SOLVENT RETENTION CAPACITY AND SWELLING INDEX OF GLUTENIN AS SELECTION TOOLS IN SOUTH AFRICAN BREAD WHEAT BREEDING

by

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Submitted in fulfilment of the requirements for the degree of *Magister Scientiae Agriculturae,* in the department of Plant Sciences (Plant Breeding), Faculty of Natural and Agricultural Sciences

UNIVERSITY OF THE FREE STATE
BLOEMFONTEIN
SOUTH AFRICA

JANUARY 2018

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ABSTRACT

To release wheat varieties which comply with strict end-use quality criteria and to deal with the polygenic nature of quality breeding, a breeder needs to be informed of quality potential in early generation populations. This research aimed to determine the use of two small scale rapid tests, solvent retention capacity (SRC) and swelling index of glutenin (SIG) as selection tools for bread wheat quality breeding. Seventeen hard red winter wheat cultivars grown in the dryland summer rainfall region, 22 hard red spring wheat cultivars grown in the irrigated summer rainfall region and nine hard red spring wheat cultivars grown in the winter rainfall region were evaluated with the SRC test requiring a 0.3 g flour sample and the SIG test requiring a 0.04 g flour sample. The relationships of the SRC and SIG parameters with grain, milling, rheological and baking quality-related parameters were determined. Combined ANOVA showed highly significant differences ($p \leq 0.001$) among cultivars, environments and cultivar x environment interaction for the measured quality parameters, and the SRC and SIG parameters. Variation between genotypes was large and genotypes contributed significantly to the variance in lactic acid SRC, distilled water SRC, sodium carbonate SRC, sodium bicarbonate SRC, sucrose SRC and lactic acid SIG, indicating the potential of these parameters for selecting improved bread wheat quality. SRC values were significantly ($p \leq 0.001$) correlated with bread making quality parameters. The highest correlations were between lactic acid SRC and flour protein content ($r=0.67$, $p \leq 0.001$) in the winter rainfall region and lactic acid SIG and flour protein content ($r=0.75$, $p \leq 0.001$) in the irrigated summer rainfall region. Correlations between SRC, SIG and bread making quality parameters were inconsistent across regions, except for lactic acid SRC and lactic acid SIG with flour protein content and lactic acid SRC, sucrose SRC and lactic acid SIG with alveogram dough strength.

Regression coefficients for grain, milling, rheological and baking quality-related characteristics, as predicted by the SRC and SIG parameters, were low to moderately low (12% to 60%), indicating that the SRC and SIG parameters are poor predictors for most of the bread wheat quality parameters in South African wheat. Lactic acid SRC and distilled water SRC were the most common predictor

variables, explaining the variation in the models for grain and milling characteristics. Lactic acid SRC, sucrose SRC and lactic acid SIG were responsible for contributing to the variation in most of the models for rheological and baking quality-related characteristics. The alkaline water retention capacity method (sodium bicarbonate SRC) was not effective in predicting bread wheat quality in this study and was initially developed for soft wheat applications. The lactic acid SRC solvent test was the most useful for assessing bread wheat quality in this study and is recommended for the evaluation of hard red winter and spring wheat bread making quality potential.

Keywords: Solvent retention capacity; swelling index of glutenin; bread making quality; wheat flour quality; hard red wheat; small scale tests.

DECLARATION

I, hereby declare that this dissertation, prepared for the degree Magister Scientiae, which was submitted by me to the University of the Free State, is my own original work and has not previously in its entirety or in part been submitted to any other University. All sources of materials and financial assistance used for this study have been duly acknowledged. I also agree that the University of the Free State has the sole right to the publication of this dissertation

Roean Wessels

ACKNOWLEDGEMENTS

I wish to extend my sincere appreciation to the following people and organisations for their contribution towards the completion of this study:

I am thankful to my supervisors, Dr Barend Wentzel and Prof Maryke Labuschagne for their guidance, support and motivation.

The ARC-SGI and Chrissie Miles for her help and guidance with the quality analysis.

Mardé Booyse for her assistance with the statistical analysis.

The Winter Cereal Trust for funding.

Sensako, PANNAR and the ARC for allowing the inclusion of their varieties in this study.

I would like to extend my gratitude to Sensako, especially Dr Francois Koekemoer for the opportunity and allowing me time for this study, Elaine and Elsabé for support and motivation.

My mother and father, Roelien and Anton, thank you for the opportunity to study, encouragement and for teaching me that without our Heavenly Father nothing would be possible.

Most importantly, I am grateful for my wife Delindie and son Nicholas for moral support, motivation and understanding of the hours spent in the office.

In dedication to my late grandmother, Anna Dorothea – It is amazing how far you are willing to go when someone believes in you.

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LIST OF ABBREVIATIONS

AACC	American Association of Cereal Chemists
ALVL	Alveogram distensibility
ALVP	Alveogram stability
ALVP/L	Alveogram stability/distensibility
ALVSTR	Alveogram dough strength
ALVW	Dough strength
AM	Approved method
ANOVA	Analysis of variance
ARC	Agricultural Research Council
ARC-SGI	Agricultural Research Council – Small Grain Institute
AWRC	Alkaline Water Retention Capacity
BFLY	Break flour yield
Bhm	Bethlehem
BU	Brabender Units
°C	Degrees Celsius
CIMMYT	International Maize and Wheat Improvement Center
Cla	Clarens
cm^3	Cubic centimetre
Cult	Cultivar
CV	Coefficient of variation
df	Degrees of freedom
DW_SRC	Distilled water solvent retention capacity
Env	Environmental
FABS	Farinogram water absorption
FC	Flour colour at a 76% flour yield
FN	Falling number
FLY	Flour yield
FPC	Flour protein content
FPT	Farinograph peak time
g	gram
g	Gravitational force
G	Genotype
GXE	Genotype by environmental interaction
GPI	Gluten performance index
hl^{-1}	Hectolitre
HLM	Hectolitre mass
HMW	High molecular weight
HMW-GS	High molecular weight glutenin subunits
HRS	Hard red spring wheat
HRW	Hard red winter wheat
HWW	Hard winter wheat
ISCW	Institute for Soil, Climate and Water
KJ	Kilo Joule
Kg	Kilogram
LA	Lactic acid
LA_SIG	Lactic acid swelling index of glutenin
LA_SRC	Lactic acid solvent retention capacity

LFV	Loaf volume
LMW	Low molecular weight
LMW-GS	Low molecular weight glutenin subunits
MABS	Mixolab water absorption
mg	Milligram
min	Minutes
ml	millilitre
mm	Millimetre
MMW	Medium molecular weight
Mo	Morreesburg
MPT	Mixogram peak time
MWA	Mixogram water absorption
N	Nitrogen
NIR	Near infrared reflectance
Nm	Newton metre
ns	Non-significant
p	Probability
PSI	Particle size index of flours
r	Pearson relationship coefficient
R^2	Coefficient of multiple determination
Ri	Riversdal
rpm	Revolutions per minute
s	Seconds
SAGL	South African Grain Laboratory
SD	Standard deviation
SDS	Sodium dodecyl sulphate
SDSS	SDS sedimentation volume
SDS-PAGE	SDS-Polyacrylamide gel electrophoresis
SE	Standard error
SE-HPLC	Size-exclusion high-performance liquid chromatography
SKCS	Single Kernel Characterisation System
SIG	Swelling index of Glutenin
SRC	Solvent Retention Capacity
SRCG1	Solvent retention capacity group 1
SRCG2	Solvent retention capacity group 2
SRW	Soft red winter wheat
S_SRC	Sucrose solvent retention capacity
SBC_SRC	Sodium bicarbonate solvent retention capacity
SC_SRC	Sodium carbonate solvent retention capacity
ton ha^{-1}	Ton per hectare
Up	Upington
TKW	Thousand kernel weight
v/v	Volume per volume
Vh	Vaalharts
WGC	Wet gluten content
w/v	Weight per volume
WTC	Wheat Technical Committee

CHAPTER 1

INTRODUCTION

To overcome the cost and expense of milling and baking hundreds of samples, cereal chemists have come up with an additional two rapid predictive tests for end-use quality assessment, namely; the Solvent Retention Capacity (SRC) test and Swelling Index of Glutenin (SIG) test. The use of these small scale rapid tests has not yet been evaluated in South African wheat, including the hard red winter (HRW) wheat and hard red (HRS) spring wheat germplasm. The results from Hammed *et al*. (2015) indicated that the high glutenin content of HRS wheat altered initial observations regarding SRC results obtained from studies conducted on soft wheats. Ongoing in-depth studies of SRC application on hard wheat is needed. The aim of this study was to evaluate the viability and accuracy of these rapid tests to determine end-use quality using small quantities of flour. The SIG test requires only 0.04 g of flour (Wang and Kovacs, 2002) and SRC only 0.3 g according to the modified protocol of the approved method (56-11.02) (AACC, 2010) used in this study (Guzmán *et al.*, 2015). Statistical analysis of SRC, SIG and traditional quality testing methods were used to clarify correlations and determine which parameters could be applied effectively to rapidly predict flour quality.

Guzmán *et al.* (2015) developed the scaled-down SRC protocol to allow large numbers of late-segregating or early-advanced breeding material, with low seed volumes, to be evaluated for quality characteristics in a shorter time. In addition to the smaller flour sample, the incubation-shaking time is reduced from 20 min to 5 min and is executed using a shaker of which shaking speed and temperature can be optimally controlled. The scaled-down method is conducted in 10 min instead of the original 50 min. The official SRC approved method 56-11.02 (AACC, 2010) requires 5 g per solvent, if the analyses is replicated twice, 40 g of flour will be required for all four solvents. Guzmán *et al*. (2015) obtained correlations between the approved method and modified protocol of r=0.96, r=0.94, r=0.95 and r=0.97 ($p \leq 0.001$) for distilled water SRC, lactic acid SRC, sodium carbonate SRC and sucrose SRC, respectively.

Other minor modifications to the SRC approved method for application in breeding were reported in numerous publications and included reduction in flour sample sizes from 5 g to 0.2 g or 1.0 g or the use of whole wheat flour instead of white flour (Bettge *et al*., 2002; Ram and Singh, 2004; Ram *et al*., 2005; Guttieri *et al*., 2008). Both scale reduction and the use of whole wheat flour reduced the amount and strength of correlations when comparing the results between the modified methods and the originally approved 5 g method. The 0.2 g whole-meal modified method proved useful for the selection of breeding lines in early generations of the breeding programme as SRC values at the very high and low extremities of the distribution ranked similarly for both the large and small-scale SRC test results (Bettge *et al*., 2002).

The International Maize and Wheat Improvement Centre (CIMMYT) and other breeding companies have recently started implementing this technique (Guzmán *et al*. 2015) as it allows for a rapid test in early generations when seed quantities are still limited. The ability of the SRC method to predict functionality have not yet been applied to South African HRW germplasm with overall high-quality characteristics and narrow protein range, as expected from the industry, warranting further investigation as small-scale rapid testing may be beneficial to local breeding programmes.

Several small-scale predictive quality tests have been developed and adapted from larger scale tests. Greenway *et al*. (1966) reported that SDS-sedimentation volume started out as a 5 g flour test and was later reduced to a whole grain flour test requiring only 1 g of sampling material. The Zeleny sedimentation test is another small-scale test used to predict bread making quality, which is based on the swelling capacity of glutenin or more specifically on the insoluble glutenin content of a sample, requiring 1.5 g of flour (Zeleny, 1947). The 2 g mixograph tests were developed from the original Swanson and Working 400 g mixograph instrument, and can accurately predict the absorption and mixing characteristics of dough (Bloksma and Bushuk, 1988).

The single kernel characterisation system (SKCS) uses only 300 kernels to predict grain diameter, moisture, texture and weight. The flour swelling volume

test requires a flour sample of only 0.45 g for starch assessment. These tests and their results, however, are directly related to milling and dough rheology characteristics as they characterise chemical and physical traits of the samples tested (Bettge *et al*., 2002). Due to the physical properties and interactions of the many flour constituents in a complex medium, physical and chemical test results are not highly correlated with baking performance. The association between SRC, SIG and traditional wheat quality parameters including grain, milling and baking quality-related characteristics were evaluated in this study (Table 1.1).

The study objectives were to:

- evaluate the various sources of variation for SRC and SIG values for hard red wheat germplasm grown in three diverse environments in South Africa
- evaluate the viability and accuracy of SRC and SIG to determine end-use quality using small quantities of flour (0.3 g per SRC solvent and 0.04 g for SIG)
- determine the correlation between SRC, SIG and traditional wheat quality parameters
- determine which SRC and SIG parameters could be applied conveniently to rapidly predict South African bread wheat quality

Table 1.1 Comparison of sample volumes and time to conduct an analysis between solvent retention capacity, swelling index of glutenin and traditional quality analysis

SRC			SIG			Traditional quality analysis		
Analyses separate contribution of each functional polymeric component			**Measures glutenin content and dough strength parameters**			**Measures combined synergetic effects of flour polymers**		
Method	**Flour sample Gram**	**Time Minutes**	**Method**	**Flour sample Gram**	**Time Minutes**	**Method**	**Flour sample Gram**	**Time Minutes**
Manual method AM 56-10 (AACC, 2010)	3.6 g	10 min	Method of Wang and Kovacs, (2002)	1.2 g	10 min	Farinogram AM 54-21 (AACC, 2010)	300 g / 600 g	30 min
						Alveogram AM 54-30A (AACC, 2010)	250 g	35 min
						Mixogram AM 54-40A (AACC, 2010)	35 g	35 min
						Mixolab AM54-60.01 (AACC, 2010)	50 g	30 min
						Protein AM 39-11.01 (AACC,2010)	5 g	5 min
						Loaf volume AM 10-10B (AACC, 2010)	110 g	150 min
Total:	**3.6 g**	**10 min**	**Total:**	**1.2 g**	**10 min**	**Total:**	**750 g - 1050 g**	**285 min**

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CHAPTER 2

BREAD WHEAT QUALITY AND THE NEED FOR SMALL-SCALE RAPID TESTS

Bread wheat (*Triticum aestivum*) is the most cultivated species of wheat. The largest application of wheat is for human consumption, being the most important protein source. The global population is predicted to reach a high of 9.3 billion in 2050, increasing the demand of wheat with an expected 60% when compared with 2010 (Rosegrant and Agcaoili, 2010). Wheat production will need to increase significantly, while the production of high quality products is essential in the face of ever increasing food prices. A further threat to food security is the fact that more than 60% of all wheat is produced in developing countries, where wheat production is more prone to be affected by temperature increases as a result of climate change. To guarantee food security and political stability, wheat producing countries need to provide a high quality, stable and reliable wheat production environment with a reasonably priced product. This emphasises the need of local and efficient breeding programmes capable of producing new varieties, while minimising the time lag between research and development.

Wheat provides 20% of the protein and 21% of calories to the world's population (Braun *et al*., 2010). The main constituent of baked goods is wheat flour. Wheat flour quality largely contributes to the quality of the final baked product (Kweon *et al*., 2011a). Flour quality evaluation is very important to breeders, millers and bakers, to ensure cultivation of wheat cultivars with superior quality characteristics and thus ensuring end-products with the same high-quality standards. Biochemical components in wheat with detailed functional properties and their interaction, determines fitness for milling and processing into a specific end-use product. Wheat classification is based on planting season (winter or spring), grain colour (white or red) and hardness (hard or soft). Flour functionality for each product type will depend on the extent of the contribution from the different flour functional polymeric components that contributes to the overall ability of flour to absorb water and create viscoelastic dough.

The quality and shelf life of baked goods is determined by moisture content of the baked product (Slade and Levine, 1991; 1994). In breeding programmes, where thousands of experimental lines are evaluated, the cost and time involved in conducting rheological and baking tests are a limiting factor. Breeding lines with inferior quality need to be eliminated to maximize the efficiency of the breeding programme in order to continue with superior lines (Bettge *et al*., 2002). Grain yield is a major factor influencing economical sustainability of farmers, while grain protein is very important for functional bread making quality (Tsilo *et al*., 2010a). In addition to the complex inheritance of grain yield and grain quality, these traits are also negatively correlated and highly affected by genotype x environment (GXE) interactions resulting in varying processing properties of a given variety over environments (Weegels *et al*., 1988; Baenziger *et al*., 1992; Walker *et al*., 2008).

Li *et al*. (2013) found that the effect of heat and drought stress on baking quality is due to altered rheological properties of dough, mainly dough extensibility, determined by gluten composition and size distribution. Selection for a high yielding line, possessing superior quality, is not an easy task and breeder's interests lay with quality traits of highly heritable and reproducible nature (Neacşu *et al*., 2009). The information on different types of GXE interactions is important for allocating breeding material to replications, locations and years (Bhatt and Derera, 1975).

Flour quality is the result of several quality attributes and their interactions. Various methods have been developed to evaluate different categories of wheat flour quality for milling, mixing, viscoelastic and baking characteristics based on the interaction of damaged starch, gluten and pentosans, also known as the three functional polymeric components of flour (Graybosch *et al*., 1999; Xiao *et al*., 2006; Kweon *et al.*, 2011a; Duyvejonck *et al*., 2012).

Tests of milling, mixing and baking vary in sample size, equipment and resources needed. The first group, for example the Zeleny sedimentation method, is straight forward to interpret and estimates the level or properties of flour constituents. The rheological tests are included in the second group of methods,

which gives an indication of dough properties. Dough rheology methods include alveography, extensography, farinography and mixography. The last group of methods are standardised baking tests, reflecting a typical bread making process.

Traditionally, the relationship between the quality of flour and baked end-product quality is determined using dough rheology methods and baking tests. Rapid tests capable of determining end-use quality require small grain quantities, are time saving and inexpensive to carry out. The need for smaller grain volumes enables early generation screening, minimizing extensive field trials in later generations, saving the breeder more time and cutting down on field trial expenses. Extensive end-use quality testing can be postponed to a later stage when higher quantities of grain are available for milling and baking tests.

Wheat proteins and starch are major contributors to flour quality. Their attributes and test methods developed to determine them and the rheological and baking interaction, will be discussed in the following paragraphs.

2.1 Proteins

On a weight basis, 80-85% of the wheat kernel is represented by the endosperm, consisting of a complex mixture of proteins and starch. The two main inter-related contributing traits regarding wheat quality are the protein content and the hardness of grain (Pomeranz and Mattern, 1988; Bushuk, 1998), however, genotype remains the major contributor to grain quality. Total protein content and the type of protein are determined by genotype, however protein content levels may vary between 6% and 25%, depending on the availability of nitrogen, which confirms strong GxE interaction (Blackman and Payne, 1987; Hoseney, 1994).

Wheat is the only cereal with the exceptional ability to form leavened bread when baked, by trapping gas in the elastic homogenous dough network formed during mixing (Wikström and Bohlin, 1996; Koen, 2006). This important property of wheat is mainly due to gluten storage proteins that confer unique viscoelastic

properties to dough as it has a direct effect on the functional properties of wheat as determined by alveography, farinography, mixography, SDS-sedimentation volumes and baking tests (Finney *et al*., 1987; Shewry and Tatham, 1997; Koekemoer *et al*., 1999; Rakszegi *et al*., 2005). Thus, the properties of proteins present in dough, determines the suitability of a wheat line for processing into bread with unique end-user requirements. Protein quantity and quality equally contributes to flour quality (DuPont and Altenbach, 2003, Caballero *et al*., 2007).

Among the many storage proteins found in the endosperm, the focal proteins include the gliadins, glutenins, albumins and globulins, however, studies showed that these proteins can mainly be divided into two major categories: gliadins and glutenins (Song and Zheng, 2007). Gliadins confer extensibility and viscosity by acting as a plasticiser, while glutenins bestow strength and elasticity to dough (Shewry *et al*., 1986). The balance between these two components determines dough quality (Singh *et al*., 1990; Hoseney, 1994; Khatkar *et al*., 1995; Khatkar *et al*., 2002; Wieser *et al*., 2006). Albumins and globulins are considered physiologically active proteins and are found in higher concentration at low protein levels when expressed as a percentage of the total protein content (Singh *et al*., 1990; Hoseney, 1994). The gluten complex adversely, are storage proteins which consists of monomeric gliadin and polymeric glutenin (Singh *et al*., 1990). Different glutenin subunits originate from the polymeric structure of glutenin, each contributing to different molecular properties of dough (MacRitchie, 1999).

Three groups of gluten proteins with two or three differing protein types within each group are categorised based on disulphide bonds responsible for linking individual glutenin polypeptides or subunits (Wieser *et al*., 1998; Bushuk, 1998). The molecular weight distribution of wheat proteins is the main contributing factor determining dough viscoelastic properties and it was determined that high molecular weight (HMW) glutenin largely contributes to dough quality potential (Wang and Kovacs, 2002a; Labuschagne *et al.*, 2004; Park *et al*., 2006).

Storage proteins are grouped into a HMW group that includes the x and y-type high molecular weight glutenin subunit (HMW-GS), a medium molecular weight (MMW) group consisting of the ω5 and ω1-, 2-type gliadins. The last group is the low molecular weight (LMW) group that includes the low molecular weight glutenin subunits (LMW-GS) and the α- and γ-gliadins. Payne *et al*. (1987) reported that hexaploid bread wheat has the following HMW-GS on its three genomes; chromosome 1A at *Glu-A1* (null, 1 and 2*), 1B at *Glu-B1* (6+8, 7, 7+8, 7+9, 17+18, 14+15) and 1D at *Glu-D1* (2+12, 5+10, 3+12, 4+12, 2+11). Subunits 1 to 7 are included in the x-type HMW-GS group and 8 to 12 in the y-type HMW-GS group. The y-type subunits' contribution are more import to dough handling properties (Wieser and Kiefer, 2001).

Hexaploid wheat have six HMW-GS genes, depending on the genetic composition of a variety, only three to five genes are expressed resulting in various amounts of HMW-GS protein. Each of the six HMW-GS genes contributes about 2% to the total protein content (Don *et al*., 2003). Shewry *et al*. (2002) reported that HMW-GS determine dough elasticity and thus the bread making potential of a specific flour and the size distribution of glutenin polymers is mainly dependant on the HMW-GS (Don *et al*., 2006).

HMW-GS 5 have shown differential potential for breadmaking, whereas and the presence of HMW-GS 2 results in reduced quality and bread making potential (Payne *et al*., 1987). Better dough strength properties were reported by Marchylo *et al*. (1992) when HMW-GS 7 was present and Uthayakumaran *et al*. (2002) reported on the positive contribution of HMW-GS 5 to improved dough properties and the minor contribution of HMW-GS 1.

The *Glu-A3*, *Glu-B3* and *Glu-D3* loci encodes the LMW-GS and is located on the short arm of the respective genome of the 3 series chromosomes (Shewry *et al*., 1986). Four gliadin groups can be distinguished, namely α, ß, γ and ω-gliadins. Disulphide bonds are not common in the ω-gliadin group and they are referred to as sulphur poor prolamins (Shewry *et al*., 1986). In addition to the composition of proteins, which affects flour protein, solubility characteristics of protein will also determine flour protein quality (MacRitchie, 1999).

Isolation and study of glutenins are complicated due to its relative insolubility. Of the total endosperm flour protein composite, glutenins contribute 45%. This emphasizes the need for isolation and purification methods to allow further studies (Orth and Bushuk, 1973; Khan and Bushuk, 1978; Ng and Bushuk, 1987). The modified fractionation method of Osborne (1907), as defined by Chen and Bushuk (1970), gives five solubility fractions for wheat proteins. These are the albumins or water-soluble proteins, the globulins or salt-soluble proteins, the gliadins, also known as the aqueous ethanol-soluble proteins, and the glutenins or dilute acetic acid-soluble proteins and lastly the insoluble protein.

The amount of protein in each fraction and the variation in HMW-GS composition correlates with end-use quality, thus the solubility characteristics of wheat protein and subunit composition is integral to flour protein quality (Orth and Bushuk, 1973; Chakraborty and Khan, 1988; Ng and Bushuk, 1987). Orth and Bushuk (1973) reported that bread volume is directly related to insoluble glutenin and inversely related to the soluble glutenin portion. The ratio of albumin to globulin and gliadin to glutenin is also positively correlated with loaf volume (LFV) per unit protein (Orth and Bushuk, 1973). Van Lill (1992) reported a weak positive correlation between the albumin fraction and dough development time, flour protein content, and water absorption.

Total glutenin content was positively correlated with farinograph dough development time, dough breakdown characteristics and extensibility (Singh *et al*., 1990). Reduced peak resistance, lower maximum resistance to extension, shorter mixing times and smaller LFV were observed with an increase of gliadin fractions (Uthayakumaran *et al*., 2002). The quantity and composition of HMW proteins relates to dough strength and peak time. Size distribution of polymeric glutenin affects dough strength significantly and HMW-GS increases resistance to break down and improves extensibility (Weegels *et al*., 1996a).

The diluted acetic acid solvent used to prepare wheat glutenin, as proposed by Osborne (1907) has two major shortcomings. The first is that a large fraction of the flour protein remains insoluble and the second is that it yields a glutenin fraction highly contaminated with gliadin, albumin and globulin proteins. Orth

and Bushuk (1973) determined that sodium dodecyl sulphate (SDS) extracted 60% of flour protein and since then many methods were developed to optimise protein extraction.

Sodium dodecyl sulphate-polyacrylamide gel electrophoresis (SDS-PAGE) became the most frequently used method for estimating molecular weights of glutenin subunits (Bunce *et al*., 1985). Currently, numerous researchers make use of size-exclusion high-performance liquid chromatography (SE-HPLC) to separate flour proteins based on molecular weights (Ohm *et al*., 2010). The use of SE-HPLC redefined the Osborne fractionation method, with better resolution of almost all proteins, without rupturing disulphide bonds. Graybosch *et al*. (1990) found highly significant correlations between protein solubilities and bread wheat quality parameters.

The gliadin-containing protein fractions are related to LFV, dough mixing time and different measures of water absorption. Glutenin-containing fractions correlate with dough mixing tolerance and LFV. Albumin and globulin protein fractions affect dough properties, however, the correlation between these salt-water soluble proteins and various quality parameters are often inconsistent and insignificant (Orth and Bushuk, 1973; Chakraborty and Khan, 1988). The HMW polymeric proteins are better correlated with flour quality parameters than the LMW polymeric protein (Ohm *et al*., 2010; Tsilo *et al.*, 2010b; Hammed *et al*., 2015).

Veraverbeke and Delcour (2002) also indicated that LMW-GS and HMW-GS quantities and composition as well as the amount of both soluble and insoluble glutenins will determine rheological qualities of dough and baking quality potential.

Insoluble gluten contains higher proportions of larger-sized polymers when compared to soluble glutenin (Gupta *et al*., 1993). This is confirmed by the findings of Wang and Kovacs (2002b) who reported that the amount of larger molecular weight glutenin largely determines the strength of dough and mixing tolerance.

Techniques such as chromatography, used for the evaluation of glutenin molecular weight distribution are not freely available (Southan and MacRitchie, 1999), emphasising the need for a small-scale rapid prediction method for glutenin contribution to end-use quality potential.

2.2 Starch

Wheat starch is comprised of amylose and amylopectin, known as glucose polymers. Amylose contributes 25% and amylopectin 75% to total starch content (Maningat *et al*., 2009). Amylose and amylopectin vary in the degree of polymerisation and branching frequency (Van der Borght *et al*., 2005) and these differences are functionally important for dough quality and bread making (Rahman *et al*., 2000). Starch content is elevated in soft wheat compared to hard wheat and ranges between 63-66% of the total kernel weight (Toepfer *et al*., 1972; Hucl and Chibbar, 1996).

Starch has many important functions in the bread making process. Among others, starch is the substrate for amylose that produces fermentable sugars for yeast fermentation. Together with wheat gluten, starch is a significant and valuable co-product in the wet-processing of wheat flour (Maningat *et al*., 2009). Starch combined with the macromolecular network of hydrated gluten forms a continuous network of particles (Song and Zheng, 2007). Under optimal dough development, the starch granules serve as attaching points to enable the formation of gluten fibrils during stretching (Labuschagne *et al*., 2007). The nonlinear rheological behaviour of starch is mainly responsible for the unique behaviour of dough (Watanabe *et al*., 2002).

The starch content of wheat is positively correlated with grain yield and inversely correlated with protein content (Hucl and Chibbar, 1996). Soft wheat starches contain a protein that is weakly expressed or absent in hard wheat. In soft wheat, this protein conceals the starch granules, resulting in a weaker protein-starch bond (Greenwell and Schofield, 1986). Serving as a reservoir for water absorption and by acting as a diluting agent for gluten, it contributes to optimal viscoelastic properties of dough. Wheat starch granules have an important and

unique role in controlling the expansion of dough during the process of baking, which is related to the gelatinisation temperature and the integrity of swollen granules in the gluten matrix (Kusunose *et al*., 1999). The size distribution of wheat starch granules plays an important role in end-use quality potential (Stoddard, 2003).

Parker (1985) determined that a second cycle of starch granules develops earlier during grain filling, resulting in a bimodal distribution of granule sizes, including the larger lenticular granules called A-type (generally larger than 10 µm in diameter) and the smaller spherical B-type (smaller than 10 µm in diameter). A third cycle of granule initiation results in a smaller class size, C-type granule (less than 5µm) (Bechtel and Wilson, 2003). Physical, chemical and functional properties vary with different granule sizes (Chiotelli and Le Meste, 2002), and the size distribution of starch granules is a significant factor that contributes to the quality of several end-products (Park *et al*., 2009).

Industrial bread bakers desire lower B-granule content in order to facilitate maximum starch recovery during processing and to reduce starch water absorption that will result in reduced baking times. Some bread making purposes require a greater B-granule content for increased water absorption (Stoddard, 2003). Dough extensibility is increased with an increase of small starch granules and the dough's resistance to extension is increased when starch granules are predominantly larger (Larsson and Eliasson, 1997).

The environment significantly influences starch content and likewise the quality characteristics of the cultivar. Damaged starch is a result of the milling process and significantly increases in water-holding capacity. Hard wheat yields more damaged starch than soft wheat, with larger mean particle sizes (Barrera *et al*., 2007). The interaction of starch and gluten gives rise to the rheological properties of dough and the gluten-starch interaction depends on stress levels of the plant due to environmental conditions. At low environmental stresses, the starch-starch interaction dominates over protein-protein interactions and the protein-protein interactions dominate at high stress levels (Khatkar and Schofield, 2002). Hence cultivar and environment choice are important factors

to consider. Labuschagne *et al*. (2007) determined that high starch content due to environmental factors, will not necessarily lead to inferior baking quality.

Baking performance is negatively influenced by an increase in damaged starch content as too high levels of water absorption prevents optimum gluten formation during mixing and reduced gas-retention capacity during fermentation. Native starch in flour is usually inactive and non-functional, and damaged starch is functional with increased water absorption and affects alveograph functional specifications (Kweon *et al*., 2011a). During the milling process, amylopectin becomes functional at room temperature with an increase of dough viscosity (Kweon *et al*., 2011a). The unique combination of starch and protein constituents determines the functional properties of the dough and ultimately the end-use quality and purpose thereof (Xiao *et al*., 2006; Song and Zheng, 2007).

In a global study, it was found that variation in cultivars, differing environments and numerous other conditions impact wheat quality characteristics. Protein content associated traits were more influenced by the environmental (Env) and GXE effects than dough rheology traits, starch characteristic and protein quality associated traits (Williams *et al*., 2008). A wide range of end-products are produced from wheat flour as the major ingredient in baked goods, each product with different processing conditions and ingredient formulas. Products with varying quality characteristics are produced from specific wheat flours, depending on the variation in levels and properties of the flour constituents (Duyvejonck *et al*. 2011).

As not all flour types are fit to produce a specific end-product, it is of great importance to determine flour quality as it will also relate to the manufacturing process of the desired end-product. The required flour functionality for bread will differ greatly from flour utilised in cookie, cake or cracker production. For example, bread flour is made from hard wheat and requires high water absorption, satisfactory gluten strength to provide strength and elasticity to dough, 10-14% protein content with good LFV and high amounts of damaged starch and arabinoxylans.

Water retention that is too high could increase baking times and energy costs (Issarny *et al*., 2017). Whereas, cookie flour requires low water absorption, weak gluten strength and reduced levels of damaged starch and pentosans (Kweon *et al*., 2011a). Cake and cookie flour retains water poorly, thus soft wheat with a protein content of 8-10% is preferred. Cookie flour will exhibit little starch damage and low dough viscosity or poor gluten strength, allowing the dough to spread further with larger cookie diameters (Delcour *et a*l., 2012). Various studies have correlated wheat flour starch quality with SRC profiles (Gao *et al*., 2006; Ni *et al*., 2006).

2.3 Grain, milling, rheological and baking characteristics

For a breeding company to successfully commercialise a new variety it needs to fulfil specific end-use release standards regarding grain, milling, rheological and baking properties as set by the South African wheat industry. To evaluate these release standards, a breeding line is compared with a biological standard where fixed deviations are allowed. The biological standard, a successful cultivar with acceptable agronomical and quality characteristics, is used as a frame of reference against which new breeding lines are evaluated and will differ depending on the production region.

Primary requirements are evaluated and are not flexible and include: hectolitre mass (HLM), falling number (FN), protein content (FPC), flour yield (FLY), flour colour (FC) (on a 76% flour yield basis), mixogram peak time (MPT), farinogram water-absorption (ABS), LFV, alveogram dough strength (ALVSTR) and alveogram stability/distensibility (ALVP/L)-values.

Secondary requirements are also evaluated. They are flexible and include thousand kernel weight (TKW), break flour yield (BFLY), farinogram dough development time, farinogram dough stability, alveogram stability (ALVP) and alveogram distensibility (ALVL) (SAGL, 2013). For final classification of a variety, data analysed over three years for the cultivar and the quality standards concerned from a minimum of five localities should be submitted. For the successful release of varieties that comply with the strict quality grading norms

of millers and bakers, and to overcome the polygenic nature of bread making quality, it is crucial for plant breeders to be informed with precise information and practices to determine end-use quality potential of genotypes. The South African wheat grading table provides minimum criteria for the grading parameters for each grade of bread wheat, separated into six grades (Table 2.1).

Table 2.1 Bread wheat grading table

	Class B (bread wheat) grading parameter		
Grade	**Hectolitre mass (kg hl^{-1})**	**Falling number (s)**	**Protein content (%)**
Grade 1	77	220	12
Grade 2	76	220	11
Grade 3	74	220	10
Grade 4	72	200	9
Utility grade	70	150	8
Other Wheat	< 70	< 150	< 8

Government Gazette (2016)

2.3.1 Grain characteristics

2.3.1.1 Test weight or hectolitre mass

Test weight is the mass of a sample of wheat in kilogram per hectolitre (kg hl^{-1}). Hectolitre measures the bulk density of grain and gives an indication of potential milling extraction (Gaines, 1991) and grain soundness (Czarnecki and Evans, 1986). Well-filled wheat kernels will have higher HLM when compared to small and elongated kernels with better packing efficiency (Dick and Matsuo, 1988). Hectolitre mass determines the weight of grain per fixed volume which will affect transportation costs (Fowler and De la Roche, 1975).

Various environmental stress-factors can contribute to reduced HLM (Wrigley and Batey, 2003), however, some varieties are genetically prone to higher HLM (Gaines *et al*., 1996b). Hectolitre mass and protein content was reportedly positively correlated (Preston *et al*., 1995; Schuler *et al*., 1995), however Gaines (1991) found no correlation between these parameters. Negative correlation between HLM and protein content was reported by Dowell *et al*. (2008). The

HLM of undamaged wheat normally varies between 70 to 85 kg hl^{-1}, but can be altered due to environmental conditions and damage due to insects (Trocolli and Di Fonzo, 1999). Nel *et al*. (1998) reported that for bread making purposes a HLM of at least 74 kg hl^{-1} is required. Grade 1 bread wheat requires a HLM of 77 kg hl^{-1} (Government Gazette, 2016).

Xiao *et al*. (2006) reported a significant negative correlation between lactic acid SRC values (lactic acid SRC) and HLM, and a highly positive correlation with protein content, supporting the findings of a negative correlation between protein content and HLM by Dowell *et al*. (2008). Both sucrose SRC values (sucrose SRC) and distilled water SRC values (distilled water SRC) correlated negatively with HLM (Xiao *et al*., 2006). To release a new line, South African release procedures allow a deviation of no more than 1.8 units less than the biological standard (SAGL, 2013).

2.3.1.2 Thousand kernel weight

Thousand kernel weight measures grain size and density, and is the mass of a thousand undamaged grain kernels and is highly affected by genotype and environment. Thousand kernel weight was reported as positively correlated with FLY by Posner and Hibs (1997) and was found to be more dependable in the prediction of expected FLY than HLM. Heavier and bigger kernels will generally have more endosperm and therefor also higher TKW (Finney *et al*., 1987; Bordes *et al*., 2008). Löffler and Busch (1982) found that TKW correlated with kernel protein content and Pomeranz *et al*. (1985) found no correlation between TKW and kernel protein content. Xiao *et al*. (2006) reported highly significant negative correlations between TKW and all four SRC parameters.

For the classification of a new variety, the potential cultivar may not differ with more than or less than 4 units from the biological standard (SAGL, 2013). The SKCS (AM55-31.01) (AACC, 2010) is used to determine TKW.

2.3.1.3 Falling number

Falling number measures alpha-amylase activity and is based on the fast gelatinisation of an aqueous suspension of flour in a boiling water bath. The liquefication of the starch paste by the alpha-amylase is measured in seconds (s). Low FN is an indication of pre-harvest sprouting and resulting enzymatic activity in partially to fulle sprouted kernels (Hagberg, 1960).
Milling characteristics are not affected by pre-harvest sprouting, however, bread quality is significantly reduced by increased alpha-amylase. Quality is unacceptable due to sticky crumb texture and a coarse crumb structure (Miles, 2010). Falling numbers below 150 s result in inferior quality bread with a sticky consistency and FN higher than 350 s result in bread with dry crumbs and reduced LFV (Miles, 2010).

The wheat grading system in South Africa makes use of the Hagberg FN method and new breeding lines should have FN higher than 250 s and the FN should not exceed a maximum 15% lower than the biological standard to qualify for release (SAGL, 2013).

2.3.1.4 Kernel hardness

Kernel hardness is the measurement of the kernel's resistance to break when subjected to pressure (Turnbull and Rahman, 2002). The milling process and the amount of flour obtained during milling are affected by the hardness of a kernel. Larger fractions, with a resulting easier sieving process, can be expected from harder wheat germplasm during milling, whilst soft wheat will break into smaller fragments (Malouf *et al*., 1992). Kernel texture is considered one of the most significant contributing parameters, next to gluten strength, that affects flour functionality.

Various methods, including near infrared reflectance (NIR) of whole grain meals, the sodium carbonate retention capacity test, the particle size index of flours (PSI) and resistance to grinding (Pearling value), have been developed to determine grain hardness (Pomeranz and Williams, 1990; Gaines, 2000). Hard

wheat will require more energy during milling with higher flour granularity, more damaged starch that will, in turn, result in higher water absorption (Pomeranz and Williams, 1990). Higher water absorption, due to higher starch damage in hard textured wheat, significantly affects dough rheological properties (Martinant *et al*., 1998, Campbell *et al*., 1987).

Van Lill and Smith (1997) found that grain with higher protein content has a tendency to be harder, with higher ash content, consequently resulting in higher water absorption. Positive correlations between protein content and hardness were reported by Huebner and Gaines (1992), Van Lill and Smith (1997) and Lyon and Shelton (1999). Bergman *et al*. (1998) and Ohm *et al*. (1998) reported positive correlations between kernel hardness and FLY. Van Lill and Smith (1997) and Edwards *et al*. (2008) found that harder grain correlates with higher FLY.

Campbell *et al*. (1987) reported that harder wheat gives a more even particle distribution during the first break of milling than soft wheat. Sissons *et al*. (2000) recommended SKCS as the best developed system to evaluate quality characteristics of individual kernels.

Xiao *et al*. (2006) reported highly significant positive correlations between lactic acid SRC, sodium carbonate SRC values (sodium carbonate SRC), distilled water SRC and SKCS hardness. This is expected, as harder wheat with high protein content will have more damaged starch as a result of milling, with subsequent higher water absorption, supporting the findings of Van Lill and Smith *et al*. (1997). Various studies have correlated SRC profiles with kernel hardness (Chen *et al*., 2005; Zhang *et al*., 2009). Only medium hard to hard red wheat is considered for release in South Africa and testing of hardness is not part of the commercial release criteria (SAGL, 2013).

2.3.2 Milling characteristics

Cleaned wheat samples are conditioned as determined by the hardness of the kernel and wheat moisture content, to between 15% and 16% moisture content (SAGL, 2013). After 20 hours, the sample is milled on a standard Bühler MLU 202 mill and passed through a bran finisher (Wahrenberger, 2004). During milling the endosperm is separated from the bran and germ. The mass of the total products is used to calculate flour yield (flour extraction rate) Bass, (1988).

2.3.2.1 Break flour yield and flour yield

Break flour is the total weight of flour obtained from the break rollers on a Bühler-mill during the process of milling when the endosperm and germ are separated from the bran. Break flour is expressed as a percentage. The first break in the milling process will determine the flow of flour through the rest of the mill, and even flow through the rest of the mill is achieved with a constant particle distribution from the first break (Campbell *et al*., 1987).

Negative correlations between BFLY and hardness were reported by Yamazaki and Donelson (1983), Gaines (1991) and Labuschagne *et al*. (1997). Barnard *et al*. (2002) and Miles (2010) reported that genotype contributed significantly and more towards total variation in BFLY than the environment. A potential breeding line can differ with 5% more or 5% less than the biological standard for BFLY (SAGL, 2013).

Flour yield is the percentage flour obtainable from a given amount of wheat and is affected by kernel plumpness, kernel hardness, endosperm-bran ratio and endosperm-bran adherence (Steve *et al*., 1995). Softer wheat has a lower FLY than hard wheat (Labuschagne *et al*., 1997). Miles (2010) and Bergman *et al*. (1998) reported that genotype significantly affects FLY. Van Lill and Smith (1997) reported that both genotype and the environment affects FLY. Xiao *et al*. (2006) reported highly significant negative correlations between all four SRC parameters and FLY. Guttieri *et al*. (2002) found that lactic acid SRC and sucrose SRC were highly and significantly, but negatively, correlated with FLY

and that distilled water SRC and FLY were positively correlated. Extraction rates of potential breeding lines are allowed a maximum of 1.5% lower than the biological standard to comply with release criteria (SAGL, 2013).

2.3.2.2 Flour protein content

To classify a potential new wheat variety for release in South Africa, the FPC of the new variety, when compared to that of the biological standard, may not be more than 1% lower (SAGL, 2013). Flower protein content below 8% will result in flour that is not suitable for bread making due to deficient dough strength (Wrigley and Batey, 2003). Flour protein composition is genetically determined, but quantity is affected by the environment (McDonald, 1992) with considerable GXE interactions (Panozzo and Eagles, 2000). Slade and Levine (1994) reported that protein quality and not quantity, determines flour functionality and performance to deliver a specific end-use product.

Slade *et al*. (1989) reported that flour protein alone is an ambiguous flour specification characteristic, since it includes functional gluten and non-functional non-gluten proteins. Even the constituents of gluten proteins, the gliadins and glutenins, result in different flour functionalities. Gaines *et al*. (2006) reported a significant positive correlation between lactic acid SRC and glutomatic gluten index, and no correlation with FPC. Xiao *et al*. (2006) reported that lactic acid SRC is highly significantly correlated with protein content ($r=0.66$, $p \leq 0.001$) and flour protein content ($r=0.60$, $p \leq 0.001$). Their findings stated that lactic acid SRC correlated with gluten quality related to LFV over a broad range of FPC. Guttieri *et al*. (2002) found that lactic acid SRC and sucrose SRC are strongly positively correlated with FPC. Hammed *et al*. (2015) reported that all four SRC solvents are highly significantly and positively correlated with FPC. In flour blends containing hard and soft wheat, Issarny *et al*. (2017) reported highly significant correlations of lactic acid SRC with FPC ($r=0.99$, $p \leq 0.01$). Li *et al*. (2013) reported highly significant correlations between SIG and FPC ($r=0.78$, $p \leq 0.0001$). Wheat with a protein content of 12% and higher are classified as Grade 1 bread wheat on a 12% moisture basis (Government Gazette, 2016).

2.3.3 Rheological characteristics

Khatkar and Schofield (2002) reported that the most commonly used methods for the evaluation and prediction of flour quality with specific end-use requirements are the empirical rheological tests. For dough to be suitable for rheological testing, a specific amount of water needs to be absorbed by the flour to ensure that dough with ideal handling characteristics is formed (Stevens, 1987).

2.3.3.1 Alveogram characteristics

An alveograph is used to measure the pressure and the air volume that is required to blow an expanding bubble from a thin sheet of dough. Information is then displayed in a graph, the alveogram. Alveography is preferred for the analysis of soft wheat biscuit flours (Finney and Shogren, 1972). Miralbés (2004) indicated that ALVW is the most important parameter available to screen for bread making quality. Irrespective of the actual water absorption of a given flour, a constant amount of water is added to obtain information on rheological properties and gluten strength, in contrast with mixography and farinography (Faridi and Rasper, 1987; Bloksma and Bushuk, 1988). Rheological information obtained includes; stability or tenacity of dough (ALVP-value) as affected by gluten properties and grain hardness associated with water absorption and pentosan content, distensibility (ALVL-value) affected by gliadin characteristics, dough strength (ALVW-value) and the ratio between stability and distensibility (ALVP/L-value) (Miles, 2010). The ALVP-value indicates the dough's ability to retain gas, the ALVL-value indicates dough handling properties and elasticity. The area under the curve of the alveograph (ALVW-value) measures the required energy needed to deform dough and is regarded as a measure of flour strength. Bordes *et al*. (2008) stated that ALVW summarises all the parameters obtainable from the alveogram.

The alveograph is thus a tool used for measuring the amalgamated effect of the three functional polymeric components of flour. Low and high ALVP-values, ALVL-values and ALVW-values correspond with weak and strong dough

respectively (Miralbés, 2004; Bordes *et al*., 2008; Miles, 2010). Van Lill and Smith (1997) indicated that all alveogram parameters are influenced by protein quality and quantity and Ames *et al*. (2003) reported that due to strong influence of protein content on ALVL and ALVW, variation in these two parameters are more influenced by environmental effects than ALVP.

Gaines *et al*. (2006) reported highly significant positive correlations between alveograph parameters and lactic acid SRC. Li *et al*. (2013) also reported highly significant positive correlations between lactic acid SRC and ALVW ($r=0.76$, $p\leq 0.0001$) and between SIG and ALVW ($r=0.90$, $p\leq 0.0001$), ALVW was also highly correlated with FPC. ALVP was highly correlated with alkaline water retention capacity (AWRC) ($r=0.84$, $p\leq 0.0001$) and distilled water SRC ($r=0.82$, $p\leq 0.0001$). This is expected, as high ALVP values are obtained from hard wheat, with higher damaged starch and resulting higher water absorption (Kweon *et al*., 2011a).

Wang and Kovacs (2002a) reported high correlations between SIG and the insoluble gluten components of flour. The high correlation between SIG and ALVW indicates the importance of gluten strength in determining functional properties of dough. The amount of unextractable protein determines dough strength and it is mainly the insoluble glutenin, which contributes the most to dough strength, independent from different solvents and extraction procedures (Orth and Bushuk, 1973; Dachkevitch and Autran, 1989), explaining the high SIG correlations with alveograph dough strength parameters. Release criteria allow a deviation of ± 20% for ALVW and ALVP, a -10% to +20% for ALVL and ± 25% for ALVP/L (SAGL, 2013).

2.3.3.2 Mixogram characteristics

The mixograph is the most applied instrument for predicting certain physical dough properties, providing information on rheological parameters essential for predicting end-use potential such as water absorption during dough processing (Wikström and Bohlin, 1996).

Dough is stretched between moving pins of the mixograph and the resistance of the dough is registered as a curve, the mixogram. Mixography as well as farinography provides information on flour's ability to absorb water and the mixing time of dough as a result of the gluten qualities of the dough (Finney and Shogren, 1972).

Mixograph peak time (MPT), is considered the primary measurement of the mixograph, measuring optimum dough development time (Fowler and De la Roche, 1975) and is a function of FPC, water absorption and dough strength (Ram *et al*., 2005). The ascending slope of the curve indicates the rate of dough development and descending slope the rate of dough breakdown. Mixing tolerance is indicated by the angle between the slopes. Soft wheat, containing lower protein content, breaks down rapidly after the peak time is reached and high protein or stronger flour results in mixograms with long peak times (Walker and Hazelton, 1996; Neacşu *et al*., 2009). Peak time is influenced by protein content and ratios (Bietz *et al*., 1973), with an increase in peak time, dough extensibility decreases, while stability, elasticity and mixing tolerance increases.

Flour with FPC higher than 12% exhibits more acceptable mixing tolerance (Hoseney, 1994). Walker and Hazelton (1996) reported that FPC and quality as well as the water absorption of a specific flour affects MPT, peak height and curve width. Gaines *et al*. (2006) reported highly significant positive correlations between MPT and lactic acid SRC.

Xiao *et al*. (2006) reported highly significant positive correlations between all four SRC parameters and mixogram water absorption (MWA). Ram *et al*. (2005) reported a highly significant positive correlation between lactic acid SRC and MPT in a study of 192 wheat genotypes. The distilled water SRC test is indicative of the flour's overall ability to retain water and was found by Duyvejonck *et al*. (2012) to be highly correlated with both FABS ($r=0.72$, $p\leq 0.0001$) and MWA ($r=0.54$, $p\leq 0.05$).

Wang and Kovacs (2002b) reported a significant correlation between MPT and SIG (r=0.62, p≤ 0.01). This indicates the link between insoluble glutenin and dough strength.

To classify a new cultivar for release in South Africa, the MPT tolerances differ depending on the biological standard used as determined by the region of cultivation (SAGL, 2013).

2.3.3.3 Mixolab characteristics

The Mixolab is a recently introduced device, from CHOPIN Technologies. Optimal dough development is measured over time with a gradual increase of temperature in a mixer fitted with two blades, which turn in opposite directions. The mixolab method measures the protein and starch characteristics of flour or ground wheat and provides information about protein breakdown, starch gelatinisation, enzyme activity and gel strength (Dubat, 2010), thus changes between the viscous liquid phase and the elastic solid phase of dough, as affected by the functional polymeric components, can be studied in a single test. Bread wheat rheological properties have been successfully determined with the mixolab method (Koksel *et al*., 2009).

The Mixolab water absorption (MABS) capacity of flour is an indication of the hydration required to obtain a maximum dough consistency of 1.1 Newton metre (Nm) on the Chopin+ protocol, equivalent to an overall farinograph value of 500 Brabender Units (BU). Dapcevic *et al*. (2009) reported a highly significant correlation (r=0.98, p≤ 0.0001) between MABS and FABS. Water absorption is determined by the maximum torque obtained during mixing. Water absorption is determined by both quantity and quality of protein and increases with an increase in protein content (Finney *et al*., 1987). Water absorption is also an indicator of baking quality, as it gives an indication of a protein molecule's potential to absorb added water (Van Lill *et al*., 1995). Preston and Kilborn (1984) reported that water absorption is determined by the joint effect of protein content, damaged starch, pentosans and gluten strength. Flour with higher FABS and MABS are

preferred, as bread volume increases with an increase in the percentage of water (Roels *et al*., 1993).

2.3.4 Baking characteristics

2.3.4.1 Sodium dodecyl sulphate-sedimentation volume

Sodium dodecyl sulphate (SDS)-sedimentation volume (SDSS) measures the sediment volume of a flour-water suspension after acidification with lactic acid. The SDSS test was developed by Zeleny (1974) and modified by Axford *et al*. (1979) to estimate bread making potential. Only the glutenin component of protein will contribute to the sedimentation volume, as other proteins, including gliadin, are soluble in the SDSS and Zeleny test solvents (Echert *et al*., 1993). De Villiers and Laubscher (1995) reported a positive correlation between SDSS values and protein content and Fowler and de la Roche (1975) reported that SDSS reflects dough development time and protein quantity.

Various researchers found significant correlations between SDSS values and mixograph parameters (Dobraszczyk and Schofield, 2002) and extensograph, alveograph and farinograph parameters (Gröger *et al*., 1997). Khathar *et al*. (1996) reported that SDSS cannot be used independently to determine bread making potential.

Eckert *et al*. (1993), De Villiers and Laubscher (1995) and Carter *et al*. (1999) reported that when FPC is in excess of 13%, the SDSS test was unable to distinguish between medium and strong quality flour. Preston *et al*. (1982) reported that SDSS values are not linearly correlated with LFV at high flour protein levels and results can easily be affected by experimental error. Axford *et al*. (1978) reported that SDSS test results correlates better with LFV than the Zeleny sedimentation test. Significant positive correlations were reported between SDSS values and the percentage of insoluble glutenin in flour (Blackman and Gill, 1980; Dachkevitch and Autran, 1989).

Although the SDSS test is considered a small scale, rapid test of bread flour quality, the test takes 30 min to complete and requires 6.3 g of ground whole meal (AACC, 2010). Seabourn *et al*. (2012) developed a hybrid SDS-SRC method, requiring only 1 g of flour and 66% less time than the original SDSS test. The hybrid method showed a highly significant correlation ($r=0.85$, $p \leq 0.001$) with LFV, suggesting that this method could conveniently be used by breeders to screen early-generation material.

Li *et al*. (2013) reported that the SIG and lactic acid SRC are better small-scale rapid tests to predict gluten strength than the SDSS test, however, SDSS correlated better with LFV than SIG. The high SDSS correlation with LFV can be explained by the fact that SDSS is influenced by soluble and insoluble glutenins, both actively contributing to LFV (Wang and Kovacs, 2002b). A highly significant correlation between lactic acid SRC and SIG ($r=0.88$, $p \leq 0.0001$) was obtained.

Li *et al*. (2013) concluded that SIG, lactic acid SRC and SDSS are reliable small-scale rapid tests for the evaluation of gluten viscoelasticity and LFV in breeding programmes. Gaines *et al*. (2006) and Roccia *et al*. (2006) reported highly significant positive correlations between SDSS volume and lactic acid SRC, whilst Deyong *et al*. (2012) could not find a correlation between these two parameters. Xiao *et al*. (2006) reported highly significant positive correlations between lactic acid SRC and SDSS volume and positive correlations between sodium carbonate SRC, distilled water SRC and SDSS volume.

2.3.4.2 Wet gluten content

The wet gluten content (WGC) is obtained by removing starch and all other soluble components from flour after washing a flour sample with a sodium chloride solution (Neufeld and Walker, 1990). Hammed *et al*. (2015) reported that WGC is highly correlated with FPC ($r=0.86$, $p \leq 0.001$) and all four SRC solvents.

2.3.4.3 Loaf volume

Loaf volume gives an indication of dough capacity to hold gas during the fermentation process and is measured by the displacement of rapeseed (Shogren and Finney, 1984). The baking test is still considered the most accurate method to asses baking quality by means of LFV (Bouachra *et al*., 2017). The ability of flour to absorb water and produce large, well-shaped loaves will determine LFV (Kent, 1984). Loaf volume is dependent on both protein quality and quantity (Orth and Bushuk, 1973; Aussenac *et al*., 2001; Koppel and Ingver, 2010).

Singh (2005) reported the importance of inter and intra-molecular disulphide bonds of gluten proteins responsible for the formation of the gluten matrix in dough that traps gas cells during the baking process. Orth and Bushuk (1973) referred to LFV per unit protein as a better index of protein quality than total LFV and found the ratios of albumin to globulin and gliadin to glutenin correlated significantly positively with LFV per unit protein. Blackman and Payne (1887) indicated that better bread making results are obtained when using hard wheat due to the flour's ability to absorb more water, resulting in increased bread yield and shelf life. With increasing protein content within a cultivar, LFV will also increase, but due to the qualitative nature of gluten, bread making quality between cultivars will differ at a given protein content (Finney *et al*., 1987; Khatkar *et al*., 1996; Bushuk, 1998). Dobraszczyk and Schofield (2002) reported that protein on its own, particularly when no significant differences in protein content occur, cannot be used to predict LFV.

Xiao *et al*. (2006) reported highly significant positive correlations of lactic acid SRC, sodium carbonate SRC, sucrose SRC, and distilled water SRC with LFV. This is expected, as higher protein associated with lactic acid SRC will result in higher LFV. The positive correlations with sodium carbonate SRC, sucrose SRC and distilled water SRC supports the findings of Blackman and Payne (1987).

Xiao *et al*. (2006) also found that SRC correlates with gluten protein quality related to LFV over a broad range of FPC. They also found that SRC results significantly correlated with SDSS data and that the 5% lactic acid SRC solvent was reliable in predicting LFV in hard winter wheat flours with a narrow range of protein content. Colombo *et al*. (2008) reported that LFV and lactic acid SRC are highly correlated and concluded that the SRC test permitted valuation of Argentinian wheat for cookie and bread quality.

Hammed *et al*. (2015) reported that distilled water SRC, sodium carbonate SRC and lactic acid SRC could be useful for the evaluation of bread making quality of HRS wheat and reported highly significant correlations of these parameters with LFV. The Zeleny test was also highly correlated with lactic acid SRC and LFV. Duyvejonck *et al*. (2012) reported that the Zeleny sedimentation test and some farinogram and alveogram parameters were better predictors of LFV than the lactic acid SRC test, although the SRC tests can be successfully applied to select for improved flour quality in European hard wheats. The Zeleny and gel protein test values are better correlated with LFV than SIG test values and both SIG and SDSS test values correlated equally to LFV ($r=0.54$, $p \leq 0.01$) (Wang and Kovacs, 2002b). Increased SIG swelling times resulted in declined correlations with LFV, attributed to the SDS solvent extracting high amounts of soluble glutenin. Thus, LFV is determined by the soluble and insoluble glutenin content. Hammed *et al*. (2015) also reported that protein fractions obtained by means of SE-HPLC, including the HMW-polymeric protein, LMW-polymeric protein and the gliadins, are involved in different degrees to determine LFV. To qualify for release in South Africa, LFV of potential cultivars may not be more than 10% lower than LFV of the biological standard (SAGL, 2013).

2.4 Small scale rapid tests

A demand for reliable early generation screening methods, requiring small sample volumes, are essential to breeders in order to increase productivity in breeding programmes. Two of these small scale rapid tests include the SRC test and SIG test.

Experimental rheological and baking tests all measure the amalgamated contributions of the main flour functional components, including damaged starch, gluten proteins and pentosans. The SRC method was developed to measure the individual functional contribution of each functional component to help predict flour functionality (Kweon *et al*., 2011a). Duyvejonck *et al*. (2011; 2012) reported that the SRC test is an acceptable, simple and rapid method to predict cookie and bread quality parameters for commercial European wheat flours.

2.4.1 Solvent retention capacity

Solvent retention capacity is a solvation test used on flour and is based on the exaggerated swelling behaviour of component polymer networks in four individual diagnostic solvents (Kweon *et al*., 2011a). The test was developed by Louis Slade at Nabisco in the 1980's (Slade and Levine, 1994), where after Gains (2000) implemented the test as an AACC International Approved Method. The SRC test can predict individual functionality of different flour constituents and it extends the AWRC test as implemented by Yamazaki in 1953 (Kweon *et al*., 2011a). The AWRC test measures the overall water absorption capacity of flours resulting from the collective contributions of functional polymeric components.

The contribution of functional polymeric components of flour to the overall flour functionality and thus the quality of the end-product, is measured using the SRC method. It measures the capacity of flour to retain a set of four solvents. The different solvents include; distilled water, 50% sucrose, 5% sodium carbonate and 5% lactic acid (Kweon *et al*., 2011a). Each solvent will predict different functional polymeric components respectively (Kweon *et al*., 2011a). These functional polymeric components include gluten characteristics, damaged starch as a result of the milling process and thirdly, pentosans or arabinoxylans that originate from the bran and aleurone layer that significantly increases water holding capacity. Pentosans contribute 2-3% to total wheat flour and are highly hydrophilic, with the ability to absorb as much as ten times their weight in water (Kulp, 1968). The fourth polymeric component measured by SRC is the gliadin characteristics.

Sucrose SRC is associated with gliadin content and differentiates flours with different water-soluble pentosans. Sodium carbonate SRC is correlated with the levels and swelling of damaged starch, or solvent-accessible amylopectin in damaged starch, as well as pentosans in flour. Lactic acid SRC is correlated with gluten strength by swelling the glutenin subunits directly affecting dough strength and distilled water SRC is influenced by the gliadin, pentosan, damaged starch and gluten strength flour constituents, distilled water SRC reflects the flour's ability to hold water (Gaines, 2000; Guttieri *et al*., 2001). Barrera *et al*. (2007) reported that all four SRC solvents as well as AWRC are significantly correlated with an increase of damaged starch content. The highest correlations were obtained with sodium carbonate SRC ($r=0.82$, $p\leq0.01$) and distilled water SRC ($r=0.97$, $p\leq0.01$).

Higher levels of damaged starch will increase lactic acid retention with resulting positive correlations between lactic acid SRC and damaged starch. Cookie flour will thus have low sodium carbonate SRC values and low sucrose SRC values. Bread flour will have high lactic acid SRC, sucrose SRC and sodium carbonate SRC values. Retention of these four solvents results in a practical flour functionality quality profile, used to predict commercial bakery performance (Guttieri *et al*., 2002). Duyvejonck *et al*. (2011) reported that flour proteins, but especially the glutenins, contributed to lactic acid SRC values, while sodium carbonate SRC values were largely affected by damage starch content. Water-extractable pentosans contributed to sucrose SRC levels and the solvent accessible pentosans affected all four the SRC values, particularly the sucrose SRC values.

Solvent retention capacity results are calculated and reported as percentages of the mass of flour gel after exposure to one of the solvents divided by the original flour weight. Kweon *et al*. (2011a) determined that it is not any individual SRC value, but rather the unique combination of SRC values that will determine specific end use potential.

All rheological and baking tests, traditionally used for quality evaluation, measure the combined contribution of the major functional flour components instead of the

individual functional contribution of each component separately (Kweon *et al*., 2011a). Analysing each individual contribution of the different functional components assist end-users to successfully predict overall flour functionality accurately. An accurate prediction of flour functionality will ensure optimised product quality and an improved understanding of the mechanisms for dough mixing and baking.

The SRC method is based on energetic thermodynamic polymer-solvent compatibility. This is in contrast with the rheological methods based on kinetics of dough development including flour polymers plasticised in water or water and sugar solutions (Kweon *et al*., 2011a). Thus, results obtained from rheological methods and the SRC method are incomparable, as rheological results are based on concentrated flour-water interaction (Kweon *et al*., 2011a). Water has the ability to hydrate and swell the functional flour polymeric components and is considered the reference SRC solvent representing the overall water-holding capacity. The total grams of water per gram of dry component represent water-holding capacity and vary between the polymeric components.

Wheat gluten holds approximately 2.8 g of water for each gram of dry gluten, starch only holds 0.3-0.45 g of water per gram of dry starch, damaged starch is able to retain 1.5-2 g of water per gram of dry starch, whereas pasted starch has the capacity to retain up to 10 g of water per gram of dry starch. Solvent accessible pentosans can retain up to 10 g of water for each gram of dry pentosans (Kweon *et al*., 2014).

Guzmán *et al*. (2015) reported that for a typical wheat sample, water absorption contributed by gluten is 27%, the combined absorption for native and damaged starch is 34% and pentosans absorb 25% of the total water of the sample. Each respective lactic acid SRC, sodium carbonate SRC and sucrose SRC solvent is a better solvent for its specific flour polymer than water alone. The role of each of the three solvents in addition to distilled water SRC is to enlarge the contribution of one functional flour component, compared with its contribution to swelling in water. Kweon *et al*. (2014) also indicated that each of the four SRC solvents contains at least 50% water. Swelling in the respective solvents will be

the result of the water that makes up the solvent, but will to a greater extent be due to the solvent with the highest compatibility with the respective flour polymers in which levels are increased.

Bettge *et al*. (2002) reported the SRC method useful to evaluate wheat breeding material in early stages when seed volumes are limited. Although originally developed to determine flour functionality for soft wheat end-products (Slade and Levine, 1994), end-use quality of hard winter wheat was successfully predicted with the SRC method (Pike and MacRitchie, 2004; Guttieri *et al*., 2005; Xiao *et al*., 2006, Barrera *et al*., 2007; Duyvejonck *et al*, 2012; Seabourn, *et al*., 2012) and quality evaluation of various soft wheat flour applications in numerous studies (Gaines, 2000; Guttieri *et al*., 2001; Guttieri *et al.*, 2002; Guttieri and Souza, 2003; Guttieri *et al*., 2004; Ram and Singh, 2004; Barrera *et al*., 2007; Fustier *et al*., 2007; Colombo *et al*., 2008; Tanhehco and NG, 2008; Kweon *et al*., 2009a; 2009b; Nishio *et al*., 2009; Pasha *et al*., 2009; Nakamura *et al*., 2010; Moiraghi *et al*., 2011; Nakamura *et al*., 2012). Solvent retention capacity and small scale SRC test profiles were used to evaluate Triticale flour for cookie making (Roccia *et al*., 2006; Barrera *et al*., 2007). Oliete *et al*. (2010) successfully determined rye and triticale flour functionality using the SRC method to produce layer cakes.

Crop management and GXE have a limited effect on SRC values and genotype differences contribute more to variation in SRC values. This indicates that quality gains from selection based on SRC values within an environment will be observable in multiple and diverse environments (Guttieri *et al*., 2001; 2002; Guttieri and Souza, 2003). The low GXE effect obtained in two studies over seven irrigation localities and two dryland and irrigated localities, respectively (Guttieri *et al*., 2001; 2002) indicate that SRC selections can be used in a breeding programme to successfully improve milling and baking characteristics. Walker *et al*. (2008) reported significant GXE interaction for all four SRC solvents on duplicate SRC tests using two flour sample sizes of 5 g and 0.2 g from soft spring and winter wheat genotypes grown over eight localities.

The results obtained by Walker *et al*. (2008) emphasises the need for multi-location evaluation when conducting the SRC method, especially when a high interaction term is found to be non-significant as a result of a similarly high error term. Dean and Voss (1999) reported that when mean squares of the treatment are compared to the mean squares of the error by the F test, a large interaction could be non-significant if the mean squares of the error are also large. Heat and drought stress affects SRC and SIG test values, although mainly controlled by genotype, the GXE interaction should not be neglected when screening for end-use quality in a breeding programme (Li *et al*., 2013). To ensure that genotypes with stable quality characteristics are promoted in breeding programmes, screening environments should include both favourable and abiotic stress conditions when selections are made.

The contrast in results obtained from the studies conducted by Walker *et al.* (2008) and Guttieri *et al*. (2001; 2002) and Guttieri and Souza, (2003), could be attributed to the differences in growing conditions that included natural precipitation and irrigation treatments between the studies. Hammed *et al*. (2015) reported that the environmental effects are higher than genotype effects on SRC values and found significant environment interaction on SRC test results in a study conducted on 10 hard red spring varieties planted at six localities.

Both the differences in genotype and environment affected SRC results, but the environment had a much larger effect on the variation for especially lactic acid SRC values. The findings of Hammed *et al*. (2015) were in line with results obtained by Pasha *et al*. (2009) who also indicated that the environmental effect on SRC values must be considered when predicting flour quality. In South Africa, spring wheat is planted in the northern areas under full irrigation in contrast to the Cape or southern production regions, where spring wheat is grown under dry land or natural precipitation conditions. Intermediate and winter wheat is grown in the summer rainfall region under dryland conditions. The variation in production practices, yield potential and fertiliser regimes will have a definite impact on quality and on SRC values.

When wheat or flour is blended, SRC values equate to the average of the sum of the corresponding SRC values, respectively, for the total combined flour from each individual wheat in the blended sample (Kweon *et al*., 2011a). Haas (2011) and Kweon *et al*. (2011b) reported that the SRC test can thus be used for blending wheat cultivars to produce constant superior flours that meet unique end-use demands.

As all four SRC solvents are water-based, their values as a measurement of individual polymeric component activity are convoluted with each other. Louise Slade de-convoluted the contribution of gluten strength from pentosan and damaged starch to evaluate the performance of gluten in the presence of other modulating networks, introducing an additional predictive SRC parameter; the gluten performance index (GPI) (Kweon *et al*, 2009a; 2009b; 2011a). The GPI is defined as lactic acid SRC/(sodium carbonate SRC + sucrose SRC).

With an increase of flour extraction, the GPI ratio increases for approximately a third of the range in FLY and then decreases when lactic acid SRC declines with an increase of sodium carbonate SRC, indicating increased damaged starch. Duyvejonck *et al*. (2012) reported better correlations when the lactic acid SRC value is amended for the contribution of non-gluten polymers, with lactic acid SRC ($r=0.69$, $p\leq 0.01$) and GPI ($r=0.75$, $p\leq 0.001$).

Hammed *et al*. (2015) reported positive significant correlations between GPI and quality parameters, however in this study, GPI was not able to better predict gluten quality than unadjusted SRC values. The reduced efficiency of GPI could be attributed to higher sucrose SRC and sodium carbonate SRC values as a result of increased protein content in HRS wheat flour in comparison to soft wheat flour.

The SDS-unextractable polymeric proteins mostly consist of HMW-GS and are highly associated with bread making quality (Gupta *et al*., 1993). Hammed *et al*. (2015) reported low correlations between SDS-extractable protein with SRC values and bread making quality parameters using SE-HPLC. However, the SDS-unextractable proteins, especially the HMW polymeric protein fraction, was

found to be highly correlated ($p \leq 0.01$) with distilled water SRC, sodium carbonate SRC and lactic acid SRC values and less significantly ($p \leq 0.05$) correlated with sucrose SRC. The LMW polymeric protein fraction was highly correlated ($p \leq 0.01$) with lactic acid SRC, due to the exaggerated swelling action of the glutenin network in lactic acid (Kweon *et al*., 2011a), indicating that lactic acid SRC is useful for the prediction of good bread making quality. The distilled water SRC solvent showed significant positive correlations with both the HMW polymeric protein fraction and the gliadin fraction. As distilled water SRC is associated with the overall water absorption of all flour constituents, this result is expected (Kweon *et al*., 2011a). Hammed *et al*. (2015) concluded that the different associations between SRC-parameters and protein molecular weight distribution could aid in the selection process for superior bread making varieties for HRS wheat.

Gaines *et al*. (2000) reported that due to the simplicity of the SRC method, variation in SRC results between laboratories and technicians are minor when compared to rheological and baking test results. Kweon *et al*. (2014) reported that, due to the small experimental error when conducting SRC tests, results can be reported using only one decimal place.

2.4.2 Swelling index of glutenin

Various small-scale rapid tests have been developed to allow screening of material in early generations, among them the SIG method requires the smallest amount of sample (0.04 g) next to the modified SRC method of Guzmán *et al*. (2015). In addition to the Zeleny sedimentation test and the SDSS test, various versions of the SDSS test were developed (Kovacs 1985; Peña *et al*., 1990) due to high correlations obtained with SDSS and LFV (Axford *et al*., 1979). These modified methods are widely applied for evaluating dough properties and bread making quality in early generation breeding nurseries (Weegels *et al*., 1996b). The gel protein test measures insoluble glutenin that forms on top of a starch pellet from a centrifuged SDS extracted flour sample. Starch is separated from the swollen glutenin by means of high centrifugation speed and the weight of the remaining gel protein represents the quantity of the insoluble glutenin in the

sample (Graveland *et al*., 1979; 1982). The simplest method for determining insoluble glutenin content is by a successive extraction technique (Orth and Bushuk, 1973), but protein fractionation and Kjeldahl determinations ensure that the process is intricate and slow. The sedimentation tests are affected by both the soluble glutenin and insoluble glutenin content, as mixing intensities in these tests are not high enough to dissolve soluble glutenin, which is not the case for the SIG test (Wang and Kovacs, 2002a).

High molecular weight glutenin highly contributes to the viscoelastic properties of flour dough (Song and Zheng, 2007). The SIG method determines the swelling power of glutenin to predict dough quality characteristics and end-use quality, especially those associated with dough strength and baking characteristics and only requires 0.04 g flour (Wang and Kovacs, 2002a). The SIG test has the ability to evaluate flour quality between varieties with a broad quality range (Wang and Kovacs, 2002a) and also varieties with a narrow range in insoluble glutenin content (Wang and Kovacs, 2002b; 2002c). The swelling capacity of glutenin depends on swelling time and mixing intensity in non-reducing solvents: SDS, lactic acid or dilute acetic acid.

When a flour sample is allowed to swell in a non-reducing LA solvent, whereafter the sample is centrifuged at low speed, the weight of the residue divided by the weight of the original sample represents the SIG. Swelling curves from SIG values versus swelling time provides information on the different stages of swelling, swollen phase and breakdown of glutenin contents, reflecting soluble and insoluble glutenin content and quality of varieties (Wang and Kovacs, 2002a). The gluten swelling curves can be applied to distinguish extra strong varieties from weak varieties when SDSS or Zeleny tests are not able to. As for the Zeleny sedimentation test and the SDSS test, a short swelling time indicates a SIG value contributed by soluble and insoluble glutenin content and reflects the quality of gluten. An increased swelling time indicates a SIG value determined by only insoluble glutenin content, as enough time would have allowed the soluble gluten to break down. Soluble glutenin is in a phase between swelling and dissolving at a short swelling time, while insoluble glutenin is in a phase between semi-swelling and complete swelling at a short swelling time.

The SIG value estimated with an increased swelling time reflects insoluble glutenin content and is not affected by flour particle size or damaged starch content in a sample (Wang and Kovacs, 2002a). Weegels *et al*. (1996b) determined that swelling volume is directly related to the amount and quality of glutenin present in a sample.

Certain quality parameters such as LFV and ALVL, for which quality characteristics is a function of glutenin quantity and quality, including soluble and insoluble glutenin, will thus be better correlated with SDSS, Zeleny, gel protein tests or SIG with a short swelling time. Quality parameters that are directly related to dough strength parameters and highly correlated to the insoluble gluten fraction, will be higher correlated with SIG test values, especially when swelling time is increased (Wang and Kovacs, 2002b; 2002c).

Insoluble glutenin consists of HMW glutenin (Gupta *et al*., 1993), which causes different functional dough properties than the LMW glutenin. Tsiami *et al*. (1997a, 1997b) reported viscous-like (elasticity) behaviour from LMW glutenin fractions and a gel-like (strength) behaviour from the HMW glutenin fractions. Wang and Kovacs (2002b) reported significant correlations between quality parameters associated with HMW and LMW glutenin groups, respectively.

Problems with other sedimentation tests include unclear sedimentation boundaries for some varieties and differences in results when sedimentation times vary for the SDSS and Zeleny test, respectively. The SIG method is simple, quick and more consistent in predicting insoluble glutenin content as well as dough strength characteristics than the Zeleny and SDSS sedimentation tests with a smaller experimental error (Wang and Kovacs, 2002a; 2002b). The SIG method allows high throughput with high reproducibility.

Wang and Kovacs (2002a) reported that stronger gluten varieties require high mixing intensities to obtain higher SIG values, indicating tolerance to vigorous vortexing conditions. Temperature affected SIG values. High temperatures increased SIG values for strong varieties and decreased SIG values for weak

varieties. To avoid different responses to temperature, it is recommended to conduct the SIG test at room temperature (24 ± 1°C).
Increased hydration of samples resulted in higher SIG values and samples that are less sticky due to SDS swelling and are easier to handle. Varieties reacting differently to increased swelling times indicate that solubility rates of glutenin is variety dependant. A strong variety's glutenin is solubilised over a longer period than that of a weak variety (He *et al*., 1991). To ensure maximum variation of SIG values among different varieties, a 20 min swelling time is preferred for the SIG method. The SIG test values are higher when the solvent-flour ratio is lower, due to the inability of the solvent to completely extract the soluble glutenin and some of the soluble glutenin might remain in a swollen state in the residue. Increased centrifugation force results in decreased SIG values and exact, and a low speed centrifugation is recommended to achieve reproducibility between tests.

Thus, the differentiation of SIG values between varieties is enhanced when mixing intensities are high, the solvent to sample ratio is increased, temperature is elevated and longer swelling times are allowed. The swelling volume of insoluble gluten is higher in SDS and this method allows for easier separation of the supernatant from the swollen glutenin by syringe. However, a solvent composed of SDS and lactic acid is recommended to prevent a watery swollen glutenin sample, which will require a higher centrifugation force to separate the supernatant from the residue.

Wang and Kovacs (2002a) reported highly significant correlations of SIG values with the gel protein test ($r \geq 0.85$, $p \leq 0.001$) and the insoluble glutenin test ($r \geq 0.93$, $p \leq 0.001$) and significant correlations were reported with the SDSS test ($r \geq 0.74$, $p \leq 0.001$) and the Zeleny sedimentation test ($r \geq 0.72$, $p \leq 0.001$). The SIG values obtained in their study were significantly better correlated with insoluble gluten content than the gel protein, SDSS and Zeleny sedimentation tests indicating that the SIG test is a better indicator of insoluble glutenin content. Short swelling times and low mixing intensities correlated with gel protein content and SDSS values, whereas long swelling times and high mixing intensities were significantly correlated with insoluble glutenin content.

The differences in swelling time and mixing intensities among small-scale methods result in different correlations with insoluble glutenin content. Sharma *et al*. (2012) reported that subunits coded by *Glu-A3* loci, *Glu-B3* and *Glu-D3* significantly affected gluten strength, as measured by SIG and mixograph mixing time and the highest correlations with gluten strength were expressed with 2*, 17+18, 5+10, *Glu-A3*, *Glu-B3g* and *Glu-D3b* subunit combinations. These results are contradictory to the results from Wang and Kovacs (2002b), who reported that the SIG measures insoluble glutenin mainly consisting of HMW-GS located on the *Glu-1 loci*.

A high troughput breeding programme requires small samples and robust, reproducible tests. Lines required to perform and meet standards of rheological tests require large quantities of seed, vary heavily by GXE and are very time consuming. Thus, the SRC and SIG tests are examined in relation to rheological standards tests in hopes to increase breeding throughput.

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CHAPTER 3

THE RELATIONSHIP OF GRAIN AND MILLING CHARACTERISTICS WITH SOLVENT RETENTION CAPACITY AND SWELLING INDEX OF GLUTENIN

Abstract

Bread wheat breeders can only conduct quality analysis on breeding material when sufficient amounts of seed are available, usually later in the breeding process. Selection for quality at a later stage in the breeding cycle means that lines with inferior quality characteristics cannot be discarded. This increase the magnitude of the breeding programme, with reduced efficiency and higher cost to release an adapted, high yielding cultivar with acceptable quality characteristics as set by the Wheat Technical Committee in South Africa. In this study five Solvent Retention Capacity (SRC) parameters and one Swelling Index of Glutenin (SIG) parameter were correlated with five grain and milling characteristics to determine their relationships using hard red spring and hard red winter wheat germplasm. Highly significant differences were observed for all measured quality parameters across the dryland and irrigated summer rainfall regions and the winter rainfall region. Genotype effect was high and significant for most measured quality parameters. Correlations between SRC, SIG, grain and milling parameters were highly significant but inconsistent across regions, with only lactic acid SRC and lactic acid SIG parameters showing consistently significant ($p \leq 0.001$) correlations with protein content. Stepwise multiple linear regressions indicated that most SRC and SIG parameters are poor predictors of grain and milling parameters and that regression coefficients across localities were higher for flour protein content with lactic acid SRC and lactic acid SIG, explaining most of the variation.

3.1 Introduction

Various small-scale rapid tests have been developed to allow screening of material in early generations of breeding, among them the SIG. This method requires the smallest amount of sample (0.04 g), close to the modified SRC method of Guzmán *et al*. (2015), which requires only 0.3 g per solvent. The use of the SRC and SIG small scale rapid tests has not yet been tested on South African HRS and HRW germplasm. The successful application of SRC to rapidly predict soft wheat flour quality has been proven by many researchers (Gaines, 2000; Guttieri *et al*., 2001; 2002; Guttieri and Souza, 2003; Guttieri *et al*., 2004; Ram and Singh, 2004; Barrera *et al*., 2007; Fustier *et al*., 2007; Colombo *et al*., 2008; Tanhehco and Ng, 2008; Kweon *et al*., 2009a; 2009b; Nishio *et al*., 2009; Pasha *et al*., 2009; Nakamura *et al*.,2010; Moiraghi *et al*., 2011; Nakamura *et al*., 2012), however, the results from Hammed *et al*. (2015) indicated that the high glutenin content of HRS wheat altered SRC results obtained from studies conducted on soft wheat. The South African wheat industry introduced certain end-use quality criteria for grain and milling characteristics that a new variety needs to comply with before the variety can be released as a new cultivar. To evaluate these criteria, a potential new cultivar is compared with a biological standard where fixed deviations are allowed. The biological standard, a successful cultivar with acceptable agronomical and quality characteristics, is used as a frame of reference against which new breeding lines are evaluated. Primary and secondary grain and milling requirements are evaluated. Primary requirements are not flexible and include: HLM, FN, FPC and FLY. The secondary requirements are flexible and include BFLY (SAGL, 2013).

Guzmán *et al.* (2015) developed the scaled-down protocol of the SRC Approved Method 56-11 (AACC, 2010) to ensure that large numbers of late-segregating or early-advanced breeding material with low seed volumes can be evaluated for quality characteristics over a shorter period. The scaled-down method is conducted five times faster than the original Approved Method 56-11 (AACC, 2010).

The SIG test has the ability to evaluate flour quality in varieties with a broad range of quality (Wang and Kovacs, 2002a) and varieties with a narrow range of insoluble glutenin content (Wang and Kovacs, 2002b; 2002c). This method determines the swelling power of glutenin to predict dough quality characteristics and end-use quality, especially those associated with dough strength and baking characteristics and only requires 0.04 g flour (Wang and Kovacs, 2002a).
This study aimed to correlate SRC and SIG rapid predictive test parameters with grain and milling characteristics and determine if grain and milling characteristics of HRS and HRW germplasm could be predicted from SRC and SIG results using small quantities of flour, in order to assist breeders with quality selection in early stages of the breeding process.

3.2 Materials and methods

3.2.1 Field trials

Forty-eight South African bread wheat cultivars were planted at six localities with four replications in 2012 as part of the National Cultivar Evaluation Programme of the Agricultural Research Council - Small Grain Institute (ARC-SCI). The three major wheat producing regions in South Africa include dryland summer rainfall regions (SRR) in the Free State where facultative wheat is planted, dryland winter rainfall regions (WRR) where spring wheat types are grown in the Western Cape and irrigated SRR where spring types are cultivated in the northern summer rainfall areas. Each environment was represented by two localities.

Experimental blocks were planted using a randomised complete block design with three replications. Testing material comprised 17 dryland winter varieties, nine dryland spring varieties and 22 irrigation spring varieties (Table 3.1). Samples were harvested with a Wintersteiger plot combine, cleaned and dried to a 12% moisture basis post-harvest before quality analysis commenced.

Trials in the dryland SRR were planted in yellow soils of average effective depth with accumulated soil water. Summer rainfall localities were represented by Bethlehem and Clarens, in the Eastern Free State with cooler temperatures and

higher summer rainfall. Planting dates for Bethlehem and Clarens were 04-07-2012 and 06-07-2012, respectively. Harvesting dates for these localities were 02-01-2013 and 07-01-2013 respectively. Experimental plots consisted of five rows of 5 m length each and an inter-row spacing of 45 cm, only the middle three rows were harvested to avoid potential side row effects.

Fertiliser was applied based on regional long term yield potential as recommended by the Agricultural Research Council (ARC) Production Guidelines of each respective area and weeds and pests were controlled when necessary during the growing season. Both the Clarens and Bethlehem trials were fertilised with 50 kg N ha^{-1}. Rainfall prior to planting was acceptable for emergence and plant establishment. From May until 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 2012 harvest. Meteorological data can be viewed in Appendix (Table A1.1) as collected from the ARC Institute for Soil Climate and Water (ARC-ISCW) (2014).

Irrigation localities included Vaalharts, planted 07-06-2012, and Upington planted 02-06-2012. Both these localities represented the cooler irrigation areas. Harvesting dates were 04-12-2012 and 07-12-2012 for Vaalharts and Upington, respectively. Warmer temperatures with lower rainfall is normal for Upington, compared with Vaalharts. Both localities have sandy soils. Plots consisted of eight rows, with a plot length of 5 m, at an inter-row spacing of 17 cm. Only the middle six rows were harvested to avoid potential side row effects. Fertiliser was applied based on long term yield potential of each respective area as recommended by the ARC Production Guidelines. Weeds and pests were controlled when necessary during the growing season and optimum irrigation practices were applied. The total fertiliser application was 220 kg N ha^{-1}. Both these localities were irrigated, resulting in high yield potentials; 10.90 ton ha^{-1} for Vaalharts and 9.03 ton ha^{-1} for Upington.

Minimum temperatures were significantly lower than the long-term average values. Maximum temperatures were lower during the first part of the growing season, however, were slightly higher during grain filling (Appendix Table A1.2).

The dryland WRR included Moorreesburg in the Swartland area, planted 23-05-2012, and Riversdal in the Rûens area, planted 09-05-2012.

Harvesting dates were 14-11-2012 for Moorreesburg and 16-11-2012 for Riversdal. Riversdal has shallow sandy soils on a rocky basis, whilst Moorreesburg has somewhat deeper loamy soils with more organic material. Experimental plots consisted of seven rows with a plot length of 5 m and 30 cm row spacing. Only the middle five rows were harvested to avoid potential side row effects.

Fertiliser was applied based on long term yield potential of each respective area as per the ARC Production Guidelines and weeds and pests were controlled when necessary during the growing season. Nitrogen was applied at a standard rate of 100 kg N ha^{-1}, with 40 kg N applied at planting and the balance more or less 42 days post planting. Moorreesburg had a good pre-planting season with high rainfall. The month of May was drier than normal, followed by a wetter than normal season. Riversdal received above average rainfall with some crop damage at the end of the season. Longer maturity cultivars were favoured by the late rains, resulting in good yields for the region. Refer to Appendix Table A1.3 for meteorological data. Yield in this region is moderate compared to the SRR. The Moorreesburg trial yielded 5.02 ton ha^{-1} and Riversdal trial 5.10 ton ha^{-1}, with high protein contents, but lower protein contents were reported for the dryland SSR.

Table 3.1 Localities and entries representing the three wheat production regions

Region	Dryland summer rainfall	Dryland winter rainfall	Irrigated summer rainfall
Localities	**Bethlehem Clarens**	**Moorreesburg Riversdal**	**Upington Vaalharts**
Entries	Elands	PAN 3471	Buffels
	Gariep	SST 015	Duzi
	Koonap	SST 027	Krokodil
	Matlabas	SST 047	PAN 3471
	PAN 3118	SST 056	PAN 3478
	PAN 3120	SST 087	PAN 3489
	PAN 3161	SST 096	PAN 3497
	PAN 3195	SST 88	Sabie
	PAN 3368	Tankwa	SST 806
	PAN 3379		SST 822
	Senqu		SST 835
	SST 316		SST 843
	SST 317		SST 866
	SST 347		SST 867
	SST 356		SST 875
	SST 387		SST 876
	SST 398		SST 877
			SST 884
			SST 895
			Tamboti
			Timbavati
			Umlazi

3.2.2 Quality analysis

Samples were milled on a standard Bühler model MLU 202 mill using the American Association of Cereal Chemists (AACC) Approved Method (AM) 26-21A (AACC, 2010). Grain and milling quality characteristics were determined at the quality laboratory of the ARC-SCI, Bethlehem in 2012 and 2013, using the appropriate Approved Methods according to the AACC (2010). Grain characteristics included HLM (AM 55-10) and FN (AM 56-81B). Milling characteristics analysed included BFLY, FLY (AM 26-21A) and FPC (AM 39-11.01). Flour samples were stored at -20°C for later analyses of SRC and SIG.

3.2.2.1 Hectolitre mass (AM 55-10)

Hectolitre mass was determined using a two-level funnel. The obtained mass was divided by five and the HLM was reported in kg hl^{-1} (AACC, 2010).

3.2.2.2 Falling number (AM 56-81B)

The time required by a metallic stirrer to fall through a boiling flour-water suspension was recorded. The recorded time, measured in seconds indirectly measures alpha-amylase activity. Results were corrected according to altitude values according to protocol (AACC, 2010).

3.2.2.3 Break flour yield, and flour yield (AM 26-21A)

Wheat samples were conditioned according to the milling temper table (AACC AM26-95) (AACC, 2010) for 18 hours preceding milling. A laboratory, pneumatic mill, Bühler model MLU-202 was used to mill the wheat samples. The formula of Bass (1988), was used to calculate the percentage of BFLY:

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

The formula of Bass (1988), was also used to calculate the percentage of FLY:

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

3.2.2.4 Flour protein content (AM 39-11.01)

A FOSS Grain Analyser 1241, with NIR-technology was used to determine FPC (AACC AM 39-11.01).

3.2.2.5 Solvent retention capacity (AM56-11 modified method)

A modified protocol (Guzmán, 2015) of the Approved Method 56-11 (AACC, 2010) was followed using four water based solvents. The SRC method was combined with the AWRC Approved Method 56-10 (AACC, 2010), which included an additional solvent. Flour samples of 0.3 g, with a moisture content of 14%, were weighed into a 2.0 ml centrifuge tube of known weight. Four SRC solvents were independently prepared using distilled water and used to obtain four SRC values. The four solvents included the following: distilled water, a 5% (v/v) lactic acid solution, a 5% (w/v) sodium carbonate solution and a 50% (w/v) sucrose solution. The solvent used for the AWRC method was prepared by dissolving 2.1 g sodium bicarbonate in 250 ml distilled water to make up a 0.1 N sodium bicarbonate solution.

For the preparation of the 5% (v/v) lactic acid solution the actual assay value on the reagent bottle was used to calculate the appropriate amount of lactic acid to be diluted for the solution.

To avoid kinetic effects on flour solvation and swelling, the solvents used in the SRC method are each used in a fivefold ratio to flour, 1.5 ml of the solvent to 0.3 g of flour according to the modified protocol of the AM 56-11.02 (AACC, 2010).

Freshly prepared lactic acid solution was used as prescribed by Thurmond and Edgar (1924) and Reiman (1934). The 50% (w/v) sodium carbonate solution was prepared a day before use to allow the sodium carbonate to dissolve completely. The sodium carbonate concentration was calculated on a weight basis instead of volume (Kweon *et al*., 2011).

After 1.5 ml of the appropriate solvent was added to the tubes, it was mixed in a vortex until suspended for 10 s. The vortexed tubes were immediately placed in a thermomixer block (Thermomixer®, Eppendorf AG, Hamburg, Germany) to shake at 1400 rpm for 5 min at 25˚C. The flour solvent suspensions were centrifuged at exactly 4000 x *g* for 2 min. After centrifuging, the supernatant liquid was discarded and the tube drained at room temperature for 10 min. The lid of the tube was dried with tissue paper. The tube weight, including that of the lid and gel, was determined and the SRC calculated as the sum of the tube and gel weight less the original empty tube weight divided by the original flour weight, thus the SRC value was calculated as a percentage of flour weight on a 14% moisture basis.

$$\% \text{ SRC} = \left[\frac{\text{Tube and gel weight} - \text{Empty tube weight}}{\text{Flour weight}}\right]\left[\frac{86}{100 - \text{Flour moisture}}\right] - 1 \times 100$$

3.2.2.6 Swelling index of glutenin

The SIG values were determined using the method of Wang and Kovacs (2002a). A flour sample of 0.04 g with a 14% moisture content was weighed into a 2.0 ml centrifuge tube of known weight, after which 0.8 ml of distilled water was added to each tube. The tubes were vortexed for 5 s until suspended and put on a thermomixer (Thermomixer®, Eppendorf AG, Hamburg, Germany) at 1400 rpm for 10 min at 25°C. The solvent, 0.4 ml isopropanol-lactic acid stock solution was then added to each tube. The flour solvent suspension was again vortexed for 5 s until suspended and put on a thermomixer at 1400 rpm for 10 min at 25°C. The suspended sample was then centrifuged at exactly 100 x *g* for 5 min. The supernatant liquid was discarded and the tube drained. The tube weight was determined and the SIG value calculated as a percentage of flour weight on a 14% moisture basis.

$$\% \text{ SIG} = \left(\frac{\text{Tube and gel weight} - \text{Empty tube weight}}{\text{Flour weight}} \right) \left(\frac{86}{100 - \text{Flour moisture}} \right) -1 \times 100$$

3.2.2.7 Electrophoresis

The method of Singh *et al*. (1991) was followed as conducted by Wentzel (2017). Electrophoresis was performed on a Mighty Small II SE250 (Hoefer Scientific Instruments). Proteins were extracted from a 20 mg flour sample. The procedure of Laemmli (1970) was followed for the gel preparation. The nomenclature as developed by Payne and Lawrence (1983) was used for HMW-GS identification.

3.2.3 Statistical analysis

The Shapiro-Wilk normality test was conducted on the data (Shapiro and Wilk, 1965). PROC GLM of SAS statistical software version 9.2 (SAS Institute Inc., Cary, NC, USA) was used for the analysis of data. Analysis of variance (ANOVA) and correlation analysis of experimental results was carried out following the same statistical procedures as reported by Wentzel (2017). Statistical analysis included simple statistics, ANOVA, correlations and stepwise multiple linear regressions.

3.2.3.1 Descriptive statistics

Descriptive statistics included means, minimum and maximum values, standard deviations and standard error values to describe data for the different quality characteristics.

3.2.3.2 Analysis of variance

Levene's test in the PROC GLM in the SAS programme was used to evaluate homogeneity of variances (Levene, 1960).

The combined ANOVA was performed across the three regions for the six trial locations for the SRC, SIG and grain and milling quality characteristics. Cultivar, environment and their interaction were analysed with the two-way ANOVA for all the quality characteristics and SRC and SIG parameters. Contribution of main effects to total variation for measured characteristics was calculated as the sum of squares of the main effect as a percentage of the total sum of squares.

3.2.3.3 Correlations

Linear relationships were calculated using Proc Corr of SAS statistical software version 9.2 (SAS Institute Inc., Cary, NC, USA), by building the Pearson's product moment correlation matrix of the pairwise correlations among dependent variables.

3.2.3.4 Stepwise multiple linear regressions

The stepwise multiple linear regression was performed using PROC REG of SAS software version 9.2 (SAS Institute Inc., Cary, NC, USA). Variables that accounted for most of total variability of the dependent variable were determined according to the method described by Draper and Smith (1966) by computing a sequence of multiple linear regression in a stepwise manner. If a variable contributed to a significant improvement of the coefficient of determination (R^2) at $p \leq 0.05$, the variable will be introduced to the model in one of the respective steps (Zahn *et al*., 2013).

The interaction between grain and milling characteristics with the fixed SRC and SIG parameters were determined to define the variation caused by grain and milling characteristics to the fixed SRC and SIG parameters.

3.3 Results

The combined AWRC with the SRC method and the SIG method resulted in a total of six measurement points from each of the respective solvents. A total of five grain and milling characteristics measurement points were included in this study.

3.3.1 Descriptive statistics

3.3.1.1 Means, minimum and maximum values, standard deviations and standard error values for the SRC and SIG parameters for the three production regions.

Lactic acid SRC mean values were highest (125.56%) in the dryland SRR (Table 3.2). The minimum lactic acid SRC value was 101.02% and the highest value 150.07%. The lactic acid SRC values in the irrigation SRR (Table 3.3) were lower with a mean value for the combined localities of 107.73%. In the WRR (Table 3.4), the lactic acid SRC mean value was 122.70%. The biggest lactic acid SRC differences between localities within a production region was also seen for the WRR (116.02% for Riversdal and 129.38% for Moorreesburg) and is attributed to the big differences in the production areas of the Rûens representing Riversdal and the Swartland representing Moorreesburg.

Distilled water SRC values ranged between 59.78% (Bethlehem) and 76.40% (Clarens) for the dryland SRR (Table 3.2) with the highest mean value of 67.32% for the three production regions. The lowest distilled water SRC values were seen for the irrigated SRR (55.99-71.95%) (Table 3.3) and 59.90-70.80% for the WRR (Table 3.4).

Sodium carbonate SRC values were the highest for the dryland SRR (Table 3.2), ranging between 63.63% and 99.61% followed by 71.25-91.03% for the WRR (Table 3.4) and the lowest values of 63.13-88.90% obtained by genotypes planted in the irrigated SRR (Table 3.3).

The sodium bicarbonate SRC values as part of the AWRC test responsible for measuring the overall water absorption capacity of flours resulting from the collective contributions of functional polymeric components, were highest for the dryland SRR. The mean sodium bicarbonate SRC values were 70.07%, 63.10% and 67.50% for the dryland SRR (Table 3.2), irrigated SRR (Table 3.3) and the WRR (Table 3.4) respectively. The sucrose SRC mean value for the dryland SRR was the highest (90.43%) (Table 3.2), followed by the irrigated SRR (89.64%) (Table 3.3) and the WRR (89.53%) (Table 3.4).

Mean lactic acid SIG values were 4.73% and 4.31% for Bethlehem and Clarens respectively (Table 3.2). Mean lactic acid SIG values were 4.52%, 4.35% and 3.97% for the dryland SRR (Table 3.2), irrigated SRR (Table 3.3) and WRR (Table 3.4) respectively.

Table 3.2 Mean values, range and standard error for solvent retention capacity and swelling index of glutenin characteristics for 17 wheat cultivars evaluated in the dryland summer rainfall region

Characteristic	Environment	MEAN	MIN	MAX	SD	SE
Lactic acid SRC (%)	Bethlehem	130.49	106.81	146.54	9.76	1.38
	Clarens	120.62	101.02	150.07	11.80	1.67
	Combined	125.56	101.02	150.07	11.86	1.19
Distilled water SRC (%)	Bethlehem	67.02	59.78	71.60	2.97	0.42
	Clarens	67.62	60.38	76.40	3.18	0.45
	Combined	67.32	59.78	76.40	3.08	0.30
Sodium carbonate SRC (%)	Bethlehem	79.04	63.63	99.32	7.31	1.02
	Clarens	86.78	77.57	99.61	5.81	0.82
	Combined	82.87	63.63	99.61	7.64	0.76
Sodium bicarbonate SRC (%)	Bethlehem	71.80	61.31	104.81	10.63	1.49
	Clarens	68.33	61.26	92.99	7.01	0.98
	Combined	70.07	61.26	104.81	9.13	0.90
Sucrose SRC (%)	Bethlehem	89.31	62.03	103.54	9.99	1.40
	Clarens	91.56	60.53	102.42	10.84	1.52
	Combined	90.43	60.53	103.54	10.43	1.03
Lactic acid SIG (%)	Bethlehem	4.73	4.00	5.36	0.33	0.05
	Clarens	4.31	3.57	5.23	0.39	0.05
	Combined	4.52	3.57	5.36	0.42	0.04

SRC=solvent retention capacity, SIG=swelling index of glutenin, MEAN=mean values, MIN=minimum values, MAX=maximum values, SD=standard deviation, SE=standard error

Table 3.3 Mean values, range and standard error for solvent retention capacity and swelling index of glutenin characteristics for 22 wheat cultivars evaluated in the irrigated summer rainfall region

Characteristic	Environment	MEAN	MIN	MAX	SD	SE
Lactic acid SRC (%)	Upington	106.05	91.14	129.91	9.96	1.25
	Vaalharts	109.38	93.75	132.84	7.78	0.97
	Combined	107.73	91.14	132.84	9.05	0.80
Distilled water SRC (%)	Upington	64.20	55.99	71.95	3.30	0.41
	Vaalharts	63.29	57.81	69.00	2.52	0.31
	Combined	63.75	55.99	71.95	2.96	0.26
Sodium carbonate SRC (%)	Upington	74.57	63.13	82.11	4.81	0.60
	Vaalharts	79.08	69.09	88.90	4.11	0.51
	Combined	76.84	63.13	88.90	5.00	0.44
Sodium bicarbonate SRC (%)	Upington	63.59	57.08	73.57	3.56	0.44
	Vaalharts	62.61	56.83	67.87	2.50	0.31
	Combined	63.10	56.83	73.57	3.10	0.27
Sucrose SRC (%)	Upington	89.54	80.31	102.24	4.10	0.50
	Vaalharts	89.75	79.49	97.81	3.70	0.46
	Combined	89.64	79.49	102.24	3.89	0.34
Lactic acid SIG (%)	Upington	3.78	3.27	4.69	0.30	0.04
	Vaalharts	4.16	3.52	4.99	0.34	0.04
	Combined	3.97	3.27	4.99	0.37	0.03

SRC=solvent retention capacity, SIG=swelling index of glutenin, MEAN=mean values, MIN=minimum values, MAX=maximum values, SD=standard deviation, SE=standard error

Table 3.4 Mean values, range and standard error for solvent retention capacity and swelling index of glutenin characteristics for nine wheat cultivars evaluated in the winter rainfall region

Characteristic	Environment	MEAN	MIN	MAX	SD	SE
Lactic acid SRC (%)	Moorreesburg	129.38	120.66	140.58	5.10	0.98
	Riversdal	116.02	106.40	126.08	6.42	1.24
	Combined	122.70	106.40	140.58	8.86	1.21
Distilled water SRC (%)	Moorreesburg	65.43	61.82	69.72	2.05	0.39
	Riversdal	66.11	59.90	70.80	2.70	0.52
	Combined	65.77	59.90	70.80	2.40	0.33
Sodium carbonate SRC (%)	Moorreesburg	78.21	71.25	82.97	3.26	0.63
	Riversdal	82.67	75.04	91.03	4.84	0.93
	Combined	80.44	71.25	91.03	4.67	0.64
Sodium bicarbonate SRC (%)	Moorreesburg	64.34	58.66	69.55	2.40	0.46
	Riversdal	70.65	59.93	98.00	12.98	2.50
	Combined	67.50	58.66	98.00	9.78	1.33
Sucrose SRC (%)	Moorreesburg	93.39	89.20	99.13	2.92	0.56
	Riversdal	85.68	65.14	94.15	9.20	1.77
	Combined	89.53	65.14	99.13	7.80	1.06
Lactic acid SIG (%)	Moorreesburg	4.54	4.10	4.93	0.23	0.04
	Riversdal	4.17	3.23	4.86	0.37	0.07
	Combined	4.35	3.23	4.93	0.36	0.05

SRC=solvent retention capacity, SIG=swelling index of glutenin, MEAN=mean values, MIN=minimum values, MAX=maximum values, SD=standard deviation, SE=standard error

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

Hectolitre mass means for the dryland SRR (Table 3.5) were within the range to qualify for Grade 1 bread wheat (77.00 kg hl^{-1}) (Government Gazette, 2016). The mean HLM for this region was 77.64 kg hl^{-1} with a range of 68.50 kg hl^{-1} and 82.80 kg hl^{-1}, as expected in dryland low yielding environments. Clarens had a higher grain yield and lower HLM compared to Bethlehem, however stripe rust (*Puccinia striiformis* f.sp.*tritici*) had to be controlled at Clarens during the season and could have affected kernel plumpness and HLM. All the genotypes planted in the high potential irrigated SSR (Table 3.6) had HLM higher than 77.00 kg hl^{-1} with a mean of 83.32 kg hl^{-1}. Vaalharts had the highest HLM and grain yield. For the combined irrigated SRR, the HLM ranged between 78.60 kg hl^{-1} and 86.40 kg hl^{-1}.

In the WRR (Table 3.7), Moorreesburg had a high and acceptable mean HLM (81.13 kg hl^{-1}) with a range of 77.00 kg hl^{-1} to 84.40 kg hl^{-1}. Riversdal had a narrower HLM range, between 74.10 kg hl^{-1} and 81.70 kg hl^{-1} and a somewhat lower mean of 79.56 kg hl^{-1}.

The mean HLM for the WRR was 80.34 kg hl^{-1}. Flour protein content was highest for the dryland SRR (Table 3.5), whilst the mean BFLY in the dryland SRR (Table 3.5) was also, unexpectedly, the highest between the three regions at 22.09% indicating softer wheat. The mean BFLY for the irrigated SRR was 21.00% (Table 3.6) and the WRR was 20.42% (Table 3.7).

Mean FLY for the dryland SRR (Table 3.5) was 74.65% and lower than FLY (77.70%) obtained in the irrigated SRR (Table 3.6) and WRR (Table 3.7) (75.21%) and correlated with HLM and yields obtained for each of the production regions respectively.

Higher grain yield is generally associated with lower protein content. This was the case for the three regions with the highest FPC for the dryland SRR (Table 3.5) genotypes (13.63%), followed by the WRR (Table 3.7) genotypes

(12.12%) and the lowest FPC (11.90%) for the irrigated SRR (Table 3.6) genotypes.

The FN for the dryland SRR (Table 3.5) ranged between 241 s and 410 s with the highest mean of 348.98 s among the three production regions. The mean FN for the irrigated SRR (Table 3.6) was 346.13 s. In the WRR (Table 3.7), the mean FN for the Riversdal genotypes were 287 s as a result of late rain during the grain filling and maturing stages of the crop. The mean FN for the WRR was thus negatively affected and the lowest amongst the regions, but still acceptable as high quality grain, at 331.37 s.

Table 3.5 Mean values, range and standard error for grain and milling characteristics for 17 wheat cultivars evaluated in the dryland summer rainfall region

Characteristic	Environment	MEAN	MIN	MAX	SD	SE
HLM (kg hl^{-1})	Bethlehem	78.07	72.80	81.90	1.76	0.25
	Clarens	77.21	68.50	82.80	3.74	0.52
	Combined	77.64	68.50	82.80	2.94	0.29
BFLY (%)	Bethlehem	22.20	18.20	26.70	2.19	0.31
	Clarens	21.99	17.60	26.80	2.62	0.37
	Combined	22.09	17.60	26.80	2.41	0.24
FLY (%)	Bethlehem	74.92	72.40	77.60	1.28	0.18
	Clarens	74.38	71.20	77.10	1.54	0.22
	Combined	74.65	71.20	77.60	1.44	0.14
FPC (%)	Bethlehem	14.40	12.60	16.20	0.86	0.13
	Clarens	12.89	10.80	15.40	1.23	0.19
	Combined	13.63	10.80	16.20	1.31	0.14
FN (s)	Bethlehem	331.20	241.00	398.00	38.81	5.44
	Clarens	366.76	314.00	410.00	33.23	4.65
	Combined	348.98	241.00	410.00	40.15	3.98

HLM=hectolitre mass, BFLY=break flour yield, FLY=flour yield, FPC=flour protein content, FN=falling number, MEAN=mean values, MIN=minimum values, MAX=maximum values, SD=standard deviation, SE=standard error

Table 3.6 Mean values, range and standard error for grain and milling characteristics for 22 wheat cultivars evaluated in the irrigated summer rainfall region

Characteristic	Environment	MEAN	MIN	MAX	SD	SE
HLM (kg hl^{-1})	Upington	82.88	79.40	85.20	1.24	0.15
	Vaalharts	83.75	78.60	86.40	1.52	0.19
	Combined	83.32	78.60	86.40	1.45	0.13
BFLY (%)	Upington	21.11	17.90	24.70	1.77	0.22
	Vaalharts	20.90	17.20	25.70	2.09	0.26
	Combined	21.00	17.20	25.70	1.93	0.17
FLY (%)	Upington	77.96	74.00	80.10	1.18	0.15
	Vaalharts	77.45	74.40	80.20	1.19	0.15
	Combined	77.70	74.00	80.20	1.21	0.11
FPC (%)	Upington	11.32	9.60	14.90	1.11	0.14
	Vaalharts	12.52	10.50	15.50	1.15	0.15
	Combined	11.90	9.60	15.50	1.28	0.12
FN (s)	Upington	315.21	254.00	385.00	23.46	2.89
	Vaalharts	377.05	310.00	410.00	38.21	4.70
	Combined	346.13	254.00	410.00	44.28	3.85

HLM=hectolitre mass, BFLY=break flour yield, FLY=flour yield, FPC=flour protein content, FN=falling number, MEAN=mean values, MIN=minimum values, MAX=maximum values, SD=standard deviation, SE=standard error

Table 3.7 Mean values, range and standard error for grain and milling characteristics for nine wheat cultivars evaluated in the winter rainfall region

Characteristic	Environment	MEAN	MIN	MAX	SD	SE
HLM (kg hl^{-1})	Moorreesburg	81.13	77.00	84.80	2.10	0.40
	Riversdal	79.56	74.10	81.70	1.90	0.37
	Combined	80.34	74.10	84.80	2.14	0.29
BFLY (%)	Moorreesburg	20.04	16.80	23.40	1.57	0.30
	Riversdal	20.80	17.70	23.00	1.59	0.31
	Combined	20.42	16.80	23.40	1.61	0.22
FLY (%)	Moorreesburg	74.75	72.50	76.40	1.12	0.21
	Riversdal	75.68	70.70	79.30	1.61	0.31
	Combined	75.21	70.70	79.30	1.45	0.20
FPC (%)	Moorreesburg	13.01	11.30	16.80	1.06	0.20
	Riversdal	11.23	9.80	14.60	1.20	0.23
	Combined	12.12	9.80	16.80	1.44	0.20
FN (s)	Moorreesburg	375.74	336.00	410.00	28.34	5.45
	Riversdal	287.00	205.00	370.00	47.95	9.23
	Combined	331.37	205.00	410.00	59.39	8.08

HLM=hectolitre mass, BFLY=break flour yield, FLY=flour yield, FPC=flour protein content, FN=falling number, MEAN=mean values, MIN=minimum values, MAX=maximum values, SD=standard deviation, SE=standard error

3.3.2 Analysis of variance

3.3.2.1 Combined ANOVA for SRC and SIG parameters

The variance component contribution for the 17 cultivars in the dryland SRR is summarised in Table 3.8, and the genotype x environment means for the individual dryland localities in Tables 3.9 - 3.11. Variance component contribution for the 22 cultivars in the irrigated SRR is summarised in Table 3.12, and the genotype x environment means for the individual irrigated SRR localities in Tables 3.13 – 3.15. The WRR variance component contribution for the nine cultivars is summarised in Table 3.16 and the genotype x environment means for the individual WRR localities in Table 3.17.

The combined ANOVA for the dryland SRR (Table 3.8), irrigated SRR (Table 3.12) and WRR (Table 3.16) indicated highly significant differences among cultivars and their reaction to the environment. Significant cultivar x environment interactions indicated that cultivars will perform differently based on their reaction with a specific environment. Cultivar variance contribution was much higher than environmental variance contribution at all three production regions, except for lactic acid SRC in the WRR with a highly significant ($p \leq 0.001$) cultivar contribution of 16.46% and a much higher environmental contribution of 57.92% ($p \leq 0.001$) to total variation.

Table 3.8 Combined analysis of variance for solvent retention capacity and swelling index of glutenin characteristics for 17 wheat cultivars in the dryland summer rainfall region

		Mean squares					
SOURCE	**df**	**LA_SRC**	**DW_SRC**	**SC_SRC**	**SBC_SRC**	**S_SRC**	**LA_SIG**
Environment	1	2433.05***	9.05**	1509.74***	307.15***	129.45***	4.60***
Rep (Environment)	4	60.11**	4.40**	24.06***	10.08***	17.38***	0.12**
Cultivar	16	586.20***	44.09***	121.63***	199.99***	319.98***	0.51***
Cult x Env	16	61.43***	9.53***	127.86***	296.52***	344.76***	0.17***
Error	64	14.24	1.14	3.79	1.88	2.36	0.03
CV (%)		3.01	1.59	1.70	1.96	2.35	3.72
R^2		0.94	0.92	0.99	0.99	0.96	0.90
Variance component contribution (% of SS)							
Environment	1	17.48	0.94	25.87	3.65	1.18	25.80
Rep (Environment)	4	1.73	1.84	1.65	0.48	0.63	2.76
Cultivar	16	67.39	73.66	33.34	38.04	46.60	45.61
Cult x Env	16	7.06	15.92	35.05	56.40	50.21	15.66

* p≤0.05, ** p≤0.01, *** p≤0.001, ns=non-significant, df=degrees of freedom, LA_SRC=lactic acid SRC, DW_SRC=distilled water SRC, SC_SRC=sodium carbonate SRC, SBC_SRC=sodium bicarbonate SRC, S_SRC=sucrose SRC, LA_SIG =lactic acid SIG, Cult x Env=cultivar x environment interaction, CV=coefficient of variance, R^2= coefficient of determination, SS=sum of squares

Analysing the two WRR localities separately shows a highly significant cultivar effect (p≤0.001) for lactic acid SRC at Riversdal (Appendix Table A1.4) and a non-significant cultivar and non-significant environment effect at Moorreesburg (Appendix Table A1.5). The high genotype effect indicates that SRC and SIG parameters could be successfully used for quality selection and breeding regardless the environmental impact across the three production regions.

3.3.2.1.1 Lactic acid solvent retention capacity

The largest variation was attributed to cultivars in both the summer rainfall regions with a total contribution share of 67.39% (p≤0.001) in the dryland SRR (Table 3.8) and 54.71% (p≤0.001) in the irrigated SRR (Table 3.12). In the WRR (Table 3.16), cultivar effect was highly significant (p≤0.001), but it contributed only 16.46% of total variation when compared to the environment contribution of 57.92%.

A highly significant cultivar effect (p≤0.001) for lactic acid SRC (Appendix Table A1.4) and FPC (Appendix Table A1.6) at Riversdal was obtained and a non-significant cultivar and environment effect at Moorreesburg for lactic acid SRC (Appendix Table A1.5) and FPC (Appendix Table A1.7). The cultivar x environment contribution was highest for the irrigated SRR at 26.61% (p≤0.001) (Table 3.12). The cultivar x environment contribution was smaller in the dryland SRR (Table 3.8) at 7.06% (p≤0.001) and in the WRR 10.18% (p≤0.01) (Table 3.16).

In the dryland SRR (Table 3.9), lactic acid SRC values ranged between 108.74% (SST 316) and 144.80% (Koonap) across localities. The environments and cultivars differed significantly. In the irrigation SRR (Table 3.13), cultivar and environments differed significantly. The lactic acid SRC values across the localities ranged between 103.67% (PAN 3489) and 121.41% (SST 843). The lactic acid SRC value for SST 843 was significantly higher than for the rest of the cultivars. Cultivars in the WRR (Table 3.17) also differed significantly with mean lactic acid SRC values across the localities of 119.61% (SST 087) and 128.98% (SST 047). The lactic acid SRC value of SST 047 was significantly higher than for the rest of the cultivars and differences among environments were significant.

3.3.2.1.2 Distilled water solvent retention capacity

Cultivar contribution to the variation was highly significant (p≤0.001) and it contributed the most to the total variation of distilled water SRC across all three production regions. The cultivar variance contribution was highest in the dryland SRR (Table 3.8) at 73.66% (p≤0.001). Cultivar x environment interaction contribution to variation was the highest for the irrigated SRR (Table 3.12) at 20.75% (p≤0.001). Environmental differences were significant with overall low contributions to the total variance.

In the dryland SRR (Table 3.9), distilled water SRC environmental means ranged between 67.02% (Bethlehem) and 67.62% (Clarens) with a significant difference between the environments.

Cultivar average differences were significant with Koonap distilled water SRC value of 72.82% significantly higher than that of the rest of the cultivars. Environmental as well as cultivar differences were significant in the irrigated SRR (Table 3.13). The distilled water SRC means for the cultivars ranged between 68.69% (SST 822) and 59.38% (SST 835) across localities.

In the WRR (Table 3.17), environmental differences and cultivar differences were significant. Cultivar means across environments ranged between 62.79% (SST 056) and 69.11% (Tankwa). The cultivar mean for Tankwa was significantly higher than the rest of the cultivars.

Table 3.9 Genotype and environmental means for lactic acid and distilled water solvent retention capacity in the dryland summer rainfall region

	Lactic acid SRC (%)				Cult		Distilled water SRC (%)				Cult	
Cultivar	**Bhm**		**Cla**		**Means**		**Bhm**		**Cla**		**Means**	
Elands	134.57	**bcd**	128.35	**bc**	131.45	**c**	67.83	**cdef**	68.12	**defg**	67.98	**cde**
Gariep	135.99	**abcd**	128.55	**bc**	132.28	**bc**	60.98	**j**	65.76	**hijk**	63.37	**i**
Koonap	142.60	**a**	147.00	**a**	144.80	**a**	70.35	**ab**	75.30	**a**	72.82	**a**
Matlabas	139.61	**abc**	132.13	**b**	135.87	**b**	66.72	**efg**	71.47	**b**	69.09	**c**
PAN 3118	125.47	**fg**	118.31	**fg**	121.88	**de**	64.82	**hi**	66.47	**ghij**	65.64	**h**
PAN 3120	120.18	**gh**	117.84	**fg**	119.01	**ef**	69.22	**abc**	68.02	**defg**	68.62	**cd**
PAN 3161	136.32	**abcd**	124.52	**cde**	131.60	**bc**	68.79	**bcd**	67.06	**fghi**	67.93	**cde**
PAN 3195	129.81	**def**	121.53	**def**	125.67	**d**	61.68	**j**	61.60	**l**	61.64	**j**
PAN 3368	141.44	**ab**	127.20	**bcd**	134.32	**bc**	63.57	**i**	64.19	**k**	63.88	**i**
PAN 3379	139.24	**abc**	121.72	**def**	130.48	**c**	69.49	**abc**	68.68	**cdef**	69.09	**c**
Senqu	137.27	**abc**	128.69	**bc**	132.98	**bc**	68.99	**bcd**	65.37	**ijk**	67.18	**efg**
SST 316	111.59	**i**	105.89	**h**	108.74	**h**	70.97	**a**	70.29	**bc**	70.63	**b**
SST 317	126.23	**fg**	104.51	**h**	115.37	**fg**	68.00	**cdef**	65.29	**jk**	66.64	**fgh**
SST 347	127.39	**ef**	120.37	**ef**	123.88	**d**	65.82	**gh**	66.16	**hij**	65.99	**gh**
SST 356	115.09	**ghi**	104.11	**h**	109.60	**h**	68.50	**cde**	69.42	**cd**	68.96	**c**
SST 387	123.03	**fg**	105.50	**h**	114.27	**g**	66.24	**fgh**	69.01	**cde**	67.63	**def**
SST 398	133.54	**cde**	115.70	**g**	122.84	**de**	67.39	**defg**	67.28	**efgh**	67.33	**ef**
Env Mean	130.49	**a**	120.624	**b**	125.59		67.02	**b**	67.62	**a**	67.32	
LSD Cult	6.89		5.82		4.41		1.78		1.78		1.23	
LSD Env	1.51						0.42					

Means followed by the same letter, did not differ significantly at p=0.05. Bhm=Bethlehem, Cla=Clarens, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

3.3.2.1.3 Sodium carbonate solvent retention capacity

The combined ANOVA for sodium carbonate SRC showed highly significant (p≤0.001) differences for cultivars and average values were 33.34%, 39.63% and 58.34% for the dryland SRR (Table 3.8), irrigated SRR (Table 3.12) and WRR (Table 3.16), respectively. Environmental effect on sodium carbonate SRC was the highest among all the SRC parameters and ranged between 16.93% (p≤0.001) for the irrigated SRR and 25.87% (p≤0.001) for the dryland SRR. Cultivar x environment interaction was highly significant (p≤0.001) across all the regions with the lowest contribution to variation of 9.69% in the WRR.

In the dryland SRR (Table 3.10), sodium carbonate SRC cultivar differences were significant. Differences between environments were also significant. In the irrigated SRR (Table 3.14) environment means were 79.08% at Upington and 74.57% at Vaalharts with significant differences. Cultivar means differed significantly across environments. In the WRR (Table 3.17) differences between cultivars and environments were significant. Cultivar means across environments ranged between 85.62% (SST 88) and 74.82% (SST 056).

3.3.2.1.4 Sodium bicarbonate solvent retention capacity

Cultivar differences were all highly significant (p≤0.001) across the three production regions. Total contribution of cultivars to variation was 38.04%, 69.38% and 45.21% for the dryland SRR (Table 3.8), irrigated SRR (Table 3.12) and WRR (Table 3.16), respectively. The environment contribution to the total variation ranged between 2.23% (p≤0.001) for the irrigated SRR and 10.61% (p≤0.001) for the WRR. The cultivar x environment interaction contribution to the total variation was very high for sodium bicarbonate SRC, especially in the dryland SRR at 56.40% (p≤0.001) and the WRR at 41.26% (p≤0.001).

Cultivar means differences across localities were significant for sodium bicarbonate SRC in the dryland SRR (Table 3.10). SST 356 had the highest sodium bicarbonate SRC value (84.53%) across localities and PAN 3368 the lowest (63.50%). Differences between localities were significant.

In the irrigated SRR (Table 3.14), environment differences and cultivar differences were significant. Cultivar contribution to total variation across environments ranged between 67.52% (PAN 3489) and 59.21% (SST 835). In the WRR (Table 3.17), both environment and cultivar differences were significant. Cultivar means across environments ranged between 80.39% (Tankwa) and 61.65% (PAN 3471).

3.3.2.1.5 Sucrose solvent retention capacity

The three production regions showed highly significant ($p \leq 0.001$) cultivar effects for this characteristic. Cultivar contribution of to total variation was 46.60%, 73.63% and 37.41% for the dryland SRR (Table 3.8), irrigated SRR (Table 3.12) and WRR (Table 3.16), respectively. The environment effect was non-significant in the irrigated SRR and highly significant ($p \leq 0.001$) but with low contribution to variation at the dryland SRR (1.18%) and high contribution to the total variation at the WRR (24.87%).

In the dryland SRR (Table 3.11) cultivar means across environments ranged between 99.60% (PAN 3379) and 73.46% (PAN 3195). The sucrose SRC value obtained by PAN 3379 was significantly higher than the rest of the cultivars. In the irrigated SRR (Table 3.15), differences among environments were not significant. Cultivar differences were significant and ranged between 97.78% (SST 843) and 83.47% (Krokodil) across environments. The sucrose SRC value of SST 843 was significantly higher than for the rest of the cultivars. In the WRR (Table 3.17), differences between environments and cultivars were significant. Cultivar means across localities ranged between 96.07% (SST 047) and 88.32% (SST 056).

3.3.2.1.6 Lactic acid swelling index of glutenin

Cultivar differences were all highly significant ($p \leq 0.001$) across the three production regions. Cultivar contribution to total variation was 45.61%, 46.75% and 33.25% for the dryland SRR (Table 3.8), irrigated SRR (Table 3.12) and WRR (Table 3.16), respectively.

The environmental contribution to the variation was highly significant ($p \leq 0.001$) with similar contribution across the three production regions of 25.80%, 25.71% and 27.57% for the dryland SRR, irrigated SRR and WRR, respectively. The cultivar x environment interaction was lower than for the SRC parameters and was 15.66% ($p \leq 0.001$), 13.30% ($p \leq 0.001$) and 12.78% ($p \leq 0.05$) for the dryland SRR, irrigated SR and WRR, respectively.

Cultivar as well as environment differences were significant in the dryland SRR (Table 3.11). Cultivar means across localities ranged between 5.01% (Matlabas) and 3.95% (SST 316). In the irrigated SRR (Table 3.15) SST 843 had the highest lactic acid SIG value across both localities with a significantly higher cultivar mean value compared to the other cultivars of 4.79% across the environments. The minimum lactic acid SIG value obtained was for PAN 3471 at 3.54%. Environmental differences were significant in the WRR (Table 3.17). Cultivar differences were also significant and the cultivar means across environments ranged between 3.99% (PAN 3471) and 4.64% (Tankwa). The cultivar performance regarding highest lactic acid SIG values obtained corresponded with cultivar performance for highest lactic acid SRC values obtained in both the SRR and at Moorreesburg in the WRR.

Table 3.10 Genotype and environmental means for sodium carbonate and sodium bicarbonate solvent retention capacity in the dryland summer rainfall region

	Sodium carbonate SRC (%)				Cult		Sodium bicarbonate SRC (%)				Cult	
Cultivar	**Bhm**		**Cla**		**Means**		**Bhm**		**Cla**		**Means**	
Elands	77.50	**fg**	81.90	**de**	79.70	**de**	66.28	**def**	66.17	**efg**	66.23	**fg**
Gariep	82.76	**c**	80.72	**e**	81.74	**d**	77.03	**c**	64.77	**fghi**	70.90	**d**
Koonap	98.11	**a**	85.71	**cd**	91.91	**a**	76.95	**c**	69.58	**cd**	73.27	**c**
Matlabas	82.54	**cd**	87.26	**bc**	84.42	**c**	66.35	**def**	65.72	**fgh**	66.04	**fg**
PAN 3118	79.57	**ef**	90.13	**b**	84.85	**c**	64.61	**f**	66.01	**efg**	65.31	**g**
PAN 3120	80.20	**de**	88.07	**bc**	84.14	**c**	67.23	**de**	68.41	**cde**	67.82	**e**
PAN 3161	79.84	**ef**	95.29	**a**	87.57	**b**	66.24	**def**	90.59	**a**	78.42	**b**
PAN 3195	72.15	**i**	87.80	**bc**	79.98	**de**	62.23	**g**	80.71	**b**	71.47	**d**
PAN 3368	76.93	**gh**	79.60	**e**	78.27	**e**	64.33	**fg**	62.67	**i**	63.50	**h**
PAN 3379	83.34	**bc**	86.95	**bc**	85.15	**c**	68.30	**d**	66.55	**efg**	67.43	**ef**
Senqu	80.06	**e**	79.74	**e**	79.90	**de**	68.28	**d**	66.47	**efg**	67.37	**ef**
SST 316	85.61	**b**	95.73	**a**	90.67	**a**	74.97	**c**	69.67	**c**	72.32	**cd**
SST 317	74.81	**h**	85.17	**cd**	79.99	**de**	67.79	**de**	63.51	**hi**	65.65	**g**
SST 347	66.21	**j**	82.14	**de**	74.17	**f**	93.87	**b**	62.96	**i**	78.42	**b**
SST 356	66.42	**j**	96.46	**a**	81.44	**d**	101.90	**a**	67.16	**def**	84.53	**a**
SST 387	78.95	**efg**	90.36	**b**	84.66	**c**	66.09	**ef**	64.30	**gih**	65.20	**g**
SST 398	78.77	**efg**	82.35	**de**	80.56	**d**	68.23	**d**	66.42	**efg**	67.33	**ef**
Env	79.05		86.78		82.89		71.81		68.33		70.07	
Mean	**b**		**a**				**a**		**b**			
LSD Cult	2.47		3.94		2.26		2.10		2.45		1.58	
LSD Env	0.77						0.54					

Means followed by the same letter, did not differ significantly at p=0.05. Bhm=Bethlehem, Cla=Clarens Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 3.11 Genotype and environmental means for sucrose solvent retention capacity and lactic acid swelling index of glutenin in the dryland summer rainfall region

	Sucrose SRC (%)				Cult		Lactic acid SIG (%)				Cult	
Cultivar	**Bhm**		**Cla**		**Means**		**Bhm**		**Cla**		**Means**	
Elands	92.82	**cde**	93.44	**e**	93.13	**e**	4.54	**efg**	4.52	**bc**	4.53	**def**
Gariep	62.49	**j**	94.67	**de**	78.58	**i**	4.48	**fgh**	4.35	**bcd**	4.41	**efgh**
Koonap	70.47	**i**	96.67	**bcd**	83.57	**h**	4.94	**bcd**	4.98	**a**	4.96	**a**
Matlabas	95.66	**bc**	95.64	**cde**	95.65	**bc**	5.06	**abc**	4.95	**a**	5.01	**a**
PAN 3118	92.07	**de**	95.47	**cde**	93.77	**de**	4.64	**ef**	4.36	**bcd**	4.50	**defg**
PAN 3120	93.75	**bcde**	96.73	**bcd**	95.24	**bcd**	4.51	**fg**	4.28	**cd**	4.39	**fgh**
PAN 3161	94.49	**bcd**	64.73	**g**	79.61	**i**	4.68	**def**	4.37	**bcd**	4.53	**def**
PAN 3195	85.29	**g**	61.63	**h**	73.46	**j**	5.12	**ab**	4.35	**bcd**	4.74	**bc**
PAN 3368	91.90	**de**	89.67	**f**	90.79	**f**	5.25	**a**	4.44	**bc**	4.85	**ab**
PAN 3379	102.19	**a**	97.00	**abc**	99.60	**a**	5.07	**ab**	4.11	**de**	4.59	**cde**
Senqu	95.88	**b**	90.90	**f**	93.39	**e**	4.42	**fgh**	4.39	**bcd**	4.40	**efgh**
SST 316	95.73	**b**	96.35	**bcd**	96.04	**b**	4.24	**h**	3.66	**f**	3.95	**j**
SST 317	93.22	**bcde**	95.55	**cde**	94.39	**bcde**	4.31	**gh**	3.84	**ef**	4.08	**ij**
SST 347	78.10	**h**	96.90	**bc**	87.50	**g**	5.08	**ab**	4.37	**bcd**	4.73	**bc**
SST 356	88.82	**f**	99.20	**a**	94.01	**cde**	4.55	**efg**	3.90	**ef**	4.22	**hi**
SST 387	91.20	**ef**	98.37	**ab**	94.79	**bcde**	4.80	**cde**	3.82	**ef**	4.31	**gh**
SST 398	94.10	**bcd**	93.56	**e**	93.83	**de**	4.78	**de**	4.58	**b**	4.68	**bcd**
Env Mean	89.31 **b**		91.56 **a**		90.43		4.73 **a**		4.31 **b**		4.52	
LSD Cult	2.87		2.20		1.77		0.27		0.29		0.19	
LSD Env	0.61						0.07					

Means followed by the same letter, did not differ significantly at p=0.05. Bhm=Bethlehem, Cla=Clarens, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 3.12 Combined analysis of variance for solvent retention capacity and swelling index of glutenin characteristics for 22 wheat cultivars in the irrigated summer rainfall region

		Mean squares					
SOURCE	**df**	**LA_SRC**	**DW_SRC**	**SC_SRC**	**SBC_SRC**	**S_SRC**	**LA_SIG**
Environment	1	351.15***	27.32***	131.64***	17.53***	1.46ns	4.66***
Rep (Environment)	4	25.65ns	10.30***	1.19ns	4.52**	20.25***	0.08*
Cultivar	21	268.71***	34.31***	14.68***	25.95***	69.53***	0.40***
Cult x Env	21	130.68***	11.32***	11.91***	5.76***	10.07***	0.11***
Error	84	18.65	1.42	1.00	1.00	2.73	0.03
CV (%)		4.01	1.87	1.32	1.60	1.84	4.14
R^2		0.86	0.90	0.89	0.89	0.88	0.88
		Variance component contribution (% of SS)					
Environment	1	3.40	2.38	16.93	2.23	0.07	25.71
Rep (Environment)	4	0.99	3.60	0.61	2.30	4.09	1.87
Cultivar	21	54.71	62.8	39.63	69.38	73.63	46.75
Cult x Env	21	26.61	20.75	32.16	15.39	10.66	13.30

* p≤0.05, ** p≤0.01, *** p≤0.001, ns=non-significant, df=degrees of freedom, LA_SRC=lactic acid SRC, DW_SRC=distilled water SRC, SC_SRC=sodium carbonate SRC, SBC_SRC=sodium bicarbonate SRC, S_SRC=sucrose SRC, LA_SIG =lactic acid SIG, Cult x Env=cultivar x environment interaction, CV=coefficient of variance, R^2= coefficient of determination, SS=sum of squares

Table 3.13 Genotype and environmental means for lactic acid and distilled water solvent retention capacity in the irrigated summer rainfall region

	Lactic acid SRC (%)				Cult		Distilled water SRC (%)				Cult	
Cultivar	**Up**		**Vh**		**Means**		**Up**		**Vh**		**Means**	
Buffels	121.50	**ab**	108.10	**efgh**	114.80	**bc**	64.42	**cdef**	62.84	**ghij**	63.63	**fg**
Duzi	119.85	**abc**	110.34	**def**	115.10	**bc**	61.87	**hijk**	63.17	**ghij**	62.52	**ghi**
Krokodil	106.22	**efg**	109.98	**defg**	108.10	**defg**	58.64	**l**	63.52	**ghi**	61.08	**jk**
PAN 3471	103.44	**g**	98.80	**ijk**	101.12	**hi**	63.55	**efgh**	63.85	**fgh**	63.70	**fg**
PAN 3478	109.75	**defg**	99.05	**ijk**	105.47	**efgh**	66.30	**ab**	66.08	**cde**	66.19	**cd**
PAN 3489	110.93	**defg**	96.41	**k**	103.67	**fghi**	66.26	**abc**	67.98	**abc**	67.12	**bc**
PAN 3497	94.52	**h**	104.19	**ghi**	100.32	**i**	60.69	**jk**	64.48	**efg**	62.59	**ghi**
Sabie	111.95	**cdef**	120.06	**bc**	116.00	**bc**	61.97	**hijk**	67.40	**bcd**	64.68	**ef**
SST 806	104.88	**fg**	98.57	**ijk**	102.35	**hi**	65.27	**bcde**	64.00	**fgh**	64.64	**ef**
SST 822	108.00	**efg**	110.64	**def**	109.32	**de**	68.08	**a**	69.30	**ab**	68.69	**a**
SST 835	103.14	**g**	98.03	**jk**	100.59	**hi**	60.26	**kl**	58.50	**k**	59.38	**l**
SST 843	114.61	**bcde**	128.20	**a**	121.41	**a**	65.78	**bcd**	65.66	**def**	65.72	**de**
SST 866	104.71	**fg**	97.45	**jk**	101.08	**hi**	63.51	**efgh**	62.06	**hij**	62.79	**gh**
SST 867	109.41	**defg**	93.74	**k**	101.57	**hi**	62.96	**fghi**	62.78	**ghij**	62.87	**gh**
SST 875	104.83	**fg**	105.02	**fgh**	104.92	**efghi**	62.24	**hij**	66.38	**cde**	64.31	**f**
SST 876	103.39	**g**	102.53	**hij**	103.04	**ghi**	61.19	**ijk**	66.14	**cde**	63.67	**fg**
SST 877	109.87	**defg**	94.38	**k**	102.12	**hi**	62.97	**fghi**	57.25	**k**	60.11	**kl**
SST 884	106.49	**efg**	95.43	**k**	100.96	**hi**	62.22	**hij**	61.63	**ij**	61.92	**hij**
SST 895	102.95	**gh**	113.80	**de**	108.38	**def**	66.31	**ab**	69.91	**a**	68.11	**ab**
Tamboti	116.62	**abcd**	121.14	**b**	118.88	**ab**	62.55	**ghi**	64.81	**efg**	63.68	**fg**
Timbavati	123.73	**a**	106.83	**fgh**	115.28	**bc**	61.25	**ijk**	61.29	**j**	61.27	**ijk**
Umlazi	111.15	**defg**	114.44	**cd**	113.13	**cd**	64.11	**defg**	63.38	**ghi**	63.74	**fg**
Env Mean	109.38 **a**		106.05 **b**		107.62		63.29 **b**		64.20 **a**		63.75	
LSD Cult	8.47		5.90		5.07		1.85		2.07		1.37	
LSD Env	1.53						0.41					

Means followed by the same letter, did not differ significantly at p=0.05. Up=Upington, Vh=Vaalharts, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 3.14 Genotype and environmental means for sodium carbonate and sodium bicarbonate solvent retention capacity in the irrigated summer rainfall region

	Sodium carbonate SRC (%)				Cult		Sodium bicarbonate SRC (%)				Cult	
Cultivar	**Up**		**Vh**		**Means**		**Up**		**Vh**		**Means**	
Buffels	76.82	**fgh**	72.81	**fg**	74.00	**ghi**	61.72	**gh**	62.74	**fghi**	61.96	**efg**
Duzi	75.09	**h**	73.99	**fg**	74.31	**ghi**	60.12	**ijk**	61.94	**ghi**	60.55	**hi**
Krokodil	70.05	**i**	75.53	**defg**	73.91	**ghi**	57.92	**l**	64.73	**def**	59.54	**j**
PAN 3471	78.72	**defgh**	78.50	**abc**	78.56	**cd**	63.75	**de**	66.04	**bcd**	64.29	**d**
PAN 3478	83.17	**abc**	66.08	**jk**	72.69	**hi**	63.57	**ef**	67.75	**bc**	64.56	**d**
PAN 3489	85.36	**a**	66.59	**jk**	72.15	**i**	66.49	**ab**	70.81	**a**	67.52	**a**
PAN 3497	81.86	**abcd**	68.88	**ij**	72.73	**hi**	61.71	**gh**	63.10	**efgh**	62.04	**efg**
Sabie	81.58	**abcd**	72.00	**gh**	74.84	**fgh**	63.86	**cde**	65.03	**cdef**	64.14	**d**
SST 806	77.74	**defgh**	64.79	**k**	68.63	**j**	62.85	**efg**	60.99	**hijk**	62.41	**efg**
SST 822	80.10	**cdef**	69.63	**hi**	72.74	**hi**	65.30	**bc**	65.61	**cde**	65.37	**cd**
SST 835	75.65	**gh**	77.72	**bcd**	77.11	**def**	59.66	**k**	57.77	**l**	59.21	**j**
SST 843	83.42	**abc**	80.75	**ab**	81.35	**a**	65.25	**bcd**	63.89	**defg**	64.92	**cd**
SST 866	79.85	**cdefg**	74.39	**fg**	76.01	**efg**	61.57	**ghi**	61.26	**ghij**	61.50	**fgh**
SST 867	77.12	**efgh**	72.65	**fg**	73.98	**ghi**	60.43	**ghijk**	60.33	**ijkl**	60.41	**hij**
SST 875	78.66	**defgh**	78.70	**abc**	78.69	**bcd**	61.98	**g**	65.52	**cde**	62.82	**e**
SST 876	78.70	**defgh**	77.43	**cde**	77.80	**cde**	61.79	**gh**	65.01	**cdef**	62.56	**ef**
SST 877	75.52	**gh**	74.76	**efg**	74.99	**fgh**	62.11	**fg**	58.29	**kl**	61.20	**gh**
SST 884	84.26	**ab**	77.69	**bcd**	79.64	**abc**	66.95	**a**	63.30	**efgh**	66.08	**bc**
SST 895	81.50	**abcde**	80.78	**a**	80.99	**ab**	66.59	**ab**	68.74	**ab**	67.10	**ab**
Tamboti	79.68	**cdefg**	77.98	**abcd**	78.48	**cd**	61.43	**ghij**	63.91	**defg**	62.02	**efg**
Timbavati	76.24	**fgh**	77.85	**bcd**	77.37	**cde**	60.03	**jk**	59.14	**jkl**	59.82	**ij**
Umlazi	78.66	**defgh**	78.51	**abc**	78.56	**cd**	62.33	**fg**	63.10	**efgh**	62.52	**efg**
Env Mean	79.08 **a**		74.57 **b**		75.89		62.61 **b**		63.59 **a**		62.84	
LSD Cult	4.40		2.89		2.38		1.53		2.74		13.17	
LSD Env	0.78						0.47					

Means followed by the same letter, did not differ significantly at p=0.05. Up=Upington, Vh=Vaalharts, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 3.15 Genotype and environmental means for sucrose solvent retention capacity and lactic acid swelling index of glutenin in the irrigated summer rainfall region

	Sucrose SRC				Cult		Lactic acid SIG				Cult	
Cultivar	**Up**		**Vh**		**Means**		**Up**		**Vh**		**Means**	
Buffels	87.98	**ghijk**	84.91	**k**	86.45	**gh**	4.32	**bcd**	3.54	**hij**	3.93	**defgh**
Duzi	86.57	**jk**	85.43	**jk**	86.00	**hi**	4.20	**cd**	3.83	**def**	4.02	**cdef**
Krokodil	80.76	**l**	86.17	**ijk**	83.47	**j**	3.75	**fgh**	3.82	**def**	3.79	**ghij**
PAN 3471	90.08	**defghi**	88.55	**fghi**	89.32	**ef**	3.73	**fgh**	3.35	**j**	3.54	**k**
PAN 3478	88.44	**ghij**	89.04	**defgh**	88.74	**f**	4.00	**defg**	3.57	**hi**	3.79	**hij**
PAN 3489	91.83	**bcde**	91.01	**bcdef**	91.42	**bcd**	3.67	**gh**	3.69	**fgh**	3.68	**ijk**
PAN 3497	89.41	**efghi**	88.32	**ghi**	88.87	**f**	3.61	**h**	3.60	**ghi**	3.60	**jk**
Sabie	93.55	**ab**	92.17	**bc**	92.86	**b**	4.16	**cd**	4.06	**b**	4.11	**bcd**
SST 806	88.70	**fghij**	87.77	**hij**	88.24	**fg**	4.20	**cd**	3.84	**def**	4.02	**cdef**
SST 822	92.34	**abcd**	93.00	**b**	92.67	**bc**	4.12	**cde**	3.93	**bcde**	4.02	**cdef**
SST 835	87.45	**hijk**	90.84	**bcdefg**	89.15	**ef**	4.24	**cd**	3.77	**efg**	4.00	**cdef**
SST 843	95.13	**a**	100.43	**a**	97.78	**a**	4.89	**a**	4.69	**a**	4.79	**a**
SST 866	85.19	**k**	87.06	**hijk**	86.13	**hi**	4.25	**cd**	3.54	**hij**	3.90	**efgh**
SST 867	87.42	**ijk**	81.42	**l**	84.42	**ij**	4.43	**bc**	3.50	**ij**	3.96	**cdefgh**
SST 875	91.39	**bcdef**	90.39	**cdefg**	90.89	**cde**	4.20	**cd**	4.03	**bc**	4.12	**bcd**
SST 876	90.45	**cdefg**	89.36	**defgh**	89.91	**def**	3.82	**efgh**	3.49	**ij**	3.66	**ijk**
SST 877	86.50	**jk**	86.22	**ijk**	86.36	**gh**	4.19	**cd**	3.48	**ij**	3.84	**fhgi**
SST 884	94.19	**ab**	91.24	**bcde**	92.72	**bc**	4.06	**def**	3.90	**bcde**	3.98	**cdefg**
SST 895	93.00	**abc**	93.39	**b**	93.20	**b**	4.14	**cde**	3.99	**bcd**	4.07	**cde**
Tamboti	90.29	**cdefgh**	91.49	**bcd**	90.89	**cde**	4.44	**bc**	3.85	**cdef**	4.15	**bc**
Timbavati	90.05	**defghi**	88.69	**efghi**	89.37	**ef**	4.63	**ab**	3.92	**bcde**	4.28	**b**
Umlazi	93.70	**ab**	92.88	**bc**	93.29	**b**	4.32	**bcd**	3.85	**cdef**	4.09	**cd**
Env Mean	89.75	**a**	89.54	**a**	89.64		4.16	**a**	3.78	**b**	3.97	
LSD Cult	2.85		2.59		1.90		0.34		0.19		0.19	
LSD Env	0.57						0.06					

Means followed by the same letter, did not differ significantly at P=0.05. Up=Upington, Vh=Vaalharts, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 3.16 Combined analysis of variance for solvent retention capacity and swelling index of glutenin characteristics for nine wheat cultivars in the winter rainfall region

		Mean squares					
SOURCE	**df**	**LA_SRC**	**DW_SRC**	**SC_SRC**	**SBC_SRC**	**S_SRC**	**LA_SIG**
Environment	1	2407.34***	6.14*	268.72***	537.58***	801.57***	1.88***
Rep (Environment)	4	40.45*	3.21ns	2.06ns	7.96ns	3.03ns	0.15*
Cultivar	8	85.51***	26.51***	84.21***	285.67***	150.75***	0.28***
Cult x Env	8	52.90**	3.74*	13.99***	261.26***	137.08***	0.11*
Error	32	14.99	1.36	2.88	3.77	3.35	0.04
CV (%)		3.16	1.78	2.11	2.88	2.04	4.47
R^2		0.88	0.86	0.92	0.98	0.97	0.82
Variance component contribution (% of SS)							
Environment	1	57.92	2.02	23.27	10.61	24.87	27.57
Rep (Environment)	4	3.89	4.21ns	0.71	0.63	0.38	8.64
Cultivar	8	16.46	69.62	58.34	45.12	37.41	33.25
Cult x Env	8	10.18	9.82	9.69	41.26	34.02	12.78

* p≤0.05, ** p≤0.01, *** p≤0.001, ns=non-significant, df=degrees of freedom, LA_SRC=lactic acid SRC, DW_SRC=distilled water SRC, SC_SRC=sodium carbonate SRC, SBC_SRC=sodium bicarbonate SRC, S_SRC=sucrose SRC, LA_SIG =lactic acid SIG, Cult x Env=cultivar x environment interaction, CV=coefficient of variance, R^2= coefficient of determination, SS=sum of squares

Table 3.17 Genotype and environmental means for lactic acid, distilled water, sodium carbonate, sodium bicarbonate, sucrose solvent retention capacity and lactic acid swelling index of glutenin in the winter rainfall region

	Lactic acid SRC				Cult		Distilled water SRC				Cult		Sucrose SRC				Cult	
Cultivar	**Mo**		**Ri**		**Means**		**Mo**		**Ri**		**Means**		**Mo**		**Ri**		**Means**	
PAN 3471	125.97	**abcd**	115.04	**cdef**	120.51	**bc**	64.50	**cd**	61.68	**f**	63.09	**ef**	77.35	**B**	76.71	**e**	77.03	**e**
SST 015	132.89	**ab**	109.96	**ef**	121.43	**bc**	65.81	**bc**	66.81	**bcd**	66.31	**bc**	76.60	**B**	80.54	**cd**	78.57	**e**
SST 027	124.00	**d**	119.46	**bc**	121.73	**bc**	67.04	**ab**	67.34	**bc**	67.19	**b**	76.59	**B**	77.72	**de**	77.16	**e**
SST 047	132.21	**ab**	125.74	**a**	128.98	**a**	67.18	**ab**	67.51	**bc**	67.35	**b**	80.95	**a**	83.50	**bc**	82.23	**cd**
SST 056	134.73	**a**	121.86	**ab**	128.30	**a**	62.38	**e**	63.19	**ef**	62.79	**f**	72.08	**c**	77.56	**de**	74.82	**f**
SST 087	129.75	**abcd**	109.46	**f**	119.61	**bc**	63.75	**de**	64.78	**de**	64.27	**de**	81.02	**a**	85.88	**ab**	83.45	**bc**
SST 096	131.81	**abc**	115.50	**cde**	123.66	**b**	64.81	**cd**	65.64	**cd**	65.23	**cd**	77.13	**b**	84.31	**b**	80.72	**d**
SST 88	124.64	**cd**	110.68	**def**	117.66	**c**	64.93	**cd**	68.24	**ab**	66.59	**bc**	82.24	**a**	89.00	**a**	85.62	**a**
Tankwa	128.40	**abcd**	116.50	**bcd**	122.45	**b**	68.49	**a**	69.73	**a**	69.11	**a**	79.94	**a**	88.84	**a**	84.39	**ab**
Env mean	129.38 **a**		116.02 **b**		122.70		65.43 **b**		66.11 **a**		65.77		78.21 **b**		82.67 **a**		80.44	
LSD Cult	7.40		5.92		4.55		1.90		2.14		1.37		2.57		3.27		2.00	
LSD Env	2.15						0.65						0.94					

	Sodium bicarbonate SRC				Cult		Sucrose SRC				Cult		Lactic acid SIG				Cult	
Cultivar	**Mo**		**Ri**		**Means**		**Mo**		**Ri**		**Means**		**Mo**		**Ri**		**Means**	
PAN 3471	62.20	**ab**	61.09	**c**	61.65	**c**	89.98	**d**	86.88	**bc**	88.43	**c**	4.20	**d**	3.78	**d**	3.99	**d**
SST 015	64.83	**ab**	64.37	**b**	64.60	**b**	92.56	**cd**	91.87	**a**	92.22	**b**	4.47	**bc**	3.87	**d**	4.17	**cd**
SST 027	65.43	**ab**	64.33	**b**	64.88	**b**	94.15	**bc**	92.06	**a**	93.11	**b**	4.71	**a**	4.36	**ab**	4.54	**ab**
SST 047	64.41	**ab**	64.76	**b**	64.59	**b**	98.60	**a**	93.54	**a**	96.07	**a**	4.36	**cd**	4.43	**ab**	4.40	**bc**
SST 056	61.88	**b**	61.47	**c**	61.68	**c**	90.14	**d**	86.50	**c**	88.32	**c**	4.82	**a**	4.09	**bcd**	4.46	**ab**
SST 087	66.06	**a**	66.49	**b**	66.28	**b**	95.53	**b**	90.12	**ab**	92.83	**b**	4.47	**bc**	3.92	**cd**	4.20	**cd**
SST 096	65.18	**ab**	65.14	**b**	65.16	**b**	91.70	**cd**	90.97	**a**	91.34	**b**	4.80	**a**	4.34	**abc**	4.57	**ab**
SST 88	63.55	**ab**	92.96	**a**	78.26	**a**	93.79	**bc**	69.02	**d**	81.41	**d**	4.41	**bc**	4.04	**bcd**	4.23	**c**
Tankwa	65.53	**ab**	95.25	**a**	80.39	**a**	94.00	**bc**	70.16	**d**	82.08	**d**	4.62	**ab**	4.65	**a**	4.64	**a**
Env Mean	64.34 **b**		70.65 **a**		67.50		93.39 **a**		85.68 **b**		89.53		4.54 **a**		4.17 **b**		4.35	
LSD Cult	3.97		2.61		2.28		2.75		3.53		2.15		0.21		0.43		0.23	
LSD Env	1.08						1.01						0.11					

Means followed by the same letter, did not differ significantly at p=0.05. Mo=Moorreesburg, Ri=Riversdal, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

3.3.2.2 Combined ANOVA for grain and milling characteristics

The variance component contribution for the 17 cultivars in the dryland SRR is summarised in Table 3.18, and the genotype x environment means for the individual dryland localities in Tables 3.19 – 3.21. Variance component contribution for the 22 cultivars in the irrigated SRR is summarised in Table 3.22, and the genotype x environment means for the individual irrigated SRR localities in Tables 3.23 – 3.25. The WRR variance component contribution for the nine cultivars is summarised in Table 3.26 and the genotype x environment means for the individual WRR localities in Tables 3.27.

The combined ANOVA for the dryland SRR (Table 3.18), irrigated SRR (Table 3.22) and WRR (Table 3.26) indicated highly significant differences among cultivars and their reaction to the environment. Environment effect was significant for all grain and milling characteristics except for BFLY in the WRR (Table 3.26). Significant cultivar x environment interactions were seen. The cultivar effect was significant for all grain and milling characteristics. Cultivar effect made the highest contribution to the total variation across all the localities over the three production regions, except for FPC and FN in the WRR (Table 3.26) and FPC in the dryland SRR (Table 3.18), however, across localities for the respective regions the significant cultivar effect indicated that all the grain and milling characteristics could be used in the breeding programme for quality selection in improvement.

3.3.2.2.1 Hectolitre mass

Cultivars made highly significant ($p \leq 0.001$) contributions to variation for HLM in the dryland SRR (Table 3.18), irrigated SRR (Table 3.22) and the WRR (Table 3.26) regions. Cultivar x environment interaction contributed 24.51% ($p \leq 0.001$) to the total variation in the dryland SRR and was not significant in the irrigated SRR. In the WRR, cultivar x environment interaction contributed 9.92% ($p \leq 0.05$) to the total variation. In the dryland SRR (Table 3.19) the HLM means for the cultivars varied between 74.25 kg hl^{-1} (SST 387) and 80.88 kg hl^{-1} (Koonap).

Differences between Bethlehem and Clarens were significant. In the irrigated SRR (Table 3.23) the mean HLM values were higher than the dryland SRR HLM values, ranging between 82.07 kg hl^{-1} (SST 884) and 84.87 kg hl^{-1} (PAN 3471). Cultivar differences were significant as well as differences between Upington and Vaalharts. Differences between cultivars and environments were significant in the WRR (Table 3.27). PAN 3471 obtained the highest HLM of 82.93 kg hl^{-1} and the lowest HLM was obtained by SST 88 (77.97 kg hl^{-1}). PAN 3471 and SST 047 did not differ significantly.

3.3.2.2.2 Break flour yield

Cultivar made the largest contribution to variation in BFLY ($p \leq 0.001$) across all three production regions; dryland SRR (Table 3.18), irrigated SRR (Table 3.22) and the WRR (Table 3.26). Cultivar contribution towards variation in BFLY was 88.25%, 88.92% and 82.51% for the dryland SRR irrigated SRR and the WRR, respectively. Thus, grain hardness was not a result of environment effect or increased protein content due to low potential in the dryland SRR, but due to genetically fixed characteristics of the genotypes. Environment effect was non-significant in the dryland SRR and contribution towards the variation was 0.30% at $p \leq 0.05$ in the irrigated SRR. The highest environment effect was observed in the WRR at $p \leq 0.001$ and 5.61% variance contribution.

The environments in the dryland SRR (Table 3.19) did not differ significantly. Gariep had the highest BFLY with a mean value of 25.83% across localities, indicating that this genotype had low grain hardness. PAN 3379 had the hardest grain with the lowest BFLY (18.58%).

Most cultivars differed significantly, and nine cultivars expressed a BFLY higher than 22%, indicating low grain hardness. Cultivar mean values for BFLY varied between 24.07% (Timbavati) and 17.90% (SST 895) in the irrigated SRR. Environments differed significantly. Riversdal had the highest BFLY of 20.80% and differed significantly from Moorreesburg (20.04%) in the WRR (Table 3.27). Cultivar means across localities differed significantly and ranged between 19.70% (SST 88) and 22.54% (SST 047).

3.3.2.2.3 Flour yield

Cultivar made the largest contribution to variation for FLY across the three production regions; dryland SRR (Table 3.18), irrigated SRR (Table 3.22) and the WRR (Table 3.26). Cultivar effect was highly significant ($p \leq 0.001$) in the dryland SRR (63.63%), the irrigated SRR (59.51%) and significant ($p \leq 0.05$) in the WRR (35.00%). Environment and its interaction with the cultivars was significant ($p \leq 0.001$) in the dryland and irrigated SRR and environmental contribution to the total variation was lower when compared with the cultivar x environment variance contribution.

The mean FLY in the dryland SRR (Table 3.20) was 74.65% with cultivars differing significantly in the range of 76.72% (PAN 3368) to 73.40% (PAN 3120). Differences between environments were significant. Flour yields were higher for the cultivars planted in the irrigated SRR (Table 3.24) than in the dryland SRR. Cultivar means across localities differed significantly with a minimum FLY of 74.87% obtained by SST 822 and a maximum FLY of 79.72% obtained by PAN 3479.

The Upington and Vaalharts trials differed significantly for this characteristic. In the WRR (Table 3.27), cultivar differences were significant across localities and the mean FLY varied between 73.74% (Tankwa) and 76.45% (SST 027). The WRR localities differed significantly.

3.3.2.2.4 Flour protein content

Cultivar effect was highly significant ($p \leq 0.001$) and contribution towards the total variation was 29.77% in the dryland SRR (Table 3.18), 43.68% in the irrigated SRR (Table 3.22) and 35.59% in the WRR (Table3.26). The environment effect was significant with very high contribution to variation, indicating that the environment affected cultivar FPC expression.

The environmental effect was higher than the cultivar effect in the dryland SRR and in the WRR and FPC expression was least affected in the high yielding irrigation SRR. The cultivar x environment interaction was highest in the dryland SRR (24.86% at p≤0.001), followed by the irrigated SRR (15.41% at p≤0.001) and non-significant in the WRR.

Bethlehem in the dryland SRR (Table 3.20) had the highest FPC of 14.40%. The FPC of the dryland SRR trials was exceptionally high with only PAN 3161 and PAN 3379 with FPC below 12% at Clarens. The FPC mean across localities was 13.65% and cultivar differences were significant. Cultivar performance for FPC ranged between 12.18% (PAN 3379) and 14.55% (PAN 3368) across localities. PAN 3368 did not differ significantly from Koonap, Matlabas, PAN 3118, PAN 3120, Senqu, and SST 398.

In the high potential irrigated SRR trials (Table 3.24) FPC was lower than in the low yield potential localities in the dryland SRR. Mean cultivar FPC for the combined localities was 11.88% and cultivars differed significantly with values ranging from 10.82% (PAN 3479) to 14.80% (SST 843). SST 843 had the highest FPC across localities, and differences between the localities were significant. In the WRR (Table 3.27) mean cultivar values differed significantly for FPC and ranged between 11.37% (SST 056) and 14.15% (SST 047). Moorreesburg had the highest FPC and differences between environments were significant.

3.3.2.2.5 Falling number

Cultivar contributed the most to FN variation across the three production regions, including the dryland SRR (Table 3.18), irrigated SRR (Table 3.22) and the WRR (Table 3.26). Cultivar contribution was significant (p≤0.01) for the dryland localities of the SRR (21.36%) and the WRR (12.47%) and highly significant (p≤0.001) in the irrigated SRR (42.37%). The strong environmental effect on FN was noticeable in the highly significant (p≤0.001) contribution to variation across all the production regions.

The total variation attributed to the environment for the dryland SRR, irrigated SRR and WRR was 19.81%, 40.07% and 56.86% respectively. The cultivar x environment interaction was also significant with contributions to variation of 21.33% ($p \leq 0.01$) in the dryland SRR, 10.44% ($p \leq 0.001$) in the irrigated SRR and 18.59% ($p \leq 0.001$) in the WRR.

FN means in the dryland SRR (Table 3.21) differed significantly. The mean FN across localities was 348.98 s and varied between 324.17 s (Matlabas) and 385.50 s (Koonap). Cultivar differences were significant. Clarens obtained higher FN, and differed significantly from Bethlehem. Cultivar means ranged between 392.48 s (SST 884) and 300.93 s (Krokodil) (Table 3.25).

Upington had higher FN and differed significantly from Vaalharts. In the WRR (Table 3.27) Moorreesburg had higher FN (375.74 s) and differed significantly from Riversdal. Cultivar means across localities differed significantly and ranged from 297.34 s (SST 087) to 363.34 s (SST 027).

Table 3.18 Combined analysis of variance for grain and milling characteristics for 17 wheat cultivars in the dryland summer rainfall region

		Mean squares				
SOURCE	**df**	**HLM**	**BFLY**	**FLY**	**FPC**	**FN**
Environment	1	18.55**	1.12ns	7.41***	47.73***	32260.75***
Rep (Environment)	4	9.64***	1.90**	1.26**	0.46ns	1012.33ns
Cultivar	16	31.09***	32.24***	8.28***	2.60***	2173.81**
Cult x Env	16	13.39***	1.88***	2.77***	2.17***	2170.77**
Error	64	1.65	0.47	0.30	0.31	890.42
CV (%)		1.65	3.10	0.73	4.06	8.55
R^2		0.88	0.95	0.91	0.90	0.65
Variance component contribution (% of SS)						
Environment	1	2.12	0.19	3.56	34.18	19.81
Rep (Environment)	4	4.41	1.30	2.43	1.31	2.49
Cultivar	16	56.90	88.25	63.63	29.77	21.36
Cult x Env	16	24.51	5.14	21.25	24.86	21.33

* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, ns=non-significant, df=degrees of freedom, HLM=hectolitre mass, BFLY=break flour yield, FLY=flour yield, FPC=flour protein content, FN=falling number, Cult x Env=cultivar x environment interaction, CV=coefficient of variance, R^2= coefficient of determination, SS=sum of squares

Table 3.19 Genotype and environmental means of individual localities for hectolitre mass and break flour yield in the dryland summer rainfall region

	HLM (kg hl^{-1})				Cult		BFLY (%)				Cult	
Cultivar	**Bhm**		**Cla**		**Means**		**Bhm**		**Cla**		**Means**	
Elands	78.53	**bcd**	81.20	**ab**	79.87	**a**	24.00	**b**	24.43	**bcd**	24.22	**bc**
Gariep	77.37	**efg**	78.70	**bcd**	78.03	**cd**	25.93	**a**	25.73	**a**	25.83	**a**
Koonap	79.53	**b**	82.23	**a**	80.88	**a**	21.33	**def**	21.57	**g**	21.45	**f**
Matlabas	78.23	**cde**	75.80	**efg**	77.02	**cde**	22.47	**cd**	22.77	**f**	22.62	**e**
PAN 3118	77.03	**fg**	72.17	**hi**	74.60		24.33	**b**	24.73	**abc**	24.53	**b**
PAN 3120	80.77	**a**	75.97	**defg**	78.37	**bc**	21.10	**ef**	23.97	**cde**	22.53	**e**
PAN 3161	76.53	**fg**	76.77	**def**	76.65	**def**	23.50	**bc**	23.47	**def**	23.48	**cd**
PAN 3195	77.63	**def**	71.17	**i**	74.40	**g**	24.37	**b**	25.40	**ab**	24.88	**b**
PAN 3368	78.20	**cde**	80.97	**ab**	79.58	**ab**	24.37	**b**	23.90	**cde**	24.13	**bc**
PAN 3379	78.33	**cde**	74.77	**efgh**	76.55	**ef**	18.67	**h**	18.50	**k**	18.58	**h**
Senqu	78.53	**bcd**	81.47	**ab**	80.00	**a**	23.70	**b**	22.93	**Ef**	23.32	**de**
SST 316	76.77	**fg**	75.60	**efg**	76.18	**ef**	19.70	**gh**	18.17	**K**	18.93	**h**
SST 317	79.17	**bc**	81.10	**ab**	80.13	**a**	19.43	**h**	18.87	**Jk**	19.15	**h**
SST 347	81.80	**a**	79.67	**abc**	80.73	**a**	20.77	**fg**	19.73	**Ij**	20.25	**g**
SST 356	76.30	**g**	74.23	**fgh**	75.27	**fg**	19.40	**h**	18.53	**k**	18.97	**h**
SST 387	74.87	**h**	73.63	**ghi**	74.25	**g**	22.33	**d**	20.23	**hi**	21.28	**f**
SST 398	77.53	**def**	77.20	**cde**	77.37	**cde**	21.97	**de**	20.87	**gh**	21.42	**f**
Env Mean	78.07 **a**		77.21 **b**		77.64		22.20 **a**		21.99 **a**		22.09	
LSD Cult	1.16		2.79		1.48		1.14		1.13		0.79	
LSD Env	0.51						0.27					

Means followed by the same letter, did not differ significantly at p=0.05. Bhm=Bethlehem, Cla=Clarens, HLM=hectolitre mass, BFLY=break flour yield, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 3.20 Genotype and environmental means of individual localities for flour yield and flour protein content in the dryland summer rainfall region

	FLY (%)				Cult		FPC (%)				Cult	
Cultivar	**Bhm**		**Cla**		**Means**		**Bhm**		**Cla**		**Means**	
Elands	74.70	**ef**	75.57	**bc**	75.13	**de**	14.03	**efg**	13.30	**bcde**	13.67	**cde**
Gariep	75.53	**cd**	75.40	**bcd**	75.47	**cd**	13.25	**g**	14.30	**ab**	13.78	**bcde**
Koonap	73.93	**gh**	75.87	**ab**	74.90	**def**	14.40	**def**	14.10	**abc**	14.22	**abcd**
Matlabas	74.60	**fg**	75.33	**bcde**	74.97	**def**	15.53	**abc**	13.05	**cde**	14.54	**a**
PAN 3118	75.93	**bc**	73.70	**fg**	74.82	**ef**	15.13	**abcd**	13.20	**bcde**	14.36	**abc**
PAN 3120	73.17	**i**	73.63	**fgh**	73.40	**h**	14.73	**bcde**	13.80	**abcd**	14.36	**abc**
PAN 3161	76.67	**ab**	75.93	**ab**	76.30	**ab**	13.80	**efg**	11.10	**h**	12.72	**ghi**
PAN 3195	77.33	**a**	74.30	**ef**	75.82	**bc**	14.60	**cde**	12.40	**ef**	13.50	**def**
PAN 3368	76.57	**b**	76.87	**a**	76.72	**a**	14.25	**def**	14.85	**a**	14.55	**a**
PAN 3379	75.37	**cde**	72.63	**hi**	74.00	**gh**	13.55	**fg**	11.27	**gh**	12.18	**i**
Senqu	74.60	**fg**	75.03	**bcde**	74.82	**ef**	15.70	**ab**	12.87	**def**	14.00	**abcde**
SST 316	73.33	**hi**	71.87	**i**	72.60	**i**	13.60	**fg**	11.77	**gh**	12.50	**hi**
SST 317	74.23	**fg**	74.63	**cdef**	74.43	**fg**	14.00	**efg**	12.80	**def**	13.40	**efg**
SST 347	75.70	**c**	74.57	**cdef**	75.13	**de**	13.50	**fg**	12.33	**efg**	12.92	**fgh**
SST 356	73.20	**hi**	71.80	**i**	72.50	**i**	14.70	**cde**	12.50	**ef**	13.60	**def**
SST 387	73.90	**ghi**	72.93	**gh**	73.42	**h**	15.80	**a**	11.00	**h**	13.40	**efg**
SST 398	74.86	**def**	74.40	**def**	74.63	**ef**	14.30	**def**	14.50	**a**	14.42	**ab**
Env Mean	74.92 **a**		74.38 **b**		74.65		14.40 **a**		12.89 **b**		13.65	
LSD Cult	0.75		1.04		0.63		0.98		1.13		0.72	
LSD Env	0.22						0.25					

Means followed by the same letter, did not differ significantly at p=0.05. Bhm=Bethlehem, Cla=Clarens, FLY=flour yield, FPC=flour protein content, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 3.21 Genotype and environmental means for falling number in the dryland summer rainfall region

	FN (s)				Cult	
Cultivar	**Bhm**		**Cla**		**Means**	
Elands	354.33	**ab**	370.33	**cd**	362.33	**abcd**
Gariep	371.33	**a**	341.33	**de**	356.33	**abcde**
Koonap	362.00	**ab**	409.00	**a**	385.50	**a**
Matlabas	305.00	**bcd**	343.33	**de**	324.17	**e**
PAN 3118	331.00	**abcd**	373.00	**bcd**	352.00	**abcde**
PAN 3120	290.33	**cd**	383.33	**abc**	336.83	**cde**
PAN 3161	329.33	**abcd**	322.00	**e**	325.67	**e**
PAN 3195	324.00	**abcd**	407.00	**ab**	365.50	**abc**
PAN 3368	312.67	**abcd**	370.67	**cd**	341.67	**bcde**
PAN 3379	338.67	**abcd**	409.00	**a**	373.83	**ab**
Senqu	348.00	**abc**	384.33	**abc**	366.17	**abc**
SST 316	328.67	**abcd**	355.00	**cde**	341.83	**bcde**
SST 317	322.67	**abcd**	341.33	**de**	332.00	**cde**
SST 347	285.67	**d**	384.67	**abc**	335.17	**cde**
SST 356	367.67	**a**	375.00	**abcd**	371.33	**ab**
SST 387	347.33	**abc**	319.67	**e**	333.50	**cde**
SST 398	311.67	**abcd**	346.00	**de**	328.83	**de**
Env Mean	331.20 **b**		366.77 **a**		348.98	
LSD Cult	60.34		35.85		34.42	
LSD Env	11.81					

Means followed by the same letter, did not differ significantly at p=0.05. Bhm=Bethlehem, Cla=Clarens, FN=falling number, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 3.22 Combined analysis of variance for grain and milling characteristics for 22 wheat cultivars in the irrigated summer rainfall region

		Mean squares				
SOURCE	**df**	**HLM**	**BFLY**	**FLY**	**FPC**	**FN**
Environment	1	25.13***	1.44*	8.76***	44.08***	479.97***
Rep (Environment)	4	7.73***	0.84*	1.83**	1.16*	0.32ns
Cultivar	21	3.58***	20.62***	5.41***	4.12***	24.17***
Cult x Env	21	1.74ns	1.09***	1.12**	1.45***	5.95***
Error	84	1.28	0.31	0.45	0.44	1.00
CV (%)		1.36	2.66	0.86	5.55	0.28
R^2		0.61	0.95	0.80	0.84	0.93
Variance component contribution (% of SS)						
Environment	1	9.12	0.30	4.58	22.28	40.07
Rep (Environment)	4	11.23	0.69	3.83	2.35	0.11ns
Cultivar	21	27.30	88.92	59.51	43.68	42.37
Cult x Env	21	13.28	4.72	12.33	15.41	10.44

* p≤0.05, ** p≤0.01, *** p≤0.001, ns=non-significant, df=degrees of freedom, HLM=hectolitre mass, BFLY=break flour yield, FLY=flour yield, FPC=flour protein content, FN=falling number, Cult x Env=cultivar x environment interaction, CV=coefficient of variance, R^2= coefficient of determination, SS=sum of squares

Table 3.23 Genotype and environmental means of individual localities for hectolitre mass and break flour yield in the irrigated summer rainfall region

	HLM (kg hl^{-1})				Cult		BFLY (%)				Cult	
Cultivar	**Up**		**Vh**		**Means**		**Up**		**Vh**		**Means**	
Buffels	83.47	**abcdef**	83.40	**bcde**	83.43	**cdef**	22.87	**cde**	23.93	**a**	23.40	**bc**
Duzi	83.80	**abcde**	82.93	**bcdef**	83.37	**dcef**	23.90	**ab**	23.20	**abcd**	23.55	**ab**
Krokodil	83.80	**abcde**	82.87	**bcdef**	83.33	**cdefg**	22.70	**de**	22.63	**cde**	22.67	**d**
PAN 3471	84.73	**abcd**	85.00	**a**	84.87	**a**	19.77	**g**	20.40	**fgh**	20.08	**fg**
PAN 3478	84.53	**abcd**	83.73	**abcd**	84.13	**abcd**	19.57	**ghi**	20.17	**fghi**	19.87	**gh**
PAN 3489	83.67	**abcde**	82.73	**cdef**	83.20	**cdefg**	18.40	**jk**	20.77	**fg**	19.58	**ghi**
PAN 3497	85.13	**a**	84.33	**ab**	84.73	**ab**	21.00	**f**	20.93	**f**	20.97	**e**
Sabie	82.27	**ef**	82.07	**efg**	82.17	**fg**	22.03	**e**	22.27	**de**	22.15	**d**
SST 806	84.73	**abcd**	83.87	**abc**	84.30	**abc**	19.63	**gh**	19.40	**ij**	19.52	**ghij**
SST 822	83.87	**abcde**	82.00	**efg**	82.93	**defg**	20.87	**f**	20.50	**fgh**	20.68	**ef**
SST 835	84.27	**abcde**	83.53	**abcde**	83.90	**abcd**	19.20	**ghij**	19.70	**hi**	19.45	**ghij**
SST 843	85.00	**ab**	81.67	**fg**	83.33	**cdefg**	19.17	**ghij**	18.70	**jk**	18.93	**j**
SST 866	84.87	**abc**	82.53	**cdefg**	83.70	**abcde**	19.80	**g**	19.87	**ghi**	19.83	**ghi**
SST 867	82.87	**cdef**	84.07	**abc**	83.47	**bcde**	22.10	**e**	22.80	**bcde**	22.45	**d**
SST 875	83.33	**abcdef**	82.80	**bcdef**	83.07	**cdefg**	19.13	**ghij**	19.26	**ij**	19.20	**ij**
SST 876	84.20	**abcde**	82.87	**bcdef**	83.53	**bcde**	18.87	**hij**	19.63	**hij**	19.25	**hij**
SST 877	83.93	**abcde**	82.73	**cdef**	83.33	**cdefg**	23.37	**bcd**	21.90	**e**	22.63	**d**
SST 884	83.00	**bcdef**	81.13	**g**	82.07	**g**	18.73	**ij**	20.50	**fgh**	19.62	**ghi**
SST 895	83.73	**abcde**	81.40	**fg**	82.57	**efg**	17.73	**k**	18.07	**k**	17.90	**k**
Tamboti	83.07	**abcdef**	82.67	**cdefg**	82.87	**defg**	22.70	**de**	22.87	**bcd**	22.78	**dc**
Timbavati	81.53	**f**	82.80	**bcdef**	82.17	**fg**	24.53	**a**	23.60	**ab**	24.07	**a**
Umlazi	82.73	**def**	82.20	**defg**	82.47	**efg**	23.70	**abc**	23.27	**abc**	23.48	**ab**
Env Mean	83.75	**a**	82.88	**b**	83.32		20.90	**a**	21.11	**b**	21.00	
LSD Cult	2.10		1.60		1.30		0.88		0.95		0.60	
LSD Env	0.39						0.19					

Means followed by the same letter, did not differ significantly at p=0.05. Up=Upington, Vh=Vaalharts, HLM=hectolitre mass, BFLY=break flour yield, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 3.24 Genotype and environmental means of individual localities for flour yield and flour protein content in the irrigated summer rainfall region

	FLY (%)						FPC (%)					
Cultivar	**Up**		**Vh**		**Cult Means**		**Up**		**Vh**		**Cult Means**	
Buffels	77.23	**defg**	78.97	**abc**	78.10	**cde**	13.33	**bcde**	10.67	**efgh**	12.00	**cdef**
Duzi	77.77	**bcdef**	78.37	**bcdef**	78.07	**cde**	13.53	**abcd**	11.97	**c**	12.75	**bc**
Krokodil	78.30	**bcdef**	77.30	**ghi**	77.80	**defg**	11.53	**fg**	10.87	**defg**	11.20	**ghi**
PAN 3471	76.83	**fgh**	77.73	**efgh**	77.28	**fghi**	11.03	**g**	10.93	**defg**	10.98	**hi**
PAN 3478	76.93	**efgh**	77.93	**defgh**	77.43	**efghi**	12.03	**efg**	10.45	**fgh**	11.40	**efghi**
PAN 3489	76.93	**efgh**	78.37	**bcdef**	77.65	**defgh**	11.67	**fg**	10.83	**efgh**	11.25	**fghi**
PAN 3497	79.63	**a**	79.80	**a**	79.72	**a**	10.85	**g**	10.80	**efgh**	10.82	**i**
Sabie	77.70	**bcdef**	77.17	**hij**	77.43	**efghi**	12.83	**bcdef**	11.73	**cd**	12.28	**cd**
SST 806	78.73	**abc**	78.73	**bcd**	78.73	**bc**	12.17	**defg**	11.37	**cde**	11.77	**cdefgh**
SST 822	75.20	**i**	74.53	**k**	74.87	**j**	12.73	**bcdef**	13.53	**b**	13.13	**b**
SST 835	78.80	**ab**	79.13	**ab**	78.97	**ab**	12.07	**efg**	11.00	**defg**	11.53	**defghi**
SST 843	77.53	**cdefg**	76.30	**j**	76.92	**hi**	14.87	**a**	14.73	**a**	14.80	**a**
SST 866	78.17	**bcd**	78.23	**bcdefg**	78.20	**bcde**	11.53	**fg**	11.30	**cdef**	11.42	**efghi**
SST 867	77.40	**defg**	78.67	**bcde**	78.03	**cdef**	13.07	**bcde**	10.37	**gh**	11.72	**cdefgh**
SST 875	77.40	**defg**	78.17	**cdefg**	77.78	**defg**	11.65	**fg**	11.40	**cde**	11.50	**defghi**
SST 876	77.30	**defg**	78.33	**bcdef**	77.82	**defg**	12.60	**bcdef**	11.53	**cde**	11.96	**cdefg**
SST 877	77.13	**defg**	78.20	**bcdefg**	77.67	**defgh**	13.95	**ab**	11.00	**defg**	12.18	**cde**
SST 884	75.77	**hi**	77.66	**fghi**	76.71	**i**	12.50	**cdef**	11.00	**defg**	11.60	**defghi**
SST 895	76.87	**fgh**	76.77	**ij**	76.82	**i**	12.45	**cdef**	10.90	**defg**	11.68	**defgh**
Tamboti	78.13	**bcdef**	78.47	**bcdef**	78.30	**bcd**	12.50	**cdef**	10.73	**efgh**	11.62	**defgh**
Timbavati	76.40	**ghi**	77.87	**defgh**	77.13	**ghi**	12.87	**bcdef**	9.95	**h**	11.70	**defgh**
Umlazi	77.67	**bcdef**	78.47	**bcdef**	78.07	**cde**	13.70	**abc**	11.03	**defg**	12.10	**cde**
Env Mean	77.45	**b**	77.96	**a**	77.70		12.52	**a**	11.32	**b**	11.88	
LSD Cult	1.23		0.96		0.77		1.40		0.90		0.79	
LSD Env	0.23						0.24					

Means followed by the same letter, did not differ significantly at p=0.05. Up=Upington, Vh=Vaalharts, FLY=flour yield, FPC=flour protein content, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 3.25 Genotype and environmental means for falling number in the irrigated summer rainfall region

	FN (s)				Cult	
Cultivar	**Up**		**Vh**		**Means**	
Buffels	341.00	**b**	325.33	**abc**	336.45	**b**
Duzi	336.67	**b**	291.00	**def**	323.41	**b**
Krokodil	314.67	**c**	267.33	**f**	300.93	**b**
PAN 3471	335.00	**bc**	304.00	**cde**	326.00	**b**
PAN 3478	335.00	**bc**	318.33	**abcd**	330.16	**b**
PAN 3489	340.33	**b**	317.33	**bcde**	333.66	**b**
PAN 3497	348.33	**b**	318.33	**abcd**	339.62	**b**
Sabie	339.00	**b**	307.00	**cde**	329.71	**b**
SST 806	336.33	**b**	331.67	**abc**	334.98	**b**
SST 822	348.67	**b**	285.67	**ef**	330.38	**b**
SST 835	410.00	**a**	317.33	**bcde**	383.10	**a**
SST 843	410.00	**a**	320.00	**abcd**	383.87	**a**
SST 866	410.00	**a**	324.00	**abc**	385.03	**a**
SST 867	410.00	**a**	305.00	**cde**	379.52	**a**
SST 875	410.00	**a**	322.00	**abcd**	384.45	**a**
SST 876	410.00	**a**	320.00	**abcd**	383.87	**a**
SST 877	410.00	**a**	310.00	**cde**	380.97	**a**
SST 884	410.00	**a**	349.67	**a**	392.48	**a**
SST 895	410.00	**a**	342.00	**ab**	390.26	**a**
Tamboti	410.00	**a**	320.00	**abcd**	383.87	**a**
Timbavati	410.00	**a**	317.33	**bcde**	383.10	**a**
Umlazi	410.00	**a**	321.33	**abcd**	384.26	**a**
Env Mean	377.05 **a**		315.21 **b**		359.09	
LSD Cult	20.36		31.83		16.90	
LSD Env	5.61					

Means followed by the same letter, did not differ significantly at p=0.05. Up=Upington, Vh=Vaalharts, FN=falling number, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 3.26 Combined analysis of variance for grain and milling characteristics for nine wheat cultivars in the winter rainfall region

		Mean squares				
SOURCE	**df**	**HLM**	**BFLY**	**FLY**	**FPC**	**FN**
Environment	1	32.98***	7.71***	11.67**	42.84***	106311.41***
Rep (Environment)	4	5.73**	0.13ns	1.29ns	0.92ns	187.07ns
Cultivar	8	15.34***	14.17***	4.85**	4.89***	2913.41**
Cult x Env	8	3.00*	1.22***	2.33ns	0.54ns	4344.24***
Error	32	1.22	0.19	1.15	0.62	682.49
CV (%)		1.37	2.12	1.42	6.51	7.88
R^2		0.84	0.96	0.67	0.82	0.88
Variance component contribution (% of SS)						
Environment	1	13.65	5.61	10.51	39.00	56.86
Rep (Environment)	4	9.49	0.38	4.66	3.35	0.40
Cultivar	8	50.78	82.51	35.00	35.59	12.47
Cult x Env	8	9.92	7.12	16.80	3.93	18.59

* p≤0.05, ** p≤0.01, *** p≤0.001, ns=non-significant, df=degrees of freedom, HLM=hectolitre mass, BFLY=break flour yield, FLY=flour yield, FPC=flour protein content, FN=falling number, Cult x Env=cultivar x environment interaction, CV=coefficient of variance, R^2= coefficient of determination, SS=sum of squares

Table 3.27 Genotype and environmental means of individual localities for hectolitre mass, break flour yield, flour yield, flour protein content and falling number in the winter rainfall region

	HLM (kg hl^{-1})						BFLY (%)						FLY (%)					
Cultivar	**Mo**		**Ri**		**Cult Means**		**Mo**		**Ri**		**Cult Means**		**Mo**		**Ri**		**Cult Means**	
PAN 3471	84.33	**a**	81.53	**a**	82.93	**a**	18.87	**e**	19.00	d	18.94	**d**	78.80	**a**	75.83	**abc**	77.32	**ab**
SST 015	83.00	**ab**	79.00	**bc**	81.00	**bc**	19.73	**cd**	21.67	b	20.70	**b**	75.40	**ab**	75.03	**bc**	75.22	**abc**
SST 027	82.27	**bc**	80.17	**ab**	81.22	**bc**	21.87	**b**	22.63	a	22.25	**a**	75.80	**a**	77.10	**ab**	76.45	**a**
SST 047	82.43	**bc**	81.33	**a**	81.88	**ab**	22.97	**a**	22.10	ab	22.54	**a**	75.20	**ab**	74.50	**c**	74.85	**bcd**
SST 056	80.07	**de**	78.60	**bc**	79.34	**de**	20.00	**c**	21.70	b	20.85	**b**	73.57	**c**	76.00	**abc**	74.79	**bcd**
SST 087	78.93	**ef**	78.10	**bc**	78.52	**ef**	17.47	**f**	18.00	e	17.74	**e**	74.37	**bc**	76.17	**abc**	75.27	**abc**
SST 096	79.50	**ef**	80.37	**ab**	79.94	**cd**	19.77	**cd**	20.00	c	19.89	**c**	74.33	**bc**	74.47	**c**	74.40	**cd**
SST 88	78.20	**f**	77.73	**c**	77.97	**f**	19.37	**de**	20.03	c	19.70	**c**	75.00	**ab**	77.80	**a**	76.40	**a**
Tankwa	81.40	**cd**	79.23	**abc**	80.32	**cd**	20.33	**c**	22.03	ab	21.18	**b**	73.27	**c**	74.20	**c**	73.74	**d**
Env Mean	81.13 **a**		79.56 **b**		80.34		20.04 **b**		20.80 **a**		20.42		74.75 **b**		75.68 **a**		75.38	
LSD Cult	1.37		2.33		1.30		0.62		0.86		0.51		1.24		2.31		1.26	
LSD Env	0.61						0.24						0.59					

	FPC (%)						FN (s)					
Cultivar	**Mo**		**Ri**		**Cult Means**		**Mo**		**Ri**		**Cult Means**	
PAN 3471	12.80	**b**	10.70	**c**	11.75	**cd**	408.00	**a**	225.33	**c**	316.67	**bc**
SST 015	13.10	**ab**	10.36	**c**	11.73	**cd**	383.00	**ab**	233.00	**c**	308.00	**c**
SST 027	13.60	**ab**	11.23	**bc**	12.42	**bc**	383.00	**ab**	343.67	**a**	363.34	**a**
SST 047	14.53	**a**	13.77	**a**	14.15	**a**	389.67	**a**	310.00	**ab**	349.84	**a**
SST 056	12.27	**b**	10.47	**c**	11.37	**d**	367.33	**ab**	268.67	**bc**	318.00	**bc**
SST 087	12.30	**b**	10.97	**c**	11.64	**cd**	345.67	**b**	249.00	**c**	297.34	**c**
SST 096	12.20	**b**	10.67	**c**	11.44	**d**	345.00	**b**	335.33	**a**	340.17	**ab**
SST 88	12.73	**b**	10.70	**c**	11.72	**cd**	391.67	**a**	298.00	**ab**	344.84	**ab**
Tankwa	13.57	**ab**	12.20	**b**	12.89	**b**	368.33	**ab**	320.00	**a**	344.17	**ab**
Env Mean	13.01 **a**		11.23 **b**		12.12		375.74 **a**		287.00 **b**		331.37	
LSD Cult	1.49		1.23		0.93		42.99		47.34		30.72	
LSD Env	0.44						14.48					

Means followed by the same letter, did not differ significantly at p=0.05. Mo=Moorreesburg, Ri=Riversdal, HLM=hectolitre mass, BFLY=break flour yield, FLY=flour yield, FPC=flour protein content, FN=falling number, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

3.3.3. Correlations

3.3.3.1 Correlations between the SRC, SIG and grain and milling characteristics

There were significant correlations between SRC and SIG with grain and milling characteristics. More significant correlations were evident between the SRC, SIG and grain and milling characteristics in the irrigated SRR than in the other regions (Table 3.29).

Significant differences across the production regions explains the inconsistent correlations within the regions. The dryland conditions in the SRR resulted in high FPC with low FLY. The cultivar x environment interaction was also much higher in the dryland SRR when compared with the irrigated SRR and the WRR (Tables 3.18, 3.22 and 3.26).

3.3.3.1.1 Hectolitre mass

Hectolitre mass was positively correlated with lactic acid SRC ($p \leq 0.001$) in the dryland SRR (Table 3.28), and in the WRR (Table 3.30) ($p \leq 0.05$). In the irrigated SRR (Table 3.29), HLM was negatively correlated with lactic acid SRC ($p \leq 0.01$). There were no significant correlations between HLM and distilled water SRC. Hectolitre mass was negatively correlated with sodium carbonate SRC ($p \leq 0.001$) in the dryland SRR and also in the WRR ($p \leq 0.01$). Only in the WRR did HLM correlate negatively with sodium bicarbonate SRC ($p \leq 0.05$). In the irrigated SRR HLM was negatively ($p \leq 0.001$) correlated with sucrose SRC and positively ($p \leq 0.05$) in the WRR. A weak correlation ($p \leq 0.05$) occurred between HLM and lactic acid SIG in the dryland SRR.

Overall correlations between HLM and SRC and SIG parameters were weak and inconsistent across regions. Hectolitre mass was negatively correlated with sodium carbonate SRC in the two dryland localities of the SRR (-0.35***) and the WRR (-0.40**).

Hectolitre mass correlations with lactic acid SRC was 0.33*** in the dryland SRR and 0.29* in the dryland WRR.

3.3.3.1.2 Break flour yield

Positive correlations were seen between BFLY and lactic acid SRC in the dryland SRR (Table 3.28) (p≤0.001) and in the irrigated SRR (Table 3.29) (p≤0.01). Negative correlations occurred between BFLY and distilled water SRC in the dryland SRR (p≤0.001) and irrigated SRR (p≤0.001). In the WRR, BFLY was positively correlated with distilled water SRC (p≤0.001). In the irrigated SRR, BFLY was negatively correlated with sodium carbonate SRC (p≤0.001). Sodium bicarbonate SRC was negatively correlated (p≤0.001) with BFLY only in the irrigated SRR. A negative correlation (p≤0.001) between BFLY and sucrose SRC occurred in both the dryland and irrigated SRR's. One correlation (p≤0.001) occurred between BFLY and lactic acid SIG in the dryland SRR.

3.3.3.1.3 Flour yield

In the dryland SRR (Table 3.28), FLY was positively correlated (p≤0.001) with lactic acid SRC. In both the irrigated SRR (Table 3.29) and WRR (Table 3.30), FLY correlated negatively (p≤0.001) with lactic acid SRC supporting the finding of Guttieri *et al*. (2002). Negative correlations (p≤0.001) occurred between FLY and distilled water SRC in the dryland and irrigated SRR. Flour yield was also negatively correlated with SC_SRC in the dryland SRR (p≤0.001) and in the irrigated SRR (p≤0.001). One negative correlation (p≤0.001) occurred between FLY and sodium bicarbonate SRC in the irrigated SRR. Flour yield and S_SRC was negatively correlated in the dryland SRR (p≤0.05) and in the irrigated SRR (p≤0.001). Flour yield correlated positively (p≤0.001) with lactic acid SIG in the dryland SRR and negatively (p≤0.001) in both the irrigated SRR and WRR.

Correlations between FLY and SRC and SIG parameters were somewhat higher when compared to other parameters and inconsistent across regions. Highly significant negative correlations between all four SRC parameters and FLY as was found in this study except for the positive correlation (0.56***) between FLY

and lactic acid SRC in the WRR. In addition to the positive correlation of lactic acid SRC with FLY in the dryland SRR, lactic acid SIG also correlated positively with FLY (0.50***).

In both the irrigated SRR and WRR, FLY correlations with the protein interactive lactic acid SRC and lactic acid SIG parameters were negative.

3.3.3.1.4 Flour protein content

Flour protein content correlated positively (p≤0.001) with lactic acid SRC across all the production regions, including the dryland SRR (Table 3.28), the irrigated SRR (Table 3.29) and the WRR (Table 3.30). A negative correlation (p≤0.001) was evident between FPC and sodium carbonate SRC in the dryland SRR, whilst these two parameters were positively correlated (p≤0.01) in the irrigated SRR. Positive correlations between FPC and sucrose SRC was obtained in the irrigated SRR (p≤0.001) and in the WRR (p≤0.01). Lactic acid SIG correlations with FPC was overall stronger and correlated positively (p≤0.001) across all three production regions.

Higher and consistent correlations between FPC and lactic acid SRC occurred across the production regions of the dryland SRR (0.56***), irrigated SRR (0.59***) and WRR (0.67***). This was also the case for the lactic acid SIG correlations with FPC across the regions of the dryland SRR (0.59***), irrigated SRR (0.75***) and WRR (0.54***).

3.3.3.1.5 Falling number

A strong correlation (p≤0.001) occurred between FN and lactic acid SRC in the WRR (Table 3.30). Sodium carbonate SRC was positively (p≤0.01) correlated with FN in the dryland SRR (Table 3.28) and positively (p≤0.001) in the irrigated SRR (Table 3.30), whilst a negative (p≤0.05) correlation occurred in the WRR. Weak negative correlations (p≤0.05) occurred between sucrose SRC and FN in the irrigated SRR and WRR.

Falling number was weakly and negatively correlated with lactic acid SIG in the dryland SRR, whilst strong positive (p≤0.001) correlations occurred between these two parameters in the irrigated SRR and WRR. Correlations between FN and SIG and SRC parameters were high and significant, however very inconsistent across regions.

Table 3.28 Significant correlations between grain and milling characteristics and solvent retention capacity and swelling index of glutenin characteristics for the dryland summer rainfall region

Characteristic	LA_SRC	DW_SRC	SC_SRC	SBC_SRC	S_SRC	LA_SIG
HLM	0.33***		-0.35***			0.21*
BFLY	0.45***	-0.49***			-0.40***	0.34***
FLY	0.56***	-0.37***	-0.4***		-0.24*	0.50***
FPC	0.44***		-0.45***			0.59***
FN			0.26**			-0.28**

* p≤0.05, ** p≤0.01, *** p≤0.001, HLM=hectolitre mass, BFLY=break flour yield, FLY=flour yield, FPC=flour protein content, FN=falling number, LA_SRC=lactic acid SRC, DW_SRC=distilled water SRC, SC_SRC=sodium carbonate SRC, SBC_SRC=sodium bicarbonate SRC, S_SRC=sucrose SRC, LA-SIG=lactic acid SIG

Table 3.29 Significant correlations between grain and baking quality-related characteristics and solvent retention capacity and swelling index of glutenin characteristics for the irrigated summer rainfall region

Characteristic	LA_SRC	DW_SRC	SC_SRC	SBC_SRC	S_SRC	LA_SIG
HLM	-0.25**				-0.34***	
BFLY	0.26**	-0.32***	-0.31***	-0.40***	-0.40***	
FLY	-0.39***	-0.40***	-0.28**	-0.33***	-0.47***	-0.36***
FPC	0.59***		0.26**		0.46***	0.75***
FN			0.38***		0.17*	0.55***

* p≤0.05, ** p≤0.01, *** p≤0.001, HLM=hectolitre mass, BFLY=break flour yield, FLY=flour yield, FPC=flour protein content, FN=falling number, LA_SRC=lactic acid SRC, DW_SRC=distilled water SRC, SC_SRC=sodium carbonate SRC, SBC_SRC=sodium bicarbonate SRC, S_SRC=sucrose SRC, LA_SIG =lactic acid SIG

Table 3.30 Significant correlations between grain and baking quality-related characteristics and solvent retention capacity and swelling index of glutenin characteristics for the winter rainfall region

Characteristic	LA_SRC	DW_SRC	SC_SRC	SBC_SRC	S_SRC	LA_SIG
HLM	0.29*		-0.40**	-0.31*	0.32*	
BFLY		0.50***				
FLY	-0.36**					-0.44***
FPC	0.67***				0.39**	0.54***
FN	0.64***		-0.28*		0.30*	0.57***

* p≤0.05, ** p≤0.01, *** p≤0.001, HLM=hectolitre mass, BFLY=break flour yield, FLY=flour yield, FPC=flour protein content, FN=falling number, LA_SRC=lactic acid SRC, DW_SRC=distilled water SRC, SC_SRC=sodium carbonate SRC, SBC_SRC=sodium bicarbonate SRC, S_SRC=sucrose SRC, LA_SIG =lactic acid SIG

3.3.4 Stepwise multiple linear regressions

3.3.4.1 SRC and SIG parameters responsible for variation in grain and milling characteristics

The regression coefficient (Model R-Square) and the probability of the estimated SRC and SIG variables predicting grain and milling characteristics were determined. The Model R-Square was calculated from Van Ark (1995): Model R-Square = r^2 x 100, with r^2 being the regression coefficient.

Stepwise multiple linear regressions were used to determine which independent variable (SRC and SIG parameters) caused the highest level of variation in the dependent variable (grain and milling characteristics).

The prediction equation developed by Leilah and Al-Khateeb (2005) was calculated, for example: HLM ($\hat{Y}$) in the dryland SRR is formulated using SRC and SIG parameters as follows: (Table 3.31)

$\hat{Y}$ = 71.37 – 0.16 (sodium carbonate SRC) + 0.30 (distilled water SRC)

Regression coefficients for the SRC and SIG parameters to describe variation in grain and milling characteristics were low to moderate (16% to 60%) across the three wheat production areas of the dryland SRR (Table 3.31), irrigated SRR (Table 3.32) and the WRR (Table 3.33). The low regression coefficients indicate that grain and milling characteristics will be poorly predicted by most of the SRC and SIG parameters in this study.

3.3.4.1.1 Hectolitre mass

In the dryland SRR (Table 3.31) and WRR (Table 3.33), sodium carbonate SRC and distilled water SRC together, significantly contributed 20% and 49% to the total variation in HLM for the respective localities. In the irrigated SRR (Table 3.32), the model explained 16% of the variation in HLM as was significantly contributed by sucrose SRC. Both sucrose SRC and distilled water SRC was found to be negatively correlated with HLM (Xiao *et al*., 2006), however in this study the regression coefficients for these parameters were low. Distilled water SRC contributed 11% ($p \leq 0.01$) to the total variation in HLM for the dryland SRR and 9% ($p \leq 0.05$) for the WRR. Sucrose SRC contributed 16% ($p \leq 0.001$) to the total variation in HLM for the irrigated SRR.

3.3.4.1.2 Break flour yield

In the dryland SRR (Table 3.31) the regression coefficient for BFLY was 46%, with distilled water SRC (23%) and lactic acid SRC (24%), contributing significantly to the variation in BFLY. In the irrigated SRR (Table 3.32), sucrose SRC, lactic acid SRC, distilled water SRC and sodium carbonate SRC contributed significantly to the total variation in BFLY. They contributed 14%, 24%, 4% and 3% respectively to the total regression coefficient (45%) for BFLY. In the WRR (Table 3.33), the regression coefficient was 46% for BLFY as significantly contributed by distilled water SRC (23%) and sodium carbonate SRC (24%).

The variation explained by distilled water SRC for BFLY is expected since distilled water SRC gives an indication of water absorption.

Low BFLY from the first break in the milling process is an indication of increased grain hardness, with more damaged starch and higher water absorption as a result. The total variance contribution from this parameter, although significant, was 23%, 4% and 23% respectively for the dryland SRR, irrigated SRR and WRR.

3.3.4.1.3 Flour yield

Flour yield had a regression coefficient of 41%, 28% and 19% in the dryland SRR (Table 3.31), irrigated SRR (Table 3.32) and WRR (Table 3.33), respectively. In the dryland SRR, lactic acid SRC contributed 29% ($p \leq 0.001$) and distilled water SRC 12% ($p \leq 0.001$) to the variation in FLY. The largest contribution towards the FLY variation in the irrigated SRR was from sucrose SRC, contributing 23% ($p \leq 0.001$), followed by lactic acid SRC contributing 5% ($p \leq 0.05$). In the WRR, lactic acid SIG alone explained a total of 19% ($p \leq 0.001$) towards variation in FLY. The independent SRC and SIG variables contributed significantly to the variation in FLY, however regression coefficients were low and inconsistent across regions.

3.3.4.1.4 Flour protein content

Flour protein content had a regression coefficient of 45%, 60% and 58% in the dryland SRR (Table 3.31), irrigated SRR (Table 3.32) and WRR (Table 3.33), respectively. Lactic acid SIG was the independent variable responsible for explaining the highest variation in FPC across all three production regions. In the dryland SRR, lactic acid SIG contributed 37% ($p \leq 0.001$) to the variation in FPC, 58% ($p \leq 0.001$) in the irrigated SRR and 45% ($p \leq 0.001$) in the WRR. Given the high correlations obtained between lactic acid SRC and FPC it was expected that lactic acid SRC would play a bigger role in the regression coefficient of FPC.

3.3.4.1.5 Falling number

Falling number had a regression coefficient of 20%, 51% and 48% in the dryland SRR (Table 3.31), irrigated SRR (Table 3.32) and WRR (Table 3.33),

respectively. In the dryland SRR independent variables for FN were lactic acid SIG and lactic acid SRC, which contributed 6% ($p \leq 0.05$) and 14% ($p \leq 0.001$) respectively.

In the irrigated SRR (Table 3.32) the predictor variables included lactic acid SIG, lactic acid SRC, sodium carbonate SRC and distilled water SRC each contributing 30% ($p \leq 0.001$), 14% ($p \leq 0.001$), 5% ($p \leq 0.01$) and 3% ($p \leq 0.05$), respectively to the variation in FN. In the WRR lactic acid SIG contributed 41% ($p \leq 0.001$) and distilled water SRC 7% ($p \leq 0.001$) to the total variation in FN (Table 3.33). The protein SRC and SIG parameters, including lactic acid SRC and lactic acid SIG, explained most of the variation in the regression coefficients across the three wheat production regions, although correlations between these parameters were inconsistent across the three regions.

Table 3.31 Solvent retention capacity and swelling index of glutenin parameters responsible for variation in milling and grain characteristics in the dryland summer rainfall region

Dependent Variable: HLM						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	71.40***					
SC_SRC	-0.16***	0.09	0.09	-0.35***	6.80*	0.0112
DW_SRC	0.30**	0.11	0.20	0.09ns	9.43**	0.0031

Dependent Variable: BFLY						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	33.65***					
DW_SRC	-0.36***	0.23	0.23	-0.49***	20.17***	<.0001
LA_SRC	0.10***	0.24	0.46	0.45***	30.07***	<.0001

Dependent Variable: FLY						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	76.03***					
LA_SRC	0.07***	0.29	0.29	0.56***	27.54***	<.0001
DW_SRC	-0.15***	0.12	0.41	-0.37***	14.00***	0.0004

Dependent Variable: FPC						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	12.06***					
LA_SIG	1.65***	0.37	0.37	0.59***	41.31***	<.0001
SBC_SRC	-0.04*	0.04	0.41	-0.08ns	4.68*	0.0339
SC_SRC	-0.04*	0.04	0.45	-0.45***	4.88*	0.0305

Dependent Variable: FN						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	380.22***					
LA_SIG	-65.45***	0.06	0.06	-0.28**	4.29*	0.042
LA_SRC	2.10***	0.14	0.20	-0.004ns	12.08***	0.0009

* p≤0.05, ** p≤0.01, *** p≤0.001, ns=non-significant. HLM=hectolitre mass, BFLY=break flour yield, FLY=flour yield, FPC=flour protein content, FN=falling number, LA_SRC=lactic acid SRC, DW_SRC=distilled water SRC, SC_SRC=sodium carbonate SRC, SBC_SRC=sodium bicarbonate SRC, LA_SIG=lactic acid SIG

Table 3.32 Solvent retention capacity and swelling index of glutenin parameters responsible for variation in milling and grain characteristics in the irrigated summer rainfall region

Dependent Variable: HLM						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	95.98***					
S_SRC	-0.14***	0.16	0.16	-0.34***	19.58***	<.0001
Dependent Variable: BFLY						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	41.71***					
S_SRC	-0.19***	0.14	0.14	-0.40***	17.07***	<.0001
LA_SRC	0.12***	0.24	0.38	0.008ns	41.18***	<.0001
DW_SRC	-0.17**	0.04	0.42	-0.32***	7.2**	0.0085
SC_SRC	-0.07*	0.03	0.45	-0.31***	5.18*	0.0249
Dependent Variable: FLY						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	91.13***					
S_SRC	-0.12***	0.23	0.23	-0.47***	31.73***	<.0001
LA_SRC	-0.03*	0.05	0.28	-0.40***	6.51*	0.0122
Dependent Variable: FPC						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	0.60ns					
LA_SIG	2.19***	0.58	0.58	0.75***	148.64***	<.0001
LA_SRC	0.02*	0.02	0.60	0.59***	5.01*	0.0273
Dependent Variable: FN						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	208.94**					
LA_SIG	85.77***	0.30	0.30	0.55***	44.87***	<.0001
LA_SRC	-1.90***	0.14	0.44	0.09ns	25.78***	<.0001
SC_SRC	1.94**	0.05	0.49	0.38***	9.75**	0.0023
DW_SRC	-2.36*	0.03	0.51	-0.15ns	5.57*	0.0202

* p≤0.05, ** p≤0.01, *** p≤0.001, ns=non-significant. HLM=hectolitre mass, BFLY=break flour yield, FLY=flour yield, FPC=flour protein content, FN=falling number, LA_SRC=lactic acid SRC, DW_SRC=distilled water SRC, SC_SRC=sodium carbonate SRC, S_SRC=sucrose SRC, LA_SIG=lactic acid SIG

Table 3.33 Solvent retention capacity and swelling index of glutenin parameters responsible for variation in milling and grain characteristics in the winter rainfall region

Dependent Variable: HLM						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	80.88***					
SC_SRC	-0.28***	0.16	0.16	-0.40**	9.74**	0.0029
DW_SRC	0.33*	0.09	0.25	0.03ns	6.46*	0.0141
Dependent Variable: BFLY						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	-0.56ns					
DW_SRC	0.49***	0.25	0.25	0.50***	17.18***	0.0001
SC_SRC	-0.14**	0.10	0.35	0.02ns	8.25**	0.0059
Dependent Variable: FLY						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	82.89***					
LA_SIG	-1.76***	0.19	0.19	-0.44***	12.31***	0.0009
Dependent Variable: FPC						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	-17.01***					
LA_SRC	0.12***	0.45	0.45	0.67***	42.90***	<.0001
DW_SRC	0.21***	0.13	0.58	0.22ns	15.28***	0.0003
Dependent Variable: FN						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	-685.10**					
LA_SRC	4.67***	0.41	0.41	0.64***	36.72***	<.0001
DW_SRC	6.74*	0.07	0.48	0.14ns	0.06**	0.11

* p≤0.05, ** p≤0.01, *** p≤0.001, ns=non-significant. HLM=hectolitre mass, BFLY=break flour yield, FLY=flour yield, FPC=flour protein content, FN=falling number, LA_SRC=lactic acid SRC, DW_SRC=distilled water SRC, SC_SRC=sodium carbonate SRC, LA_SIG=lactic acid SIG

3.3.5 Electrophoresis

The cultivars developed for specific production regions varied in the frequencies for HMW-GS combinations (Table 3.34). The HMW-GS combination simmilarities for varieties within a specific region could be a result of genetic selection for adapted traits in the region that is associated with specific subunits. In the dryland SRR, cultivars expressed 1, 2* and null subunits at the *Glu-A1* locus, 7+8 and 7+9 subunits were expressed more frequently for the *Glu-B1* locus and the 5+10 subunit pair at the *Glu-D1* locus was present in all cultivars except PAN 3368, PAN 3379 and SST 316 which had the 2+12 subunit pair. In the WRR, cultivars expressed 1 and null subunits at the *Glu-A1* locus, 7+8 and 13+16 subunits at the *Glu-B1* locus and the 2+12 and 5+10 subunits at the *Glu-D1* locus. In the irrigated SRR, the 1 and 2* subunits were expressed at the *Glu-A1* locus, 7+8, 13+16 and 17+18 subunits were more frequently expressed at the *Glu-B1* locus and 2+12 and 5+10 subunits at the *Glu-D1* locus.

Table 3.34 Observed frequencies of high molecular weight glutenin subunit combinations

Localities	Entries	HMW 1A	HMW 1B	HMW 1D
	Elands	1	7+9	5+10
	Gariep	1	7+9	5+10
	Koonap	1	17+18	5+10
	Matlabas	NULL	7+8	5+10
	PAN 3118	2*	7+8	5+10
	PAN 3120	2*	7+9	5+10
	PAN 3161	2*	7+8	5+10
Dryland SRR	PAN 3195	2*	7+9	5+10
Bethlehem	PAN 3368	2*	7+8	2+12
Clarens	PAN 3379	2*	7+8	2+12
	Senqu	1	7+9	5+10
	SST 316	1	7+9	2+12
	SST 317	NULL	7+9	5+10
	SST 347	2*	7+9	5+10
	SST 356	1	7+9	5+10
	SST 387	2*	7+9	5+10
	SST 398	NULL	7+9	5+10
	PAN 3471	1	7+8	2+12
	SST 015	1	7+8 (13+16)2'	5+10 (2+12)2'
	SST 027	1	13+16	5+10
WRR	SST 047	1	7+8	2+12
Moorreesburg	SST 056	1	13+16	5+10
Riversdal	SST 087	NULL	13+16	5+10
	SST 096	1	7+8	2+12
	SST 88	1	7+8	2+12
	Tankwa	NULL	7+8	5+10 (2+12)2'
	Buffels	2*	17+18	2+12
	Duzi	2*	17+18	2+12
	Krokodil	2*	7+9	2+12
	PAN 3471	1	7+9 (13+16)2'	5+10
	PAN 3478	1	13+16	2+12
	PAN 3489	1	13+16	5+10
	PAN 3497	1	7+8 (17+18)2'	2+12
	Sabie	2*	17+18	2+12
	SST 806	1	7+5	2+12
Irrigated SRR	SST 822	1	13+16 (7+8)2'	5+10
Upington	SST 835	1	7+8	2+12
Vaalharts	SST 843	2*	7+8	2+12
	SST 866	1	7+8	5+10
	SST 867	1	7+8	5+10
	SST 875	1	7+8	5+10
	SST 876	1	7+8	5+10
	SST 877	1	7+8	5+10
	SST 884	1	7+8	5+10
	SST 895	1	7+8	5+10
	Tamboti	2*	17+18	2+12
	Timbavati	2*	17+18	2+12
	Umlazi	2*	17+18	2+12

3.4 Discussion and conclusions

Mean values for SRC obtained in this study were highest for lactic acid SRC, followed by sucrose SRC, sodium carbonate SRC and distilled water SRC. This trend was comparable to studies conducted by Xiao *et al*. (2006), Kweon *et al*. (2011) Guzmán *et al*. (2015), Hammed *et al*. (2015) and Issarny *et al*. (2017). The SRC values were similar to values reported by Xiao *et al.* (2006) and Guzmán *et al*. (2015) and lower than values reported by Kweon *et al*. (2011), Hammed *et al*. (2015) and Issarny *et al*. (2017). The lactic acid SRC values in the irrigation SRR (Table 3.3) were lower with a mean value for the combined localities of 107.73%. These results for the high and low potential production regions is expected, since high yields obtained under irrigation farming practices, are inversely correlated with protein content. This is confirmed by Duyvejonck *et al*. (2011) who reported that flour proteins, especially the glutenins, contribute to lactic acid SRC values and Issarny *et al*. (2017) who reported highly significant correlations of lactic acid SRC with FPC ($r=0.99$, $p \leq 0.01$). Lactic acid SRC mean values complied with the required criteria reported by Kweon *et al*. (2011) for HRS with increased LFV

Distilled water SRC values were lower in the irrigated high potential SRR with lower FPC associated with softer wheat. Starch damage, during the milling process, for soft wheat is lower than for hard wheat with lower water absorption. Distilled water SRC reflects the flour's ability to hold water (Gaines, 2000; Guttieri *et al*., 2001). None of the genotypes planted in the irrigated SRR or WRR complied with the requirements of Kweon *et al*. (2011) who reported that a distilled water SRC of 73% is desired for increased LFV in Canadian HRS genotypes.

Gaines (2000) and Guttieri *et al*. (2001) reported that sodium carbonate SRC is correlated with the levels and swelling of damaged starch, or solvent-accessible amylopectin in damaged starch, as well as flour pentosan content. Sodium carbonate SRC values for high LFV flour, as indicated by Kweon *et al*. (2011), is 91%. Only a few varieties in the dryland and irrigated SRR met this requirement.

High sodium bicarbonate SRC values, associated with overall water absorption, corresponded with the high distilled water SRC values measured for the dryland SRR.

Kweon *et al*. (2011) indicated that sucrose SRC values required for good bread baking quality is 115%, however none of the sucrose SRC values of the genotypes in this study were more than 103.54%. Sucrose SRC is associated with gliadin content and differentiates flours with different water-soluble pentosans (Gaines, 2000; Guttieri *et al*., 2001). All the functional polymeric components of flours affect distilled water SRC namely, the gliadin, pentosan, damaged starch and gluten strength and is mainly a measurement of the flour's ability to hold water (Kweon *et al*., 2011).

The lactic acid SRC values and the lactic acid SIG values were higher in the dryland SRR with high FPC. Yield potential for the SRR was low, relative to the irrigated SRR and the WRR, with a range between 3.69 ton per hectare (ton ha^{-1}) for Bethlehem and 5.43 ton ha^{-1} for Clarens. Lower yields obtained at Bethlehem was associated with higher FPC.

The SIG values corresponded with studies conducted by Wang and Kovacs (2002a; 2002b). Li *et al*. (2013) reported highly significant correlations between SIG and FPC ($r=0.78$, $p\leq0.0001$), explaining the lactic acid SIG results associated with protein levels across all three environments.

A negative correlation between protein content and HLM was reported by Dowell *et al*. (2008), as was found in this study, where HLM was found to be lower in regions with higher FPC.

Negative correlations between BFLY and grain hardness were reported by Yamazaki and Donelson (1983), Gaines (1991) and Labuschagne *et al*. (1997) whilst positive correlations between protein content and grain hardness were reported by Huebner and Gaines (1992), Van Lill and Smith (1997) and Lyon and Shelton (1999). Higher protein content could result in harder grain with lower

BFLY. This was not the case in the dryland SRR, where protein content was high, with high distilled water SRC and sodium carbonate SRC values.

ANOVA indicated highly significant ($p \leq 0.001$) cultivar, environment and cultivar x environment interaction for most of the SRC and SIG parameters as well as for the grain and milling characteristics. The significant interactions were a result of variable interaction between the cultivars and the specific environmental conditions at each locality within a production region.

Differences in the three production regions of the dryland and irrigated SRR and the WRR also resulted in different cultivar x environment interaction, emphasising the massive differences amongst these regions and that breeding criteria for these regions will differ.

The environmental effect was significant for all parameters except for BFLY in the dryland SRR, with a strong and significant ($p \leq 0.001$) cultivar effect for BFLY across the three production regions. The environment effect for sucrose SRC was also insignificant. No significant cultivar x environment interaction was measured for HLM in the dryland SRR and for FLY and FPC in the irrigated SRR. Variation amongst genotypes were much larger than among environments for the SRC, SIG, grain and milling characteristics. This indicates that these parameters are highly heritable, and can be used in a breeding programme to successfully improve quality characteristics. Barnard *et al*. (2002) and Miles (2010) also reported that genotype contributed more and significantly towards total variance in BFLY than the environment.

Bergman *et al*. (1998) and Miles (2010) also reported that genotype significantly affects FLY and Van Lill and Smith (1997) reported that both genotype and the environment affects FLY.

The strong lactic acid SRC and protein content association reported by various researchers (Xiao *et al*., 2006 and Issarny *et al*., 2017) and the lack of significant cultivar effect for FPC at Moorreesburg, could be the reason for the reduced

variance component contribution of genotypes towards lactic acid SRC in the WRR.

High and significant (p≤0.001) environmental interaction was only measured for lactic acid SRC in the WRR, FN in the WRR and irrigated SRR, and FPC in the dryland SRR and WRR. The cultivar x environment interaction was higher for sodium carbonate SRC, sodium bicarbonate SRC and sucrose SRC in the dryland SRR.

More grain and milling characteristics were correlated with lactic acid SRC and lactic acid SIG with higher and more significant correlations. Correlations across regions were inconsistent between SRC, SIG and all grain and milling characteristics except for FPC with lactic acid SRC and lactic acid SIG parameters which measured strong, significant (p≤0.001) and positive correlations. No correlations were evident between distilled water SRC and sodium bicarbonate SRC with FN and FPC.

HLM was negatively correlated with lactic acid SRC (p≤0.01) as was found by Xiao *et al*. (2006). Positive HLM correlations with lactic acid SRC contradicted the findings of Xiao *et al*. (2006) who reported a significant negative correlation between lactic acid SRC values and HLM, but supporting the findings of Preston *et al*. (1995) and Schuler *et al*. (1995) who reported a positive correlation between FPC and HLM. Correlations between BFLY and SRC and SIG parameters were weak and inconsistent across regions. It would be expected that high protein content localities will have harder wheat as a result of lower BFLY's.

In this study, high protein localities also had higher BFLY for example, in the dryland SRR the mean BFLY value was 22.09% (Table 3.5) and the FPC 13.63%, compared to the irrigated SRR (Table 3.6) with a BFLY value of 21.00% and FPC of 12.52% and in the WRR (Table 3.7) the mean BFLY was 20.42% and the FPC 12.12%. This explains the positive correlations between BFLY and LA_SRC in the dryland SRR (Table 3.28) (p≤0.001) and in the irrigated SRR (Table 3.29) (p≤0.01). The strong positive correlation between BFLY and

distilled water SRC (0.50***) in the WRR was unexpected as higher BFLY is an indication of softer wheat (Yamazaki and Donelson, 1983; Gaines, 1991; Labuschagne *et al*., 1997).

Harder wheat will result in higher starch damage during milling with higher water absorption (Pomeranz and Williams, 1990) as measured by distilled water SRC, explaining the negative correlations between BFLY and distilled water SRC in the dryland SRR ($p \leq 0.001$) and irrigated SRR ($p \leq 0.001$). Xiao *et al*. (2006) reported highly significant positive correlations between lactic acid SRC, distilled water SRC and SKCS hardness.

In both the irrigated SRR and WRR, FLY correlated negatively with lactic acid SRC supporting the findings of Guttieri *et al*. (2002). The positive correlation of lactic acid SRC with FLY in the dryland SRR contradicted the findings of Guttieri *et al*. (2002) and Xiao *et al*. (2006). Negative correlations ($p \leq 0.001$) were evident between FLY and distilled water SRC in the dryland and irrigated SRR, this was in contrast with the findings of Guttieri *et al*. (2002) and supported the findings of Xiao *et al*. (2006). Flour yield and sucrose SRC was negatively correlated in the dryland SRR ($p \leq 0.05$) and in the irrigated SRR ($p \leq 0.001$) as was found by Guttieri *et al*. (2002).

Correlations between FLY and SRC and SIG parameters were somewhat higher when compared to other parameters and inconsistent across regions. Xiao *et al*. (2006) reported highly significant negative correlations between all four SRC parameters and FLY as was found in this study except for the positive correlation between FLY and lactic acid SRC in the WRR.

In addition to the positive correlation of lactic acid SRC with FLY in the dryland SRR, lactic acid SIG also correlated positively with FLY. In both the irrigated SRR and WRR, FLY correlations with the protein interactive lactic acid SRC and lactic acid SIG parameters were negative. The positive correlation of HLM with lactic acid SRC and lactic acid SIG in the dryland SRR could be explained by the very high protein content (13.69%) and low FLY (74.56%) obtained in this low potential region. Xiao *et al*. (2006) reported a significant high positive correlation

between lactic acid SRC and protein content, as was found in this study. Issarny *et al*. (2017) reported highly significant correlations of lactic acid SRC with FPC ($r=0.99$, $p\leq0.01$).

Li *et al*. (2013) reported highly significant correlations between SIG and FPC ($r=0.78$, $p\leq0.0001$), supporting the findings of this study. The negative correlation between FPC and sodium carbonate SRC in the dryland SRR contradicted the findings of Hammed *et al*. (2015), who reported a positive correlation, however this predictor variable only explained 4% ($p\leq0.05$) of the variation in FPC.

Regression coefficients for the SRC and SIG parameters to describe variation in grain and milling characteristics were low to moderate (16% to 60%) across the three wheat production areas. The lactic acid SRC and distilled water SRC parameters were the predictor variables most commonly contributing to the regression coefficient explaining the variation in the models for grain and milling characteristics. The sodium bicarbonate SRC variable was most uncommon in the model across regions. Correlations observed was significant, but inconsistent across regions. Stepwise multiple linear regression indicated that most SRC and SIG parameters are poor predictors of grain and milling parameters and that regression coefficients across localities were higher for FPC with lactic acid SRC and lactic acid SIG explaining most of the variation.

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CHAPTER 4

THE RELATIONSHIP OF RHEOLOGICAL AND BAKING QUALITY-RELATED CHARACTERISTICS WITH SOLVENT RETENTION CAPACITY AND SWELLING INDEX OF GLUTENIN

Abstract

Quality analysis on breeding material can only be conducted when sufficient amounts of seed are available, usually later in the breeding process. Selection for quality by breeders at a later stage in the breeding cycle means that lines with inferior quality characteristics cannot be discarded, increasing the magnitude of the breeding programme. The efficiency of the programme will be reduced with higher cost to release an adapted, high yielding cultivar with acceptable quality characteristics as set by the Wheat Technical Committee in South Africa. In this study five small-scale rapid tests, including Solvent Retention Capacity (SRC) parameters and one Swelling Index of Glutenin (SIG) parameter were correlated with six rheological characteristics and three baking quality-related characteristics to determine their relationships using hard red spring and hard red winter wheat germplasm. Highly significant cultivar differences were measured for all rheological, baking quality-related characteristics, SRC and SIG parameters, with a strong genotype effect. The environment effect was highly significant across regions, especially for FPC, which affected the rheological and baking quality-related characteristics differently across the regions, thus the cultivar and location differences contributed significantly to variation in quality parameters, SRC and SIG values. Correlations between SRC, SIG, rheological and baking quality-related parameters were highly significant and differences in the quality parameters across the production regions resulted in inconsistent correlations. Only lactic acid SRC and SIG correlated consistently with the rheological and baking quality-related characteristics over the three production regions.

Stepwise multiple linear regressions indicated that most SRC and SIG parameters are poor predictors of rheological and baking quality-related

parameters in South African wheat, with low regression coefficients and inconsistent predictor variables across localities. Lactic acid SRC, sucrose SRC and lactic acid SIG exhibited the most positive correlations with the rheological and baking quality-related characteristics and were the independent parameters occurring in most of the models.

4.1 Introduction

End-use release criteria for bread wheat cultivars, regarding rheological and baking characteristics, as determined by the South African wheat industry need to comply with primary and secondary requirements. The primary requirements are fixed and include mixogram peak time (MPT), farinogram water-absorption (FABS), alveogram dough strength (ALVSTR), the ratio between alveogram stability (ALVP) and distensibility (ALVL) or alveogram configuration ratio (ALVP/L) and loaf volume (LFV). In this study, mixogram water absorption (MAB) was used instead of FABS as Dapcevic *et al*. (2009) reported a highly significant correlation ($r=0.98$, $p\leq0.0001$) between MABS and FABS. The secondary requirements are flexible and include ALVP and ALVL (SAGL, 2013). The assessment of these end-use release criteria requires as much as 1050 g of flour and takes up to 285 min to complete (Table 1.1). Among the small-scale rapid tests, the modified SRC protocol (Guzmán *et al*., 2015) of the Approved Method (AM) 56-11 (AACC, 2010) and the SIG method (Wang and Kovacs, 2002a) requires only 0.3 g and 0.04 g of flour, respectively. The contribution of functional polymeric components of flour to the overall flour functionality, and thus the quality of the end-product, is measured using the SRC method. The SIG method determines the swelling power of glutenin to predict dough quality characteristics and end-use quality, especially those associated with dough strength and baking characteristics.

The use of the SRC and SIG small scale rapid tests has not yet been tested on South African hard red spring wheat (HRS) and hard red winter wheat (HRW) germplasm.

Hammed *et al*. (2015) indicated that SRC results obtained from high gluten content HRS challenged the results obtained from the various studies on soft wheat germplasm (Slade and Levine, 1994; Gaines, 2000; Guttieri *et al*., 2001; Ram and Singh, 2004; Barrera *et al*., 2007; Nakamura *et al*., 2012).

This study aimed to determine the correlation of SRC and SIG values with rheological and baking quality related values and determine if rheological and baking quality related characteristics of HRS and HRW germplasm could be predicted from SRC and SIG, using small quantities of flour, in order to assist breeders with quality selection in early generations of the breeding process.

4.2 Materials and methods

4.2.1 Field trials

The same field trials and material as described in chapter 3 were used for evaluating the correlations between rheological and baking quality-related characteristics with SRC and SIG. Refer to sub-section 3.2.1.

4.2.2 Quality analysis

Samples were milled on a standard Bühler model MLU 202 mill using the AM 26-21A (AACC, 2010). Rheological and baking quality characteristics were determined at the quality laboratory of the ARC-SGI, Bethlehem in 2012 and 2013, using the appropriate Approved Methods according to the AACC, 2010.

Rheological characteristics included the Mixolab to determine MAB (AM 54-60.01) and the alveograph to determine ALVSTR, ALVL, ALVP and ALVP/L ratio (AM 54-30A). A mixograph was used to determine MPT (AM 54-40A). Baking characteristics included SDS-sedimentation volume (SDSS) (AM 56-70), wet gluten content (WGC) (AM 38-12A) and LFV (AM 10-05).

4.2.2.1 Mixolab analysis (AACC AM 54-60.01)

The Mixolab (Chopin technologies) measured the torque of dough during mixing with an increase in temperature (AACC, 2010). The Chopin+ protocol was followed and moisture content (AM 44-15A) (AACC, 2010) was determined before the analysis commenced. Water absorption was measured in the beginning of the mixolab analyses in order to determine the required water and flour volumes to form dough with a consistency of 1.1 Nm on the Chopin+ protocol that is equivalent to an overall farinograph value of 500 BU.

4.2.2.2 Alveograph analysis (AACC AM 54-30A)

A Chopin Alveograph NG, requiring 250 g of flour was used to determine dough resistance to stretching where a specially prepared sheet of dough with a specific thickness is expanded with air pressure into a bubble until it ruptures (AACC, 2010). Moisture content (AM 44-15A) (AACC, 2010) was measured beforehand in order to add the correct volume of a 2.5% sodium chloride solution to the sample. An Alveolink was used to interpret the different parameters. The different parameters included in this study were ALVP, ALVL and ALVP/L. Dough strength (ALVW) is represented by the area under the alveogram curve and was used to determine ALVSTR measured from the deformation energy (ALVW) of dough, and calculated as ALVW/6.54.

4.2.2.3 Mixograph analysis (AACC AM 54-40A)

Mixograph peak time, which is considered the primary measurement of the mixograph (National Manufacturing Corporation, Lincoln, Nebraska), was measured using a 35 g flour sample (AACC, 2010). Mixsmart software was used to analyse the mixograms. To determine flour weight and the appropriate water volume required for the analyses, protein content (AM 46-30) (AACC, 2010) and moisture content (AM 44-15A) (AACC, 2010) were obtained from the flour samples. The resistance of dough upon stretching was registered on a graph to determine optimum dough development time.

4.2.2.4 SDS-sedimentation volume (AACC AM 56-70)

SDS-sedimentation volumes were determined following the AACC (2010) AM 56-70 protocol, using a 5 g flour sample. Results were reported in ml.

4.2.2.5 Wet gluten content (AACC AM 38-12A)

A Glutomatic system, using 10 g of flour, was used to determine WGC (AACC, 2010). Flour samples were washed with a 2% sodium chloride solution and centrifuged. The following formula was used to determine WGC:

$$\%\ \text{WGC (14\% moisture basis)} = \left[\frac{\text{Total wet gluten (g)} \times 86}{100 - \text{flour moisture}} \right]$$

4.2.2.6 Loaf volume (AACC AM 10-10B)

The optimised straight dough bread making method was followed according to AM 10-10B (AACC, 2010). LFV was determined by applying the rapeseed displacement procedure (AM 10-05) (AACC, 2010).

4.2.2.7 Solvent retention capacity (AACC AM 56-11 modified method)

Refer to sub section 3.2.2.5.

4.2.2.8 Swelling index of glutenin

Refer to sub section 3.2.2.6.

4.2.2.9 SDS page

Refer to sub section 3.2.2.7.

4.2.3 Statistical analysis

Descriptive statistics, analysis of variance, correlations and stepwise multiple linear regressions were performed across the three regions for the six trial locations for the SRC, SIG and rheological and baking quality-related characteristics. Refer to sub section 3.2.3.

4.3 Results

The combined AWRC with the SRC method and the SIG method resulted in a total of six measurement points from each of the respective solvents. A total of nine rheological and baking quality-related characteristic measurement points were included in this study.

4.3.1 Descriptive statistics

4.3.1.1 Means, minimum and maximum values, standard deviations and standard error values for the rheological and baking quality-related characteristics

Mixolab water absorption was highest in the dryland SRR (Table 4.1), ranging between 56.80% and 68.60% with a mean of 62.63% for Clarens and Bethlehem combined. Mixolab water absorption was 59.93% (Table 4.2) for the irrigated SRR and 59.20% for the WRR (Table 4.3).

Alveogram dough strength for the dryland SRR (Table 4.1), irrigated SRR (Table 4.2) and WRR (Table 4.3) were 48.15 J x 10^{-4}, 37.72 J x 10^{-4} and 43.49 J x 10^{-4}, respectively.

Higher ALVSTR values were obtained in the dryland SRR, whilst the biggest range of ALVSTR values was obtained between varieties in the irrigated SRR, with a range of 24.30 J x 10^{-4} and 66.10 J x 10^{-4} (Table 4.2).

Alveogram dough stability was higher in the dryland SRR (Table 4.1) with a combined mean of 86.19 mm H_2O and a range of 64 mm H_2O and 118 mm H_2O for the different cultivars. The combined mean for ALVP in the irrigated SRR (Table 4.2) was 61.12 mm H_2O with the biggest range of 39.00 mm H_2O and 120.00 mm H_2O for the different cultivars. The WRR (Table 4.3) had a mean ALVP value of 76.94 mm H_2O for the combined localities, with the smallest range of 56 mm H_2O to 97 mm H_2O.

Alveogram dough distensibility was higher in the irrigated SRR (Table 4.2), with a mean of 148.10 mm for the combined localities. Vaalharts had the highest ALVL value and the variation between the cultivars was also the highest with a range between 64 mm and 265 mm. Mean ALVL values for the combined localities of the dryland SRR (Table 4.1) and the WRR (Table 4.3) were 115.66 mm and 118.22 mm, respectively.

The mean ALVP/L values for the dryland SRR (Table 4.1), irrigated SRR (Table 4.2) and WRR (Table 4.3) were 0.77 mm H_2O mm^{-1}, 0.45 mm H_2O mm^{-1} and 0.67 mm H_2O mm^{-1}, respectively. The largest range of ALVP/L was obtained by the irrigated SRR, varying between 0.17 mm H_2O mm^{-1} and 1.53 mm H_2O mm^{-1} for the respective cultivars.

Mean MPT values for the dryland SRR (Table 4.1), irrigated SRR (Table 4.2) and WRR (Table 4.3) were 2.83 min, 2.39 min and 2.57 min, respectively. The highst cultivar reaction towards the environment for MPT was seen in the dryland SRR with a MPT range between 1.19 min and 4.50 min.

SDS-sedimentation volumes for the combined localities in each production region were 86.09 ml, 87.92 ml and 91.39 ml for the dryland SRR (Table 4.1), irrigated SRR (Table 4.2) and the WRR (Table 4.3), respectively.

The highest SDSS value of 98 ml was obtained in the irrigated SRR (Table 4.2), and the biggest variation amongst cultivars was in the dryland SRR with a range of 64 ml to 96 ml (Table 4.1).

Wet gluten content values were highest (41.19%) in the dryland SRR (Table 4.1) with the biggest range of 33.10% to 51.10% for the different cultivars. In the irrigated SRR (Table 4.2) the mean WGC value was the lowest at 35.31% and in the WRR at 37.48% (Table 4.3).

Mean LVF values were higher in the dryland SRR (973 cm^3) with a range of 800 to 1030 cm^3 between the different cultivars (Table 4.1). In the irrigated SRR (Table 4.2), LFV ranged between 780 cm^3 and 1030 cm^3, with the lowest mean of 916 cm^3 obtained in this region. The WRR (Table 4.3) had LFV values that ranged between 855 and 1030 cm^3, and an average mean of 955 cm^3.

Table 4.1 Mean values, range and standard error for rheological and baking quality–related characteristics for 17 wheat cultivars evaluated in the dryland summer rainfall region

Characteristic	Environment	MEAN	MIN	MAX	SD	SE
	Bethlehem	63.55	58.00	68.60	2.22	0.31
MAB (%)	Clarens	61.71	56.80	65.90	1.88	0.26
	Combined	62.63	56.80	68.60	2.24	0.22
	Bethlehem	51.73	37.30	67.00	7.81	1.19
ALVSTR (J x 10^{-4})	Clarens	44.64	28.40	61.90	7.36	1.11
	Combined	48.15	28.40	67.00	8.34	0.89
	Bethlehem	91.49	66.00	118.00	14.22	1.99
ALVP (mm H_2O)	Clarens	80.67	64.00	117.00	12.59	1.80
	Combined	86.19	64.00	118.00	14.44	1.44
	Bethlehem	107.49	70.00	147.00	16.13	2.35
ALVL (mm)	Clarens	123.67	87.00	162.00	18.26	2.64
	Combined	115.66	70.00	162.00	18.97	1.95
	Bethlehem	0.88	0.53	1.62	0.25	0.04
ALVP/L (mm H2O mm^{-1})	Clarens	0.67	0.42	1.34	0.19	0.03
	Combined	0.77	0.42	1.62	0.24	0.02
	Bethlehem	3.09	1.93	4.50	0.59	0.08
MPT (min)	Clarens	2.57	1.91	3.71	0.40	0.06
	Combined	2.83	1.91	4.50	0.56	0.06
	Bethlehem	87.22	70.00	95.00	7.50	1.06
SDSS (ml)	Clarens	84.94	64.00	96.00	7.94	1.13
	Combined	86.09	64.00	96.00	7.77	0.78
	Bethlehem	43.15	37.30	51.10	2.85	0.41
WGC (%)	Clarens	39.18	33.10	47.40	3.99	0.58
	Combined	41.19	33.10	51.10	3.98	0.40
	Bethlehem	1008	925	1030	22.90	3.21
LFV (cm^3)	Clarens	936	800	1030	64.50	9.21
	Combined	973	800	1030	60.02	6.00

MAB=mixolab water-absorption, ALVSTR=alveogram dough strength, ALVP=alveogram dough stability, ALVL=alveogram dough distensibility, ALVP/L=alveogram configuration ratio, MPT=mixogram peak time, SDSS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, MEAN=mean values, MIN=minimum values, MAX=maximum values, SD=standard deviation, SE=standard error

Table 4.2 Mean values, range and standard error for rheological and baking quality–related characteristics for 22 wheat cultivars evaluated in the irrigated summer rainfall region

Characteristic	Environment	MEAN	MIN	MAX	SD	SE
MAB (%)	Upington	61.04	58.10	65.80	1.74	0.21
	Vaalharts	58.80	55.10	62.70	1.78	0.22
	Combined	59.93	55.10	65.80	2.08	0.18
ALVSTR (J x 10^{-4})	Upington	36.46	24.30	66.10	8.20	1.03
	Vaalharts	39.02	26.60	50.80	6.01	0.77
	Combined	37.72	24.30	66.10	7.30	0.66
ALVP (mm H_2O)	Upington	63.55	46.00	120.00	14.00	1.75
	Vaalharts	58.65	39.00	99.00	13.30	1.68
	Combined	61.12	39.00	120.00	13.82	1.23
ALVL (mm)	Upington	144.11	85.00	197.00	22.66	2.83
	Vaalharts	152.28	64.00	265.00	36.19	4.63
	Combined	148.10	64.00	265.00	30.19	2.70
ALVP/L (mm H2O mm^{-1})	Upington	0.47	0.26	1.38	0.21	0.03
	Vaalharts	0.43	0.17	1.53	0.24	0.03
	Combined	0.45	0.17	1.53	0.23	0.02
MPT (min)	Upington	2.23	1.44	3.92	0.41	0.05
	Vaalharts	2.55	1.72	4.37	0.49	0.06
	Combined	2.39	1.44	4.37	0.48	0.04
SDSS (ml)	Upington	86.98	72.00	96.00	6.16	0.76
	Vaalharts	88.83	74.00	98.00	6.07	0.75
	Combined	87.92	72.00	98.00	6.16	0.54
WGC (%)	Upington	34.17	29.05	41.69	2.73	0.34
	Vaalharts	36.48	28.38	44.90	3.67	0.46
	Combined	35.31	28.38	44.90	3.41	0.30
LFV (cm^3)	Upington	903	780	1030	55.06	6.99
	Vaalharts	928	800	1030	64.09	8.14
	Combined	916	780	1030	60.80	5.46

MAB=mixolab water-absorption, ALVSTR=alveogram dough strength, ALVP=alveogram dough stability, ALVL=alveogram dough distensibility, ALVP/L=alveogram configuration ratio, MPT=mixogram peak time, SDSS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, MEAN=mean values, MIN=minimum values, MAX=maximum values, SD=standard deviation, SE=standard error

Table 4.3 Mean values, range and standard error for rheological and baking quality–related characteristics for nine wheat cultivars evaluated in the winter rainfall region

Characteristic	Environment	MEAN	MIN	MAX	SD	SE
MAB (%)	Moorreesburg	59.04	53.00	63.30	2.31	0.45
	Riversdal	59.36	55.40	61.90	1.67	0.32
	Combined	59.20	53.00	63.30	2.00	0.27
ALVSTR (J x 10^{-4})	Moorreesburg	45.84	35.80	53.80	4.15	0.80
	Riversdal	41.14	29.10	52.80	6.08	1.17
	Combined	43.49	29.10	53.80	5.67	0.77
ALVP (mm H_2O)	Moorreesburg	77.04	62.00	96.00	9.01	1.73
	Riversdal	76.85	56.00	97.00	11.24	2.16
	Combined	76.94	56.00	97.00	10.09	1.37
ALVL (mm)	Moorreesburg	117.59	84.00	144.00	19.75	3.80
	Riversdal	118.85	93.00	142.00	15.21	2.93
	Combined	118.22	84.00	144.00	17.47	2.38
ALVP/L (mm H2O mm^{-1})	Moorreesburg	0.68	0.44	1.13	0.19	0.04
	Riversdal	0.66	0.41	1.04	0.15	0.03
	Combined	0.67	0.41	1.13	0.17	0.02
MPT (min)	Moorreesburg	2.69	1.81	3.59	0.48	0.09
	Riversdal	2.46	2.13	3.02	0.21	0.04
	Combined	2.57	1.81	3.59	0.38	0.05
SDSS (ml)	Moorreesburg	90.63	80.00	95.00	3.91	0.75
	Riversdal	92.15	84.00	96.00	3.53	0.68
	Combined	91.39	80.00	96.00	3.77	0.51
WGC (%)	Morreesburg	39.20	31.30	46.20	3.03	0.58
	Riversdal	35.76	31.10	43.40	3.24	0.62
	Combined	37.48	31.10	46.20	3.56	0.48
LFV (cm^3)	Morreesburg	970	895	1030	41.65	8.01
	Riversdal	939	855	1030	54.16	10.42
	Combined	954	855	1030	50.42	6.86

MAB=mixolab water-absorption, ALVSTR=alveogram dough strength, ALVP=alveogram dough stability, ALVL=alveogram dough distensibility, ALVP/L=alveogram configuration ratio, MPT=mixogram peak time, SDSS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, MEAN=mean values, MIN=minimum values, MAX=maximum values, SD=standard deviation, SE=standard error

4.3.2 Analysis of variance

4.3.2.1 Combined ANOVA for rheological and baking quality-related characteristics

The variance component contribution for the 17 cultivars in the dryland SRR is summarised in Table 4.4, and the genotype x environment means for the individual dryland localities in Tables 4.5 – 4.9. Variance component contribution for the 22 cultivars in the irrigated SRR is summarised in Table 4.10, and the genotype x environment means for the individual irrigated SRR localities in Tables 4.11 – 4.15. The WRR variance component contribution for the nine cultivars is summarised in Table 4.16 and the genotype x environment means for the individual WRR localities in Tables 4.17 – 4.19.

The combined ANOVA for the dryland SRR (Table 4.4), irrigated SRR (Table 4.10) and WRR (Table 4.16) indicated highly significant differences among cultivars and their reaction to the environment. The largest variation was attributed to highly significant ($p \leq 0.001$) cultivar effects across all three production regions. The environment effect was significant for all rheological and baking quality-related characteristics except for MAB, ALVP, ALVL and ALVP/L, only in the WRR.

Cultivar x environment interaction was significant across the regions except for MPT in the irrigated SRR and ALVSTR and ALVL in the WRR, indicating that cultivar performance was subjected to specific environmental conditions.

4.3.2.1.1 Mixolab water absorption

Cultivar differences were highly significant ($p \leq 0.001$) across the three production regions. Cultivar contributed, 45.74%, 60.55% and 69.40% to variation for the irrigated SRR (Table 4.10), WRR (Table 4.16), and dryland SRR (Table 4.4) respectively. The environmental contribution to variation was highly significant ($p \leq 0.001$) in the dryland (16.99%) and irrigated SRR (29.18%) and non-significant in the WRR. The cultivar x environment interaction was significant

across regions, with the highest contribution to variation in the WRR (14.33%) ($p \leq 0.05$). In the dryland and irrigated SRR the cultivar x environment effect was highly significant ($p \leq 0.001$), but with a lower contribution to variation.

In the dryland SRR (Table 4.5) cultivar means across environments ranged between 59.32% (PAN 3195) and. 65.80% (PAN 3120). The MAB value for PAN 3120 was significantly higher than that of the rest of the cultivars. In the irrigated SRR (Table 4.11) cultivar differences were significant and ranged between 57.80% (SST 866) and 62.97% (SST 822). Vaalharts had higher MAB values than Upington and differences between the localities were significant. In the WRR (Table 4.17), Moorreesburg and Riversdal did not differ significantly from each other in terms of MAB. Differences between cultivars were significant and cultivar means across environments ranged between 61.79% (SST 015) and 58.25% (SST 88).

4.3.2.1.2 Alveogram dough strength

The three production regions showed highly significant ($p \leq 0.001$) cultivar effects for this characteristic. Cultivar contributed 60.09%, 61.87% and 41.10% to variation for ALVSTR for the dryland SRR (Table 4.4), irrigated SRR (Table 4.10) and WRR (Table 4.16), respectively. The environment effect was highly significant for all the regions ($p \leq 0.001$) and contributed from 3.12% in the irrigated SRR to 18.28% to variation in the dryland SRR. The cultivar x environment interaction contributed significantly ($p \leq 0.001$) to variation in the irrigated SRR, significant ($p \leq 0.01$) in the dryland SRR and non-significant in the WRR.

In the dryland SRR (Table 4.5) cultivar means across environments ranged between 60.98 J x 10^{-4} (PAN 3161) and 38.40 J x 10^{-4} (SST 317). In the irrigated SRR (Table 4.11), SST 843 had the highest ALVSTR value at Upington and Vaalharts. The cultivar means across the irrigated SRR ranged between 58.28 J x 10^{-4} (SST 843) and 27.37 J x 10^{-4} (SST 876). The ALVSTR means value of SST 843, was significantly higher than the rest of the cultivars. Cultivar means for the WRR (Table 4.17) ranged from 48.29 J x 10^{-4} (SST 047) to

37.39 J x 10^{-4} (SST 88). All the localities differed significantly across the three production regions.

4.3.2.1.3 Alveogram dough stability

Cultivars were the largest contributor to the total variation. Highly significant ($p \leq 0.01$) cultivar effects were observed across the three production regions. Cultivar contributions to variation were 69.12%, 82.02% and 68.30% for the dryland SRR (Table 4.4), irrigated SRR (Table 4.10) and the WRR (Table 4.16), respectively. Environmental effects were highly significant ($p \leq 0.001$) in the SRR and non-significant in the WRR.

Cultivar x environment interaction was highly significant ($p \leq 0.001$) for all three regions with the largest contributor to variation in the WRR (20.20%) and the lowest in the dryland SRR (6.68%).

In the dryland SRR (Table 4.6), Koonap had the highest ALVP value of 114.33 mm H_2O (Bethlehem) and Gariep the lowest value of 65.33 mm H_2O (Clarens). Cultivar means ranged from 112.17 mm H_2O (Koonap) to 71.00 mm H_2O (PAN 3195). SST 843 had significantly higher ALVP values than the other cultivars at the irrigated SRR (Table 4.12) localities and for the combined localities. Cultivar means across localities ranged from 101.83 mm H_2O (SST 843) to 46.25 mm H_2O (Timbavati). In the WRR (Table 4.17), the lowest ALVP value of 61.33 mm H_2O was obtained for SST 027 in Riversdal and the highest value of 91.33 mm H_2O for SST 096 in Moorreesburg. Cultivar means ranged from 91.00 mm H_2O (SST 096) to 63.83 mm H_2O (SST 027). Environmental means for Moorreesburg did not differ significantly from Riversdal (Table 4.17).

4.3.2.1.4 Alveogram dough distensibility

The cultivar effect was highly significant (p≤0.001) in the dryland SRR (Table 4.4), irrigated SRR (Table 4.10) and WRR (Table 4.16) with the highest contribution to variation of 40.75%, 69.34% and 47.63% in the respective regions. The environment contributed 18.36% (p≤0.001) in the dryland SRR and 1.82% (p≤0.01) to variation in the irrigated SRR. The cultivar x environment interaction was highly significant (p≤0.001) in both the dryland (17.88%) and irrigated (12.05%) SRR. Cultivar effect, environment effect and cultivar x environment interaction were non-significant in the WRR (Table 4.16). Significant differences were observed for cultivars in the dryland SRR (Table 4.6). Cultivar means ranged from 140.80 mm (PAN 3368) to 90.60 mm (Koonap).

Alveogram dough distensibility values were higher in the irrigated SRR (Table 4.12). The cultivar means ranged from 184.54 mm (Duzi) to 93.07 mm (SST 843). In the WRR (Table 4.18), ALVL values ranged from 134.34 mm (SST 027) to 97.84 mm (Tankwa) and Riversdal did not differ significantly from Moorreesburg.

4.3.2.1.5 Alveogram configuration ratio

Highly significant differences (p≤0.001) were observed for cultivars in the dryland SRR (Table 4.4), irrigated SRR (Table 4.10), and in the WRR (Table 4.16). Cultivars were the largest contributor to the total variation, contributing 55.31%, 78.89% and 52.00% respectively, in the dryland SRR, irrigated SRR and WRR. The environmental effect was highly significant (p≤0.001) in the dryland SRR, significant (p≤0.01) in the irrigated SRR and non-significant in the WRR.
The cultivar x environmental interaction was highly significant across the production regions, with the highest contributor to variation in the WRR (26.25%) (Table 4.16) and the lowest in the irrigated SRR (10.57%) (Table 4.10).

Cultivar means in the dryland SRR (Table 4.7) ranged from 0.56 mm H_2O mm^{-1} (Gariep and PAN 3368) to 1.23 mm H_2O mm^{-1} (Koonap). The highest ALVP/L

value of 1.29 mm H_2O mm^{-1} was obtained by Koonap in Bethlehem and the lowest value of 0.48 mm H_2O mm^{-1} by Gariep in Clarens. In the irrigated SRR (Table 4.13), the cultivar means ranged from 0.25 mm H_2O mm^{-1} (Duzi and Timbavati) to 1.09 mm H_2O mm^{-1} (SST 843). Environmental means ranged from 0.43 mm H_2O mm^{-1} (Upington) to 0.47 mm H_2O mm^{-1} (Vaalharts) and differed significantly. In the WRR (Table 4.18), cultivar means ranged from 0.48 mm H_2O mm^{-1} (SST 027) to 0.90 mm H_2O mm^{-1} (SST 096). Environmental means for Riversdal (0.66 mm H_2O mm^{-1}) and Moorreesburg (0.68 mm H_2O mm^{-1}) did not differ significantly.

4.3.2.1.6 Mixogram peak time

Cultivars revealed highly significant ($p \leq 0.001$) differences for MPT values with the highest contribution to total variation for the dryland SRR (56.28%) (Table 4.4), the irrigated SRR (71.96%) (Table 4.10) and the WRR (52.04%) (Table 4.16). The environment contributed 21.48%, 11.31% and 9.23% to variation for the dryland SRR, irrigated SRR and the WRR, respectively and highly significant ($p \leq 0.001$) across the three regions. The cultivar x environment interaction varied across regions, with the highest contribution to variation in the WRR of 28.87% ($p \leq 0.001$) and 7.19% ($p \leq 0.05$) in the dryland SRR. The cultivar x environment interaction was non-significant in the irrigated SRR.

In the dryland SRR (Table 4.7) MPT means for the cultivars varied between 3.57 min (Senqu) and 2.13 min (PAN 3120). In the irrigated SRR (Table 4.13) SST 843 had the highest MPT value of 3.99 min in Upington as well as in Vaalharts (3.69 min). Cultivar means for MPT ranged from 2.04 min (Timbavati) to 3.84 min (SST 843). Cultivar means in the WRR (Table 4.18) varied between 2.09 min (SST 015) and 3.02 min (Tankwa). The highest MPT value (3.49 min) was obtained by Tankwa in Moorreesburg and the lowest by SST 015 (1.88 min) also in Moorreesburg.

4.3.2.1.7 SDS-sedimentation volume

The cultivar effect was highly significant (p≤0.001) across the production regions of the dryland SRR (Table 4.4), irrigated SRR (Table4.10) and WRR (Table 4.16). Cultivar contributed 37.53%, 47.98% and 60.84% to variation in the dryland SRR, irrigated SRR, and in the WRR, respectively.

The environment effect was significant (p≤0.01) and low in the dryland SRR (Table 4.4) and contributed 2.18% to the total variation and 2.27% (p≤0.05) in the irrigated SRR (Table 4.10). The environment effect was significant (p≤0.05) and low in the WRR (Table 4.16). The cultivar x environment interaction was significant (p≤0.001) and contributed more towards the total variation (42.33%) in the dryland SRR (Table 4.4) than the cultivars. In the irrigated SRR (Table 4.10), the cultivar x environment interaction significantly (p≤0.01) contributed 17.29% to the total variation and 13.95% (p≤0.05) in the WRR (Table 4.16).

Cultivar means ranged from 78.50 ml (PAN 3120 and SST 398) to 92.50 ml (Matlabas) in the dryland SRR (Table 4.8). Matlabas, Koonap and PAN 3161 did not differ significantly. In the irrigated SRR (Table 4.14), Umlazi had the highest SDSS volume at Upington (95.67 ml) and Vaalharts (94.00 ml). Cultivar means ranged from 94.83 ml (Umlazi) to 78.00 ml (SST 877). In the WRR (Table 4.19), SDSS values ranged from 94.17 ml (SST 015) to 85.67 ml (Tankwa).

4.3.2.1.8 Wet gluten content

Cultivar effect was highly significant (p≤0.001) in the dryland SRR (Table 4.4), irrigated SRR (Table 4.10) and the WRR (Table 4.16). Cultivar contributed most to the total variation across the regions. The contribution of cultivar to variation was 49.86%, 40.01% and 47.37% in the dryland SRR, irrigated SRR, and in the WRR, respectively.

The environment effect was highly significant for the three regions, with the highest contribution to the total variation in the dryland SRR (25.15%) (Table 4.4) and the lowest contribution of 11.56% in the irrigated SRR (Table 4.10).

The cultivar x environment effect was highly significant (p≤0.001) in the irrigated SRR (Table 4.10), and contributed 15.07% to the total variation, significant (p≤0.05) in the dryland SRR (Table 4.4) and contributed 7.29% to variation and 10.60% in the WRR (Table 4.16).

In the dryland SRR (Table 4.8), cultivar means ranged from 36.92% (PAN 3161) to 46.85% (SST 398). The highest WGC percentage was obtained by PAN 3120 (48.73%) in Bethlehem and the lowest WGC percentage by Matlabas (34.70%) in Clarens. Environmental means for Clarens differed significantly from that of Bethlehem. In the irrigated SRR (Table 4.14), the highest WGC percentage of 42.23% was obtained by Timbavati in Upington and the lowest percentage of 29.82% by PAN 3471 in Upington. Cultivar means ranged from 31.61% (PAN 3471) to 39.83% (SST 822). Environmental means for Upington differed significantly from that of Vaalharts. In the WRR (Table 4.19), SST 047 had the highest WCG percentage of 45.57% in Moorreesburg and SST 88 the lowest percentage of 32.23% in Riversdal. The two localities differed significantly from each other with cultivar means ranging from 36.40% (SST 087) to 43.44% (SST 047).

4.3.2.1.9 Loaf volume

Highly significant differences (p≤0.001) were observed for cultivars in the three production regions. Cultivar contributed more to the total variation in the irrigated SRR (Table 4.10) and WRR (Table 4.16), but less than the environment in the dryland SRR (Table 4.4). The cultivar contributions to the total variation were 30.37%, 43.38% and 37.85% for the dryland SRR (Table 4.4), irrigated SRR (Table 4.10), and in the WRR (Table 4.16), respectively. The environment effect was highly significant (p≤0.001) and made a higher contribution to the total variation in the dryland SRR (36.64%) (Table 4.4) and lowest in the irrigated SRR at 4.23% (Table 4.10). The environment had a highly significant (p≤0.001) effect on LFV for the WRR (Table 4.16) and contributed 9.93% to the total variation.

The cultivar x environment interaction was highly significant (p≤0.001) in the SRR with the highest contribution to the total variation in the irrigated SRR (34.80%)

(Table 4.10) and 19.08% in the dryland SRR (Table 4.4). In the WRR (Table 4.16), cultivar x environment interaction was significant ($p \leq 0.01$) and contributed 19.90% to the total variation. Cultivar means ranged from 919 cm^3 (SST 387) to 1018 cm^3 (PAN 3118) in the dryland SRR (Table 4.9). The environmental means were higher at Bethlehem (1008 cm^3) compared to Clarens (936 cm^3) and differed significantly. In the irrigated SRR (Table 4.15), the highest LFV was obtained by Timbavati (1030.00 cm^3) at Upington and the lowest LFV was obtained by PAN 3478 (820.00 cm^3) at Vaalharts. Cultivar means ranged between 843 cm^3 (PAN 3471) and 988 cm^3 (Sabie). Environmental means for Upington and Vaalharts differed significantly. In the WRR (Table 4.19), environmental means ranged from 939 cm^3 (Riversdal) to 970 cm^3 (Moorreesburg) and differed significantly. Cultivar means ranged from 923 cm^3 (Tankwa) to 1024 cm^3 (SST 047). The highest LFV was obtained for SST 015 (1030 cm^3) (Moorreesburg) and the lowest LFV by Tankwa (888 cm^3) (Riversdal).

Table 4.4 Combined analysis of variance for rheological and baking quality-related characteristics for 17 wheat cultivars in the dryland summer rainfall region

		Mean squares								
SOURCE	**df**	**MAB**	**ALVSTR**	**ALVP**	**ALVL**	**ALVP/L**	**MPT**	**SDS**	**WGC**	**LVF**
Environment	1	86,44***	1093,70***	2923,87***	6214,81***	0,98***	6,70***	128,79**	382,11***	130662,22***
Rep (Environment)	4	2,40***	39,42*	80,74ns	351,51*	0,04*	0,24**	41,33*	22,21***	2254,16*
Cultivar	16	22,06***	224,70***	891,40***	861,85***	0,20***	1,10***	138,69***	47,34***	6769,44***
Cult x Env	16	2,04***	35,90**	86,18***	378,29***	12,76***	0,14*	156,40***	6,92*	4253,15***
Error	64	0,42	11,47	28,18	111,93	0,01	0,06	14,70	3,05	654,19
CV (%)		1,04	7,03	6,16	9,15	13,77	8,74	4,45	4,24	2,63
R^2		0.95	0.91	0.92	0.81	0.88	0.88	0.85	0.88	0.89
		Variance component contribution (% of SS)								
Environment	1	16.99	18.28	14.17	18.36	17.41	21.48	2.18	25.15	36.64
Rep (Environment)	4	1.89	2.64	1.57	4.15	2.83	3.10	2.80	5.58	2.53
Cultivar	16	69.40	60.09	69.12	40.75	55.31	56.28	37.53	49.86	30.37
Cult x Env	16	6.42	9.60	6.68	17.88	12.76	7.19	42.33	7.29	19.08

* p≤0.05, ** p≤0.01, *** p≤0.001, ns=non-significant, df=degrees of freedom, MAB=mixolab water-absorption, ALVSTR=alveogram dough strength, ALVP=alveogram dough stability, ALVL=alveogram dough distensibility, ALVP/L=alveogram configuration ratio, MPT=mixogram peak time, SDSS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, Cult x Env=cultivar x environment interaction, CV=coefficient of variance, R^2= coefficient of determination, SS=sum of squares

Table 4.5 Genotype and environmental means for mixolab water-absorption and alveogram dough strength in the dryland summer rainfall region

	MAB (%)				Cult		ALVSTR (J x 10^{-4})				Cult	
Cultivar	**Bhm**		**Cla**		**Means**		**Bhm**		**Cla**		**Means**	
Elands	62.57	**h**	61.57	**fg**	62.07	**f**	53.90	**bcd**	49.17	**bc**	51.53	**cd**
Gariep	58.90	**j**	59.87	**hi**	59.38	**h**	42.10	**gh**	39.27	**d**	40.40	**h**
Koonap	66.47	**b**	65.33	**a**	65.90	**a**	58.73	**ab**	55.10	**a**	56.92	**ab**
Matlabas	64.67	**cd**	60.97	**gh**	62.82	**def**	61.35	**a**	47.80	**bc**	54.58	**bc**
PAN 3118	63.27	**gh**	62.23	**def**	62.75	**def**	62.50	**a**	48.43	**bc**	54.06	**bc**
PAN 3120	67.73	**a**	63.87	**b**	65.80	**a**	48.67	**defg**	47.05	**c**	48.02	**def**
PAN 3161	64.20	**def**	62.50	**cdef**	63.35	**cd**	63.77	**a**	56.80	**a**	60.98	**a**
PAN 3195	60.50	**i**	58.13	**j**	59.32	**h**	42.65	**fgh**	37.75	**d**	40.20	**h**
PAN 3368	63.73	**efg**	63.03	**bcd**	63.38	**cd**	60.00	**ab**	48.45	**bc**	54.23	**bc**
PAN 3379	65.03	**cd**	63.63	**bc**	64.33	**b**	56.90	**abc**	47.47	**bc**	52.18	**cd**
Senqu	63.33	**fgh**	61.30	**fg**	62.32	**ef**	48.35	**defg**	25.80	**ab**	50.58	**cde**
SST 316	64.37	**cde**	61.43	**fg**	62.90	**de**	50.35	**cde**	40.97	**d**	44.72	**fg**
SST 317	64.33	**cde**	61.47	**fg**	62.90	**de**	40.67	**h**	36.13	**d**	38.40	**h**
SST 347	61.40	**i**	59.73	**i**	60.57	**g**	46.67	**efgh**	46.83	**c**	46.75	**ef**
SST 356	63.73	**efg**	61.73	**efg**	62.73	**def**	45.55	**efgh**	38.00	**d**	41.02	**gh**
SST 387	61.00	**i**	59.47	**i**	60.23	**g**	47.43	**defgh**	29.35	**e**	40.20	**h**
SST 398	65.20	**c**	62.87	**bcde**	64.03	**bc**	49.53	**def**	40.03	**d**	44.78	**fg**
Env	63.56		61.71		62.63		51.73		44.64		48.21	
Mean	**a**		**b**				**a**		**b**			
LSD Cult	0.90		1.23		0.75		6.94		5.63		4.30	
LSD Env	0.26						1.46					

Means followed by the same letter, did not differ significantly at p=0.05. Bhm=Bethlehem, Cla=Clarens, MAB=mixolab water-absorption, ALVSTR=alveogram dough strength, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 4.6 Genotype and environmental means for alveogram dough stability and alveogram dough distensibility in the dryland summer rainfall region

	ALVP (mm H_2O)				Cult		ALVL (mm)				Cult	
Cultivar	**Bhm**		**Cla**		**Means**		**Bhm**		**Cla**		**Means**	
Elands	101.33	**bcd**	80.33	**cde**	90.83	**bc**	94.67	**fgh**	126.67	**bcdef**	110.67	**ef**
Gariep	73.00	**g**	65.33	**h**	69.17	**g**	108.50	**cdef**	136.00	**abc**	125.00	**bcd**
Koonap	114.33	**a**	110.00	**a**	112.17	**a**	84.00	**h**	95.00	**h**	90.60	**g**
Matlabas	104.67	**abc**	85.00	**bc**	96.80	**b**	110.67	**cdef**	133.33	**defgh**	112.00	**ef**
PAN 3118	85.67	**ef**	76.67	**def**	81.17	**d**	122.00	**abc**	149.00	**a**	135.50	**ab**
PAN 3120	103.33	**bcd**	81.00	**cd**	92.17	**bc**	89.67	**gh**	131.50	**abcde**	106.40	**ef**
PAN 3161	110.67	**ab**	105.33	**a**	108.00	**a**	102.00	**defg**	121.67	**cdef**	111.83	**ef**
PAN 3195	73.33	**g**	68.67	**gh**	71.00	**g**	110.00	**cdef**	117.50	**cdefg**	113.75	**de**
PAN 3368	81.33	**fg**	73.50	**efg**	78.20	**def**	134.00	**a**	145.33	**ab**	140.80	**a**
PAN 3379	93.33	**ed**	90.67	**b**	92.00	**bc**	130.00	**ab**	128.00	**bcdef**	129.00	**abc**
Senqu	105.33	**abc**	77.67	**cdef**	91.50	**bc**	84.33	**h**	133.67	**abcd**	109.00	**ef**
SST 316	96.33	**cd**	80.67	**cde**	88.50	**c**	103.67	**defg**	109.67	**fgh**	106.67	**ef**
SST 317	77.33	**fg**	67.33	**gh**	72.33	**fg**	101.67	**efg**	130.33	**abcde**	116.00	**de**
SST 347	79.33	**fg**	78.33	**cdef**	78.33	**de**	118.00	**abcd**	134.00	**abc**	126.00	**bcd**
SST 356	93.33	**ed**	81.67	**cd**	87.50	**c**	99.00	**efgh**	100.33	**gh**	99.67	**fg**
SST 387	78.00	**fg**	71.00	**fgh**	74.50	**efg**	123.00	**abc**	111.00	**efgh**	118.20	**cde**
SST 398	84.67	**ef**	77.33	**def**	81.00	**d**	114.33	**bcde**	115.67	**cdefg**	115.00	**de**
Env	91.49		80.67		86.19		107.49		123.67		115.65	
Mean	**a**		**b**				**b**		**a**			
LSD Cult	10.08		7.50		6.20		16.24		20.51		12.76	
LSD Env	2.12						4.35					

Means followed by the same letter, did not differ significantly at p=0.05. Bhm=Bethlehem, Cla=Clarens, ALVP=alveogram dough stability, ALVL=alveogram dough distensibility, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 4.7 Genotype and environmental means for alveogram dough configuration ratio and mixogram peak time in the dryland summer rainfall region

	ALVP/L (mm H2O mm^{-1})				Cult		MPT (min)				Cult	
Cultivar	**Bhm**		**Cla**		**Means**		**Bhm**		**Cla**		**Means**	
Elands	0.93	**cd**	0.64	**defgh**	0.76	**def**	3.74	**ab**	3.21	**a**	3.48	**a**
Gariep	0.64	**e**	0.48	**i**	0.56	**h**	3.74	**ab**	2.98	**ab**	3.36	**a**
Koonap	1.29	**a**	1.18	**a**	1.23	**a**	3.52	**bc**	3.09	**a**	3.31	**ab**
Matlabas	0.95	**bcd**	0.76	**bcd**	0.87	**bcd**	3.24	**cde**	2.88	**abcd**	3.06	**bc**
PAN 3118	0.71	**e**	0.52	**hi**	0.62	**gh**	3.09	**cde**	2.56	**def**	2.82	**cde**
PAN 3120	1.16	**ab**	0.62	**defghi**	0.94	**bc**	2.16	**i**	2.28	**fgh**	2.13	**g**
PAN 3161	1.10	**abc**	0.87	**b**	0.99	**b**	3.31	**bcde**	2.63	**cde**	2.98	**cd**
PAN 3195	0.69	**e**	0.59	**fghi**	0.64	**fgh**	2.82	**efgh**	2.39	**efgh**	2.61	**ef**
PAN 3368	0.58	**e**	0.53	**ghi**	0.56	**h**	3.39	**bcd**	2.68	**bcde**	3.04	**bc**
PAN 3379	0.79	**de**	0.72	**cdef**	0.74	**ef**	2.48	**hi**	2.12	**hi**	2.26	**g**
Senqu	1.28	**a**	0.58	**fghi**	0.93	**bc**	4.20	**a**	2.93	**abc**	3.57	**a**
SST 316	0.93	**cd**	0.74	**bcde**	0.84	**cde**	2.98	**defg**	2.61	**cdef**	2.79	**cdef**
SST 317	0.77	**de**	0.52	**hi**	0.65	**fgh**	2.49	**ghi**	2.08		2.29	**g**
SST 347	0.68	**e**	0.59	**efghi**	0.64	**fgh**	2.55	**fghi**	2.46	**hi**	2.51	**fg**
SST 356	0.95	**bcd**	0.82	**abc**	0.88	**bcd**	3.09	**cde**	2.51	**ef**	2.74	**def**
SST 387	0.63	**e**	0.59	**fghi**	0.61	**gh**	3.04	**cdef**	2.16	**ghi**	2.60	**ef**
SST 398	0.74	**e**	0.68	**cdefg**	0.71	**efg**	2.54	**ghi**	1.94	**i**	2.30	**g**
Env	0.88		0.67		0.77		3.09		2.57		2.81	
Mean	**a**		**b**				**a**		**b**			
LSD Cult	0.22		0.15		0.13		0.50		0.34		0.29	
LSD Env	0.04						0.10					

Means followed by the same letter, did not differ significantly at p=0.05. Bhm=Bethlehem, Cla=Clarens, ALVP/L=alveogram configuration ratio, MPT=mixogram peak time, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 4.8 Genotype and environmental means for SDS-sedimentation volume and wet gluten content in the dryland summer rainfall region

	SDSS (ml)				Cult		WGC (%)				Cult	
Cultivar	**Bhm**		**Cla**		**Means**		**Bhm**		**Cla**		**Means**	
Elands	90.67	**a**	84.67	**cde**	87.67	**bcde**	42.03	**ef**	36.97	**fgh**	39.50	**efg**
Gariep	92.33	**a**	85.33	**bcd**	88.83	**abcd**	40.37	**fg**	39.07	**defg**	39.72	**efg**
Koonap	91.33	**a**	94.33	**a**	92.83	**a**	45.97	**bc**	42.73	**bc**	44.35	**bc**
Matlabas	92.00	**a**	93.00	**a**	92.50	**a**	43.23	**de**	34.70	**h**	38.97	**gh**
PAN 3118	90.00	**a**	91.00	**abc**	90.50	**ab**	43.43	**cde**	42.67	**bc**	43.05	**cd**
PAN 3120	70.33	**cd**	79.67	**def**	78.50	**h**	48.73	**a**	43.73	**ab**	46.23	**ab**
PAN 3161	92.00	**a**	92.67	**a**	92.33	**a**	38.87	**g**	34.97	**h**	36.92	**h**
PAN 3195	87.33	**ab**	91.00	**abc**	89.17	**abc**	43.76	**cde**	38.40	**efg**	41.08	**def**
PAN 3368	83.33	**bc**	88.00	**abc**	85.67	**cdef**	43.87	**cde**	41.90	**bcd**	43.08	**cd**
PAN 3379	70.00	**e**	91.33	**ab**	82.00	**fgh**	41.40	**efg**	36.20	**fgh**	38.80	**gh**
Senqu	88.33	**ab**	78.00	**f**	83.17	**efg**	42.63	**def**	39.77	**cdef**	41.20	**de**
SST 316	90.67	**a**	75.67	**f**	83.17	**efg**	41.93	**ef**	35.90	**gh**	38.92	**gh**
SST 317	92.33	**a**	66.50	**f**	82.00	**fgh**	44.90	**bcd**	41.03	**bcde**	42.97	**cd**
SST 347	93.67	**a**	86.00	**bcd**	89.83	**abc**	43.63	**cde**	38.67	**defg**	41.15	**de**
SST 356	91.67	**a**	73.50	**f**	84.40	**defg**	38.85	**g**	37.07	**fgh**	37.78	**gh**
SST 387	75.67	**de**	84.67	**cde**	80.17	**gh**	41.83	**ef**	34.75	**h**	39.00	**fg**
SST 398	78.33	**cd**	78.67	**ef**	78.50	**h**	46.93	**ab**	46.77	**a**	46.85	**a**
Env Mean	87.22	**a**	84.94	**b**	85.95		43.15	**a**	39.18	**b**	41.15	
LSD Cult	6.48		6.58		4.50		2.71		3.32		2.08	
LSD Env	1.54						0.71					

Means followed by the same letter, did not differ significantly at p=0.05. Bhm=Bethlehem, Cla=Clarens, SDSS=SDS-sedimentation volume, WGC=wet gluten content, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 4.9 Genotype and environmental means for loaf volume in the dryland summer rainfall region

Cultivar	LVF (cm^3) Bhm		Cla		Cult Means	
Elands	1025	**a**	952	**bcde**	988	**bcde**
Gariep	1025	**a**	972	**abcd**	998	**abc**
Koonap	1023	**ab**	980	**abcd**	1002	**abc**
Matlabas	1028	**a**	925	**de**	977	**cde**
PAN 3118	1013	**abcd**	1023	**a**	1018	**a**
PAN 3120	1025	**a**	1008	**ab**	1017	**ab**
PAN 3161	1010	**abcd**	908	**ef**	960	**ef**
PAN 3195	943	**e**	908	**ef**	926	**g**
PAN 3368	1008	**abcd**	1000	**abc**	1004	**abc**
PAN 3379	1010	**abcd**	840	**g**	928	**g**
Senqu	1025	**a**	956	**bcde**	991	**abcd**
SST 316	1017	**abc**	948	**cde**	983	**cde**
SST 317	995	**cd**	865	**fg**	930	**fg**
SST 347	992	**d**	942	**cde**	967	**de**
SST 356	1002	**bcd**	835	**g**	935	**fg**
SST 387	995	**cd**	843	**g**	919	**g**
SST 398	1007	**abcd**	985	**abc**	998	**abc**
Env Mean	1008 **a**		936 **b**		973	
LSD Cult	22.02		58.57		29.86	
LSD Env	10.23					

Means followed by the same letter, did not differ significantly at p=0.05. Bhm=Bethlehem, Cla=Clarens, LFV=loaf volume, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 4.10 Combined analysis of variance for rheological and baking quality-related characteristics for 22 wheat cultivars in the irrigated summer rainfall region

		Mean squares								
SOURCE	**df**	**MABS**	**ALVSTR**	**ALVP**	**ALVL**	**ALVP/L**	**MPT**	**SDS**	**WGC**	**LVF**
Environment	1	164,22***	204,02***	761,05***	11,39**	0,06**	3,38***	111,93*	38,38***	19250,20***
Rep (Environment)	4	3,80***	8,57ns	53,67*	7,02***	0,04***	0,16**	16,30ns	4,36**	359,85ns
Cultivar	21	12,26***	192,88***	940,05***	20,66***	0,25***	1,02***	112,83***	6,32***	9393,06***
Cult x Env	21	3,21***	65,03***	82,05***	3,59***	0,03***	0,05ns	40,65**	3,02***	7534,60***
Error	84	0,70	11,74	20,62	1,00	0,01	0,04	18,53	1,00	1033,76
CV (%)		1,40	9,08	7,43	0,68	16,96	8,31	4,90	2,85	3,51
R2		0.90	0.86	0.93	0.88	0.93	0.89	0.69	0.76	0.83
		Variance component contribution (% of SS)								
Environment	1	29.18	3.12	3.16	1.82	0.85	11.31	2.27	11.56	4.23
Rep (Environment)	4	2.70	0.52	0.89	4.49	2.53	2.08	1.32	5.26	0.32
Cultivar	21	45.74	61.87	82.02	69.34	78.89	71.96	47.98	40.01	43.38
Cult x Env	21	11.99	20.86	7.16	12.05	10.57	3.82	17.29	15.07	34.80

* p≤0.05, ** p≤0.01, *** p≤0.001, ns=non-significant, df=degrees of freedom, MAB=mixolab water-absorption, ALVSTR=alveogram dough strength, ALVP=alveogram dough stability, ALVL=alveogram dough distensibility, ALVP/L=alveogram configuration ratio, MPT=mixogram peak time, SDSS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, Cult x Env=cultivar x environment interaction, CV=coefficient of variance, R^2= coefficient of determination, SS=sum of squares

Table 4.11 Genotype and environmental means for mixolab water-absorption and alveogram dough strength in the irrigated summer rainfall region

	MAB (%)				Cult		ALVSTR (J x 10^{-4})				Cult	
Cultivar	**Up**		**Vh**		**Means**		**Up**		**Vh**		**Means**	
Buffels	59.53	**bcde**	59.60	**ijkl**	59.57	**ghijk**	39.83	**cdef**	31.03	**ijk**	35.43	**def**
Duzi	59.43	**bcde**	60.53	**fghi**	59.98	**fghi**	35.87	**defg**	31.53	**ijk**	33.70	**ef**
Krokodil	56.03	**i**	62.07	**bcd**	59.05	**ijkl**	33.43	**fgh**	39.20	**cdef**	36.32	**cdef**
PAN 3471	56.73	**hi**	61.03	**defgh**	58.88	**jkl**	37.03	**defg**	35.57	**efghi**	36.48	**cde**
PAN 3478	58.53	**efg**	59.93	**hijk**	59.23	**hijk**	37.03	**defg**	27.65	**k**	33.28	**ef**
PAN 3489	58.80		60.80	**efgh**	59.80	**ghij**	41.03	**bcd**	37.30	**defg**	39.17	**bcd**
PAN 3497	59.00	**def**	61.73	**cde**	60.37	**efg**	32.15	**gh**	38.47	**defg**	35.94	**cdef**
Sabie	59.43	**bcde**	62.23	**bc**	60.83	**def**	40.67	**bcde**	41.57	**bcd**	41.12	**b**
SST 806	58.07	**efgh**	59.47	**ijkl**	58.77	**klm**	42.47	**bcd**	39.60	**cdef**	41.03	**b**
SST 822	61.70	**a**	64.23	**a**	62.97	**a**	41.53	**bcd**	40.27	**bcde**	40.90	**b**
SST 835	57.73	**fgh**	59.90	**hijk**	58.82	**kl**	34.07	**efg**	33.73	**ghij**	33.90	**ef**
SST 843	60.33	**abcd**	65.17	**a**	62.75	**ab**	50.10	**a**	63.73	**a**	58.28	**a**
SST 866	56.53	**hi**	59.07	**kl**	57.80	**m**	36.00	**defg**	31.87	**hijk**	33.93	**ef**
SST 867	57.77	**fgh**	58.60	**l**	58.18	**lm**	47.15	**ab**	29.87	**jk**	36.78	**cde**
SST 875	58.77	**def**	61.47	**cdefg**	60.12	**efgh**	40.35	**bcdef**	43.37	**bc**	42.16	**b**
SST 876	57.07	**ghi**	60.40	**ghij**	58.73	**klm**	26.60	**h**	28.13	**k**	27.37	**g**
SST 877	57.03	**ghi**	59.33	**jkl**	58.18	**lm**	36.50	**defg**	28.20	**k**	32.35	**f**
SST 884	60.87	**abc**	61.87	**bcde**	61.37	**cd**	46.60	**abc**	36.60	**efgh**	41.50	**b**
SST 895	60.93	**ab**	62.97	**b**	61.95	**bc**	41.50	**bcd**	45.00	**b**	43.25	**b**
Tamboti	59.30	**cdef**	61.23	**cdefg**	60.27	**efg**	37.77	**defg**	33.87	**ghij**	35.82	**def**
Timbivati	60.20	**abcd**	59.63	**ijkl**	59.86	**ghi**	40.97	**bcde**	27.60	**k**	35.62	**def**
Umlazi	60.33	**abcd**	61.67	**cdef**	61.00	**cde**	45.03	**abc**	34.83	**fghi**	39.93	**bc**
Environmental Mean	58.80	**b**	61.04	**a**	59.93		39.02	**a**	36.46	**b**	37.92	
LSD Cult	1.59		1.17		0.97		6.93		4.81		4.09	
LSD Env	0.29						1.23					

Means followed by the same letter, did not differ significantly at p=0.05. Up=Upington, Vh=Vaalharts, MAB=mixolab water-absorption, ALVSTR=alveogram dough strength, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 4.12 Genotype and environmental means for alveogram dough stability and alveogram dough distensibility in the irrigated summer rainfall region

	ALVP (mm H_2O)				Cult		ALVL (mm)				Cult	
Cultivar	**Up**		**Vh**		**Means**		**Up**		**Vh**		**Means**	
Buffels	56.33	**def**	52.00	**hij**	54.17	**ghij**	152.33	**defgh**	163.67	**abcde**	160.40	**bc**
Duzi	44.00	**h**	50.33	**ij**	47.17	**kl**	202.33	**bc**	177.33	**a**	184.54	**a**
Krokodil	45.33	**h**	60.33	**efg**	52.83	**ij**	172.00	**de**	155.00	**bcdefg**	159.90	**bc**
PAN 3471	58.67	**de**	63.00	**def**	60.83	**ef**	134.00	**ghij**	142.33	**fgh**	139.93	**de**
PAN 3478	55.00	**def**	58.67	**fgh**	57.20	**fghi**	142.00	**fghi**	136.33	**hi**	137.97	**e**
PAN 3489	69.67	**c**	69.33	**cd**	69.50	**d**	126.33	**hijk**	119.00	**j**	121.11	**f**
PAN 3497	51.67	**efgh**	64.67	**cdef**	58.17	**fghi**	145.50	**efghi**	148.00	**cdefgh**	147.47	**cde**
Sabie	54.00	**defg**	66.00	**cde**	60.00	**f**	169.00	**def**	158.00	**bcdef**	160.34	**bc**
SST 806	55.67	**def**	62.67	**def**	59.17	**fg**	178.00	**cd**	164.67	**abc**	168.51	**b**
SST 822	58.00	**de**	63.33	**def**	60.67	**ef**	164.67	**def**	170.33	**ab**	168.70	**b**
SST 835	48.33	**fgh**	58.67	**fgh**	53.50	**hij**	160.33	**defg**	157.00	**bcdef**	157.96	**bc**
SST 843	90.00	**a**	113.67	**a**	101.83	**a**	99.00	**kl**	90.67	**k**	93.07	**h**
SST 866	58.33	**de**	59.33	**efg**	58.83	**fgh**	121.67	**ijk**	120.67	**ij**	120.96	**f**
SST 867	57.33	**de**	54.67	**ghij**	56.00	**fghij**	160.00	**defg**	147.00	**defgh**	151.91	**cde**
SST 875	60.67	**d**	71.00	**c**	65.83	**de**	159.33	**defg**	151.33	**cdefgh**	153.64	**cd**
SST 876	46.00	**gh**	55.33	**ghi**	50.67	**jkl**	155.33	**defg**	146.67	**efgh**	149.16	**cde**
SST 877	54.33	**defg**	49.33	**ij**	51.83	**jk**	141.33	**fghi**	150.00	**cdefgh**	147.50	**cde**
SST 884	78.67	**b**	71.33	**c**	75.00	**c**	109.67	**jk**	117.67	**j**	115.63	**fg**
SST 895	88.00	**a**	84.00	**b**	86.00	**b**	72.00	**l**	115.33	**j**	106.12	**gh**
Tamboti	54.67	**def**	61.33	**efg**	58.00	**fghi**	161.33	**defg**	144.00	**fgh**	148.99	**cde**
Timbavati	44.00	**h**	48.50	**j**	46.25	**l**	241.00	**a**	164.00	**abcd**	186.18	**a**
Umlazi	54.00	**defg**	62.33	**ef**	59.00	**fg**	207.50	**b**	139.00	**gh**	153.56	**cd**
Env Mean	58.65		63.55		61.02		152.28		144.11		146.98	
	b		**a**				**a**		**b**			
LSD Cult	8.65		6.68		5.35		28.04		17.24		14.41	
LSD Env	1.60						4.82					

Means followed by the same letter, did not differ significantly at p=0.05. Up=Upington, Vh=Vaalharts, ALVP=alveogram dough stability, ALVL=alveogram dough distensibility, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 4.13 Genotype and environmental means for alveogram dough configuration ratio and mixogram peak time in the irrigated summer rainfall region

	ALVP/L (mm H2O mm^{-1})				Cult		MPT (min)				Cult	
Cultivar	**Up**		**Vh**		**Means**		**Up**		**Vh**		**Means**	
Buffels	0.38	**efgh**	0.32	**hi**	0.35	**hi**	2.24	**fg**	2.06	**efg**	2.19	**hij**
Duzi	0.22	**ij**	0.29	**i**	0.25	**j**	2.17	**gh**	2.12	**defg**	2.15	**ij**
Krokodil	0.26	**hij**	0.39	**fgh**	0.33	**ij**	2.49	**defg**	2.15	**defg**	2.32	**fghi**
PAN 3471	0.44	**defg**	0.44	**ef**	0.44	**efg**	2.87	**cd**	2.12	**defg**	2.50	**def**
PAN 3478	0.47	**def**	0.43	**ef**	0.45	**ef**	2.19	**gh**	2.00	**g**	2.09	**ij**
PAN 3489	0.57	**d**	0.59	**cd**	0.58	**d**	2.78	**cde**	2.50	**bc**	2.64	**cd**
PAN 3497	0.34	**efghij**	0.44	**ef**	0.39	**fghi**	2.40	**efg**	2.06	**efg**	2.23	**hij**
Sabie	0.30	**ghij**	0.42	**efg**	0.36	**fghi**	2.33	**fg**	1.99	**g**	2.16	**ij**
SST 806	0.32	**fghij**	0.39	**fgh**	0.36	**ghi**	2.42	**efg**	2.37	**bcd**	2.39	**efgh**
SST 822	0.36	**efghi**	0.38	**fghi**	0.37	**fghi**	2.39	**fg**	2.11	**defg**	2.25	**ghij**
SST 835	0.30	**ghij**	0.38	**fghi**	0.34	**hij**	2.30	**fg**	2.01	**fg**	2.16	**ij**
SST 843	0.92	**b**	1.27	**a**	1.09	**a**	3.99	**a**	3.69	**a**	3.84	**a**
SST 866	0.48	**de**	0.50	**de**	0.49	**de**	2.94	**c**	2.53	**bc**	2.73	**bc**
SST 867	0.36	**efghi**	0.41	**efgh**	0.39	**fghi**	2.92	**c**	2.28	**cdef**	2.60	**cde**
SST 875	0.38	**efgh**	0.47	**ef**	0.43	**efgh**	2.65	**cdef**	2.29	**cde**	2.47	**defg**
SST 876	0.30	**ghij**	0.38	**fghi**	0.34	**ij**	1.86	**h**	1.61	**h**	1.73	**k**
SST 877	0.39	**efgh**	0.33	**ghi**	0.36	**ghi**	2.48	**efg**	2.01	**fg**	2.25	**ghij**
SST 884	0.73	**c**	0.61	**c**	0.67	**c**	2.67	**cdef**	2.47	**bc**	2.57	**cde**
SST 895	1.32	**a**	0.76	**b**	0.98	**b**	3.44	**b**	2.57	**b**	2.92	**b**
Tamboti	0.34	**efghij**	0.43	**ef**	0.38	**fghi**	2.15	**gh**	2.05	**efg**	2.10	**ij**
Timbavati	0.19	**j**	0.30	**i**	0.25	**j**	2.16	**gh**	1.97	**g**	2.04	**j**
Umlazi	0.27	**hij**	0.46	**ef**	0.38	**fghi**	2.46	**efg**	2.11	**defg**	2.29	**fghi**
Env Mean	0.43	**b**	0.47	**a**	0.45		2.55	**a**	2.23	**b**	2.39	
LSD Cult	0.16		2.02		0.09		0.38		0.28		0.23	
LSD Env	0.03						0.07					

Means followed by the same letter, did not differ significantly at p=0.05. Up=Upington, Vh=Vaalharts, ALVP/L=alveogram configuration ratio, MPT=mixogram peak time, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 4.14 Genotype and environmental means for SDS-sedimentation volume and wet gluten content in the irrigated summer rainfall region

	SDSS (ml)				Cult		WGC (%)				Cult	
Cultivar	**Up**		**Vh**		**Means**		**Up**		**Vh**		**Means**	
Buffels	90.67	**abcde**	89.33	**abc**	90.00	**abcde**	37.47	**bcde**	33.08	**de**	34.81	**defgh**
Duzi	91.33	**abcde**	88.33	**abcd**	89.83	**bcde**	40.13	**ab**	37.00	**bc**	38.24	**ab**
Krokodil	96.00	**a**	93.33	**a**	94.67	**ab**	32.19	**ghi**	33.66	**de**	33.08	**fghi**
PAN 3471	94.00	**abc**	78.67	**ef**	86.33	**defgh**	29.82	**i**	32.77	**def**	31.61	**i**
PAN 3478	85.33	**efgh**	82.00	**cdef**	83.67	**h**	36.89	**bcdef**	35.75	**bcd**	36.20	**bcd**
PAN 3489	85.67	**defgh**	85.00	**bcde**	85.33	**efgh**	33.30	**fghi**	31.97	**ef**	32.50	**hi**
PAN 3497	87.33	**defg**	90.00	**ab**	88.67	**cdefg**	30.78	**hi**	33.80	**de**	32.89	**gih**
Sabie	94.00	**abc**	90.33	**ab**	92.17	**abc**	36.86	**bcdef**	34.46	**cde**	35.40	**cdef**
SST 806	94.67	**ab**	90.33	**ab**	92.50	**abc**	35.14	**defg**	32.85	**def**	33.75	**efghi**
SST 822	91.33	**abcde**	90.00	**ab**	90.80	**abcd**	39.25	**abc**	40.21	**a**	39.83	**a**
SST 835	85.67	**defgh**	83.67	**bcde**	84.67	**fgh**	35.82	**cdefg**	32.83	**def**	34.01	**defgh**
SST 843	90.67	**abcde**	89.33	**abc**	90.00	**abcde**	38.29	**abcd**	38.28	**ab**	38.28	**ab**
SST 866	81.33	**gih**	84.33	**bcde**	82.83	**hi**	33.12	**fghi**	33.03	**de**	33.06	**fghi**
SST 867	87.67	**cdefg**	82.67	**bcdef**	85.17	**efgh**	37.41	**bcde**	29.86	**f**	32.83	**ghi**
SST 875	92.00	**abcd**	89.67	**abc**	90.83	**abcd**	34.98	**defg**	34.36	**cde**	34.60	**defgh**
SST 876	77.33	**i**	88.00	**abcd**	82.67	**hi**	38.60	**abcd**	36.98	**bc**	37.62	**abc**
SST 877	80.33	**hi**	75.67	**f**	78.00	**i**	39.16	**abc**	33.38	**de**	35.65	**cde**
SST 884	86.33	**defgh**	81.33	**def**	83.83	**gh**	40.02	**ab**	33.85	**de**	36.28	**bcd**
SST 895	88.67	**bcdef**	85.00	**bcde**	86.83	**defgh**	34.12	**efgh**	32.47	**ef**	33.11	**fghi**
Tamboti	84.00	**fgh**	93.67	**a**	88.83	**cdef**	37.79	**bcde**	33.51	**de**	35.19	**defg**
Timbavati	94.33	**ab**	90.00	**ab**	92.17	**abc**	42.23	**a**	32.62	**ef**	35.52	**cde**
Umlazi	95.67	**a**	94.00	**a**	94.83	**a**	38.33	**abcd**	34.57	**cde**	36.05	**bcde**
Env Mean	88.83	**a**	86.98	**b**	87.94		36.48	**a**	34.17	**b**	35.02	
LSD Cult	6.58		7.67		4.97		3.94		3.10		2.40	
LSD Env	1.50						0.74					

Means followed by the same letter, did not differ significantly at p=0.05. Up=Upington, Vh=Vaalharts, SDSS=SDS-sedimentation volume, WGC=wet gluten content, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 4.15 Genotype and environmental means for loaf volume in the irrigated summer rainfall region

Cultivar	LVF (cm^3) Up		Vh		Cult Means	
Buffels	1010	**a**	878	**efghi**	944	**bcd**
Duzi	1000	**a**	870	**fghi**	935	**bcdefg**
Krokodil	933	**bcd**	863	**ghij**	898	**ghij**
PAN 3471	852	**f**	833	**ij**	843	**l**
PAN 3478	900	**def**	820	**j**	860	**jkl**
PAN 3489	870	**def**	840	**hij**	855	**kl**
PAN 3497	930	**bcde**	915	**cdef**	921	**cdefgh**
Sabie	978	**abc**	998	**a**	988	**a**
SST 806	892	**def**	920	**cde**	905	**efghij**
SST 822	892	**def**	983	**ab**	938	**bcdef**
SST 835	910	**def**	882	**efgh**	896	**hij**
SST 843	858	**f**	1020	**a**	939	**bcdef**
SST 866	903	**def**	860	**ghij**	882	**ijk**
SST 867	1000	**a**	910	**cdef**	964	**ab**
SST 875	868	**ef**	923	**cde**	901	**fghij**
SST 876	875	**def**	895	**cdefg**	883	**hijk**
SST 877	992	**ab**	930	**cd**	961	**ab**
SST 884	925	**cde**	893	**defg**	909	**defghi**
SST 895	858	**f**	855	**ghij**	857	**kl**
Tamboti	982	**abc**	900	**cdefg**	941	**bcde**
Timbavati	1030.	**a**	900	**cdefg**	952	**abc**
Umlazi	1005	**a**	940	**bc**	966	**ab**
Env Mean	928 **a**		903 **b**		915	
LSD Cult	64.21		45.16		38.29	
LSD Env	1.99					

Means followed by the same letter, did not differ significantly at p=0.05. Up=Upington, Vh=Vaalharts, LFV=loaf volume, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 4.16 Combined analysis of variance for rheological and baking quality-related characteristics for nine wheat cultivars in the winter rainfall region

		Mean squares								
SOURCE	**df**	**MAB**	**ALVSTR**	**ALVP**	**ALVL**	**ALVP/L**	**MPT**	**SDS**	**WGC**	**LVF**
Environment	1	1,43ns	298,69***	0,46ns	21,41ns	0,01ns	0,72***	31,13*	159,82***	13379,63***
Rep (Environment)	4	1,18ns	12,87ns	6,04ns	122,93ns	0,01ns	0,02ns	3,48ns	7,30ns	4685,19***
Cultivar	8	16,12***	87,66***	461,13***	962,83***	0,10***	0,51***	57,25***	3977***	6375,12***
Cult x Env	8	3,81*	27,15ns	136,34***	381,41ns	0,05***	0,28***	13,13*	8,90*	3351,50**
Error	32	1,48	13,68	18,64	153,26	0,01	0,02	4,52	2,92	775,29
CV (%)		2,06	8,5	5,61	10,47	14,30	5,74	2,33	4,56	2,92
R^2		0.78	0.74	0.89	0.70	0.81	0.91	0.81	0.86	0.82
		Variance component contribution (% of SS)								
Environment	1	0.67	17.50	0.01	0.13	0.46	9.23	4.13	23.79	9.93
Rep (Environment)	4	2.22	3.02	0.45	3.04	2.29	0.9	1.85	4.35	13.91
Cultivar	8	60.55	41.10	68.30	47.63	52.00	52.04	60.84	47.37	37.85
Cult x Env	8	14.33	12.73	20.20	18.87	26.25	28.87	13.95	10.60	19.90

* p≤0.05, ** p≤0.01, *** p≤0.001, ns=non-significant, df=degrees of freedom, MAB=mixolab water-absorption, ALVSTR=alveogram dough strength, ALVP=alveogram dough stability, ALVL=alveogram dough distensibility, ALVP/L=alveogram configuration ratio, MPT=mixogram peak time, SDSS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, Cult x Env=cultivar x environment interaction, CV=coefficient of variance, R^2= coefficient of determination, SS=sum of squares

Table 4.17 Genotype and environmental means of individual localities for mixolab water-absorption, alveogram dough strength and alveogram dough stability in the winter rainfall region

	MAB (%)				Cult		ALVSTR (J x 10^{-4})				Cult		ALVP (mm H_2O)				Cult	
Cultivar	**Mo**		**Ri**		**Means**		**Mo**		**Ri**		**Means**		**Mo**		**Ri**		**Means**	
PAN 3471	60.03	**a**	58.57	**d**	59.30	**bc**	47.33	**a**	39.03	**bc**	43.18	**bcd**	83.00	**b**	75.67	**cd**	79.34	**cd**
SST 015	62.90	**a**	60.67	**ab**	61.79	**a**	47.23	**a**	47.57	**a**	47.40	**ab**	81.00	**b**	86.33	**ab**	83.67	**bc**
SST 027	55.70	**d**	56.63	**e**	56.17	**d**	46.97	**a**	36.30	**bc**	41.64	**cde**	66.33	**cd**	61.33	**e**	63.83	**f**
SST 047	60.97	**ab**	59.76	**bcd**	60.37	**ab**	49.17	**a**	47.40	**a**	48.29	**a**	80.67	**b**	90.00	**a**	85.34	**b**
SST 056	57.63	**cd**	58.13	**de**	57.88	**c**	44.63	**ab**	39.33	**bc**	41.98	**cd**	73.00	**c**	69.00	**de**	71.00	**e**
SST 087	58.93	**bc**	60.47	**abc**	59.70	**b**	47.83	**a**	42.50	**ab**	45.17	**abc**	72.67	**c**	82.00	**bc**	77.34	**d**
SST 096	59.07	**bc**	61.63	**a**	60.35	**b**	46.67	**a**	47.80	**a**	47.24	**ab**	91.33	**a**	90.67	**a**	91.00	**a**
SST 88	57.63	**cd**	58.87	**cd**	58.25	**c**	38.80	**b**	35.97	**bc**	37.39	**e**	64.00	**d**	73.67	**d**	68.84	**ef**
Tankwa	58.47	**c**	59.53	**bcd**	59.00	**bc**	43.97	**ab**	34.37	**c**	39.17	**de**	81.33	**b**	63.00	**e**	72.17	**e**
Env Mean	59.04	**a**	59.36	**a**	59.20		45.84	**a**	41.14	**b**	43.49		77.04	**a**	76.85	**a**	76.94	
LSD Cult	2.44		1.71		1.43		5.90		6.87		4.35		7.27		7.68		5.08	
LSD Env	0.67						2.05						2.39					

Means followed by the same letter, did not differ significantly at p=0.05. Mo=Moorreesburg, Ri=Riversdal, MAB=mixolab water-absorption, ALVSTR=alveogram dough strength, ALVP=alveogram dough stability, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 4.18 Genotype and environmental means of individual localities for alveogram dough distensibility, alveogram dough configuration ratio and mixogram peak time in the winter rainfall region

	ALVL (mm)				Cult		ALVP/L (mm H2O mm^{-1})				Cult		MPT (min)				Cult	
Cultivar	**Mo**		**Ri**		**Means**		**Mo**		**Ri**		**Means**		**Mo**		**Ri**		**Means**	
PAN 3471	110.00	**ab**	119.67	**abc**	114.84	**bcd**	0.77	**b**	0.64	**cde**	0.71	**bcd**	2.84	**bc**	2.43	**bcd**	2.64	**b**
SST 015	132.33	**a**	126.33	**abc**	129.33	**ab**	0.62	**bcd**	0.69	**bcd**	0.66	**cd**	1.88	**e**	2.30	**cd**	2.09	**d**
SST 027	131.00	**a**	137.67	**a**	134.34	**a**	0.50	**d**	0.45	**f**	0.48	**f**	2.96	**b**	2.45	**bcd**	2.71	**b**
SST 047	118.00	**a**	105.00	**c**	111.50	**cde**	0.70	**bc**	0.86	**a**	0.78	**b**	2.59	**c**	2.78	**a**	2.69	**b**
SST 056	128.33	**a**	137.67	**a**	133.00	**a**	0.57	**cd**	0.50	**ef**	0.54	**ef**	2.31	**d**	2.27	**d**	2.29	**c**
SST 087	130.67	**a**	111.33	**bc**	121.00	**abc**	0.56	**cd**	0.74	**abc**	0.65	**de**	2.26	**d**	2.31	**cd**	2.29	**c**
SST 096	94.67	**bc**	113.33	**bc**	104.00	**de**	0.98	**a**	0.82	**ab**	0.90	**a**	3.02	**b**	2.37	**cd**	2.70	**b**
SST 88	127.33	**a**	109.00	**bc**	118.17	**bcd**	0.51	**d**	0.68	**bcd**	0.60	**de**	2.83	**bc**	2.66	**ab**	2.75	**b**
Tankwa	86.00	**c**	109.67	**bc**	97.84	**e**	0.95	**a**	0.58	**def**	0.77	**bc**	3.49	**a**	2.55	**abc**	3.02	**a**
Env Mean	117.59	**a**	118.85	**a**	118.22		0.68	**a**	0.66	**a**	0.67		2.69	**a**	2.46	**b**	2.57	
LSD Cult	23.33		19.34		14.56		0.18		0.16		0.11		0.26		0.26		0.17	
LSD Env	6.86					0.05						0.08						

Means followed by the same letter, did not differ significantly at p=0.05. Mo=Moorreesburg, Ri=Riversdal, ALVL=alveogram dough distensibility, ALVP/L=alveogram configuration ratio, MPT=mixogram peak time, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

Table 4.19 Genotype and environmental means for SDS-sedimentation volume, wet gluten content and loaf volume in the winter rainfall region

	SDSS (ml)				Cult		WGC (%)				Cult		LVF (cm^3)				Cult	
Cultivar	**Mo**		**Ri**		**Means**		**Mo**		**Ri**		**Means**		**Mo**		**Ri**		**Means**	
PAN 3471	91.67	**a**	92.33	**abc**	92.00	**a**	39.43	**b**	35.00	**cd**	37.22	**bc**	947	**cd**	957	**bc**	952	**bcd**
SST 015	93.33	**a**	95.00	**a**	94.17	**a**	39.03	**b**	34.90	**cd**	36.97	**bc**	927	**d**	968	**b**	948	**cd**
SST 027	92.00	**a**	93.67	**ab**	92.84	**a**	39.50	**b**	34.97	**cd**	37.24	**bc**	1022	**ab**	940	**bcd**	981	**b**
SST 047	83.33	**c**	89.67	**c**	86.50	**b**	45.57	**a**	41.30	**a**	43.44	**a**	1030	**a**	1018	**a**	1024	**a**
SST 056	90.00	**ab**	94.33	**ab**	92.17	**a**	39.43	**b**	34.10	**cd**	36.77	**bc**	962	**cd**	888	**e**	925	**d**
SST 087	90.67	**ab**	94.67	**ab**	92.67	**a**	39.40	**b**	33.40	**d**	36.40	**c**	980	**bc**	902	**de**	941	**cd**
SST 096	94.00	**a**	93.33	**ab**	93.67	**a**	37.83	**bc**	36.50	**bc**	37.17	**bc**	963	**cd**	975	**ab**	969	**bc**
SST 88	94.00	**a**	91.67	**c**	92.84	**a**	35.13	**c**	32.23	**d**	33.68	**d**	968	**cd**	892	**de**	930	**d**
Tankwa	86.67	**bc**	84.67	**d**	85.67	**b**	37.50	**bc**	39.47	**ab**	38.49	**b**	936	**cd**	910	**cde**	923	**d**
Env Mean	90.63	**b**	92.15	**a**	1108.89		39.20	**a**	35.76	**b**	37.48		970	**a**	934	**b**	955	
LSD Cult	4.05		3.27		2.50		2.83		3.08		2.01		47.33		49.04		32.75	
LSD Env	1.18						0.95						15.44					

Means followed by the same letter, did not differ significantly at p=0.05. Mo=Moorreesburg, Ri=Riversdal, SDSS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, Cult Means=cultivar means for the two localities, Env mean=environmental means, LSD Cult=least significant difference for cultivars, LSD Env=least significant difference for environments

4.3.3. Correlations

4.3.3.1 Correlations between the SRC, SIG and rheological and baking quality-related characteristics

There were significant correlations between SRC and SIG with rheological and baking quality-related characteristics. More significant correlations were evident between SRC, SIG and rheological and baking quality-related characteristics in the dryland (Table 4.20) and irrigated SRR (Table 4.21) than in the WRR (Table 4.22).

4.3.3.1.1 Mixolab water-absorption

Mixolab water-absorption was positively correlated ($p \leq 0.001$) with lactic acid and distilled water SRC in the dryland SRR (Table 4.20) and the irrigated SRR (Table 4.21). Mixolab water-absorption was positively ($p \leq 0.001$) correlated with sodium bicarbonate SRC in the irrigated SRR. Mixolab water-absorption was positively correlated with sucrose SRC in the dryland SRR ($p \leq 0.01$) and the irrigated SRR ($p \leq 0.001$). In the dryland SRR lactic acid SIG correlated positively ($p \leq 0.001$) with Mixolab water-absorption.

4.3.3.1.2 Alveogram dough strength

The highest number of correlations was evident between ALVSTR with SRC and SIG parameters for the irrigated SRR (Table 4.21). Alveogram dough strength was positively correlated with lactic acid SRC in the dryland SRR ($p \leq 0.001$) (Table 4.20), irrigated SRR ($p \leq 0.001$) (Table 4.21) and in the WRR ($p \leq 0.01$) (Table 4.22). Correlations between ALVSTR and sodium bicarbonate were highly significant ($p \leq 0.001$), with a positive correlation in the irrigated SRR (Table 4.21) and a negative correlation in the WRR (Table 4.22). In the irrigated SRR and the WRR, ALVSTR was positively correlated ($p \leq 0.001$) with sucrose SRC.

More significant correlations between ALVSTR and the SRC and SIG parameters were evident in the irrigated SRR where ALVSTR was positively correlated with distilled water SRC ($p \leq 0.001$) and sodium carbonate SRC ($p \leq 0.01$). Alveogram dough strength and lactic acid SIG was positively correlated in the dryland SRR (0.60***) (Table 4.20) and in the irrigated SRR (0.64***) (Table 4.21).

4.3.3.1.3 Alveogram dough stability

Alveogram dough stability was positively correlated with the SRC and SIG parameters in the dryland SRR (Table 4.21) and the irrigated SRR (Table 4.21). No significant correlations were evident between ALVP and SRC and SIG parameters in the WRR (Table 4.22). In dryland and irrigated SRR, ALVP was positively correlated with lactic acid SRC and lactic acid SIG. A strong correlation with ALVP across the regions was evident with distilled water SRC in the dryland (0.58***) (Table 4.20) and irrigated SRR (0.46***) (Table 4.21). The only correlation ($p \leq 0.01$) between ALVP and sodium carbonate SRC was in the irrigated SRR (Table 4.21). The strongest correlation was between ALVP and sucrose SRC (0.64***) in the irrigated SRR (Table 4.21). Sodium bicarbonate SRC correlated positively with ALVP in the dryland ($p \leq 0.01$) (Table 4.20) and irrigated SRR ($p \leq 0.001$) (Table 4.21).

4.3.3.1.4 Alveogram dough distensibility

Alveogram dough distensibility had the lowest number of correlations with SRC and SIG parameters. Significant correlations between ALVL, SRC and SIG parameters were negative in the dryland SRR (Table 4.20) and irrigated SRR (Table 4.21). There were no correlations between ALVL, SRC and SIG parameters in the WRR (Table 4.22). Alveogram dough distensibility had the highest negative correlation ($p \leq 0.001$) with sodium bicarbonate SRC in the irrigated SRR (-0.45***) (Table 4.21) and -0.22* ($p \leq 0.05$) in the dryland SRR (Table 4.20). There were no correlations between ALVL and lactic acid SRC and SIG for all the regions. Distilled water and ALVL correlated negatively in the dryland (-0.40***) (Table 4.20) and irrigated SRR (-0.26**) (Table 4.21).

The only correlations between sodium carbonate SRC (-0.27**) and sucrose SRC (-0.33***) with ALVL were in the irrigated SRR (Table 4.21).

4.3.3.1.5 Alveogram dough configuration ratio

One correlation occurred between ALVP/L and lactic acid SRC (0.33***) in the dryland SRR (Table 4.20). More correlations between ALVP/L and the SRC and SIG parameters were obtained in the irrigated SRR (Table 4.21). The strongest correlation was between ALVP/L with distilled water SRC (0.56***) in the dryland SRR (Table 4.20) and these parameters had a significant correlation in the irrigated SRR (0.36***). Sodium carbonate and sucrose SRC correlated ($p \leq 0.001$) positively with ALVP/L in the irrigated SRR. Alveogram dough configuration ratio correlated with sodium bicarbonate in the dryland (0.24*) and irrigated SRR (0.45***). Correlations between lactic acid SIG and ALVP/L were weak and significant in the dryland (0.22*) and irrigated SRR (0.23**).

4.3.3.1.6 Mixogram peak time

Mixogram peak time correlated with lactic acid SRC (0.60***) in the dryland SRR (Table 4.20) and there were no correlations between these two parameters in the irrigated SRR (Table 4.21) and WRR (Table 4.22). One weak correlation was seen between distilled water SRC (0.29*) and MPT in the WRR and between sodium carbonate SRC and MPT in the irrigated SRR (0.32***). Sucrose SRC correlated positively ($p \leq 0.001$) with MPT in the irrigated SRR. Lactic acid SIG correlated positively with MPT in the dryland (0.34***), irrigated SRR (0.50***) and the WRR (0.36**).

4.3.3.1.7 Wet gluten content

Lactic acid SRC correlated positively with WGC in the dryland SRR (Table 4.20), irrigated SRR (Table 4.21) and WRR (Table 4.22).

Lactic acid correlations with WGC were 0.28**, 0.56*** and 0.64*** for the dryland SRR, irrigated SRR and WRR, respectively. Wet gluten content was negatively

correlated with sodium carbonate in the dryland SRR (-0.29**) and positively in the irrigated SRR (0.18*). Sucrose SRC correlated significantly with WGC in the irrigated SRR (0.38***) and in the WRR (0.36**). Lactic acid SIG correlated strongly with WGC and correlations between these parameters were 0.46***, 0.60*** and 0.47*** for the respective dryland SRR, irrigated SRR and WRR.

4.3.3.1.8 SDS-sedimentation volume

SDS-sedimentation volume correlated significantly with lactic acid SRC in the dryland SRR (0.35***) (Table 4.20) and irrigated SRR (0.36***) (Table 4.21). There were no correlations between lactic acid SRC and SDSS in the WRR (Table 4.22). Distilled water and SDSS were negatively correlated ($p \leq 0.01$) in the WRR. Sodium bicarbonate SRC was positively correlated ($p \leq 0.01$) with SDSS in the dryland SRR and negatively correlated ($p \leq 0.05$) in the WRR.

One negative correlation ($p \leq 0.001$) between sucrose SRC and SDSS (-0.35***) occurred in the dryland SRR (Table 4.20). Lactic acid SIG was positively correlated with SDSS in the dryland SRR ($p \leq 0.05$) (Table 4.20) and irrigated SRR ($p \leq 0.01$) (Table 4.21), and negatively correlated in the WRR ($p \leq 0.01$) (Table 4.22).

4.3.3.1.9 Loaf volume

Loaf volume and lactic acid SRC was positively correlated in the dryland SRR (0.49***) (Table 4.20), irrigated SRR (0.58***) (Table 4.21) and the WRR (0.39**) (Table 4.22). Loaf volume was negatively correlated with sodium carbonate SRC in the dryland SRR (-0.34***) and with sodium bicarbonate SRC (-0.29*) in the irrigated SRR. Sucrose SRC and loaf volume was positively correlated ($p \leq 0.001$) in the WRR. Significant correlations were evident between lactic acid SIG and LFV in the dryland SRR (0.49***), irrigated SRR (0.52***) and WRR (0.35*).

Table 4.20 Significant correlations between rheological and baking quality-related characteristics and solvent retention capacity and swelling index of glutenin characteristics for the dryland summer rainfall region

Characteristic	LA_SRC	DW_SRC	SC_SRC	SBC_SRC	S_SRC	LA_SIG
MAB	0.31**	0.53***			0.29**	0.32***
ALVSTR	0.66***					0.60***
ALVP	0.45***	0.58***		0.21*		0.32**
ALVL		-0.40***		-0.22*		
ALVP/L	0.33***	0.56***		0.24*		0.22*
MPT	0.60***					0.34***
WGC	0.28**		-0.29**			0.46***
SDSS	0.35***			0.32**	-0.35***	0.21*
LFV	0.49***		-0.34***			0.49***

* p≤0.05, ** p≤0.01, *** p≤0.001. MAB=mixolab water-absorption, ALVSTR=alveogram dough strength, ALVP=alveogram dough stability, ALVL=alveogram dough distensibility, ALVP/L=alveogram configuration ratio, MPT=mixogram peak time, SDSS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, LA_SRC=lactic acid SRC, DW_SRC=distilled water SRC, SC_SRC=sodium carbonate SRC, SBC_SRC=sodium bicarbonate SRC, S_SRC=sucrose SRC, LA_SIG =lactic acid SIG

Table 4.21 Significant correlations between rheological and baking quality-related characteristics and solvent retention capacity and swelling index of glutenin characteristics for the irrigated summer rainfall region

Characteristic	LA_SRC	DW_SRC	SC_SRC	SBC_SRC	S_SRC	LA_SIG
MAB	0.35***	0.49***		0.48***	0.59***	
ALVSTR	0.53***	0.37***	0.25**	0.31***	0.64***	0.64***
ALVP	0.23*	0.46***	0.25**	0.52***	0.64***	0.29**
ALVL		-0.26**	-0.27**	-0.45***	-0.33***	
ALVP/L		0.36***	0.29***	0.45***	0.54***	0.23**
MPT			0.32***		0.35***	0.50***
WGC	0.56***		0.18*		0.38***	0.60***
SDSS	0.36***					0.27**
LFV	0.58***			-0.29**		0.52***

* p≤0.05, ** p≤0.01, *** p≤0.001. MAB=mixolab water-absorption, ALVSTR=alveogram dough strength, ALVP=alveogram dough stability, ALVL=alveogram dough distensibility, ALVP/L=alveogram configuration ratio, MPT=mixogram peak time, SDSS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, LA_SRC=lactic acid SRC, DW_SRC=distilled water SRC, SC_SRC=sodium carbonate SRC, SBC_SRC=sodium bicarbonate SRC, S_SRC=sucrose SRC LA_SIG =lactic acid SIG

Table 4.22 Significant correlations between rheological and baking quality-related characteristics and solvent retention capacity and swelling index of glutenin characteristics for the winter rainfall region

Characteristic	LA_SRC	DW_SRC	SC_SRC	SBC_SRC	S_SRC	LA_SIG
MAB						
ALVSTR	0.30*			-0.47***	0.58***	
ALVP						
ALVL						
ALVP/L						
MPT		0.29*				0.36**
WGC	0.64***				0.36**	0.47***
SDSS		-0.37**		-0.32*		-0.37**
LFV	0.39**			-0.35**	0.53***	0.35*

* p≤0.05, ** p≤0.01, *** p≤0.001. MAB=mixolab water-absorption, ALVSTR=alveogram dough strength, ALVP=alveogram dough stability, ALVL=alveogram dough distensibility, ALVP/L=alveogram configuration ratio, MPT=mixogram peak time, SDSS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, LA_SRC=lactic acid SRC, DW_SRC=distilled water SRC, SC_SRC=sodium carbonate SRC, SBC_SRC=sodium bicarbonate SRC, S_SRC=sucrose SRC, LA_SIG=lactic acid SIG

4.3.4 Stepwise multiple linear regressions

4.3.4.1 SRC and SIG parameters responsible for variation in rheological and baking quality-related characteristics

Regression coefficients for the SRC and SIG parameters to describe variation in rheological and baking quality-related characteristics were relatively low and ranged between 12% and 59% across the three production areas of the dryland SRR (Table 4.23), irrigated SRR (Table 4.24) and the WRR (Table 4.25). The highest regression coefficient (59%) obtained across the regions was for ALVSTR.

4.3.4.1.1 Mixolab water-absorption

Mixolab water-absorption regression coefficients were 40% in the dryland SRR (Table 4.23) and 47% in the irrigated SRR (Table 4.24). In the dryland SRR distilled water SRC contributed 30% (p≤0.001) and lactic acid SIG 10% (p≤0.01) to the variation in MAB.

In the irrigated SRR (Table 4.24), the independent variables; sucrose SRC, sodium carbonate SRC and distilled water SRC, respectively contributed 33%, (p≤0.001) 9% (p≤0.001) and 5% (p≤0.01) to the total variation of 47% in MAB.

4.3.4.1.2 Alveogram dough strength

In the dryland SRR (Table 4.23) lactic acid SRC alone contributed 39% (p≤0.001) to the variation in ALVSTR. In the irrigated SRR (Table 4.24) sucrose SRC, lactic acid SIG and distilled water SRC contributed 41% (p≤0.001), 15% (p≤0.001) and 3% (p≤0.01) to the variation in ALVSTR. Sucrose SRC was the only independent variable responsible for contributing 34% (p≤0.001) to the variation in ALVSTR in the WRR (Table 4.25). The predictor variables had inconsistent correlations with ALVSTR across regions and varied in the models for the different regions.

4.3.4.1.3 Alveogram dough stability

In the dryland SRR (Table 4.23), distilled water SRC, lactic acid SRC and sucrose SRC contributed 34% (p≤0.001), 17% (p≤0.001) and 5% (p≤0.05) to the variation in ALVP. The total coefficient of determination was 56%. Sucrose SRC was highly correlated with ALVP in the irrigated SRR (Table 4.24) and contributed 45% (p≤0.001) to the variation in the model. Sodium bicarbonate contributed 5% (p≤0.01) to the total variation of 50% for ALVP.

4.3.4.1.4 Alveogram dough distensibility

Alveogram dough distensibility had regression coefficients of 41% in the dryland SRR (Table 4.23) and 32% in the irrigated SRR (Table 4.24).

In the dryland SRR distilled water SRC, sucrose SRC and sodium carbonate SRC respectively contributed 18% (p≤0.001), 17% (p≤0.001) and 6% (p≤0.05) to the variation in ALVL. Sucrose SRC and sodium carbonate SRC was not significantly correlated with ALVL.

In the irrigated SRR, sodium bicarbonate SRC, lactic acid SRC and sucrose SRC respectively contributed 21% (p≤0.001), 4% (p≤0.05) and 7% (p≤0.001) to the variation in ALVL. Lactic acid was not significantly correlated with ALVL and contributed at a lower significance value towards ALVL.

4.3.4.1.5 Alveogram configuration ratio

In the dryland SRR (Table 4.23), the independent variables responsible for 52% of the variation in ALVP/L were distilled water SRC, sucrose SRC and lactic acid SRC, respectively contributing 32% (p≤0.001), 14% (p≤0.001) and 6% (p≤0.01).

In the irrigated SRR (Table 4.24) sucrose SRC made the highest contribution to the variation in ALVP/L of 33% (p≤0.001), and sodium bicarbonate contributed 3% (p≤0.05). Sucrose SRC was not significantly correlated with ALVP/L in the dryland SRR, but correlated significantly in the irrigated SRR.

4.3.4.1.6 Mixogram peak time

Regression coefficients for MPT were 42% in the dryland SRR (Table 4.23), 33% in the irrigated SRR (Table 4.24) and 13% in the WRR (Table 4.25). Lactic acid alone contributed 42% (p≤0.001) to the variation in the dryland SRR. In the irrigated SRR, lactic acid SIG, sucrose SRC and lactic acid SRC contributed 23% (p≤0.001), 5% (p≤0.01) and 5% (p≤0.01), respectively. Lactic acid SRC was not significantly correlated with MPT. In the WRR lactic acid SIG contributed to the variation in the model.

4.3.4.1.7 SDS-sedimentation volume

In the dryland SRR (Table 4.23), lactic acid SRC contributed 20% (p≤0.001) and sodium bicarbonate 12% (p≤0.01) to the total variation in SDSS. In the irrigated SRR (Table 4.24) lactic acid SRC alone contributed 12% (p≤0.001) to the variation in SDSS.

In the WRR (Table 4.25), sodium bicarbonate, lactic acid SRC and sucrose SRC, respectively, contributed 10% ($p \leq 0.05$), 17% ($p \leq 0.01$) and 7% ($p \leq 0.05$) to the variation. Lactic acid SRC and sucrose SRC were not significantly correlated with SDSS in the WRR.

4.3.4.1.8 Wet gluten content

Regression coefficients for WGC were 28% in the dryland SRR (Table 4.23), 43% in the irrigated SRR (Table 4.24) and 47% in the WRR (Table 4.25). Lactic acid was the only independent variable responsible for significantly ($p \leq 0.001$) explaining the variation in WGC in the dryland SRR. In the irrigated SRR, lactic acid SIG explained 39% ($p \leq 0.001$) and lactic acid SRC 4% ($p \leq 0.01$) of the variation in WGC. In the WRR, lactic acid SRC explained 41% ($p \leq 0.001$) and distilled water SRC 6% ($p \leq 0.05$) of the variation in WGC. Distilled water SRC was not significantly correlated with WGC in the WRR.

4.3.4.1.9 Loaf volume

Regression coefficients for LFV were 22% in the dryland SRR (Table 4.23), 51% in the irrigated SRR (Table 4.24) and 35% in the WRR (Table 2.26). In the dryland SRR, lactic acid SIG was the only predictor variable, with a significant ($p \leq 0.001$) contribution to the variation in the model. Lactic acid SRC, sodium bicarbonate SRC and lactic acid SIG contributed 37% ($p \leq 0.001$), 11% ($p \leq 0.001$) and 3% ($p \leq 0.05$) respectively, to the regression coefficient in the irrigated SRR. Sucrose SRC explained 29% ($p \leq 0.001$) and lactic acid SIG explained 6% ($p \leq 0.05$) of the variation in the model in the WRR.

Table 4.23 Solvent retention capacity and swelling index of glutenin parameters responsible for variation in rheological and baking quality-related characteristics in the dryland summer rainfall region

Dependent Variable: MAB						
Variable Entered	Parameter Estimate	Partial R-Square	Model R-Square	Correlation R	F Value	Pr > F
Intercept	27.26***					
DW_SRC	0.41***	0.30	0.30	0.53***	29.39***	<.0001
LA_SIG	1.80**	0.10	0.40	0.32***	11.54**	0.0011
Dependent Variable: ALVSTR						
Variable Entered	Parameter Estimate	Partial R-Square	Model R-Square	Correlation R	F Value	Pr > F
Intercept	-8.85ns					
LA_SRC	0.46***	0.39	0.39	0.66***	43.74***	<.0001
Dependent Variable: ALVP						
Variable Entered	Parameter Estimate	Partial R-Square	Model R-Square	Correlation R	F Value	Pr > F
Intercept	-139.46***					
DW_SRC	2.98***	0.34	0.34	0.57***	35.65***	<.0001
LA_SRC	0.45***	0.17	0.51	0.45***	23.72***	<.0001
S_SRC	-0.35*	0.05	0.56	0.01ns	6.79*	0.0113
Dependent Variable: ALVL						
Variable Entered	Parameter Estimate	Parameter R-Square	Partial R-Square	Model Correlation R	F Value	Pr > F
Intercept	272.44***					
DW_SRC	-4.53***	0.18	0.18	-0.40***	15.17***	0.0002
S_SRC	0.99***	0.17	0.35	0.08ns	17.5***	<.0001
SC_SRC	0.70*	0.06	0.41	0.04ns	6.78*	0.0113
Dependent Variable: ALVP/L						
Variable Entered	Parameter Estimate	Partial R-Square	Model R-Square	Correlation R	F Value	Pr > F
Intercept	-2.9***					
DW_SRC	0.06***	0.32	0.32	0.56***	31.76***	<.0001
S_SRC	-0.01***	0.14	0.46	-0.05ns	17.83***	<.0001
LA_SRC	0.01**	0.06	0.52	0.33***	7.68**	0.0072
Dependent Variable: MPT						
Variable Entered	Parameter Estimate	Partial R-Square	Model R-Square	Correlation R	F Value	Pr > F
Intercept	-0.93ns					
LA_SRC	0.03***	0.42	0.42	0.60***	49.75***	<.0001
Dependent Variable: SDSS						
Variable Entered	Parameter Estimate	Partial R-Square	Model R-Square	Correlation R	F Value	Pr > F
Intercept	26.73*					
LA_SRC	0.31***	0.20	0.20	0.35***	17.06***	0.0001
SBC_SRC	0.30**	0.12	0.32	0.32**	11.39**	0.0012
Dependent Variable: WGC						
Variable Entered	Parameter Estimate	Partial R-Square	Model R-Square	Correlation R	F Value	Pr > F
Intercept	17.93***					
LA_SIG	5.14***	0.28	0.28	0.46***	26.73***	<.0001
Dependent Variable: LFV						
Variable Entered	Parameter Estimate	Partial R-Square	Model R-Square	Correlation R	F Value	Pr > F
Intercept	671.76***					
LA_SIG	66.68***	0.22	0.22	0.49***	19.68***	<.0001

* p≤0.05, ** p≤0.01, *** p≤0.001. MAB=mixolab water-absorption, ALVSTR=alveogram dough strength, ALVP=alveogram dough stability, ALVL=alveogram dough distensibility, ALVP/L=alveogram configuration ratio, MPT=mixogram peak time, SDSS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, LA_SRC=lactic acid SRC, DW_SRC=distilled water SRC, SC_SRC=sodium carbonate SRC, SBC_SRC=sodium bicarbonate SRC, S_SRC=sucrose SRC, LA_SIG=lactic acid SIG

Table 4.24 Solvent retention capacity and swelling index of glutenin parameters responsible for variation in rheological and baking quality-related characteristics in the irrigated summer rainfall region

Dependent Variable: MAB						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	29.41***					
S_SRC	0.32***	0.33	0.33	0.59**	53.29***	<.0001
SC_SRC	-0.12***	0.09	0.42	-0.02ns	16.57***	<.0001
DW_SRC	0.18**	0.05	0.47	0.49***	9.69**	0.0024
Dependent Variable: ALVSTR						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	-85.70***					
S_SRC	0.68***	0.41	0.41	0.65***	72.6***	<.0001
LA_SIG	8.52***	0.15	0.56	0.64***	35.8***	<.0001
DW_SRC	0.46**	0.03	0.59	0.38***	7.4**	0.0076
Dependent Variable: ALVP						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	-183.18***					
S_SRC	1.98***	0.45	0.45	0.64***	86.19***	<.0001
SBC_SRC	1.07**	0.05	0.50	0.52**	9.73**	0.0023
Dependent Variable: ALVL						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	453.03***					
SBC_SRC	-2.90***	0.21	0.21	-0.45***	31.21***	<.0001
LA_SRC	1.03***	0.04	0.25	0.14ns	5.58*	0.0198
S_SRC	-2.61***	0.07	0.32	-0.33***	12.45***	0.0006
Dependent Variable: ALVP/L						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	-3.05***					
S_SRC	0.03***	0.33	0.33	0.54***	51.27***	<.0001
SBC_SRC	0.02*	0.03	0.36	0.45***	5.94*	0.0165
Dependent Variable: MPT						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	-1.78*					
LA_SIG	0.68***	0.23	0.23	0.50***	31.26***	<.0001
S_SRC	0.04**	0.05	0.28	0.35***	7.47**	0.0074
LA_SRC	-0.02**	0.05	0.33	0.17ns	8.19**	0.0051
Dependent Variable: SDSS						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	63.01***					
LA_SRC	0.23***	0.12	0.12	0.36***	14.23***	0.0003
Dependent Variable: WGC						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	9.27**					
LA_SIG	4.00***	0.39	0.39	0.60***	67.15***	<.0001
LA_SRC	0.09**	0.04	0.43	0.56***	7.59**	0.0069
Dependent Variable: LFV						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	810.66***					
LA_SRC	3.25	0.37	0.37	0.58	61.11	<0.0001
SBC_SRC	-6.03	0.11	0.48	-0.29	23.26	<0.0001
LA_SIG	33.99	0.03	0.51	0.52	5.44	0.0216

* p≤0.05, ** p≤0.01, *** p≤0.001. MAB=mixolab water-absorption, ALVSTR=alveogram dough strength, ALVP=alveogram dough stability, ALVL=alveogram dough distensibility, ALVP/L=alveogram configuration ratio, MPT=mixogram peak time, SDSS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, LA_SRC=lactic acid SRC, DW_SRC=distilled water SRC, SC_SRC=sodium carbonate SRC

Table 4.25 Solvent retention capacity and swelling index of glutenin parameters responsible for variation in rheological and baking quality-related characteristics in the winter rainfall region

Dependent Variable: ALVSTR						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	5.65ns					
S_SRC	0.42***	0.34	0.34	0.58***	26.48***	<.0001
Dependent Variable: MPT						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	0.92ns					
LA_SIG	0.38**	0.13	0.13	0.36**	7.52**	0.0084
Dependent Variable: SDSS						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	156.29***					
SBC_SRC	-0.35***	0.10	0.10	0.32*	5.97*	0.0180
LA_SRC	-0.15*	0.17	0.27	0.26ns	11.92**	0.0011
S_SRC	-0.26*	0.07	0.34	0.07ns	5.31*	0.0254
Dependent Variable: WGC						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	-21.61ns					
LA_SRC	0.28***	0.41	0.41	0.64***	36.38***	<.0001
DW_SRC	0.38*	0.06	0.47	0.12ns	6.12*	0.0168
Dependent Variable: LVF						
Variable Entered	**Parameter Estimate**	**Partial R-Square**	**Model R-Square**	**Correlation R**	**F Value**	**Pr > F**
Intercept	521.09***					
S_SRC	3.16***	0.29	0.29	0.53***	20.78***	<.0001
LA_SIG	34.7*	0.06	0.35	0.34*	4.58*	0.0371

* p≤0.05, ** p≤0.01, *** p≤0.001. ALVSTR=alveogram dough strength, MPT=mixogram peak time, SDSS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, LA_SRC=lactic acid SRC, DW_SRC=distilled water SRC, SBC_SRC=sodium bicarbonate SRC, S_SRC=sucrose SRC, LA_SIG=lactic acid SIG

4.4 Discussion and conclusions

Typical SRC results for blending flour required for increased LFV on Canadian HRS wheat was reported by Kweon *et al*. (2011) as follow; distilled water SRC=73%, lactic acid SRC=148%, sodium carbonate SRC=91% and sucrose SRC=115%. Since SRC and SIG have not been used for quality evaluation of HRS and HRW genotypes in South Africa, there are no guidelines of the required values for South African high quality, high protein germplasm.

The mean values for SRC obtained in this study were highest for lactic acid SRC, followed by sucrose SRC, sodium carbonate SRC and distilled water SRC. This trend was comparable to studies conducted by Xiao *et al*. (2006), Kweon *et al*. (2011), Guzmán *et al*. (2015), Hammed *et al*. (2015) and Issarny *et al*. (2017). The SRC values were similar to values reported by Xiao *et al.* (2006) and Guzmán *et al*. (2015) and lower than values reported by Kweon *et al*. (2011), Hammed *et al*. (2015) and Issarny *et al*. (2017). The lactic acid SRC values in the irrigation SRR were lower with a mean value for the combined localities of 107.73%. These results for the high and low potential production regions are expected, since high yields obtained under irrigation farming practices, are inversely correlated with protein content. This is confirmed by Duyvejonck *et al*. (2011) who reported that flour proteins, especially the glutenins, contribute to lactic acid SRC values and Issarny *et al*. (2017), who reported highly significant correlations of lactic acid SRC with FPC ($r=0.99$, $p\leq0.01$). Distilled water SRC values were lower in the irrigated high potential SRR with lower FPC associated with softer wheat. Starch damage, during the milling process, for soft wheat is lower than for hard wheat with lower water absorption. Distilled water SRC reflects the flour's ability to hold water (Gaines, 2000; Guttieri *et al*., 2001). High protein content is associated with higher water absorption (Ohm *et al*., 2010).

The SIG values corresponded with studies conducted by Wang and Kovacs (2002a; 2002b). Li *et al*. (2013) reported highly significant correlations between SIG and FPC ($r=0.78$, $p\leq0.0001$), explaining the lactic acid SIG results associated with protein inter-related characteristics across all three environments.

Across the three production regions, the rheological and baking quality-related characteristic values were mostly higher in the dryland SRR and lowest in the irrigated SRR, except for ALVL. Mixolab water absorption was higher in the dryland SRR where genotypes expressed higher FPC. Preston and Kilborn, (1984) reported that water absorption is determined by protein content, damaged starch, pentosans and gluten strength. Flour with higher ABS and MAB are preferred, as bread volume increases with an increase in the percentage of water (Roels *et al*., 1993). Kweon *et al*. (2011) reported that ABS indicates the water needed for dough to reach a certain consistency at the point of optimum development and is mainly governed by damaged starch and pentosan content. Ames *et al*. (2003) reported that due to strong influence of protein content on ALVW and ALVL, variation in these parameters are more influenced by environmental effects, and in this study ALVSTR correlated positively with FPC across the production regions, and ALVL correlated negatively with ALVSTR and ALVP values across the production regions. Alveogram dough stability as affected by gluten properties and grain hardness associated with water absorption and pentosan content (Miles, 2010) was higher in the dryland SRR. Walker and Hazelton (1996) reported that protein content and quality as well as the water absorption of a specific flour affects MPT.

In this study higher MPT values were obtained at localities with higher protein content. As reported by Hammed *et al*. (2015), in this study WGC and FPC correlated positively across the production regions. The glutenin component of protein will contribute to the sedimentation volume as other proteins such as gliadin are soluble in the SDSS test solvents (Echert *et al*., 1993).

De Villiers and Laubscher (1995) reported a positive correlation between SDSS values and protein content, however SDSS cannot be used independently when protein content is higher than 13% (Echert *et al*., 1993; De Villiers and Laubscher, 1995; Carter *et al*., 1999). Loaf volume increases with increasing protein content within a cultivar as seen in this study, however the qualitative nature of gluten will result in different bread making qualities amongst cultivars at a given protein content (Finney *et al*., 1987; Khatkar *et al*., 1996; Bushuk, 1998).

Analysis of variance indicated highly significant ($p \leq 0.001$) cultivar, environment and cultivar x environment interaction for most of the SRC and SIG parameters, as well as for the rheological and baking quality-related characteristics. Differences in the three production regions of the dryland, irrigated SRR and the WRR resulted in different cultivar x environment interactions for the quality parameters, especially the protein inter-related parameters. The environment effect was insignificant for MAB, ALVP, ALVL and ALVP/L only in the WRR. The cultivar effect was highly significant ($p \leq 0.001$) for all SRC, SIG, rheological and baking quality-related parameters.

Cultivar made a higher contribution to variation than the environment or cultivar x environment interaction for most of the quality parameters, indicating high heritability and that all rheological and baking quality-related characteristics could be used in the breeding programme for quality selection. The cultivar x environment interaction was insignificant for MPT in the irrigated SRR and for ALVSTR and ALVL in the WRR. Alveogram configuration ratio coefficient of variance was high as was reported by Bordes *et al*. (2008) and Miles (2010).

There were significant correlations of SRC and SIG with rheological and baking quality-related characteristics. More significant correlations were evident between SRC, SIG and rheological and baking quality-related characteristics in the dryland (Table 4.20) and irrigated SRR (Table 4.21) than in the WRR (Table 4.22).

Significant differences across the production regions explains the inconsistent correlations within the regions. Pasha *et al*. (2009) and Hammed *et al*. (2015) reported on the environment effect that needs to be considered when using SRC as a quality selection tool. Lactic acid SRC, sucrose SRC and lactic acid SIG exhibited the most positive and stronger correlations with the rheological and baking quality-related characteristics. Dapcevic *et al*. (2009) reported a highly significant correlation of 0.98 ($p \leq 0.0001$) between MAB and ABS, indicating that these parameters can be interpreted as equivalent to each other. Xiao *et al*. (2006) reported highly significant positive correlations between all four SRC parameters and mixogram water absorption (MWA).

Ram *et al*. (2005) reported a significant positive correlation between flour SRC profile and ABS, whilst Hammed *et al*. (2015) and Issarny *et al*. (2017) reported highly significant correlations between distilled water SRC and sodium carbonate SRC with ABS, reflecting overall water absorption and higher water absorption due to high damaged starch content in hard wheat. Similar results were obtained in this study, except for correlations between MAB and sodium carbonate SRC. Distilled water is indicative of the flour's overall ability to retain water and was found by Duyvejonck *et al*. (2012) to be highly correlated with both ABS ($p \leq 0.0001$) and MWA ($p \leq 0.05$).

Overall more significant and stronger correlations were evident between ALVSTR with lactic acid SRC, sucrose SRC and lactic acid SIG. Gaines *et al*. (2006) reported highly significant positive correlations between alveogram parameters and lactic acid SRC. Li *et al*. (2013) also reported highly significant positive correlations between lactic acid SRC and ALVW ($p \leq 0.0001$) and between SIG and ALW ($p \leq 0.0001$).

Wang and Kovacs (2002a) reported high correlations between SIG and the insoluble gluten components of flour.

The high correlation between SIG and ALVW indicates the importance of gluten strength in determining functional properties of dough. Dough strength is mainly determined by the amount of unextractable protein, mainly insoluble glutenin, independent from different solvents and extraction procedures (Orth and Bushuk, 1973; Dachkevitch and Autran, 1989), explaining the high SIG correlations with alveogram dough strength parameters. Quality parameters that are directly related to dough strength parameters and highly correlated to the insoluble gluten fraction will be higher correlated with SIG test values, especially when swelling time is increased (Weegels *et al*., 1996).

The findings of this study were in line with Gaines *et al*. (2006) who reported highly significant positive correlations between alveograph parameters and lactic acid SRC. Kweon *et al*. (2011) also reported on the positive correlation ($p \leq 0.0001$) between distilled water SRC and AWRC (sodium bicarbonate SRC) with ALVP. This is expected as high ALVP values are obtained from hard wheat, with higher damaged starch, resulting in higher water absorption.

Low and high ALVP-values, ALVL-values and ALVW-values correspond with weak and strong dough, respectively (Miralbés, 2004; Bordes *et al*., 2008; Miles, 2010) and are influenced by protein quality and quantity (Van Lill and Smith, 1997). This explains the positive correlations with lactic acid SRC and SIG, also indicative of protein quality and quantity controlled by gluten content (Gaines, 2000; Guttieri *et al*., 2001). Better correlations across the production regions between ALVL and sucrose SRC were expected as both parameters are affected by gliadin characteristics.

Walker and Hazelton (1996) reported that protein content and quality as well as the water absorption of a specific flour affects MPT, explaining the positive correlations with lactic acid SRC and SIG, but not the weak correlation with distilled water SRC reported in this study. Ram *et al*. (2005) also reported a highly significant positive correlation between lactic acid SRC and MPT.

Wang and Kovacs (2002b) reported a significant correlation between MPT and SIG ($p \leq 0.01$), indicative of the link between insoluble glutenin and dough strength. Hammed *et al*. (2015) reported that WGC is highly correlated with flour protein ($p \leq 0.001$) and all four SRC solvents, explaining the high correlations with lactic acid SRC and SIG. Li *et al*. (2013) reported that the SIG and lactic acid SRC tests are better small-scale rapid tests to predict gluten strength than the SDSS test. Gaines *et al*. (2006) and Roccia *et al*. (2006) reported highly significant positive correlations between SDSS and lactic acid SRC, as was found in this study. Deyong *et al*. (2012) could not find a correlation between SDSS and lactic acid SRC. Xiao *et al*. (2006) reported positive correlations between sodium carbonate SRC, distilled water SRC and SDSS volume, contradicting the results obtained in this study.

Xiao *et al*. (2006) reported highly significant positive correlations between, lactic acid SRC and LFV. This is expected as higher protein associated with lactic acid SRC will result in higher loaf volumes. Similar results were obtained in this study. Xiao *et al*. (2006) also found that SRC correlates with the quality of gluten protein related to LFV over a wide range of flour protein contents. Their findings stated that SRC results significantly correlated with SDSS volume and that the 5% lactic acid SRC solvent was reliable in predicting LFV in HWW flours with a narrow range of protein content. Colombo *et al*. (2008) reported LFV and lactic acid SRC are highly correlated. Hammed *et al*. (2015) reported that lactic acid SRC significantly correlated with LFV. Wang and Kovacs, (2002b) reported significant correlations between LFV and SIG.

Regression coefficients for the SRC and SIG predictor variables, to describe variation in rheological and baking quality-related characteristics, were relatively low and ranged between 12% and 59% across the three production regions. The highest regression coefficient (59%) obtained across the regions was for ALVSTR.

The low regression coefficients indicate that rheological and baking quality-related characteristics were poorly predicted by most of the SRC and SIG parameters in

this study. The contribution of the independent variables towards variation in the quality characteristics were mostly inconsistent across regions. Distilled water is associated with the flour's overall ability to hold water and sodium carbonate is associated with damaged starch content and indirectly water holding ability, explaining their contributions towards MAB. Lactic acid SRC and SIG and ALVSTR are both correlated with dough strength and flour protein content (Gaines *et al*., 2006; Li *et al*. 2013). Sucrose SRC is indicative of gliadin characteristics and the high contribution in the irrigated SRR and WRR towards dough strength was unexpected. Kweon *et al*. (2011) reported that ALVP was highly correlated with AWRC or sodium bicarbonate SRC ($p \leq 0.0001$) and distilled water SRC ($p \leq 0.0001$), this is expected as high ALVP values are obtained from hard wheat, with higher damaged starch and resulting higher water absorption. However, in this study distilled water SRC and sodium bicarbonate SRC only contributed 34% and 5% to the total variation, respectively, and the contribution across the regions were inconsistent.

Mixograph peak time is the primary measurement of the mixograph, measuring optimum dough development time (Fowler and De la Roche, 1975) and is a function of protein content, water absorption and dough strength (Ram *et al*., 2005). Peak time is influenced by protein content and ratios (Bietz *et al*., 1973), explaining the lactic acid SRC and SIG protein inter-related parameters contribution toward variation in the model for MPT. The high contribution of the protein interactive SRC and SIG parameters towards WGC was expected as WGC is highly correlated with FPC.

The lactic acid SRC contribution in the model for FPC was inconsistent across regions, but was expected and supported the findings of Xiao *et al*. (2006). Lactic acid SIG correlated with LFV ($p \leq 0.01$) as reported by Wang and Kovacs, (2002b), and explains the SIG contribution towards variance in LFV.

Lactic acid SRC, sucrose SRC and lactic acid SIG exhibited the most positive correlations with the rheological and baking quality-related characteristics and were the independent parameters occurring in most of the models. Sucrose SRC is associated with gliadin inter-related characteristics, and lactic acid SRC and SIG with the gluten inter-related characteristics.

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CHAPTER 5

GENERAL CONCLUSIONS AND RECOMMENDATIONS

Mean values of SRC and SIG parameters obtained in this study were in line with results obtained by other researchers on hard wheat germplasm. Combined ANOVA showed highly significant differences among cultivars, environments and cultivar x environment interaction for the measured quality parameters and the SRC and SIG parameters, which varied across the dryland summer rainfall region, irrigated summer rainfall region and the winter rainfall region. Variation between genotypes was large and genotypes contributed significantly to the variance in lactic acid SRC, distilled water SRC, sodium carbonate SRC, sodium bicarbonate SRC, sucrose SRC and lactic acid SIG, indicating the usefulness of these parameters for selecting improved bread wheat quality.

Cultivar x environment interaction was significant for the SRC and SIG parameters. Differences in the dryland summer rainfall region, irrigated summer rainfall region and the winter rainfall region resulted in varying cultivar x environment interactions, emphasising the large differences between the regions and genetic makeup of the spring and winter cultivars produced in South Africa. Quality performance of cultivars were affected by protein content differences among regions as a result of high and low yield potential within a region.

Differences between cultivars and environments resulted in inconsistent correlations of SRC and SIG parameters with quality characteristics across the regions, indicating that more localities within a region and years are needed to confirm test results. Correlations obtained in this study were in line with findings of other studies conducted on hard wheat. More frequent significant correlations of SRC and SIG with grain, milling, rheological and baking quality related characteristics were evident in the summer rainfall regions than in the winter rainfall region.

Correlations between SRC, SIG and grain and milling characteristics were inconsistent across regions, except for lactic acid SRC and lactic acid SIG with flour protein content. The highest correlations were obtained between lactic acid SRC, SIG and flour protein content. Correlations between SRC, SIG and rheological and baking quality related characteristics were inconsistent across regions, with more significant and stronger correlations of alveogram dough strength with lactic acid SRC, sucrose SRC and lactic acid SIG. Overall, more grain, milling, rheological and baking quality-related characteristics were correlated with lactic acid SRC, distilled water SRC and lactic acid SIG.

Regression coefficients for the grain, milling, rheological and baking quality-related characteristics as predicted by the SRC and SIG parameters were low to moderately low (12% to 60%), indicating that the SRC and SIG parameters are poor predictors of most of the bread wheat quality parameters. Lactic acid SRC and distilled water SRC were the most common predictor variables, explaining relatively more of the variation in the models for grain and milling characteristics. Grain hardness was not included as a quality parameter in this study, the inclusion of this parameter is recommended for a better understanding of how distilled water SRC relates to water absorption, grain hardness and the collective quality profile of a HRS and HRW cultivar. Lactic acid SRC, sucrose SRC and lactic acid SIG were responsible for contributing to the variation in most of the models for rheological and baking quality-related characteristics. Multiple stepwise regressions indicated that SRC and SIG parameters contributed inconsistently towards the variation in bread wheat quality across regions and lactic acid SRC was the parameter occurring in most of the models responsible for the highest variance contribution.

The AWRC method (sodium bicarbonate SRC) was not effective in predicting bread wheat quality in this study and was initially developed for soft wheat applications. The lactic acid, distilled water, sucrose SRC solvents and the SIG method can be indicative of bread wheat quality characteristics, when small amounts of seed are available for running the small scale predictive test to streamline the breeding

programme in early generations. The lactic acid SRC solvent was the most useful parameter for assessing bread wheat quality in this study and is recommended for the evaluation of HRW and HRS wheat bread making quality potential.

Significant correlations and regression coefficients obtained in this study were lower when compared with other hard wheat studies. The low correlations could be a result of the narrow quality range of genotypes used in this study, as all entries evaluated were accepted by the industry in accordance with the high quality release criteria of the WTC.

Appendix

Table A1.1 Meteorological data for the dryland summer rainfall region in 2012 with deviations from the long-term mean (2005-2013)

Dryland summer rainfall region							
Locality	**Crop development stage**	**Total seasonal rainfall (mm)**		**Monthly temperatures (°C)**			
				Minimum		**Maximum**	
Bethlehem	Pre-seeding (January-May)	**208.53**	(-132.28)	**5.23**	(-4.57)	**25.09**	(+1.40)
	Seeding (June and July)	**35.06**	(+13.28)	**-2.03**	(-0.55)	**16.42**	(-0.56)
	Early growth (August)	**0.76**	(-0.85)	**0.58**	(-0.10)	**21.26**	(+1.36)
	Pre-anthesis (September)	**42.93**	(+30.42)	**4.48**	(+0.02)	**20.28**	(-3.36)
	Post-anthesis and grain filling (October and November)	**189.73**	(-47.42)	**11.28**	(+0.39)	**25.23**	(-0.04)
Clarens	Pre-seeding (January-May)	**286.51**	(-68.99)	**5.22**	(-4.45)	**23.54**	(+0.98)
	Seeding (June and July)	**74.93**	(+50.83)	**-0.75**	(-0.68)	**15.69**	(-0.51)
	Early growth (August)	**10.16**	(-6.73)	**2.08**	(-0.35)	**19.73**	(+0.37)
	Pre-anthesis (September)	**58.09**	(+61.97)	**5.15**	(-0.72)	**18.82**	(-3.79)
	Post-anthesis and grain filling (October and November)	**289.56**	(+13.50)	**10.53**	(+0.03)	**23.32**	(-0.53)

Values in brackets indicate deviations of the year value from the nine-year mean (2005 to 2013) (ARC-ISCW 2014)

Table A1.2 Meteorological data for the irrigated summer rainfall region in 2012 with deviations from the long-term mean (2005-2013)

Irrigated summer rainfall region							
Locality	**Crop development stage**	**Total seasonal rainfall (mm)**		**Monthly temperatures (°C)**			
				Minimum		**Maximum**	
Upington	Pre-seeding (January-May)	**133.86**	(-5.97)	**7.03**	(-6.86)	**31.72**	(-0.41)
	Seeding (June and July)	**31.24**	(+15.05)	**3.03**	(-0.13)	**22.64**	(+0.34)
	Early growth (August)	**0.76**	(-0.38)	**2.43**	(-0.45)	**24.69**	(+0.57)
	Pre-anthesis (September)	**1.02**	(+0.74)	**4.15**	(-1.73)	**27.73**	(-0.45)
	Post-anthesis and grain filling (October and November)	**62.48**	(-8.17)	**12.96**	(-0.23)	**35.29**	(+2.35)
Vaalharts	Pre-seeding (January-May)	**170.95**	(-26.95)	**6.64**	(-4.00)	**31.52**	(+0.67)
	Seeding (June and July)	**12.2**	(-35.48)	**-0.16**	(-1.97)	**21.94**	(-0.16)
	Early growth (August)	**1.78**	(-2.23)	**4.14**	(+1.52)	**25.23**	(+1.18)
	Pre-anthesis (September)	**12.45**	(+3.16)	**5.72**	(-0.38)	**26.87**	(-1.67)
	Post-anthesis and grain filling (October and November)	**119.88**	(-2.93)	**13.57**	(+0.71)	**33.45**	(+1.33)

Values in brackets indicate deviations of the year value from the nine-year mean (2005 to 2013) (ARC-ISCW 2014)

Table A1.3 Meteorological data for the winter rainfall region in 2012 with deviations from the long-term mean (2005-2013)

Dryland winter rainfall region							
Locality	**Crop development stage**	**Total seasonal rainfall (mm)**		**Monthly temperatures (°C)**			
				Minimum		**Maximum**	
Morreesburg	Pre-seeding (January-May)	**15.94**	(-8.53)	**15.51**	(-0.29)	**28.46**	(-0.10)
	Seeding (June and July)	**62.35**	(-23.06)	**8.23**	(-0.77)	**17.57**	(-0.67)
	Early growth (August)	**108.50**	(+29.28)	**6.21**	(-1.61)	**16.79**	(-1.31)
	Pre-anthesis (September)	**38.00**	(-0.09)	**8.45**	(-0.52)	**19.95**	(-0.54)
	Post-anthesis and grain filling (October and November)	**8.33**	(-11.77)	**14.70**	(+0.63)	**28.46**	(+0.92)
Riversdal	Pre-seeding (January-May)	**171.60**	(+15.07)	**7.58**	(-6.33)	**25.52**	(-0.32)
	Seeding (June and July)	**149.40**	(+50.08)	**12.97**	(-0.21)	**16.86**	(-1.56)
	Early growth (August)	**62.60**	(+13.94)	**5.04**	(-0.90)	**17.1**	(-1.62)
	Pre-anthesis (September)	**21.40**	(+1.96)	**6.87**	(-0.43)	**20.15**	(-0.59)
	Post-anthesis and grain filling (October and November)	**95.60**	(-23.53)	**12.68**	(+0.25)	**24.2**	(+0.04)

Values in brackets indicate deviations of the year value from the nine-year mean (2005 to 2013) (ARC-ISCW 2014)

Table A1.4 Combined analysis of variance for solvent retention capacity and swelling index of glutenin characteristics for nine wheat cultivars in Riversdal

		Mean squares					
SOURCE	**df**	**LA_SRC**	**DW_SRC**	**SC_SRC**	**SBC_SRC**	**S_SRC**	**LA_SIG**
Rep (Environment)	2	66.96*	4.54ns	2.47ns	9.81*	02.95ns	0.29*
Cultivar	8	93.82***	19.43***	68.46***	540.26***	265.88***	0.26**
Error	16	11.71	1.53	3.57	2.28	4.17	0.06
CV (%)		2.95	1.87	2.28	2.14	2.38	5.94
R2		0.83	0.87	0.91	0.99	0.97	0.73
		Variance component contribution (% of SS)					
Rep (Environment)	2	12.49	4.81	0.81	12.49	0.27	15.91
Cultivar	8	70.02	82.25	89.83	70.02	96.7	57.06

* p≤0.05, ** p≤0.01, *** p≤0.001, ns=non-significant, df=degrees of freedom, LA_SRC=lactic acid SRC, DW_SRC=distilled water SRC, SC_SRC=sodium carbonate SRC, SBC_SRC=sodium bicarbonate SRC, S_SRC=sucrose SRC, LA-SIG=lactic acid SIG, Cult x Env=cultivar x environment interaction, CV=coefficient of variance, R^2= coefficient of determination, SS=sum of squares

Table A1.5 Combined analysis of variance for solvent retention capacity and swelling index of glutenin characteristics for nine wheat cultivars in Morreesburg

		Mean squares					
SOURCE	**df**	**LA_SRC**	**DW_SRC**	**SC_SRC**	**SBC_SRC**	**S_SRC**	**LA_SIG**
Rep (Environment)	2	13.95ns	1.87ns	1.65ns	6.11ns	3.12ns	0.01ns
Cultivar	8	44.59ns	10.81***	29.74***	6.67ns	21.95***	0.13***
Error	16	18.27	1.20	2.20	5.26	2.53	0.01
CV (%)		3.30	1.67	1.89	3.56	1.7	2.66
R2		0.57	0.82	0.87	0.44	0.82	0.82
		Variance component contribution (% of SS)					
Rep (Environment)	2	4.12	3.42	1.19	8.16	2.81	0.97
Cultivar	8	52.70	79.02	86.09	35.62	78.98	81.34

* p≤0.05, ** p≤0.01, *** p≤0.001, ns=non-significant, df=degrees of freedom, LA_SRC=lactic acid SRC, DW_SRC=distilled water SRC, SC_SRC=sodium carbonate SRC, SBC_SRC=sodium bicarbonate SRC, S_SRC=sucrose SRC, LA-SIG=lactic acid SIG, Cult x Env=cultivar x environment interaction, CV=coefficient of variance, R^2= coefficient of determination, SS=sum of squares

Table A1.6 Combined analysis of variance for grain, milling, rheologic and baking quality-related characteristics for nine wheat cultivars in Riversdal

		Mean squares													
SOURCE	**df**	**HLM**	**BFLY**	**FLY**	**FPC**	**FN**	**MAB**	**ALVSTR**	**ALVP**	**ALVL**	**ALVP/L**	**MPT**	**SDSS**	**WGC**	**LVF**
Rep (Environment)	2	10.04*	0.02ns	0.76ns	0.34ns	223.44ns	1.26ns	8.45ns	7.37ns	169.15ns	0.01ns	0.03ns	5.15ns	9.83*	4362.04*
Cultivar	8	5.58*	7.67***	4.63*	3.62***	5919.42***	6.79***	86.42**	369.76***	459.34*	0.06***	0.09**	32.01***	25.38***	5966.12***
Error	16	1.81	0.25	1.78	0.5	748.11	0.97	15.74	19.66	124.9	0.01	0.02	3.56	3.17	821.04
CV (%)		1.69	2.9	1.76	6.32	9.53	1.66	9.64	5.77	9.4	13.75	6.01	2.05	4.98	3.02
R2		0.69	0.94	0.58	0.79	0.8	0.78	0.74	0.9	0.67	0.78	0.6	0.82	0.81	0.83
		Variance component contribution (% of SS)													
Rep (Environment)	2	21.44	0.07	2.28	1.82	0.75	3.49	1.76	0.45	5.63	3.59	5.03	3.18	7.19	12.54
Cultivar	8	47.62	93.87	55.29	76.81	79.23	74.99	72.01	89.98	61.13	74.38	64.31	79.18	74.28	68.59

* p≤0.05, ** p≤0.01, *** p≤0.001, ns=non-significant, df=degrees of freedom, HLM=hectolitre mass, BFLY=break flour yield, FLY=flour yield, FPC=flour protein content, FN=falling number, MAB=mixolab water-absorption, ALVSTR=alveogram dough strength, ALVP=alveogram dough stability, ALVL=alveogram dough distensibility, ALVP/L=alveogram configuration ratio, MPT=mixogram peak time, SDSS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, Cult x Env=cultivar x environment interaction, CV=coefficient of variance, R^2= coefficient of determination, SS=sum of squares

Table A1.7 Combined analysis of variance for grain, milling, rheologic and baking quality-related characteristics for nine wheat cultivars in Morreesburg

		Mean squares													
SOURCE	**df**	**HLM**	**BFLY**	**FLY**	**FPC**	**FN**	**MAB**	**ALVSTR**	**ALVP**	**ALVL**	**ALVP/L**	**MPT**	**SDSS**	**WGC**	**LVF**
Rep (Environment)	2	1.42ns	0.24ns	1.82ns	1.50ns	150.70ns	1.10ns	17.29ns	4.70ns	76.70ns	0.01ns	0.01ns	1.18ns	4.78ns	1367.59ns
Cultivar	8	12.76***	7.73***	2.56**	1.18ns	1338.23ns	13.14***	28.38ns	227.70***	884.90***	0.10***	0.70***	38.37***	23.29***	3799.54**
Error	16	0.63	0.13	0.52	0.74	616.87	1.99	11.62	17.62	181.62	0.01	0.02	5.48	2.67	747.80
CV (%)		0.98	1.79	0.96	6.62	6.61	2.39	7.44	5.45	11.46	14.79	5.5	2.58	4.16	2.82
R2		0.91	0.97	0.74	0.6	0.53	0.77	0.58	0.87	0.71	0.83	0.94	0.78	0.82	0.73
		Variance component contribution (% of SS)													
Rep (Environment)	2	2.48	0.73	11.26	10.21	1.44	1.58	7.72	0.45	1.51	1.49	0.21	0.91	4.01	6.07
Cultivar	8	88.77	96.06	63.23	49.31	51.28	75.59	50.73	86.21	69.82	81.28	93.89	77.07	78.11	67.40

* p≤0.05, ** p≤0.01, *** p≤0.001, ns=non-significant, df=degrees of freedom, HLM=hectolitre mass, BFLY=break flour yield, FLY=flour yield, FPC=flour protein content, FN=falling number, MAB=mixolab water-absorption, ALVSTR=alveogram dough strength, ALVP=alveogram dough stability, ALVL=alveogram dough distensibility, ALVP/L=alveogram configuration ratio, MPT=mixogram peak time, SDSS=SDS-sedimentation volume, WGC=wet gluten content, LFV=loaf volume, Cult x Env=cultivar x environment interaction, CV=coefficient of variance, R^2= coefficient of determination, SS=sum of squares