (Finney *et al*., 1987; Dong *et al*., 1992; Preston *et al*., 1992; Khatkar *et al*., 1996; Lukow, 1997; Martinant *et al*., 1998).

Using Mixsmart software 44 parameters can be measured on a single mixogram curve (Pon *et al*., 1989). The software constructs a midline curve, which divides the mixogram into two envelope curves where both the upper envelope as well as the midline curve (Walker and Walker, 1992; Dobraszczyk and Schofield, 2002) are then analysed. The 44 parameters result from measurements made at different heights, widths and slopes as well as areas on the mixogram curve. All results or measurements made are expressed as a single value (Walker and Walker, 1992). Computerisation of the mixograph resulted in more measurement-points, reduced labour and time as well as elimination of human interpretation error (Lukow, 1997). Martinant

et al. (1998) found strong correlations between midline and top envelope parameters, with midline parameters exhibiting better repeatability. Chung *et al*. (2001) reported significant correlations between bake mixing times and midline peak time and Martinant *et al*. (1998) reported a negative correlation between grain protein content and peak time as was also reported by Bordes *et al*. (2008).

Curve-height measurements, determined as a percentage of the full scale, are informative about dough consistency and are expressed as “value, %”. Curve-width measurements are the difference between the top and bottom envelope, and midline-width measurements “borrow” some information from the top envelope. Curve-widths are indicative of the dough’s tolerance to mixing. Slopes are determined by dividing the value (%) by the certain time in question, where small values will be indicative of flat, stable curves and large values will be indicative of a quick rise and/or breakdown which are undesirable, indicative of poor tolerance to mixing and sensitive to the mixing time. Integral values, representative of work input to develop the dough, are determined from starting point up to the specific time in question. It is determined by multiplying the vertical axis (% torque) with the horizontal axis (minutes) and is therefore expressed as torque*min. Areas under the midline curve are indicative of dough strength and exhibits correlations with other parameters. Midline peak time exhibited no correlations with other parameters. Curve-heights exhibited strong relations with curve-heights throughout the complete mixing process.

Water-absorption, determined on a mixograph, seems to be higher than water-absorption determined on a farinograph and it could be partly attributed to the different mixing actions of these two apparatuses, the differences that occur in dough consistency in these two apparatuses and because the amount of water added to perform a mixogram, relates to the flour protein content of the sample being analised (Wikström and Bohlin, 1996; Ingelin, 1997). Finney (1997) reported an increase in peak time, but a decrease in peak height when water-absorption increased. When pre-harvest sprouting occurred (low falling numbers), only a gradual dough-weakening could be

observed on mixograms as sprouting percentages increased, but peak times and water-absorptions were not much affected (Kulp *et al*., 1983). The mixograph is used worldwide to evaluate the functionality of wheat flour dough, but Europe prefers the farinograph because it has been in use in Europe long before the mixograph (Lukow, 1997; Weipert, 1997). Ingelin (1997) reported the mixograph to be a better predictor of baking mixing times than the farinograph because of the differences in the mixing mechanisms between these two apparatuses.

Finney and Shogren (1972) stated that peak times longer than five minutes, usually exhibit too much tolerance, which results in insufficient extensibility leading to undesirable elasticity, and is therefore undesirable for bread production compared to medium to medium-long peak times that usually exhibit acceptable tolerance and other dough handling properties, making it desirable for bread production. Short peak times exhibit too much extensibility and too little elasticity for stable dough production (Finney *et al*., 1987).

Lundh and MacRitchie (1989) found that the differences in peak times were attributed to differences in glutenin proportions. Differences in peak times, dough strength and bread making potential are better when cultivars contain subunits 5+10, 7+8, 17+18, 1 and 2* than when possessing subunits 6+8, 2+12 and 20 (Gupta and MacRitchie, 1994). Khatkar *et al*. (1996) agreed with this, but found that 2+12 produced strong doughs and acceptable loaf volumes. They also found that 7+8 in combination with 2* or 1 or 5+10, resulted in greater peak heights and loaf volumes.

Peak height is a function of protein content as well as the water-absorbing capacity of the flour. Optimum peak height occurs when optimum mixing has taken place and all the flour dough components are hydrated. Curve-height increases with increasing protein content (Hoseney, 1994). Wikström and Bohlin (1996) and Martinant *et al*. (1998) reported peak height to correlate with grain hardness. Khatkar *et al*. (1996) reported no correlation between SDS-sedimentation volumes and curve-width as well as height of the descending slope. They also reported strong positive correlations between the

slope of the descending arm and the curve-width of the descending arm as well as between peak height and curve-width at peak height. This implies that genotypes exhibiting high peak heights (values >55) and high curve-widths at peak height, will also exhibit high values for the descending arm (slope) and width of the descending arm, indicative of poor tolerance to over-mixing.

Dobraszczyk and Schofield (2002) reported correlations between flour protein content and mixogram peak height, protein content and mixogram tailheight as well as between protein content and envelope peak height. Chung *et al*. (2001) reported significant correlations between protein content and midline peakwidth, between bake mixing times and curve-width at six minutes, between bake mixing times and midline curve-width at two minutes and between loaf volume and midline peakwidth.

A negative correlation between flour protein content and mixogram tolerance (descending slope) was reported by Souza *et al*. (1993) as well as Chung *et al*. (2001) who also reported significant correlations between protein content and midline ascending slope.

Ohm and Chung (1999) and Chung *et al*. (2001) stated that curve-width at six minutes is indicative of mixing tolerance. Chung *et al*. (2001) reported significant correlations between protein content and envelope peak-area, between bake mixing times and midline peak-area and between loaf volume and envelope peak-area. Khatkar *et al*. (1996) observed strong correlations between peak time and work input.

During the classification of new cultivars in South Africa, the tolerances for peak time differ, depending on which quality standard is used, e.g. for Elands (Free State dry land areas) and Kariega (southern dry land areas), a tolerance of +15% to –25% is allowed. When compared to SST 806 (irrigation areas), a tolerance of +20% to –10% is allowed (SAGL, 2010).

2.3.2 Farinogram characteristics

The farinograph is an instrument that mixes dough, using two sigmoid blades, which turn at differential speeds, folding the dough into itself. The mixing action is recorded on a graph, called a farinogram (Walker and Hazelton, 1996). Information such as dough development behaviour, dough stability (the resistance of dough to mixing) as well as water-absorption can be obtained from the farinogram.

Water-absorption is the most widely used farinograph measurement and it relates to the volume of water required to centre the peak-area of the farinogram on the 500 Brabender Unit line or it indicates the required water needed for dough to reach a certain consistency at the point of optimum development. Water-absorption gives an indication of the potential of the protein molecules to absorb the added water, and therefore is an indicator of baking quality (MacRitchie, 1984; Van Lill *et al*., 1995). Van Lill and Smith (1997) reported that grain with higher protein content tended to be harder and give higher ash-content flour, which then results in higher water-absorption.

Stability is an indication of the flour's tolerance to mixing and stronger flours tend to be more stable (D'Appolonia and Kunerth, 1969; Eliasson and Larsson, 1993; Miralbés, 2004). Miralbés (2004) also reported a linear relationship between stability and protein content. Weipert (1997) reported a strong correlation between the angle of the ascending and descending slopes with protein and wet gluten content as well as with development time, stability and water-absorption as determined on the farinograph.

In 1992, Van Lill reported that the albumin protein fraction, has a weak positive correlation with flour protein content, dough development time, dough stability and water-absorption. A positive correlation was found between the globulin protein fraction, and dough development time. Gliadin and glutenin are significantly correlated with flour protein content, dough development time, stability, and water-absorption as well as loaf volume. In a cultivar, water-absorption increases as protein content increases, although water-absorption

is a function of protein quantity and protein quality (Finney *et al*., 1987). Zounis and Quail (1997) reported significant correlations between farinograph water-absorption (FABS) and mixogram peak height as well as between FABS and maximum mixograph bandwidth.

Water-absorption is of utmost importance when a cultivar is released in South Africa and values between 62 – 64% are desirable (Koekemoer, 2003). A tolerance of ±2.5% is allowed for water-absorption, ±25% for dough development time and +10% to –30% for stability, when comparing a potential new cultivar to the biological standard during cultivar classification (SAGL, 2010).

2.3.3 Alveogram characteristics

The alveograph is an instrument that measures the pressure as well as the air volume required to blow an expanding bubble from a thin sheet of dough. The obtained graph, the alveogram, provides information such as dough stability or dough tenacity (P-value), dough extensibility or distensibility (L-value), dough strength (W-value) and the ratio between P and L (P/L-value), all important when cultivars are released in South Africa. The P-value gives information on the dough's ability to retain gas or it can be seen as the resistance to elastic deformation; low and high P-values correspond to weak and strong flour doughs, respectively. The L-value indicates dough handling properties; low and high L values correspond to weak and strong flour doughs, respectively. The W-value (area under the curve) gives information on the energy that is required to deform the dough. In this case, low and high W values correspond to weak and strong flour doughs, respectively (Walker and Hazelton, 1996; Miralbés, 2004; Bordes *et al*., 2008). All these parameters are influenced by protein quantity (Van Lill and Smith, 1997) and quality.

Hou *et al*. (1996) reported that certain HMW-GS have more influence on the alveograph parameters, indicating the genetic control of the specific measurement. It has been shown (Branlard and Dardevet 1985; Hou *et al*.,

1996; Payne *et al*., 1987) that HMW-GS 1 correlates positively with the L-value, GS 2* with the P-value and P/L-value, while GS pair 5+10 with the P- and W-values.

Miralbés (2004) stated that the W-value should be regarded as the single most important selector for screening for bread making quality and Bordes *et al*. (2008) agreed, that the W-value summarises all other parameters obtainable from an alveogram. Sadouki *et al*. (2006) found significant correlations over three harvests between the alveogram W-values and mixogram peak times. They reported correlations between the W-values and mixogram peak-areas, as well as significant correlations between W-values and dough weakening characteristics (mixing tolerances), in this case determined by the difference in peak height at peak time and curve-height at six minutes mixing time. P-values were also correlated to mixogram peak-areas for all three harvests and with peak times for two harvests. They also observed that W-values, and to a lesser extent P values, were influenced by year effect. During classification of a new cultivar in South Africa, a deviation of ±20% is allowed for the W-value and the P-value, for the L-value a deviation of -10% to +20% is allowed and for the P/L-value ±25% when compared to the biological standard (SAGL, 2010).

2.4 BAKING QUALITY-RELATED AND BAKING CHARACTERISTICS

In bread making, all ingredients are mixed until a smooth, cohesive dough forms consisting of a visco elastic gluten protein matrix, which is of utmost importance during the fermentation process. During the fermentation of yeast-leavened dough, carbon dioxide (CO_2) is produced, resulting from the enzymatic action of yeast over starch. The viscoelastic gluten protein matrix traps the CO_2, contributing to the formation of a porous crumb structure. Gluten expands during the dough proving process and the porous structure is fixed during the baking process. The final product, being bread, is therefore a denatured protein network supporting the dough components (Shewry and Tatham, 1989).

The two main components of gluten, namely gliadins and glutenins are responsible for the unique viscoelastic character of wheat dough (Branlard *et al*., 2001). The balance as well as the interaction between the different flour components, such as starch, lipids and proteins is very important, although the proteins are known to play the most important role in determining bread making quality (Cauvain, 2003).

2.4.1 SDS-sedimentation volume

Sodium dodecyl sulphate (SDS)-sedimentation volume is the measurement of a sediment volume of a flour-water suspension after it has been acidified with lactic acid (Krattiger and Law, 1991; Eckert *et al*., 1993). This test is a good indicator of end-use quality, especially where wheat contains a low to medium protein content (Krattiger and Law, 1991). SDS-sedimentation volume is effective in differentiating between different wheat quality-types. In addition, the sedimentation volume is independent of whether whole meal or white flour is used (Axford *et al*., 1979; Dick and Quick, 1983; Kovacs, 1985; Carter *et al*., 1999), but a disadvantage is the ineffectiveness of this test to distinguish between medium to strong quality flour samples when protein content is higher than 13% (Ayoub *et al*., 1993; Eckert *et al*., 1993; Carter *et al*., 1999). Higher SDS-sedimentation volumes usually indicate stronger gluten and better quality (Eckert *et al*., 1993; Carter *et al*., 1999).

Fowler and De la Roche reported (1975) that SDS-sedimentation volume reflects protein quantity and dough development time, both being important basic quality characteristics. Moonen *et al*. (1982) reported SDS-sedimentation volume to be the best predictor of baking potential and dough strength of hard wheat. Wheat breeding programmes utilise this test to get an indication of differences in protein content as well as gluten quality, where both these characteristics are of great importance regarding end-use quality, especially when protein contents are below 13% (De Villiers and Laubscher, 1995; Carter *et al*., 1999). Dobraszczyk and Schofield (2002) found correlations between SDS-sedimentation volumes and several mixogram parameters.

2.4.2 Wet gluten content

Wet gluten is obtained by washing a flour sample with a sodium chloride solution to remove the starch and all other soluble components (Neufeld and Walker, 1990). Ponte and Ingelin (1997) stated that strong gluten wheat usually exhibit more resistance to dough stretching as well as dough breakdown (over mixing) than weaker gluten. Pitz (1997) reported that strong gluten result in mixograms that take longer to reach a peak, which confirmed this. The bandwidths of such mixograms are usually wider and the mixograms are stable (take long to break down after peak time is reached). Lang *et al*. (1992) found that higher gluten concentrations resulted in higher peak heights and work input to obtain full dough development, although peak time decreases.

2.4.3 Loaf volume

Being the final test in assessing wheat bread making quality, loaf volume indicates the dough's capacity to retain gas during the fermentation process and is measured by rapeseed displacement (Shogren and Finney, 1984). Bread quality is determined by the quality and the quantity of all raw materials involved and the processing method being applied (Cauvain, 2003). Loaf volume is evaluated by the ability of the flour to produce large, well-shaped loaves and by the water-absorbing capacity of the flour (Kent, 1984). Hard wheat is preferable for bread making purposes due to the higher water-absorption capacity that results in increased bread yield and an increased shelf life (Blackman and Payne, 1987). Weak dough generally has low content of and exhibits excessive extensibility, conferred by gliadin, resulting in low loaf volumes and a poor crumb structure. Excessive good quality glutenin results in too much elasticity and too little extensibility (Shewry and Tatham, 1989).

Sandstedt and Ofelt (1940) found that loaf volumes decreased when protein content was higher than 13%. Finney *et al*. (1987) and Khatkar *et al*. (1996) stated that loaf volume increases with increasing protein content within a cultivar, but for a given protein content, bread making quality differences occur

between cultivars, due to differences in the qualitative nature of the gluten proteins affecting the rheological properties (Khatkar *et al*., 1996). Differences are attributed to the variation in the glutenin fraction of gluten between the cultivars (Weegels *et al*., 1996; Janssen *et al*., 1996a; b; Uthayakumaran *et al*., 1999).

De Villiers and Laubscher (1995) found positive correlations between SDS-sedimentation volumes and loaf volumes. Dobraszczyk and Schofield (2002) reported that the three mixogram parameters that gave the best prediction of loaf volume were midline peak bandwidth, ten minute height and envelope peak height. They also stated that mixogram parameters alone were not good predictors of loaf volume, but when combined with protein content they were good predictors of loaf volume. Protein alone, especially where no significant differences occur in protein content, is also not a good predictor of loaf volume. In South Africa, loaf volumes of potential breeding lines should not be more than 10% less than loaf volumes of the biological standard during the classification of potential new cultivars (SAGL, 2010).

2.5 EXTERNAL FACTORS AFFECTING WHEAT GRAIN QUALITY

Wheat flour consists of starch (amylose and amylopectin) and gluten (glutenin and gliadin). Grain protein synthesis occurs during the grain-filling period of the wheat plant and gluten proteins are present as early as six days after anthesis. Grain starch synthesis starts later during the fruiting period, and as the grain matures, starch deposition increases. Therefore, good starch synthesis leads to high grain yields, and could be accompanied by low protein contents resulting from good growing conditions later during the grain-filling period without sufficient available nitrogen. Excessive nitrogen at early growth stages results in higher yields whereas availability of nitrogen after anthesis will result in high protein contents (Kent, 1984; Hoseney, 1994), which might also imply improvement of baking quality (Kent, 1984).

A constant complaint from bakers is the lack of consistency in dough handling properties in flour for bread production. Considering the fact that the breeders

have already attended the needs of the miller and the baker by “building in” the genetic potential for required quality characteristics, the wheat producer’s crop management and environmental factors also contribute to deliver acceptable quality to the miller, which will then in turn deliver acceptable flour to the baker. Genotype is therefore the responsibility of the breeder and crop management considering environment is the responsibility of the farmer (Wrigley and Batey, 2003).

Soil nutritional status plays an important role in determining the availability of nutrients to the developing plant and grain. The availability of nitrogen determines the yield as well as protein content. For bread making purposes, protein content should be above 8% or else a lack of dough strength will occur which might make the flour unsuitable for bread production (Wrigley and Batey, 2003).

Drought usually leads to low yield and high protein content. Water logging (excessive rainfall and/or poor drainage) leads to lower grain yield and poor quality. Various diseases such as rust might prevent the plant contributing fully to grain-filling and smaller grains will then be harvested, with a resulting lower hectolitre mass, which might downgrade the crop. Frost and even low temperatures during and after anthesis, will affect seed set or result in under-developed grain. These grains will appear “pinched” and again lower hectolitre mass will be obtained, unsuitable for a good milling grade (Wrigley and Batey, 2003). Rain at harvest may cause the crop to germinate in the ears, with the detrimental effects on bread making quality already indicated.

Variations in temperature like high temperatures (above 35℃) and CO_2 levels during grain-filling cause weakening in dough properties.This environmental factor can result in complete loss of bread making quality and this factor is predicted to occur more frequently with global warming (Wrigley and Batey, 2003), although genotypes that show tolerance to this “heat-shock” effect have been identified (Blumenthal *et al*., 1995). Higher temperatures are linked to higher concentrations of CO_2, which leads to higher starch deposition in the grain and therefore high yields, but, if not enough supply of nitrogen is

available, also to lower protein deposition (below 8%), which is unacceptable for bread making purposes due to limited amounts of visco elastic gluten (Blumenthal *et al*., 1996).

Other non-environmental factors influencing wheat quality are post-harvest moisture content and temperature. Both are critical during wheat-storage after being harvested. Insects, mites and fungi attack the grain if the moisture content is too high (above 14.5%) and mycotoxins can then develop which will make the grain unacceptable for human and animal consumption. Temperatures above 30℃ cause dough characteristics to change – an increase in dough strength and a decrease in extensibility occurs. Milling characteristics are not influenced by heat damage, but due to the gluten-functionality that changes, serious effects are found on physical dough properties (Wrigley and Békés, 1999).

2.6 WHEAT GRADING IN SOUTH AFRICA

Four classes of wheat are distinguished in South Africa, namely Bread wheat, (Class B), Biscuit wheat (Class C), Durum wheat (Class D) and “Other” wheat (Class O). Hardness as such is not part of wheat grading, but during the release of cultivars, only red wheat cultivars showing medium hard to hard endosperm are allowed in the B-class (SAGL, 2010).

Other characteristics playing an important role in wheat grading are hectolitre mass, falling number and protein content. Assuming that the wheat being received at the silo’s has no insect or disease damage or other unwanted material, a B1-grade will be obtained if the hectolitre mass is 77 kg hl^{-1} or higher, the falling number is 220 s or higher and protein content must be 12% or higher. To receive a B2-grade, the hectolitre mass must be between 76 and 77 kg hl^{-1}, falling number is 220 s or higher and protein content must be between 11 and 12%. For a B3-grade, hectolitre mass must be between 74 and 76 kg hl^{-1}, falling number 220 s or higher and protein content must be between 10 and 11%. Grade B4 consists of wheat that has a hectolitre mass between 72 and 74 kg hl^{-1}, a falling number of between 200 and 220 s and a

protein content of between 9 and 10%. When a hectolitre mass between 70 and 72 kg hl^{-1} is obtained and the falling number is between 150 and 200 s and the protein content is between 8 and 9%, the wheat will be graded as utility grade. Class “Other wheat” has a hectolitre mass less than 70 kg hl^{-1}, falling numbers less than 150 s and protein contents lower than 8% (SAGL, 2010).

Although the breeder considers all the quality aspects, the genotype-environmental interactions have such a great influence on end-use quality (Cauvain, 2003) only exceptional cultivars will deliver a consistent profit to all role-players who handle the wheat between the fields and the table (Van Lill and Smith, 1997).

REFERENCES

Anjum, F.M. and Walker, C.E., 1991. Review on the significance of starch and protein to wheat kernel hardness. Journal of the Science of Food and Agriculture 56: 1-13.

Anonymous, 2001. Falling number report, 2001. ARC-Small Grain Institute, Bethlehem, RSA.

Axford, D.W., McDermott, E.E. and Redman, D.G., 1979. Note on the SDS-test of bread making quality: Comparison with Pelshenke and Zeleny tests. Cereal Chemistry 56: 582-584.

Aucamp, J.C., 2003. Assessment of South African bread wheat cultivars for milling quality. MSc thesis. University of the Free State, Bloemfontein, RSA.

Ayoub, M., Fregeau-Reid, J. and Smith, D.L., 1993. Evaluation of the SDS-sedimentation test for the assessment of eastern Canadian bread wheat quality. Canadian Journal of Plant Science 73: 995-999.

Baenziger, P.S., Clements, R.L., McIntosh, M.S., Yamazaki, W.T., Starling, T.M., Sammons, D.J. and Johnson, J.W., 1992. Effect of cultivar, environment and their interaction and stability analyses on milling and baking quality of soft red winter wheat. Crop Science 25: 5-8.

Baker, R.J. and Dyck, P.L., 1975. Relation of several quality characteristics to hardness in two spring wheat crosses. Canadian Journal of Plant Science 55: 625-627.

Barlow, K.K., Buttrose, M.S., Simmonds, D.H. and Vesk, M., 1973. The nature of the starch-protein interface in wheat endosperm. Cereal Chemistry 50: 443-451.

Bass, E.J., 1988. Wheat flour milling. Pages 1-68 in: Wheat: Chemistry and Technology. Volume II. 3rd edition. Y. Pomeranz, ed. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA.

Basset, L.M., Allan, R.E. and Rubenthaler, G.L., 1989. Genotype X environment interactions on soft white winter wheat quality. Agronomy Journal 81: 955-960.

Bechtel, D.B., Wilson, J.D. and Martin, C.R., 1996. Determining endosperm texture in developing hard and soft red winter wheats dried by different methods using the single kernel wheat characterisation system. Cereal Chemistry 73: 567-570.

Bergman, C.J., Gualberto, D.G., Campbell, K.G., Sorrels, M.E. and Finney, P.L., 1998. Genotype and environment effects on wheat quality traits in a population derived from soft by hard cross. Cereal Chemistry 75: 729-737.

Berman, M., Bason, M.L., Ellison, F., Peden, G. and Wrigley, C.W., 1996. Image analysis of whole grains to screen for flour-milling yield in wheat breeding. Cereal Chemistry 73: 323-327.

Bettge, A.D., Morris, C.F. and Greenblatt, G.A., 1995. Assessing genotypic softness in single wheat kernels using starch granule-associated friabilin as biochemical marker. Euphytica 86: 65-72.

Bhatt, G.M., 1972. Inheritance of heading date, plant height and kernel weight in two spring wheat crosses. Crop Science 12: 95-98.

Bietz, J.A. and Wall, S.J., 1972. Wheat gluten subunits: Molecular weights determined by SDS-polyacrylamide gel electrophoresis. Cereal Chemistry 49: 416-430.

Blackman, J.A. and Payne, P.I., 1987. Grain Quality. Pages 455-485 in: Wheat Breeding, its scientific basis. F.G.H. Lupton, ed. Chapman and Hall Ltd, University Press, Cambridge, UK.

Blumenthal, C., Békés, F., Gras, P.W., Barlow, E.W.R. and Wrigley, C.W., 1995. Identification of wheat genotypes tolerant to the effects of heat stress on grain quality. Cereal Chemistry 72: 539-544.

Blumenthal, C., Rawson, H.M., McKenzie, E., Gras, P.W., Barlow, E.W.R. and Wrigley, C.W., 1996. Changes in the grain quality of field-grown wheat due to doubling the level of atmospheric carbon dioxide. Cereal Chemistry 73: 762-776.

Bordes, J., Branlard, G., Oury, F.X., Charmet, G. and Balfourier, F., 2008. Agronomic characteristics, grain quality and flour rheology of 372 bread wheats in a worldwide core collection. Journal of Cereal Science 48: 569-579.

Branlard, G. and Dardevet, M., 1985. Diversity of grain protein and bread wheat quality. II. Correlation between HMW subunits of glutenin and flour quality characteristics. Journal of Cereal Science 3: 345-354.

Branlard, G., Dardevet, M., Saccomano, R., Laguotte, F. and Gourdon, J., 2001. Genetic diversity of wheat storage proteins and bread wheat quality. Euphytica 119: 59-67.

Bushuk, W., 1998. Wheat breeding for end-product use. Euphytica 100: 137-145.

Carter, B.P., Morris, C.F. and Anderson, J.A., 1999. Optimising the SDS-sedimentation test for end-use quality selection in a soft white and club wheat breeding program. Cereal Chemistry 76: 907-911.

Carver, B.F., 1996. Yield and hard wheat quality attributes in hard x soft red winter progeny. Crop Science 36: 433-438.

Cauvain, S.P., 2003. Bread making: an overview. Pages 1-27 in: Bread making. Improving quality. 1st edition. S.P. Cauvain, ed. Woodhead Publishing Limited, Cambridge, England and CRS Press LLC, USA.

Chamberlain, N., Collins, T.H. and McDermott, E.E., 1981. Alpha-amylase and bread properties. International Journal of Food Science and Technology 16:127-152.

Charles, S.G., Patrick, L.F. and Gordon, R., 1996. Milling and baking qualities of some wheats developed for Eastern or North-western regions of the United States and grown at both locations. Cereal Chemistry 73: 521-525.

Chung, O.K., Ohm, J.B., Caley, M.S. and Seabourn, B.W., 2001. Prediction of baking characteristics of hard winter wheat flours using computer-analysed mixograph parameters. Cereal Chemistry 78: 493-497.

Czarnecki, E. and Evans, L.E., 1986. Effect of weathering during delayed harvest on test weight, seed size and grain hardness of wheat. Canadian Journal of Plant Science 66: 473-482.

D'Appolonia, B.L. and Kunerth, W.H., 1969. The farinograph handbook. 1st edition. B.L. D'Appolonia and W.H. Kunerth, eds. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA.

De Villiers, O.T. and Laubscher, E.W., 1995. Use of the SDS-test to predict the protein content and bread volume of wheat cultivars. South African Journal of Plant and Soil 12: 140-142.

Dexter, J.E., Williams, P.C., Edwards, N.M. and Martin, D.G., 1988. The relationships between durum wheat vitreousness, kernel hardness and processing quality. Journal of Cereal Science 53: 169-181.

Dhlaliwal, A.S., Mares, D.J. and Marshall, D.R., 1987. Effect of 1B/1R chromosome translocation on milling and quality characteristics of bread wheats. Cereal Chemistry 64: 72-76.

Dick, J.W. and Matsuo, R.R., 1988. Durum wheat and pasta. Pages 507-547 in: Wheat: Chemistry and Technology. Volume II. 3rd edition. Y. Pomeranz, ed. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA.

Dick, J.W. and Quick, J.S., 1983. A modified screening test for rapid estimation of gluten strength in early generation durum wheat breeding lines. Cereal Chemistry 60: 315-318.

Dobraszczyk, B.J., 1994. Fracture mechanics of vitreous and mealy wheat endosperm. Journal of Cereal Science 19: 273-282.

Dobraszczyk, B.J. and Schofield, J.D., 2002. Rapid assessment and prediction of wheat and gluten baking quality with the 2-g direct drive mixograph using multivariate statistical analysis. Cereal Chemistry 79: 607-612.

Doekes, G.J. and Belderok, B., 1976. Kernel hardness and baking quality of wheat: a genetic analysis using chromosome substitution lines. Euphytica 25: 565-576.

Don, C., Lichtendonk, W.J., Plijter, J.J. and Hamer, R.J., 2003. Understanding the link between GMP and dough: from glutenin particles in flour towards developed dough. Journal of Cereal Science 38: 157-165.

Donelson, J.R., Gaines, C.S., Andrews, L.C. and Finney, P.L., 2002. Prediction of test weight from a small volume specific gravity measurement. Cereal Chemistry 79: 227-229.

Dong, H., Sears, R.G., Cox, T.S., Hoseney, R.C., Lookhart, G.L. and Shogren, M.D., 1992. Relationships between protein composition and mixograph and loaf characteristics in wheat. Cereal Chemistry 69: 132-136.

Dowell, F.E., Maghirang, E.B., Pierce, R.O., Lookhart, G.L., Bean, S.R., Xie, F., Caley, M.S., Wilson, J.D., Seabourn, B.W., Ram, M.S., Park, S.H. and Chung, O.K., 2008. Relationship of bread quality to kernel, flour and dough properties. Cereal Chemistry 85: 82-91.

Dowell, F.E., Maghirang, E.B., Xie, F., Lookhart, G.L., Pierce, R.O., Seabourn, B.W., Seabourn, Bean, S.R., Wilson, J.D. and Chung, O.K., 2006. Predicting wheat quality characteristics and functionality using near-infrared spectroscopy. Cereal Chemistry 83: 529-536.

DuPont, F.M. and Altenbach, S.B., 2003. Molecular and biochemical impacts of environmental factors on wheat grain development and protein synthesis. Journal of Cereal Science 38: 133-146.

DuPont, F.M., Chan, R. and Lopez, R., 2007. Molar fractions of HMW glutenin subunits are stable when wheat is grown under various mineral nutrition and temperature regimens. Journal of Cereal Science 45: 134-139.

DuPont, F.M., Hurkman, W.J., Vensel, W.H., Chan, R., Lopez, R., Tanaka, C.K., Altenbach, S.B., 2006. Differential accumulation of sulfur-rich and sulfur-poor wheat flour proteins is affected by temperature and mineral nutrition during grain development. Journal of Cereal Science 44: 101-112.

Eckert, B., Amend, T. and Belitz, H.D., 1993. The course of SDS- and Zeleny-sedimentation tests for gluten quality and related phenomena studied using the light microscope. Lebensmittel Wissenschaft und Technologie - Food Science and Technology 196: 122-125.

Edwards, R.A., Ross, A.S., Mares, D.J., Ellison, F.W. and Tomlinson, J.D., 1989. Enzymes from rain-damaged and laboratory-germinated wheat. I. Effects on product quality. Journal of Cereal Science 10: 157-167.

Eliasson, A. and Larsson, K., 1993. Cereals in bread making, a molecular colloidal approach. Marcal Dekker, Inc., New York .

Figueroa, J.D.C., Maucher, T., Reule, W. and Peña, R.J., 2009. Influence of HMW glutenins on viscoelastic properties of intact wheat kernel and relation to functional properties of wheat dough. Cereal Chemistry 86: 139-144.

Finney, K.F., 1997. Factors influencing the mixogram. Pages 19-26 in: The mixograph handbook. 1st edition. C.E. Walker, J.L. Hazelton and M.D. Shogren, eds. National Manufacturing Division, TMCO, Lincoln, NE68508-2935, USA.

Finney, K.F. and Shogren, M.D., 1972. A 10g mixograph for determining and predicting functional properties of wheat flours. Bakers Digest 46: 32-35, 38-42, 77.

Finney, K.F., Yamazaki, W.T., Youngs, V.L. and Rubenthaler, G.L., 1987. Quality of hard, soft and durum wheats. Pages 677-748 in: Wheat and wheat improvement. 2nd edition. E.G. Heyne, ed. American Society of Agronomy, Inc., Crop Science Society of America, Inc., Soil Science Society of America, Inc., USA.

Fowler, A.A. and Priestly, R.J., 1991. Focus on quality. Food industries of South Africa 44: 15-25.

Fowler, D.B. and De la Roche, I.A., 1975. Wheat quality evaluation. 2. Relationships among prediction tests. Canadian Journal of Plant Science 55: 251-262.

Gaines, C.S., 1991. Associations among quality attributes of red and white soft wheat cultivars across locations and crop years. Cereal Chemistry 68: 56-59.

Gaines, C.S., Finney, P.L. and Andrews, L.C., 1997. Influence of kernel size and shrivelling on soft wheat milling and baking quality. Cereal Chemistry 74: 700-704.

Gaines, C.S., Finney, P.F., Fleege, L.M. and Andrews, L.C., 1996b. Predicting a hardness measurement using the Single Kernel Characterisation System. Cereal Chemistry 73: 278-283.

Gaines, C.S., Finney, P.L and Rubenthaler, G.L., 1996a. Milling and baking qualities of some wheats developed for Eastern and North-western regions in the United States and grown at both locations. Cereal Chemistry 73: 521-525.

Gibson, L.R., McCluskey, P.J., Tilley, K.A. and Paulsen, G.M., 1998. Quality of hard red winter wheat grown under high temperature conditions during maturation and ripening. Cereal Chemistry 75: 421-427.

Gras, P.W. and O'Brien, L., 1992. Application of a 2g mixograph to early generation selection for dough strength. Cereal Chemistry 69: 254-257.

Graybosch, R.A., Peterson, C.J., Shelton, D.R. and Baenziger, P.S., 1996. Genotypic and environmental modification of wheat flour protein composition in relation to end-use quality. Crop Science 36: 296-300.

Greenwell, P. and Schofield, J.D., 1986. A starch granule protein associated with endosperm softness in wheat. Cereal Chemistry 63: 379-380.

Gupta, R.B. and MacRitchie, F., 1994. Allelic variation at glutenin subunit and gliadin loci, Glu-1, Glu-3 and Gli-1 of common wheats. II. Biochemical bias of the allelic effects on dough properties. Journal of Cereal Science 19: 19-29.

Hagberg, S., 1960. A rapid method for determining alpha-amylase activity. Cereal Chemistry 37: 218-222.

Hazen, S.P. and Ward, R.W., 1997. Variation in soft winter wheat characteristics measured by the Single Kernel Characterisation System. Crop Science 37:1079-1086.

Hoseney, R.C., 1994. Principles of cereal science and technology. 2nd edition. R.C.Hoseney, ed. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA.

Hou, G., Yamamoto, H. and NG, P.K.W., 1996. Relationships of quality of glutenin subunits of selected US soft wheat flours to rheological and baking properties. Cereal Chemistry 73: 358-363.

Huebner, F.R. and Gaines, C.S., 1992. Relationship between wheat kernel hardness, environment and gliadin composition. Cereal Chemistry 69: 148-151.

Huebner F.R., Nelsen T.C., Chung O.K. and Bietz J.A., 1997. Protein distributions among hard red winter wheat varieties as related to environment and baking quality. Cereal Chemistry 74: 123-128.

Ingelin, M.E., 1997. Comparison of two recording dough mixers. Pages 5-11 in: The mixograph handbook. 1st edition. C.E. Walker, J.L. Hazelton and M.D. Shogren, eds. National Manufacturing Division, TMCO, Lincoln, NE 68508-2935, USA.

Jalaluddin, M.D. and Harrison, S.A., 1989. Heritability, genetic correlation and genotype x environment interactions of soft red winter wheat yield and test weight. Cereal Research Communications 17: 43-49.

Janssen, A.M., Van Vliet, T. and Vereijken, J.M., 1996a. Rheological behaviour of wheat glutens at small and large deformations. Comparison of two glutens differing in bread making potential. Journal of Cereal Science 23: 19-31.

Janssen, A.M., Van Vliet, T. and Vereijken, J.M., 1996b. Rheological behaviour of wheat glutens at small and large deformations. Effect of gluten composition. Journal of Cereal Science 23: 33-42.

Jones, J. and Kosina, P. 2007. What determines wheat quality? http://www.knowledgebank.cimmyt.org. 24-04-2008.

Kaldy, M.S. and Rubenthaler, G.L., 1987. Milling, baking and physical-chemical properties of selected soft white winter and spring wheats. Cereal Chemistry 64: 302-307.

Kent, N.L., 1984. Technology of cereals. 3rd edition (reprinted with corrections). N.L. Kent, ed. Pergamon Press, Oxford.

Khatkar, B.S., Bell, A.E. and Schofield, J.D., 1996. A comparative study of the inter-relationships between mixograph parameters and bread making qualities of wheat flours and glutens. Journal of the Science of Food and Agriculture 72: 71-85.

Koekemoer, F.P., 2003. Genetic variability of South African spring wheats for milling and bread making quality. PhD Thesis, University of the Free State, Bloemfontein, RSA.

Koekemoer, F.P., Labuschagne, M.T. and Van Deventer, C.S., 1999. A selection strategy for combining high grain yield and high protein content in South African wheat cultivars. Cereal Research Communications 27: 107-114.

Koen, E., 2006. The use of gluten proteins to predict bread and durum wheat quality. PhD Thesis, University of the Free State, Bloemfontein, RSA.

Kosmolak, F.G. and Dyck, P.L., 1981. Milling and baking qualities of the spring wheat cultivars from the People's Republic of China. Cereal Chemistry 58: 246-247.

Kovacs, M.I.P., 1985. An improved SDS-sedimentation test for early generation screening of durum wheat quality. Sciences Des Aliments 5: 123-131.

Krattiger, A.F. and Law, C.N., 1991. The effects of adding NaCl and 2-mercaptoethanol and of other modifications to the SDS-sedimentation test. Pages 156-169 in: Gluten Proteins. W. Bushuk and R. Tkachuk, eds. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA.

Kulp, K., Roewe-Smith, P. and Lorenz, K., 1983. Pre-harvest sprouting of winter wheat. I. Rheological properties of flours and physicochemical characteristics of starches. Cereal Chemistry 60: 355-359.

Labuschagne, M.T., Claassen, A. and Van Deventer, C.S., 1997. Biscuit-making quality of backcross derivatives of wheat differing in kernel hardness. Euphytica 96: 263-266.

Labuschagne, M.T. and Van Vuuren, A., 2000. The inheritance and expression of grain texture in wheat, as measured by a microtome procedure. Euphytica 112: 261-265.

Lang, C.E., Neises, E.K. and Walker, C.E., 1992. Effects of additives on flour water dough mixograms. Cereal Chemistry 69: 587-591.

Li, Y.Z. and Posner, E.S., 1989. An experimental milling technique for various flour extraction levels. Cereal Chemistry 66: 324-328.

Löffler, C.M. and Busch, R.H., 1982. Selection for grain protein, grain yield and nitrogen partitioning efficiency in hard red spring wheat. Crop Science 22: 591-595.

Lukow, O.M., 1997. Quality screening using the mixograph in Canada. Pages 73-74 in: The mixograph handbook. 1st edition. C.E. Walker, J.L. Hazelton and M.D. Shogren, eds. National Manufacturing Division, TMCO, Lincoln, NE 68508-2935, USA.

Lundh, G. and MacRitchie, F., 1989. Size-exclusion HPLC characterisation of gluten protein fractions varying in bread making potential. Journal of Cereal Science 10: 247-253.

Lyon, D.J. and Shelton, D.R., 1999. Fallow management and nitrogen fertiliser influence on winter wheat kernel hardness. Crop Science 39: 448-452.

MacRitchie, F., 1984. Baking quality of wheat flours. Advances in Food Research 29: 201-277.

MacRitchie, F., 1999. Wheat proteins: Characterisation and role in flour functionality. Cereal Foods World 44: 188-193.

Mailhot, W.C. and Patton, J.C., 1988. Criteria of flour quality. Pages 69-90 in: Advances in cereal science and technology. Volume X. Y. Pomeranz, ed. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA.

Malouf, R.B., Lin, W.D.A. and Hoseney, R.C., 1992. Wheat hardness. II. Effect of starch granule protein on endosperm tensile strength. Cereal Chemistry 69: 169-173.

Marais, G.F. and D'Appolonia, B.L., 1981. Factors contributing to baking quality difference in hard red spring wheat. II. Bases for different loaf volume properties. Cereal Chemistry 58: 444-447.

Marchylo, B.A., Lukow, O.M. and Kruger, J.E., 1992. Quantitative variation in HMW subunit 7 in some Canadian wheats. Journal of Cereal Science 15: 29-37.

Marshall, D.R., Mares, D.J., Moss, H.J. and Ellison, F.W., 1986. Effects of grain shape and size on milling yields in wheat. II. Experimental studies. Australian Journal of Agricultural Research 37: 331-342.

Martinant, J.P., Nicolas, Y., Bouguennec, A., Popineau, Y., Saulnier, L. and Branlard, G., 1998. Relationships between mixograph parameters and indices of wheat grain quality. Journal of Cereal Science 27: 179-189.

Miralbés, C., 2004. Quality control in the milling industry using near-infrared transmittance spectroscopy. Food Chemistry 88: 621-628.

Monsalve-Gonzalez, A. and Pomeranz, Y., 1993. Effect of spring and winter growth habitat on compositional milling and baking characteristics of winter wheats. Cereal Chemistry 70: 354-359.

Moonen, J.H.E., Scheepstra, A. and Graveland, A., 1982. Use of the SDS-sedimentation tests and SDS-polyacrylamide gel electrophoresis for screening breeder's samples of wheat for bread making quality. Euphytica 31: 677-690.

Morris, C.F., 1992. Impact of blending hard and soft white wheats on milling and baking quality. Cereal Foods World 37: 643-648.

Morris, C.F., 2002. Puroindolines: the molecular genetic basis of wheat grain hardness. Plant Molecular Biology 48: 633-647.

Morris, C.F. and Rose, S.P., 1996. Wheat. Pages 3-54 in: Cereal Grain Quality. 1st edition. R.J. Henry and P.S. Kettlewell, eds. Chapman and Hall, London, UK.

Neacşu, A., Stanciu, G. and Sãulescu, N.N., 2009. Most suitable mixing parameters for use in breeding bread wheat for processing quality. Cereal Research Communications 37: 83-92.

Nel, M.M., Agenbag, G.A. and Purchase, J.L., 1998. Sources of variation for yield, protein content and hectolitre mass of spring wheat (*Triticum aestivum* L.) cultivars of the Western and Southern Cape. South African Journal of Plant and Soil 15: 72-79.

Neufeld, K.J. and Walker, C.E., 1990. Evaluation of commercial wheat gluten using the mixograph. Cereal Foods World 35: 667-669.

Ohm, J.B., Chung, O.K. and Deyoe, C.W., 1998. Single kernel characteristics of hard winter wheats in relation to milling and baking quality. Cereal Chemistry 75: 156-161.

Ohm, J.B. and Chung, O.K., 1999. Gluten, pasting, and mixograph parameters of hard winter wheat flours in relation to bread making. Cereal Chemistry 76: 606-613.

Oliver, J.R., Blakeney, A.B. and Allen, H.M., 1993. The colour of flour streams as related to ash and pigment contents. Journal of Cereal Science 17: 169-182.

Osborne, T.B., 1907. The protein of the wheat kernel. Publication No 84, Carnegie Institute Washington DC.

Payne, P.I., Nightingale, M.A., Krattiger, A.F. and Holt, L.M., 1987. The relationship between HMW glutenin subunit composition and bread making quality of British grown wheat varieties. Journal of the Science of Food and Agriculture 40: 51-65.

Perten, H., 1964. Application of the falling number method for evaluating alpha-amylase activity. Cereal Chemistry 41: 127-140.

Peterson, C.J., Graybosch, R.A., Baenziger, P.S. and Grombacher, A.W., 1992. Genotype and environment effects on quality characteristics of hard winter wheat. Crop Science 32: 98-103.

Pitz, W.J., 1997. Mixograph application for the evaluation of wheat used for pasta. Pages 65-66 in: The mixograph handbook. 1st edition. C.E. Walker, J.L. Hazelton and M.D. Shogren, eds. National Manufacturing Division, TMCO, Lincoln, NE 68508-2935, USA.

Pomeranz, Y. and Mattern, P.J., 1988. Genotype and genotype X environment interaction effects on hardness estimates in winter wheat. Cereal Foods World 33: 371-374.

Pomeranz, Y., Peterson, C.J. and Mattern, P.J., 1985. Hardness of winter wheats grown under widely different climatic conditions. Cereal Chemistry 62:463-467.

Pomeranz, Y. and Williams, P.C., 1990. Wheat hardness: its genetic, structural and biochemical background, measurement and significance. Pages 471-548 in: Advances in cereal science and technology. Volume X. Y. Pomeranz, ed. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA.

Pon, C.R., Lukow, O.M. and Buckley, D.J., 1989. A multichannel, computer-based system for analysing dough rheology. Journal of Texture Studies 19: 343-360.

Ponte, J.G.(Jnr) and Ingelin, M.E., 1997. Effects of baking ingredients and additives on mixograms. Pages 55-62 in: The mixograph handbook. 1st edition. C.E. Walker, J.L. Hazelton and M.D. Shogren, eds. National Manufacturing Division, TMCO, Lincoln, NE 68508-2935, USA.

Posner, E.S. and Hibbs, A.N., 1997. Wheat flour milling. E.S. Posner and A.N. Hibbs, eds. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA.

Preston, K.R., Lukow, O.M. and Morgan, B., 1992. Analysis of relationships between flour quality properties and protein fractions in a world wheat collection. Cereal Chemistry 69: 560-567.

Preston, K.R., Morgan, B.C. and Dexter, J.E., 1995. Influence of protein segregation on the quality characteristics of Biggar and Genesis Canada Prairie spring wheat. Canadian Journal of Plant Science 75: 599-604.

Pumphrey, F.V. and Rubenthaler, G.L., 1983. Lodging effects on yield and quality of soft white wheat. Cereal Chemistry 60: 268-270.

Rakszegi, M., Békés, F., Láng, L., Tamás, L., Shewry, P.R. and Bedo, Z., 2005. Technological quality of transgenic wheat expressing an increased amount of a HMW glutenin subunit. Journal of Cereal Science 42: 15-23.

Rogers, D.E., Hoseney, R.C., Lookhart, G.L., Curran, S.P., Lin, W.D.A. and Sears, R.G., 1993. Milling and cookie baking quality of near-isogenic lines of wheat differing in kernel hardness. Cereal Chemistry 70: 183-187.

Sadouki, H., Cazalis, R. and Azzout, B., 2006. Fractionation of Algerian common wheat proteins with 50 p. 100 2-propanol: relationship with the technological quality. Lebensmittel Wissenschaft und Technologie - Food Science and Technology 39: 70-79.

SAGL, 2010. Analysis procedure and evaluation norms for the classification of wheat breeders' lines for the RSA. September 2010 revision.

Sandstedt, R.M. and Ofelt, C.W., 1940. A varietal study of the relation between protein quality and protein content. Cereal Chemistry 17: 714-725.

Saint Pierre, C., Peterson, C.J., Ross, A.S., Ohm, J.B., Verhoeven, M.C., Larson, M., and Hoefer, B., 2008. Winter wheat genotypes under different levels of nitrogen and water stress: Changes in grain protein composition. Journal of Cereal Science 47: 407-416.

Schuler, S.F., Bacon, R.K., Finney, P.L. and Gbur, E.E., 1995. Relationship of test weight and kernel properties to milling and baking quality in soft red winter wheat. Crop Science 35: 949-953.

Shewry, P.R., 2003. Wheat gluten proteins. Pages 1-13 in: Wheat gluten protein analyses. P.R. Shewry and G.L. Lookhart, eds. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA.

Shewry, P.R. and Tatham, A.S., 1989. New light on an old technology. The structure of wheat gluten and its role in bread making. Outlook on Agriculture 18: 65-71.

Shewry, P.R., Tatham, A.S., Forde, J., Kreis, M. and Miflin, B.J., 1986. The classification and nomenclature of wheat gluten proteins: a re-assessment. Journal of Cereal Science 4: 97-106.

Shogren, M.D. and Finney, K.F., 1984. Bread making test for 10 grams of flour. Cereal Chemistry 61: 418-423.

Singh, N.K., Donovan, R. and MacRichie, F., 1990. Use of sonication and size-exclusion HPLC in the study of wheat flour proteins. II. Relative quantity of glutenin as a measure of bread making quality. Cereal Chemistry 67: 161-170.

Souza, E., Tyler, J.M., Kephart, K.D. and Kruk, M., 1993. Genetic improvement in milling and baking quality of hard red spring wheat cultivars. Cereal Chemistry 70: 280-285.

Steve, F.S., Robert, K.B., Patrick, L.F. and Edward, E.G., 1995. Relationship of test weight and kernel properties to milling and baking quality in soft winter wheat. Crop Science 35: 949-953.

Symes, K.J., 1965. The inheritance of grain hardness in wheat as measured by the particle size index. Australian Journal of Agricultural Research 16: 113-123.

Symes, K.J., 1969. Influence of a gene causing hardness on the milling and baking quality of two wheats. Australian Journal of Agricultural Research 20: 971-979.

Tsilo, T.J., Hareland, G.A., Simsek, S., Chao, S. and Anderson, J.A., 2010. Genome mapping of kernel characteristics in hard red spring wheat breeding lines. Theoretical and Applied Genetics 121:717-730.

Turnbull, K.M. and Rahman, S., 2002. Endosperm texture in wheat. Journal of Cereal Science 36: 327-337.

Uthayakumaran, S., Beasley, H.L., Stoddard, F.L., Keentok, M., Phan-Thien, N.,Tanner, R.I. and Békés, F., 2002. Synergistic and additive effects of

three HMW glutenin subunit loci. I. Effects on wheat dough rheology. Cereal Chemistry 79: 294-300.

Uthayakumaran, S., Gras, P.W., Stoddard, F.L. and Békés, F., 1999. Effect of varying protein content and glutenin-to-gliadin ratio on the functional properties of wheat dough. Cereal Chemistry 76: 389-394.

Uthayakumaran, S., Tömösközi, S., Tatham, A.S., Savage, A.W.J., Gianibelli, M.C., Stoddard, F.L. and Békés, F., 2001. Effects of gliadin fractions on functional properties of dough depending on molecular size and hydrophobicity. Cereal Chemistry 78: 138-141.

Van Lill, D., 1992. Environmental effects on yield and bread making quality of some South African wheat cultivars. PhD Thesis, University of Stellenbosch, Stellenbosch, RSA.

Van Lill, D. and Purchase, J.L., 1995. Directions in breeding for winter wheat yield and quality in South Africa from 1930 to 1990. Euphytica 82: 79-87.

Van Lill, D., Purchase, J.L., Smith, M.F., Agenbag, G.A. and De Viliers, O.T., 1995. Multivariate assessment of environmental effects on hard red winter wheat. I. Principle components analysis on yield and bread making characteristics. South African Journal of Plant and Soil 12: 158-163.

Van Lill, D. and Smith, M.F., 1997. A quality assurance strategy for wheat (*Triticum aestivum* L.) where growth environment predominates. South African Journal of Plant and Soil 14: 183-191.

Veraverbeke, W.S. and Delcour, J.A., 2002. Wheat protein composition and properties of wheat glutenin in relation to bread making functionality. Critical Reviews in Food Science and Nutrition 42: 179-208.

Walker, C.E. and Hazelton, J.L., 1996. Dough rheological tests. Cereal Foods World 41: 23-28.

Walker, A.E. and Walker, C.E., 1992. Documentation and user's instructions for Mixsmart. National Manufacturing Division, TMCO, 507 J. Street, Lincoln, NE68508, USA.

Walker, C.E., Walker, A.E. and Hazelton, J.L., 1997. Computerising the mixograph: Data collection and analysis. Pages 39-43 in: The mixograph handbook. 1st edition. C.E. Walker, J.L. Hazelton and M.D.

Shogren, eds. National Manufacturing Division, TMCO, Lincoln, NE 68508-2935, USA.

Weegels, P.L., Van de Pijpekamp, A.M., Graveland, A., Hamer, R.J. and Schofield, J.D., 1996. Depolymerisation and re-polymerisation of wheat glutenin dough processing. I. Relationships between glutenin macro-polymer content and quality parameters. Journal of Cereal Science 23: 103-111.

Weipert, D., 1997. The mixograph in Europe. Pages 75-81 in: The mixograph handbook. 1st edition. C.E. Walker, J.L. Hazelton and M.D. Shogren, eds. National Manufacturing Division, TMCO, Lincoln, NE 68508-2935, USA.

Wieser, H., Antes, S. and Seilmeier, W., 1998. Quantitative determination of gluten protein types in wheat flour by reversed-phase HPLC. Cereal Chemistry 75: 644-650.

Wieser, H., Bushuk, W. and MacRitchie, F., 2006. The polymeric glutenins. Pages 213- 240 in: Gliadin and glutenin. The unique balance of wheat quality. C.W. Wrigley, F. Békés and W. Bushuk, eds. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA.

Wieser, H. and Kieffer, R., 2001. Correlations of the amount of gluten protein types to the technological properties of wheat flours determined on a micro-scale. Journal of Cereal Science 34: 19-27.

Wikström, K. and Bohlin, L., 1996. Multivariate analysis as a tool to predict bread volume from mixogram parameters. Cereal Chemistry 73: 686-690.

Wrigley, C.W. and Batey, I.L., 2003. Assessing grain quality. Pages 71-96 in: Bread making. Improving quality. 1st edition. S.P. Cauvain, ed. Woodhead Publishing Limited, Cambridge, England and CRS Press LLC, USA.

Wrigley, C.W. and Békés, F., 1999. Glutenin-protein formation during the continuum from anthesis to processing. Cereal Foods World 44: 562-565.

Yamazaki, W.T. and Donelson, J.R., 1983. Kernel hardness of some U.S. wheats. Cereal Chemistry 60: 344-350.

Zounis, S. and Quail, K.J., 1997. Predicting test bakery requirements from laboratory mixing tests. Journal of Cereal Science 25: 185-196.

CHAPTER 3

GRAIN AND MILLING CHARACTERISTICS AND THEIR RELATIONSHIP WITH SELECTED MIXOGRAM PARAMETERS

ABSTRACT

Limited amount of seed is available for quality testing of experimental lines during the early breeding phases. At this time, bread wheat breeders need to select lines possessing the grain characteristics ensuring acceptable rheological properties of lines in the later breeding phases. Usually then, discrimination against more specific unsatisfactory rheological characteristics occur, when sufficient seed become available for rheological tests requiring larger sample sizes. This study examined the relationships between 13 selected mixogram parameters and grain and milling characteristics usually performed for wheat breeders on breeding material. Although all genotypes used in this study were already commercially released cultivars in South Africa, already complying with the strict release criteria set by the Wheat Technical Committee (WTC) in South Africa, significant differences were observed for all measured characteristics. Highly significant ($p \leq 0.001$) correlations were observed between mixogram parameters and grain and milling characteristics, although no significant correlations were observed between mixogram parameters and hectolitre mass, and between mixogram parameters and flour colour. Multiple stepwise regressions revealed low to moderate contributions made by the grain characteristics to variation in the mixogram parameters, and low contributions of milling characteristics to variation in mixogram parameters.

3.1 INTRODUCTION

During the release process of South African bread wheat cultivars, the WTC sets strict criteria for certain grain and milling characteristics of potential bread wheat cultivars. The primary grain and milling requirements are fixed and non-negotiable and include characteristics such as hectolitre mass (HLM), falling

number (FLN), flour yield (FLY), flour colour expressed on a 76% flour yield basis (C76), grain- (GPC) and flour protein content (FPC). Additional routine analyses performed on samples include vitreous kernels (VK), thousand kernel mass (TKM), kernel diameter (DIAM), hardness index (HI), break flour yield (BFLY) and flour colour (FCL) (SAGL, 2010). Taking into consideration that some of these tests require large amounts of grain and/or flour, are labour intensive and time-consuming, the mixograph, when applying Mixsmart software, can assist wheat breeders in selecting earlier for potential breeding lines to prevent discarding of material during the advanced breeding phases for unacceptable dough and baking characteristics. Sometimes, it also happens that a breeder might only have a small amount of seed available and would like to predict the possible flour and dough characteristics, maybe to utilise this wheat sample in a breeding block or to have it released as a potential cultivar during the advanced breeding phases.

Computerisation of the mixograph resulted in reduced labour, elimination of human interpretation error (Lukow, 1997) as well as more data obtainable from the mixogram. Until recently, the most used and reported mixogram parameter was peak time (Walker and Walker, 1992).

The Mixsmart software draws a midline curve on the mixogram so that upper and lower envelopes result. Midline analysis includes peak time, peak height, and other heights at different times to the left or the right of the peak. Tailheight (at the end of the analysis) as well as the height selected at an arbitrary time (Time X), which the operator chooses, is also reported. Ascending, descending and tail slopes are also reported. The midline area, which is proportional to work input, is also determined. The envelope analysis places curves along the top and bottom of the mixogram (Figure 3.1) and top-envelope peak time, peak height, ascending and descending slopes as well as bandwidth at several points are determined. All results or measurements made are expressed as a single value (Walker and Walker, 1992).

The aim of this study was to determine if selected mixogram parameters can be used as predictors for grain and milling characteristics which can be of

assistance to breeders in selecting for acceptable rheological and baking characteristics, when only a small grain sample is available.

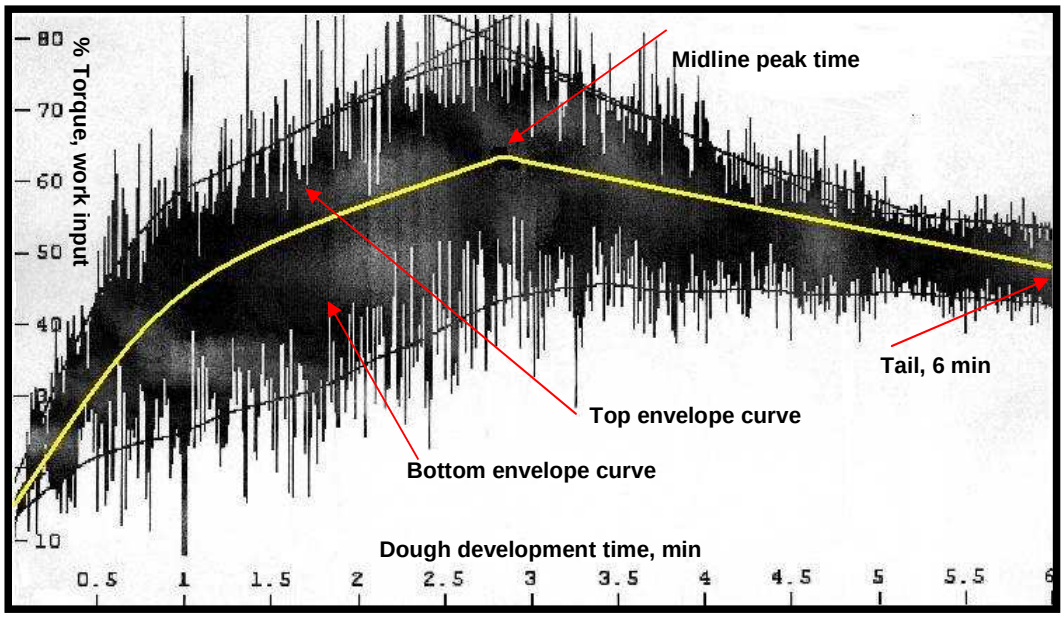

Figure 3.1 An example of a mixogram being analysed by Mixsmart software

3.2 MATERIALS AND METHODS

3.2.1 Field trials

Wheat samples of ten cultivars with four replications were obtained from the National cultivar adaptation programme of the Small Grain Institute, conducted during 2007, under dry land conditions from the summer rainfall area of South Africa. Cultivars included were Betta-DN, Caledon, Elands, Gariep, Komati, Limpopo, Matlabas, PAN3118, PAN3349 and PAN3377.

Localities chosen were representative of a specific production area. Experimental plots were planted at Bethlehem (Eastern Free State), Arlington (Central Free State) and Bothaville (North-western Free State). A randomised complete block design with four replicates was used and each experimental plot consisted of five rows, 5 m in length and with 45 cm inter-row spacing. Pest and weed control were applied when necessary during the growing season and to avoid side-row effect, only the middle three rows were

harvested. Grain samples were dried and cleaned before quality analysis commenced.

Bethlehem has yellow soils with an effective depth, higher rainfall when compared with the other two localities, lower temperatures and a lower evaporation requirement. Arlington has shallow duplex soils, moderate rainfall and moderate temperatures with a lower evaporation requirement. Bothaville has deep, yellow sandy soils where a water table is often present, the lowest rainfall of the three localities, high temperatures and high evaporation requirements.

A fertiliser mixture of 6:2:1 (31) was applied to each trial depending on the long-term yield potential of the specific area. Bethlehem and Bothaville received 242 kg ha^{-1} of fertiliser and Arlington received 220 kg ha^{-1}. Planting dates for Bethlehem, Arlington and Bothaville were 2007-06-05, 2007-06-18 and 2007-04-26 respectively. Harvesting dates for these localities were respectively 2008-01-08, 2008-01-10 and 2007-11-28. Rainfall figures reported prior to planting on all three localities were acceptable for emergence and plant establishment. During winter time (May to August) little rain was reported, which is normal for this area. Rainfall occurred from September onwards which resulted in a normal growing period for the 2007 harvest. Weather data can be viewed in Appendix A, Table 1.

3.2.2 Laboratory methods for quality analysis

All the grain samples were evaluated for hectolitre mass, kernel hardness, thousand kernel mass, kernel diameter, vitreous kernels, protein content (grain and flour) and falling number. The wheat samples were then conditioned and milled and milling characteristics were determined such as break flour yield, flour yield, flour colour and flour colour expressed on a 76% flour yield basis. Mixograph analyses were performed on all flour samples applying Mixsmart software.

3.2.2.1 **Mixograph analyses** (AACC method 54-40A)

A 35 g-mixograph was applied with Mixsmart software. Protein content (AACC procedure 46-30, 2000) and moisture content of a white flour sample (AACC procedure 44–15A, 2000) are needed before a mixogram analyses can commence in order to determine the flour weight and water volume required.

The following formulas as developed by Walker *et al*. (1997) were used to determine the required weight of flour and the required volume of water:

Firstly, protein content was converted to a 14% moisture basis (m.b.):
= [protein (as is) * 86] / (100 - moisture content)

Then, the required weight of flour was determined as follows:
= [86 / (100 – moisture content)] * 35

Lastly, the required volume of water was determined as follows:
= [(1.5 * protein 14% m.b.) + 43.6] * 0.35

The mixograms were constructed as two envelope curves and one midline curve (Figure 3.1). The Mixsmart software uses the midline as well as the top-envelope curve to analyse the mixograms.

Different measurement points determined by Mixsmart software included time values, heights, slopes, widths and areas. Time values were determined directly from the horizontal axis and were expressed in minutes. Heights, expressed as value (%), were determined as the percentage of full scale. Slopes: the value (%) divided by the time in question. Small values are indicative of flat, stable curves. Larger values are indicative of a quick rise and/or breakdown that are undesirable because it exhibits a low tolerance to over mixing. Width values are the difference in the values for the top of envelope and bottom of envelope at a specified time. Midline widths “borrow” information from the envelopes. Areas (integral values) were determined from starting point to the specified time. Integral values are indicative of the work

input for dough development and are determined as follows: the vertical axis (% torque) multiplied by the horizontal axis (minutes), therefore it is expressed as torque*min (Walker and Walker, 1992).

3.2.2.2 **Hectolitre mass** (AACC method 55-10)

Hectolitre mass was performed using a two-level funnel. Hectolitre mass was calculated by dividing the obtained mass by five and was expressed in kg hl^{-1} (AACC, 2000).

3.2.2.3 **Kernel hardness, thousand kernel mass and kernel diameter** (AACC method 55-31)

These traits were determined by using a Single Kernel Characterisation System 4100. Data were obtained from 300 kernels and hardness was based on the required force needed to crush a single kernel. Mean values from the 300 kernels were used (AACC, 2000).

3.2.2.4 **Vitreous kernels**

Vitreous kernels were determined by using a special cutter, a farinator, to cut 50 kernels longitudinally. Kernels were visually scored to determine the percentage vitreous kernels. Translucent kernels scored two, floury kernels scored zero, and kernels that appeared half-translucent half-floury, scored one.

3.2.2.5 **Protein content** (AACC method 46-30)

Crude protein content was determined on whole meal as well as white flour with a LECO FP-2000 (the Dumas combustion method). Total nitrogen (N) was measured by thermal conductivity detection (combustion at high temperature in pure oxygen set N free). Total N was multiplied by factor 5.7 to express protein content of the whole flour as well as white flour on an “as is” basis. To express protein content (whole flour as well as white flour) on a 14% m.b., moisture content was determined by following AACC procedure 44–15A, using a Brabender moisture oven. Ten grams of flour of each sample was

weighed into a moisture dish and dried at 130℃ for 1 h in the Brabender moisture oven. After 1 h, the moisture content was obtained directly from the graduated scale connected to the weighing arm of the Brabender moisture oven by weighing the samples, The following formula was applied to express protein content on a 14% m.b.:

= (Protein, as is x 86) / (100 – moisture content)

3.2.2.6 **Falling number** (AACC method 56-81B)

Falling number is the measurement of alpha-amylase activity by means of the time it takes a metallic stirrer to fall through a flour-water suspension while the suspension is being heated in a boiling water-bath. The altitude-corrected values were used (AACC, 2000).

3.2.2.7 **Break flour yield** (AACC method 26-21A)

Wheat samples were conditioned for 18 h prior to milling, according to AACC procedure 26-95 (2000), namely experimental milling: temper table. Wheat samples were milled on a laboratory, pneumatic mill, Bühler model MLU-202. The percentage of break flour yield was determined for each sample by using the following formula (Bass, 1988):

$$\% \text{ BFLY} = \left(\frac{\text{Total break flour obtained}}{\text{Total (flour + bran)}} \right) * 100$$

3.2.2.8 **Flour yield** (AACC method 26-21A)

The percentage of flour yield was determined for each sample by using the following formula (Bass, 1988):

$$\% \text{ FLY} = \left(\frac{\text{Total flour obtained}}{\text{Total (flour + bran)}} \right) * 100$$

3.2.2.9 **Flour colour** (AACC method 14-30)

Flour colour was measured on a Martin series III colour grader. The influence of the branny material present in the flour sample was measured at a

wavelength of 540 nm. The higher the expressed value, the darker the flour colour, whereas negative values indicated whiter (brighter) flour. Flour colour expressed on a 76% flour yield basis is determined as follows (personal communication, Arie Wessels):

For each 1% flour yield under 76%, 0.4 Kent Jones (KJ) units are added to the measured FCL, therefore flour colour worsens (getting darker), and for each 1% flour yield above 76%, 0.4 KJ units are subtracted from the measured FCL, therefore colour improves (less dark). This is done in order not to discriminate against higher flour-yielding cultivars that will result in darker flour colour (AACC, 2000).

3.2.3 STATISTICAL ANALYSIS

All statistical analyses were performed with Genstat for Windows, 11th edition, (Payne *et al*., 2008).

3.2.3.1 Descriptive statistics

Descriptive statistics were applied to describe some main features, such as minimum, maximum, mean values and standard deviations of the data collection.

3.2.3.2 Analysis of variance (ANOVA)

Combined analysis of variance was performed across the three environments for the selected mixogram parameters and the grain and milling characteristics. The contribution of sources of variation to total variation was calculated from the sum of squares.

3.2.3.3 Correlations

Correlations were performed to determine the relationship between the selected mixogram parameters and the grain characteristics and between the selected mixogram parameters and the milling characteristics.

3.2.3.4 Multiple stepwise regressions

To investigate how the grain characteristics interacted with the selected mixogram parameters and also separately, how the milling characteristics interacted with the selected mixogram parameters, multiple stepwise regressions were used to define the variation caused by the grain and milling characteristics to the fixed characteristics, the mixogram parameters. The independent variables that accounted for the largest amount of variation in the dependant variable were checked for significance and then entered into the regression equation. The coefficient of determination (R^2), expressed as a percentage, is an indication of the variation that can be explained by the relationship between the dependant variable and the independent variables (Van Ark, 1995). R^2 was calculated as follows: $R^2 = r^2 \times 100$, where r^2 denotes the correlation coefficient.

3.3 RESULTS AND DISCUSSION

A total of 44 measurement points were obtained from applying Mixsmart software. Parameters 1 – 22 were obtained from the envelope analysis and parameters 23 – 44 were obtained from midline analysis. All 44 measured parameters, descriptions and units of measurement are available in Appendix A, Table 2. Significant correlations, in agreement with that of Neacşu *et al.* (2009), were observed between midline and envelope mixogram parameters (Table 3.1). Since midline parameters have proved to be more repeatable (Martinant *et al*., 1998), 13 mixogram parameters, which represent the whole dough development process and that are descriptive of basic rheological aspects of the mixing process, were then selected from midline analyses for further analyses. They were:

1) Peak time (PT)
2) Peak height (PH)
3) Tailheight (TH)
4) Ascending angle from beginning until 1 min before PT (AA)
5) Descending angle from PT until 2 min after PT (DA)
6) Curve-width 1 min before PT (W-1)
7) Peakwidth (PW)

8) Curve-width 2 min after PT (W+2)
9) Tailwidth at 6 min (TW)
10) Area under curve from beginning until 1 min before PT (A-1)
11) Area under curve from beginning until PT (AP)
12) Area under curve from beginning until 2 min after PT (A+2)
13) Total area under curve (TA)

Table 3.1 Correlations between envelope (parameters 1 to 22) and midline (parameters 23 to 44) mixogram parameters

Parameter	Parameter description	Correlation	Significance
1 vs 23	Envelope left time vs midline left time	0.18	*
2 vs 24	Envelope left value vs midline left value	0.06	ns
3 vs **25**	Envelope AA vs midline AA	0.05	ns
4 vs **26**	Envelope W-1 vs midline W-1	0.34	***
5 vs **27**	Envelope A-1 vs midline A-1	0.17	ns
6 vs **28**	Envelope PT vs midline PT	0.89	***
7 vs **29**	Envelope PH vs midline PH	0.95	***
8 vs **30**	Envelope PW vs midline PW	0.58	***
9 vs **31**	Envelope AP vs midline AP	0.88	***
10 vs 32	Envelope right time vs midline right time	0.72	***
11 vs 33	Envelope right value vs midline right value	0.47	***
12 vs **34**	Envelope DA vs midline DA	0.39	***
13 vs **35**	Envelope W+2 vs midline W+2	0.86	***
14 vs **36**	Envelope A+2 vs midline A+2	0.85	***
15 vs 37	Envelope tail value vs midline tail value	0.93	***
16 vs 38	Envelope tail slope vs midline tail slope	0.68	***
17 vs 39	Envelope tail width vs midline tail width	1.00	***
18 vs 40	Envelope tail integral vs midline tail integral	0.23	*
19 vs **41**	Envelope TH vs midline TH	0.93	***
20 vs 42	Envelope time X slope vs midline time X slope	0.68	***
21 vs **43**	Envelope TW vs midline TW	1.00	***
22 vs **44**	Envelope TA vs midline TA	0.18	*

ns, Not significant, * p≤0.05, *** p≤0.001. Bold=selected mixogram parameters. AA=ascending angle from beginning until 1 min before PT, W-1=curve-width 1 min before PT, A-1= area under curve from beginning until 1 min before PT, PT=peak time, PH=peak height, PW=peakwidth, AP=area under curve from beginning until PT, DA=descending angle from PT until 2 min after PT, W+2=curve-width 2 min after PT, A+2=area under curve from beginning until 2 min after PT, TH=tailheight, TW=tailwidth, TA=total area under curve

3.3.1 DESCRIPTIVE STATISTICS

3.3.1.1 Means, minimum and maximum values and standard deviations for selected mixogram parameters

Peak time had values ranging between 2.0 min to 5.05 min with mean values ranging between 3.14 min to 3.50 min and standard deviation (SD) values ranging between 0.55 and 0.70 (Table 3.2). Acceptable PT values as required

by the South African industry range between 2.5 to 4.0 min (personal communication – Arie Wessels). Area-parameters (A-1, AP, A+2 and TA) had wide ranges and larger SD values (Table 3.2).

Table 3.2 Mean values, minimum and maximum values and standard deviations of selected mixogram parameters for a set of 10 wheat cultivars

Characteristic	Environment	MEAN	MIN	MAX	SD
PT	Bethlehem	3.14	2.00	4.76	0.67
	Arlington	3.40	2.18	5.05	0.70
	Bothaville	3.50	2.35	4.43	0.55
PH	Bethlehem	58.12	51.34	68.19	3.82
	Arlington	57.35	51.01	67.95	4.53
	Bothaville	57.20	50.33	64.68	3.87
TH	Bethlehem	47.85	43.10	55.26	3.22
	Arlington	49.25	43.35	58.52	3.36
	Bothaville	48.93	44.79	59.14	3.08
AA	Bethlehem	10.85	4.51	18.96	3.06
	Arlington	8.87	-0.62	16.70	3.89
	Bothaville	9.49	2.36	18.01	3.49
DA	Bethlehem	-5.19	-8.81	-1.95	1.40
	Arlington	-3.70	-8.69	6.88	2.67
	Bothaville	-4.45	-6.95	-1.37	1.34
W-1	Bethlehem	38.85	33.68	49.30	3.38
	Arlington	38.90	32.52	48.41	4.30
	Bothaville	37.11	29.76	47.52	3.85
PW	Bethlehem	35.01	28.92	40.25	3.07
	Arlington	35.94	29.14	41.71	2.77
	Bothaville	33.68	26.93	42.28	3.26
W+2	Bethlehem	19.83	12.57	28.62	3.83
	Arlington	23.26	12.34	44.05	6.25
	Bothaville	20.63	13.63	31.92	3.46
TW	Bethlehem	11.98	7.29	22.95	4.57
	Arlington	15.38	7.92	33.67	6.25
	Bothaville	14.21	7.52	26.85	4.27
A-1	Bethlehem	86.7	38.7	159.20	29.3
	Arlington	97.1	38.6	171.20	32.0
	Bothaville	99.0	45.0	145.50	24.2
AP	Bethlehem	142.7	96.7	216.9	30.0
	Arlington	152.5	90.3	228.4	32.7
	Bothaville	154.3	100.6	205.7	24.2
A+2	Bethlehem	199.2	155.8	274.1	30.9
	Arlington	208.5	145.6	289.1	33.3
	Bothaville	210.3	157.7	268.0	24.6
TA	Bethlehem	291.9	269.7	330.1	14.0
	Arlington	290.3	266.7	325.5	14.8
	Bothaville	286.4	261.3	317.3	14.4

PT=peak time, PH=peak height, TH=tailheight, AA=ascending angle from beginning until 1 min before PT, DA=descending angle from PT until 2 min after PT, W-1=curve-width 1 min before PT, PW=peakwidth, W+2=curve-width 2 min after PT, TW=tailwidth at 6 min, A-1=area under curve from beginning until 1 min before PT, AP=area under curve from beginning until PT, A+2=area under curve from beginning until 2 min after PT, TA=total area under curve, MEAN=mean values, MIN=minimum, MAX=maximum, SD=standard deviation

3.3.1.2 Means, minimum and maximum values and standard deviations for grain and milling characteristics

Hectolitre mass values obtained ranged from 75.40 kg hl^{-1} to 84.00 kg hl^{-1} (Table 3.3). These hectolitre mass values are indicative of an acceptable grade (sound wheat) and should therefore be of acceptable milling quality, exhibiting the potential for high flour yields, since a hectolitre mass of 74.00 kg hl^{-1} is required for bread making purposes (Nel *et al*., 1998; SAGL, 2010). Koekemoer (2003) reported that 76.00 kg hl^{-1} and above is preferable when potential breeding lines are submitted for cultivar classification.

Hardness index values ranged from 40.72% to 75.01%, where HI values from 25%-34% is classified as soft, from 35%-44% is classified as medium soft and from 45%-64% is classified as medium hard (AACC 55-31). These results confirm the large influence of environments (Table 3.10) on HI, since only medium hard to hard potential breeding lines can be submitted for commercial cultivar classification in South Africa (SAGL, 2010), although hardness testing is not performed on potential breeding lines submitted for cultivar classification (Koekemoer, 2003).

Thousand kernel mass ranged from 31.71 g to 44.60 g, indicating a wide variety of TKM values. Koekemoer (2003) reported that TKM values of 37 g and above are preferable for the South African market. Kernel diameter values were between 2.56 mm and 3.31 mm and VK ranged from 50.00% to 100.00%, confirming the large influence of the environment on VK (Table 3.10).

Grain protein content ranged from 9.00% to 14.30% and FPC ranged from 7.60% to 12.50%, with the higher values being in the desirable range of the South African processing industry (SAGL, 2010). Koekemoer (2003) confirmed that desirable levels of protein content for the South African industry is 12% or above. The expected 1% loss of GPC to FPC when being milled to flour was observed as was also reported by Halverson and Zeleny (1988) as well as Koekemoer (2003).

Falling numbers were above 250 s, therefore high and acceptable (Perten, 1964; SAGL, 2010) and ranged from 312 s to 744 s. Standard deviations were higher for FLN compared to SD values for all the other grain and milling characteristics. This could have been due to the wide range that was observed for FLN values.

Break flour yield ranged from 19.81% to 30.30% and FLY values ranged from 68.24% to 74.91%. Flour colour ranged from -4.80 KJ to 1.40 KJ and C76 ranged from -3.60 KJ to 1.90 KJ, indicating suitable flour colour for bread production.

Table 3.3 Mean values, minimum and maximum values and standard deviations of grain and milling characteristics evaluated in the three environments for a set of 10 wheat cultivars

Characteristic	Environment	MEAN	MIN	MAX	SD
HLM	Bethlehem	79.31	75.40	82.50	1.96
	Arlington	81.11	78.70	83.20	1.20
	Bothaville	81.18	78.30	84.00	1.46
HI	Bethlehem	58.70	47.48	68.92	5.05
	Arlington	60.82	40.72	69.92	6.13
	Bothaville	68.55	62.87	75.01	3.27
TKM	Bethlehem	38.11	33.71	44.60	2.62
	Arlington	37.55	31.71	42.79	2.63
	Bothaville	37.00	32.30	40.26	2.29
DIAM	Bethlehem	2.89	2.58	3.30	0.15
	Arlington	2.91	2.56	3.31	0.17
	Bothaville	2.87	2.62	3.15	0.17
VK	Bethlehem	66.90	52.00	83.00	8.54
	Arlington	69.08	50.00	93.00	11.99
	Bothaville	88.30	67.00	100.00	8.35
GPC	Bethlehem	12.58	11.30	13.30	0.50
	Arlington	11.83	9.00	13.60	0.94
	Bothaville	12.79	10.70	14.30	0.88
FLN	Bethlehem	523.0	408	744	75.1
	Arlington	395.6	312	512	51.6
	Bothaville	509.5	390	673	68.0
FPC	Bethlehem	11.13	9.40	12.10	0.63
	Arlington	10.26	7.60	12.00	0.93
	Bothaville	11.20	9.30	12.50	0.76
BFLY	Bethlehem	23.18	19.88	25.78	1.33
	Arlington	22.96	20.65	30.30	1.65
	Bothaville	22.73	19.81	27.34	1.79
FLY	Bethlehem	73.22	71.12	74.79	1.02
	Arlington	72.66	70.64	74.44	0.98
	Bothaville	72.88	68.24	74.91	1.11
FCL	Bethlehem	-2.83	-4.80	-1.50	3.30
	Arlington	-2.66	-3.90	-0.90	3.00
	Bothaville	-1.77	-3.50	1.40	4.90
C76	Bethlehem	-1.71	-3.60	0.10	0.87
	Arlington	-1.33	-2.80	1.10	0.81
	Bothaville	-0.52	-2.20	1.90	0.92

HLM=hectolitre mass, HI=hardness index, TKM=thousand kernel mass, DIAM=kernel diameter, VK=vitreous kernels, GPC=grain protein content, FLN=falling number, FPC=flour protein content, BFLY=break flour yield, FLY=flour yield, FCL=flour colour, C76=flour colour expressed on a 76% flour yield basis, MEAN=mean values, MIN=minimum, MAX=maximum, SD=standard deviation

3.3.2 ANOVA

3.3.2.1 The combined ANOVA on selected mixogram parameters

The combined ANOVA (Table 3.4) indicated highly significant ($p \leq 0.001$) differences among cultivars (genotypes) and the interaction between genotype and environments (GXE) for most of the measured mixogram

parameters. This indicated the existence of variable responses between the cultivars and the environments for nearly all the measured mixogram parameters. No significant differences were observed for replications of mixogram parameters measured. A much larger variation was found among genotypes than among environments for all measured mixogram parameters, indicating mixogram parameters to be useful for selection of acceptable quality (Peterson *et al*., 1992). Neacşu *et al.* (2009) also reported higher heritability (larger genotypic effect) for parameters PT, TW and AP, but found the environmental effect to be larger for mixogram parameters AA, PW, PH and TA. Coefficients of variation (CV's) for the selected mixogram parameters ranged from 2.3% for TH to 31.3% for DA. Bordes *et al*. (2008) also reported high CV values for DA.

3.3.2.1.1 Peak time

The combined ANOVA (Table 3.4) revealed highly significant ($p \leq 0.001$) differences for genotypes as well as GXE interaction. Significant differences ($p \leq 0.05$) were detected between environments. The largest variation was attributed to the genotypes (Table 3.5) with a total contribution share of 65.12% to the total variance. In this study, the GXE interaction contributed 11.01% to the total variance and environment contributed only 5.41%.

Peak time means for the cultivars (Table 3.6) varied between 2.41 min (Caledon) and 4.29 min (PAN3118) over the three localities and differences between the cultivars were significant. All cultivars exhibited desirable PT values, except for PAN3118 that might have a PT undesirable for the South African industry. Gariep and Matlabas did not differ significantly and Komati, PAN3349 and PAN3377 did not differ significantly. Environmental means (Table 3.6) varied between 3.14 min (Bethlehem) and 3.50 min (Bothaville). Bethlehem differed significantly from the other two localities, Arlington and Bothaville.

3.3.2.1.2 Peak height

Highly significant (p≤0.001) differences were exhibited between genotypes and for GXE interaction for PH (Table 3.4). The largest variation was contributed by the genotypes (57.76%), GXE and environment contributed 14.3% and 0.99% respectively (Table 3.5).

There were significant differences between cultivars. Environments did not differ significantly (Table 3.6).

3.3.2.1.3 Tailheight

Highly significant differences (p≤0.001) were revealed between genotypes and for GXE interaction. Significant differences (p≤0.05) were observed between environments (Table 3.4). Genotypes were the largest contributor (75.66%) to the total variance. GXE and environment contributed 10.04% and 3.55% respectively (Table 3.5). Significant differences were confirmed for cultivar and environmental means (Table 3.6).

3.3.2.1.4 Ascending angle from beginning until 1 min before peak time

Highly significant (p≤0.001) differences were observed between genotypes (Table 3.4) which contributed 48.03% to the total variance (Table 3.5). Significant differences (p≤0.01) were observed for GXE interaction (Table 3.4) which contributed 13.22% (Table 3.5) and no significant differences were observed for environments (Table 3.4) which contributed 5.46% (Table 3.5). Cultivars differed significantly and Arlington differed significantly from Bethlehem but not from Bothaville (Table 3.6).

3.3.2.1.5 Descending angle from peak time until 2 min after peak time

Highly significant (p≤0.001) differences between genotypes and significant differences (p≤0.01) between environments were observed. No differences were observed for GXE interaction (Table 3.4). Genotypes contributed 41.50% to the total variance in DA and GXE and environment contributed 11.26% and 9.45% respectively (Table 3.5).

3.3.2.1.6 Curve-width 1 min before peak time

Highly significant (p≤0.001) differences were observed for cultivars and significant differences (p≤0.01) for GXE. No differences were observed for environments (Table 3.4). Only PAN3377 differed significantly from the other cultivars (Table 3.7). Genotypes contributed 33.68% to the total variance and GXE and environment contributed 18.98% and 4.56% respectively (Table 3.5).

3.3.2.1.7 Peakwidth

Highly significant differences (p≤0.001) were revealed by the combined ANOVA for genotypes as well as GXE interaction. Significant differences (p≤0.05) were observed for environments (Table 3.4). Genotype, GXE and environment contributed 31.96%, 27.55% and 8.73% respectively to the total variance (Table 3.5).

3.3.2.1.8 Curve-width 2 min after peak time

Highly significant differences (p≤0.001) were observed between genotypes as well as GXE and significant differences (p≤0.01) were observed between environments for W+2 (Table 3.4). Genotypes, GXE and environments contributed respectively 48.30%, 16.33% and 9.11% to the total variance (Table 3.5). Bethlehem and Bothaville differed significantly from Arlington, but not from each other. There were significant differences between genotypes (Table 3.7).

3.3.2.1.9 Tailwidth

Highly significant differences (p≤0.001) were observed for genotypes and significant differences (p≤0.01) were observed for environment as well as GXE for TW (Table 3.4). Genotypes contributed 65.39% to the total variance and GXE and environment made similar contributions, 7.98% and 7.25% respectively (Table 3.5). Caledon and PAN3377 did not differ significantly from each other (Table 3.8) as well as Limpopo and PAN3349. Significant

differences were observed between Komati, Gariep and Matlabas. Arlington and Bothaville did not differ significantly from each other (Table 3.8).

3.3.2.1.10 Area under curve from beginning until 1 min before peak time

Highly significant differences (p≤0.001) were observed between genotypes (Table 3.4) which were the largest contributor (67.05%) to the total variance (Table 3.5). Significant differences (p≤0.01) were observed for the GXE component (Table 3.4) which contributed 9.53% (Table 3.5) and significant differences (p≤0.05) were observed for environments which contributed 3.49% to variation. Caledon differed significantly from the other nine cultivars. Bethlehem differed significantly from Arlington and Bothaville (Table 3.8).

3.3.2.1.11 Area under curve from beginning until peak time

Similar observations regarding differences were made for AP as for A-1, where genotypes, GXE and environments contributed 67.63%, 9.43% and 3.04% to the total variance (Table 3.5). Significant differences occurred between Caledon, Elands and PAN3118 and Betta-DN and Komati did not differ significantly. Bethlehem differed significantly from the other two environments (Table 3.8).

3.3.2.1.12 Area under curve from beginning until 2 min after peak time

As for A-1 and AP, the observed differences were similar as well as the contributions made by the different components (Table 3.4 and Table 3.5). Significant differences were observed between genotypes, but Betta-DN, Komati, Limpopo and PAN3349 did not differ significantly from one another as well as Gariep, Matlabas and PAN3377 (Table 3.8). Arlington and Bothaville did not differ significantly from each other (Table 3.8).

3.3.2.1.13 Total area

This area-parameter differed from the other area-parameters (A-1, AP and A+2). Highly significant differences (p≤0.001) were observed for genotypes

and GXE but no significant differences were observed for environments (Table 3.4). Contributions of the different components to the total variance were 53.16% for genotypes, 20.88% for GXE and 2.55% for environment (Table 3.5). Caledon, Gariep, PAN3118 and PAN3377 differed significantly from one another. The environments did not differ significantly from one another regarding this area-parameter (Table 3.8).

Table 3.4 Combined analysis of variance for the selected mixogram parameters determined on three localities for a set of 10 wheat cultivars

SOURCE	df	MEAN SQUARES												
		PT	PH	TH	AA	DA	W-1	PW	W+2	TW	A-1	AP	A+2	TA
Total	11													
Reps	9	0.46	8.92	2.04	9.98	4.11	3.95	3.76	16.35	16.29	828.20	753.40	673.60	91.88
Environment	3	1.37*	9.87	22.33*	41.23	22.12**	41.74	51.72*	128.56**	119.26**	1739.60*	1565.10*	1402.70*	318.86
Residual A	2	0.16	21.45	3.90	10.79	1.32	24.62	6.57	5.63	10.17	303.80	260.90	227.90	214.01
Genotype	6	3.67**	126.74**	105.72**	80.57**	21.60**	68.52**	42.07**	151.42**	239.03**	7435.10**	7727.60**	8139.80**	1475.36**
GXE	9	*	*	*	*	*	*	*	*	*	*	*	*	*
Residual B	18	0.31**	15.69***	7.01***	11.09**	2.93	19.30**	18.13**	25.59***	14.58**	528.50**	538.50**	553.80**	289.72***
	81	*	4.65	1.31	5.04	1.94	7.70	*	8.12	6.52	192.40	205.40	216.70	52.91
		0.09						4.02						
Grand mean		3.35	57.56	48.69	9.74	-4.45	38.29	34.87	21.24	13.86	94.30	149.80	206.0	289.53
CV (%)		8.8	3.7	2.3	23.0	31.3	7.2	5.7	13.4	18.4	14.7	9.6	7.1	2.5

* p≤0.05, ** p≤0.01, *** p≤0.001. PT=peak time, PH=peak height, TH=tailheight, AA=ascending angle from beginning until 1 min before PT, DA=descending angle from PT until 2 min after PT, W-1=curve-width 1 min before PT, PW=peakwidth, W+2=curve-width 2 min after PT, TW=tailwidth at 6 min, A-1=area under curve from beginning until 1 min before PT, AP=area under curve from beginning until PT, A+2=area under curve from beginning until 2 min after PT, TA=total area under curve

Table 3.5 Contribution (%) of each variance component to the total variation of individual mixogram parameters

SOURCE	PT	PH	TH	AA	DA	W-1	PW	W+2	TW	A-1	AP	A+2	TA
Reps	2.74	1.36	0.49	1.98	2.63	0.65	0.95	1.74	1.49	2.49	2.20	1.89	1.10
Environment	5.41	0.99	3.55	5.46	9.45	4.56	8.73	9.11	7.25	3.49	3.04	2.62	2.55
Residual A	1.84	6.52	1.86	4.29	1.69	8.07	3.33	1.20	1.85	1.83	1.52	1.28	5.14
Genotype	65.12	57.76	75.66	48.03	41.50	33.68	31.96	48.30	65.39	67.05	67.63	68.48	53.16
GXE	11.01	14.3	10.04	13.22	11.26	18.98	27.55	16.33	7.98	9.53	9.43	9.32	20.88
Residual B	13.88	19.07	8.41	27.02	33.47	34.06	27.48	23.32	16.04	15.61	16.18	16.41	17.17
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

PT=peak time, PH=peak height, TH=tailheight, AA=ascending angle from beginning until 1 min before PT, DA=descending angle from PT until 2 min after PT, W-1=curve-width 1 min before PT, PW=peakwidth, W+2=curve-width 2 min after PT, TW=tailwidth at 6 min, A-1=area under curve from beginning until 1 min before PT, AP=area under curve from beginning until PT, A+2=area under curve from beginning until 2 min after PT, TA=total area under curve

Table 3.6 Genotype and environmental means of individual localities for PT, PH, TH and AA

	PT			Cult		PH			Cult		TH			Cult		AA			Cult	
Cultivar	**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**	
Betta-DN	3.05	2.65	3.17	**2.96**	b	54.34	58.15	56.38	**56.29**	bcd	46.24	46.47	47.44	**46.72**	ab	7.88	11.46	10.11	**9.81**	cd
Caledon	2.60	2.19	2.45	**2.41**	a	54.42	62.54	58.35	**58.44**	e	44.82	47.35	45.60	**45.92**	a	10.62	16.50	14.57	**13.90**	e
Elands	4.35	3.55	4.07	**3.99**	e	56.04	56.90	54.50	**55.81**	bc	51.58	49.66	48.97	**50.07**	d	5.12	8.17	7.91	**7.07**	a
Gariep	3.89	3.07	4.02	**3.66**	d	54.44	55.69	51.99	**54.04**	a	50.03	46.20	47.11	**47.78**	c	6.19	9.85	4.38	**6.81**	a
Komati	3.14	2.75	3.26	**3.05**	bc	58.22	56.61	58.00	**57.61**	de	47.59	44.28	47.28	**46.38**	a	11.19	11.31	11.68	**11.39**	d
Limpopo	3.40	2.91	3.43	**3.25**	c	54.83	55.92	58.64	**56.46**	cd	48.12	45.31	49.01	**47.48**	bc	7.82	9.95	10.92	**9.56**	bc
Matlabas	3.72	3.67	3.59	**3.66**	d	58.34	54.96	55.90	**56.40**	cd	51.10	48.96	49.40	**49.82**	d	9.97	7.62	8.12	**8.57**	abc
PAN3118	4.02	4.61	4.24	**4.29**	f	61.78	59.66	61.81	**61.08**	f	56.71	54.57	56.29	**55.86**	e	7.67	9.04	8.83	**8.51**	abc
PAN3349	3.00	2.82	3.66	**3.16**	bc	55.45	55.11	53.16	**54.57**	ab	47.97	45.09	47.29	**46.79**	ab	6.86	10.43	6.07	**7.79**	ab
PAN3377	2.79	3.19	3.1	**3.03**	bc	65.63	65.71	63.26	**64.86**	g	48.69	50.64	50.96	**50.10**	d	15.36	14.21	12.35	**13.97**	e
Env mean	**3.40** b	**3.14** a	**3.50** b	**3.35**		**57.35** a	**58.12** a	**57.20** a	**57.56**		**49.29** b	**47.85** a	**48.93** b	**48.69**		**8.87** a	**10.85** b	**9.49** ab	**9.74**	
LSD Env	**0.2157**					**3.593**					**1.771**					**1.797**				
LSD Cult	**0.2395**					**1.751**					**0.928**					**1.823**				

Means followed by the same letter, did not differ significantly at P=0.05. PT=peak time, PH=peak height, TH=tailheight, AA=ascending angle from beginning until 1 min before PT, Cult means=cultivar means for the three localities, Env mean=environmental means, LSD Env=least significant difference for environments, LSD Cult=least significant difference for cultivars, Ar=Arlington, Be=Bethlehem, Bo=Bothaville

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Table 3.7 Genotype and environmental means of individual localities for DA, W-1, PW and W+2

	DA			Cult		W-1			Cult		PW			Cult		W+2			Cult	
Cultivar	**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**	
Betta-DN	-4.15	-5.71	-4.43	**-4.76**	bcd	35.49	40.92	38.17	**38.20**	a	33.27	35.05	33.69	**34.00**	bc	19.08	19.25	19.82	**19.38**	bc
Caledon	-4.81	-6.62	-5.67	**-5.70**	b	37.17	39.77	35.35	**37.43**	a	33.43	37.87	34.39	**35.23**	cd	19.16	20.29	18.22	**19.22**	bc
Elands	-2.57	-4.11	-3.30	**-3.33**	ef	39.79	37.70	33.21	**36.90**	a	35.77	38.05	30.41	**34.74**	bcd	27.08	23.63	21.32	**24.01**	e
Gariep	-2.22	-4.53	-3.29	**-3.34**	ef	36.41	37.51	34.76	**36.23**	a	34.22	32.45	29.21	**31.96**	a	27.12	19.62	19.52	**22.09**	de
Komati	-5.20	-5.75	-5.35	**-5.44**	bc	37.97	37.30	38.71	**37.99**	a	36.39	31.82	34.83	**34.35**	bc	20.26	14.59	17.91	**17.58**	ab
Limpopo	-2.94	-4.85	-5.15	**-4.31**	cde	34.74	36.17	38.58	**36.50**	a	34.74	31.36	34.63	**33.58**	ab	23.37	18.24	19.54	**20.39**	cd
Matlabas	-4.21	-3.40	-3.68	**-3.76**	def	36.90	38.15	35.20	**36.75**	a	38.08	36.12	34.01	**36.07**	de	24.79	24.98	24.16	**24.64**	f
PAN3118	-0.67	-4.49	-4.34	**-3.17**	f	45.04	39.86	39.33	**41.41**	a	39.57	35.60	38.27	**37.81**	f	32.34	24.56	27.02	**27.97**	g
PAN3349	-2.36	-4.76	-3.07	**-3.39**	ef	41.47	37.17	34.75	**37.80**	a	36.08	33.32	30.62	**33.34**	ab	26.17	16.75	20.25	**21.06**	cd
PAN3377	-7.87	-7.64	-6.23	**-7.25**	a	44.05	43.91	43.01	**43.66**	b	37.85	38.43	36.72	**37.67**	ef	13.24	16.43	18.58	**16.08**	a
Env mean	**-3.70** c	**-5.19** a	**-4.45** b	**-4.45**		**38.90** a	**38.85** a	**37.11** a	**38.29**		**35.94** b	**35.01** ab	**33.68** a	**34.87**		**23.26** b	**19.83** a	**20.63** a	**21.24**	
LSD Env	**0.628**					**2.715**					**1.403**					**1.299**				
LSD Cult	**1.130**					**2.254**					**1.629**					**2.315**				

Means followed by the same letter, did not differ significantly at P=0.05. DA=descending angle from PT until 2 min after PT, W-1=curve-width 1 minute before PT, PW=peakwidth, W+2=curve-width 2 minutes after PT, Cult means=cultivar means for the three localities, Env mean=environmental means, LSD Env=least significant difference for environments, LSD Cult=least significant difference for cultivars, Ar=Arlington, Be=Bethlehem, Bo=Bothaville

Table 3.8 Genotype and environmental means of individual localities for TW, A-1, AP, A+2 and TA

	TW			Cult		A-1			Cult		AP			Cult		A+2			Cult		TA			Cult	
Cultivar	**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**	
Betta-DN	12.44	10.38	12.62	**11.81**	bc	78.3	67.6	85.6	**77.1**	b	131.3	123.5	140.2	**131.7**	b	184.6	180.1	195.3	**186.7**	b	279.23	296.33	286.57	**287.38**	bcd
Caledon	11.20	8.88	9.24	**9.78**	ab	58.8	48.0	52.5	**53.1**	a	111.4	107.0	107.7	**108.7**	a	164.8	167.3	164.1	**165.4**	a	278.80	310.48	288.49	**292.59**	d
Elands	22.07	13.71	16.11	**17.29**	de	138.7	103.6	116.8	**119.7**	d	194.2	159.3	170.1	**174.5**	f	249.3	215.5	223.6	**229.5**	d	284.26	291.09	270.43	**281.93**	ab
Gariep	19.49	11.69	15.80	**15.66**	d	116.2	81.5	118.2	**105.3**	c	169.7	135.2	169.6	**158.2**	de	223.4	189.4	220.7	**211.2**	c	280.82	283.15	267.81	**277.26**	a
Komati	9.60	7.68	9.69	**8.99**	a	83.2	66.1	84.4	**77.9**	b	139.3	119.9	139.9	**133.0**	b	196.1	174.5	196.0	**188.9**	b	290.05	280.68	282.79	**284.51**	bc
Limpopo	15.13	9.61	11.45	**12.06**	c	94.1	72.0	95.2	**87.1**	b	147.5	125.8	151.9	**141.7**	bc	201.7	180.1	209.0	**196.9**	b	282.45	280.53	290.05	**284.34**	bc
Matlabas	17.05	18.15	18.22	**17.81**	e	111.8	111.2	105.5	**109.5**	cd	168.5	164.8	160.2	**164.5**	ef	225.9	219.0	215.4	**220.1**	c	294.29	286.65	288.00	**289.65**	cd
PAN3118	25.17	21.56	22.03	**22.92**	f	131.1	151.8	138.6	**140.5**	e	188.6	209.8	198.4	**198.9**	g	247.0	268.1	259.5	**258.2**	e	302.57	290.07	303.50	**298.72**	e
PAN3349	13.46	9.58	14.41	**12.48**	c	82.0	70.7	104.3	**85.7**	b	136.1	123.9	156.3	**138.8**	bc	190.7	177.6	208.8	**192.4**	b	292.34	281.50	274.79	**282.88**	ab
PAN3377	8.19	8.55	12.52	**9.76**	ab	76.7	94.7	88.4	**86.6**	b	138.6	157.7	148.9	**148.4**	cd	201.4	220.7	210.1	**210.8**	c	317.88	318.60	311.66	**316.05**	f
Env mean	**15.38** b	**11.98** a	**14.21** b	**13.86**		**97.1** b	**86.7** a	**99.0** b	**94.3**		**152.5** b	**142.7** a	**154.3** b	**149.8**		**208.5** b	**199.2** a	**210.3** b	**206.0**		**290.27** a	**291.91** a	**286.41** a	**289.53**	
LSD Env	**1.745**					**9.54**					**8.84**					**8.26**					**8.004**				
LSD Cult	**2.074**					**11.27**					**11.64**					**11.96**					**5.909**				

Means followed by the same letter, did not differ significantly at P=0.05. TW=tailwidth, A-1=curve-area from beginning until 1 minute before PT, AP=curve-area from beginning until PT, A+2=curve-area from beginning until 2 minutes after PT, TA=total curve-area, Cult means=cultivar means for the three localities, Env mean=environmental means, LSD Env=least significant difference for environments, LSD Cult=least significant difference for cultivars, Ar=Arlington, Be=Bethlehem, Bo=Bothaville

3.3.2.2 The combined ANOVA on grain and milling characteristics

The combined ANOVA indicated highly significant ($p \leq 0.001$) differences among genotypes, environments and the interaction between genotypes and environments for most of the measured grain and milling characteristics. (Table 3.9). Percentages of the total variance of each source of variation showed that the largest variation was attributed to the environments for the measured characteristics HI, VK, GPC, FLN, FPC, FCL and C76, indicating the effect of environment on these characteristics measured within a cultivar (Table 3.10). The largest variation for the measured characteristics HLM, TKM, DIAM, BFLY and FLY was attributed to the genotypes. Coefficients of variation were high for VK, FLN, FCL and C76 (Table 3.9), which was expected due to the large environmental variation for these characteristics.

3.3.2.2.1 Hectolitre mass

The combined ANOVA (Table 3.9) revealed highly significant ($p \leq 0.001$) differences for all three major components (genotype, environment and their interaction). The largest variation was attributed to the genotypes (Table 3.10) with a total contribution share of 32.17% to the total variance. This is in disagreement with previous research done by Van Lill and Purchase (1995), Gaines *et al*. (1996) and Aucamp (2003) who found the environmental factor to be the largest contributor to variance in HLM. In this study the environmental share to the total variance was 23.70% and the GXE interaction contributed 21.37% to the total variance (Table 3.10).

Hectolitre mass means for the cultivars (Table 3.11) varied between 78.98 kg hl^{-1} (PAN3349) and 81.82 kg hl^{-1} (Elands) over the three localities. PAN3349 and Elands differed significantly from each other. Environmental means (Table 3.11) varied between 79.31 kg hl^{-1}(Bethlehem) and 81.18 kg hl^{-1} (Bothaville). Bethlehem differed significantly from the other two localities, Arlington as well as Bothaville.

3.3.2.2.2 Hardness index

Highly significant differences (p≤0.001) for all three major components were indicated (Table 3.9). The largest variation was attributed to the environment (Table 3.10) with a total contribution of 42.76% to the total variance. This finding agrees with Gaines *et al*. (1996) and Aucamp (2003) but disagrees with Pomeranz and Mattern (1988) as well as Bergman *et al*. (1998) who reported genotype to be the larger contributor of variance in HI. Genotype and GXE interaction contributed 31.62% and 9.79% to the variance respectively (Table 3.10).

Cultivar means (Table 3.11) ranged between 56.44% (PAN3377) and 68.59% (Komati) over the three localities and these two cultivars differed significantly from each other. Environmental means (Table 3.11) ranged between 58.70% (Bethlehem) and 60.82% (Arlington). Bethlehem differed significantly from Arlington.

3.3.2.2.3 Thousand kernel mass

Highly significant differences (p≤0.001) were indicated for genotypes, and GXE interaction and significant differences (p≤0.01) were observed for environment (Table 3.9). The largest variation was attributed to genotypes (Table 3.10) which contributed 40.91% to the total variance. This is in agreement with Bhatt and Derera (1975) and Aucamp (2003) who also reported genotype to have a large influence on TKM. GXE interaction contributed 27.02% and environment was the smallest contributor (3.24%) to the total variance (Table 3.10). Aucamp (2003) reported GXE to be the smallest contributor to TKM.

Cultivar means (Table 3.11) ranged between 35.05 g (Limpopo) and 40.77 g (Matlabas) over the three localities and these two cultivars differed significantly from each other. Environmental means (Table 3.11) ranged between 37.00 g (Bothaville) and 38.11 g (Bethlehem). Bothaville differed significantly from Bethlehem.

3.3.2.2.4 Kernel diameter

Highly significant differences (p≤0.001) were indicated for genotypes as well as GXE interaction and significant differences (p≤0.01) were observed for environment (Table 3.9). The largest contributor to total variation (63.12%) was genotype (Table 3.10) as was also reported by Aucamp (2003). GXE interaction contributed 16.75% and environment only contributed 1.38% to variation (Table 3.10). Cultivar means (Table 3.11) ranged between 2.69 mm (Limpopo) and 3.11 mm (Matlabas) over the three localities and these two cultivars differed significantly from each other. Environmental means (Table 3.11) ranged between 2.87 mm (Bothaville) and 2.91 mm (Arlington). Bothaville differed significantly from Arlington.

A strong correlation existed between TKM and DIAM as reported by Hazen and Ward (1997), Ohm *et al*. (1998) as well as Aucamp (2003) and this could explain the large contribution made by genotypes for both these characteristics.

3.3.2.2.5 Vitreous kernels

Highly significant differences (p≤0.001) were indicated for genotypes as well as environments. No significant differences were observed for GXE interaction (Table 3.9), which contributed 6.82% to the total variance that was also observed by Aucamp (2003). Environment made the largest contribution to variation (49.84%) and genotype contributed 16.44% to the total variation (Table 3.10). Aucamp (2003) also reported environment to be the main contributor to vitreous kernels. Cultivar means (Table 3.12) ranged between 64.67% (Elands) and 82.17% (Betta-DN) over the three localities and these two cultivars differed significantly from each other regarding VK. Environmental means (Table 3.12) ranged between 66.90% (Bethlehem) and 88.30% (Bothaville). Bothaville differed significantly from Arlington and Bethlehem.

3.3.2.2.6 Grain protein content

Significant differences (p≤0.01) were revealed for genotypes as well as the GXE interaction. Significant differences (p≤0.05) were revealed for environment (Table 3.9), but environment was the largest contributor (21.64%) to the total variance for GPC (Table 3.10) as was also found by Aucamp (2003). GXE and genotype contributed 18.13% and 11.16% respectively to the total variance (Table 3.10).

Cultivar means (Table 3.12) ranged between 11.98% (Matlabas) and 12.85% (Caledon) over the three localities and these two cultivars differed significantly. Environmental means (Table 3.12) ranged between 11.83% (Arlington) and 12.79% (Bothaville). Arlington differed significantly from Bethlehem as well as Bothaville.

3.3.2.2.7 Falling number

Highly significant differences (p≤0.001) were observed for environments as well as genotypes (Table 3.9). Environment was the largest contributor (43.72%) to the total variance. Genotype contributed 15.36% and GXE 9.77% to the total variance (Table 3.10). Baker and Kosmolak (1977) and Fenn *et al*. (1994) reported GXE interaction to be the largest contributor to variation in FLN. Van Lill and Purchase (1995), Barnard *et al*. (1997), Van Lill and Smith (1997) and Nel *et al*. (2000) reported genotypes to be the higher contributors to variance.

Cultivar means (Table 3.12) ranged between 440.00 s (Gariep) and 562.70 s (PAN3349) over the three localities and these two cultivars differed significantly. Environmental means (Table 3.12) ranged between 395.60 s (Arlington) and 523.00 s (Bethlehem). Arlington differed significantly from Bethlehem as well as Bothaville.

3.3.2.2.8 Flour protein content

Significant differences (p≤0.01) were revealed for genotypes as well as the GXE interaction. Significant differences (p≤0.05) were revealed for

environment (Table 3.9), but environment was the largest contributor (23.22%) to the total variance for FPC. GXE and genotype contributed 17.93% and 10.64% respectively to the total variance (Table 3.10). Cultivar means (Table 3.12) ranged between 10.38% (Elands) and 11.29% (Caledon) over the three localities and these two cultivars differed significantly. Environmental means (Table 3.12) ranged between 10.26% (Arlington) and 11.20% (Bothaville). Arlington differed significantly from Bethlehem as well as Bothaville.

3.3.2.2.9 Break flour yield

Highly significant differences ($p \leq 0.001$) were revealed for genotypes as well as the GXE interaction (Table 3.9). Genotypes were the largest contributor (30.19%) to the total variance for BFLY (Table 3.10), which was also found by Barnard *et al*. (2002) and Aucamp (2003). Pomeranz *et al*. (1985) and Gaines *et al*. (1996a) reported the environmental effect to be the largest contributor to variance in BFLY. GXE and environment contributed 29.92% and 1.33% respectively to the total variance (Table 3.10). Cultivar means (Table 3.13) ranged between 20.82% (PAN3118) and 24.28% (Betta-DN) over the three localities and these two cultivars differed significantly. Environmental means (Table 3.13) ranged between 22.73% (Bothaville) and 23.18% (Bethlehem). There were no significant differences between the three localities.

Gaines *et al*. (1996) reported BFLY as a function of kernel hardness. Stenvert (1972), Yamazaki and Donelson (1983), Gaines (1991) and Labuschagne *et al*. (1997) reported negative correlations between BFLY and hardness.

3.3.2.2.10 Flour yield

Highly significant differences ($p \leq 0.001$) were revealed for genotypes and significant differences ($p \leq 0.01$) were observed for GXE interaction (Table 3.9). Genotypes were the largest contributor (41.55%) to the total variance (Table 3.10) which is contradictory to research conducted by Van Lill and Smith (1997) and Aucamp (2003). GXE and environment contributed 16.23% and 4.83% respectively to the total variance (Table 3.10).

Cultivar means (Table 3.13) ranged between 71.78% (Elands) and 73.71% (PAN3349) over the three localities and these two cultivars differed significantly. Environmental means (Table 3.13) ranged between 72.66% (Arlington) and 73.22% (Bethlehem). Bethlehem differed significantly from Arlington.

3.3.2.2.11 Flour colour

Highly significant differences (p≤0.001) were revealed for environment and significant differences (p≤0.01) were observed for genotypes (Table 3.9). Environments were the largest contributor (26.42%) to the total variance for FCL. Genotypes contributed 11.55% and GXE interaction contributed 10.35% to the total variance (Table 3.10).

Cultivar means (Table 3.13) ranged between -2.88 KJ (Limpopo) and -1.74 KJ (PAN3349) over the three localities and these two cultivars differed significantly. Environmental means (Table 3.13) ranged between -2.83 KJ (Bethlehem) and -1.77 KJ (Bothaville). Bothaville differed significantly from both Arlington and Bethlehem.

3.3.2.2.12 Flour colour (C76)

Highly significant differences (p≤0.001) were obtained for environments and significant differences (p≤0.01) were observed for genotypes (Table 3.9). Environments, GXE interaction and genotypes contributed 25.14%, 15.11% and 14.36% respectively to the total variance (Table 3.10).

Cultivar means (Table 3.13) ranged from -1.84 KJ (Limpopo) to -0.63 KJ (Matlabas) over the three localities and differences between these two cultivars were significant. Environmental means (Table 3.13) ranged from -1.71 KJ (Bethlehem) to -0.52 KJ (Bothaville) and LSD also indicated that significant differences existed between all three localities.

Table 3.9 Combined analysis of variance for grain and milling characteristics determined on three localities for a set of 10 wheat cultivars

SOURCE	df	MEAN SQUARES											
		HLM	HI	TKM	DIAM	VK	GPC	FLN	FPC	BFLY	FLY	FCL	C76
Total	119												
Reps	3	0.56	21.26	3.56	0.005294	193.47	1.90	1252.0	1.12	3.20	0.26	0.81	0.92
Environment	2	44.95***	1074.40***	12.43**	0.021636*	5548.61***	10.26*	195842.0***	10.85*	2.03	3.19	13.06***	14.78***
Residual A	6	0.41	6.96	1.08	0.002266	65.24	1.85	2672.0	1.76	1.51	0.90	0.28	0.47
Genotype	9	13.56***	176.56***	34.86***	0.220249***	406.77***	1.18**	15289.0***	1.11**	10.23***	6.10***	1.27*	1.88**
GXE	18	4.50***	27.34***	11.51***	0.029231***	84.42	0.96**	4862.0	0.93**	5.07***	1.19**	0.57	0.99
Residual B	81	1.02	8.52	2.52	0.006906	61.93	0.37	3201.0	0.38	1.22	0.53	0.58	0.59
Grand mean		80.53	62.69	37.55	2.89	74.76	12.40	476.00	10.86	22.96	72.92	-2.42	-1.19
CV (%)		1.3	4.7	4.2	2.9	10.5	4.9	11.9	5.7	4.8	1.0	31.5	64.7

* p≤0.05, ** p≤0.01, *** p≤0.001. HLM=hectolitre mass, HI=hardness index, TKM=thousand kernel mass, DIAM=kernel diameter, VK=vitreous kernels, GPC=grain protein content, FLN=falling number, FPC=flour protein content, BFLY=break flour yield, FLY=flour yield, FCL=flour colour, C76=flour colour expressed on a 76% flour yield basis

Table 3.10 Contribution (%) of each variance component to the total variation of individual grain and milling characteristics

SOURCE	HLM	HI	TKM	DIAM	VK	GPC	FLN	FPC	BFLY	FLY	FCL	C76
Reps	0.44	1.27	1.39	0.51	2.61	6.01	0.42	3.58	3.15	0.58	2.45	2.34
Environment	23.70	42.76	3.24	1.38	49.84	21.64	43.72	23.22	1.33	4.83	26.42	25.14
Residual A	0.65	0.83	0.84	0.43	1.76	11.71	1.79	11.33	2.97	4.09	1.70	2.38
Genotype	32.17	31.62	40.91	63.12	16.44	11.16	15.36	10.64	30.19	41.55	11.55	14.36
GXE	21.37	9.79	27.02	16.75	6.82	18.13	9.77	17.93	29.92	16.23	10.35	15.11
Residual B	21.67	13.73	26.60	17.81	22.53	31.35	28.94	33.30	32.44	32.72	47.53	40.67
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

HLM=hectolitre mass, HI=hardness index, TKM=thousand kernel mass, DIAM=kernel diameter, VK=vitreous kernels, GPC=grain protein content, FLN=falling number, FPC=flour protein content, BFLY=break flour yield, FLY=flour yield, FCL=flour colour, C76=flour colour expressed on a 76% flour yield basis

Table 3.11 Genotype and environmental means of individual localities for HLM, HI, TKM and DIAM

	HLM			Cult		HI			Cult		TKM			Cult		DIAM			Cult	
Cultivar	**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**	
Betta-DN	80.98	80.68	81.25	**80.97**	de	64.08	57.89	65.88	**62.62**	cd	38.42	40.35	37.10	**38.62**	d	2.90	2.93	2.79	**2.88**	c
Caledon	80.98	79.95	83.45	**81.46**	ef	65.14	62.11	70.35	**65.87**	c	37.28	37.30	36.54	**37.04**	bc	2.92	2.87	2.81	**2.87**	c
Elands	81.23	82.03	82.20	**81.82**	f	57.08	59.75	58.02	**61.62**	c	36.79	40.48	35.71	**37.66**	cd	2.85	2.98	2.76	**2.86**	c
Gariep	80.58	77.83	79.85	**79.42**	ab	63.77	56.01	67.63	**62.47**	cd	34.77	35.32	37.70	**35.93**	ab	2.74	2.69	2.83	**2.75**	ab
Komati	81.33	81.10	80.80	**81.08**	def	67.61	65.67	72.48	**68.59**	f	36.51	36.48	33.90	**35.63**	a	2.85	2.79	2.66	**2.76**	b
Limpopo	82.38	80.65	82.40	**81.81**	f	66.13	64.02	69.94	**66.70**	ef	34.32	37.24	33.60	**35.05**	a	2.68	2.76	2.64	**2.69**	a
Matlabas	80.90	79.00	81.75	**80.55**	cd	53.64	54.83	58.56	**59.01**	b	40.95	41.80	39.57	**40.77**	e	3.13	3.13	3.08	**3.11**	e
PAN3118	81.15	77.25	81.60	**80.00**	bc	60.6	60.93	72.14	**64.64**	de	40.34	36.03	39.44	**38.56**	d	3.15	2.90	3.14	**3.06**	e
PAN3349	81.25	76.45	79.25	**78.98**	a	55.41	56.44	65.06	**58.97**	b	39.23	36.44	39.44	**38.37**	d	2.99	2.83	3.00	**2.94**	d
PAN3377	80.33	78.18	79.28	**79.26**	ab	54.52	49.37	65.43	**56.44**	a	36.89	39.67	37.12	**37.89**	cd	2.94	3.04	2.97	**2.98**	d
Env mean	**81.11** b	**79.31** a	**81.18** b	**80.53**		**60.82** b	**58.70** a	**59.55** ab	**62.69**		**37.55** ab	**38.11** b	**37.00** a	**37.55**		**2.91** b	**2.89** ab	**2.87** a	**2.89**	
LSD Env	**0.3513**					**1.443**					**0.568**					**0.02604**				
LSD Cult	**0.8183**					**2.370**					**1.289**					**0.06750**				

Means followed by the same letter, did not differ significantly at P=0.05. HLM=hectolitre mass, HI=hardness index, TKM=thousand kernel mass, DIAM=kernel diameter, Cult means=cultivar means for the three localities, Env mean=environmental means, LSD Env=least significant difference for environments, LSD Cult=least significant difference for cultivars, Ar=Arlington, Be=Bethlehem, Bo=Bothaville

Table 3.12 Genotype and environmental means of individual localities for VK, GPC, FLN and FPC

	VK			Cult		GPC			Cult		FLN			Cult		FPC			Cult	
Cultivar	**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**	
Betta-DN	83.00	69.00	94.50	**82.17**	f	11.80	12.73	13.63	**12.72**	cde	389.50	467.00	491.80	**449.40**	ab	10.23	10.98	11.73	**10.98**	bc
Caledon	72.25	68.25	94.50	**78.33**	def	12.13	13.10	13.33	**12.85**	e	415.00	519.80	570.80	**501.80**	c	10.50	11.75	11.63	**11.29**	c
Elands	52.75	62.50	78.75	**64.67**	a	11.23	12.18	13.03	**12.14**	ab	356.50	471.00	544.20	**457.30**	abc	9.55	10.40	11.20	**10.38**	a
Gariep	64.50	68.75	86.00	**73.08**	bcde	12.05	12.93	11.85	**12.28**	abcd	365.50	510.30	444.30	**440.00**	a	10.65	11.45	10.25	**10.78**	abc
Komati	73.25	78.00	93.00	**81.42**	f	11.45	12.57	13.35	**12.46**	abcde	362.30	531.10	487.50	**460.30**	abc	10.85	11.07	11.63	**11.18**	c
Limpopo	72.50	71.75	93.50	**79.25**	ef	12.58	12.58	13.15	**12.77**	de	391.80	453.80	515.50	**453.70**	ab	9.93	11.08	11.55	**10.85**	abc
Matlabas	68.75	68.75	92.50	**76.67**	cdef	11.43	12.10	12.43	**11.98**	a	414.30	552.50	500.00	**488.90**	bc	10.13	10.53	11.08	**10.58**	ab
PAN3118	69.00	57.00	88.50	**71.50**	bc	11.53	12.95	13.10	**12.53**	bcde	382.80	525.50	506.80	**471.70**	abc	10.15	11.60	11.53	**11.09**	c
PAN3349	73.00	66.50	79.00	**72.83**	bcd	11.70	12.63	11.73	**12.02**	a	456.50	667.50	564.00	**562.70**	d	9.55	11.50	10.40	**10.48**	ab
PAN3377	61.75	58.50	82.75	**67.67**	ab	12.38	12.10	12.28	**12.25**	abc	422.00	531.50	470.00	**474.50**	abc	11.08	10.90	10.98	**10.98**	bc
Env mean	**69.08** a	**66.90** a	**88.30** b	**74.76**		**11.83** a	**12.58** b	**12.79** b	**12.40**		**395.60** a	**523.00** b	**509.50** b	**476.00**		**10.26** a	**11.13** b	**11.20** b	**10.86**	
LSD Env	**4.419**					**0.7443**					**28.29**					**0.7267**				
LSD Cult	**6.392**					**0.4919**					**45.96**					**0.5034**				

Means followed by the same letter, did not differ significantly at P=0.05. VK=vitreous kernels, GPC=grain protein content, FLN=falling number, FPC=flour protein content, Cult means=cultivar means for the three localities, Env mean=environmental means, LSD Env=least significant difference for environments, LSD Cult=least significant difference for cultivars, Ar=Arlington, Be=Bethlehem, Bo=Bothaville

Table 3.13 Genotype and environmental means of individual localities for BFLY, FLY, FCL and C76

	BFLY			Cult		FLY			Cult		FCL			Cult		C76			Cult	
Cultivar	**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**	
Betta-DN	23.27	24.75	24.81	**24.28**	d	71.68	73.49	73.405	**72.86**	bc	-2.53	-3.38	-2.00	**-2.63**	ab	-0.78	-2.38	-0.98	**-1.38**	abcd
Caledon	21.33	23.31	22.80	**22.48**	b	72.73	73.93	73.358	**73.34**	cd	-2.78	-3.08	-1.80	**-2.55**	ab	-1.48	-2.25	-0.75	**-1.49**	abc
Elands	23.57	22.09	23.20	**22.95**	bc	71.23	71.73	72.367	**71.78**	a	-2.50	-3.00	-1.90	**-2.47**	ab	-0.58	-1.30	-0.43	**-0.77**	e
Gariep	23.00	24.33	24.09	**23.81**	cd	72.08	72.89	73.215	**72.73**	b	-2.75	-1.93	-2.28	**-2.32**	abc	-1.18	-0.65	-1.18	**-1.00**	cde
Komati	22.92	23.62	23.37	**23.30**	bc	73.05	74.56	73.140	**73.58**	d	-3.18	-3.13	-1.48	**-2.59**	ab	-2.00	-2.56	-0.33	**-1.63**	ab
Limpopo	22.03	23.44	23.88	**23.12**	bc	73.38	73.35	73.430	**73.39**	cd	-3.08	-3.83	-1.75	**-2.88**	a	-2.05	-2.75	-0.73	**-1.84**	a
Matlabas	24.97	24.04	20.97	**23.33**	bc	71.99	71.99	71.420	**71.80**	a	-2.60	-2.65	-1.70	**-2.32**	abc	-0.98	-1.05	0.13	**-0.63**	e
PAN3118	21.80	20.61	20.04	**20.82**	a	72.68	72.38	72.422	**72.49**	b	-3.00	-2.65	-2.23	**-2.63**	ab	-1.70	-1.18	-0.83	**-1.23**	abcde
PAN3349	23.28	22.05	23.24	**22.86**	b	74.06	74.03	73.035	**73.71**	d	-2.03	-2.25	-0.95	**-1.74**	c	-1.28	-1.48	0.23	**-0.84**	de
PAN3377	23.46	23.57	20.91	**22.64**	b	73.70	73.83	72.965	**73.50**	d	-2.20	-2.43	-1.60	**-2.08**	bc	-1.28	-1.55	-0.38	**-1.07**	cde
Env mean	**22.96** a	**23.18** a	**22.73** a	**22.96**		**72.66** a	**73.22** b	**72.88** ab	**72.92**		**-2.66** a	**-2.83** a	**-1.77** b	**-2.42**		**-1.33** b	**-1.71** a	**-0.52** c	**-1.19**	
LSD Env	**0.672**					**0.5193**					**0.2898**					**0.3737**				
LSD Cult	**0.898**					**0.5933**					**0.6187**					**0.6240**				

Means followed by the same letter, did not differ significantly at P=0.05. BFLY=break flour yield, FLY=flour yield, FCL=flour colour, C76=flour colour at a 76% flour yield basis, Cult means=cultivar means for the three localities, Env mean=environmental means, LSD Env=least significant difference for environments, LSD Cult=least significant difference for cultivars, Ar=Arlington, Be=Bethlehem, Bo=Bothaville

3.3.3 CORRELATIONS

3.3.3.1 Correlations between the 13 selected mixogram parameters

Highly significant ($p \leq 0.001$) positive and negative correlations were observed between most of the selected mixogram parameters (Table 3.14). In agreement with Khatkar *et al*. (1996) and Martinant *et al*. (1998), PT did not exhibit positive correlations with most of the other mixogram parameters. Tailheight was found to be the most positively correlated with all the other mixogram parameters contradictory to Martinant *et al*. (1998) who reported TA to be the most correlated mixogram parameter to the other mixogram parameters, depending on which parameters were used for the different studies. Strong correlations ($r>0.9$) were observed between some area-parameters indicating that these parameters describe the same quality characteristics.

Peak time exhibited highly significant ($p \leq 0.001$) positive correlations with the area-parameters A-1, AP and A+2 but a significant ($p \leq 0.01$) negative correlation with the area-parameter TA. Peak time also had highly significant ($p \leq 0.001$) positive correlations with the two width-parameters after PT, W+2 and TW, consistent with same findings by Martinant *et al*. (1998) and Neacşu *et al*. (2009), but no correlations were observed between PT and the two width-parameters before PT. The parameter PT also showed a highly significant ($p \leq 0.001$) positive correlation with the height parameter TH, but a significant ($p \leq 0.001$) negative correlation with the height parameter PHin accordance with Wikström and Bohlin, (1996) and; Martinant *et al*. (1998). A highly significant ($p \leq 0.001$) negative correlation with AA was revealed, and a positive correlation with DA, in contrast with what was reported by Wikström and Bohlin (1996) and Martinant *et al*. (1998).

In agreement with Martinant *et al*. (1998) and Neacşu *et al*. (2009), peak height exhibited a highly significant positive ($p \leq 0.001$) correlation with the area-parameter TA but no correlations were observed with the other area-parameters, which were expected, since PH and PT is negatively correlated and PT had positive correlations with the area-parameters except with TA.

Highly significant (p≤0.001) positive correlations were also observed between PH and TH (Martinant *et al*., 1998), AA, W-1 and PW (Khatkar *et al*., 1996; Martinant *et al*., 1998). A highly significant (p≤0.001) negative correlation was observed between PH and DA, in contrast with a report by Martinant *et al*. (1998), and a significant (p≤0.05) negative correlation was observed between PH and TW.

Tailheight exhibited highly significant (p≤0.001) positive correlations with all width-parameters (W-1, PW, W+2 and TW) as well as with all area-parameters (A-1, AP, A+2 and TA). Martinant *et al*. (1998) also reported highly significant correlations between TH and PW, TW and TA. A significant (p≤0.05) positive correlation was found between TH and DA.

The ascending angle showed highly significant (p≤0.001) positive correlations with PW and TA and very highly significant (p≤0.001) negative correlations with DA, W+2, TW, A-1, AP and A+2. A significant (p≤0.05) positive correlation was observed between AA and W-1. The descending angle had highly significant (p≤0.001) positive correlations with W+2 (Khatkar *et al*., 1996), TW and A-1 and a highly significant (p≤0.001) negative correlation with TA. Martinant *et al*. (1998) reported a negative correlation between DA and TW. A significant (p≤0.05) positive correlation was observed between DA and AP and a significant (p≤0.05) negative correlation was observed between DA and W-1. Martinant *et al*. (1998) revealed a highly significant positive (p≤0.001) correlation between DA and PW in contrast to this study, revealing no significant correlation between these two parameters.

Curve-width 1 min before PT exhibited highly significant (p≤0.001) positive correlations with PW and TA. Peakwidth showed a highly significant (p≤0.001) positive correlation with TA (Martinant *et al*., 1998) a highly significant (p≤0.01) positive correlation with W+2 and a significant (p≤0.05) positive correlation with A+2. Curve-width 2 min after PT had highly significant (p≤0.001) positive correlations with TW, A-1, AP and A+2. Tailwidth had highly significant (p≤0.001) positive correlations with three of the area-

parameters, A-1, AP and A+2 and a significant ($p \leq 0.05$) negative correlation with the other area parameter, TA.

Curve-area 1 min before PT had highly significant ($p \leq 0.001$) positive correlations with AP and A+2. The curve-area from beginning until PT also had a highly significant ($p \leq 0.001$) positive correlation with A+2.

Table 3.14 Significant correlations between the 13 selected mixogram parameters

	PT	PH	TH	AA	DA	W-1	PW	W+2	TW	A-1	AP	A+2	TA
PT	**1.00**												
PH	-0.22 *	**1.00**											
TH	0.64 ***	0.49 ***	**1.00**										
AA	-0.63 ***	0.73 ***		**1.00**									
DA	0.38 ***	-0.56 ***	0.19 *	-0.68 ***	**1.00**								
W-1		0.62 ***	0.39 ***	0.25 **	-0.22 *	**1.00**							
PW		0.68 ***	0.58 ***	0.43 ***		0.52 ***	**1.00**						
W+2	0.50 ***		0.61 ***	-0.45 ***	0.77 ***		0.33 **	**1.00**					
TW	0.80 ***	-0.21 *	0.69 ***	-0.60 ***	0.68 ***			0.84 ***	**1.00**				
A-1	0.99 ***		0.71 ***	-0.59 ***	0.33 ***			0.50 ***	0.80 ***	**1.00**			
AP	0.97 ***		0.76 ***	-0.51 ***	0.25 **			0.47 ***	0.77 ***	0.99 ***	**1.00**		
A+2	0.94 ***		0.81 ***	-0.42 ***			0.21 *	0.45 ***	0.74 ***	0.97 ***	0.99 ***	**1.00**	
TA	-0.26 **	0.93 ***	0.46 ***	0.62 ***	-0.51 ***	0.67 ***	0.72 ***		-0.20 *				**1.00**

* p≤0.05, ** p≤0.01, *** p≤0.001. PT=peak time, PH=peak height, TH=tailheight, AA=ascending angle from beginning until 1 min before PT, DA=descending angle from PT until 2 min after PT, W-1=curve-width 1 min before PT, PW=peakwidth, W+2=curve-width 2 min after PT, TW=tailwidth at 6 min, A-1=area under curve from beginning until 1 min before PT, AP=area under curve from beginning until PT, A+2=area under curve from beginning until 2 min after PT, TA=total area under curve

3.3.3.2 Correlations between selected mixogram parameters and grain and milling characteristics

No correlations were observed between selected mixogram parameters and HLM or FCL. Bhatt and Derera (1975) reported no significant correlations between FCL and other traits, and concluded that FCL should not be considered as a single criterion for selection. Highly significant correlations were observed between some mixogram paramaters and grain as well as milling characteristics (Table 3.15). Kernel diameter was the grain characteristic to exhibit the most positive correlations with the selected mixogram parameters. Flour yield was the milling characteristic to exhibit the most negative correlations with selected mixogram parameters.

Hardness index exhibited a highly significant ($p \leq 0.001$) negative correlation with W-1 and also significant ($p \leq 0.01$) negative correlations with PW and TA, which was expected, since these three mixogram parameters were correlated (Table 3.14). Souza *et al*. (1993), Ohm and Chung (1999) and Figueroa *et al*. (2009) reported highly significant negative correlations between HI and PT, contradictory with Wikström and Bohlin (1996) and Martinant *et al*. (1998) who reported positive correlations between HI and PT. Wikström and Bohlin (1996) also reported positive correlations between HI and PH, PW and TA.

Thousand kernel mass exhibited a significant ($p \leq 0.01$) positive correlation with PW and significant ($p \leq 0.05$) positive correlations with TH and TA. Kernel diameter had highly significant ($p \leq 0.001$) positive correlations with TH, PW, TW, A+2 and TA and significant ($p \leq 0.01$) positive correlations with PH, W-1, W+2, A-1 and AP. Vitreous kernels had significant ($p \leq 0.01$) negative correlations with W-1 and PW and also significantly ($p \leq 0.05$) negative with AP and A+2.

Grain protein content showed a highly significant ($p \leq 0.001$) positive correlation with AA and a highly significant ($p \leq 0.001$) negative correlation with DA and TW. It also showed a significant ($p \leq 0.01$) positive correlation with PH and significant ($p \leq 0.01$) negative correlations with PT (Martinant *et al*., 1998;

Bordes *et al*., 2008) W+2 and A-1. It also exhibited a significant (P≤0.05) negative correlation with AP.

Falling number showed a significant (p≤0.05) positive correlation with AA. Significant (p≤0.01) negative correlations were observed between FLN and DA, W+2 as well as TW. A significant (p≤0.05) negative correlation was also observed between FLN and TH as well as between FLN and PW.

Flour protein content showed highly significant (p≤0.001) positive correlations with PH (Souza *et al*., 1993; Khatkar *et al*., 1996; Martinant *et al*., 1998; 1996; Chung *et al*., 2001; Dobraszczyk and Schofield, 2002; Neacşu *et al*., 2009), AA (Chung *et al*., 2001) and TA (Khatkar *et al*. 1996; Martinant *et al*., 1998; Dobraszczyk and Schofield, 2002; Neacşu *et al*., 2009) and highly significant (p≤0.001) negative correlations with DA, (Souza *et al*., 1993; Chung *et al*., 2001) in contrast with Martinant *et al*., (1998), W+2 and TW. Khatkar *et al*. (1996), Martinant *et al*. (1998) and Chung *et al*. (2001) also reported significant positive correlations between FPC and PW. Significant (p≤0.01) negative correlations were observed between FPC and PT (Souza *et al*., 1993), A-1 and AP. Dobraszczyk and Schofield (2002) reported positive correlations between FPC and TH in contrast with Bordes *et al*. (2008) who reported no correlations between these two parameters.

Break flour yield exhibited a highly significant (p≤0.001) negative correlation with TH and significant (p≤0.05) negative correlations with PH, TW, AP and A+2. Flour yield showed a highly significant (p≤0.001) positive correlation with AA and highly significant (p≤0.001) negative correlations with PT (Souza *et al*., 1993), TH, DA (Souza *et al*., 1993), W+2, TW, A-1, AP and A+2. It also correlated significantly positive with PH (Souza *et al*., 1993), W-1 and TA.

Flour colour expressed on a 76% flour yield basis exhibited highly significant (p≤0.01) positive correlations with PT and A-1 as well as significantly (p≤0.05) positive correlations with AP and A+2. A significant (p≤0.05) negative correlation was observed though between C76 and AA.

Table 3.15 Significant correlations between the grain and milling characteristics and the selected mixogram parameters

	PT	PH	TH	AA	DA	W-1	PW	W+2	TW	A-1	AP	A+2	TA
HLM													
HI						-0.32 ***	-0.30 **						-0.28 **
TKM			0.20 *				0.25 **						0.23 *
DIAM		0.25 **	0.44 ***			0.28 **	0.39 ***	0.27 **	0.31 ***	0.26 **	0.29 **	0.31 ***	0.37 ***
VK						-0.26 **	-0.27 **				-0.18 *	-0.19 *	
GPC	-0.24 **	0.26 **		0.41 ***	-0.40 ***			-0.29 **	-0.30 ***	-0.24 **	-0.21 *		
FLN			-0.19 *	0.21 *	-0.24 **		-0.20 *	-0.28 **	-0.25 **				
FPC	-0.25 **	0.46 ***		0.59 ***	-0.55 ***			-0.36 ***	-0.36 ***	-0.25 **	-0.19 *		0.30 ***
BFLY		-0.20 *	-0.37 ***						-0.22 *		-0.20 *	-0.22 *	
FLY	-0.48 ***	0.21 *	-0.31 ***	0.41 ***	-0.33 ***	0.23 *		-0.41 ***	-0.52 ***	-0.46 ***	-0.44 ***	-0.41 ***	0.19 *
FCL													
C76	0.26 **			-0.20 *						0.24 **	0.23 *	0.22 *	

* p≤0.05, ** p≤0.01, *** p≤0.001. PT=peak time, PH=peak height, TH=tailheight, AA=ascending angle from beginning until 1 min before PT, DA=descending angle from PT until 2 min after PT, W-1=curve-width 1 min before PT, PW=peakwidth, W+2=curve-width 2 min after PT, TW=tailwidth at 6 min, A-1=area under curve from beginning until 1 min before PT, AP=area under curve from beginning until PT, A+2=area under curve from beginning until 2 min after PT, TA=total area under curve, HLM=hectolitre mass, HI=hardness index, TKM=thousand kernel mass, DIAM=kernel diameter, VK=vitreous kernels, GPC=grain protein content, FLN=falling number, FPC=flour protein content, BFLY=break flour yield, FLY=flour yield, FCL=flour colour, C76=flour colour expressed on a 76% flour yield basis

3.3.4 MULTIPLE STEPWISE REGRESSIONS

Multiple stepwise regressions were applied to determine which character (independent variables) was the most responsible for the variation in another character (dependant variables), with the mixogram parameters being the dependant variables and the grain (Table 3.16) and milling (Table 3.17) characteristics being the independent variables.

3.3.4.1 Grain characteristics responsible for the variation in selected mixogram parameters

Multiple coefficient of determination was low to moderate (6.4% to 45.6%), regarding the grain characteristics as independent variables in explaining the variation in several mixogram parameters (Table 3.16), indicating that mixogram parameters are poorly predictable by grain characteristics. With DIAM as the grain characteristic exhibiting the most positive correlations with selected mixogram parameters, it was expected that DIAM would be an independent variable occurring in most of the models.

Total curve-area was the mixogram parameter with the highest coefficient of determination (R^2 = 45.6%). The independent variables for TA were DIAM, FPC, HI and TKM, with FPC making the largest contribution, namely 15.8%, DIAM contributing 13.8%, HI contributing 8.6% and TKM contributing 7.4%. All contributions made by the different independent variables were highly significant ($p \leq 0.001$).

Mixogram parameter TH had a coefficient of determination of 40.9%, indicating that the certain grain characteristics involved in explaining the variation in TH, contributed 40.9% to the variation in TH. Independent variables for TH were DIAM and TKM, which contributed 19.3% and 21.6% respectively. Although TKM made a larger contribution, it was only significant ($p \leq 0.01$) whereas the smaller contribution made by DIAM was highly significant ($p \leq 0.001$).

Variation in the mixogram parameter AA was explained by highly significant ($p \leq 0.001$) contributions made by the independent variables FPC, GPC and FN, which explained 35.1%, 1.7% and 0.02% respectively. The coefficient of determination for AA was 36.9%.

Peak height's coefficient of determination was 35.3% explained by FPC, contributing 21.1%, GPC contributing 4.0% and DIAM contributing 10.2%. All contributions were highly significant ($p \leq 0.001$). FPC and GPC, which contributed 30.8% and 1.0% respectively, both highly significant contributions ($p \leq 0.001$), explained the variation in DA. The total coefficient of determination was 31.8%.

Peak width's coefficient of determination was 28.5%, with predictor variables being DIAM, HI, VK, TKM and FN. Contributions were all highly significant ($p \leq 0.001$), with DIAM contributing 15%, TKM contributing 5.8%, HI contributing 3.2%, FN contributing 2.8% and VK contributing 1.7% to the variance in PW. The coefficient of determination for W+2 was 20.6%. Variables that contributed to the variance in W+2 were DIAM, HI, VK and TKM which contributed 13.2%, 0.003%, 2.3% and 5.1% respectively. All variables made highly significant contributions ($p \leq 0.001$).

Predictor variables for the mixogram parameter TW were FPC, DIAM and GPC, all making highly significant ($p \leq 0.001$) contributions to the variation in TW. Respectively they contributed 13.3%, 5.7% and 0.3% to the total coefficient of determination for TW, being 19.3%. The parameter W-1 was predicted by HI, DIAM and VK with R^2 being 14.3%. The variables explained respectively 10.5%, 3.3% and 0.5% of the variation in W-1 and all three variables made highly significant contributions ($p \leq 0.001$).

Kernel diameter, FPC and GPC contributed 6.5%, 3.7% and 0.1% respectively to $R^2 = 10.3\%$ for A-1, all contributions were significant ($p \leq 0.01$). Kernel diameter was the only predictor variable to the mixogram parameter A+2 with $R^2 = 9.9\%$, making a highly significant contribution ($p \leq 0.001$). Kernel diameter and GPC made significant ($p \leq 0.01$) contributions to AP, with R^2 =

9.7%. Kernel diameter's contribution was 8.1% and GPC's contribution was 1.5%. Peak time had a coefficient of determination of only 6.4%, explained by FPC and GPC, where FPC made a highly significant (p≤0.001) contribution of 6.0% and GPC contributed significantly (p≤0.05) 0.4%.

Table 3.16 The total R^2 for all the grain characteristics in the model, responsible for the variation in the selected mixogram parameters added to the regression on a stepwise basis

Mixogram parameter TA (Full scale R^2 = 45.6 %)						
Constant	**DIAM**	**FPC**	**HI**	**TKM**	**R^2**	**F-value**
193.7 (a)	33.150				0.138	<0.001***
22.1 (b)	*7.620*					
97.5	41.37	6.67			0.296	<0.001***
27.5	*7.1*	*1.3*				
149.2	33.62	8.16	-0.725		0.382	<0.001***
28.8	*6.95*	*1.28*	*0.18*			
151	83.9	8.13	-0.856	-3.688	0.456	<0.001***
27.2	*14.3*	*1.21*	*0.173*	*0.9320*		
Mixogram parameter TH (Full scale R^2 = 40.9 %)						
Constant	**DIAM**	**TKM**			**R^2**	**F-value**
23.27	8.800				0.193	<0.001***
4.79	*1.650*					
18.8	28.33	-1.385			0.409	<0.01**
4.17	*3.31*	*0.212*				
Mixogram parameter AA (Full scale R^2 = 36.9 %)						
Constant	**FPC**	**GPC**	**FN**		**R^2**	**F-value**
-16.14	2.383				0.351	<0.001***
3.25	*0.298*					
-13.01	3.130	-0.907			0.368	<0.001***
3.67	*0.513*	*0.51*				
-13.01	3.140	-0.899	-.0004		0.369	<0.001***
3.68	*0.522*	*0.516*	*.00333*			
Mixogram parameter PH (Full scale R^2 = 35.3 %)						
Constant	**FPC**	**GPC**	**DIAM**		**R^2**	**F-value**
34.62	2.112				0.211	<0.001***
4.1	*0.376*					
40.06	3.411	-1.576			0.251	<0.001***
4.57	*0.64*	*0.635*				
9.14	3.190	-0.878	8.54		0.353	<0.001***
8.39	*0.599*	*0.615*	*1.99*			
Mixogram parameter DA (Full scale R^2 = 31.8 %)						
Constant	**FPC**	**GPC**			**R^2**	**F-value**
9.04	-1.242				0.308	<0.001***
1.87	*0.172*					
7.7	-1.560	0.387			0.318	<0.001***
2.12	*0.297*	*0.295*				

Table 3.16 Continued

Mixogram parameter PW (Full scale R^2 = 28.5 %)							
Constant	**DIAM**	**HI**	**VK**	**TKM**	**FN**	**R^2**	**F-value**
13.14	7.520					0.150	<0.001***
4.77	*1.650*						
22.37	6.310	-.0915				0.182	<0.001***
6.4	*1.720*	*0.043*					
20.37	6.68	-.0255	-.0427			0.199	<0.001***
6.49	*1.73*	*0.0598*	*0.0271*				
21.72	16.63	-.0872	-0.02	-.744		0.257	<0.001***
6.29	*3.7*	*0.0614*	*0.0273*	*0.247*			
25.18	16.48	-.1032	-.0089	-.742	-.00614	0.285	<0.001***
6.41	*3.65*	*0.061*	*0.0274*	*0.243*	*0.00294*		
Mixogram parameter W+2 (Full scale R^2 = 20.6 %)							
Constant	**DIAM**	**HI**	**VK**	**TKM**		**R^2**	**F-value**
42.9	-1.994					0.132	<0.001***
5.14	*0.471*						
42.72	-2.038	0.053				0.132	<0.001***
5.88	*0.823*	*0.817*					
42.57	-1.812	0.23	-.00946			0.155	<0.001***
5.82	*0.825*	*0.815*	*0.00527*				
16.3	-1.958	0.856	-.01121	7.26		0.206	<0.001***
11.2	*0.805*	*0.827*	*0.00517*	*2.67*			
Mixogram parameter TW (Full scale R^2 = 19.3 %)							
Constant	**FPC**	**DIAM**	**GPC**			**R^2**	**F-value**
37.37	-2.165					0.133	<0.001***
5.54	*0.509*						
10.9	-1.836	7.92				0.190	<0.001***
10.7	*0.507*	*2.76*					
7.2	-2.3	8.43	0.588			0.193	<0.001***
12.1	*0.864*	*2.87*	*0.886*				
Mixogram parameter W-1 (Full scale R^2 = 14.3 %)							
Constant	**HI**	**DIAM**	**VK**			**R^2**	**F-value**
50.53	-0.195					0.105	<0.001***
3.31	*0.053*						
34.58	-0.157	4.68				0.138	<0.001***
8.17	*0.055*	*2.2*					
33.28	-.1138	4.92	-.0277			0.143	<0.001***
8.34	*0.0769*	*2.22*	*0.0348*				
Mixogram parameter A-1 (Full scale R^2 = 10.3 %)							
Constant	**DIAM**	**FPC**	**GPC**			**R^2**	**F-value**
-37.2	45.500					0.065	0.005**
45.9	*15.900*						
56.1	37.500	-6.47				0.102	0.002**
62	*16.000*	*2.94*					
63.2	36.5	-5.58	-1.13			0.103	0.006**
70.2	*16.7*	*5.02*	*5.15*				
Mixogram parameter A+2 (Full scale R^2 = 9.9 %)							
Constant	**DIAM**					**R^2**	**F-value**
38.1	58.100					0.099	<0.001***
46.7	*16.100*						
Mixogram parameter AP (Full scale R^2 = 9.7 %)							
Constant	**DIAM**	**GPC**				**R^2**	**F-value**
0.6	51.600					0.081	0.002**
46.2	*16.000*						
77.2	43.700	-4.33				0.097	0.003**
71.2	*16.9*	*3.07*					

Table 3.16 Continued

Mixogram parameter PT (Full scale R^2 = 6.4 %)				
Constant	**FPC**	**GPC**	**R^2**	**F-value**
5.311	-0.181		0.060	0.007**
0.716	*0.066*			
5.588	-0.115	-0.08	0.064	0.02*
0.818	*0.115*	*0.114*		

* p≤0.05, ** p≤0.01, *** p≤0.001. (a)=correlation coefficient, (b)=standard error of correlation coefficient, R^2=coefficient of multiple determination, TA=total area under curve, TH=tailheight, AA=ascending angle from beginning until 1 min before PT, PH=peak height, DA=descending angle from PT until 2 min after PT, PW=peakwidth, W+2=curve-width 2 minutes after PT, TW=tailwidth, W-1=curve-width 1 minute before PT, A-1=curve-area from beginning until 1 minute before PT, A+2=curve-area from beginning until 2 minutes after PT, AP=area under curve from beginning up to PT, PT=peak time, DIAM=kernel diameter, FPC=flour protein content, HI=hardness index, TKM=thousand kernel mass, VK=vitreous kernels, GPC=grain protein content, FN=falling number

3.3.4.2 Milling characteristics responsible for the variation in selected mixogram parameters

Multiple coefficient of determination was low (11.1% to 26.7%) regarding the milling characteristics (Table 3.17) for explaining the variation in mixogram parameters, indicating that mixogram parameters are poorly predictable by milling characteristics. Flour yield was the milling characteristic the most positively correlated to the selected mixogram parameters and it is therefore clear why FLY appeared in all the models.

Tailwidth, the dependant variable with the highest coefficient of determination, being R^2 = 26.7%, was explained by the independent variable FLY which was the only predictor in this regression. Flour yield made a highly significant contribution (p≤0.001). Independent variables FLY and C76 contributed 23.2% and 0.6% respectively to R^2 = 23.8% for mixogram parameter PT. Although C76 explained only 0.6%, contributions by both variables were highly significant (p≤0.001).

The variation in the mixogram parameter TH was explained by variables BFLY and FLY, which contributed 13.4% and 9.7% respectively. Both contributions were highly significant (p≤0.001). The coefficient of determination for A-1 was 21.4%, again predicted by FLY which made a highly significant (p≤0.001) contribution. Flour yield was the only variable making a highly significant (p≤0.001) contribution to the variation in AP, where R^2 = 19.3%. The predictor variable for the variation in W+2 was FLY,

contributing 17.1%. The contribution was highly significant (p≤0.001). Flour yield explained 16.8% of the variation in A+2, again making a highly significant contribution (p≤0.001). Flour yield and C76 explained the variation in AA with R^2 = 16.8%, with FLY contributing 16.6% and C76 contributing 0.2%, both being highly significant contributions (p≤0.001). The variation in DA, with R^2 = 11.1%, was explained by FLY, making a highly significant (p≤0.001) contribution.

Table 3.17 The total R^2 for all the milling characteristics in the model, responsible for the variation in the selected mixogram parameters added to the regression on a stepwise basis

Mixogram parameter TW (Full scale R^2 = 26.7 %)				
Constant	**FLY**		**R^2**	**F-value**
201.8(a)	-2.578		0.267	<0.001***
28.7(b)	*0.393*			
Mixogram parameter PT (Full scale R^2 = 23.8 %)				
Constant	**FLY**	**C76**	**R^2**	**F-value**
25.11	-0.299		0.232	<0.001***
3.65	*0.050*			
23.63	-0.2772	0.057	0.238	<0.001***
3.94	*0.0544*	*0.0577*		
Mixogram parameter TH (Full scale R^2 = 23.2 %)				
Constant	**BFLY**	**FLY**	**R^2**	**F-value**
65.78	-0.744		0.134	<0.001***
4	*0.174*			
136	-0.7443	-0.963	0.232	<0.001***
18.6	*0.165*	*0.25*		
Mixogram parameter A-1 (Full scale R^2 = 21.4 %)				
Constant	**FLY**		**R^2**	**F-value**
1022	-12.730		0.214	<0.001***
164	*2.240*			
Mixogram parameter AP (Full scale R^2 = 19.3 %)				
Constant	**FLY**		**R^2**	**F-value**
1043	-12.250		0.193	<0.001***
168	*2.310*			
Mixogram parameter W+2 (Full scale R^2 = 17.1 %)				
Constant	**FLY**		**R^2**	**F-value**
160.6	-1.911		0.171	<0.001***
28.2	*0.387*			
Mixogram parameter A+2 (Full scale R^2 = 16.8 %)				
Constant	**FLY**		**R^2**	**F-value**
1057	-11.670		0.168	<0.001***
174	*2.390*			
Mixogram parameter AA (Full scale R^2 = 16.8 %)				
Constant	**FLY**	**C76**	**R^2**	**F-value**
-90.8	1.379		0.166	<0.001***
20.7	*0.284*			
-86.9	1.323	-0.151	0.168	<0.001***
22.5	*0.310*	*0.329*		

Table 3.17 Continued

Mixogram parameter DA (Full scale R^2 = 11.1 %)			
Constant	**FLY**	**R^2**	**F-value**
41.3	-0.627	0.111	<0.001***
11.9	*0.163*		

* p≤0.05, ** p≤0.01, *** p≤0.001. (a)=correlation coefficient, (b)=standard error of correlation coefficient, R^2=coefficient of multiple determination, TW=tailwidth, PT=peak time, TH=tailheight, A-1=area under curve from beginning until 1 minute before PT, AP=area under curve from beginning until PT, W+2=curve-width 2 minutes after PT, A+2=area under curve from beginning until 2 minutes after PT, AA=ascending angle from beginning until 1 min before PT, DA=descending angle from PT until 2 min after PT, FLY=flour yield, BFLY=break flour yield, C76=flour colour expressed on a 76% flour yield basis

3.4 CONCLUSIONS

The combined ANOVA indicated highly significant (p≤0.001) differences among cultivars, environments and the interaction between cultivars and environments for most of the selected mixogram parameters and the measured grain and milling characteristics. This indicated variable responses between the cultivars and the environments for nearly all selected mixogram parameters and grain and milling characteristics measured.

A much larger variation was found among genotypes than among environments for all measured mixogram parameters indicating higher heritability for these parameters. The largest variation was attributed to the environments for the measured characteristics HI, VK, GPC, FLN, FPC, FCL and C76 and genotypes were responsible for the largest variation for the measured characteristics HLM, TKM, DIAM, BFLY and FLY.

Tailheight was found to be the most highly correlated with all the other mixogram parameters. No correlations were observed between selected mixogram parameters and HLM and FCL, although highly significant (p≤0.001) correlations were observed between some mixogram parameters and grain as well as milling characteristics.

Multiple coefficient of determination was low to moderate (6.4% to 45.6%), regarding the grain characteristics and the independent variables DIAM, FPC and GPC were common in most models explaining the variation in the selected mixogram parameters. The independent variable not significant in any of the models was HLM.

Multiple coefficient of determination was low (11.1% to 26.7%) for the milling characteristics and the independent variable FLY was common in all models explaining the variation in the selected mixogram parameters. The independent variable not significant in any of the models was FCL.

Although highly significant correlations were observed, multiple coefficients of determination exhibited grain and milling characteristics as poor predictors of mixogram parameters.

REFERENCES

AACC – American Association of Cereal Chemists, 2000. Approved methods of the AACC, 10th edition. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA.

Aucamp, J.C., 2003. Assessment of South African bread wheat cultivars for milling quality. MSc thesis. University of the Free State, Bloemfontein, RSA.

Baker, R.J. and Kosmolak, F.G., 1977. Effects of genotype x environment interaction on bread wheat quality in Western Canada. Canadian Journal of Plant Science 57: 185-189.

Barnard, A., Purchase, J.L., Smith, M.F. and Van Lill, D., 1997. Determination of pre-harvest sprouting resistance of South African winter wheat (*Triticum aestivum* L.) cultivars. South African Journal of Plant and Soil 14: 4-8.

Barnard, A.D., Labuschagne, M.T. and Van Niekerk, H.A., 2002. Heritability estimates of bread wheat quality traits in the Western Cape province of South Africa. Euphytica 127: 115-122.

Bass, E.J., 1988. Wheat flour milling. Pages 1-68 in: Wheat: Chemistry and Technology. Volume II. 3rd edition. Y. Pomeranz, ed. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA.

Bergman, C.J., Gualberto, D.G., Campbell, K.G., Sorrels, M.E. and Finney, P.L., 1998. Genotype and environment effects on wheat quality traits in a population derived from soft by hard cross. Cereal Chemistry 75: 729-737.

Bhatt, G.M. and Derera, N.F., 1975. Genotype x environment interactions for heritabilities of and correlations among quality traits in wheat. Euphytica 24: 597-604.

Bordes, J., Branlard, G., Oury, F.X., Charmet, G. and Balfourier, F., 2008. Agronomic characteristics, grain quality and flour rheology of 372 bread wheats in a worldwide core collection. Journal of Cereal Science 48: 569-579.

Chung, O.K., Ohm, J.B., Caley, M.S. and Seabourn, B.W., 2001. Prediction of baking characteristics of hard winter wheat flours using computer-analysed mixograph parameters. Cereal Chemistry 78: 493-497.

Dobraszczyk, B.J. and Schofield, J.D., 2002. Rapid assessment and prediction of wheat and gluten baking quality with the 2-g direct drive mixograph using multivariate statistical analysis. Cereal Chemistry 79: 607- 612.

Fenn, D., Lukow, O.M., Bushuk, W. and Depauw, R.M., 1994. Milling and baking quality of 1BL/1RS translocation wheats. I. Effects of genotype and environment. Cereal Chemistry 71: 189-195.

Figueroa, J.D.C., Maucher, T., Reule, W. and Peña, R.J., 2009. Influence of HMW glutenins on viscoelastic properties of intact wheat kernel and relation to functional properties of wheat dough. Cereal Chemistry 86: 139-144.

Gaines, C.S., 1991. Associations among quality attributes of red and white soft wheat cultivars across locations and crop years. Cereal Chemistry 68: 56-59.

Gaines, C.S., Finney, P.L and Rubenthaler, G.L., 1996. Milling and baking qualities of some wheats developed for Eastern and North-western regions in the United States and grown at both locations. Cereal Chemistry 73: 521-525.

Halverson, J. and Zeleny, L., 1988. Criteria of wheat quality. Pages 69-91 in: Wheat Chemistry and Technology. Volume III. 3rd edition. Y. Pomeranz, ed. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA.

Hazen, S.P. and Ward, R.W., 1997. Variation in soft winter wheat characteristics measured by the Single Kernel Characterisation System. Crop Science 37: 1079-1086.

Koekemoer, F.P., 2003. Genetic variability of South African spring wheats for milling and bread making quality. PhD Thesis, University of the Free State, Bloemfontein, RSA.

Khatkar, B.S., Bell, A.E. and Schofield, J.D., 1996. A comparative study of the inter-relationships between mixograph parameters and bread making qualities of wheat flours and glutens. Journal of the Science of Food and Agriculture 72: 71-85.

Labuschagne, M.T., Claassen, A. and Van Deventer, C.S., 1997. Biscuit-making quality of backcross derivatives of wheat differing in kernel hardness. Euphytica 96: 263-266.

Lukow, O.M., 1997. Quality screening using the mixograph in Canada. Pages 73-74 in: The mixograph handbook. 1st edition. C.E. Walker, J.L. Hazelton and M.D. Shogren, eds. National Manufacturing Division, TMCO, Lincoln, NE 68508-2935, USA.

Martinant, J.P., Nicolas, Y., Bouguennec, A., Popineau, Y., Saulnier, L. and Branlard, G., 1998. Relationships between mixograph parameters and indices of wheat grain quality. Journal of Cereal Science 27: 179-189.

Neacşu, A., Stanciu, G. and Sãulescu, N.N., 2009. Most suitable mixing parameters for use in breeding bread wheat for processing quality. Cereal Research Communications 37: 83-92.

Nel, M.M., Agenbag, G.A. and Purchase, J.L., 1998. Sources of variation for yield, protein content and hectolitre mass of spring wheat (*Triticum aestivum* L.) cultivars of the Western and Southern Cape. South African Journal of Plant and Soil 15: 72-79.

Nel, M.M., Agenbag, G.A. and Purchase, J.L., 2000. Sources of variation in spring wheat (*Triticum aestivum* L.) cultivars of the Western and Southern Cape. I. Milling and dough development characteristics. South African Journal of Plant and Soil 17: 30-39.

Ohm, J.B., Chung, O.K. and Deyoe, C.W., 1998. Single kernel characteristics of hard winter wheats in relation to milling and baking quality. Cereal Chemistry 75: 156-161.

Ohm, J.B. and Chung, O.K., 1999. Gluten, pasting, and mixograph parameters of hard winter wheat flours in relation to bread making. Cereal Chemistry 76: 606-613.

Payne, R.W., Murray, D.A., Harding, S.A. and Baird, D.B., 2008. Genstat for Windows. 11th edition. Introduction. VSN International, Hemel Hempstead.

Perten, H., 1964. Application of the falling number method for evaluating alpha-amylase activity. Cereal Chemistry 41: 127-140.

Peterson, C.J., Graybosch, R.A., Baenziger, P.S. and Grombacher, A.W., 1992. Genotype and environment effects on quality characteristics of hard winter wheat. Crop Science 32: 98-103.

Pomeranz, Y. and Mattern, P.J., 1988. Genotype and genotype X environment interaction effects on hardness estimates in winter wheat. Cereal Foods World 33: 371-374.

Pomeranz, Y., Peterson, C.J. and Mattern, P.J., 1985. Hardness of winter wheats grown under widely different climatic conditions. Cereal Chemistry 62: 463-467.

SAGL, 2010. Analysis procedure and evaluation norms for the classification of wheat breeders' lines for the RSA. September 2010 revision.

Souza, E., Tyler, J.M., Kephart, K.D. and Kruk, M., 1993. Genetic improvement in milling and baking quality of hard red spring wheat cultivars. Cereal Chemistry 70: 280-285.

Stenvert, N.L., 1972. The measurement of wheat hardness and its effect on milling characteristics. Australian Journal of Experimental Agriculture and Animal Husbandry 12: 159-164.

Van Ark, H., 1995. Introduction to linear correlation and regression. Agricultural Research Council Agrimetrics Institute, Pretoria, RSA.

Van Lill, D. and Purchase, J.L., 1995. Directions in breeding for winter wheat yield and quality in South Africa from 1930 to 1990. Euphytica 82: 79-87.

Van Lill, D. and Smith, M.F., 1997. A quality assurance strategy for wheat (*Triticum aestivum* L.) where growth environment predominates. South African Journal of Plant and Soil 14: 183-191.

Walker, C.E., Hazelton, J.L. and Shogren, M.D., 1997. 35-gram Mixograph – Absorption, flour and water amount table. Pages 117-124 in: The mixograph handbook. 1st edition. C.E. Walker, J.L. Hazelton and M.D. Shogren, eds. National Manufacturing Division, TMCO, Lincoln, NE 68508-2935, USA.

Walker, A.E. and Walker, C.E., 1992. Documentation and user's instructions for Mixsmart. National Manufacturing Division, TMCO, 507 J. Street, Lincoln, NE 68508, USA.

Wikström, K. and Bohlin, L., 1996. Multivariate analysis as a tool to predict bread volume from mixogram parameters. Cereal Chemistry 73: 686-690.

Yamazaki, W.T. and Donelson, J.R., 1983. Kernel hardness of some U.S. wheats. Cereal Chemistry 60: 344-350.

CHAPTER 4

THE RELATIONSHIP BETWEEN SELECTED MIXOGRAM PARAMETERS AND OTHER RHEOLOGICAL, BAKING QUALITY-RELATED AND BAKING CHARACTERISTICS

ABSTRACT

During the release process of South African hard red wheat cultivars, strict criteria are set by the Wheat Technical Committee regarding certain rheological properties and loaf volume. Taking into consideration that some of these tests require large amounts of flour, are labour intensive and time-consuming, the mixograph, when applying Mixsmart software, can assist wheat breeders in selecting earlier for potential breeding lines in order to prevent discarding high-yielding lines during advanced breeding phases due to unacceptable farinogram and alveogram characteristics and undesirable loaf volumes. Highly significant ($p \leq 0.001$) correlations between the mixogram parameter TA and FABS, STRENGTH and LFV12% were observed as well as between the mixogram parameter TH and P/L. Multiple stepwise regressions revealed low to relatively high contributions made by the selected mixogram parameters, explaining the variation in other rheological and baking characteristics.

4.1 INTRODUCTION

The Wheat Technical Committee (WTC) set strict release criteria regarding rheological and baking characteristics during the final classification stages of potential bread wheat cultivars in South Africa. The primary rheological and baking characteristics are fixed, non-negotiable and include characteristics such as mixogram peak time (PT), farinogram water-absorption (FABS), alveogram dough strength (STRENGTH), alveogram configuration ratio (P/L-value) and loaf volume (LFV). Additional results are regarded as secondary requirements and include mixogram water-absorption (MABS), alveogram dough stability (P-value), alveogram dough distensibility (L-value) and loaf volume expressed on a 12% (LFV12%) protein basis (SAGL, 2010). Other

routine analyses also performed on potential breeding lines included SDS-sedimentation volume (SDS) and wet gluten content (WGC). To perform all these analyses, large amounts of flour are needed, and some of these analyses are laborious, time-consuming and require highly skilled staff. Wheat breeders therefore want a set of rapid, small-scale tests that might predict all these analyses. The mixograph applied with Mixsmart software, can assist wheat breeders in selecting earlier for potential breeding lines in order to prevent discarding high-yielding lines during the advanced breeding phases for unacceptable dough and baking characteristics. Mixsmart software can supply the breeders with additional information apart from the generally used and most frequently reported on characteristic, peak time (Walker and Walker, 1992; Dobraszczyk and Schofield, 2002).

The aim of this study was to determine if rheological and baking characteristics can be predicted from selected mixogram parameters (Chapter 3, Section 3.3) which can be of assistance to breeders to select for acceptable rheological and baking characteristics.

4.2 MATERIALS AND METHODS

4.2.1 Field trials

See Chapter 3 (Section 3.2.1).

4.2.2 Laboratory methods for quality analysis

All the material was evaluated for the selected mixogram parameters (explained in Chapter 3, Section 3.3), and other rheological characteristics which included mixogram water-absorption, farinogram water-absorption, alveogram P-value, alveogram L-value, alveogram P/L-value, alveogram dough strength and baking characteristics including SDS-sedimentation volume, wet gluten content, loaf volume and loaf volume expressed on a 12% protein basis (corrected loaf volume).

4.2.2.1 **Mixograph analyses** (AACC method 54-40A)

As explained in Chapter 3 (Section 3.2.2.1). Selected parameters used were discussed in Chapter 3 (Section 3.3). Mixogram water-absorption (MABS) was determined using the following equation:

$y = (1.5\ x) + 43.6,$

where *x* represented flour protein content (14% moisture basis) and *y* represented the water-absorption percentage (AACC, 2000).

4.2.2.2 **Farinograph analyses** (AACC method 54-21)

The procedure for constant flour weight was applied. Due to small sample sizes, only farinogram water-absorption was determined on 300 g of white flour. Water-absorption is the volume of water required for dough to reach a definite consistency, namely 500 Brabender units. The volume of water added is expressed as a percentage of the flour mass and it is reported on a 14% moisture basis (AACC, 2000).

4.2.2.3 **Alveograph analyses** (AACC method 54-30A)

Chopin alveograph analyses were performed on 250 g of white flour, where a 2.5% NaCl solution was added according to a sample's moisture content. Moisture content of the white flour was determined by following AACC procedure 44 – 15A, using a Brabender moisture oven.

Parameters computed by an Alveolink and used for this study, were dough strength (W-value), P-value, L-value and P/L-value. P-value is obtained by multiplying the maximum curve height with a constant factor of 1.1. According to AACC, official methods handbook, the P-value is an indication of the resistance of the dough to extension. The L-value is the curve length, measured along the base line and it indicates dough extensibility. The P/L-value is the ratio between stability and extensibility (distensibility).

4.2.2.4 SDS-sedimentation volume

SDS-sedimentation volumes were determined with the AACC 56-70 (AACC, 2000) method, with slight modifications. Results were reported in millilitre on flour sample sizes of 5 g. Gluten proteins are known to expand in the presence of lactic acid and SDS and the obtained sedimentation volumes gave information about both protein quantity and quality (AACC, 2000).

4.2.2.5 **Wet gluten content** (AACC method 38-12A)

Wet gluten content was measured using a Glutomatic system where 10 g of flour was washed with 2% NaCl solution and centrifuged. Wet gluten content was determined as follows:

$$\text{Wet gluten content, \% (14\% moisture basis)} = \frac{\text{Total wet gluten (g)} \times 860}{100 - \text{\% sample moisture}}$$

4.2.2.6 **Loaf volume** (AACC method 10-10B)

The optimised, straight-dough baking procedure was followed (AACC 10-10B, 2000). Loaf volume was determined by rapeseed displacement. Corrected loaf volume (LFV12%) was estimated for each sample by standardising the loaf volume to 12% protein, where 40 cm^3 was added to the obtained LFV for each percent of protein content below 12% and subtracting 40 cm^3 from the obtained LFV for each percent of protein content above 12% (personal communication, Arie Wessels) (AACC, 2000).

4.2.3 STATISTICAL ANALYSIS

All statistical analyses were performed with Genstat for Windows, 11th edition, (Payne *et al*., 2008).

4.2.3.1 Descriptive statistics

Descriptive statistics were applied to describe some main features, such as minimum, maximum, mean values and standard deviations of the data collection.

4.2.3.2 Analysis of variance (ANOVA)

Combined analysis of variance was performed across the three environments for the selected mixogram parameters (Chapter 3, Section 3.3.1.1) and the rheological and baking characteristics.

4.2.3.3 Correlations

Correlations were performed to determine the relationship between the selected mixogram parameters and the rheological and baking characteristics.

4.2.3.4 Multiple stepwise regressions

This was done to investigate how the selected mixogram parameters interacted with the rheological and baking characteristics. Multiple stepwise regressions were used to define the variation caused by selected mixogram parameters to the fixed characteristics, the rheological and baking characteristics. The independent variables, the selected mixogram parameters that accounted for the largest amount of variation in the dependant variable, were checked for significance and then entered into the regression equation. The coefficient of determination (R^2), expressed as a percentage, is an indication of the variation that can be explained by the relationship between the dependant variable and the independent variables (Van Ark, 1995). R^2 is calculated as follows: $R^2 = r^2 \times 100$, where r^2 denotes the correlation coefficient.

4.3 RESULTS AND DISCUSSION

4.3.1 DESCRIPTIVE STATISTICS

4.3.1.1 Means, minimum and maximum values and standard deviations for selected mixogram parameters

See Chapter 3 (Section 3.3.3.1).

4.3.1.2 Means, minimum and maximum values and standard deviations for rheological, baking quality-related and baking characteristics

Water-absorption values determined on the mixograph were higher than values determined on the farinograph (Table 4.1) as was also reported previously (Wikström and Bohlin, 1996; Ingelin, 1997).

Table 4.1 Mean values, minimum and maximum values and standard deviations of rheological, baking quality-related and baking characteristics evaluated in the three environments

Characteristic	Environment	MEAN	MIN	MAX	SD
MABS	Bethlehem	60.29	57.70	61.75	0.94
	Arlington	59.07	55.00	61.60	1.45
	Bothaville	60.39	57.55	62.35	1.14
FABS	Bethlehem	57.74	55.35	60.25	1.21
	Arlington	57.42	53.60	60.95	1.70
	Bothaville	58.11	54.30	62.00	1.96
P	Bethlehem	71.55	50.00	101.0	13.02
	Arlington	75.85	56.00	115.0	13.27
	Bothaville	72.13	51.00	98.0	13.02
L	Bethlehem	112.8	65.0	176.0	25.10
	Arlington	90.6	43.0	165.0	28.50
	Bothaville	94.7	39.0	163.0	31.90
P/L	Bethlehem	0.69	0.32	1.44	0.28
	Arlington	0.96	0.41	2.28	0.46
	Bothaville	0.88	0.31	1.85	0.41
STRENGTH	Bethlehem	41.78	29.82	57.19	8.78
	Arlington	37.73	25.69	56.42	6.87
	Bothaville	38.30	19.27	57.34	8.33
SDS	Bethlehem	85.36	70.00	95.00	5.66
	Arlington	85.15	75.00	94.00	4.79
	Bothaville	84.62	75.00	94.00	5.52
WGC	Bethlehem	35.11	27.14	43.55	3.46
	Arlington	31.43	17.88	42.99	4.88
	Bothaville	34.02	23.94	45.24	4.40
LFV	Bethlehem	888.10	730.00	985.00	46.80
	Arlington	838.50	710.00	1010.00	69.40
	Bothaville	870.20	856.00	1005.00	69.40
LFV12%	Bethlehem	923.10	856.00	1009.00	39.50
	Arlington	905.60	799.00	1071.00	60.00
	Bothaville	902.40	775.00	1010.00	57.20

MABS=mixogram water-absorption, FABS=farinogram water-absorption, P=alveogram dough stability, L=alveogram dough distensibility, P/L=alveogram configuration ratio, STRENGTH=alveogram dough strength, SDS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, LFV12%=loaf volume expressed on a 12% protein basis, MEAN=mean values, MIN=minimum, MAX=maximum, SD=standard deviation

This could be caused by the difference in dough consistency and functioning between these two apparatuses. Higher absorption values are preferable,

because more dough per unit flour is produced (Mamuya, 2000). The WTC concentrates on FABS, and values between 58% - 65% are regarded as acceptable, depending on protein content. Usually higher FABS can be expected if protein contents are high (15% and above), as long as this was not caused by stress factors during the grain-filling period.

Alveogram configuration ratios (P/L) of 0.5 mm to 1.0 mm are preferred by the South African market, since it usually results in good quality bread acceptable to consumers (personal communication, Arie Wessels). Mean values for P/L were therefore acceptable (0.69 mm to 0.96 mm). Minimum dough strength of 250 10^{-4}J is preferred by bakers. If flour protein contents are in the order of 10%, bakers expect dough strength to be above 400 10^{-4}J (personal communication, Arie Wessels).

SDS-sedimentation values ranged from 70 ml to 95 ml (Table 4.1) with standard deviation values between 4.79 and 5.66. Wet gluten content ranged between 17.88% to 45.24% and standard deviation values between 3.46 and 4.88 (Table 4.1). The lowest and highest LFV's and LFV12%'s were obtained at Arlington, ranging between 710 cm^3 to 1010 cm^3 and between 799 cm^3 and 1071 cm^3 respectively.

4.3.2 ANOVA

4.3.2.1 The combined ANOVA on selected mixogram parameters

See Chapter 3 (Section 3.3.2.1).

4.3.2.2 The combined ANOVA on rheological, baking quality-related and baking characteristics

The combined ANOVA (Table 4.2) indicated highly significant ($p \leq 0.001$) differences among cultivars (genotypes) for FABS, alveogram characteristics (P, L, P/L and STRENGTH) and all baking quality-related characteristics (SDS, WGC, LFV and LFV12%). Significant differences ($p \leq 0.01$) were observed among environments for L and P/L. Loaf volume, MABS and P revealed significant differences ($p \leq 0.05$) for the environment. GXE was highly

significant (p≤0.001) for P, LFV and LFV12% and significant (p≤0.01) for MABS, L, P/L, WGC and for FABS (p≤0.05). The largest variation was attributed to the genotypes for FABS, P, L, P/L, STRENGTH, SDS, WGC, LFV and LFV12% (Table 4.3). Environment was responsible for the largest variation in MABS.

Variation coefficients (CV's) for the alveogram characteristics P/L and STRENGTH were high, as was also found by Bordes *et al*. (2008). Coefficients of variation were low for both water-absorption measurements (Table 4.2) due to the small variation observed (Table 4.4) in MABS (59.13% to 60.54%) and FABS (56.05% to 59.49%). Baking parameters (SDS, WGC, LFV, LFV12%) had CV's ranging from 2.9% to 8.4%, which were low.

4.3.2.2.1 Mixogram water-absorption

The combined ANOVA (Table 4.2) revealed highly significant differences (p≤0.01) for the GXE component and significant differences (p≤0.05) for genotypes as well as environments. The largest variation was attributed to the environment (Table 4.3) with a total contribution of 20.44% to the total variance. In this study GXE interaction contributed 17.84% and genotypes contributed 10.41% to the total variance (Table 4.3).

Mixogram water-absorption means for the cultivars (Table 4.4) varied between 59.13% (Elands) and 60.54% (Caledon) over the three localities. Elands differed significantly from Betta-DN, Caledon, Komati, PAN3118 and PAN3377. Caledon and Komati did not differ significantly. Environmental means (Table 4.4) varied between 59.07% (Arlington) and 60.39% (Bothaville). Arlington differed significantly from the other two localities, Bethlehem and Bothaville.

4.3.2.2.2 Farinogram water-absorption

Highly significant differences (p≤0.001) were observed for the genotypes and significant differences (p≤0.05) for the GXE component (Table 4.2). The largest variation was caused by genotypes (40.26%), and GXE and

environment contributed 14.40% and 2.84% respectively to the total variance (Table 4.3). This is contradictory to Mamuya (2000) who reported environment to be the largest contributor to variation.

Farinogram water-absorption means varied from 56.05% (Gariep) to 59.49% (PAN3118). Significant differences were observed between cultivars (Table 4.4). Environments did not differ from one another. Environmental means ranged from 57.42% (Arlington) to 58.11% at Bothaville (Table 4.4).

4.3.2.2.3 Alveogram dough stability

Table 4.2 revealed highly significant ($p \leq 0.001$) differences for genotypes and the GXE component and significant differences ($p \leq 0.05$) for the environment. The largest contributor to the variance in P was made by genotypes at 66.02%, indicating high heritability for this parameter. GXE contributed 14.03% and environments contributed only 2.13% to the total variance in P (Table 4.4).

Cultivar means ranged between 58.58 mm (Caledon) and 96.83 mm (PAN3118). Environmental means ranged between 71.55 mm (Bethlehem) and 75.85 mm (Arlington). Arlington differed significantly from Bethlehem and Bothaville.

4.3.2.2.4 Alveogram dough distensibility

Highly significant differences ($p \leq 0.001$) were observed for genotypes and significant differences ($p \leq 0.01$) for environments and GXE (Table 4.2). Genotypes made the largest contribution (55.25%) to the total variance and GXE and environments contributed 10.64% and 10.40% respectively (Table 4.3).

Cultivar means for L ranged from 59.00 mm (PAN3349) to 144.80 mm (Caledon). Environmental means ranged from 90.60 mm (Arlington) to 112.80 mm (Bethlehem). Arlington and Bothaville differed significantly from Bethlehem, but not from each other (Table 4.4).

4.3.2.2.5 Alveogram P/L ratio

Highly significant (p≤0.001) differences were observed for genotypes and significant differences were observed for environments and GXE (Table 4.2). Genotypes made the largest contribution (57.53%) to the total variance, GXE contributed 11.70% and environment contributed 7.92% (Table 4.3). This is in agreement with Mamuya (2000) who also reported genotypes to be the largest contributor to variation.

Cultivar means ranged from 0.41 mm H_2Omm^{-1} for Caledon to 1.47 mm H_2Omm^{-1} for PAN3118 (Table 4.4). PAN3118 differed significantly from all other cultivars. Environmental means ranged from 0.69 mm H_2Omm^{-1} (Bethlehem) to 0.96 mm H_2Omm^{-1} (Arlington). Bethlehem differed significantly from Arlington and Bothaville (Table 4.4).

4.3.2.2.6 Alveogram dough strength

Highly significant differences (p≤0.001) were observed for genotype (Table 4.2). The genotypic share to the total variation was 20.06% and contribution by the GXE and the environmental component were 8.67% and 4.84% respectively (Table 4.3). Mamuya (2000) reported on results obtained during 1997 that genotypes were the largest contributor to variation, and during 1998, he reported environment to be the largest contributor.

Cultivar means ranged from 33.05 10^{-4}J (Gariep) to 46.48 10^{-4}J (PAN3377). Environmental means ranged from 37.73 10^{-4}J (Arlington) to 41.78 10^{-4}J (Bethlehem) and environments did not differ significantly.

4.3.2.2.7 SDS-sedimentation volume

Genotypes revealed highly significant differences (p≤0.001) for SDS-sedimentation volumes (Table 4.2) and the contribution to the total variation made by genotypes was high at 80.74% (Table 4.3), indicating the high heritability for this parameter. Mamuya (2000) also reported genotypes to be the largest contributor to variation. Contributions made by the GXE and

environmental components were low at 1.90% and 0.35% respectively (Table 4.3).

Cultivar means ranged from 78.97 ml (Komati) to 93.00 (Matlabas). Environmental means ranged from 84.62 ml (Bothaville) to 85.35 ml (Bethlehem). Environments did not differ from one another (Table 4.5).

4.3.2.2.8 Wet gluten content

Highly significant differences (Table 4.2) were revealed for genotypes ($p \leq 0.001$) and GXE ($p \leq 0.01$). Contribution to the total variation was 36.51% for genotypes, 14.08% for GXE and 11.75% for environments, which is contradictory to Mamuya (2000) who reported environment to be the largest contributor.

Cultivar means ranged from 30.07% (Matlabas) to 39.78% (Caledon). Environmental means ranged from 31.43% (Arlington) to 35.11% (Bethlehem). Arlington differed significantly from Bethlehem (Table 4.5).

4.3.2.2.9 Loaf volume

Highly significant differences ($p \leq 0.001$) were observed for genotypes and GXE and significant differences were observed for environments ($p \leq 0.05$). Genotypes were the largest contributor to the total variation, contributing 40.06% and GXE and environments contributed 23.31% and 9.85% respectively.

The lowest loaf volume (Table 4.5) was obtained for PAN3349 (798.80 cm^3) and the highest for Caledon (940.00 cm^3). Environmental means ranged from 838.50 cm^3 (Arlington) to 888.10 cm^3 (Bethlehem).

4.3.2.2.10 Loaf volume expressed on a 12% protein basis (LFV12%)

Highly significant differences (Table 4.2) were observed for genotypes and GXE ($p \leq 0.001$). Genotypes, GXE and environments contributed 49.23%, 17.68% and 2.93% respectively to the total variance. Mamuya (2000) reported

GXE to be the largest contributor to variation on results obtained during 1997, but results obtained during 1998 revealed genotypes to be the largest contributor.

Cultivar means ranged from 853.70 cm^3 (PAN3349) to 968.30 cm^3 (Caledon) and environmental means ranged from 902.40 cm^3 (Bothaville) to 923.10 cm^3 (Bethlehem). Bethlehem and Bothaville differed significantly from each other (Table 4.5).

Table 4.2 Combined analysis of variance for rheological, baking quality-related and baking characteristics

SOURCE	df	MEAN SQUARES									
		MABS	FABS	P	L	P/L	STRENGTH	SDS	WGC	LFV	LFV12%
Total	119										
Reps	3	2.40	3.34	11.73	789.90	0.11	72.38	14.27	30.12	1612.00	615.00
Environment	2	21.57*	4.67	218.09*	5569.70**	0.77**	192.03	5.79	143.06	25205.00*	4972.00
Residual A	6	4.13	2.77	30.01	287.00	0.03	98.36	5.85	29.99	4831.00	1233.00
Genotype	9	2.44*	14.71***	1505.62***	6573.40***	1.24***	176.96***	299.89***	98.81***	22779.00***	18544.00***
GXE	18	2.09**	2.63*	159.96***	632.40**	0.13**	38.22	3.53	19.06**	6628.00***	3330.00***
Residual B	81	0.94	1.40	42.52	263.00	0.05	55.15	6.06	7.99	1274.00	1148.00
Grand mean		59.92	57.76	73.17	99.40	0.84	39.27	85.05	33.52	865.60	910.40
CV (%)		1.6	2.0	8.9	16.3	25.9	18.9	2.9	8.4	4.1	3.7

* p≤0.05, ** p≤0.01, *** p≤0.001. MABS=mixogram water-absorption, FABS=farinogram water-absorption, P=alveogram dough stability, L=alveogram dough distensibility, P/L=alveogram configuration ratio, STRENGTH=alveogram dough strength, SDS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, LFV12%=loaf volume expressed on a 12% protein basis

Table 4.3 Contribution (%) of each variance component to the total variation in rheological, baking quality-related and baking characteristics

SOURCE	MABS	FABS	P	L	P/L	STRENGTH	SDS	WGC	LFV	LFV12%
Reps	3.41	3.05	0.17	2.21	1.77	2.74	1.28	3.71	0.95	0.54
Environment	20.44	2.84	2.13	10.40	7.92	4.84	0.35	11.75	9.85	2.93
Residual A	11.74	5.04	0.88	1.61	1.05	7.43	1.05	7.39	5.66	2.18
Genotype	10.41	40.26	66.02	55.25	57.53	20.06	80.74	36.51	40.06	49.23
GXE	17.84	14.40	14.03	10.64	11.70	8.67	1.90	14.08	23.31	17.68
Residual B	36.16	34.41	16.77	19.89	20.03	56.26	14.68	26.57	20.17	27.44
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

MABS=mixogram water-absorption, FABS=farinogram water-absorption, P=alveogram dough stability, L=alveogram dough distensibility, P/L=alveogram configuration ratio, STRENGTH=alveogram dough strength, SDS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, LFV12%=loaf volume expressed on a 12% protein basis

Table 4.4 Genotype and environmental means of individual localities for MABS, FABS, P, L and P/L

	MABS			Cult		FABS			Cult		P			Cult		L			Cult		P/L			Cult	
Cultivar	**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**	
Betta-DN	58.94	60.06	61.19	**60.06**	cd	57.54	57.45	57.97	**57.65**	bcd	73.25	64.25	65.25	**67.58**	b	97.50	118.80	109.50	**108.60**	f	0.75	0.55	0.60	**0.63**	b
Caledon	59.35	61.23	61.04	**60.54**	d	58.24	58.76	57.97	**58.32**	d	62.25	58.00	55.50	**58.58**	a	122.80	156.80	154.80	**144.80**	h	0.51	0.37	0.36	**0.41**	a
Elands	57.80	59.20	60.40	**59.13**	a	56.14	57.19	57.54	**56.95**	ab	80.50	88.75	76.75	**82.00**	d	66.00	79.50	73.20	**72.90**	bc	1.24	1.12	1.22	**1.19**	e
Gariep	59.58	60.78	58.98	**59.78**	abcd	56.22	56.40	55.52	**56.05**	a	77.00	63.75	72.75	**71.17**	bc	80.50	121.20	63.50	**88.40**	de	1.05	0.53	1.25	**0.94**	d
Komati	60.18	60.21	61.04	**60.47**	d	56.49	57.10	57.19	**56.92**	ab	66.00	58.98	58.25	**61.08**	a	101.20	123.50	110.20	**111.70**	fg	0.68	0.50	0.53	**0.57**	ab
Limpopo	58.49	60.21	60.93	**59.88**	abcd	56.84	57.10	57.71	**57.22**	b	77.00	65.75	66.25	**69.67**	bc	78.80	113.20	112.50	**101.50**	ef	0.99	0.59	0.65	**0.74**	bc
Matlabas	58.79	59.39	60.21	**59.46**	abc	56.75	58.15	57.01	**57.30**	bc	72.50	79.50	70.00	**74.00**	c	77.20	96.80	79.00	**84.30**	cd	1.01	0.84	0.89	**0.91**	cd
PAN3118	58.83	61.00	60.89	**60.24**	cd	58.59	58.41	61.47	**59.49**	e	107.50	94.75	88.25	**96.83**	e	57.50	82.80	67.80	**69.30**	ab	1.92	1.18	1.32	**1.47**	f
PAN3349	58.56	60.85	59.20	**59.54**	ab	57.97	58.85	57.89	**58.24**	cd	78.50	76.00	90.00	**81.50**	d	86.00	106.50	74.50	**59.00**	a	0.98	0.72	1.22	**0.97**	d
PAN3377	60.21	59.95	60.06	**60.08**	cd	59.16	57.98	60.77	**59.40**	e	64.00	65.75	78.25	**69.33**	bc	138.80	129.00	102.20	**123.30**	g	0.47	0.52	0.79	**0.59**	ab
Env mean	**59.07** a	**60.29** b	**60.39** b	**59.92**		**57.42** a	**57.74** a	**58.11** a	**57.76**		**75.85** b	**71.55** a	**72.12** a	**73.17**		**90.60** a	**112.80** b	**94.70** a	**99.40**		**0.96** b	**0.69** a	**0.88** b	**0.84**	
LSD Env	1.1118					0.910					2.998					9.27					0.1005				
LSD Cult	0.7886					0.960					5.297					13.17					0.1777				

Means followed by the same letter, did not differ significantly at P=0.05. MABS=mixogram water-absorption, FABS=farinogram water-absorption, P=alveogram dough stability, L=alveogram dough distensibility, P/L=alveogram configuration ratio, Cult means=cultivar means for the three localities, Env mean=environmental means, LSD Env=least significant difference for environments, LSD Cult=least significant difference for cultivars, Ar=Arlington, Be=Bethlehem, Bo=Bothaville

Table 4.5 Genotype and environmental means of individual localities for STRENGTH, SDS, WGC, LFV and LFV12%

	STRENGTH			Cult		SDS			Cult		WGC			Cult		LFV			Cult		LFV12%			Cult	
Cultivar	**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**		**Ar**	**Be**	**Bo**	**Means**	
Betta-DN	39.14	40.79	40.25	**40.06**	bc	83.75	84.00	83.75	**83.83**	d	32.39	35.70	35.63	**34.57**	de	780.00	871.30	897.50	**849.60**	bc	851.00	912.20	908.50	**890.60**	b
Caledon	37.16	39.91	40.56	**39.21**	bc	81.50	79.00	78.25	**79.58**	ab	36.54	41.66	41.13	**39.78**	f	915.00	958.80	946.20	**940.00**	e	975.00	968.70	961.20	**968.30**	c
Elands	33.33	42.35	34.90	**36.86**	ab	83.75	85.00	72.25	**83.67**	d	27.99	33.12	36.32	**32.48**	bcd	768.80	828.80	882.50	**826.70**	ab	866.70	892.70	914.50	**891.30**	b
Gariep	35.97	34.07	29.09	**33.05**	a	82.00	81.50	79.75	**81.08**	bc	31.92	36.72	30.63	**33.09**	cd	845.00	923.80	805.00	**857.90**	c	899.00	945.70	875.00	**906.60**	b
Komati	36.74	38.04	36.43	**37.07**	ab	79.25	78.90	78.75	**78.97**	a	35.66	35.91	36.71	**36.09**	e	810.00	848.10	890.00	**849.40**	bc	848.00	885.20	905.00	**879.40**	ab
Limpopo	34.71	39.68	41.78	**38.72**	abc	82.25	81.75	82.00	**82.00**	cd	30.98	36.81	35.55	**34.44**	de	812.50	902.50	832.50	**849.20**	bc	895.50	939.50	850.50	**895.20**	b
Matlabas	34.14	44.61	33.49	**37.41**	ab	91.75	94.25	93.00	**93.00**	g	27.61	30.55	32.04	**30.07**	a	911.20	885.00	902.50	**899.60**	d	986.20	944.00	939.50	**956.60**	c
PAN3118	41.67	51.19	40.52	**44.46**	cd	90.50	92.00	90.00	**90.83**	f	28.11	31.84	32.18	**30.71**	ab	817.50	877.50	885.00	**860.00**	c	891.50	894.20	904.00	**896.60**	b
PAN3349	37.00	41.82	39.22	**39.35**	bc	86.75	87.00	87.50	**87.08**	e	30.09	36.34	27.93	**31.45**	abc	785.00	871.20	740.00	**798.80**	a	866.00	891.20	804.00	**853.70**	a
PAN3377	47.44	45.30	46.71	**46.48**	d	90.00	90.25	91.00	**90.42**	f	33.00	32.46	32.09	**32.52**	bcd	940.00	913.80	921.20	**925.00**	de	977.00	957.80	962.20	**965.70**	c
Env mean	**37.73** a	**41.78** a	**38.30** a	**39.27**		**85.15** a	**85.35** a	**84.62** a	**85.05**		**31.43** a	**35.11** b	**34.02** ab	**33.52**		**838.50** a	**888.10** b	**870.20** ab	**865.60**		**905.60** ab	**923.10** b	**902.40** a	**910.40**	
LSD Env	5.426					1.323					2.996					38.03					19.21				
LSD Cult	6.032					1.999					2.296					29.00					27.53				

Means followed by the same letter, did not differ significantly at P=0.05. STRENGTH=alveogram dough strength, SDS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, LFV12%=loaf volume expressed on a 12% protein basis, Cult means=cultivar means for the three localities, Env mean=environmental means, LSD Env=least significant difference for environments, LSD Cult=least significant difference for cultivars, Ar=Arlington, Be=Bethlehem, Bo=Bothaville

4.3.3 CORRELATIONS

4.3.3.1 Correlations between the selected mixogram parameters

See Chapter 3 (Section 3.3.3.1).

4.3.3.1.1 Correlations between the selected mixogram parameters and rheological, baking quality-related and baking characteristics

Significant positive correlations were observed between PT and alveogram parameters P and P/L ($p \leq 0.001$) and between PT and SDS (Table 4.6). Mamuya (2000) agreed with the latter and also with Sadouki *et al*. (2006) who reported significant correlations between PT and STRENGTH. Sadouki *et al*. (2006) further reported significant positive correlations between PT and P ($p \leq 0.01$). Souza *et al*. (1993) reported positive correlations ($P \leq 0.05$) between PT and LFV12%.

In agreement with Souza *et al*. (1993, $p \leq 0.01$), Khatkar *et al*. (1996), Ohm and Chung (1999, $p \leq 0.01$), Chung *et al*. (2001, $p \leq 0.1$) and Neacşu *et al*. (2009) peak height exhibited significant positive correlations ($p \leq 0.001$) with both water-absorption parameters (MABS and FABS), with alveogram parameters L and STRENGTH and with the baking characteristic LFV. Peak height also exhibited significant positive correlations ($p \leq 0.001$) with LFV12%. Significant positive correlations ($p \leq 0.01$) were also observed between PH and baking quality-related characteristics, SDS and WGC (Ohm and Chung, 1999). Khatkar *et al*. (1996) also reported significant correlations ($p \leq 0.001$) between PH and SDS.

High positive correlations ($p \leq 0.001$) were observed between TH and FABS, P, P/L and SDS (Dobraszczyk and Schofield, 2002). In agreement with Bordes *et al*. (2008), positive correlations ($p \leq 0.01$) were observed between TH and STRENGTH.

Significant positive correlations ($p \leq 0.001$) were found between AA and MABS, FABS, L, STRENGTH, WGC (Ohm and Chung, 1999, $p \leq 0.01$), LFV (Ohm and

Chung, 1999, p≤0.01) and LFV12%. The descending angle revealed significant positive correlations (p≤0.001) with P and P/L.

Width-parameter, W-1, had significant correlations (p≤0.001) with FABS, STRENGTH and SDS. Peak width had significant correlations (p≤0.001) with FABS and STRENGTH, W+2 and TW both correlated significantly (p≤0.001) with P, P/L and SDS (Khatkar *et al*., 1996; Dobraszczyk and Schofield, 2002). Ohm and Chung (1999) reported significant correlations (p≤0.01) between PW and WGC. Chung *et al.* (2001) reported correlations (p≤0.1) between PW and LFV as well as Neacşu *et al*. (2009) who reported significant correlations (p≤0.001) between TW and LFV and also correlations (p≤0.05) between TW and SDS (Dobraszczyk and Schofield, 2002). Khatkar *et al*. (1996), Ohm and Chung (1999) and Magnus *et al*. (2000) reported significant correlations between PW and LFV. Ohm and Chung (1999) reported significant correlations (p≤0.01) between TW and LFV, between W+2 and LFV, between W+2 and WGC and between W-1 and WGC.

Area-parameters, A-1, AP and A+2, exhibited the same trends as they correlated significantly (p≤0.001) with P, P/L and SDS. Dobraszczyk and Schofield (2002) reported high correlations between AP and SDS. The parameter TA correlated significantly (p≤0.001) with MABS and FABS, L and STRENGTH, SDS (Khatkar *et al*., 1996, (p≤0.01); Dobraszczyk and Schofield, 2002, (p≤0.01); LFV (Neacşu *et al*., 2009) and LFV12%.

Table 4.6 Significant correlations between the 13 selected mixogram parameters and rheological, baking quality-related and baking characteristics

	PT	PH	TH	AA	DA	W-1	PW	W+2	TW	A-1	AP	A+2	TA
MABS	-0.26 **	0.47 ***		0.61 ***	-0.56 ***			-0.36 ***	-0.38 ***	-0.26 **	-0.21 *		0.32 ***
FABS		0.58 ***	0.33 ***	0.37 ***	-0.38 ***	0.37 ***	0.30 ***						0.58 ***
P	0.63 ***		0.66 ***	-0.46 ***	0.48 ***		0.23 *	0.59 ***	0.67 ***	0.66 ***	0.66 ***	0.65 ***	
L	-0.72 ***	0.41 ***	-0.43 ***	0.74 ***	-0.70 ***			-0.61 ***	-0.72 ***	-0.69 ***	-0.64 ***	-0.59 ***	0.37 ***
P/L	0.68 ***	-0.22 *	0.58 ***	-0.62 ***	0.70 ***			0.70 ***	0.79 ***	0.68 ***	0.64 ***	0.61 ***	-0.21 *
STRENGTH		0.49 ***	0.25 **	0.38 ***	-0.41 ***	0.37 ***	0.33 ***						0.48 ***
SDS	0.32 ***	0.25 **	0.53 ***			0.31 ***	0.36 **	0.33 ***	0.40 ***	0.39 ***	0.42 ***	0.44 ***	0.36 ***
WGC	-0.57 ***	0.29 **	-0.35 ***	0.65 ***	-0.57 ***			-0.52 ***	-0.63 ***	-0.58 ***	-0.55 ***	-0.50 ***	0.18 *
LFV	-0.35 ***	0.52 ***		0.67 ***	-0.56 ***		0.23 *	-0.32 ***	-0.32 ***	-0.32 ***	-0.26 *	-0.19 *	0.45 ***
LFV (12%)	-0.26 **	0.32 ***		0.42 ***	-0.32 ***		0.20 *			-0.22 *	-0.18 *		0.34 ***

* p≤0.05, ** p≤0.01, *** p≤0.001. PT=peak time, PH=peak height, TH=tailheight, AA=ascending angle from beginning until 1 min before PT, DA=descending angle from PT until 2 min after PT, W-1=curve-width 1 min before PT, PW=peakwidth, W+2=curve-width 2 min after PT, TW=tailwidth at 6 min, A-1=area under curve until 1 min before PT, AP=area under curve until PT, A+2=area under curve until 2 min after PT, TA=total area under curve, MABS=mixogram water-absorption, FABS=farinogram water-absorption, P=alveogram dough stability, L=alveogram dough distensibility, P/L=alveogram configuration ratio, STRENGTH=alveogram dough strength, SDS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, LFV (12%) = loaf volume expressed on a 12% protein basis

4.3.4 MULTIPLE STEPWISE REGRESSIONS

Multiple stepwise regressions were applied to determine which mixogram parameters (independent variables) were the most responsible for variation in the dependant variables, being the rheological, baking quality-related and baking characteristics (Table 4.7).

Multiple coefficient of determination was low to relatively high (25.8% to 76.8%), regarding the mixogram parameters as independent variables in explaining the variation in the rheological, baking quality-related and baking characteristics (Table 4.7).

4.3.4.1 Mixogram parameters responsible for the variation in rheological, baking quality-related and baking characteristics

The alveogram P/L value was the rheological characteristic with the highest coefficient of determination (R^2 = 76.8%). Independent variables for P/L included TW, DA, W+2, A-1, PT, AP, AA, A+2 and TH, with TW making the largest contribution (62.0%). The parameter DA contributed 5.2%, A-1 contributed 4.1%, AP contributed 1.6%, A+2 and TH contributed each 1.30%, PT contributed 0.8%, W+2 contributed 0.4% and AA contributed 0.1%. Although some contributions were less than 1.0%, all contributions made by the different independent variables were highly significant ($p \leq 0.001$).

The rheological characteristic L had a coefficient of determination of 76.5%. The involved mixogram parameters for L were TW, A-1, AP, TH, A+2, PT, DA and AA. The parameter TW was the highest contributor (52.3%) to the variation in L. Parameters AP, TH, A-1, DA, AA, A+2 and PT contributed 9.9%, 6%, 3.7%, 1.9%, 1.3%, 1.0% and 0.4% respectively to the total variation in L. All contributions made by the independent variables were highly significant ($p \leq 0.001$).

The rheological characteristic P had a coefficient of determination of 69.8% with AA, PT, A-1, TW, TH, A+2, DA and PH, AP, TA and W+2 contributing

21.1%, 19.1%, 11.5%, 7.0%, 5.6%, 1.5%, 1.2%, 1.2%, 0.8%, 0.7% and 0.1% respectively to the variation in P. All contributions made by the different mixogram parameters were highly significant ($p \leq 0.001$).

The baking quality-related characteristic WGC had a coefficient of determination of 64.8%. Independent variables, all contributing significantly ($p \leq 0.001$), were AA, making the highest contribution of 42.0%, TW, A-1, DA, PT, W+2, A+2, TH, PH, and TA each contributing 9.2%, 0.2%, 1.2%, 5.2%, 0.6, 0.6%, 3.6%, 0.2% and 2.0% respectively to the total variation in WGC.

LFV's coefficient of determination was 52.3%, with AA explaining the largest part of the variation in LFV by contributing 44.6%. Other independent variables contributing significantly ($p \leq 0.001$) to the variation were DA, PH, PT, A-1, W+2 and TW, contributing 1.9%, 0.1%, 0.5%, 0.5%, 1.2% and 3.5% respectively to the total variation in LFV.

Predictor variables for the baking characteristic SDS were TH, A+2, TW, A-1, PW, TA, W+2, PT and PH, with TH making the largest contribution (28.6%). Contributions made by the variables were all highly significant ($p \leq 0.001$). Respectively they contributed 2.8%, 3.1%, 0.4%, 0.3%, 12.7%, 2.4%, 0.4% and 0.1% to the total coefficient of determination for SDS, which was 50.8%.

Mixogram water-absorption was predicted by AA, DA, TW, W+2, TA and PT with R^2 being 50.0%. The variables explained 37.5%, 3.7%, 0.6%, 0.1%, 7.9% respectively and 0.2% of the variation in MABS and all contributions were highly significant ($p \leq 0.001$).

The variation in FABS were explained by PH, contributing 34.1%, TA, contributing 0.8%, DA, contributing 0.5%, AA, contributing 1.2%, W-1, contributing 0.2%, TH, contributing 0.2% and PW, contributing 3.1%. All contributions were highly significant ($p \leq 0.001$). The total coefficient of determination was 40.1%.

Variation in the rheological characteristic, STRENGTH, was highly significantly ($p \leq 0.001$) explained by the mixogram parameters PH, TA, DA, AA, W-1 and PW, each contributing 24.3%, 0.5%, 2.6%, 0.2%, 0.8% and 0.1% respectively to the total coefficient of determination of 28.5%.

Corrected loaf volume was the baking characteristic having the lowest coefficient of determination (R^2 = 25.8%) as explained by the mixogram parameters AA, TA, PH, DA, PT, A-1, PW and AP. The mixogram parameter AA made the largest contribution, 17.6%, AP contributed 3.6%, PH contributed 1.9%, TA contributed 1.4%, A-1 contributed 1.1%, PW contributed 0.4%, PT contributed 0.4% and DA contributed 0.1%, although some contributions were low, they were all highly significant ($p \leq 0.001$).

Table 4.7 The total R^2 for selected mixogram parameters in the model, responsible for the variation in rheological, baking quality-related and baking characteristics added to the regression on a stepwise basis

P/L (Full scale R^2 = 76.8%)											
Constant	**TW**	**DA**	**W+2**	**A-1**	**PT**	**AP**	**AA**	**A+2**	**TH**	**R^2**	**F-value**
0.007*(a)*	0.0604									0.620	<0.001***
0.064 (b)	*0.00435*										
0.508	0.04439	0.0628								0.672	<0.001***
0.131	*0.00551*	*0.0146*									
0.709	0.05053	0.0732	-.01127							0.676	<0.001***
0.213	*0.00753*	*0.017*	*0.00945*								
0.507	0.0084	0.0919	0.00382	0.00582						0.717	<0.001***
0.206	*0.0125*	*0.0166*	*0.00959*	*0.00141*							
1.126	0.0078	0.1077	-.00067	0.01402	-0.364					0.725	<0.001***
0.41	*0.0123*	*0.0187*	*0.00985*	*0.00492*	*0.209*						
-0.442	0.0127	0.16	-.0151	-.0251	-0.053	0.0313				0.741	<0.001***
0.715	*0.0122*	*0.0269*	*0.011*	*0.0156*	*0.236*	*0.0118*					
-0.953	0.0156	0.1554	-.0154	-.0389	0.063	0.0412	-.0123			0.742	<0.001***
0.927	*0.0126*	*0.0275*	*0.0111*	*0.0222*	*0.272*	*0.0165*	*0.0142*				
-0.772	0.011	0.1622	-.0231	0.0676	0.002	-.1668	-0.021	0.1044		0.755	<0.001***
0.912	*0.0125*	*0.0271*	*0.0113*	*0.0502*	*0.267*	*0.0898*	*0.0144*	*0.0444*			
-0.249	0.0003	0.1022	-.0271	0.0733	-0.258	-.0961	-.0165	0.0299	0.0916	0.768	<0.001***
0.916	*0.013*	*0.0359*	*0.0112*	*0.0492*	*0.282*	*0.0923*	*0.0142*	*0.0527*	*0.0369*		

Table 4.7 Continued

L (Full scale R^2 = 76.5%)										
Constant	**TW**	**A-1**	**AP**	**TH**	**A+2**	**PT**	**DA**	**AA**	**R^2**	**F-value**
156.57	-4.127								0.523	<0.001***
5.37	*0.363*									
167.58	-2.665	-0.332							0.560	<0.001***
6.26	*0.583*	*0.106*								
5	-1.525	-3.485	2.963						0.659	<0.001***
28.6	*0.552*	*0.552*	*0.511*							
58.9	1.884	-8.15	7.69	-7.62					0.719	<0.001***
28.2	*0.852*	*1.07*	*1.06*	*1.54*						
85.1	1.827	-1.34	-6.08	-9.24	7.17				0.729	<0.001***
30.6	*0.841*	*3.45*	*6.73*	*1.71*	*3.46*					
33	2.163	-3.2	-4.1	-9.58	6.54	21.6			0.733	<0.001***
54.3	*0.888*	*3.8*	*6.93*	*1.73*	*3.5*	*18.6*				
81.9	1.49	-2.41	0.53	-3.71	1.22	5.7	-8.15		0.752	<0.001***
56.7	*1.1*	*3.91*	*7.06*	*3.16*	*3.89*	*19.6*	*2.83*			
186.8	1.04	-2.02	3.67	-3.18	-1.6	-17.9	-7.79	2.67	0.765	<0.001***
69.5	*1.09*	*3.83*	*7.01*	*3.1*	*3.96*	*21.3*	*2.77*	*1.07*		

Table 4.7 Continued

P (Full scale R^2 = 69.8%)													
Constant	**AA**	**PT**	**TW**	**DA**	**A-1**	**AP**	**W+2**	**A+2**	**TH**	**PH**	**TA**	**R^2**	**F-value**
89.68	-1.695											0.211	<0.001***
3.12	*0.301*												
39.19	-0.394	11.3										0.402	<0.001***
8.69	*0.339*	*1.85*											
42	-0.123	5.05	1.118									0.472	<0.001***
8.24	*0.327*	*2.37*	*0.286*										
40.41	0.338	7.9	0.667	1.395								0.484	<0.001***
8.24	*0.429*	*2.92*	*0.394*	*0.847*									
102.4	0.716	-34.96	-0.454	3.906	1.108							0.599	<0.001***
13.1	*0.385*	*7.94*	*0.401*	*0.87*	*0.194*								
50.2	0.085	-23.7	-0.407	4.195	-0.131	0.922						0.607	<0.001***
36.9	*0.567*	*10.9*	*0.4*	*0.886*	*0.843*	*0.61*							
52.2	0.094	-24	-0.559	3.88	0.01	0.8	0.217					0.608	<0.001***
37.3	*0.569*	*10.9*	*0.508*	*1.1*	*0.894*	*0.661*	*0.444*						
58.9	-0.229	-26.3	-0.73	4.13	3.94	-6.88	-0.07	3.86				0.623	<0.001***
36.8	*0.58*	*10.8*	*0.506*	*1.09*	*2.03*	*3.62*	*0.457*	*1.79*					
94.1	0.077	-43.8	-1.445	0.08	4.33	-2.12	-0.338	-1.16	6.17			0.679	<0.001***
35.1	*0.542*	*10.8*	*0.497*	*1.37*	*1.88*	*3.53*	*0.428*	*2.02*	*1.41*				
68.9	0.197	-41.5	-1.328	1.42	3.93	-4.17	-0.766	1.17	6.64	-2.2		0.691	<0.001***
36.8	*0.538*	*10.7*	*0.494*	*1.51*	*1.87*	*3.63*	*0.473*	*2.3*	*1.41*	*1.09*			
103	0.05	-54.6	-1.741	1.63	4.4	-5.23	-0.705	2.04	7.45	-2.22	-.285	0.698	<0.001***
71.7	*0.549*	*19.9*	*0.559*	*1.79*	*1.96*	*3.69*	*0.477*	*2.54*	*1.6*	*1.09*	*0.422*		

Table 4.7 Continued

WGC (Full scale R^2 = 64.8%)												
Constant	**AA**	**TW**	**A-1**	**DA**	**PT**	**W+2**	**A+2**	**TH**	**PH**	**TA**	**R^2**	**F-value**
25.507	0.8228										0.420	<0.001***
0.923	*0.0891*											
32.85	0.533	-.3264									0.512	<0.001***
1.78	*0.103*	*0.0696*										
33.59	0.514	-.2752	-.0134								0.514	<0.001***
2.03	*0.106*	*0.0962*	*0.0174*									
32.88	0.347	-0.089	-.0408	-0.525							0.526+	<0.001***
2.05	*0.144*	*0.145*	*0.0236*	*0.308*								
17.2	0.358	0.036	-.2831	-0.883	10.49						0.578	<0.001***
4.63	*0.136*	*0.142*	*0.0686*	*0.307*	*2.81*							
18.6	0.36	-0.11	-0.159	-1.189	10.3	0.209					0.584	<0.001***
13.2	*0.202*	*0.18*	*0.317*	*0.392*	*3.87*	*0.158*						
17.2	0.428	-0.075	-0.98	-1.242	10.78	0.269	-0.805				0.590	<0.001***
13.2	*0.208*	*0.182*	*0.728*	*0.393*	*3.88*	*0.164*	*0.643*					
26.9	0.513	-0.273	-0.873	-2.366	5.9	0.195	-2.198	1.716			0.626	<0.001***
13	*0.201*	*0.185*	*0.699*	*0.51*	*4.01*	*0.159*	*0.75*	*0.525*				
23.9	0.527	-0.259	-0.922	-2.205	6.18	0.143	-1.917	1.772	-.266		0.628	<0.001***
13.9	*0.203*	*0.187*	*0.705*	*0.569*	*4.04*	*0.179*	*0.87*	*0.534*	*0.413*			
80.5	0.43	-0.354	-1.222	-1.359	-9.31	0.205	-0.909	1.538	-.207	-0.39	0.648	<0.001***
26.4	*0.202*	*0.186*	*0.699*	*0.651*	*7.35*	*0.176*	*0.94*	*0.53*	*0.404*	*0.156*		

Table 4.7 Continued

LFV (Full scale R^2 = 52.3%)									
Constant	**AA**	**DA**	**PH**	**PT**	**A-1**	**W+2**	**TW**	**R^2**	**F-value**
745.9	12.29							0.446	<0.001***
13.1	*1.26*								
741.3	9.89	-6.29						0.465	<0.001***
13.1	*1.71*	*3.07*							
708.5	9.4	-6.14	0.67					0.466	<0.001***
80.3	*2.09*	*3.1*	*1.61*						
675	11.72	-5.9	-1.39	11.5				0.471	<0.001***
117	*3.11*	*3.14*	*4.13*	*10.8*					
1042	12.6	-5.17	1.2	-91	2.29			0.476	<0.001***
385	*3.23*	*3.22*	*4.88*	*103*	*2.29*				
1153	11.49	-13.15	2.28	-113	2.58	3.41		0.488	<0.001***
388	*3.28*	*5.76*	*4.88*	*103*	*2.28*	*2.05*			
704	10.1	-15.95	-1.66	7	-0.89	-1.48	8.4	0.523	<0.001***
408	*3.22*	*5.68*	*4.94*	*108*	*2.52*	*2.63*	*2.96*		

Table 4.7 Continued

SDS (Full scale R^2 = 50.8%)											
Constant	**TH**	**A+2**	**TW**	**A-1**	**PW**	**TA**	**W+2**	**PT**	**PH**	**R^2**	**F-value**
42.6	0.872									0.286	<0.001***
6.19	*0.127*										
51.08	0.653	-.0093								0.314	<0.001***
7.94	*0.229*	*0.0242*									
59.91	-0.402	0.606	0.572							0.345	<0.001***
9.06	*0.533*	*0.309*	*0.247*								
57.87	-0.372	-0.137	0.649	-0.798						0.349	<0.001***
9.41	*0.535*	*0.957*	*0.264*	*0.973*							
59.18	-0.422	-0.282	0.604	-0.84	0.179					0.352	<0.001***
9.55	*0.539*	*0.974*	*0.27*	*0.976*	*0.215*						
31.4	-0.694	0.136	0.382	1.249	-0.037	0.4463				0.479	<0.001***
10.1	*0.488*	*0.881*	*0.247*	*0.967*	*0.198*	*0.0859*					
29.19	-0.062	-0.14	0.6	1.646	0.17	0.4972	-0.525			0.503	<0.001***
9.99	*0.554*	*0.873*	*0.261*	*0.965*	*0.215*	*0.0873*	*0.23*				
-0.6	-0.317	-0.372	0.704	1.492	0.185	0.645	-0.57	9.16		0.507	<0.001***
32	*0.612*	*0.905*	*0.281*	*0.978*	*0.215*	*0.174*	*0.235*	*9.35*			
-6.4	-0.190	-0.211	0.713	1.484	0.172	0.666	-0.604	10.16	-.229	0.508	<0.001***
34.8	*0.680*	*0.981*	*0.283*	*0.981*	*0.218*	*0.181*	*0.248*	*9.67*	*0.528*		

Table 4.7 Continued

MABS (Full scale R^2 = 50.0%)								
Constant	**AA**	**DA**	**TW**	**W+2**	**TA**	**PT**	**R^2**	**F-value**
57.688	0.2289						0.375	<0.001***
0.282	*0.0272*							
57.558	0.1614	-0.177					0.412	<0.001***
0.279	*0.0364*	*0.0653*						
57.58	0.1858	-0.223	0.0324				0.418	<0.001***
1.74	*0.0523*	*0.0792*	*0.0297*					
57.54	0.1835	-0.241	0.0264	0.0116			0.419	<0.001***
1.76	*0.0534*	*0.11*	*0.0397*	*0.0505*				
63.83	0.1043	-0.347	-.0332	0.0848	-.0776		0.498	<0.001***
2.22	*0.0532*	*0.106*	*0.0396*	*0.0502*	*0.0183*			
62.98	0.1276	-0.315	-.0572	0.0883	-.0723	0.221	0.500	<0.001***
2.56	*0.0638*	*0.116*	*0.0536*	*0.0506*	*0.02*	*0.332*		

FABS (Full scale R^2 = 40.1%)									
Constant	**PH**	**TA**	**DA**	**AA**	**W-1**	**TH**	**PW**	**R^2**	**F-value**
44.04	0.238							0.341	<0.001***
1.76	*0.031*								
41.25	0.146	0.0281						0.349	<0.001***
2.89	*0.082*	*0.0231*							
41.96	0.126	0.0285	-.0671					0.354	<0.001***
3	*0.085*	*0.0231*	*0.0754*						
41.09	0.191	0.0206	-.1298	-.0873				0.366	<0.001***
3.04	*0.095*	*0.0236*	*0.0864*	*0.0597*					
40.47	0.200	0.0249	-.1283	-0.098	-.0276			0.368	<0.001***
3.22	*0.097*	*0.0247*	*0.0867*	*0.0624*	*0.0453*				
40.29	0.140	0.0267	-.1575	-.0619	-.0206	0.0485		0.370	<0.001***
3.24	*0.135*	*0.0249*	*0.0983*	*0.0846*	*0.0468*	*0.0764*			
37.92	0.047	0.0531	-.1181	0.0282	-.0036	0.1395	-.1638	0.401	<0.001***
3.32	*0.138*	*0.0267*	*0.0976*	*0.0907*	*0.0463*	*0.0836*	*0.0673*		

Table 4.7 Continued

STRENGTH (Full scale R^2 = 28.5%)								
Constant	**PH**	**TA**	**DA**	**AA**	**W-1**	**PW**	**R^2**	**F-value**
-17.63	0.988						0.243	<0.001***
9.27	*0.161*							
-28.3	0.633	0.108					0.248	<0.001***
15.3	*0.433*	*0.122*						
-19.8	0.399	0.112	-0.805				0.274	<0.001***
15.6	*0.442*	*0.12*	*0.392*					
-21.3	0.513	0.098	-0.915	-0.153			0.276	<0.001***
16	*0.501*	*0.124*	*0.453*	*0.313*				
-15.3	0.424	0.057	-0.93	-0.051	0.263		0.284	<0.001***
16.8	*0.507*	*0.129*	*0.453*	*0.326*	*0.237*			
-13.8	0.409	0.039	-1.002	-0.068	0.26	0.126	0.285	<0.001***
17.4	*0.51*	*0.137*	*0.491*	*0.33*	*0.238*	*0.322*		

Table 4.7 Continued

LFV12% (Full scale R^2 = 25.8%)										
Constant	**AA**	**TA**	**PH**	**DA**	**PT**	**A-1**	**PW**	**AP**	**R^2**	**F-value**
849.7	6.23								0.170	<0.001***
13	*1.25*									
719	4.98	0.494							0.184	<0.001***
105	*1.6*	*0.394*								
671	6.59	1.745	-5.74						0.203	<0.001***
108	*1.86*	*0.841*	*3.42*							
675	6.29	1.722	-5.71	-0.86					0.204	<0.001***
109	*2.15*	*0.849*	*3.43*	*3.11*						
647	7.85	1.996	-7.29	-0.68	7.5				0.207	<0.001***
117	*3.1*	*0.937*	*4.12*	*3.12*	*10.8*					
1110	8.96	0.27	-4.02	0.25	-121	2.88			0.218	<0.001***
383	*3.22*	*1.65*	*4.85*	*3.2*	*102*	*2.27*				
1062	9.62	0.66	-4.47	1.18	-114	2.77	-1.59		0.222	<0.001***
390	*3.37*	*1.75*	*4.9*	*3.49*	*103*	*2.28*	*2.33*			
1062	9.62	0.66	-4.47	1.18	-114	2.77	-1.59	-24	0.258	<0.001***
390	*3.37*	*1.75*	*4.9*	*3.49*	*103*	*2.28*	*2.33*	*10.3*		

*** p≤0.001. (a)=correlation coefficient, (b)=standard error of correlation coefficient, R^2=coefficient of multiple determination, P/L=alveogram configuration ratio, L=alveogram dough distensibility, P=alveogram dough stability, WGC=wet gluten content, LFV=loaf volume, SDS=SDS-sedimentation volume, MABS=mixogram water-absorption, FABS=farinogram water-absorption, STRENGTH=alveogram dough strength, LFV12%=loaf volume expressed on a 12% protein basis, TW=tailwidth at 6 min, DA=descending angle from PT until 2 min after PT, W+2=curve-width 2 min after PT, A-1=area under curve from beginning until 1 min before PT, PT=peak time, AP=area under curve from beginning until PT, AA=ascending angle from beginning until 1 min before PT, A+2=area under curve from beginning until 2 min after PT, TH=tailheight, PH=peak height, TA=total area under curve, PW=peakwidth, W-1=curve-width 1 min before PT

4.4 CONCLUSIONS

The combined ANOVA showed highly significant ($p \leq 0.001$) differences among cultivars, environments and their interaction for most of the rheological, baking quality-related and baking characteristics. This indicated the existence of variable responses between the cultivars and the environments for nearly all selected mixogram parameters and rheological, baking quality-related and baking characteristics measured.

Much larger variation was found among genotypes than among environments for all measured mixogram parameters, indicating higher heritability for these parameters. The largest variation was attributed to the environments for the measured characteristic MABS and genotypes were responsible for the largest variation for the measured characteristics FABS, P, L, P/L, STRENGTH, SDS, WGC, LFV and LFV12%.

Highly significant ($p \leq 0.001$) positive and negative correlations were observed between most of the selected mixogram parameters, with TH being the parameter exhibiting the most correlations with all the other mixogram parameters. Highly significant ($p \leq 0.001$) correlations were observed between some mixogram parameters and rheological and baking characteristics.

Multiple coefficients of determination were low to relatively high (28.5% to 76.8%), regarding the rheological, baking quality-related and baking characteristics. Independent variables occurring frequently in predictions were AA, DA, PT, TA, TW, PH and A-1, explaining the variation in the rheological, baking quality-related and baking characteristics. The parameter W-1 was the variable occurring least in the models. Regarding the rheological characteristics, coefficients of determination ranged from 28.5% for STRENGTH to 76.8% for P/L, with TW, AA and PH occurring mostly as independent variables. Coefficients of determination for the baking quality-related and baking characteristics ranged from 25.8% for LFV12% to 64.8% for WGC, with AA as the independent variable occurring frequently.

For a parameter to be effective in predicting another parameter, the secondary characteristics (selected mixogram parameters) need to exhibit higher narrow sense heritability than the primary characteristics (rheological and baking characteristics measured) (personal communication, Prof Klaus Pakendorf). If primary criteria (regarding rheological and baking characteristics) during cultivar release are taken into consideration, the mixogram parameter TA should predict FABS, STRENGTH and LFV12% effectively and TH should predict P/L effectively since TA and TH exhibited higher heritability than FABS, STRENGTH, LFV12% and P/L.

Therefore, when wheat breeders only have small sample sizes available for constructing a mixogram, they could benefit from using the mixogram parameters TA and TH to select for acceptable rheological and baking characteristics that cannot be discriminated against by the WTC during the final release stages of potential wheat breeding lines.

REFERENCES

AACC – American Association of Cereal Chemists, 2000. Approved methods of the AACC, 10th edition. American Association of Cereal Chemists, Inc., St. Paul, Minnesota, USA.

Bordes, J., Branlard, G., Oury, F.X., Charmet, G. and Balfourier, F., 2008. Agronomic characteristics, grain quality and flour rheology of 372 bread wheats in a worldwide core collection. Journal of Cereal Science 48: 569-579.

Chung, O.K., Ohm, J.B., Caley, M.S. and Seabourn, B.W., 2001. Prediction of baking characteristics of hard winter wheat flours using computer-analysed mixograph parameters. Cereal Chemistry 78: 493-497.

Dobraszczyk, B.J. and Schofield, J.D., 2002. Rapid assessment and prediction of wheat and gluten baking quality with the 2-g direct drive mixograph using multivariate statistical analysis. Cereal Chemistry 79: 607- 612.

Ingelin, M.E., 1997. Comparison of two recording dough mixers. Pages 5-11 in: The mixograph handbook. 1st edition. C.E. Walker, J.L. Hazelton

and M.D. Shogren, eds. National Manufacturing Division, TMCO, Lincoln, NE 68508-2935, USA.

Khatkar, B.S., Bell, A.E. and Schofield, J.D., 1996. A comparative study of the inter-relationships between mixograph parameters and bread making qualities of wheat flours and glutens. Journal of the Science of Food and Agriculture 72: 71-85.

Magnus, E.M., Bråthen, E., Sahlstrøm, S., Vogt, G. and Færgestad, E.M., 2000. Effects of flour composition, physical dough properties and baking process on hearth loaf properties studied by multivariate statistical methods. Journal of Cereal Science 32: 199-212.

Mamuya, I.N., 2000. Genotype X environment interaction for quality parameters of irrigated spring wheat. MSc Thesis, University of the Free State, Bloemfontein, RSA.

Neacşu, A., Stanciu, G. and Sãulescu, N.N., 2009. Most suitable mixing parameters for use in breeding bread wheat for processing quality. Cereal Research Communications 37: 83-92.

Ohm, J.B. and Chung, O.K., 1999. Gluten, pasting, and mixograph parameters of hard winter wheat flours in relation to bread making. Cereal Chemistry 76: 606-613.

Payne, R.W., Murray, D.A., Harding, S.A. and Baird, D.B., 2008. Genstat for Windows. 11th edition. Introduction. VSN International, Hemel Hempstead.

SAGL, 2010. Analysis procedure and evaluation norms for the classification of wheat breeders' lines for the RSA. September 2010 revision.

Sadouki, H., Cazalis, R. and Azzout, B., 2006. Fractionation of Algerian common wheat proteins with 50 p.100 2-propanol: relationship with the technological quality. Lebensmittel Wissenschaft und Technologie - Food Science and Technology 39: 70-79.

Souza, E., Tyler, J.M., Kephart, K.D. and Kruk, M., 1993. Genetic improvement in milling and baking quality of hard red spring wheat cultivars. Cereal Chemistry 70: 280-285.

Van Ark, H., 1995. Introduction to linear correlation and regression. Agricultural Research Council Agrimetrics Institute, Pretoria, RSA.

Walker, A.E. and Walker, C.E., 1992. Documentation and user's instructions for Mixsmart. National Manufacturing Division, TMCO, 507 J. Street, Lincoln, NE68508, USA.

Wikström, K. and Bohlin, L., 1996. Multivariate analysis as a tool to predict bread volume from mixogram parameters. Cereal Chemistry 73: 686-690.

CHAPTER 5

GENERAL CONCLUSIONS AND RECOMMENDATIONS

In this study, a much larger variation was found among genotypes than among environments for all measured mixogram parameters, indicating mixogram parameters to be useful for selection of acceptable bread wheat quality, as a positive response on selection can be expected.

Since low to moderate multiple coefficients of determination (6.4% to 45.6%) were observed for grain and milling characteristics in explaining variation in the selected mixogram parameters, it was concluded that these mixogram parameters cannot be predicted effectively by grain and milling characteristics. Grain and milling characteristics determined in this study, can therefore be of no assistance to wheat breeders in indicating desirable rheological characteristics during advanced breeding phases.

Multiple coefficients of determination for rheological, baking quality-related and baking characteristics as predicted by the selected mixogram parameters were low to relatively high (28.5% to 76.8%). For a secondary parameter (mixogram parameter) to be effective in predicting a primary parameter (farinogram water-absorption, alveogram dough strength, alveogram P/L-value and loaf volume expressed on a 12% protein basis), the narrow sense heritability of the secondary parameters need to be higher than those of the primary parameters. Therefore, this study concluded that the total area (TA) under the midline curve as determined by Mixsmart software can be indicative of farinogram water-absorption, alveogram dough strength and loaf volume expressed on a 12% protein basis. The mixogram-parameter, tailheight (TH), was found to be indicative of alveogram P/L-value.

Therefore, if wheat breeders can supply sufficient sample to construct a mixogram, evaluated by Mixsmart software, they can benefit from using these mixogram parameters to select for acceptable rheological and baking characteristics as desired by the South African industry.

SUMMARY

The main objective of this research was to determine relationships between selected mixogram parameters and grain, milling, rheological, baking quality-related and baking quality characteristics to assist wheat breeders in selecting earlier for desirable primary rheological and baking criteria as required by the Wheat Technical Committee in South Africa when only small grain/flour samples are available.

Highly significant differences were observed from combined ANOVA's among genotypes, environments and GXE interactions for most of the measured characteristics. Genotypes contributed significantly to the variance in hectolitre mass, thousand kernel mass, kernel diameter, break flour yield, flour yield, farinogram water-absorption, alveogram dough stability (P-value), alveogram dough distensibility (L-value), alveogram P/L-value, alveogram dough strength, SDS-sedimentation volume, wet gluten content, loaf volume and loaf volume expressed on a 12% protein basis. Environments had a larger effect on hardness index, vitreous kernels, grain protein content, falling number, flour protein content, flour colour, flour colour expressed on a 76% flour yield basis and mixogram water-absorption.

Highly significant positive and negative correlations were observed between the selected mixogram parameters (as determined by Mixsmart software) and grain, milling, rheological, baking quality-related and baking characteristics. Multiple stepwise regressions indicated mixogram parameters to be poorly predictable by grain and milling characteristics. Mixogram parameters (total area and tailheight) were identified as selection criteria to assist wheat breeders in selecting earlier for acceptable primary rheological and baking criteria of importance during cultivar release in South Africa.

Key words: bread wheat, quality, grain, milling, rheological, baking, Mixsmart, cultivar release process

OPSOMMING

Die doel van die studie was om te bepaal watter broodkoring-kwaliteitseienskap/pe, bepaalbaar op ‘n klein monster koring/meel, vir koringtelers tot hulp kan wees om vroegtydig koringlyne uit te skakel wat tydens die finale evaluasie vir cultivar-vrystelling ongewenste primêre reologiese- en bakeienskappe mag openbaar en dus afgekeur gaan word.

Gesamentlike variansie analises het hoogs betekenisvolle verskille aangedui vir kultivars, omgewings en genotipe x omgewingsinteraksies vir die meeste eienskappe. Genotipes was hoofsaaklik verantwoordelik vir die variasie in hektolitermassa, duisendkorrelmassa, korreldeursnee, breekmeel-opbrengs, meelekstraksie, farinogram waterabsorpsie, alveogram deegstabiliteit (P-waarde), alveogram deegelastisiteit (L-waarde), alveogram P/L-waarde, alveogram deegsterkte, SDS-sedimentasie volume, nat gluten inhoud, broodvolume en aangepaste broodvolume. Omgewing het ‘n groter invloed gehad op hardheid, horingagtige korrels, graanproteïeninhoud, valgetal, meelproteïeninhoud, meelkleur, aangepaste meelkleur en waterabsorpsie soos op ‘n miksograaf bepaal.

Hoogs betekenisvolle positiewe en negatiewe korrelasies tussen geselekteerde miksogram-eienskappe en graan-, maal-, reologie-, bak-verwante en bak-eienskappe is waargeneem. Stapsgewyse meervoudige regressies het aangedui dat miksogram-eienskappe swak voorspel word deur graan- en maal-eienskappe. Miksogram-eienskappe, bepaal met Mixsmart sagteware, is geïdentifiseer wat koringtelers kan help in vroeë selektering van verlangde primêre reologiese- en bak-eienskappe (farinogram waterabsorpsie, alveogram deegsterkte, alveogram P/L-waarde en aangepaste broodvolume), soos verlang deur die Koring Tegniese Kommittee tydens die kultivar-vrystellingsproses in Suid-Afrika.

Sleutelwoorde: broodkoring, kwaliteit, graan, maal, reologie, bak, Mixsmart, kultivar-vrystellingsproses

Appendix

Table 1 Weather data for the three localities during 2007

Locality	Latitude	Longitude	Altitude	Month	Temp (N)	Temp (X)	Rain
Bethlehem	-28.1628	28.29733	1653	1	13.03	28.25	25.20
				2	12.68	29.31	25.10
				3	10.56	27.18	33.90
				4	7.76	23.73	44.50
				5	0.08	20.79	1.50
				6	-1.33	16.49	27.60
				7	-2.89	17.33	0
				8	-0.73	20.36	0
				9	6.76	26.14	37.80
				10	9.46	20.54	158.70
				11	10.62	23.77	96.70
				12	12.24	24.57	86.30
Arlington	-27.53229	27.56386	1601	1	14.52	31.91	19.80
				2	13.93	32.82	29.90
				3	11.18	29.72	23.30
				4	8.96	25.30	40.30
				5	0.99	21.00	1.00
				6	-0.97	17.17	27.80
				7	-2.81	17.93	0.60
				8	-0.25	20.82	0
				9	7.97	28.79	0
				10	10.6	22.81	93.30
				11	11.05	25.73	106.60
				12	13.43	26.87	78.10
Bothaville	-27.30342	26.68219	1316	1	14.84	31.69	34.80
				2	13.16	32.45	25.40
				3	11.79	29.84	37.30
				4	8.93	25.72	22.50
				5	1.36	22.71	2.30
				6	0.04	18.37	20.80
				7	-2.18	18.82	0
				8	0.57	22.60	2.70
				9	8.38	29.00	65.20
				10	11.33	24.94	103.20
				11	12.44	28.10	121.30
				12	14.03	28.21	74.40

Temp (N) = average minimum temperature ℃, Temp (X) = average maximum temperature ℃

Table 2 Mixsmart parameters, descriptions and units of measurement

Mixsmart parameter	Description	Unit
1) Envelope left time	Time from starting point until 1 min before envelope peak time	min
2) Envelope left value	Envelope curve height at 1 min before envelope peak time	%
3) Envelope left slope	Envelope curve slope from beginning until 1 min before envelope peak time	%/min
4) Envelope left width	Envelope curve-width at 1 min before envelope peak time	%
5) Envelope left integral	Envelope area under envelope curve from beginning until 1 min before envelope peak time	%Torque*min
6) Envelope peak time	Time where envelope curve reaches a peak	min
7) Envelope peak value	Envelope curve height at envelope peak time	%
8) Envelope peak width	Envelope curve-width at envelope peak time	%
9) Envelope peak integral	Envelope area under envelope curve from beginning until envelope peak time	%Torque*min
10) Envelope right time	Envelope time from beginning until 2 min after envelope peak time	min
11) Envelope right value	Envelope curve height at 2 min after envelope peak time	%
12) Envelope right slope	Envelope slope from envelope peak time until 2 min after envelope peak time	%/min
13) Envelope right width	Envelope curve-width at 2 min after envelope peak time	%
14) Envelope right integral	Envelope area under envelope curve from beginning until 2 min after envelope peak time	%Torque*min
15) Envelope tail value	Envelope curve height at end of mixing process measured on envelope curve (e.g. 6.5 min)	%
16) Envelope tail slope	Envelope slope from envelope peak time until end of mixing process measured on envelope curve	%/min
17) Envelope tail width	Envelope curve-width at end of mixing process measured on envelope curve	%
18) Envelope tail integral	Envelope area under curve from beginning until end of mixing process measured on envelope curve	
19) Envelope time X value	Envelope curve height at 6 min	%
20) Envelope time X slope	Envelope slope from envelope peak time until 6 min measured on envelope curve	%/min
21) Envelope time X width	Envelope curve-width at 6 min	%
22) Envelope time X integral	Envelope area under envelope curve from starting point until 6 min	%Torque*min
23) Midline left time	Time from starting point until 1 min before peak time measured on midline curve	min
24) Midline left value	Midline curve height at 1 min before midline peak time	%

Table 2 Continued

25) Midline left slope	Midline curve slope from beginning until 1 min before midline peak time	%/min
26) Midline left width	Midline curve-width at 1 min before midline peak time	%
27) Midline left integral	Midline area under curve from beginning until 1 min before midline peak time	%Torque*min
28) Midline peak time	Time where midline curve reaches a peak – Optimum dough development	min
29) Midline peak value	Midline curve height at midline peak time	%
30) Midline peak width	Midline curve-width at midline peak time	%
31) Midline peak integral	Midline area under curve from beginning until midline peak time	%Torque*min
32) Midline right time	Midline time from beginning until 2 min after midline peak time	min
33) Midline right value	Midline curve height at 2 min after midline peak time	%
34) Midline right slope	Slope measured from midline peak time until 2 min after midline peak time	%/min
35) Midline right width	Midline curve-width at 2 min after midline peak time	%
36) Midline right integral	Midline area under curve from beginning until 2 min after midline peak time	%Torque*min
37) Midline tail value	Midline curve height at end of mixing process (e.g. 6.5 min)	%
38) Midline tail slope	Slope from midline peak time until end of mixing process measured on midline curve	%/min
39) Midline tail width	Midline curve-width at end of mixing process	%
40) Midline tail integral	Midline area under curve from beginning until end of mixing process	%Torque*min
41) Midline time X value	Midline curve height at 6 min	%
42) Midline time X slope	Slope from midline peak time till 6 min measured on midline curve	%/min
43) Midline time X width	Midline curve-width at 6 min	%
44) Midline time X integral	Midline area under curve from beginning until 6 min	%Torque*min

min=minute(s)