ASSESSMENT OF SOUTH AFRICAN BREAD WHEAT CULTIVARS FOR MILLING QUALITY

BY

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CHAPTER 1

INTRODUCTION

Wheat (*Triticum aestivum* L.) is the single most important and widely grown cereal food crop in the world. The consumption of wheat foods, as a major component of a diet, not only provides carbohydrates, but is also a substantive source of protein, vitamins and minerals (Betschart, 1988). Cultivation, production and processing of superior wheat grain play an important role in human nutrition in many regions of the world.

High quality baked goods begin with good quality grain. Different people have different interpretations of good quality. To the producer it is high yield, resistance to pathogens and resistance to weather damage prior to harvest. The miller is interested in the ease of milling, flour extraction and the suitability of the flour for his customers' use. The concept of baking will vary with the end-product use, whether it is for bread, cake, biscuits, pasta or noodle products. At the end of the line the consumer is interested in the flavour, texture, nutritional value and cost of the product (Simmonds, 1989). Therefore, any property of the wheat, the grain flour or bread that can be measured or ranked can be regarded as an aspect of its quality. In this study the focus will be on the grain and flour quality.

The history of experimental milling and baking in South Africa, dates back to 1928 when experimental facilities were installed at the Stellenbosch Elsenburg College of Agriculture. The Wheat Board (established in 1938) introduced the purchase and sale of wheat on a quality basis (Fowler and Priestley, 1991a) and remained the sole purchaser of all wheat produced in South Africa until the deregulation of this single channel wheat marketing system in 1997. Since then, the decontrolled free trade environment was established and the wheat industry as a whole (wheat breeders and the processing industries, in collaboration with the agricultural sector) is now responsible to control and maintain the quality standards of wheat grain for the different market demands.

To obtain the best milling quality, the physical state of the wheat is of primary importance. In the way of superior milling results, a lot of problems and obstacles may occur. Genotypes differ genetically in kernel characteristics, grain hardness, bran content, disease and pest resistance and agronomic traits. These genetic differences could have an effect on the production of good quality seed. The intrinsic nature of wheat could further be affected by environmental factors during the growing period, such as frost damage, diseases (like mildew (*Erysiphe graminis*), smuts (*Ustilago tritici, Tilletia spp.*), rusts (*Puccinia* spp.), scab (*Fusarium* spp.) and black point (*Helminthosporium* spp.)), insect damage, soil and nutrient properties, agronomical practices

and environmental conditions at different stages of plant development. Therefore, variation in quality can be expected from season to season.

South Africa is a net importer of wheat. The past four years showed that domestic use of wheat is constant at about 2.5 million tonnes, while the annual production over the same period averages around 2.158 million tonnes (Ferreira, 2002). It is thus important that locally grown cultivars are consistently of high grade.

Considering the extreme variation in the climatic conditions, such as rainfall, daily minimum and maximum temperatures and nutritional status of different soil types, South Africa is a country with diverse wheat producing regions. In this study the focus was on wheat quality of the Free State province, which accounts for approximately 50% of the total wheat production of the country. In this region winter and facultative wheat types are planted during the autumn and winter months (April to July) on residual soil moisture conserved during the summer rainfall period (October to March).

Hard red wheat types are developed and cultivated to fulfil mainly bread baking requirements and all cultivars are screened for milling and baking quality against local grading standards to ensure quality control before being released for commercial production. Three year's data, over five localities per year is used for the evaluations. Wheat lines have to comply with all the quality criteria prescribed by the milling and baking industries.

But what happens to wheat quality after release, when the cultivar is grown in more areas under different conditions? All over the world, researchers have found that the environmental conditions influence the milling and baking quality of wheat. Cultivar x environment interactions were found for flour yield, percent flour or grain protein and hardness or softness (Baenziger *et al.* 1985; Pomeranz *et al.*, 1985; Bassett *et al.*, 1989). Schuler *et al.* (1995) found that the environment apparently influences end-use quality in ways not visually discernible.

The objectives of this research were thus to:

- assess South African winter and facultative wheat cultivars for bread wheat grain and milling quality.

- study the effect of genotype x environment interaction on the stability of winter wheat quality.

- characterise South African winter wheat cultivars for milling performance.

CHAPTER 2

LITERATURE REVIEW

2.1 THE HISTORY OF WHEAT MILLING

Wheat (*Triticum aestivum* L.) is the single most important and widely grown food crop in the world because of its genetic diversity and unique quality characteristics. It has been a substantial food crop, since people first began to settle in permanent communities, thousands of years ago. Grinding of wheat seed dates back to ancient civilisations that cultivated and processed wheat in areas around the Mediterranean sea. After the first attempts by these primitive people, to pound selected grain with stones to release the edible seeds from their hulls, a long history of milling and baking followed. This method of crushing wheat led to the invention of the mortar and pestle (about 10 000 years ago) and the saddle stone (about 5 000 years ago) to improve the process. These quern stones were the predecessors of later stone mills. During the ancient Egyptian times, the mortar and pestle grinding had evolved into a multi-step process with sieving, further grinding and final sieving after the grinding and winnowing process. The manufacturing of larger saddle stones, grooved rubbing surfaces and hoppers to feed grain to the lower stone, subsequently followed. The lever mill (a flat furrowed stone moving back and forth in a horizontal arc over a fixed lower furrowed stone) that subjected the grain to both shearing and grinding was an improvement on the saddle stone. Then, about 2 300 years ago, the rotary mills came into use (Bass, 1988). For centuries only minor technological improvements were made to the milling process as such. Only the nature of the energy source changed from hand mills to those driven by draught-animals and later to water and windmills. The first windmill was used in Babylon, about 4000 years ago. These mills occurred commonly in Persia during the tenth century (Wêreldspektrum, 1982). Water and wind driven mills were used until the late 19th century and were eventually replaced by steam-powered and subsequently by electrical mills.

With the invention of the middlings purifier, iron roller mill and plan sifter, grinding and sifting turned into a large-scale, continuous and highly mechanized process with lower labour requirements. The purifier, roller mill and sifter underwent many improvements since they were first introduced to the milling process over a century ago, but their basic principles remain unchanged and most of today's modern mills incorporate these three constituents into their designs. A surge towards new technology led to the installation of roller mill plants (McGee, 2002). The processing of wheat using cast iron rolls in stead of millstones was first reported in

central Europe in 1923. Porcelain rolls were used for a short time up to about 1930, but cast iron rolls remained the favourite (Cook, 2001).

All these improvements also increased the need for rapid, separate conveying of the numerous mill stocks, leading to the development of the pneumatic conveying. According to Bass (1988) the main achievements that took place in milling during the 20th century were in the handling of material, refinement and improvement of the existing machinery, remote control of machines and conveying systems and finally, the automation and computerisation of the milling process. With all the developments in milling equipment there are now less mills in a country, but their capacity and technical sophistication far outpace the mills of 50 years ago (McGee, 2002).

Mills most commonly found today, are roller mills, attrition mills, impact mills, cutters, bran dusters and pearlers. The principal forces of grinding are compression, shear, abrasion and impact. Most mills work on a combination of these principles (Posner and Hibbs, 1997). The roller mill is extensively used in mills to grind wheat into flour. Wheat kernels fall into the grinding zone formed by a pair of rolls rotating towards each other at different speeds and are subjected to the grinding action. Flour milling involves several pairs of rolls used in sequence. From the first to the last pair of rolls the roll gap is set successively narrower as the particle size of the feed stock becomes smaller. For size reduction, mechanical energy is needed to break the grain, distribute it and overcome friction between the moving parts of the machine. The energy consumed has a high dependence on the physical properties of the grain to be ground (Fang *et al.*, 1998).

The milling process involves the removal of the bran (the pericarp, seed coat, nuclear epidermis and the aleurone layer) and the germ from the endosperm (Dobraszczyk, 1994; Hoseney, 1994). This milling process can be classified into four systems, namely: the break, the sizing, the reduction- and tailing system. During the break system the endosperm is separated from the bran and germ. The sizing process separates the small bran pieces attached to the large pieces of endosperm and in the reduction system the endosperm is reduced to flour. By the tailing system, fibre is separated from the endosperm recovered from the other three systems. The purifying section of the mill comprises of a system of cleaning machines, all based on sorting of size, gravity, separation sorting of shape, scouring and magnetism principles. In the grinding operation, energy is expended to break apart the bran and endosperm and reduce the endosperm to flour. This results in heat generation and moisture loss of the ground material (Posner and Hibbs, 1997).

The milling roll can significantly affect mill performance and economic efficiency by the energy consumption at a specific feed rate, differences in flour releases, roll surface temperatures and

evaporation losses (Cook, 2001). This is the reason for improvements of iron rollers being dynamic to date. In order to address the common problem concerning consistency in wheat flour, research on wheat milling developments is a continuous process, for example the use of Digital Image Analysis (DIA) to determine the influence of bran levels in flour. Although flour is produced by high specifications, there are variations that are not detected by the standard flour colour grade testing specifications. This analysis detects bran levels in the flour that are not possible with the normal colour grading systems and provides the miller with valuable milling control information (Cliffe, 2002).

Due to the interaction between the mill and the wheat grain, not only the machinery but also the physical characteristics of the grain will be of prime importance to achieve the highest milling performance.

Wheat is treated as a commodity that is classified by bran colour (red or white), growth habit (spring and winter) and kernel hardness (hard or soft). Although the concept of wheat milling and baking will vary with the type of wheat and end product, high quality baked goods begin with good quality wheat. Wheat grain characteristics that account for the milling performance (high flour extraction yielding flour of the right colour) of bread wheat cultivars are kernel morphology, test weight (an international grading standard), kernel weight, kernel size, bran content, wheat kernel hardness and moisture content. Flour quality is mainly considered as flour yield, flour colour and flour protein content.

2.2 KERNEL CHARACTERISTICS

Since milling and flour quality is related to grain morphology, it is important to look at kernel characteristics and its importance in milling performance. Desirable aspects would be: large and uniform kernel size, plumpness and spherical shape, high density and well filled kernels (Fowler and Priestley, 1991b). Short grains with a narrow crease, rounder rather than longer as well as consistency of shape and plumpness are good kernel characteristics. Kernels should exhibit a uniform, smooth surface with the absence of depressions or corrugations on the surface, with small to medium sized embryos protruding, rather than sunken or depressed. A large dense brush is undesirable. Semi translucency is desirable for hard grained samples in the appropriate protein range and absence of weather damage is also required (Berman *et al.*, 1996). Kernel morphology could be used in the early stages of selection for milling quality breeding.

2.2.1 Test weight

One of the oldest and most widely used criteria of physical quality in grain marketing is the weight per unit volume or test weight (Halverson and Zeleny, 1988). Test weight is useful in indicating the relative condition of the wheat (Donelson *et al.*, 2002) and is widely recognized as an important wheat grading factor.

Test weight (usually expressed in kilograms per hectolitre) represents the weight of wheat per volume, interpreted as a measure of kernel soundness. The principle of this test is the packing of kernels into a container (Czarnecki and Evans, 1986). Plump kernels pack more uniformly, giving rise to a higher test weight, whereas small, elongated kernels pack more randomly and give low test weight values (Dick and Matsuo, 1988). Fully mature, plump and undamaged kernels are high in test weight. Test weight is thus a function of packing efficiency and kernel density (Jalaluddin and Harrison, 1989). Packing efficiency is a trait associated with heritable traits like grain shape and size, whereas kernel density is related to the environment where it was grown.

In the past the miller used test weight, commonly associated with sound plump kernels, as a rough indication of the expected flour yield. Several researchers reported a significant correlation between these two traits. Fowler and De la Roche (1975b), Gaines (1991) and Monsalve-Gonzalez and Pomeranz (1993) reported positive correlations. However, the relation is highly variable and also dependent on the genotypes.

Test weight is not always a reliable guide of the amount of flour that should be extracted from a certain amount of wheat (Posner and Hibbs, 1997). In a study conducted by Schuler *et al.* (1995) test weight, which has been considered an indicator for potential flour yield, failed to show any correlation with flour yield. Other researchers confirmed their finding. Berman *et al.* (1996) found that test weight accounted for only 17% of the variation in flour yield, similar to the weak positive correlation between test weight and flour yield observed by Marshall *et al.* (1986). However, when wheat varieties from the same locality are used in a blend, test weight may be considered as one of the factors in determining the potential flour yield (Posner and Hibbs, 1997).

Both grain yield and test weight are very important economic characteristics of wheat and selection for both the characteristics are important to the wheat breeder. Jalaluddin and Harrison (1989) found that these two characteristics were not negatively correlated and simultaneous selection is possible.

In the study conducted by Hazen and Ward (1997), test weight exhibited a highly significant correlation with both kernel size and kernel weight. Monsalve-Gonzalez and Pomeranz (1993) also established significant correlation between test weight and kernel weight (r=0.72) and so did Ohm *et al.* (1998). Schuler *et al.* (1994) suggested the following model to illustrate the interaction of kernel and spike characteristics in producing a given test weight:
Test weight ($kg.m^{-3}$) = 976.23 – 75.29(kernel width) + 1.03(spike length) – 1.54(kernels per spike). This model could account for only 47% of the variability in test weight.

Many researchers observed a significant correlation between test weight and flour protein content (Bassett *et al.*, 1989; Schuler *et al.*, 1994; Preston *et al.*, 1995; Schuler *et al.*, 1995). In contrast, no correlation was found between test weight versus protein content by Gaines (1991). Bassett *et al.* (1989) studied soft white winter wheat and found that grain yield and test weight were also correlated with, kernel hardness, flour moisture, sedimentation and cookie diameter. Ohm *et al.* (1998) found test weight to be significantly correlated with single kernel hardness index. Gaines (1991) reported that cultivars with high test weight produced less break flour.

As already mentioned, the environmental factors play an important role on the realisation of high test weight. Observations by Gaines *et al.* (1996a) indicated that the environmental component had a major effect on test weight. Therefore, test weight can be seen as the yardstick of environmental influences (Gaines, 1991), especially of what is happening between florescence and harvesting. The ratio of endosperm to bran is lower in small kernels and also results in lower test weight (Dick and Matsuo, 1988). Many types of weathering damage can occur in wheat kernels before harvest. Kernels that are shrivelled or immature have reduced test weight (Schuler *et al.*, 1994). Rain-induced preharvest sprouting (Donelson *et al.*, 2002), lodging or delayed harvest may also reduce test weight significantly. Czarnecki and Evans (1986) reported a significant reduction in test weight caused by moderate amounts of precipitation, affecting the density and packing efficiency when exposed to weathering. Similarly, Carver (1996) found that delayed harvest due to rainfall, resulted in lower test weights. This reduction may be due to the changes in kernel shape or roughening of the bran coat which influences grain packing. It may also decrease due to a decline in kernel density or kernel mass.

High test weight cultivars, tolerant to weathering would be advantageous in areas where heavier precipitation occurs during the harvesting season. The Free State province of South Africa is an example of such an area.

2.2.2 Kernel size

2.2.2.1 Thousand kernel weight

The weight per thousand kernels usually gives an indication of the kernel size. The thousand kernel weight can give the miller important information on the milling ability of wheat, because this trait is one of the quality parameters highly correlated with flour yield (Posner and Hibbs, 1997).

Bhatt (1972) studied the inheritance of kernel weight in two spring wheat crosses and found that the heritability of kernel weight indicated that considerable progress could be made by applying selection pressure. The genotype therefore plays an important role in the determination of kernel weight.

Plumper wheat kernels have a larger percentage endosperm and thus higher thousand kernel weight. This, eventually, results in higher flour yield. The percentage seed coat and germ decrease as the endosperm steadily increases during this growth phase. Monsalve-Gonzalez and Pomeranz (1993) concluded that the growth habitat has an affect on kernel characteristics. A short grain filling period imposed a major restriction on kernel development and affected kernel weight. Therefore, kernel weight correlates well with flowering date (Huebner and Gaines, 1992). The rate of grain filling is lower in dry environments than in wet environments and affects thousand kernel weight negatively (Debelo *et al.,* 2001). Gibson *et al.* (1998) reported kernel weight decrease particularly when high temperatures occurred continuously during maturation. According to Du Plessis and Agenbag (1994) kernel weight was not influenced by fertiliser treatment with nitrogen and sulphur, but favourable moisture conditions resulted in higher kernel weight. Czarnecki and Evans (1986) reported a significant decrease in thousand kernel weight caused by delayed harvesting.

In wheat that has been prematurely ripened due to unfavourable growing conditions, the percentage endosperm is less than in fully matured wheat. Physical and chemical differences are found not only among different varieties, but also among differently sized kernels of the same variety. In the latter case, the differences are due to environmental influences, like moisture, humidity, temperature, fertilisation and wind that affect the photosynthesis just before the ripening phase of the grain (Posner and Hibbs, 1997).

Jalaluddin and Harrison (1989) and Debelo *et al.* (2001) reported a significant correlation between thousand kernel weight and grain yield. This correlation reveals why thousand kernel weight had been identified as a very reliable indicator for yield losses (Pretorius, 1983) or as an indirect selection criteria for yield and drought tolerance (Debelo *et al.,* 2001).

Highly significant correlation (r=0.75) between thousand kernel weight and test weight was reported by Jalaluddin and Harrison (1989), but kernel weight is not a direct component of test weight, although it is associated with kernel density, which is a component of test weight.

There is controversy concerning the correlation between kernel weight and protein content per kernel. Kernel weight correlates well to protein content per kernel (r=0.94) (Löffler and Busch, 1982). Preston *et al.* (1995) observed that kernel weight resulted in consistently strong negative responses to increasing protein content. Pomeranz *et al.* (1985) did not find a significant correlation between thousand kernel weight and protein content.

The thousand kernel weight is not only affected by climatic conditions, but also by disease infections. Pretorius (1983) found that thousand kernel weight and protein content was significantly reduced by stem rust infections.

2.2.2.2 Kernel diameter

There are significant positive correlations between single kernel weight and diameter (size) (Fang *et al.*, 1998; Ohm *et al.*, 1998). These parameters have a significant correlation with the percentage of large kernels. This may be the reason why thousand kernel weight is generally used for determining kernel size because it is a faster technique.

Gibson *et al.* (1998) observed that flour yield is greatly dependent on the diameter and size distribution of kernels. Flour yield is associated positively and linearly with kernel diameter. Kernel volume has a higher correlation with kernel diameter than with kernel length (Ghaderi *et al.*, 1971). A fairly regular decrease in flour yield is found as wheat kernels decrease in size. The ash content of flour milled to the same extraction level from small kernels is significantly higher than that of flour from larger kernels. Within the same cultivar, large kernels possess a lower protein content than small kernels. A comparison of protein content between the whole wheat and the end flour shows a smaller protein loss with large kernels (Posner and Hibbs, 1997).

Berman *et al.* (1996) combined four kernel size image descriptors (means of grain area, lengths of minor and major axes and ellipsoidal volume) obtained by image analysis of the wheat kernels, with the test weight of the samples to predict milling quality. These kernel images and test weight accounted for 66% of the variation in the flour yield of 38 grain samples.

The test weight is not related to the diversity of seed size within a sample of grain. Kernel width and length indicated very weak negative correlations with test weight (Schuler *et al.*, 1994).

Smaller kernels are usually a little softer than large kernels. The reason might be that smaller kernels develop later and had less time to produce full plump kernels (Gaines *et al.*, 1996b). Wheat with larger kernel size, requires more power to fracture during milling than wheat with smaller kernel size (Fang *et al.*, 1998).

2.2.3 Kernel hardness

Kernel hardness is used as important criteria to classify wheat and plays a significant role in wheat marketing (Bechtel *et al.*, 1993). The primary basis of determining different end uses of wheat, is not its gluten-forming properties, but its kernel hardness. Kernel hardness, in addition to protein quantity and protein quality, is the single most important aspect of wheat utilisation and classification (Slaughter *et al.*, 1992). Almost all of the world's wheat production and trade is defined as either soft or hard. Van Deventer (1999) also suggested the use of wheat kernel hardness in the South African wheat classification system. Generally speaking, hard wheat is used for bread and soft wheat for cookies, cakes and pastries.

Kernel hardness refers to the texture of the kernel, that is, if the endosperm is physically hard or soft (Bettge *et al.*, 1995). There are various hypotheses explaining kernel hardness, most common is the interaction of starch granules with the surrounding storage protein matrix. Barlow *et al.* (1973) concluded that the nature of starch and storage protein adhesion differs between hard and soft wheat cultivars and that the total water-soluble material (not individual storage components) appears to play the role of a "cementing substance" between starch granules and storage protein. It is likely that through the amount and composition of this material the genetic control of kernel hardness is expressed. Three basic mechanisms that account for kernel hardness have been postulated: chemically induced adhesion between the protein matrix and the starch granule, continuity of the protein matrix and the net charge on the protein (as revised by Anjum and Walker, 1991). In hard wheat endosperm, the cells are tightly packed with the starch granules held firmly in the matrix, in soft wheat air spaces and discontinuities make it friable (Osborne, 1991). The correlation between kernel hardness and kernel density were high (r=0.71) (Ohm *et al.,* 1998), confirming the above mentioned.

Hard and soft wheat is distinguished by the expression of the *hardness* gene, located on the short arm of chromosome 5D. The short arm of chromosome 5D also controls the expression of a protein marker (friabilin) for grain softness. The quantity level of the 15-kDa proteins

(puroindoline a and b) also referred to as friabilin, present on the surface of water-washed starch, is highly correlated with wheat grain softness. The results of Malouf *et al.* (1992) support the hypothesis that the 15-kDa proteins associated with soft wheat starch granules have a dominant influence on wheat endosperm texture. It is present on the surface of water-washed starch from soft wheat in high amounts, in small amounts in hard wheat and absent on durum wheat starch (Giroux and Morris, 1997; 1998). The tensile strength of reconstituted tablets made from hard wheat were greater than those made of soft wheat flour (Malouf and Hoseney, 1992), suggesting that the 15-kDa friabilin acts as a non-sticking agent between starch granules and the protein matrix.

Because of the economic importance associated with kernel hardness, this aspect of texture assessment has received considerable attention. In time a variety of methods were developed for determining the degree of kernel hardness. Some of the methods are: "biting" (Biffen, 1908), granularity or particle size index (PSI) (Cutler and Brinson, 1935), resistance to pearling, grinding time, NIR diffuse reflectance spectroscopy (Delwiche and Norris, 1993), and the single kernel characterisation system (SKCS) force to crush (Osborne *et al.,* 1997). Delwiche (1993) measured single kernel wheat hardness by using the non-destructive optical near infrared transmittance of intact kernels. Irving *et al.* (1989) investigated kernel hardness differentiation based on fluorescence. Results of all the methods of kernel hardness determination were strongly affected by moisture content and the best determination should be evaluated at optimum moisture content (Obuchowski and Bushuk, 1980a).

Kernel hardness is inherited simply and is controlled by one or two major genes and perhaps some minor genes (Baker, 1977), therefore the simple genetic control of this character should permit easy manipulation by the plant breeder. Lukow *et al.* (1989) found evidence of hard wheat, perhaps with one or more minor (modifier) genes, which slightly reduce the kernel hardness of a specific variety. There was no evidence of a major gene conferring medium kernel hardness characteristics in spring wheat. Crosses between hard and soft wheat to improve insect and foliar disease resistance, tolerance to soil acidity and aluminium toxicity by utilising sources over kernel hardness classes, occur often. The progeny of such a cross may have other potential weaknesses like, low test weight, sensitivity to drought or, as Carver (1996) noted in the progeny of a hard red winter wheat crossed with a soft red winter wheat, consistent decreases in kernel hardness and flour yield.

Factors affecting kernel hardness are the genotype (most important factor), growing environment (Anjum and Walker, 1991; Monsalve-Gonzalez and Pomeranz, 1993; Morris *et al.*, 1999), growing season, protein content, moisture, kernel size and the bran. Therefore millers

and bakers should expect significant variation of kernel hardness due to both cultivar and environmental effects (Hazen and Ward, 1997).

Bechtel *et al.* (1996) indicated that hard wheat grain is hard throughout seed development and soft wheat gain is soft during the whole developmental time. Variation in kernel hardness of winter wheat grown under different environmental conditions was mainly affected by genotype (Pomeranz and Mattern, 1988). Bergman *et al.* (1998) detected genotype as the main source of variation in a population derived from a soft by hard cross. Wheat containing the 1B/1R translocation had consistently harder grain than wheat without the translocation (Dhaliwal *et al.*, 1987).

Depending on the growth conditions, phenotypic kernel hardness can vary considerably due to environment (Morris, 1992), either in such a way that genotype hardness cannot be determined reliably or environmental conditions can have only a limited effect (Fowler and De la Roche, 1975b; Pomeranz *et al.*, 1985). Kernel hardness decreased approximately by 8% with delayed harvest at similar rates for different cultivars evaluated by Czarnecki and Evans (1986).

Kernel hardness affects the milling process, wheat milling performance as well as the resultant flour quality (Gaines *et al.,* 1996a). It influences conditioning before milling (Williams, 1998), the flow, the sifting area and energy consumption of the mill (Bettge *et al.*, 1995). During milling, hard wheat behaves differently from soft wheat. Hard wheat requires more force and energy (Fang *et al.*, 1998) to fracture the kernels and maintain large particles throughout the milling process (Cutler and Brinson, 1935; Malouf and Hoseney, 1992). This in turn, affects the resultant flour quality viz. flour yield, flour particle size and flour density (Pomeranz and Williams, 1990). During roller milling, the endosperm of hard wheat kernels tends to shatter rather than to powder and breakage of both starch granules and protein matrix occur (Posner and Hibbs, 1997). The large flour particles, have a well-defined shape like fine crystalline sugar (Osborne, 1991), pass through sieves more readily and typically of hard wheat, yield flour that contains more damaged starch (Malouf and Hoseney, 1992). Flour from soft wheat, on the other hand, is made up of fine cell contents (Rogers *et al.*, 1993) with no defined structure, has poor flow properties and takes longer to sieve. The flour particle size is not of great importance in bread making, but indeed plays a role in cookie and cracker products. In these products, small particles in the flour are important.

Devaux *et al.* (1998) indicated that the main difference between hard and soft wheat used in their study, was the proportion of isolated starch granules released when the grain was fragmented. If hard wheat is milled to a fine particle size, starch damage will be very high (Hoseney, 1987). Damaged starch has a high water absorption capacity (Bettge *et al.*, 1995)

and therefore shows why hard wheat has higher water absorption during the dough development of breadmaking. Starch damage, along with the increase in protein content at higher mill settings, are probably the major factors for differences in most rheological quality measurements, since there is a positive correlation between water absorption and starch damage (De la Roche and Fowler, 1975; Williams, 1998).

Many researchers have found a correlation between flour yield and kernel hardness (Ohm *et al.*, 1998), indicating that cultivars with harder kernel texture tend to have higher flour yield values. While examining soft wheat cultivars, Bassett *et al.* (1989) found flour yield was significantly correlated (r=0.72 to 0.81) with kernel hardness measurements. Bergman *et al.* (1998) also observed this correlation between flour extraction and kernel hardness, but the selection for hardness had no consistent and detectible impact on flour yield (Carver, 1994).

Biffen (1908) already mentioned that it appears to be a general characteristic of hard wheat to contain a higher total nitrogen percentage than soft wheat when grown under the same conditions. Carver (1994) studied the correlated selection responses in milling and flour quality of two hard red winter populations (differing widely in parental origin) and found selection for high kernel hardness scores that increased protein concentration, while lower kernel hardness levels decreased it. The factors that control kernel hardness, apparently control protein content in the evaluated segregating populations, as well. Correlative effects of kernel hardness selection are expressed primarily in the protein quantity, not protein quality. Bergman *et al.* (1998) found a genetic correlation between kernel hardness and protein content and explained this association between the two traits by the close linkage between the *Ha* gene and the high protein yielding gene known as *Pro 2*. Other researchers that indicated that there is a correlation between kernel hardness and protein composition, were Huebner and Gaines (1992) and Lyon and Shelton (1999). It appears as if confusion exists regarding this correlation. Studies by Miller *et al.* (1984) and Pomeranz *et al.* (1985) failed to reveal similar results, the correlation between kernel hardness and protein content was either very low or insignificant, reflecting the lack of relationship between the parameters. The study by Kilborn *et al.* (1982) found an inverse relationship between protein content and energy requirements throughout the reduction process for four wheat cultivars with various protein contents.

Obuchowski and Bushuk (1980b) found that although hardness values of debranned grain ranked wheat cultivars in the same order as for values determined on whole wheat, bran had a definite influence on the kernel hardness evaluation. They also found no relationship between the protein content and endosperm hardness of debranned wheat.

Kernel hardness classification as determined by the Perten 4100 SKCS can be classified as follows (Williams, 1998):

Hardness classification	SKCS HI
Extra hard	90-100+
Very hard	80-89
Hard	65-79
Medium hard	50-64
Medium soft	40-49
Soft	30-39
Extra soft	negative and up to 14

Blending wheat of different market hardness classes results in grain lots with quality characteristics intermediate between those of the original components (Morris, 1992).

Correlation analysis showed no relationship of kernel hardness with kernel weight, width or test weight (Hazen and Ward, 1997).

2.2.4 Vitreous kernels

Vitreous means to have a glass-like or translucent appearance. Immature wheat grains are vitreous before harvesting but as maturation proceeds, some grains remain vitreous while others become mealy (Posner and Hibbs, 1997). Vitreousness is probably caused by mainly hydrogen that bond together all the constituents of the kernel, in such a way that the optical characteristics (including the refraction index) of the kernel differ from those of individual constituents. The kernel allows the passage of light, which makes the kernels appear translucent. Vitreous character is the result of lack of air spaces within the kernel. Air spaces make the opaque grain less dense and are formed during drying. Protein shrinks, ruptures and then leaves air spaces upon drying (Hoseney, 1987). In vitreous kernels the protein shrinks, but remains intact (Dobraszczyk, 1994).

Vitreousness is generally associated with kernel hardness and high protein content, and mealiness (opaqueness) with softness and low protein content. According to Stenvert (1972), wheat can be recognised as being hard by its vitreous appearance, which merge to starchy or soft grains with decreasing hardness. Similarly, Dexter *et al.* (1988) observed that vitreous fractions of durum wheat was the hardest and contained the highest amount of protein. This is not always true, because soft wheat cultivars grown under the correct conditions can have

vitreous grain, but remain soft. The opposite is also true, hard wheat can have an opaque or floury matrix and still be quite hard. The vitreous character results during the final drying in the field, because if grain is harvested before it matures and is dried by freeze-drying, the grain has a mealy appearance (Hoseney, 1987).

Hardness and vitreousness is often confused. Vitreousness occurs in all wheat varieties as a consequence of maturing conditions (Pomeranz and Williams, 1990). These conditions include sufficiently high nitrogen availability and high temperatures. Biffen (1908) already observed that wheat grown continuously on comparatively poor and unmanured soil, rarely produced translucent grain. Adverse weather during a delay in harvest may also affect the percentage vitreous kernels in the grain (Czarnecki and Evans, 1986). Vitreousness is thus largely determined and influenced by environmental conditions. Kernel hardness on the other hand, is under strong genetic control (Hoseney, 1987; Pomeranz and Williams, 1990).

2.2.5 Moisture content

Wheat grain is harvested at a moisture percentage of below 15% and dried to at least 12.5% moisture content to reduce the risk of the development of mouldiness when in storage. When the moisture content is too high, heat damage could occur as a consequence of a rise in temperature while in storage (Posner and Hibbs, 1997).

The initial grain moisture content is very important to the miller before the conditioning is conducted. The moisture content, in relation to kernel hardness, is used to determine the amount of water to be added for conditioning purposes (Williams, 1998). The addition of water to wheat before milling is a routine procedure, that enhances the efficiency of flour extraction (Delwiche, 2000).

Moisture content also has an important influence on the other kernel characteristics; hardness, test weight and kernel weight.

2.3 THE MILLING PROCESS

The Bühler mill is a small, simplified experimental mill that represents commercial milling. These mills can accommodate samples larger than 500g.

2.3.1 Conditioning

Conditioning, or tempering, is the controlled addition of moisture to a wheat sample prior to milling, to improve millability (Bass, 1988). The primary aim of conditioning is to change the mechanical characteristics of the different tissues of the kernel and thereby improve the separation of the endosperm and the bran to limit bran contamination during flour extraction. The addition of water also triggers a number of biochemical events in the kernel, which modify characteristics of the kernel (Gobin *et al.*, 1996). This is to toughen the bran to ensure that it will resist powdering during the milling process (powered bran cannot be separated from the flour at any stage of the milling action) and to facilitate the physical separation of endosperm from the bran. It also aids in mellowing the endosperm in order that it may be easily reduced to flour and to ensure that flour leaving the grinding rolls are in optimum condition for sifting. Another aim of conditioning is to ensure that the grinding produces the optimum level of starch damage consistent with the wheat kernel hardness and flour end-uses (Bass, 1988). Gobin *et al.* (1996) found that conditioning not only influenced milling quality, but also the technological and biochemical quality of the final flour product due to the possible reduction of disulfide groups of protein that remain reduced even after lengthy storage.

Williams (1998) found that kernel hardness and the moisture content of the grain when received, is part of the fundamental knowledge a miller should possess before tempering is conducted. Kernel hardness is indicative of the rate and quantity of water uptake during tempering. Although it is generally accepted that hard wheat endosperm diffuses water at a slower rate than soft wheat endosperm, the exact nature of the interaction is not well understood, but it appears to be affected by vitreousness and the agglomeration of starch and protein in the endosperm (Pomeranz and Williams, 1990). Delwiche (2000) found that moisture affects wheat texture and that soft and hard wheat exhibit the same trend with moisture content, however they do it at different response rates.

Water moves more rapidly through small and soft wheat grains than through hard wheat grain. Glenn and Johnston (1994) reported that water diffusion in mealy (soft) endosperm was 1.8 to 4.6 times faster than in hard vitreous endosperm. Consequently, the amount of water added and the optimum time of equilibration are both different for hard and soft wheat (Osborne, 1991). Usually water is added to obtain a moisture content of approximately 16.0 to 16.5% for hard wheat and 14.5 to 15.0% for soft wheat (Williams, 1998). Tempering can be modified by increasing the temperature, moisture component and tempering period. The optimal amount of water and tempering time differs according to the grain characteristics. Hard wheat needs the addition of more water and longer conditioning periods than soft wheat. The optimum conditioning according to kernel hardness is of utmost importance to prevent problems during

the milling process. For example, when soft wheat is conditioned for a relatively long period, the endosperm literally sucks the water out of the bran, resulting in brittle bran and "sticky" endosperm. The brittle bran may cause flour colour and flour ash problems, while the "sticky" endosperm will result in sifting and flow problems in the mill (Wylie, 2002).

Moisture content affects the endosperm compressive strength of hard wheat more than soft wheat (Delwiche, 2000), therefore moisture content has a positive correlation with the energy required to mill the wheat (Fang *et al.*, 1998). Dobraszczyk (1994) found that the fracture toughness decreases as the moisture content increases, irrespective of the degree of vitreousness. He also mentioned that an increase in moisture content increases the energy to fracture the endosperm.

2.3.2 Break flour yield

The objective of the break system is to open the wheat kernel and remove the endosperm from the bran coat with the least amount of bran contamination.

Break release percentage is the amount of ground material obtained, consisting of mainly big and smaller endosperm particles, flour and fine bran, reported as a percentage of the original material being tested through a certain sieve aperture. The break system consists of two parts, the primary break system, which releases relatively pure particles of endosperm and the secondary or tail break system, which cleans the bran and releases smaller pieces of endosperm along with more fine pieces of bran. The first three fractions of white flour obtained and sifted out during Bühler milling, are referred to as break flour (Bass, 1988).

The breaking system in a mill is very sensitive to variations from the optimum wheat tempering level. Break flour from low-moisture wheat has higher ash values than similar flours from well-tempered wheat (Posner and Hibbs, 1997). Kilborn *et al.* (1982) found that break flour release was highly correlated with the energy requirement for all breaks ($r=-0.98$).

Break flour yield is primarily a function of wheat kernel hardness (Gaines *et al.*, 1996b). During milling, hard wheat produces less break flour yield than soft wheat (Stenvert, 1972). This has been confirmed by the research of Gaines (1991), Rogers *et al.* (1993) and Labuschagne *et al.* (1997) who obtained higher break flour yield from softer textured wheat, usually resulting from lower protein soft wheat. Therefore, break flour yields correlated negatively with kernel hardness parameters (Ohm *et al.*, 1998). Yamazaki and Donelson (1983) likewise found a negative association between kernel hardness and breakflour yield in a set of predominately

soft wheat cultivars. In the study by Morris *et al.* (1999) the traditional measure of grain kernel hardness (break flour) was poorly correlated with other hardness measurements, this could be explained by the tempering of the grain. Tempering improves the correlation between breakflour yield and particle size index (Yamazaki and Donelson, 1983).

Kosmolak and Dyck (1981) found a positive correlation between break flour yield and larger kernel size. Break four yield also resulted in significant negative correlations with test weight, kernel density and percentage large kernels (Ohm *et al.*, 1998). A negative correlation between break flour yield and flour protein content for red wheat cultivars was reported by Gaines (1991).

2.3.3 Flour Yield

Flour yield is a key bread wheat quality trait, since higher flour yield from a certain amount of wheat means more profit to the miller. Flour yield, also referred to as extraction, is expressed as the percentage of flour obtained from a given amount of wheat (Bass, 1988). Flour extraction is a complex trait, a combination of many minor effects. As already mentioned, grain size and shape, the thickness of the bran coat and the endosperm to bran ratio influence the proportion of endosperm in the kernel. Factors that affect the removal of the endosperm, as well as the amount of endosperm present within the wheat kernel, have an impact on flour yield (Schuler *et al.*, 1995). Kernel hardness, cell wall thickness and endosperm adherence to the bran affect the ease of separation of the endosperm from the non-endosperm components (Marshall *et al.*, 1986). The expertise of the miller is also an important factor in achieving optimum and good quality flour (Posner and Hibbs, 1997), because factors such as feed rate, roll gap, roll speed, roll differential and tempering procedure also play a significant role (Kilborn *et al.*, 1982).

Plump kernels (favoured by high photosynthetic rates and longer grain filling rates) have a larger percentage endosperm and thus influence flour yield (Planchon, 1969). Altaf-Ali *et al.* (1969) found that kernel diameter was correlated to flour yield and Marshall *et al.* (1986) reported the importance of kernel volume in predicting flour yield. These findings were confirmed by Yamazaki (1976) and Pumphrey and Rubenthaler (1983) who found that an increase in the degree and amount of kernel shrivelling, caused by poor growing conditions, reduced the proportion of endosperm to bran, and this was responsible for a decrease in flour yield. Smaller kernels caused a decrease in the milling quality (flour yield), because the proportions of endosperm that can be extracted as flour are less and there is an increase in the difficulty of accomplishing the extraction (Wrigley *et al.*, 1994).

Work by Ohm *et al.* (1998) on single kernel characterisation indicated that flour yield was significantly correlated to kernel hardness, test weight and kernel density and may be potential parameters for estimating flour yielding capacity of wheat. In the study conducted by Bassett *et al.* (1989), the flour yield was highly correlated with kernel hardness, protein content, sedimentation and cookie diameter. Similarly, Labuschagne *et al.* (1997) reported that the presence of the softness genes in their study was associated with a reduction of flour yield. Souza *et al.* (1993) also found a correlation between flour yield and flour protein. The contamination of one wheat class, based on kernel hardness and colour (when hard red spring wheat was contaminated by soft white spring wheat or by hard white spring wheat), influenced flour yield significantly (Habernicht *et al.*, 2002).

Abdel-Aal *et al.* (1997) studied the milling properties of spring type spelt and einkorn wheat and found that the flour yield of all the spelt material was high and comparable to those of common hard red spring wheat, but einkorn and durum wheat were significantly lower in flour yield.

Van Lill and Smith (1997) reported that both genotype and environment contributed significantly to the variation in flour yield for winter wheat grown in the Free State. Although significant effects of genotype, environment and genotype by environment interactions were found for flour yield, the effect of genotype was the largest source of variation (Bergman *et al.*, 1998).

2.4 FLOUR CHARACTERISTICS

2.4.1 Flour colour

Flour colour is regarded as one of the major criteria for quality of flour, playing an important role in the control of the flour production process. Since consumers prefer white bread above brown bread, bakers will grant a higher grade to whiter flour.

Two independent factors, brightness and yellowness control the whiteness of flour. The milling process, through particle size and bran inclusion, influences brightness whereas yellowness is due to the carotenoid pigments inherited in some wheat genotypes. For decades, millers have controlled pigmentation by bleaching the flour. As consumer demands for reduced additive use in food products became stronger, the production and marketing of unbleached flour was perceived as an advantage (Oliver *et al.*, 1993).

Variance in colour may be due to genetic, environment, genotype x environment (GXE) interactions or the milling process. When breeding for rust resistance by using the resistance

gene *Lr 19,* from *Agropyron* species, yellow flour pigmentation might be incorporated (Knott, 1980) in the progeny. Environmental effects that might be the reason for darkened flour colour values are frost damage, immature harvested kernels and black point in wheat kernels (Bass, 1988). Particles of bran, dark millstreams and flour extraction rate might also influence flour colour.

Flour colour from bran contamination is one of the most obvious effects of the quality characteristics of the flour particles, influenced by the grinding in the reduction action (Posner and Hibbs, 1997). As far as economic benefits to the miller are concerned, wheat with light-coloured bran is desirable, because the inclusion of the bran fraction would have less effect on the colour of the flour.

Van Lill and Purchase (1995) indicated that the flour colour of winter wheat cultivars, released since 1965 in South Africa, was 46% brighter than the old cultivars released from 1930 to 1964. The miller prefers the increase in potential for flour extraction, while maintaining the flour colour.

The measurement of brightness (influenced by the dulling effect of bran particles) correlates strongly with ash content and flour extraction (Patton and Dishaw, 1968; Shuey and Skarsaune, 1973; Posner and Hibbs, 1997). Li and Posner (1989) found a linear relationship (r=0.995) between flour colour and flour extraction. This relationship could be used to compare superiority of wheat cultivars in terms of colour degradation. A slower rise in flour colour as flour yield is increased, indicates a better wheat quality. Significant correlations were found between flour pigment content and starch damage (Baker *et al.*, 1971)

Abdel-Aal *et al.* (1997) studied the milling properties of spring type spelt and einkorn wheat and found that spelt flour was similar in whiteness to hard red spring wheat flour, whereas einkorn wheat was somewhat yellow, but not as distinctly yellow as durum flour.

2.4.2 Flour protein content

Along with wheat kernel hardness, protein content is one of the most important factors in determining the end use quality of wheat (Fowler and De la Roche, 1975a; Delwiche, 1995) and is important in the classification of wheat. Trade premiums are often offered on high protein wheat.

All the morphological parts of the wheat kernel contain protein, with the germ or embryo containing the highest concentration, but due to the small size, contributes very little to total

protein. The major proportion of the total protein is contributed by the gliadin and glutenin components of the storage protein (Hoseney, 1994).

The milling process does not have a significant effect on protein content. It may not be necessary to measure both grain and flour protein (Bhatt and Derera, 1975). Flour protein content is usually around 1% less than the grain protein content (Hoseney, 1994). The protein content of pearled wheat was 1-3% lower than that of the original grain (Obuchowski and Bushuk, 1980b). A comparison of protein content between the whole wheat and the end flour, indicates a smaller protein loss with large kernels (Posner and Hibbs, 1997).

Differences in bread baking quality have usually been attributed to differences in protein quality. Wheat quality is based on the protein quality and quantity. Protein quality and content (quantity) are thus very important and are both considered primary characteristics in measuring the potential of flour in relation to its end use properties (Mailhot and Patton, 1988). The direct relationship between protein content in wheat and the baking quality of flour is widely known. The quality and quantity of gluten largely determine the physical dough properties and hence the quality of the final product (Naeem *et al.*, 2002). Products made from hard wheat typically require cultivars possessing relatively high protein content due to its correlation with the dough strength of panned bread quality. Protein content has a large influence on rheological characteristics of the dough and is therefore used as an estimate of baking quality. When considering dough properties, it is known that wheat's protein composition controls the special dough properties that make bread wheat flour suitable for leavened products (MacRitchie, 1999). Branlard and Dardevet (1985) carried out their research on the relationships between protein content and quality characteristics of 70 wheat cultivars by analysing the high molecular weight (HMW) glutenin. Their research indicated that there are relationships between different glutenin subunits and rheological characteristics (strength, tenacity, swelling and extensibility) of the dough that are independent and not influenced by protein content. Andrews and Skerritt (1996) also found protein content and total gluten content to be generally highly correlated with dough extensibility. Fowler and De la Roche (1975a) indicated that protein content was the most effective predictor of loaf volume.

Labuschagne *et al.* (1997) reported that the protein content was significantly influenced by the presence of the softness genes. Some contradictory information about the influence of protein content on kernel hardness exists in the literature. A highly significant negative correlation was obtained between protein content and particle size and a positive correlation between protein content and flour yield (Obuchowski and Bushuk, 1980b).

Grain yield and grain protein content are negatively associated in wheat (Halloran, 1981; Löffler and Busch, 1982; Koekemoer, 1996) and no selection has proved to improve both traits simultaneously (Löffler and Busch, 1982; Stoddard and Marshall, 1990). When the grain yield increases and grain protein concentration decreases, the milling and baking quality of bread flour could be affected. The research by Costa and Kronstad (1994) revealed a negative association between grain protein concentration and grain yield and also between grain protein concentration and harvest index. Cox *et al.* (1985) detected significant variability in nitrogen assimilation after anthesis. This nitrogen assimilation after anthesis strongly influenced grain protein, explaining 27 to 39% of the variation, but no relationship was found with grain protein concentration. Thus, genetic variation in nitrogen assimilation has a role in determining grain yield and protein concentration in wheat. Huebner and Gaines (1992) reported a similar effect and indicated that protein composition varied among kernels from spikes that flowered at different dates. Although there is a general negative correlation between yield and protein content, it has been possible in many breeding programmes to increase yield while holding a constant protein level (Edwards, 1997).

Genetic improvement of protein content may involve the use of exotic and unadapted wheat as parents (Löffler and Busch, 1982). High grain protein percentages were reported for wild tetraploid wheat *Triticum turgidum* var. *dicoccoides,* the immediate progenitor of most of the cultivated wheat. Their grain protein content ranged between 14.1 and 35.1%. This far exceeds protein values of cultivated wheat ranging between 7 and 21%. Although GXE interactions were highly significant (caused mainly by fluctuation between years), a high and significant genetic component of variation was found within and between populations. The data enable the formulation of a strategy for collecting high protein genotypes to be used as a good source of genes for increasing the grain protein levels of cultivated wheat (Levy and Feldman, 1989). High protein types were also reported in other species of *Triticum* and *Aegilops*. The hard spelt lines evaluated by Abdel-Aal *et al.* (1997) contained over 14% protein compared to the hard red spring and durum wheat, containing 13.4 and 12.7% protein respectively, when grown under the same conditions.

Flour protein concentration is most sensitive to environmental fluctuations, while the percentage protein present as glutenin (independent of flour protein content) was found to be nearly totally genotype dependant (Graybosh *et al.*, 1996). Differences resulting from the environment were the primary source of variation in protein content as found by Bergman *et al.* (1998). Grain protein content in Australian wheat studied by Stoddard and Marshall (1990) varied widely. The bulk of this variation was attributed to environmental factors. Grain exposed to warm dry climates during the filling period, tends to be harder in texture and has a higher protein content (Bergman *et al.*, 1998). Du Plessis and Agenbag (1994) reported that increasing levels of

nitrogen resulted in a higher protein content of two spring wheat cultivars produced in the Swartland. Wheat producers need to pay attention to grain protein content and need to use nitrogen fertilisers to help maintain consistent quality in hard red winter wheat production (Lyon and Shelton, 1999). Miller *et al.* (1984) indicated that the protein content of wheat from localities was highly variable and mainly reflected the amount of fertiliser used and the time of fertiliser application. The level of substrate and available soil nitrogen is controlled by environmental factors such as moisture, temperature and nitrogen fertilisers. Therefore, the significant effect that environment has on protein level should not be unexpected.

2.4.3 Ash content

Ash is the residual inorganic material left after incineration and is expressed as a percentage of the original sample. The gradient of ash content increases from the centre to the outer layers of the kernel, so that the highest concentration is located in the seed coat or bran (Fowler and Priestley, 1991b). This variability of mineral content can be due to environmental and genetic factors and their interaction. Millers use wheat ash as a quality factor to evaluate the product and are looking for wheat that will produce low ash flours. The ash itself does not affect flour properties and thus, it can be argued, that ash content should not be regarded as a flour quality parameter in bakers' specifications. However, ash values of wheat can be an important tool for the adjustments and control of mills (Posner and Hibbs, 1997). Fowler and De la Roche (1975a) considered the use of flour ash useful as a measure of milling efficiency rather than of wheat quality. The ash content of flour is correlated with flour colour brightness and provides a means of monitoring the milling process through the assessment of the grade value of flour streams (Oliver *et al.*, 1993).

A greater proportion of the ash was removed by the debranning of durum and hard red spring wheat cultivars than in soft wheat cultivars. Although a high positive correlation was observed between flour colour and protein content, the ash content appears not to be related to protein content (Preston *et al.,* 1995).

2.5 GENOTYPE, ENVIRONMENT AND THEIR INTERACTION (GXE) INFLUENCES ON MILLING QUALITY

Quality can be regarded as the ability of the grain to meet the requirements of the processor and depends on the cultivar and environment in which the crop is grown. For the production of high quality grain, it is important to understanding the factors that contribute to variation in wheat quality.

Plant breeders and agronomists have identified three sources of variation in plant characteristics; genotypes, environment and GXE interaction. Wheat quality characteristics may be divided into those largely inherited and those influenced by the growing conditions in different environments (Nel *et al.,* 1998). Significant variation in quality characteristics exists among cultivars, and while most breeding programmes focus on the importance of genotypes, the importance of environment should not be underestimated.

Potential exists to identify and select genotypes with enhanced end-use quality consistent across production regions. Superior milling and baking quality traits of wheat are genetically influenced and have been bred into the widely used cultivars accepted as standards, but environmental conditions do affect the milling and baking quality of wheat significantly (Baenziger *et al.*, 1985; Peterson *et al.*, 1992; 1998). Even among the wheat varieties recognized as having desirable quality traits, the influence of environment can be substantial (Edwards, 1997). Therefore, both the unique genetics of wheat cultivars and their environment during growth have independent and interactive influences on all physical and biochemical quality attributes of wheat.

Quantitative traits are strongly affected by environment and by GXE interactions. Considering protein content, for example, plants which are quantitatively similar might carry different genes for that trait (Levy and Feldman, 1989). The environment plays a significant role due to the polygenic nature of most of the quality characteristics. The classification of locations could be useful in breeding for specific adaptability within sub regions. Some cultivars are more stable over environments and will deliver stable quality, irrespective of the environment in which they are grown.

Some unexpected and/or unknown environmental factors affect the kernel hardness and quality of the grain. How different varieties respond to environmental factors is not known (Faridi *et al.*, 1987). Some of the environmental conditions that might have an influence on grain and resultant flour quality are heat or cold stress, rainfall, temperature (climate) soil, fertiliser use, crop rotation (agronomic characteristics), foliar disease and insect pests.

In environments with diverse moisture supply, temperature, soil type and biotic stress, GXE interaction is expected to be large and may result in failure to differentiate performance of genotypes across environments (Collaku *et al.*, 2002). Environmental variation due to weather conditions is often considered as a major factor influencing quality traits in wheat. Nel *et al.* (1998) reported that temperature and rainfall are the most critical environmental factors affecting yield and quality in the Western Cape. Temperature is a major component of environmental variation and has a marked effect on grain filling in wheat. As a result of the

influence on starch synthesis and the duration of grain filling, grain weight and yield reduce under high temperature conditions (Panozzo and Eagles, 1998). Temperature variation during grain filling reduces grain quality; rising temperatures reduce grain size, produce lower test weight and reveal a rise in protein content. This higher protein did not always produce gluten of high quality and dramatic decreases in dough strength have been reported (Wrigley *et al.*, 1994). The kernel hardness of the grain is related to the accumulated temperatures above 30°C during the second 14 days after anthesis. The increase in kernel hardness is much larger in soft than hard wheat cultivars (Panozzo and Eagles, 1998).

Environmental conditions during maturation and ripening of wheat have a major influence on kernel characteristics that contribute to grain yield and milling quality. Results demonstrate significant reduction of flour yield at high temperatures that cause decreased yield and kernel weight; the high temperatures also increase kernel hardness. Flour quality is damaged most when high temperatures are maintained continuously from early grain filling to ripeness (Gibson *et al.,* 1998). On the other hand milling-related parameters such as test weight, wheat ash, flour ash, flour colour and yield are adversely affected by low temperatures. The response to frost was dependent on both the temperature and the stage of maturity of the plant. At early maturity, temperatures below –3 °C result in decreased kernel weight and protein content, but increased kernel hardness. The effects are less evident at later maturity when seed moisture is below 45% (Preston *et al.*, 1991). Temperature stress on roots directly affects grain properties (test weight, kernel weight and diameter, kernel hardness and protein content) that are important for milling and baking (Guedira *et al.*, 2002). Gaines *et al.* (1996a) reported that the drier growing region in Washington, favoured the production of larger, better filled (high mean test weights) and harder kernel texture that tend to produce superior milling characteristics. Moist environments should produce softer kernels that generally produce less starch damage during milling and have lower water absorption.

Data of test weight as showed by Jalaluddin and Harrison (1989) indicates that kernel weight and test weight are more controlled by heredity than environment, within the range of normal growing conditions. A significant GXE interaction was observed by Bhatt and Derera (1975) for test weight, grain and flour protein content, flour yield, flour colour and the bread volume. Fowler and De la Roche (1975b) found that the environmental component for test weight, thousand kernel weight and yield was of major significance (the genotypic variability for these traits was consistently low). Significant environmental interaction was also found for kernel hardness and mixograph peak area.

According to Pomeranz *et al.* (1985), the environmental influences were larger on thousand kernel mass and protein content, whereas the influences of genotype was more important for

kernel hardness than the growing location and conditions. In contrast to Pomeranz *et al.* (1985), Gaines *et al.* (1996a) reported that the environment had a larger influence on kernel hardness than genotype. These researchers further reported that the environment also had a larger effect on test weight and breakflour yield than genotypes did. Flour yield and mixograph mixing time was slightly influenced by environmental differences.

Gaines (1991) found that the year, locality, cultivation practices, environmental and climatic conditions had tremendous effects on protein content and kernel hardness of genotypes. The environment largely influenced the yield, protein content and protein related parameters. The reduction in test weight and kernel weight with increase in protein content may be related to environmental stress (drought) rather than a direct response of protein content. The study by Baenziger *et al.* (1985) revealed that flour yield and protein content indicated highly significant differences among environments. Various environmental factors affected grain protein content. Flour protein concentration is most sensitive to environmental fluctuations (Graybosh *et al.*, 1996). Protein quality is largely influenced by the genetic factors, thus wheat varieties inherits the protein quality from their parents (Bushuk, 1985), whereas protein quantity is largely under environmental control. In the series of trials conducted by Robert (1997), the protein percentage indicated a very high proportion of the total variation due to environment. The wheat producer can adjust the protein content by cultivation practices, but quality is inherent to a cultivar.

Kernel hardness, kernel weight and kernel width are all significantly affected by cultivar, environment and the interaction of cultivar x environment. Cultivar has the largest variance component for kernel hardness and weight. Kernel width is the only trait where environmental variance was larger than cultivar variance. The GXE interaction has a larger influence on kernel width and weight than on kernel hardness. Variation among environments is small for kernel weight and width (Hazen and Ward, 1997).

Collaku *et al.* (2002) found the genotypic effect to be significant for the flour yield, protein content and kernel softness, when soft red winter wheat cultivars were evaluated over 16 localities. Genotypes accounted for 37% of the total variability in flour yield and for 20% of the total variation in protein content. Significant GXE interaction was observed for flour yield and protein content. Sixty three percent of the variation in kernel softness was attributed to genotypic effects compared to the GXE interaction that was only 0.3%. GXE interaction variance components accounted for 16% of the phenotypic variance in flour yield and for 6% of protein content variation. Environmental components, particularly over years, were highly significant and had a strong effect on the milling and baking traits.

Lin and Czuchajowska (1997) carried out their research on milling performance of club and soft white winter wheat. The club wheat was significantly lower in test weight and thousand kernel weight and significantly higher in kernel hardness scores. There were no differences in protein or ash content, but the club wheat exhibited better milling performance as indicated by flour yield. Growing conditions controlled total flour yield. The club wheat often demonstrated more uniform grain characteristics and milling performance than soft white winter wheat. The quality characteristics of wheat cultivars containing the 1B/1R translocation, were affected largely by the genotype, rather than by the environment (Fenn *et al.*, 1994).

Under South African circumstances, Laubscher (1980), while studying spring wheat cultivars in the Western and Southern Cape, found that the variation in protein content and bread volume is dominated by the influence of the environmental effects. The study conducted by Nel *et al.* (1998) revealed that the environment contributed 86.7% to the variation in test weight, GXE interaction was responsible for 12.5% of the variation and that of cultivars, although significant, was only 0.8%. When looking at grain protein content, results indicated that environment contribution to variation in protein content is by far the largest, but significant GXE interaction was also observed. Van Lill *et al.* (1995a) reported large variation for characteristics such as protein content, Mixograph development time and baking strength index, among winter wheat cultivars grown in the Free State. Canonical variate analysis indicated that of all the environmental variables examined by Van Lill *et al.* (1995b), climatic conditions during grain filling influences yield, grain protein content and dough-development time.

The presence of *Lr29, Lr34. Lr35* and *Lr37* leaf rust resistance genes causes a significant increase in flour protein content. These leaf rust resistance genes do not have negative effects on milling quality in general (Labuschagne *et al.*, 2002b).

2.6 STATISTICAL ANALYSIS

2.6.1 Analysis of variance (ANOVA)

The analysis of variance is a conventional statistical analysis where a specific trait of genotypes is measured in environments over replicates, in order to analyse the total variation contained in the genotypes, environments and replications. It is a univariate technique, whereby the statistical evidence for differences between cultivars or environments can be shown for each variate or trait separately. It is employed to determine if the probability of observed genotypic differences is real or not. The magnitudes of the sum of squares of the variance components are used to quantify sources of variation.

2.6.2 Canonical variate analysis (CVA)

The analysis of variance is a univariate technique whereby the statistical evidence for differences between cultivars or environments can be shown for each variate or trait separately. The ANOVA does not give an indication of how the genotypes group or which variates are most important in discriminating between groups. Canonical variate analysis (CVA), also known as linear discriminant analysis, is used when it is of interest to show differences between groups rather than between individuals (Van Lill and Smith, 1997; De Lange and Labuchagne, 2000; Labuschagne *et al.*, 2002a) and to help with the interpretation of results when there is more than one group.

The canonical approach allows the explanation of relationships in a data set among two large sets of variables. The variables are first reduced to a smaller set of variates that account for most of the variability in the data set (Mamuya, 2000). Canonical variates are constructed from linear combinations of a set of variables selected to maximise covariance with the canonical variates of a second set of variables. The canonical correlation then expresses the overall degree of relationship between the two constructed variates (Graybosh *et al.*, 1993)

Graybosh *et al.* (1993) utilised the canonical analysis to examine whether biochemical parameters could effectively account for the observed variation in quality measurements. Van Lill *et al.* (1995b) used CVA to determine whether groups of variables differ from each other for yield and quality attributes in wheat. Similarly, De Lange and Labuschagne (2000) employed CVA to examine the differences in classes to grade quality of small white canning bean cultivars. Labuschagne *et al.* (2002a) applied CVA to group irrigated spring wheat according to breadmaking quality.

2.6.3 Correlations

If the association between two characteristics could be observed directly, it is a phenotypic correlation and is caused by genetic and environmental influences. The environment largely determines phenotypic correlation, when both characteristics have low heratibility. Genetic correlation is considered when the characteristics have high levels of heritability (Falconer, 1981).

A correlation coefficient between two quality attributes, that is usually high for most cultivars or a narrow distribution of coefficients around the class mean, suggests a strong heritable

association and possibly a narrow gene base (Gaines, 1991). A low correlation will be indicative of non-heritable or less complementary gene action and a more general combinability.

The correlation coefficient (r), also known as Pearson's coefficient of correlation, is a measure of the linear relationship between the two traits. This only indicates the extent to which variates are linearly related (Draper and Smith, 1981) and may vary between –1 and 1. A negative value indicates that the observation for one variable becomes smaller while the observation for the other one becomes larger. If the coefficient equals zero, there is no correlation present. If the correlation coefficient is exactly –1 or 1, it indicates a perfect relationship. Such a correlation seldom occurs for biological variables (Van Ark, 1995). Generally a correlation coefficient of about ±0.7 or more is regarded as indicating a fairly strong correlation. In the region of ±0.9 it indicates a very strong correlation and near ±0.5 the correlation is moderate. A weak correlation is in the range of –0.3 to +0.3 (Rayner, 1969).

Milling and baking tests provide information on a number of inter correlated variables which makes interpretation difficult (Eskridge *et al.,* 1994). Knowledge of these correlations are of interest to breeders, because it is important to understand how the selection process to improve one character, will affect and change the other correlating characteristics. Incorporation of two highly recommended traits that are correlated negatively could be a time and cost consuming breeding process because direct selection pressure should be applied to those traits if genetic improvement is desired. Positive correlations provide the tool of indirect selection and simultaneous improvement in both traits and will accelerate the breeding process for better milling or flour quality.

When correlations occur that are not usually observed, the correlations between traits may result merely from selection pressure being placed on several traits. Or when characteristics that usually correlate do not correlate significantly, it might result from limited trait variation in the samples studied (Bergman *et al.*, 1998)

2.6.4 Multiple regressions

The correlation between two characters does not necessarily imply a cause and effect relationship between characteristics. Linear multiple regression analysis can be useful when the main interest is on the prediction of the response variable from a set of predictor variables (Lee and Kaltsikes, 1973) and to obtain the combined effect of all these variables (Van Ark, 1995). Fitting of a multiple regression model (equation) can become complex. Alternative ways of introducing or forcing predictor variables in and out of a model exist and is known as stepwise

regression (Van Ark, 1995). Stepwise multiple regression techniques are often utilised to reveal the most important character responsible for the variation in another. It also helps ascertaining the number and nature of causative influences and is used for prediction purposes (Pomeranz and Mattern 1988; Fang *et al.*, 1998).

The following formula is generally used:

$Y = a + b_1X_1 + b_2X_2 \ldots + b_nX_n$

where

Y = the dependent or response variable

a = the intercept of the regression on the Y-axis

b_1 to b_n = regression coefficients for the "n" independent or predictor variables and

X_1 to X_n = the "n" independent or predictor variables (Van Ark, 1995).

This is determined at a certain coefficient of determination (R^2), which indicates the proportion of the variation attributable to, or explained by the relationship between Y and X and is usually expressed as a percentage (Van Ark, 1995). It is calculated by $R^2 = r^2 \times 100$, where r denotes the correlation coefficient.

Lee and Kaltsikes (1973) and Ashri *et al.* (1974) used multiple stepwise regression to show the most important yield component in durum wheat and safflower respectively. Eversmeyer *et al.* (1973) identified the meteorological and biological variables useful in explaining variation in stem rust severities. Stepwise multiple regression was used to measure the effect of independent variables on dependant variables when different rates of N and P fertilisers were used (Read and Warder, 1974). Fenn *et al.* (1994) utilised stepwise regression to indicate that most of the variability in the dough stickiness of 1BL/1RS translocation wheat can be explained by protein content and gluten strength.

2.6.5 AMMI analysis

Interpretation of the performance of a number of genotypes evaluated in a broad range of environments is always affected by GXE interaction. Since genotype responses are multivariate rather than univariate, multivariate techniques are generally more effective in explaining GXE interactions (Zobel *et al.*, 1988). Additive Main effects and Multiplicative Interaction (AMMI) analysis is a valuable tool in understanding complex GXE interactions over seasons (Annicchiarico, 1997; Purchase, 1997). The AMMI analysis gave more precise estimates of genotypic yields within locations than means across replicates in international

wheat yield trials (Crossa *et al.*, 1991). This analysis highlighted superior selections with both broad and specific adaptation.

The AMMI analysis isolates genotype and environment main effects by means of analysis of variance and then uses Principal Component Analysis (PCA) to explain the GXE interaction. The data is then graphically illustrated in a biplot to show both main and interaction effects. The AMMI proved to be effective in determining the stability of genotypes over environments. Purchase *et al.* (2000b) used the AMMI stability values to analyse the yield stability of wheat genotypes in the Free State. Similarly, Adugna and Labuschagne (2002) evaluated the phenotypic yield stability of linseed grown in Ethiopia. The AMMI model is thus an effective analysis to describe the GXE interaction and stability.

Purchase *et al.* (2000a) recommended the use of the AMMI model from the basis of GXE interaction and suggested the use of the model to identify superior genotypes to be released as cultivars for commercial production in the Free State, since the model can summarise relationships and patterns of genotypes and environments successfully.

Although the AMMI analysis is usually exerted in the assessment of GXE interaction on grain yield, Mamuya (2000) used the analysis to successfully explain the GXE interaction for quality parameters of irrigated spring wheat.

CHAPTER 3

MILLING CHARACTERISTICS OF THE WINTER AND FACULTATIVE WHEAT CULTIVARS

3.1 INTRODUCTION

Wheat cultivation under dryland conditions in the summer rainfall region of South Africa accounts for approximately 50% of the total annual bread wheat production (South African Grain Laboratory, 2002) of 2.1 million metric tons produced in the country. This is obtained by growing mainly winter and facultative cultivars in the Free State province (Barnard *et al.* 1999).

Almost 90% of the total production of the country is used for bread making purposes. Production in the Free State area is providing a constant and important source of bread wheat grain to the milling and baking industry of South Africa. Since the majority of grain is processed for human consumption, the quality is of paramount importance. Quality can be regarded as the ability of the grain to meet the requirements of the processor and depends on the cultivar and environment in which the crop is grown.

An integrated marketing chain stretches from the plant breeders to the producers, buyers and finally to the milling and baking industries. Each of the role players in this chain support the goal of marketing grades of wheat that are consistently of high quality. Producers have to grow varieties of good intrinsic quality. This wheat has to be sorted efficiently according to physical conditions and have specific quality attributes, because wheat classes and the physical condition are the most important factors determining wheat potential and end product quality (Dexter and Marchylo, 2000). Quality characteristics important to the producer, that will determine market grade and price, are test weight and protein content. In South Africa the test weight, protein content and falling number are regarded as important to classify bread wheat cultivars according to different subclasses and grades (Barnard and Burger, 2002).

Quality attributes important to the end use of hard red winter wheat include flour extraction (flour yield), kernel hardness, dough handling and bread making quality. The most important milling characteristics are percentage break flour yield, flour extraction, and flour colour (Van Lill and Purchase, 1995). Milling quality describes the characteristics important in the milling process, such as the kernel morphology and flour yield. These milling characteristics determine the quantity and quality of flour extracted from the grain. Flour yield is a measurement of the straight grade flour recovered during milling. Breeders use flour yield as an indication of the way in which a line will perform in an industrial mill relative to other lines milled in the same

manner (Bergman *et al.*, 1998). Genotypes with high flour yield offer the milling industry added value. Prediction of these grain and milling characteristics is therefore extremely important to the processing industries.

Variation in flour yield will likely result from several combined factors. The inherent cultivar differences are in the amount of endosperm and the interaction between aleurone cells and the innermost cells of the endosperm (Bergman *et al.*, 1998). Milling quality is also related to the physical state of the grain (Ohm *et al.*, 1998). Aspects to consider would be kernel hardness, weight and size, plumpness and shape. These traits will have a direct or indirect effect on the milling quality of the grain. Protein content is included in the battery of tests used to predict the quality of potential new lines, because it is a very important quality trait affecting the dough mixing and baking quality traits. Therefore, flour protein of the flour product sold by millers is also of significant value.

The identification of the basic components determining and influencing quality and the explanation of their mode of action, perplexed cereal chemists for decades (Fowler and De la Roche, 1975a). Wheat breeders strive to maintain grain quality desired by the milling and baking industries while developing cultivars profitable to the producer. Therefore it is important to assess the quality situation of bread wheat cultivars produced in the Free State.

3.2 MATERIAL AND METHODS

3.2.1 Field trials

Grain samples of 13 South African hard red winter and facultative bread wheat cultivars were obtained from the cultivar evaluation trials of the Small Grain Institute. Trials were conducted in the dryland, summer rainfall region of South Africa during the wheat cropping cycles of 1997, 1998 and 1999.

Field trials were planted at six localities throughout the Free Sate. Due to variation in growth period and vernalisation requirements of the winter and facultative wheat cultivars, a first and a second planting were included in the experiment in order to gather the desired data. The two planting dates of the trials were three weeks apart in the western and central regions and four weeks apart in the eastern Free State. The first planting date for localities in the western Free State was the last week in April, central Free State localities were planted during the third week in May and the first planting in the eastern Free State took place during the third week of June.

The second planting date was the third week in May (for the western Free State), second week in June (central Free State) and the third week in July (eastern Free State).
The genotypes, their type, origin and year of release are tabulated in Table 3.1.

Table 3.1 Facultative and winter wheat cultivars.

Genotype	Type	Originating Institution	Release date	First planting	Second planting
Betta-DN	Facultative pure line	Small Grain Institute	1993	✓	✓
Caledon	Facultative pure line	Small Grain Institute	1996		✓
Elands	Facultative pure line	Small Grain Institute	1998		✓
Gariep	Facultative pure line	Small Grain Institute	1994	✓	✓
Limpopo	Facultative pure line	Small Grain Institute	1994		✓
Molen	Winter pure line	Small Grain Institute	1986	✓	
PAN 3235	Facultative pure line	PANNAR	1995		✓
PAN 3349	Facultative pure line	PANNAR	1997		✓
SST 124	Facultative pure line	Monsanto	1987		✓
SST 367	Winter pure line	Monsanto	1996	✓	
SST 966	Winter hybrid	Monsanto	1996	✓	
SST 972	Facultative hybrid	Monsanto	1997		✓
Tugela-DN	Facultative pure line	Small Grain Institute	1992	✓	✓

✓ Indicates cultivars, included in the trials that were planted at the first and/or second planting dates.

Experimental plots consisting of five rows (five metres in length, with a 45 centimetre inter row spacing) were planted, using a randomised complete block design with four replicates. All the 3:2:1 (25) N.P.K fertiliser was applied at planting, at a rate of 150 kg ha^{-1} in the western and central Free State. The high potential sites, the eastern Free State and those on the soil water table in the western Free State, Bultfontein and Wesselsbron, received 250 kg ha^{-1}.

Trials were harvested, air-dried and cleaned prior to quality testing.

3.2.2 Laboratory methods for quality analysis

All the material was evaluated for test weight, thousand kernel weight, kernel diameter, kernel hardness, moisture content, vitreous kernels, break flour yield, flour yield, flour colour and flour protein content. The quality analyses were conducted in triplicate.

3.2.2.1 Test weight (TW)

The DICKEY-JOHN Grain analysis Computer II was used in determining the test weight (in kilograms per hectolitre) of all the samples. A sufficient grain sample is poured into the hopper, this is dropped into the grain cell, levelled by a strike-off mechanism whereafter the test weight is displayed.

3.2.2.2 Thousand kernel weight (TKW)

One thousand kernels were counted with a numerical seed counter. This count only included whole, sound kernels from which broken kernels and foreign material had been removed, to ensure the most accurate results. The weight was determined in grams.

3.2.2.3 Single Kernel Characterisation System (SKCS)

The Single Kernel Characterisation System (SKCS) model 4100 of Perten Instruments Co, Reno, NV was used to determine kernel characteristics. Wheat was deposited into the hopper; three hundred individual wheat kernels were picked up by vacuum, weighed and crushed. The instrument's computer software then calculates a hardness index for each sample based on the kernel crush profile, moisture, size and weight. Information gathered was then processed to provide weight, size (the diameter), moisture and the hardness index on an individual kernel basis. The hardness index was expressed as a percentage of the pressure of two rollers to crush the kernels (Perten Instruments, 1995) and is a function of moisture, size, weight and the force-deformation curve derived from crushing individual kernels (Martin *et al.*, 1993).

3.2.2.4 Moisture content (MOIST)

The moisture value determined by the SKCS was used in this study.

3.2.2.5 Vitreous kernels (VK)

Fifty kernels were cut longitudinally with a special cutter and were visually scored to determine the percentage vitreous kernels. The vitreous kernels are clear and translucent in appearance

and score two, while a mealy, floury kernel that has a whitish appearance scores one. The number of vitreous kernels was then expressed as a percentage.

3.2.2.6 Bühler mill break flour yield (BFLY) and flour extraction (FLY)

All the wheat samples were milled in a laboratory pneumatic mill, Bühler model MLU-202 (manufactured by Bühler Bros., Inc., Uzwil, Switzerland). The AACC method 26-21A for milling hard wheat was followed (AACC, 2000).

The amount of water to be added to a wheat sample for tempering depends on the vitreousness of the wheat kernels, the moisture of the wheat as well as the weight of the sample to be milled. A table that takes the above-mentioned into consideration, is used to determine the desired moisture content. The quantity of water to add to the wheat, is then determined by comparing the original moisture against the desired moisture (AACC, 2000). Wheat samples of 1.5 kg were weighed into airtight containers, conditioned and shaken to ensure equal distribution of water. Conditioning was done 18 hours prior to milling.

The mill fractions, as illustrated in Figure 3.1, were handled as follows:
Fractions B1-3 are the flour from the break rollers. After being sifted and weighed, this flour represents the break flour yield. Fractions C1-3 are the flour from the reduction rollers. Bran still containing pieces of endosperm is called the pollard (bran and flour).

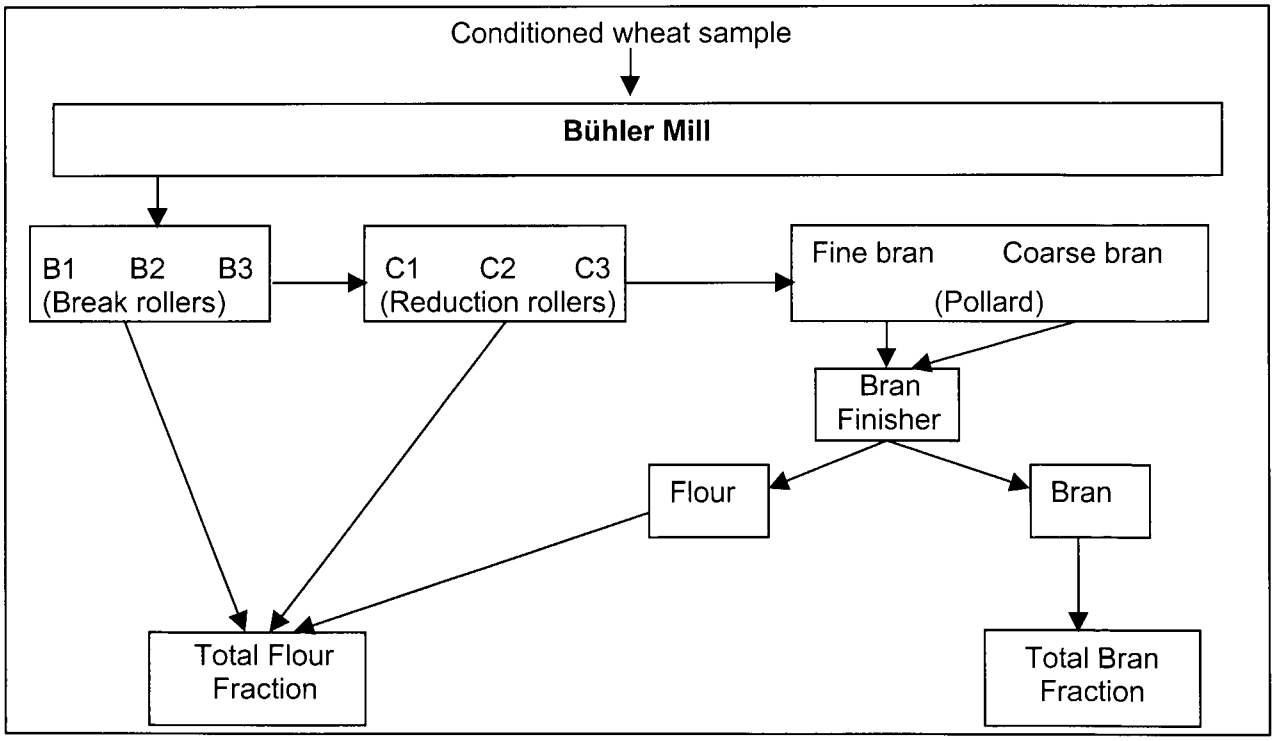

Figure 3.1 The Bühler milling process

Thus, the amount of flour from the three break rollers determines the break flour yield and the quantity of endosperm (or flour) separated from the bran is the total flour yield. It is expressed as percentage extraction (Bass, 1988):

$$\text{Extraction \%} = \frac{\text{Total flour fraction}}{\text{Total (flour + bran fractions)}} \times 100$$

3.2.2.7 Flour colour (FCL)

A Martin series III flour colour grader was used to evaluate the flour brightness of colour at a wavelength of 540 nm and expressed as a single value. Calibration of the instrument against a standard flour sample (with a known colour value) preceded sample measurements. The higher the value the darker the flour, whereas a more negative value indicates bright and whiter flour.

3.2.2.8 Flour protein content (FPC)

The LECO FP-2000 Nitrogen/Protein Analyser, a non-dispersive infrared microcomputer, was used to determine flour protein content. The samples were placed into a combustion chamber and the furnace and flow of oxygen gas caused the sample to combust. This process converted all elemental nitrogen into N_2 and NO_x. In the catalyst heater all NO_x gases were reduced to N_2. The nitrogen gas in the flour thus assessed the protein quantity.

3.2.3 Statistical analysis

3.2.3.1 Analysis of variance (ANOVA)

Combined analysis of variance for the 10 quality characteristics was performed across six (1997 and 1998) and five environments (1999) respectively. Analyses were done for the two planting dates. The combined ANOVA was used to test the significance of cultivar, environment and the interactions for the measured traits.

ANOVAs on the individual localities were carried out to compare genotype (cultivar) means for each character. The cultivar means for all the characteristics were used to compare the performance of the genotypes with one another. Cultivar differences were determined by

means of the least significant difference (LSD) (0.05) (Appendix 1 and 2). The AGROBASE 20 (Agrobase, 1999) computer programme was utilised to perform the analysis of variance.

3.2.3.2 Correlation matrix

The correlation matrix, to calculate the phenotypic correlations, was performed on the kernel and milling quality data of 1997 to 1999. The correlations were determined by using the computer software programme, AGROBASE 20 (Agrobase, 1999).

3.2.3.3 Canonical variate analysis (CVA)

Multivariate analysis is used to understand complex relationships between many variates or characteristics. The method generally used, is principal component analysis, but it is only for the interest in individuals. Canonical variate analysis (CVA) is used when it is of more interest to point out differences between groups rather than between individuals, e.g. genotypes. The variability in the large number of quality variables were firstly reduced to a smaller set of variables, which accounts for most of the variance. This new set of variables, called canonical variates (CV), are linear combinations of the original measurements, and is thus indicated as vectors of loading for the original measurements. With this approach, a set of directions is obtained in such a way that the ratio of between-group variability to within-group variability in each direction is maximised (Van Lill and Purchase, 1995). The scores found for each of the canonical variates are then correlated with the original characteristics, to find those that are the most important in discriminating between groups. The less important variates were deleted (one by one) from the analyses, until only those with reasonable correlation coefficients ($r>0.5$) were retained. In this study, the variates were the grain and milling quality characteristics that were measured on wheat genotypes in different environments. The data were analysed, using the statistical computer program GenStat (2000).

3.2.3.4 Multiple stepwise regression

To investigate how the physical kernel characteristics interact to produce a given flour yield or flour colour, the all-possible subset variable selection technique was used to identify a smaller number of subsets (Draper and Smith, 1981). This multiple stepwise regressions were used to define the variation caused by each of the other characteristics to the fixed characteristic, for example to investigate how all the kernel characteristics interact to influence break flour yield.

This was done for the dependent (response) characteristics: test weight, kernel hardness, breakflour yield, flour yield and flour colour. The statistical computer program GenStat (2000) was used to calculate the multiple stepwise regressions and to select the independent variables that accounted for the largest amount of variation in the dependant variable checked for significance and entered it into the regression equation.

3.3 RESULTS AND DISCUSSION

3.3.1 Combined analysis of variance

The combined analysis of variance was carried out across six environments (1997 and 1998) and five environments (1999) for the three different years. This was done for the two planting dates. The analysis indicated highly significant ($P< 0.01$) differences among genotypes (G), environments (E) and GXE interactions, for most of the measured traits (Tables 3.2 and 3.3). This indicated that there were variable responses of the cultivars to the environments for nearly all 10 evaluated quality characteristics.

Percentages of the total variance of each source of variation were calculated from the variance components.

3.3.1.1. Test weight (TW)

TW is one of the important features in wheat grading and is of economic importance to the producer and the grain industries. Therefore, a TW of 76 kg hl^{-1} is specified by most countries importing wheat (Fowler and Priestley, 1991b). To be graded as suitable for breadmaking purposes, in South Africa, a minimum TW of 74 kg hl^{-1} is required (Nel *et al.*, 1998; Barnard and Burger, 2002).

The analysis of variance revealed significant differences for all three major components (genotypes, environments and their interaction), at both planting dates in all three years. If the first planting date, as presented in Table 3.2 is considered, the largest variation was attributed to the environments. The share of this component varied from 39.3% to 59.3% of the total variance over the three years (Table 3.4). The environment means for test weight (Appendix 1) ranged from 75.7 to 78.9 kg hl^{-1} in 1997, 75.1 to 78.7 kg hl^{-1} during 1998 and in 1999 from 76.4 to 78.7 kg hl^{-1}. The variability accounting for genotypes ranged from 16.5% to 31.5% over the three years (Table 3.4). The cultivar means were between 75.6 kg hl^{-1} and 79.2 kg hl^{-1} over the

three years. The least significant differences (Appendix 1) indicated that Gariep and Betta-DN are the cultivars with a higher TW at most of the localities planted at a first planting date over the three years of evaluation. Tugela-DN and Molen had significantly lower TW values than the other cultivars. Although significantly lower, only at a very few localities were values below 76 kg hl^{-1}. The GXE interaction explained a 18.0 to 23.1% share of the total variance component over the three years.

For the second planting date, again environments caused most of the variation in TW, except during 1998 where the environment's contribution was only 12.7% and most of the variation was due to the GXE interaction component. Variation among genotypes was responsible for between 6.0 and 32.0% and the GXE interaction for between 15.8 and 41.3% of the total variation in TW. Environmental means ranged between 75.2 and 81.2 kg hl^{-1} over the three-year period. The LSD indicated significant differences between cultivars at individual localities (see Appendix 2). PAN 3349 and SST 972 resulted in significantly lower TW values than the rest of the cultivars, while SST 124, Betta-DN, Gariep, Elands and PAN 3235 were the cultivars with higher TW values at most of the localities during 1997 to 1999.

It became evident that over the three-year period most of the variation in TW was due to environment and the interaction between the genotypes and environment. This is in agreement with other researchers who also found that the environmental effects have a large effect on TW. Van Lill and Purchase (1995) found that the influence of year relative to that of cultivars was large for winter wheat in South Africa. Observations by Gaines *et al.* (1996a) indicated that the environmental component has a major effect on TW. It appears as if environmental conditions between florescence and harvesting had the largest effect on TW. Kernels that are shrivelled or immature, reduce TW (Schuler *et al.*, 1994). Rain-induced preharvest sprouting (Donelson *et al.*, 2002), lodging or delayed harvest (Carver, 1996) may also reduce TW significantly. Czarnecki and Evans (1986) found significantly lower TW caused by precipitation, affecting the kernels' density and packing efficiency when exposed to this weathering. All the above mentioned weathering effects may be due to the changes in kernel shape or roughening of the bran coat which influences grain packing. It may also decrease due to a decline in kernel density or kernel weight.

3.3.1.2 Thousand kernel weight (TKW)

Considering the TKW, in all three years significant variance was observed for the major components of variance at both planting dates (Tables 3.2 and 3.3). Genotype and environment was alternately the largest contributor to variance at the two planting dates over

the three years. Genotype's contribution ranged between 19.8 to 66.6% (first planting dates) and 25.7 to 53.8% (second planting dates) and those of the environments were between 22.3 and 61.1% at the first planting date and between 21.2 and 62.4% at the second planting dates. The GXE interaction was responsible for only a low percentage of the variation, 6.7 to 16.9% over planting dates and years (Table 3.4).

Environment means varied between 30.4 and 42.9 at the first planting dates and between 29.8 and 40.2 for the second planting dates, (Appendix 1 and 2). Cultivars with significantly heavier kernels were Tugela-DN (both planting dates) and SST 972 (in the trials planted at a second planting date). The light weighted kernels were Molen and SST 367 at the first planting date and SST 124 (at the second planting date) with kernels weighing significantly less at the second planting dates of the three year period.

From this, it is evident that both environment and the cultivars played an important role in the determination of kernel weight. Bhatt (1972) found that the heritability of kernel weight is high, therefore the genotype has an important influence on the variance in TKW, but the environmental conditions have an influence as well. Factors that influence the grain filling period, had major effects on the TKW. It could be drought (Debelo *et al.*, 2001) or high temperatures (Gibson *et al.*, 1998) that affect the grain filling and hence the TKW negatively. Favourable moisture conditions resulted in higher kernel weight (Du Plessis and Agenbag, 1994). In wheat that has prematurely ripened due to unfavourable growing conditions, the percentage endosperm is less than in fully matured wheat, resulting in lower TKW. Czarnecki and Evans (1986) reported a significant decrease in TKW caused by delayed harvesting. The TKW is not only affected by climatic conditions, but could also be affected by disease infections such as stem rust infections (Pretorius, 1983).

Significant correlation between TKW and TW was reported by Jalaluddin and Harrison (1989), but TKW is not a direct component of TW, it is only associated with kernel density which is a component of TW. Therefore, the influence of environment on both characteristics was observed in this study.

3.3.1.3 Kernel diameter (DIAM)

The analysis of variance indicated significant differences at $P<0.01$ at both planting dates over the three years (Tables 3.2 and 3.3), only the GXE interaction at the first planting date of 1999 was significant at $P<0.05$. It is evident that the genotypes made the largest contribution to

variation in DIAM, 33.5 to 64.6% over the three years (first planting dates) and 35.5 to 53.3% over years for the second planting date.

Environments contributed between 15.7 and 52.1% to the total variance over years and planting dates. The contribution of the GXE interaction was low (5.3 to 19.8%) over years and planting dates (Table 3.4). Environment means ranged between 2.2 and 2.8 mm diameter over planting dates and years. Tugela-DN (both planting dates) and SST 972 (second planting date) had significantly larger kernels over the three years. Although not always significant, Limpopo and Caledon were the cultivars with smaller kernels at the second planting date (Appendix 2).

Because of the strong correlation between TKW and DIAM (r=0.89) as found by Hazen and Ward (1997), Fang *et al.* (1998) and Ohm *et al.* (1998) and the use of TKW to determine kernel size, the large genotypic contribution (Bhatt, 1972) to kernel weight could apply for DIAM as well. The genotype therefore plays an important role in the determination of kernel size. Differences in the size of kernels from the same variety might be due to environmental influences, such as moisture, humidity, temperature and fertilisation that affect the photosynthesis before the ripening phase of the grain (Posner and Hibbs, 1997).

3.3.1.4 Kernel hardness (HI)

The ANOVA of the first and second planting dates revealed significant variance at $P<0.01$ for genotypes, environments and interaction components (Tables 3.2 and 3.3). The percentage environmental contribution to the total variance in HI, was 43.5 to 65.2% for the first and 18.0 to 68.6% for the second planting dates. This was followed by the genotypes contributing 20.0 to 39.3% and 20.7 to 71.3% to the total variation for the two respective planting dates. The genotype contribution during the second planting dates of 1998 and 1999 was 60.7 and 71.3%, indicating that cultivars also played an important role in the differences for HI. The GXE interaction component of variance was very low (3.5 to 9.5%), except at the first planting date of 1999 when it was 16.3% of the total variation. Table 3.4 reflects the percentage contribution of each of the variance components.

HI means for the environment were between 49.7 and 86.5 over the three years and means for cultivars ranged from 62.52 (1998) to 74.2 (1997). Gariep, Tugela-DN and SST 367 were significantly harder cultivars. Molen, SST 966 and Betta-DN were softer than the other cultivars planted at the first planting date (Appendix 1). SST 124, Tugela-DN and Caledon were significantly harder at most of the localities of the second planting date over the three years. SST 972 had the softest kernels, significantly softer at all 18 localities (Appendix 2).

If the cultivars should be classified according to the international hardness classification system (Williams, 1998) most of the cultivars will be classified as hard, only SST 972 will be medium hard, for 1997 and 1999. During a wet year (as in 1998) the HI could be affected to such an extent that it fell into another hardness class. During 1998 the majority of cultivars were in the medium hard class, only Tugela-DN, SST 124 and Caledon (at the second planting date) were stable and still fell in the hard class. The hybrids, SST 966 and SST 972 were in the medium soft class in this year.

Manley *et al.* (2001) also reported significant differences in HI between cultivars of the Southern and Western Cape, but differences over most of the localities were insignificant. As in this study, Gaines *et al.* (1996a) reported that the environment had a larger influence on HI than genotype. Research by Pomeranz and Mattern (1988) and Bergman *et al.* (1998) identified genotype as the main source of variation in HI. Variation of HI due to both genotype and environmental effects (Hazen and Ward, 1997) should be expected. Although HI is inherited simply and is controlled by only one or two major genes and perhaps some minor genes (Baker, 1977), it is also affected by the growing environment (Anjum and Walker, 1991; Monsalve-Gonzalez and Pomeranz, 1993; Morris *et al.*, 1999), growing season, protein content, moisture content, kernel size and the bran of the kernel. Depending on the growth conditions, HI can vary considerably due to environment (Morris, 1992), either in such a way that genotype hardness cannot be determined reliably or, environmental conditions can have only a limited effect (Fowler and De la Roche, 1975b; Pomeranz *et al.*, 1985). This could be the reason for the genotypic effect on HI not being prominent, at the first planting dates of all three years and the second planting date of 1997.

HI decreased by approximately 8% with delayed harvest at similar rates for different cultivars evaluated by Czarnecki and Evans (1986). The average HI at both planting dates of 1998 was lower than in the other two years. This year was distinguished by high rainfall during the harvesting season. The wet conditions during ripening and/or delayed harvest could have resulted in the overall lower HI of 1998.

Wheat containing the 1B/1R translocation had consistently harder grain than wheat without the translocation (Dhaliwal *et al.*, 1987). This could be the reason for Tugela-DN also revealing harder kernels, because this cultivar has the 1B/1R translocation, as well. SST 972 is a F1 hybrid, consistently classed in a softer class than the other cultivars. The softer kernel texture might result from male and female parents differing in HI (one with hard and the other with soft kernels), as Carver (1996) noted in the progeny of a hard winter wheat crossed with soft winter wheat, consistently decreased HI. The HI of the other hybrid, SST 966, varied a lot over the three years, but in the wet cropping season of 1998, fell into the same class as SST 972.

3.3.1.5 Moisture content (MOIST)

According to the ANOVA of both planting dates, all three major components revealed significant variance at P<0.01 (Tables 3.2 and 3.3). The environment contributed largely to the variance in MOIST (71.1 to 91.3%), interactions contributed between 5.0 and 11.7%. Only for the first planting date of 1999 interaction's contribution was 21.9%. The genotypes had little effect on the variation in MOIST and contributed only 0.7 to 5.4% to the total variation over years and planting dates (Table 3.4). Environment means for MOIST were between 9.2 and 12.3% (Appendix 1 and 2).

MOIST was primarily influenced by the environment. Cultivar effects were destroyed due to the drying process just after harvesting, which preceded the quality analysis. Grain moisture content is not a problem quality trait and can easily be controlled.

3.3.1.6 Vitreous kernels (VK)

Significant variances among environments for VK were revealed by the ANOVA (Tables 3.1 and 3.2) at P<0.01 significant levels. Variances among genotypes were also significant, except during 1998 at the first planting date. GXE interactions were not significant during 1998 and 1999, first planting dates. The environment mainly caused the differences in VK. Environments contributed between 24.7 and 46.1%, genotypes between 8.6 and 23.2% and the interaction component 11.5 to 30.0% to the total variation in VK (Table 3.4).

Environment means ranged between 48.3 and 82.2% over years and planting dates. According to the LSD values of the individual localities, there were no significant differences in percentage VK between cultivars at the first planting dates of 1997 to 1999 (Appendix 1). At the second planting date, there were small differences in VK among cultivars, only SST 972 had a significantly lower percentage VK than most of the other cultivars over localities (Appendix 2).

Vitreousness is largely determined and influenced by environmental conditions and occurs in all wheat varieties as a consequence of maturing conditions (Pomeranz and Williams, 1990) during the final drying in the field (Hoseney, 1987). These conditions include sufficiency of nitrogen availability and high temperatures. Biffen (1908) observed that wheat grown continuously on poor soil rarely produced vitreous grain. Adverse weather during a delay in harvest may also affect the percentage VK in the grain (Czarnecki and Evans, 1986).

The vitreous character of the grain is often used as an indicator of kernel hardness, but from these results and many others, it is clear that VK is more influenced by the environment than

Table 3.2 Analysis of variance for the 10 quality characteristics evaluated from material planted at the first planting date.

SOURCE	df	MEAN SQUARES									
		TW	TKW	DIAM	HI	MOIST	VK	BFLY	FLY	FCL	FPC
1997											
Total	107										
Genotype	5	9.183 **	135.59 **	0.392 **	737.53 **	0.059 **	591.91 **	100.83 **	8.031 **	8.564 **	2.909 *
Reps	2	2.120	4.89	0.002	23.86	0.024	316.33	0.792	0.55	0.81	3.164
Environments	5	25.851 **	150.81 **	0.354 **	816.49 **	7.259 **	660.78 **	9.64 **	10.421 **	7.262 **	19.978 **
GXE	25	2.568 **	5.804 **	0.015 **	35.595 **	0.115 **	106.13 *	3.207 **	3.042 **	1.239 **	1.541
Residual	70	0.486	0.872	0.005	9.737	0.014	54.733	0.83	0.263	0.389	1.113
Grand mean		77.693	33.930	2.376	70.775	11.372	70.222	24.485	75.384	1.617	12.888
R-squared		0.878	0.963	0.924	0.927	0.975	0.714	0.916	0.902	0.804	0.672
CV (%)		0.900	2.750	2.920	4.410	1.050	10.540	3.720	0.680	38.590	8.190
1998											
Total	107										
Genotype	5	8.987 **	57.158 **	0.167 **	352.16 **	0.2 **	297.3	57.929 **	9.005 **	4.112 **	5.405 **
Reps	2	0.226	4.744	0.009	27.949	0.042	151.26	1.51	0.926	1.703	5.134
Environments	5	31.823 **	176.31 **	0.197 **	1147.9 **	12.245 **	1487.7 **	34.226 **	100.9 **	5.259 **	2.212
GXE	25	1.936 **	6.046 **	0.015 **	26.772 **	0.134 **	92.934	1.684	2.988 **	1.844 **	1.733 *
Residual	70	0.222	1.642	0.004	8.334	0.02	83.012	1.072	0.882	0.388	1.005
Grand mean		76.542	38.222	2.612	56.832	10.111	56.398	25.546	75.936	1.600	12.387
R-squared		0.942	0.920	0.891	0.934	0.980	0.665	0.871	0.910	0.780	0.566
CV (%)		0.620	3.350	2.380	5.080	1.380	16.150	4.050	1.240	38.940	8.090
1999											
Total	89										
Genotype	5	10.174 **	92.217 **	0.207 **	155.33 **	0.218 **	125.34 **	55.423 **	4.101 **	3.254 **	3.189 **
Reps	2	0.187	0.903	0.002	11.35	0.013	37.378	0.189	0.694	0.115	0.416
Environments	4	15.905 **	38.689 **	0.089 **	501.55 **	3.603 **	645.12 **	40.878 **	8.763 **	2.596 **	9.633 **
GXE	20	1.715 **	2.304 **	0.004 *	28.489 **	0.222 **	32.122	1.37 **	1.851 **	1.636 **	0.867 *
Residual	58	0.217	0.5	0.002	1.92	0.005	28.872	0.229	0.33	0.250	0.441
Grand mean		78.059	34.386	2.441	68.970	11.522	75.011	22.993	75.057	0.791	11.744
R-squared		0.922	0.958	0.924	0.968	0.985	0.701	0.972	0.831	0.804	0.740
CV (%)		0.600	2.060	1.870	2.010	0.620	7.160	2.080	0.770	63.210	5.660

**Significantly different at P<0.01, *Significantly different at P<0.05, TW=Test weight, TKW=Thousand kernel weight, DIAM=Diameter, HI=Hardness index, MOIST=moisture content, VK= Vitreous kernels, BFLY=Break flour yield, FLY=Flour yield, FCL=Flour colour, FPC=Flour protein content.

Table 3.3 Analysis of variance for the 10 quality characteristics evaluated from material planted at a second planting date.

SOURCE	df	MEAN SQUARES									
		TW	TKW	DIAM	HI	MOIST	VK	BFLY	FLY	FCL	FPC
1997											
Total	179										
Genotype	9	8.357 **	115.536 **	0.316 **	436.301 **	0.208 **	381.393 **	82.014 **	9.531 **	5.626 **	1.155
Reps	2	1.043	3.529	0.008	3.073	0.091	36.906	1.117	0.256	1.054	2.066
Environments	5	175.645 **	505.318 **	0.836 **	2603.353 **	6.841 **	1350.636 **	83.165 **	29.329 **	12.044 **	52.441 **
GXE	45	4.374 **	6.203 **	0.01 **	21.712 **	0.119 **	140.48 **	4.376 **	1.908 **	1.25 **	1.702
Residual	118	0.819	1.652	0.004	8.805	0.036	38.352	0.834	0.775	0.504	1.186
Grand mean		77.382	33.512	2.385	74.108	11.374	72.544	24.874	75.517	1.637	13.478
R-squared		0.923	0.952	0.935	0.995	0.907	0.786	0.932	0.777	0.740	0.716
CV (%)		1.170	3.840	2.800	4.000	1.670	8.540	3.670	1.170	43.360	8.080
1998											
Genotype	9	16.686 **	137.401 **	0.242 **	797.464 **	0.25 **	530.035 **	59.859 **	12.627 **	9.025 **	2.614 **
Reps	2	0.869	2.757	0.002	1.407	0.008	68.867	0.956	1.391	0.962	2.522
Environments	5	11.876 **	97.511 **	0.128 **	762.995 **	18.344 **	1013.973 **	31.12 **	82.111 **	18.912 **	21.976 **
GXE	45	4.305 **	8.646 **	0.018 **	9.176 **	0.142 **	130.912 **	2.318 **	3.115 **	1.878 **	1.81 **
Residual	118	0.544	1.537	0.004	3.548	0.019	39.443	0.476	0.401	0.375	0.953
Grand mean		77.569	37.871	2.587	62.518	10.258	64.4	24.785	76.182	1.208	13.106
R-squared		0.863	0.921	0.890	0.965	0.979	0.773	0.934	0.934	0.856	0.662
CV (%)		0.950	3.270	2.390	3.010	1.330	9.750	2.780	0.830	50.700	7.450
1999											
Genotype	9	9.501 **	94.156 **	0.314 **	584.782 **	0.181 **	229.158 **	65.817 **	9.557 **	6.359 **	1.925 **
Reps	2	3.572	3.643	0.022	7.623	0.01	27.822	0.515	0.425	0.072	0.28
Environments	5	36.72 **	126.493 **	0.351 **	265.22 **	6.861 **	670.316 **	25.094 **	30.008 **	13.71 **	1.331 **
GXE	45	2.082 **	4.923 **	0.008 **	9.714 **	0.044 **	48.429 **	1.645 **	1.232 **	1.855 **	0.908 **
Residual	118	0.322	0.641	0.003	2.914	0.004	21.156	0.248	0.261	0.229	0.354
Grand mean		78.739	34.237	2.399	71.981	11.429	76.878	23.866	76.125	0.332	12.669
R-squared		0.907	0.958	0.936	0.953	0.987	0.754	0.964	0.914	0.886	0.610
CV (%)		0.720	2.340	2.230	2.370	0.560	5.980	2.090	0.670	144.100	4.700

**Significantly different at P<0.01, *Significantly different at P<0.05, TW=Test weight, TKW=Thousand kernel weight, DIAM=Diameter, HI=Hardness index, MOIST=moisture content, VK= Vitreous kernels, BFLY=Break flour yield, FLY=Flour yield, FCL=Flour colour, FPC=Flour protein content.

Table 3.4 **Percentage of each variance component for the combined analysis of variance for kernel and milling characteristics, evaluated across localities at a first and second planting date, 1997–1999.**

SOURCE	TW		TKW		DIAM		HI		MOIST		VK		BFLY		FLY		FCL		FPC	
	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
1997																				
Genotype	16.5	6.0	41.1	25.7	44.0	35.5	39.3	20.7	0.7	4.1	22.1	16.3	72.8	50.9	21.4	20.9	30.8	22.1	6.1	2.1
Environments	46.6	70.3	45.8	62.4	39.7	52.1	43.5	68.6	89.6	74.5	24.7	32.0	7.0	28.6	27.7	35.7	26.1	26.3	42.1	53.2
GXE	23.1	15.8	8.8	6.9	8.6	5.7	9.5	5.2	7.1	11.7	19.8	30.0	11.6	13.6	40.5	20.9	22.3	24.6	16.2	15.5
Reps	1.5	0.2	0.6	0.2	0.1	0.2	0.5	0.0	0.1	0.4	4.7	0.3	0.2	0.2	0.6	0.1	1.2	0.9	2.7	0.8
Residual	12.3	7.7	3.7	4.8	7.6	6.5	7.3	5.5	2.5	9.3	28.6	21.4	8.4	6.8	9.8	22.3	19.6	26.0	32.9	28.4
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1998																				
Genotype	16.7	32.0	19.8	53.8	33.5	53.3	20.0	60.7	1.5	2.2	8.6	23.2	49.9	62.9	6.5	15.9	16.6	26.5	16.7	7.1
Environments	59.3	12.7	61.1	21.2	39.6	15.7	65.2	32.3	91.3	89.4	42.8	24.7	29.5	18.2	73.4	57.5	21.3	30.9	6.8	33.1
GXE	18.0	41.3	10.5	16.9	15.2	19.8	7.6	3.5	5.0	6.2	13.4	28.7	7.2	12.2	10.9	19.6	37.3	27.6	26.7	24.5
Reps	0.2	0.4	0.7	0.2	0.7	0.1	0.6	0.0	0.1	0.0	1.7	0.7	0.5	0.2	0.3	0.4	2.8	0.6	6.3	1.5
Residual	5.8	13.7	8.0	7.9	10.9	11.1	6.6	3.5	2.0	2.2	33.5	22.7	12.9	6.6	9.0	6.6	22.0	14.4	43.4	33.8
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
1999																				
Genotype	31.5	21.0	66.6	47.5	64.6	53.3	22.3	71.3	5.4	4.2	11.2	20.3	57.5	72.1	18.1	26.6	22.0	24.2	16.2	16.2
Environments	39.3	45.0	22.3	35.4	22.3	33.0	57.5	18.0	71.1	89.3	46.1	33.0	33.9	15.3	31.0	46.4	14.0	29.0	39.2	6.2
GXE	21.2	23.0	6.7	12.4	5.3	6.5	16.3	5.9	21.9	5.2	11.5	21.5	5.7	9.0	32.7	17.2	44.2	35.3	17.7	38.1
Reps	0.2	1.8	0.3	0.4	0.3	0.8	0.7	0.2	0.1	0.0	1.3	0.5	0.1	0.1	1.2	0.3	0.3	0.1	0.8	0.5
Residual	7.8	9.3	4.2	4.2	7.6	6.4	3.2	4.7	1.5	1.3	29.9	24.6	2.8	3.6	16.9	9.5	19.6	11.4	26.0	39.0
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

TW=Test weight, TKW=Thousand kernel weight, DIAM=Diameter, HI=Hardness index, MOIST=moisture content, VK= Vitreous kernels, BFLY=Break flour yield, FLY=Flour yield, FCL=Flour colour, FPC=Flour protein content, 1st=first planting date, 2nd=second planting date.

true HI. Kernel hardness by means of the SKCS determination or other kernel hardness measurements should be recommended.

3.3.1.7 Break flour yield (BFLY)

The analysis of variance indicated significant differences among genotypes and environments at P<0.01 (Tables 3.1 and 3.2). GXE interactions were also significantly different, except at the first planting date during 1998. Genotypes were by far the most important contributor to variance in break flour yield (Table 3.4). Contributions varied between 49.9 and 72.8%. This is in agreement with Barnard *et al.* (2002) who also found significant genotype effects for BFLY. Contributions by the environment were between 7.0 and 33.9% and that of the GXE interaction between 5.7 and 13.6% over the two planting dates of the three years.

Individual genotype means for BFLY ranged widely between 19.76 and 27.85% and for environments between 21.6 and 27.11% over years and planting dates. Tugela-DN and SST 367 had significantly lower BFLY than the other cultivars (first planting date) at most of the localities (Appendix 1). For the second planting date, Tugela-DN, SST 124, and SST 972 were the cultivars with the lowest BFLY (significantly lower than the other cultivars) at most of the localities. Betta-DN had the highest BFLY over the three years at both planting dates (Appendix 2).

Kernel hardness is under strong genetic control (Hoseney, 1987; Pomeranz and Williams, 1990) and BFLY is primarily a function of wheat kernel hardness (Gains *et al.,* 1996b). Therefore, the results of this study, indicating strong genotypic contributions for the variation in BFLY, are in line with this relationship between HI and BFLY. Many researchers have found BFLY correlates negatively with hardness parameters (Stenvert, 1972; Yamazaki and Donelson, 1983; Gains, 1991; Rogers *et al.* 1993; Labuschagne *et al.* 1997; Ohm *et al.*, 1998). The results of this study is contradictory to that of Pomeranz *et al.* (1985) and Gaines *et al.* (1996a) who reported that the environment had a larger effect on BFLY than genotypes did.

3.3.1.8. Flour yield (FLY)

A FLY (extraction) of about 76% for white flour is the directive for new cultivars in South Africa. The ANOVA's (Tables 3.1 and 3.2) indicates that genotype, environment and their interaction contributed significantly (at P<0.01) to the variation in FLY. The largest contribution to variation in FLY came from the environment (27.7 to 73.4% at both planting dates of the three

years) compared to the variance in genotypes that contributed only between 6.5 and 26.6%. That of the interaction component was from 10.9 to 40.5% over planting dates and years (Table 3.4). This is in agreement with Van Lill and Smith (1997) and Nel *et al.* (2000) who reported that milling characteristics of winter and spring wheat are highly susceptible to environmental effects. As found by Peterson *et al.* (1992), but in contrast with Nel *et al.* (2000), cultivar x environment affected the FLY significantly. The environmental factors responsible for variation in milling quality are not always clear (Gibson *et al.*, 1998), because FLY is a combination of many minor effects. Grain size and shape, the thickness of the bran coat and the endosperm to bran ratio influence the proportion of endosperm in the kernel and factors that affect the removal of the endosperm, as well as the amount of endosperm present within the wheat kernel, have an impact on FLY (Schuler *et al.*, 1995). Environmental conditions during maturation and ripening appears to have the largest impact on kernel characteristics that contribute to FLY.

Environment means for percentage FLY ranged from 71.4 to 78.2%, means for individual cultivars were from 68.1 to 79.3% over the three years. The cultivar with a significantly lower FLY at most of the localities was Molen. Betta-DN and Gariep were the cultivars with the best FLY at the majority of localities, at the first planting date (Appendix 1). At the second planting date, Tugela-DN and SST 972 had significantly lower and SST 124 significantly higher FLY at most localities over the three years (Appendix 2).

3.3.1.9. Flour colour (FCL)

In all three years, significant variance ($P<0.01$) was observed for genotypes, environments and their interaction concerning variation in FCL (Tables 3.2 and 3.3). Environments and GXE interaction contributed largely to the total variance in FCL. Environment contribution was between 14.0 and 30.9% and the interactions' 22.3 to 44.2%. Genotypes added a further 16.6 to 30.8% to the total variation in FCL (Table 3.4).

Variance in colour may be due to genetic, environment, GXE interactions or the milling process. Higher FCL values from bran contamination are the most obvious effects of the quality of flour particles, influenced by grinding in the reduction action (Posner and Hibbs, 1997). As in this study, Van Lill and Purchase (1995) noted susceptibility of cultivars to interaction with year effects for FCL. They found that the FCL of modern cultivars was 46% brighter than winter wheat cultivars released in South Africa, before 1965.

The FCL range was particularly wide. Environment means were between –0.4 and 2.4 and genotype means between –0.03 and 2.43 over years and planting dates. At the first planting date, not one cultivar was prominent over the three years with significantly better (lower) FCL values (Appendix 1). SST 124 and Betta-DN had lower FCL values than the rest of the cultivars at the second planting date (Appendix 2).

3.3.1.10 Flour protein content (FPC)

The ANOVA's indicated significant differences between environments at $P<0.01$, except during 1998, at the first planting date. There were also significant differences (at $P<0.01$ or $P<0.05$) between genotypes, except for the second planting date in 1997. The GXE interactions differed significantly during 1998 and 1999, but not during 1997 (for both planting dates) (Tables 3.2 and 3.3). The environment and the GXE interaction had the largest influence on the total variance in FPC. Environments contributed 6.8 to 53.2% and the interaction component varied from 16.2 to 43.4% of the total variation in FPC. Cultivar (genotype) contributions were from 2.1 to 16.7% of the total variance (Table 3.4). These findings were in agreement with Robert (1997), who found that the protein percentage indicated a very high proportion of the total variation due to environment and interaction effects. The significant effect that environment has on protein level was not unexpected. Research indicated that the environmental influences were large on protein content (Pomeranz *et al.*, 1985; Stoddard and Marshall, 1990; Bergman *et al.*, 1998). Du Plessis and Agenbag (1994) reported that increasing levels of nitrogen resulted in higher protein contents. Miller *et al.* (1984) indicated that the protein content of wheat from localities was highly variable and mainly reflected the amount of fertiliser used and the time of fertiliser application. The level of substrate and available soil nitrogen is controlled by environmental factors such as moisture, temperature and nitrogen fertilisers. Therefore, the amount of nitrogen fertilisers used, influence the protein content of hard red winter wheat.

Environment means were between 11.0 and 14.6% FPC. The minimum required protein contents in the South African grading system are 9% for the BL subclass, 10% for the BS subclass and 12% for the BP subclass (Barnard and Burger, 2002). Therefore the cultivars for this study were of higher grades, according to protein content only. At most of the localities, at both planting dates, there were almost no significant differences between cultivars with regard to FPC (Appendix 1 and 2), further emphasising the large environmental effects.

3.3.2 Canonical variate analysis (CVA)

The previous ANOVA analysis (a univariate technique) indicated that there are real significant differences between the genotypes individually, but it does not indicate how these cultivars group together or, which of all the measured characteristics are the most important in discriminating between the 13 cultivars. Therefore multivariate analysis is used to understand complex relationships between many variates or characteristics. The most commonly used method is principal component analysis for the interest in individual cultivars, but the canonical variate analysis (CVA) is used when it is of importance to indicate differences between groups rather than between individual genotypes. In this study, the variates represent the grain and milling quality characteristics that were measured on wheat genotypes over different environments. It is important to know, as far as quality is concerned, which genotypes can be grouped together to improve the quality of stored grain for milling and baking purposes. The analysis can also provide a tool to determine the milling quality of new and unknown cultivars.

3.3.2.1 The CVA to discriminate between genotypes planted at the first planting date

The 10 characteristics measured were reduced to a smaller set that accounted for most of the variability in the data. Canonical variates (CV) were constructed from linear combinations of a set of characteristics, selected to maximise covariance with the canonical variates of a second set of variables. The horizontal separation (on the x-axis) represented the one set of canonical variates (CV1) and the vertical separation (on the y-axis) represented the other set of canonical variates (CV2). The canonical correlation then expressed the overall degree of relationship between the two groups of constructed variates. This correlation can either be negative or positive, indicating the direction of the grouping. The first two discriminant latent vectors and correlation coefficients of cultivars for grain and milling characteristics are presented in Table 3.5.

The kernel and milling characters that best differentiated between cultivars planted at the first planting date during 1997 to 1999 were reduced to TKW, DIAM, HI, BFLY and TW. These characteristics are listed in Table 3.5. The first two canonical variates (CV1 and CV2) explained 98.11% (75.15% and 22.69% from the two individual axis) of the total variation among groups (cultivars) during 1997, 96.06% (71.6% from CV axis 1 and 24.48% from CV axis 2) and 97.05% (83.07 and 13.98% from the two separate axis) during the seasons of 1998 and 1999 respectively. Most of the characters correlated strongly with the CV scores on at least one of the axis, with BFLY the most prominent (r=0.909, r=–0.813 and r=0.749) during the three years.

DIAM had the strongest correlation with the CV scores (r=–0.802) during 1999, the correlations were r=–0.717 and r=0.539 in the other two years.

Table 3.5 Discriminant analysis for grain and milling characters, the first two latent vectors and correlation coefficients for genotypes planted at the first planting date of 1997 to 1999.

Character	Latent vectors (Loadings)		Correlation coefficients	
	CV axis 1	CV axis 2	CV axis 1	CV axis 2
1997	**75.15%**	**22.96%**		
TKW	–0.107	–0.578	–0.667	–0.061
DIAM	–2.918	6.477	–0.714	0.023
HI	–0.078	–0.178	–0.480	–0.533
BFLY	0.534	–0.593	0.909	–0.294
1998	**71.61%**	**24.48%**		
TKW	–0.089	–0.275	0.376	0.079
DIAM	5.036	11.563	0.539	0.251
HI	–0.098	0.213	0.131	0.613
BFLY	–0.854	0.484	–0.813	–0.190
1999	**83.07%**	**13.98%**		
TKW	–0.355	1.108	–0.689	0.662
DIAM	–3.898	–16.004	–0.802	0.358
BFLY	0.764	0.190	0.749	0.141
TW	1.053	0.208	0.276	0.417

The canonical variate means for each cultivar (scores for CV1 and CV2) were plotted in Figures 3.2, 3.3 and 3.4, illustrating the groupings of genotypes for the kernel and milling characteristics (TKW, DIAM, HI, BFLY and TW) that differentiate them effectively over the three years. In such a plot, the points (representing the genotypes) closer together are similar and points further away are dissimilar with regard to the characteristics that discriminate between them.

The groups observed with regard to the mentioned characteristics were Gariep with Betta-DN in all the years of evaluation. These two cultivars have lower TKW and DIAM values, hard kernels, yielding high BFLY. Molen and SST 966 grouped together during 1997 and 1998, mainly due to softer textured kernels than the rest of the cultivars. Only during 1999 these two cultivars (Molen and SST 966) formed a grouping with Gariep and Betta-DN. This was mainly because HI was not one of the discriminating characteristics. If the HI is omitted, Molen and SST 966 will group with Gariep and Betta-DN on the basis of TW, BFLY, TKW and DIAM in all three years. On the other hand, Tugela-DN was not similar with regard to these characteristics

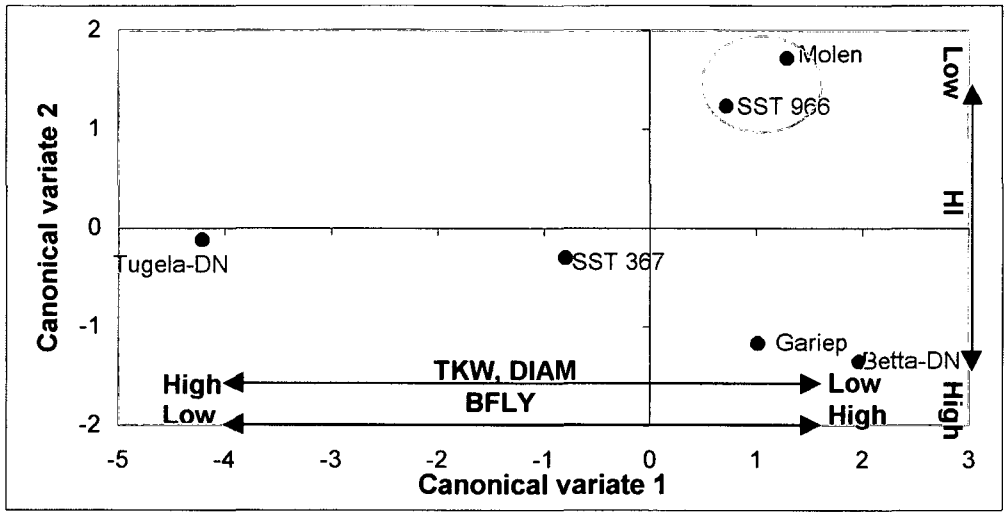

Figure 3.2 **Group means of the genotypes planted during 1997 at the first planting date.**

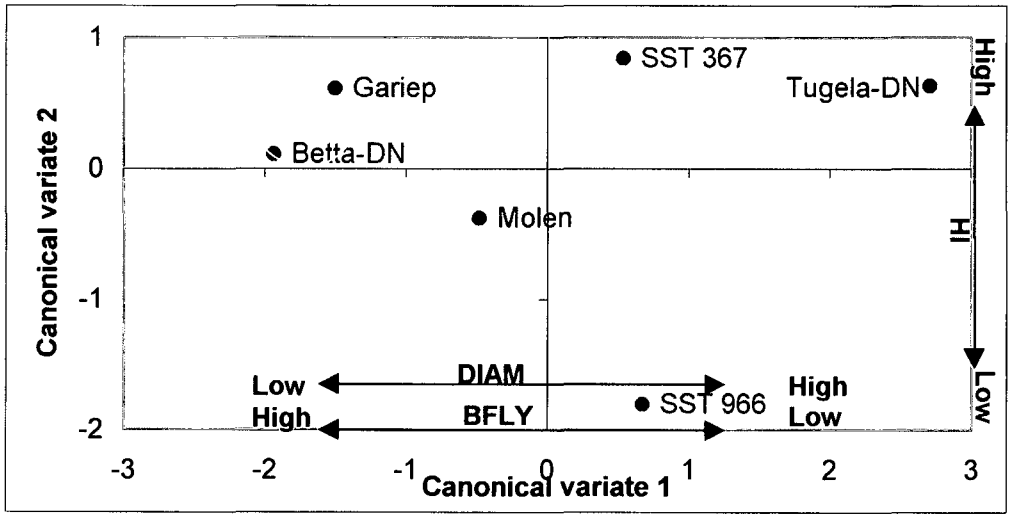

Figure 3.3 **Group means of the genotypes planted during 1998 at the first planting date.**

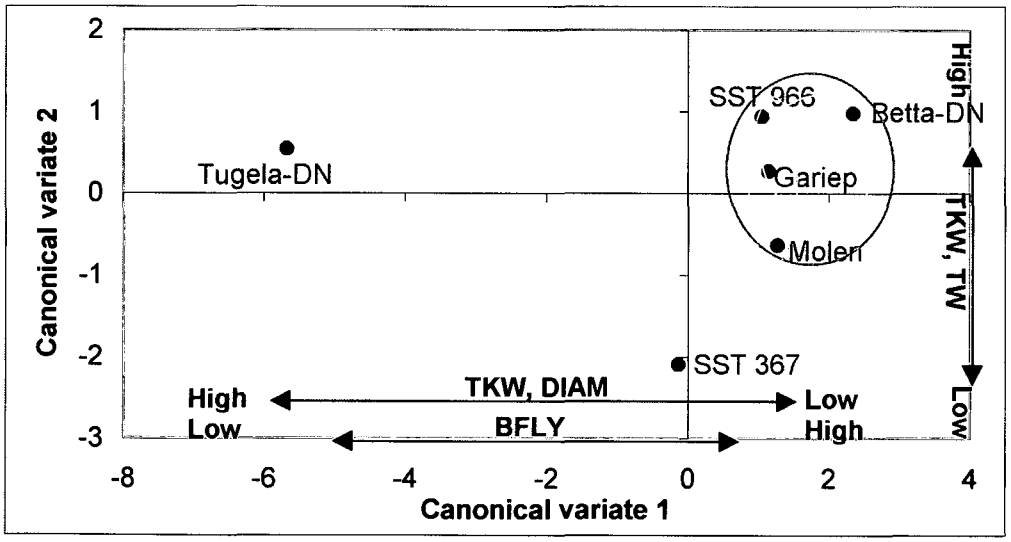

Figure 3.4 **Group means of the genotypes planted during 1999 at the first planting date.**

to any of the other cultivars. This cultivar had larger sized kernels (reflected in DIAM and TKW), harder kernels and yields less BFLY than the cultivars with relatively softer textured kernels. The same was true for SST 367 that did not group with any of the other cultivars in all three years. This cultivar is not very stable with regard to its grouping over years. It was intermediate with regard to all the measured characteristics in 1997, in 1998 its kernel hardness was the hardest, compared to all the other cultivar groups and in 1999 this cultivar's size (DIAM and TKW), and TW values were low and it yielded higher BFLY.

3.3.2.2 The CVA to discriminate between genotypes planted at the second planting date

The first two, discriminant latent vectors and correlation coefficients of cultivars (planted at a second planting date) for grain and milling characteristics are presented in Table 3.6. The kernel and milling characters that best discriminated between cultivars planted at a second planting date during 1997 to 1999 were more or less the same as for the first planting date. The 10 characteristics were reduced (as with the first planting date) to TKW, DIAM, HI, BFLY and TW. This time FLY also played a role, but during the 1997 season only. These characteristics are listed in Table 3.6.

Table 3.6 Discriminant analysis for grain and milling characters, the first two latent vectors and correlation coefficients for genotypes planted at the second planting date of 1997 to 1999.

Character	Latent vectors (Loadings)		Correlation coefficients	
	CV axis 1	CV axis 2	CV axis 1	CV axis 2
1997	**74.00%**	**18.77%**		
TKW	–0.366	0.336	0.423	0.322
DIAM	7.376	–8.531	0.610	0.083
HI	–0.089	–0.092	–0.080	–0.671
BFLY	–0.670	–0.107	–0.826	0.087
FLY	0.023	–0.329	–0.199	–0.581
1998	**60.94%**	**27.59%**		
TW	0.300	–0.139	0.514	–0.170
TKW	–0.132	–0.385	–0.535	–0.449
DIAM	1.458	4.702	–0.636	–0.174
HI	0.211	0.093	0.549	0.678
BFLY	0.839	–0.466	0.574	–0.686
1999	**50.16%**	**39.40%**		
TKW	0.327	–0.227	–0.516	–0.062
DIAM	–2.367	6.700	–0.697	0.136
HI	0.225	0.257	0.493	0.845
BFLY	0.932	–0.224	0.787	–0.552

For the second planting date, the first two canonical variates (CV1 and CV2) explained 98.11% of the total variation among cultivars during 1997, 88.53% and 89.56% during the seasons of 1998 and 1999 respectively. Most of the characters correlated moderately to strongly with the CV scores on at least one of the axis. As with the first planting date, BFLY had the strongest correlation (r=–0.826, and r=–0.686) during 1997 and 1998. The correlation was r=0.787 during 1999. HI had the strongest correlation with the CV scores (r=0.845) during 1999, the correlations were r=–0.671 in 1997 and r=0.678 in 1998. Therefore, these two characteristics are the most suitable to use for discriminating between the cultivars. As indicated by the ANOVA, this reveals that genotypes had a large influence on these characteristics. The heritability of these traits is also high.

The genotype canonical variate scores (for CV1 and CV2) were plotted against each other in Figures 3.5, 3.6 and 3.7, to illustrate the groupings of genotypes for the second planting date of the three years, 1997 to 1999, with regard to the above mentioned. It is clear that the groups for the measured kernel and milling characteristics are Tugela-DN with SST 124 in two of the three years (during 1998 they did not group together). These two cultivars had harder kernels with lower BFLY and higher FLY, mainly resulting from larger kernels. Betta-DN, Caledon, Elands, Gariep, Limpopo and PAN 3235 formed a group. This group is often referred to as the Betta-types and have similar agronomic characteristics. According to the CVA, they mainly have smaller kernels with lower kernel hardness values (compared to the other cultivar groups), producing higher BFLY than Tugela-DN and SST 124. SST 972 and PAN 3349 were not similar to each other or to any of the other cultivars and each stood alone, in all three years, with regard to the mentioned quality characters. SST 972 had large kernels, was much softer, yielded low break flour and the resulting FLY was also lower than that of the other groups. This is no surprise, and confirms the analysis of the means where SST 972 differed significantly from the other cultivars as to kernel characteristics. PAN 3349 was intermediate between the groups with regard to kernel size, HI, BFLY and FLY in all three years.

These cultivar groupings can aid grain depot owners in storing together the grain of cultivars that grouped with regard to kernel size (TKW and DIAM), HI, BFLY and TW. This will help to improve the quality of stored grain for milling purposes. The analysis further proved to be a useful tool in determining the milling quality of new and unknown cultivars, to indicate with which of the most widely produced cultivars within a region, the new line will group strongly to.

The most important kernel and milling characteristics, excluded by the CVA, to differentiate between cultivars, was kernel size (TKW and DIAM), HI and BFLY. It is important to note that

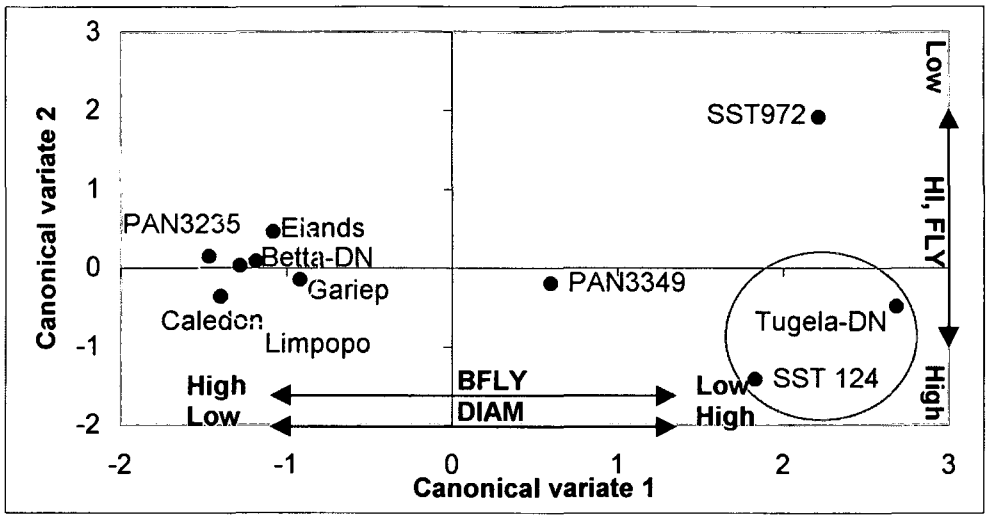

Figure 3.5 **Group means of the genotypes planted during 1997 at the second planting date.**

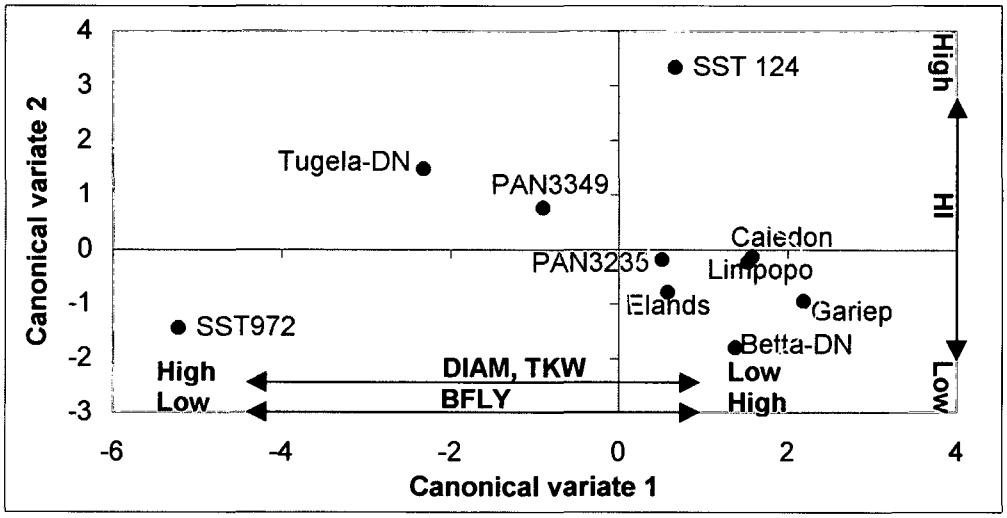

Figure 3.6 **Group means of the genotypes planted during 1998 at the second planting date.**

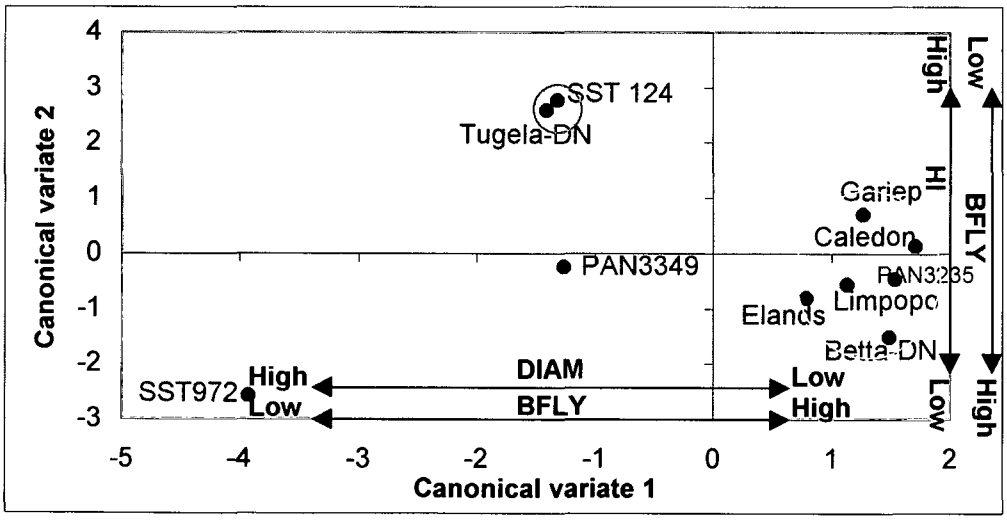

Figure 3.7 **Group means of the genotypes planted during 1999 at the second planting date.**

the genetic component, as previously discussed, has a large influence on all of these characteristics. Although the environment influences kernel size, genotype plays a very important role in the expression of this trait. Bhatt (1972) found that the heritability of kernel weight indicated that the application of selection pressure could lead to considerable progress. Jalaluddin and Harrison (1989) and Debelo *et al.* (2001) reported a significant correlation between TKW and grain yield. This is important to wheat producers because higher TKW will also help in realising better yields, subsequently affecting their profit. The strong relationship between HI and BFLY was again emphasised as important, by the outcome of the CVA. Therefore, it is understandable why BFLY is used as selection and determination criteria for kernel hardness.

3.3.3 Phenotypic correlation matrixes

Correlations between the different kernel and milling characteristics were determined to find the relative association between characteristics. A positive correlation indicates that an increase (or decrease) in one character will also result in an increasing (or decreasing) effect on the trait associated with it. The implication in a breeding programme will be that an improvement in one of the characteristics will simultaneously improve the other characteristic without selecting for that trait specifically. Negative correlations imply that an increase in one characteristic will lead to a decrease in the other associated characteristic. Such a correlation between two important characteristics can delay the progress of a breeding programme and needs special attention and direct selection should be applied. Correlations between kernel and milling traits are also applicable in predicting some of the results before the purchasing of the wheat.

The correlation matrix was performed on the individual data of the two planting dates of the three years (Tables 3.5 to 3.10). Values close to zero, indicates the absence of correlations. The closer the values are to one, the higher the correlation. Only moderately high, to high($r>0.500$) and significant correlations were discussed.

TW correlated positively with HI during the first planting date of 1998 ($r=0.551$) and the second planting date of 1997 ($r=0.717$). This correlation was positive and significant at both planting dates of all three years, but did not exceed $r=0.500$ in others than the above-mentioned. This is agreement with Bassett *et al.* (1989) who found TW to be correlated with HI in soft white winter wheat. Ohm *et al.* (1998) also found TW to be significantly correlated with the single kernel hardness index. The report by Gaines (1991), that cultivars with high TW produced less break flour, further confirm the correlation between TW and HI, because HI is negatively correlated

with BFLY. Similar negative correlations between TW and BFLY were detected in the present study, but were too low or insignificant to be mentioned.

As expected from the kernel characteristics, weight and size, TKW had positive correlations with DIAM (r>=0.778) at both planting dates of all three years. This was in agreement with the high, significant correlation detected by Hazen and Ward (1997) in kernel weight vs. kernel width (r=0.890). Larger kernels contain more endosperm and will have a higher TKW. These findings confirm the use of TKW in determining kernel size. Fang *et al.* (1998) and Ohm *et al.* (1998) also observed significant positive correlations between single kernel weight and diameter and these parameters had a significant correlation with the amount of large kernels.

TKW and DIAM had a positive correlation with MOIST. The coefficients of correlation were r= 0.536 and r=0.570 for TKW and DIAM, respectively. This was found only at the first planting date of 1997. It is true that higher moisture contents will increase the kernel weight and diameter.

TKW and DIAM correlated negatively with BFLY. The TKW and BFLY correlation during 1997 was r=–0.527 and in 1999 r=–0.553 for the first and second planting dates respectively. DIAM had moderate to high negative correlations with BFLY during 1997 for the second planting date (r=–0.508) and during 1999 for both the planting dates (r=–0.514 and r=–0.706). These findings are in contradiction with that of Kosmolak and Dyck (1981) who found a positive correlation between BFLY and large kernel size. The reason might be that smaller kernels are usually a little softer than large kernels as explained by Gaines *et al.* (1996b) and that this might influence the correlation of BFLY with the kernel characteristics, TKW and DIAM, rather than the kernel size alone.

HI correlated negatively with BFLY over years and seasons, but only correlations observed at the first planting dates of 1998 and 1999 (r=–0.651 and r=–0.547) were high enough to be mentioned. These findings were similar to the findings of many other researchers. During milling, harder wheat produces less BFLY (Stenvert, 1972). This has been confirmed by the research of Yamazaki and Donelson (1983), Gaines (1991), Rogers *et al.* (1993) and Labuschagne *et al.* (1997) who obtained higher BFLY from softer textured wheat. The poor correlations between HI and BFLY in 1997 (both planting dates), 1998 and 1999 second planting dates are in agreement with those of Morris *et al.* (1999). This poor or lack of correlation could be explained by the tempering of the grain, because tempering improves the correlation between BFLY and particle size index (Yamazaki and Donelson, 1983) and might be insufficient for the mentioned cases.

HI correlated positively with the percentage VK at the first planting dates of all three years (1997: r=0.512, 1998: r=0.576 and 1999:r=0.539). This correlation was also present at the second planting dates, but correlation values were just below 0.5 (r=0.418, r=0.441, and r=0.487). According to Stenvert (1972) wheat can be recognised as being hard by its vitreous appearance. This positive correlation explains why VK is generally associated with HI and the use of VK to obtain an indication of the grain kernel hardness. Similarly, Dexter *et al.* (1988) observed that vitreous fractions of durum wheat had the hardest grain. The grain merges into starchy kernels with decreasing hardness.

VK correlated negatively with BFLY (r=–0.518; r= –0.479) and FLY (r= –0.584; r=–0.404) in 1998 and 1999 first planting dates respectively. The correlation was very low and insignificant in other years and planting dates. The negative correlation between BFLY and HI just further explained the correlation between the VK and HI, that correlated positively in this study and confirmed the utilisation of VK as another measurement of kernel hardness and therefore also explains the negative correlation between VK an BFLY.

During 1998, at the first planting date, high negative correlations were found between FLY and HI (r=–0.631). The same negative, but very low correlations were observed for all the other years and planting dates, except at the first planting date of 1997. The negative correlations between HI, VK and FLY are in contrast with the findings of other researchers. It is common knowledge that a positive correlation exists between kernel hardness and FLY. Harder wheat tends to yield more flour and softer wheat indicates a reduction in flour yield (Bassett *et al.*, 1989; Labuschagne *et al.*, 1997; Ohm *et al.*, 1998). This could be due to other errors prior to or in the grinding process, affecting the FLY and influencing the correlation result of HI with FLY. Uniform application of the appropriate amount of temper water is essential; the flour extraction rate decreases as tempered wheat moisture content increases. Variation in ambient temperature and relative humidity can have marked effects on FLY. The millroom environment affects flour yield, changes in relative humidity have a greater effect on the milling results than temperature changes. FLY could decline due to regrinding and the padding effect of unsifted flour (AACC, 2000). Another reason could be the small range in hardness values between most of the cultivars.

HI correlated negatively with FPC in 1997 at the second planting date only (r=–0.563). This confirms research by Obuchowski and Bushuk (1980b) who found a high, significant negative correlation between protein content and particle size (another measurement of kernel hardness). Confusion exists in the literature regarding this correlation. Many researchers found a positive correlation between kernel hardness and protein content (Huebner and Gaines, 1992; Carver, 1994; Labuschagne *et al.,* 1997; Bergman *et al,* 1998; Lyon and Shelton, 1999). Miller

et al. (1984) and Pomeranz *et al.* (1985) failed to reveal the same results, the correlation between HI and FPC was either very low or insignificant, reflecting the lack of relationship between the parameters.

MOIST correlated positively with VK during 1999, second planting date (r=0.502). During the other years and planting dates, low and varying correlations were found. MOIST had a negative correlation with FLY during 1998, at both planting dates, r=–0.716 and r=–0.653, and a positive correlation at the second planting date of 1999 (r=0.512). MOIST correlations with FLY and VK were very inconsistent and no conclusions could be drawn from these varying correlations.

FLY had positive correlations with BFLY. During 1998, first and second planting dates, the correlation was worth mentioning (r=0.610 and r=0.591), but in the other years and planting dates the correlation was either very low and/or insignificant. Kosmolak and Dyck (1981) found a positive correlation between BFLY and large kernel size and on the other hand, larger kernels produce more flour. The 1998 season favoured the development of plump kernels (indicated by the genotype means in the previous subsection). Therefore, kernel size could indirectly account for the relationship between FLY and BFLY in the 1998 season.

FLY correlated negatively with FCL, 1997 and 1998 first planting dates (r=–0.550 and –0.570). In the other years and planting dates this correlation was always negative varying between r=–0.371 and r=–0.482. Barnard (2000) also reported a negative correlation between FCL and FLY (r=–0.439) for spring wheat grown in the Western Cape. The correlation indicates possible darker flour from too high extraction rates. FCL from bran contamination is one of the most obvious effects of darker FCL, influenced by the grinding and reduction action of the mill (Posner and Hibbs, 1997). Li and Posner (1989) also found a linear relationship between FCL and flour extraction levels.

Table 3.7 Correlation matrix of the 10 milling characteristics evaluated from material planted at the first planting date during 1997.

	TW	TKW	DIAM	HI	MOIST	VK	BFLY	FLY	FCL	FPC
TW	1.000									
TKW	-0.073	1.000								
DIAM	-0.159	0.849 **	1.000							
HI	0.491 **	-0.155	0.049	1.000						
MOIST	-0.560 **	0.341 **	0.570 **	-0.073	1.000					
VK	0.453 **	-0.116	-0.070	0.512 **	-0.221 *	1.000				
BFLY	-0.243 **	-0.527 **	-0.477 **	-0.300 **	0.153	-0.208 *	1.000			
FLY	-0.132	0.234 *	0.155	-0.212 *	0.300 **	-0.388 **	0.386 **	1.000		
FCL	-0.028	0.187	0.236 *	0.133	0.079	0.257 **	-0.328 **	-0.550 **	1.000	
FPC	-0.148	0.034	0.074	0.173	0.217 *	0.505 **	0.084	-0.274 **	0.480 **	1.000

Table 3.8 Correlation matrix of the 10 milling characteristics evaluated from material planted at the first planting date during 1998.

	TW	TKW	DIAM	HI	MOIST	VK	BFLY	FLY	FCL	FPC
TW	1.000									
TKW	0.314 **	1.000								
DIAM	0.003	0.778 **	1.000							
HI	0.551 **	-0.013	-0.223 *	1.000						
MOIST	0.752 **	0.473 **	0.081	0.662 **	1.000					
VK	0.228 *	-0.181	-0.314 **	0.576 **	0.288 **	1.000				
BFLY	-0.175	-0.206 *	-0.189 *	-0.651 **	-0.409 **	-0.518 **	1.000			
FLY	-0.434 **	-0.109	0.202 *	-0.631 **	-0.716 **	-0.584 **	0.610 **	1.000		
FCL	-0.115	0.222 *	0.091	0.168	0.249 **	0.311 **	-0.385 **	-0.570 **	1.000	
FPC	-0.257 *	-0.162	-0.174	0.068	-0.146	0.383 **	-0.129	-0.114	0.274 **	1.000

Table 3.9 Correlation matrix of the 10 milling characteristics evaluated from material planted at the first planting date during 1999.

	TW	TKW	DIAM	HI	MOIST	VK	BFLY	FLY	FCL	FPC
TW	1.000									
TKW	0.185	1.000								
DIAM	0.065	0.930 **	1.000							
HI	0.245 *	-0.126	-0.103	1.000						
MOIST	-0.115	-0.070	-0.148	0.406 **	1.000					
VK	0.271 **	0.147	0.106	0.539 **	0.173	1.000				
BFLY	-0.238 *	-0.412 **	-0.514 **	-0.547 **	0.099	-0.479 **	1.000			
FLY	-0.073	-0.087	-0.106	-0.447 **	-0.061	-0.404 **	0.398 **	1.000		
FCL	0.076	0.162	0.245 *	0.278 **	0.179	0.245 *	-0.378 **	-0.442 **	1.000	
FPC	-0.054	0.250 *	0.180	-0.198	0.263 **	0.044	0.262 **	-0.079	0.274 **	1.000

**Significant correlation at P<0.01

*Significant correlation at P<0.05

TW = Test weight

TKW = Thousand kernel weight

DIAM = Diameter

HI = Hardness index

MOIST=Moisture content

VK = Vitreous kernels

BFLY = Break flour yield

FLY = Flour yield

FPC = Flour protein content

FCL = Flour colour

Table 3.10 Correlation matrix of the 10 milling characteristics evaluated from material planted at the second planting date during 1997.

	TW	TKW	DIAM	HI	MOIST	VK	BFLY	FLY	FCL	FPC
TW	1.000									
TKW	0.052	1.000								
DIAM	-0.014	0.918**	1.000							
HI	0.717**	-0.232**	-0.226**	1.000						
MOIST	0.313**	0.536**	0.384**	0.011	1.000					
VK	0.289**	0.035	-0.048	0.418**	0.185**	1.000				
BFLY	-0.458**	-0.466**	-0.508**	-0.375**	-0.152*	-0.103	1.000			
FLY	-0.009	-0.214**	-0.155*	0.111	-0.075	0.196**	0.226**	1.000		
FCL	-0.237**	0.485**	0.410**	-0.244**	0.259**	0.109	-0.089	-0.482**	1.000	
FPC	-0.612**	0.194**	0.234**	-0.563**	-0.012	-0.158*	0.348**	-0.021	0.357**	1.000

Table 3.11 Correlation matrix of the 10 milling characteristics evaluated from material planted at the second planting date during 1998.

	TW	TKW	DIAM	HI	MOIST	VK	BFLY	FLY	FCL	FPC
TW	1.000									
TKW	0.157*	1.000								
DIAM	0.063	0.805**	1.000							
HI	0.315**	-0.302**	-0.380**	1.000						
MOIST	0.250**	0.197**	-0.102	0.569**	1.000					
VK	0.183*	-0.029	-0.150*	0.441**	0.279**	1.000				
BFLY	0.134	-0.284**	-0.390**	-0.346**	-0.394**	-0.092	1.000			
FLY	-0.004	-0.428**	-0.237**	-0.178*	-0.653**	-0.139	0.591**	1.000		
FCL	-0.420**	0.128	0.087	-0.136	-0.060	-0.127	-0.212**	-0.371**	1.000	
FPC	-0.440**	-0.240**	-0.146*	-0.007	-0.177*	0.299**	-0.085	0.010	0.266**	1.000

Table 3.12 Correlation matrix of the 10 milling characteristics evaluated from material planted at the second planting date during 1999.

	TW	TKW	DIAM	HI	MOIST	VK	BFLY	FLY	FCL	FPC
TW	1.000									
TKW	0.066	1.000								
DIAM	0.141	0.895**	1.000							
HI	0.373**	-0.424**	-0.364**	1.000						
MOIST	0.232**	-0.339**	-0.393**	0.327**	1.000					
VK	0.191**	-0.161*	-0.283**	0.487**	0.502**	1.000				
BFLY	-0.208**	-0.553**	-0.706**	-0.077	0.057	0.100	1.000			
FLY	0.176*	-0.328**	-0.294**	-0.237**	0.512**	0.237**	0.113	1.000		
FCL	-0.256**	0.411**	0.332**	-0.218**	-0.459**	-0.228**	-0.027	-0.481**	1.000	
FPC	-0.388**	-0.003	-0.032	-0.148*	-0.070	0.040	0.030	0.036	0.015	1.000

Significant correlation at P<0.01 *Significant correlation at P<0.05 ***TW* = Test weight

TKW = Thousand kernel weight ***DIAM*** = Diameter ***HI*** = Hardness index

MOIST=Moisture content ***VK*** = Vitreous kernels ***BFLY*** = Break flour yield

FLY = Flour yield ***FPC*** = Flour protein content ***FCL*** = Flour colour

3.3.4 Stepwise multiple regression

Stepwise multiple regression techniques were utilised to reveal the most important character responsible for the variation in another. It was used to define the variation caused by each of the other characteristics to the dependent characteristic. The dependent characteristics were TW, HI, BFLY, FLY and FCL. The independent variables for TW were TKW, DIAM, HI, and VK. Those for HI were TW, TKW, DIAM, MOIST and VK; for BFLY, the independent variables were TW, TKW, DIAM, HI, and VK. The variation in FLY was investigated using TW, TKW, DIAM, HI, VK and BFLY as independent variables. For the dependent variable FCL: TW, TKW, DIAM, HI, VK, BFLY, FLY and FPC were used as independent variables

The regression is determined at a certain coefficient of determination (R^2), which indicates the proportion of the variation attributable to, or explained by the relationship between Y and X and is usually expressed as a percentage (Van Ark, 1995). It is calculated by $R^2 = r^2 x100$, where r denotes the correlation coefficient.

The traits in the model (Tables 3.13 to 3.17), indicates the best model to obtain the largest R^2 and the percentage of the variation attributable to that trait in explaining the TW, HI, BFLY, FLY and FCL.

3.3.4.1 Test weight

HI was the trait that explained the variation in the TW the best. At both planting dates, HI was important and explained between 10 to 51.1% of the variation in TW. Only at the first planting date of 1999, HI explained less than 10% of the variation in TW. DIAM and TKW contributed almost equally to the variation in TW over years and planting dates. The contribution by DIAM was between 1.4 and 8.4% and that of TKW between 1.1 and 9.8%.

The multiple coefficient of determination was low to moderate; indicating that the kernel characteristics measured in this study contributed only 16.8 to 57.6% of the variation in TW over planting dates and years. Table 3.13 indicates these coefficients of determination over the three years and two planting dates.

Test weight is a function of packing efficiency and kernel density (Jalaluddin and Harrison, 1989), associated with traits like grain shape, size and kernel density. The HI determined in this study, might be an indirect reflection of the kernel density, because the endosperm of hard wheat cultivars have higher densities.

Table 3.13 The total adjusted R^2 for all the traits in the model, explaining the variation in TW and the increase in R^2 caused by the individual traits when it was added to the regression on a stepwise basis.

First planting date:					
Traits in model	b value	Std error of b	Adjusted R^2	Increase in R^2	Model p-level
1997					
Intercept	73.710	1.730			<0.001 **
+HI	0.088	0.016	23.4	-	<0.001 **
+VK	0.031	0.013	28.3	4.9	0.018 *
+DIAM	-5.530	1.210	30.2	1.9	<0.001 **
+TKW	0.257	0.063	39.2	9.0	<0.001 **
1998					
Intercept	71.540	2.470			<0.001 **
+HI	0.084	0.014	29.7	-	<0.001 **
+TKW	0.256	0.052	39.5	9.8	<0.001 **
+DIAM	-3.650	1.280	43.3	3.8	0.005 *
1999					
Intercept	77.390	3.300			<0.001 **
+VK	0.015	0.020	6.3	-	0.452
+TKW	0.458	0.131	7.4	1.1	<0.001 **
+DIAM	-8.080	2.680	14.0	6.6	0.003 **
+HI	0.050	0.026	16.8	2.8	0.054 *
Second planting date:					
Traits in model	b value	Std error of b	Adjusted R^2	Increase in R^2	Model p-level
1997					
Intercept	63.740	2.290			<0.001 **
+HI	0.206	0.014	51.1	-	<0.001 **
+TKW	0.320	0.071	55.9	4.8	<0.001 **
+DIAM	-4.550	1.570	57.3	1.4	0.004 **
+VK	-0.020	0.014	57.6	0.3	0.131
1998					
Intercept	67.530	1.570			<0.001 **
+HI	0.082	0.013	10.0	-	<0.001 **
+TKW	0.129	0.029	17.2	7.2	<0.001 **
1999					
Intercept	63.770	2.230			<0.001 **
+HI	0.115	0.017	13.4	-	<0.001 **
+DIAM	2.793	0.622	21.8	8.4	<0.001 **

b = regression coefficient, R^2 = coefficient of determination, P-level = probability level at which the variable was accepted, ** model significant at P<0.01, * model significant at P<0.05.

3.3.4.2 Kernel hardness

The VK and MOIST could be regarded as the most important independent variance predictors for kernel hardness, interpreting up to 28.2 and 43.2%, respectively, of the variation in kernel hardness.

The other characteristics, TW, TKW and DIAM made only minor contributions and were of limited value in predicting the variance in HI.

When all the predictor variables were forced into the regression equation, 46.0 to 64.9% of the variability for HI was explained over years and planting dates. The models with all the relevant traits, to explain the variation in HI, are indicated in Table 3.14. The coefficient of determination

is moderate, because 35 to 54% of the variation in HI was not explained by any of the measured kernel characteristics.

Table 3.14 The total adjusted R^2 for all the traits in the model, explaining the variation in HI and the increase in R^2 caused by the individual traits when it was added to the regression on a stepwise basis.

First planting date:					
Traits in model	b value	Std error of b	Adjusted R^2	Increase in R^2	Model p-level
1997					
Intercept	-201.000	50.200			<0.001 **
+VK	0.240	0.066	25.5	-	<0.001 **
+TW	2.807	0.544	33.5	8.0	<0.001 **
+MOIST	1.760	1.650	38.3	4.8	0.289
+TKW	-1.656	0.336	41.3	3.0	<0.001 **
+DIAM	30.710	7.460	49.2	7.9	<0.001 **
1998					
Intercept	-27.500	13.800			0.049 *
+MOIST	8.712	0.931	43.2	-	<0.001 **
+VK	0.233	0.046	59.2	16.0	<0.001 **
+TKW	-1.071	0.302	64.5	5.3	<0.001 **
+DIAM	9.210	6.360	64.8	0.3	0.151
1999					
Intercept	-133.600	39.500			0.001 **
+VK	0.351	0.065	28.2	-	<0.001 **
+MOIST	5.290	1.080	37.7	9.5	<0.001 **
+TKW	-1.915	0.512	40.2	2.5	<0.001 **
+TW	1.321	0.400	43.1	2.9	0.001 **
+DIAM	32.000	10.600	48.1	5.0	0.003 **
Second planting date:					
Traits in model	b value	Std error of b	Adjusted R^2	Increase in R^2	Model p-level
1997					
Intercept	-125.500	17.800			<0.001 **
+TW	2.738	0.189	51.1	-	<0.001 **
+TKW	-0.952	0.281	58.1	7.0	<0.001 **
+VK	0.250	0.045	63.1	5.0	<0.001 **
+DIAM	11.880	5.790	64.3	1.2	0.042 *
+MOIST	-2.360	1.190	64.9	0.6	0.049 *
1998					
Intercept	-44.300	17.200			0.010 **
+MOIST	5.367	0.488	30.2	-	<0.001 **
+TKW	-1.006	0.100	47.5	17.3	<0.001 **
+VK	0.196	0.034	55.7	8.2	<0.001 **
+TW	0.999	0.233	59.1	3.4	<0.001 **
1999					
Intercept	-35.400	18.600			0.059
+VK	0.342	0.052	23.2	-	<0.001 **
+TKW	-1.200	0.262	35.2	12.0	<0.001 **
+TW	1.284	0.248	45.3	10.1	<0.001 **
+DIAM	8.780	5.040	46.0	0.7	0.083

b = regression coefficient, R^2 = coefficient of determination, P-level = probability level at which the variable was accepted, ** model significant at P<0.01, * model significant at P<0.05.

According to Stenvert (1972), wheat can be recognised as being hard by its vitreous appearance, which merge to starchy or soft grains with decreasing hardness. Similarly, Dexter *et al.* (1988) observed that vitreous fractions of durum wheat was the hardest and contained the highest amount of protein. In this study, the stepwise multiple regression indicated that the VK could define between 5.0 and 28.2% of the variation in HI, depending on the planting date and year.

HI has a linear relationship with MOIST, there is a decrease in MOIST with increasing HI (Manley *et al.*, 2001), therefore MOIST plays an important role in the variation of HI.

3.3.4.3 Break flour yield

The models that include all the relevant traits, to explain the variation in BFLY, are represented in Table 3.15. The most explanatory predictors for BFLY were kernel size (TKW and DIAM) and HI. These characteristics could define 41.6 to 63.3% of the variation in BFLY. The other characteristics, TW and VK made small and insignificant contributions and were of limited value in predicting BFLY.

Table 3.15 The total adjusted R^2 for all the traits in the model, explaining the variation in BFLY and the increase in R^2 caused by the individual traits when it was added to the regression on a stepwise basis.

First planting date:					
Traits in model	b value	Std error of b	Adjusted R^2	Increase in R^2	Model p-level
1997					
Intercept	58.830	9.830			<0.001 **
+TKW	-0.380	0.048	27.1	-	<0.001 **
+HI	-0.090	0.023	41.6	14.5	<0.001 **
+TW	-0.194	0.133	42.2	0.6	0.148
1998					
Intercept	22.980	7.390			0.002 **
+HI	-0.192	0.021	41.8	-	<0.001 **
+DIAM	-6.878	0.917	53.2	11.4	<0.001 **
+TW	0.451	0.101	60.6	7.4	<0.001 **
+VK	-0.055	0.013	66.0	5.4	<0.001 **
1999					
Intercept	82.610	10.000			<0.001 **
+HI	-0.174	0.029	29.1	-	<0.001 **
+DIAM	-18.290	3.120	62.0	32.9	<0.001 **
+TKW	0.463	0.155	63.3	1.3	0.004 **
+VK	-0.049	0.023	65.0	1.7	0.035 *
+TW	-0.195	0.120	65.7	0.7	0.108
Second planting date:					
Traits in model	b value	Std error of b	Adjusted R^2	Increase in R^2	Model p-level
1997					
Intercept	67.540	5.270			<0.001 **
+DIAM	-8.034	0.727	25.4	-	<0.001 **
+HI	-0.112	0.023	50.6	25.2	<0.001 **
+TW	-0.221	0.081	52.3	1.7	0.007 **
+VK	0.025	0.015	53.8	1.5	0.089
1998					
Intercept	26.210	4.940			<0.001 **
+HI	-0.202	0.014	17.1	-	<0.001 **
+DIAM	-9.954	0.737	46.7	29.6	<0.001 **
+TW	0.477	0.067	56.9	10.2	<0.001 **
1999					
Intercept	51.500	5.160			<0.001 **
+DIAM	-13.170	1.290	49.5	-	<0.001 **
+HI	-0.132	0.019	62.2	12.7	<0.001 **
+TKW	0.150	0.071	62.9	0.7	0.037 *
+TW	0.106	0.073	63.1	0.2	0.151

b = regression coefficient, R^2 = coefficient of determination, P-level = probability level at which the variable was accepted, ** model significant at P<0.01, * model significant at P<0.05.

The coefficient of determination was moderate to fairly strong; indicating that the kernel characteristics measured in this study, contributed 42.2 to 66.0% of the variation in BFLY over planting dates and years.

Kosmolak and Dyck (1981) found a positive correlation between BFLY and large kernel size. This could explain the reason for the kernel size parameter (DIAM) being important in defining some of the variation in BFLY. In this study and other research, HI correlated negatively with BFLY. Harder wheat produces less BFLY during milling (Stenvert, 1972). Therefore, HI is an important characteristic in determining the BFLY variation.

3.3.4.4 Flour yield

Models explaining the variation in flour yield are tabulated in Table 3.16. From these models, it is evident that the kernel hardness measurements, HI, BFLY and VK could be regarded as the most definable independent variance predictors for FLY, all together these predictors interpreted up to 50.0% of the variation in FLY.

TW explained less than 4% of the variation in FLY, indicating that TW is not always a reliable indicator of the amount of flour extraction. This value is even lower than that of Berman *et al.* (1996) who found that TW accounted for 17% of the variation in FLY. Schuler *et al.* (1995) also indicated that TW failed to show any correlation with FLY.

FLY is usually associated positively with kernel size. TKW and DIAM give the miller important information on the milling ability of wheat, because it is highly correlated with FLY (Posner and Hibbs, 1997; Gibson *et al.*, 1998). In this study the regression analysis indicated that the kernel size characteristics, TKW and DIAM together, explained 9.6 to 20.7% of the variation in FLY. This illustrates the difficulty in predicting flour yield by indirect calculations. The inclusion of DIAM and TKW in the predictive model as suggested by Schuler *et al.* (1995), explained only 22% of the total variability in FLY, also indicating the complexity of FLY determination.

Table 3.16 The total adjusted R^2 for all the traits in the model, explaining the variation in FLY and the increase in R^2 caused by the individual traits when it was added to the regression on a stepwise basis.

First planting date:					
Traits in model	b value	Std error of b	Adjusted R^2	Increase in R^2	Model p-level
1997					
Intercept	59.410	2.540			<0.001 **
+VK	-0.037	0.010	14.2	-	<0.001 **
+BFLY	0.388	0.049	23.4	9.2	<0.001 **
+TKW	0.287	0.053	43.1	19.7	<0.001 **
+HI	0.045	0.013	46.8	3.7	0.001 **
+DIAM	-1.608	0.928	47.8	1.0	0.086
1998					
Intercept	71.630	9.970			<0.001 **
+HI	0.021	0.032	39.2	-	0.512
+VK	-0.037	0.016	46.1	6.9	0.023 *
+BFLY	0.601	0.111	50.0	3.9	<0.001 **
+TW	-0.325	0.137	53.8	3.8	0.020 *
+DIAM	9.990	1.860	57.9	4.1	<0.001 **
+TKW	-0.298	0.074	63.4	5.5	<0.001 **
1999					
Intercept	80.830	1.110			<0.001 **
+HI	-0.052	0.018	19.0	-	0.005 **
+VK	-0.029	0.014	21.7	2.7	0.046 *
Second planting date:					
Traits in model	b value	Std error of b	Adjusted R^2	Increase in R^2	Model p-level
1997					
Intercept	68.180	1.570			<0.001 **
+BFLY	0.161	0.041	4.6	-	<0.001 **
+VK	0.023	0.011	9.0	4.4	0.040 *
+HI	0.023	0.012	10.2	1.2	0.062
1998					
Intercept	61.430	2.650			<0.001 **
+BFLY	0.523	0.049	31.2	-	<0.001 **
+TKW	-0.294	0.039	39.5	8.3	<0.001 **
+DIAM	4.990	1.020	45.4	5.9	<0.001 **
1999					
Intercept	66.870	4.870			<0.001 **
+TKW	-0.134	0.030	10.3	-	<0.001 **
+TW	0.149	0.063	13.7	3.4	0.018 *
+VK	0.028	0.013	15.5	1.8	0.031 *

b = regression coefficient, R^2 = coefficient of determination, P-level = probability level at which the variable was accepted, ** model significant at P<0.01, * model significant at P<0.05.

3.3.4.5 Flour colour

The most important variable in predicting FCL was FLY, explaining between 13.6 to 31.9% of the variation in FCL (Table 3.17). The other predictor variables varied too much over years and planting dates to draw conclusions from them.

The measurement of colour brightness is influenced by the dulling effect of bran particles. FCL correlates strongly with flour extraction levels (Posner and Hibbs, 1997). Possible darker flour with too high extraction rates indicates the inclusion of more bran particles in the flour. Therefore, flour extraction could be used to explain the variation in FCL values.

Table 3.17 The total adjusted R^2 for all the traits in the model, explaining the variation in FCL and the increase in R^2 caused by the individual traits when it was added to the regression on a stepwise basis.

First planting date:					
Traits in model	b value	Std error of b	Adjusted R^2	Increase in R^2	Model p-level
1997					
Intercept	29.880	4.940			<0.001 **
+FLY	-0.457	0.064	29.5	-	<0.001 **
+FPC	0.248	0.055	40.8	11.3	<0.001 **
+TKW	0.087	0.021	48.9	8.1	<0.001 **
1998					
Intercept	47.250	5.750			<0.001 **
+FLY	-0.315	0.031	31.9	-	<0.001 **
+TW	-0.346	0.053	47.7	15.8	<0.001 **
+TKW	0.093	0.020	56.1	8.4	<0.001 **
+FPC	0.096	0.060	56.8	0.7	0.111
1999					
Intercept	15.380	6.460			0.020 *
+FLY	-0.197	0.088	13.6	-	0.027 *
+FPC	0.318	0.081	19.3	5.7	<0.001 **
+BFLY	-0.154	0.039	30.8	11.5	<0.001 **
Second planting date:					
Traits in model	b value	Std error of b	Adjusted R^2	Increase in R^2	Model p-level
1997					
Intercept	28.550	4.020			<0.001 **
+TKW	0.084	0.013	23.1	-	<0.001 **
+FLY	-0.344	0.040	37.9	14.8	<0.001 **
+FPC	0.125	0.046	45.3	7.4	0.007 **
+VK	0.029	0.006	50.4	5.1	<0.001 **
+TW	-0.098	0.029	53.1	2.7	0.001 **
1998					
Intercept	38.340	38.340			<0.001 **
+TW	-0.225	-0.225	15.6	-	<0.001 **
+FLY	-0.274	-0.274	29.5	13.9	<0.001 **
+FPC	0.212	0.212	31.1	1.6	<0.001 **
+VK	-0.024	-0.024	33.8	2.7	0.002 **
1999					
Intercept	20.760	5.530			<0.001 **
+FLY	-0.254	0.054	22.7	-	<0.001 **
+TKW	0.235	0.033	29.6	6.9	<0.001 **
+TW	-0.201	0.049	33.7	4.1	<0.001 **
+BFLY	0.192	0.042	36.4	2.7	<0.001 **
+HI	0.064	0.016	39.0	2.6	<0.001 **
+VK	-0.032	0.011	41.8	2.8	0.002 **

b = regression coefficient, R^2 = coefficient of determination, P-level = probability level at which the variable was accepted, ** model significant at P<0.01, * model significant at P<0.05.

3.4 CONCLUSIONS

The ANOVA indicated that there were various responses of the cultivars to the environments for nearly all 10 evaluated quality characteristics. The analysis indicated highly significant (P< 0.01) differences among genotypes, environments and GXE interactions, for most of the measured traits.

The effect of cultivars was significant for all the measured kernel and milling quality characteristics, except for VK at the first planting date of 1998 and FPC at the second planting date of 1997. Genotypes contributed significantly to the variance in BFLY, DIAM, TKW and HI.

The environment had a significant influence on most of the quality characteristics, except for FPC at the first planting date of 1998. Environment had a larger effect than genotypes on TW, MOIST, VK, FLY, FCL and FPC.

Significant GXE interactions were present for most of the quality traits. Only VK (at the first planting dates of 1998 and 1999) and FPC (at both planting dates of 1997) did not indicate significant GXE interaction. The GXE interactions will be discussed further in Chapter 4.

The CVA indicated that TKW, DIAM, HI, BFLY and TW were the kernel and milling characters that differentiated the most effectively between cultivars planted at both planting dates during 1997 to 1999. Cultivars could be grouped according to these five traits to improve the milling performance of bulked grain lots at depots. The groups observed with regard to the mentioned characteristics, were Gariep with Betta-DN in all the years of evaluation. Molen and SST 966 grouped during 1997 and 1998. During 1999 only, these two cultivars formed a grouping with Gariep and Betta-DN. With regard to these characteristics, Tugela-DN was not similar to any of the other cultivars. The same was true for SST 367 that did not group with any of the other cultivars in all three years. For cultivars planted at the second planting date, the groups were Tugela-DN with SST 124 in two of the three years. Betta-DN, Caledon, Elands, Gariep, Limpopo and PAN 3235 formed a group. SST 972 and PAN 3349 were not similar to each other or to any of the other cultivars and each stood alone in all three years.

Grain depot owners and the milling industries could use these cultivar groupings, to store the grain of cultivars that grouped with regard to kernel size (TKW and DIAM), HI, BFLY and TW together and hence this will help to improve the quality and milling performance of stored grain.

As expected from the kernel characteristics, weight and size, TKW had positive correlations with DIAM. TKW and DIAM had a positive correlation with MOIST. It is true that higher MOIST will influence the kernel weight and DIAM.

TW correlated positively with HI. HI could be an indication of the kernel density, because harder kernels have higher endosperm density than softer kernels. HI correlated negatively with BFLY over years and seasons. These results confirmed findings of many other researchers. HI correlated positively with the percentage VK. This positive correlation explains why VK is generally associated with HI and the use of VK to obtain an indication of the grain HI.

VK correlated negatively with BFLY. The negative correlation between BFLY and HI just further explains correlation between the VK and HI, that correlated positively in this study and confirms the utilisation of VK as another measurement of kernel hardness, therefore also the negative correlation between VK an BFLY. High negative correlations were found between FLY and HI. The negative correlations between HI, VK and FLY are contradictory to the findings of other researchers. It is known that a positive correlation exists between kernel hardness and FLY.

FLY had positive correlations with BFLY. Kosmolak and Dyck (1981) found a positive correlation between BFLY and large kernel size and on the other hand, larger kernels produced more flour, hence, the correlation between FLY and BFLY. FLY correlated negatively with FCL. The correlation indicates possible darker flour from too high extraction rates. FCL from bran contamination is one of the most obvious effects of darker FCL, influenced by the grinding and reduction action of the mill.

The stepwise multiple regressions indicated that only small percentages of the variation in TW, HI, BFLY, FLY and FLC could be explained by the other kernel and milling characteristics determined in this study and that some of the physical kernel characteristics normally used in predicting for example flour yield, failed to do so in this evaluation.

HI explained the variation in the TW the best, it explained between 10 and 51.1% of the variation in TW. The contribution by DIAM was between 1.4 and 8.4% and that of TKW between 1.1 and 9.8%.

The VK and MOIST could be regarded as the most important independent variance predictors for kernel hardness, interpreting up to 28.2 and 43.2%, respectively. In this study the stepwise multiple regression indicated that the VK could define between 5.0 and 28.2% of the variation in HI, depending on the planting date and year. HI had linear relationships with MOIST, therefore MOIST plays an important role in the variation of HI. The other characteristics, TW, TKW and DIAM made only minor contributions and were of limited value in predicting the variance in HI. When all the predictor variables were forced into the regression equation, 46.0 to 64.9% of the variability for HI was explained over years and planting dates. The coefficient of determination is moderate, because 35 to 54% of the variation in HI was not explained by any of the measured kernel characteristics.

The most explanatory predictors for BFLY were kernel size (TKW and DIAM) and HI. These characteristics defined 41.6 to 63.3% of the variation in BFLY. The other characteristics, TW, and VK made small contributions and were of limited value in predicting BFLY. The coefficient

of determination was moderate to fairly strong; indicating that the kernel characteristics measured, contributed 62.2 to 66.0% of the variation in BFLY over planting dates and years.

It became evident that the kernel hardness measurements, HI, BFLY and VK could be regarded as the most definable independent variance predictors for flour yield, all together these predictors interpreted up to 50% of the variation in flour yield. TW explained less than 4% of the variation in FLY, indicating that TW is not always a reliable guide of the amount of FLY. FLY is usually associated positively with kernel size. TKW and DIAM give the miller important information on the milling ability of wheat, because it is often correlated with flour yield. In this study the regression analysis indicated that the kernel size characteristics, TKW and DIAM, between 9.6 and 20.7% of the variation in FLY. This illustrates the difficulty in predicting FLY by indirect calculations.

The most important variable in predicting FCL was flour yield, explaining between 13.6 to 31.9% of the variation in FCL. The other predictor variables varied widely over years and planting dates. The measurement of colour brightness is influenced by the dulling effect of bran particles, darker flour at high extraction rates, indicates the inclusion of more bran particles in the flour. Therefore, flour extraction could be used to explain the variation in FCL values. However, the regression analysis indicated low coefficients of determination, less than 32% of the variation in FCL was defined by FLY. That leaves a large portion of the variance, caused by other factors, undefined.

CHAPTER 4

THE EFFECT OF GXE INTERACTION ON THE STABILITY OF WHEAT QUALITY

4.1 INTRODUCTION

The wheat producer requires high yield, test weight, protein content and acceptable falling number from his crop to be of economical value. The milling and baking industries further add commercial value to the product, to finally fulfil the consumers' demand for good quality bread with high nutritional value. Development of cultivars that are consistently high in both grain yield and end-use quality, is thus desirable. This is a challenge to all wheat breeders.

The Wheat Technical Committee, representative of all parties, farmers, wheat breeders and members of the baking and milling industries, control the cultivar release procedure in South Africa. The procedure extends over a period of three years where wheat samples of five localities are evaluated each year to continuously improve commercial cultivars. Candidate cultivars are compared to standard cultivars and have to be within acceptable limits of the standard's quality at the same growth environment. The effect of cultivar, environment and their interaction receives no attention. As a result, the end-use quality of the commercial wheat crop often varies considerably over environments and years.

Wheat production areas, even within small regions like the Free State, are environmentally diverse in amount of precipitation, night and day temperatures, soil types and management practices. Husbandry factors such as crop rotation, monoculture, and fertiliser application also play an important role in growth conditions affecting wheat quality. Multiple environments are thus needed to assess genotypic and environmental sensitivity of cultivars effectively over seasons.

Modern milling and baking industries are characterised by high volume, highly mechanised plants with little flexibility in processing procedures. Commercial mills can process over 30 tons of wheat per hour and commercial bakeries develop about six tons of dough per hour in order to produce 8000 loaves of bread per hour (Van Lill *et al.* 1995a). Consistency (stability) in quality and performance of wheat grain and flour over time, is thus critical to the output of high quality products. Stability for end-use quality parameters should be an important breeding goal.

The ANOVA's in Chapter 3 (Tables 3.2 and 3.3) indicated significant cultivar, environment and GXE interaction effects for the measured kernel and milling characteristics. The aim of this study was to further understand how cultivars, the environment and their interaction affect grain quality and hence milling performance in different years by using the AMMI analysis.

4.2 MATERIAL AND METHODS

4.2.1 Plant material

Thirteen South African hard red winter and facultative bread wheat varieties were evaluated in this study. Due to variation in growth period requirements, two planting dates were used to sample quality data from each cultivar. Betta-DN, Gariep, Molen, SST 367, SST 966 and Tugela-DN were planted at the first planting date. Betta-DN, Caledon, Elands, Gariep, Limpopo, PAN 3235, PAN 3349, SST 124, SST 972 and Tugela-DN were planted at the second date. Betta-DN, Gariep and Tugela-DN were therefore the only cultivars evaluated at both planting dates.

4.2.2 Environments

During 1997 the material was planted at Hebron (HB) and Hennenman (HM) in the western Free State, Kroonstad (KS) and Ladybrand (LB) in the central Free State and Clarens (CL) and Ficksburg (FB) in the eastern Free State. During the 1998 season the Hebron (HB), Hennenman (HM), Excelsior (EX), Ladybrand (LB), Clocolan (CC) and Frankfort (FF) data were used for the analyses. Hennenman (HM), Wesselsbron (WB), Bultfontein fallow (BO), Bultfontein monoculture (BS), Senekal (SK) and Ladybrand (LB) (only second planting date) were used during 1999. Each locality by year combination was evaluated as a separate environment, this resulted in 17 (for the first planting date) and 18 environments (for the second planting date) analysed for the GXE interaction. The localities and their co-ordinates are listed in Table 4.1.

Table 4.1 Facultative and winter wheat localities.

Region	District (Site)	Co-ordinates	1997	1998	1999
Western Free State	Bultfontein Fallow (BO)	28° 18'S 26° 27'E			✓
	Bultfontein Monoculture (BS)	28° 18'S 26° 27'E			✓
	Hebron (HB)	29° 09'S 25° 49'E	✓	✓	
	Hennenman (HM)	27° 55'S 27° 4'E	✓	✓	✓
	Wesselsbron (WB)	27° 41'S 26° 33'E			✓
Central Free State	Excelsior (EX)	28° 51'S 27° 7'E		✓	
	Kroonstad (KS)	27° 36'S 27° 14'E	✓		
	Ladybrand (LB)	29° 15'S 27° 18'E	✓	✓	✓
	Senekal (SK)	28° 18'S 27° 42'E			✓
Eastern Free State	Clarens (CL)	28° 22'S 28° 26'E	✓		
	Clocolan (CC)	28° 58'S 27° 30'E		✓	
	Ficksburg (FB)	28° 49'S 27° 54'E	✓		
	Frankfort (FF)	27° 9'S 28° 27'E		✓	

The Free State is divided into the three regions on the basis of climatic differences. The eastern Free State has higher rainfall (Table 4.2), lower temperatures and lower evaporation than the other regions. Yellow soils of average effective depth predominate in this area.

The central Free State receives moderate rainfall and temperatures, resulting in lower evaporation. This area has shallow duplex soils.

As Table 4.2 indicates, low rainfall, high temperatures and high evaporation mark the western Free State. Deep red and yellow sandy loam soils are characteristic of this region. In the northern parts of the Western Free State, a soil water table is often present.

Table 4.2 Annual rainfall for the Free State (FS) localities (January to December).

Trial site	Long term annual average rainfall (mm)	Annual Rainfall (mm) (January – December)		
		1997	1998	1999
Western FS				
Bultfontein (BS & BO)	480.4			368.2
Hebron (HB)	506.6	433.5	658.1	
Hennenman (HM)	626.9	693.0	620.9	416.8
Wesselsbron (WB)	467.8			365.5
Central FS				
Excelsior (EX)	565.6		547.0	
Kroonstad (KS)	622.0	563.4		
Ladybrand (LB)	672.8	621.5	844.7	380.2
Senekal (SK)	627.0			500.0
Eastern FS				
Clarens (CL)	721.0	736.3		
Clocolan (CC)	695.3		711.8	
Ficksburg (FB)	744.0	773.5		
Frankfort (FF)	723.0		786.6	

4.2.3 Experiment and cultivation practices

Wheat was planted on residual soil moisture, with the planting date ranging from late in April to the end of July. Trials were planted according to a randomised complete block design with four replicates. Trial plots consisted of five rows, five meters in length, each with an inter row spacing of 45 centimetres. The spacing of five centimetres between seeds was maintained by means of a precision planter. This gives a seeding rate of approximately 16 kg ha^{-1}, depending on the seed thousand kernel weight.

To sample the wide range of cultivars effectively, two independently randomised trials were planted at each test site, at a three week interval in the western and central regions and at a four week interval in the eastern Free State. The first planting date for localities in the western Free State was the last week in April, central Free State localities were planted during the third week in May and the first planting in the eastern Free State took place in the third week of June of each year. The second planting date was the third week in May (western Free State), second week in June and the third week in July for the central and eastern Free State, respectively.

All trials were fertilised with a 3:2:1(25) N.P.K. mixture that was applied at planting, according to the long-term yield potential of the area. Fertiliser was applied at a rate of 150 kg ha^{-1} in the western and central Free State, with 250 kg ha^{-1} in the eastern Free State. The high potential sites in the western Free State, Bultfontein and Wesselsbron (on soil water table) also received 250 kg ha^{-1}. Prior to planting, all the seed were chemically treated for smut diseases (Vitavax Plus®) and the early infestation by Russian wheat aphid (Gaucho®). Mechanical and chemical weed control (Harmony Super®) was performed when necessary. No plant disease control, with the exception of stripe rust control during 1998, was conducted.

Harvesting of all trials was done with a Wintersteiger plot harvester. Each sample was air dried, without heating, to prevent rising in temperature of cultivars that might be harvested at moisture contents above 13% during the storage period. Material was cleaned with a Charter Dockage Tester before determination of all the quality parameters.

4.2.4 Quality analysis

Quality evaluation included test weight (TW), thousand kernel weight (TKW), kernel diameter (DIAM), kernel hardness (HI), moisture content (MOIST), vitreous kernel (VK), break flour yield (BFLY), flour extraction (FLY), flour colour (FCL) and flour protein content (FPC) determination. Methods of determining each of these quality characteristics were discussed under 3.2.2.1 to 3.2.2.8, in Chapter 3.

4.2.5 Statistical analysis

All statistical analyses were performed, using the AGROBASE 20 (Agrobase, 1999) computer programme. The AMMI analysis of variance was performed on the combined data for the three years, where every locality by year combination was treated as a separate environment.

The genetic variance for genotype (σ_g^2) and their interaction with the environment (σ_{GXE}^2) were calculated. These variance components were expressed as a ratio (σ_g^2 / σ_{GXE}^2) to reveal the magnitude of the genetic effects in relation to the GXE interaction. This was done by the method similar to the one used by Peterson *et al.* (1986) and Van Lill *et al.* (1995a). A ratio larger than 1.0 indicates greater influence and stability of the genetic factors of the cultivars relative to the variability associated with GXE interaction. The higher the ratio, the higher the stability of the genotype and the less it is influenced by the environment.

Stability analysis was calculated and presented in a graphical form, the AMMI biplot. These IPCA 1 stability scores were compared to the AMMI stability value (ASV) as suggested by Purchase (1997).

This ASV was calculated as follow:

$$ASV = \sqrt{\frac{SS\ IPCA\ 1}{SS\ IPCA\ 2}(IPCA\ 1)^2 + (IPCA2)^2}$$

Where, ASV=AMMI stability value, SS= sum of squares, IPCA 1 = interaction of principal component analysis one, IPCA2 = interaction of principal component analysis two.

4.3 RESULTS AND DISCUSSION

4.3.1 AMMI analysis and biplots

From Tables 4.3 and 4.4, it is evident that genotype, environment and their interaction (GXE) contributed significantly to the variation in most measured quality traits. Only for moisture content, genotypes did not contribute significantly to the variation (Table 4.3). In the ANOVA, performed on the material planted at the first planting date (Table 4.3) the contribution of genotype, environment and GXE interaction to the variation in all quality attributes, were significant at $P<0.01$, except for genotype's contribution to vitreous kernels, that was significant at a $P<0.05$ level. Evaluation of the second planting date (Table 4.4) revealed the same significant level ($P<0.01$) for nine of the quality characters, only this time the genotype contribution for flour protein content was significant at a $P<0.05$. This indicates that genotypes performed differently, that there were varying growth conditions among the localities and the presence of GXE interaction between the cultivars and their environments, for all parameters at both planting dates, except for moisture content at the first planting date.

4.3.1.1 Test weight

The AMMI analysis of variance of the first planting date reveals significant variance for all three major components. The environment contributed 57.3% to the total variation in test weight, 8.3% was from genotypes and 26.4% from GXE interaction. The variance due to genotype to interaction ratio was 0.265 (Table 4.5), indicating larger interaction effects with the environment. The IPCA 1 axis (Figure 4.1) explained 61.2% of this GXE. Almost the same tendency is observed for the second planting date. Contributions to variation were distributed as follows: 54.7% from environments, 9.5% from genotypes and 25.4% was caused by the interaction between cultivars and the growth environment. The variance due to genotype to interaction ratio was 0.350, again indicating larger interaction effects. For this planting, the IPCA 1 interpreted 56.34% of the interaction (Figure 4.2).

This is in agreement with the results of other research, where large environmental effects on TW were noted for hard red winter and spring wheat in South Africa and other countries (Baenziger *et al.*, 1985; Peterson *et al.*, 1992; Van Lill *et al.*, 1995a; Nel *et al.*, 1998; Mamuya, 2000). The percentage contribution of the GXE interaction to the total variation of the first planting date, correlates very well with the 9.85% found by Van Deventer (1986) for winter wheat in the Free State.

Figures 4.1 and 4.2 indicate the AMMI biplots for TW of the first and second planting, respectively. No distinct groups of environments could be defined, but it appears as if the eastern Free State localities resulted in lower TW values. It might be due to the relatively higher rainfall and lower temperatures, resulting in endosperm with lower densities that affects test weight in the eastern Free State.

From the IPCA scores it is evident that Molen and Gariep (first planting date) and SST 972, Gariep, Betta-DN and PAN 3235 (second planting date) were very stable for TW over environments (Tables 4.6 and 4.7). SST 367, SST 966 (Table 4.6 and Figure 4.1) Limpopo, Caledon, and SST 124's TW (Table 4.7 and Figure 4.2) fluctuated over a wide range and showed considerable interaction for TW over environments. Molen, the Tugela-types, Tugela-DN, PAN 3349 and the hybrids, SST 966 and SST 972 resulted in much lower TW values than the so-called Betta-types: SST 367, Betta-DN, Gariep, Caledon, Limpopo, PAN 3235, Elands and SST 124.

TW between 76 and 80 kg hl^{-1} are considered as high quality and are required by South African millers. The minimum requirement with cultivar release is set at 76 kg hl^{-1}. Since TW is an

important kernel characteristic in predicting FLY before actual milling, caution should be taken in choosing growth environments for production of optimal TW.

4.3.1.2 Thousand kernel weight

In the study of TKW at the first planting date, most of the variation was caused by the environment (59.8%), variation in genotypes was responsible for 26.4% and the interaction contributed a further 9.2%. The variance ratio of the genotype to interaction was 3.19 (Table 4.5), indicating that the genotype played a larger role than the interaction component. Analysis of the second planting date revealed the same results, environment contributed 54.2%, genotypes 28.7% and the interaction 12% to the total variation in TKW. The variance ratio (2.625) in Table 4.5 of cultivar to interaction again indicated that TKW was primarily determined genetically.

Findings agree with those of Van Lill and Smith (1997) and Pomeranz and Mattern (1988), who indicated that TKW is one of the milling characters strongly influenced by the environment.

Figures 4.3 and 4.4 indicate the AMMI biplots for TKW of the two planting dates, in which the IPCA 1 score explained 66% and 76% of the GXE interaction respectively for the two planting dates. Interaction patterns are identifiable for environments, the eastern Free State localities, with relative higher rainfall and lower temperatures, 98CC, 98FF, 97CL and 97FB revealed higher TKW at first (Figure 4.3) and second (Figure 4.4) planting dates. The harsh environments of the western Free State (98HM, 99HM, 97HM, 99BS, 99BO, 99WB, 97HB and 98HB) produced TKW less than the average at both planting dates, with the exception of Hennenman and Hebron during 1998 (98HM, 98HB) at the second planting date. The central Free State environment's TKW (99SK, 98EX, 98 and 99LB) formed a group between the western and eastern Free State for TKW. This is in accordance with the climatic conditions of the areas, more available moisture and lower temperatures of the eastern and central Free State favoured the development of plump, heavier kernels. At the second planting date, 98HM and 98HB associated better with the central Free State environments (98EX, 98LB, 99SK and 99LB). This may be due to higher than normal rainfall during the grain filling period at these two localities. At both planting dates, 97LB and 97KS reacted in a similar manner as the western Free State localities, this might be due to unfavourable conditions (high temperatures and low precipitation) in the after-anthesis period.

Figure 4.3 and the IPCA 1 scores in Table 4.6 indicate that Tugela-DN and the hybrid SST 966 are specifically adapted to high and moderately favourable conditions for TKW. Table 4.7 and

Table 4.3 Combined AMMI analysis of variance for quality measurements of the cultivars planted at the first planting date.

SOURCE	df	MEAN SQUARES									
		TW	TKW	DIAM	HI	MOIST	VK	BFLY	FLY	FCL	FPC
Total	305										
Environments	16	29.826 **	185.555 **	0.393 **	1503.1 **	14.78 **	2020.54 **	43.896 **	39.407 **	7.257 **	13.401 **
Reps within Env	34	0.589	1.572	0.004	13.868	0.026	82.198	0.906	0.536	0.559	2.297
Genotype	5	13.855 **	261.643 **	0.709 **	999.981 **	0.332	317.055 *	201.123 **	18.803 **	12.978 **	6.393 **
GXE	80	2.746 **	5.73 **	0.014 **	42.047 **	0.151 **	113.708 **	2.651 **	2.51 **	1.556 **	1.569 **
IPCA 1	20	5.439 **	10.152 **	0.023 **	86.678 **	0.35 **	192.889 **	3.975 **	5.236 **	3.288 **	2.496 **
IPCA 2	18	3.828 **	5.754 **	0.014 **	42.576 **	0.175 **	160.68 **	3.426 **	3.122 **	1.429 **	1.37 **
IPCA Residual	42	1.000	3.614	0.004	20.567	0.046	55.871	1.689	0.950	0.786	1.213
Residual	170	0.278	1.016		6.068	0.011	56.088	0.709	0.502	0.329	0.666

**Significant at P<0.01, *Significant at P<0.05, TW=Test weight, TKW=Thousand kernel weight, DIAM=Diameter, HI=Hardness index, MOIST=moisture content, VK= Vitreous kernels, BFLY=Break flour yield, FLY=Flour yield, FCL=Flour colour, FPC=Flour protein content.

Table 4.4 Combined AMMI analysis of variance for quality measurements of the cultivars planted at the second planting date.

SOURCE	df	MEAN SQUARES									
		TW	TKW	DIAM	HI	MOIST	VK	BFLY	FLY	FCL	FPC
Total	539										
Environments	17	75.221 **	323.864 **	0.653 **	1879.284 **	18.655 **	1744.679 **	46.115 **	44.401 **	22.408 **	25.795 **
Reps within Env	36	1.619	2.674	0.009	4.846	0.029	48.520	0.753	0.663	0.799	1.466
Genotype	9	24.772 **	324.715 **	0.798 **	1787.786 **	0.441 **	852.663 **	205.541 **	26.445 **	15.106 **	2.895 *
GXE	153	3.886 **	7.994 **	0.016 **	14.783 **	0.104 **	115.129 **	2.950 **	2.123 **	1.811 **	1.470 **
IPCA 1	25	7.504 **	24.178 **	0.051 **	24.627 **	0.225 **	267.660 **	8.856 **	4.984 **	5.095 **	2.842 **
IPCA 2	23	6.321 **	8.322 **	0.016 **	25.153 **	0.162 **	156.509 **	3.421 **	3.108 **	2.106 **	2.409 **
IPCA Residual	105	2.491	4.069		10.168	0.062	69.748	1.440	1.225	0.965	0.937
Residual	324	0.569	1.293	0.003	5.709	0.021	32.536	0.591	0.496	0.337	0.776

**Significant at P<0.01, *Significant at P<0.05, TW=Test weight, TKW=Thousand kernel weight, DIAM=Diameter, HI=Hardness index, MOIST=moisture content, VK= Vitreous kernels, BFLY=Break flour yield, FLY=Flour yield, FCL=Flour colour, FPC=Flour protein content.

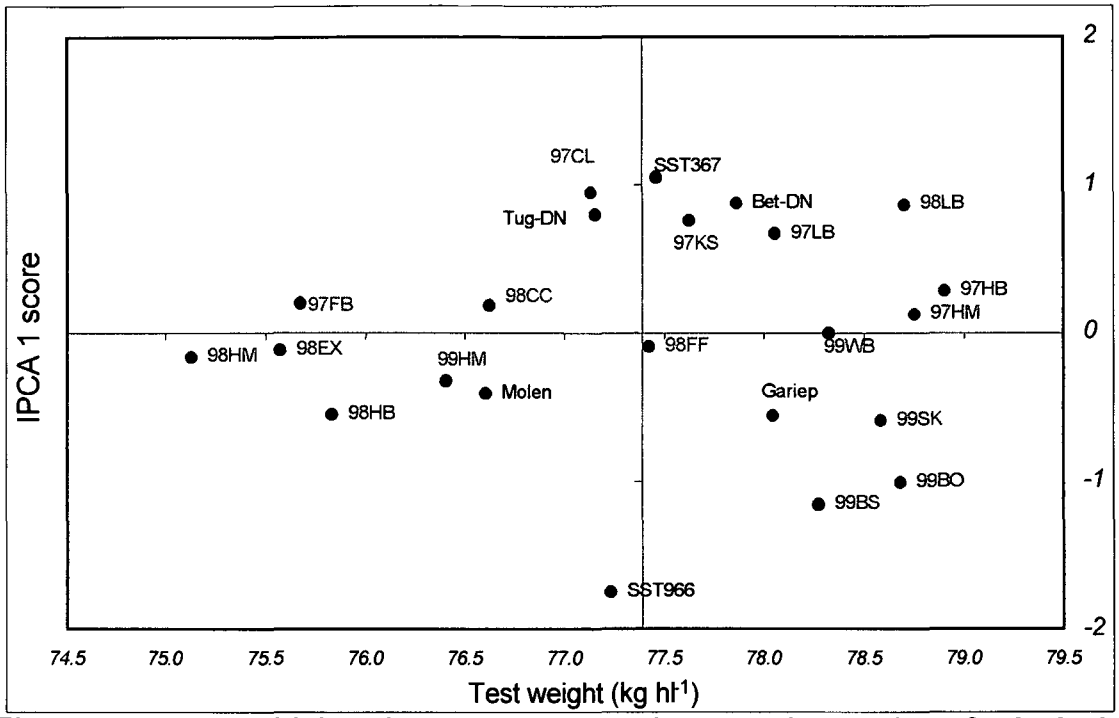

Figure 4.1 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the test weight means for six cultivars and 17 environments.

Cultivars: Bet-DN = Betta-DN, Gariep, Molen, SST 367, SST 966 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL = Clarens, 97FB = Ficksburg, 97KS= Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 9HM=Hennenman, 99SK=Senekal, 99WB=Wesselsbron

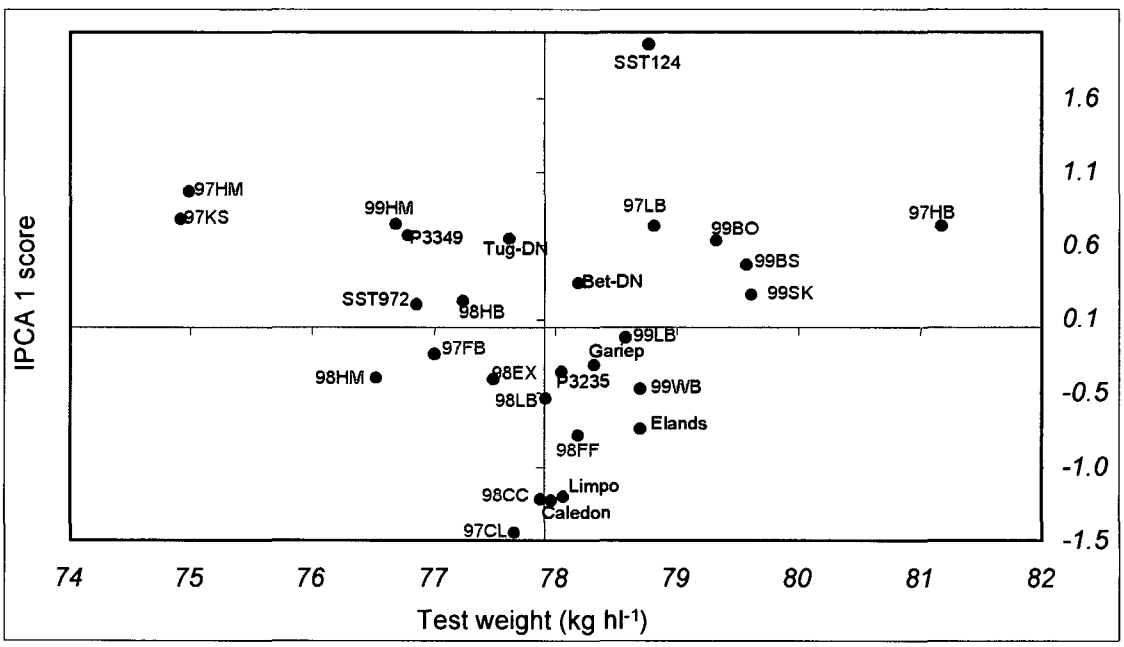

Figure 4.2 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the test weight means for 10 cultivars and 18 environments.

Cultivars: Bet-DN=Betta-DN, Caledon, Elands, Gariep, Limpo=Limpopo, P3235=PAN 3235, P3349=PAN 3349, SST 124, SST 972 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL=Clarens, 97FB=Ficksburg, 97KS=Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 99HM=Hennenman, 99LB=Ladybrand, 99SK=Senekal, 99WB=Wesselsbron

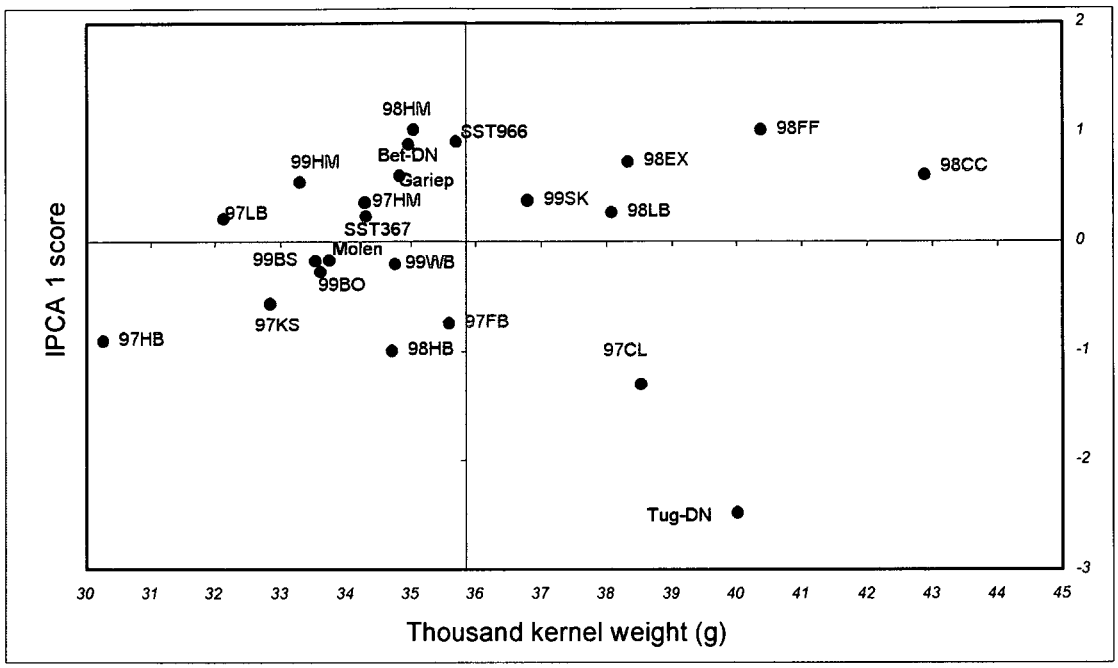

Figure 4.3 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the thousand kernel weight means for six cultivars and 17 environments.

Cultivars: Bet-DN = Betta-DN, Gariep, Molen, SST 367, SST 966 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL = Clarens, 97FB = Ficksburg, 97KS= Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 9HM=Hennenman, 99SK=Senekal, 99WB=Wesselsbron

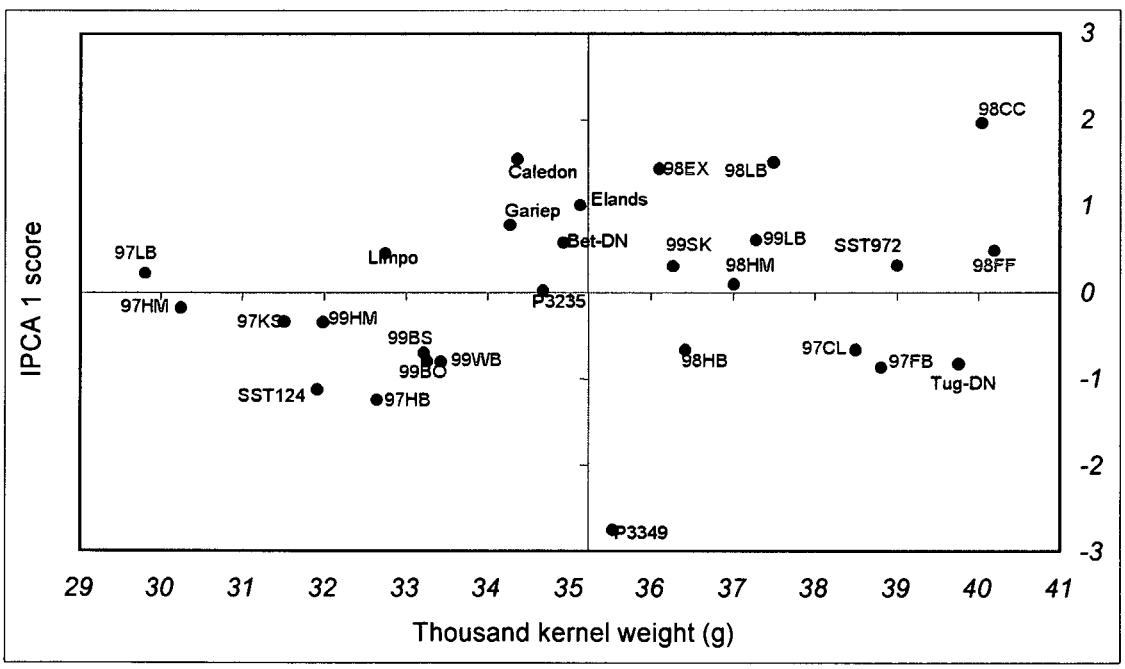

Figure 4.4 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the thousand kernel weight means for 10 cultivars and 18 environments.

Cultivars: Bet-DN=Betta-DN, Caledon, Elands, Gariep, Limpo=Limpopo, P3235=PAN 3235, P3349=PAN 3349, SST 124, SST 972 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL=Clarens, 97FB=Ficksburg, 97KS=Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 99HM=Hennenman, 99LB=Ladybrand, 99SK=Senekal, 99WB=Wesselsbron

Figure 4.4 confirm this tendency, where the hybrid SST 972, Tugela-DN and PAN 3349 (a Tugela type) are adapted to high potential environments. These cultivars, with the exception of ST 972, were also very unstable for TKW. Gariep, Betta-DN, Limpopo, PAN 3235, SST 367 and Molen (Figures 4.3 and 4.4) were stable with regard to TKW over environments. It is evident that Caledon, Elands and SST 124 were very unstable. PAN 3349 was the most unstable for TKW.

At the time of cultivar release, the wheat technical committee of South Africa recommends a TKW of 36-40g. TKW gives an indication of the amount and density of endosperm and is thus, jointly with TW, a kernel character indicative of FLY.

4.3.1.3 Kernel diameter

From the AMMI ANOVA's for DIAM it is evident that the main effects contributed more to the variation in DIAM than the GXE interaction, 53.9 and 50.8% from environments, 30.4 and 32.9% for the genotypes compared to the 9.3 and 11.0% contributions of the interaction component at the two respective planting dates. As for kernel weight, the magnitudes of ratios of the variance components, genotype and GXE interaction, is more than one (Table 4.5), reflecting the larger effect of genotype in comparison with the interaction effect for both planting dates. The same tendency in variance components contribution were observed by Mamuya (2000) on irrigated spring wheat during the 1997 growing season, the contributions were 45.7% for environment, 28.2% and 4.9% for genotype and interaction respectively. Hazen and Ward (1997) found the opposite, in their study GXE had a large influence on DIAM.

The biplots for DIAM at the first and second planting date revealed 65.7% and 77.5% of the interaction component, respectively. Since TKW and DIAM is highly correlated, it is not strange that the same tendencies and groupings are observed from DIAM AMMI biplots (figures 4.5 and 4.6) than from the TKW biplots 4.2 and 4.3. The eastern Free State, on average, resulted in the largest kernels and the central and western Free State averaged smaller kernels. Again, 97LB, 97KS, 98HM and 98HB reacted differently than the other environments in their region. The localities 97KS and 97LB produced lower and 98HM and 98HB larger DIAM values than the other localities of their respective regions.

At the first planting date (Fig. 4.5) all the cultivars, with the exception of Tugela-DN, are grouped together around the average mean DIAM of 2.48 mm. Tugela-DN had larger kernels than the other cultivars. The average DIAM of 2.46 mm at the second planting date indicates that the planting date had no influence on the DIAM. The cultivars in the second planting date form two distinct groupings. The Tugela-types namely Tugela-DN, SST 972 and PAN 3349, with larger than

average kernels and the Betta-types (SST 124, Elands. PAN 3235, Caledon Gariep, Limpopo and Betta-DN) grouped together between DIAMs of 2.3 mm and 2.4 mm.

The endosperm content is influenced by photosynthetic rates and grain filling periods and is revealed in DIAM. The DIAM gives an indication of kernel plumpness and is associated with TW and TKW.

4.3.1.4 Kernel hardness

The percentage environmental contributions to the variation in HI were 70.9% for the first and 61.1% for the second planting date. Cultivars contributed 14.7 and 30.8% and the interaction 9.9 and 4.3% to the variation of this kernel parameter, at the respective planting dates. The AMMI biplots (Figures 4.7 and 4.8) captured 69.3 and 51.6% of this interaction component respectively.

The large ratio values (1.566 and 10.854) of the variance components (genotype/GXE interaction) in Table 4.5 imply greater genotypic effect than interaction effect of variance components.

The most important factor affecting HI is genotypes (Hazen and Ward, 1997), but growing environment is just as important (Anjum and Walker, 1991; Monsalve-Gonzalez and Pomeranz, 1993; Morris *et al.*, 1999), growing season, protein content, moisture, kernel size and the bran also affect kernel hardness. Therefore significant variation of HI due to both cultivar and environmental effects should be expected (Hazen and Ward, 1997).

The mentioned AMMI biplots for HI represent the following observations: The environments of the eastern Free State, 97CC, 97CL, 98FF and 97FB, with the exception of 97CL in the second planting date, had HI of lower than the average mean of 65.3 and 69.6 at the two respective planting dates. The other environments with HI values below the averages were 98EX, 98HB, 98HM, 97KS (only second planting date) 99SK and 99HM. During 1998, the HI at Hebron were extremely high at both planting dates. High temperatures and low rainfall in this area might be the cause of this. Grain exposed to warm, dry climates during the filling periods tends to be harder in texture (Bergman *et al.*, 1998). The western Free State localities, 97HB, 97HM, 99BO, 99BS, 99HB and central Free State localities, Ladybrand (99LB, 98LB and 97LB) and Senekal (99SK) might be considered as environments producing high HI values at earlier and second planting dates. Kroonstad (97KS) expressed very hard indexes at the first planting date, but reflected softer indexes for the second planting date.

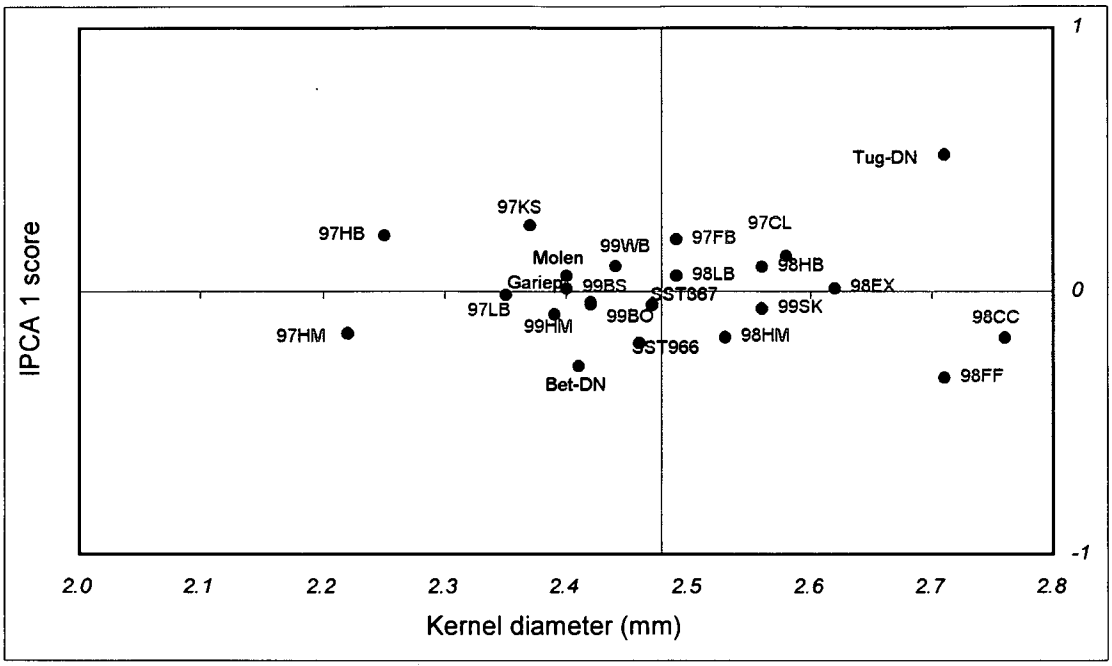

Figure 4.5 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the Kernel diameter means for six cultivars and 17 environments.

Cultivars: Bet-DN = Betta-DN, Gariep, Molen, SST 367, SST 966 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL = Clarens, 97FB = Ficksburg, 97KS= Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 9HM=Hennenman, 99SK=Senekal, 99WB=Wesselsbron

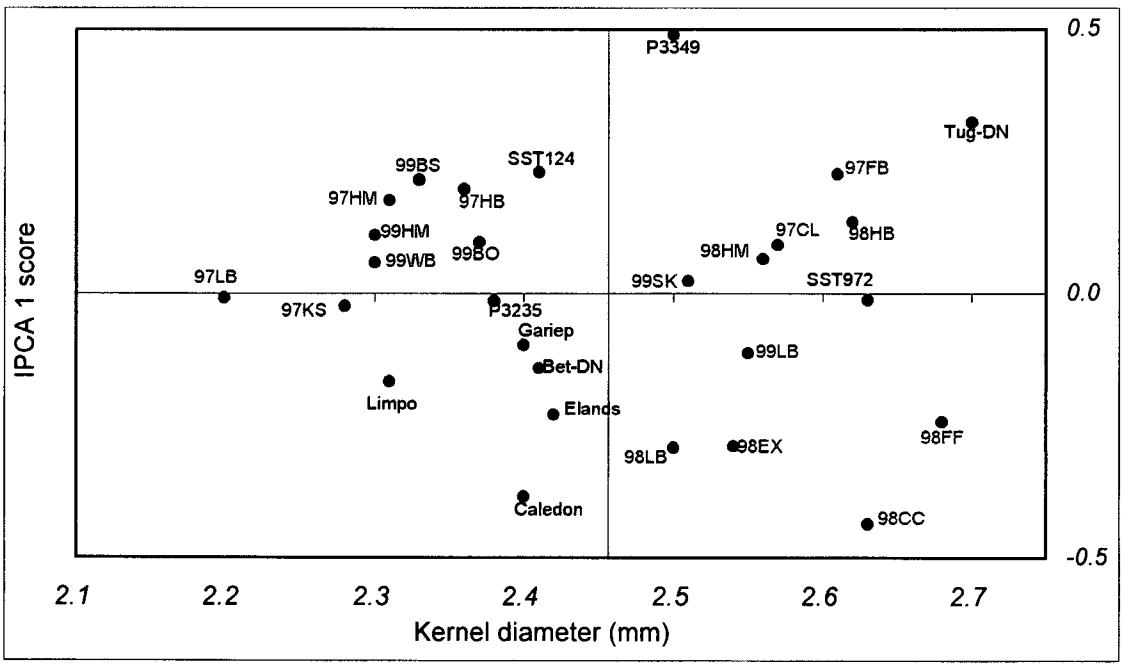

Figure 4.6 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the kernel diameter means for 10 cultivars and 18 environments.

Cultivars: Bet-DN=Betta-DN, Caledon, Elands, Gariep, Limpo=Limpopo, P3235=PAN 3235, P3349=PAN 3349, SST 124, SST 972 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL=Clarens, 97FB=Ficksburg, 97KS=Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 99HM=Hennenman, 99LB=Ladybrand, 99SK=Senekal, 99WB=Wesselsbron

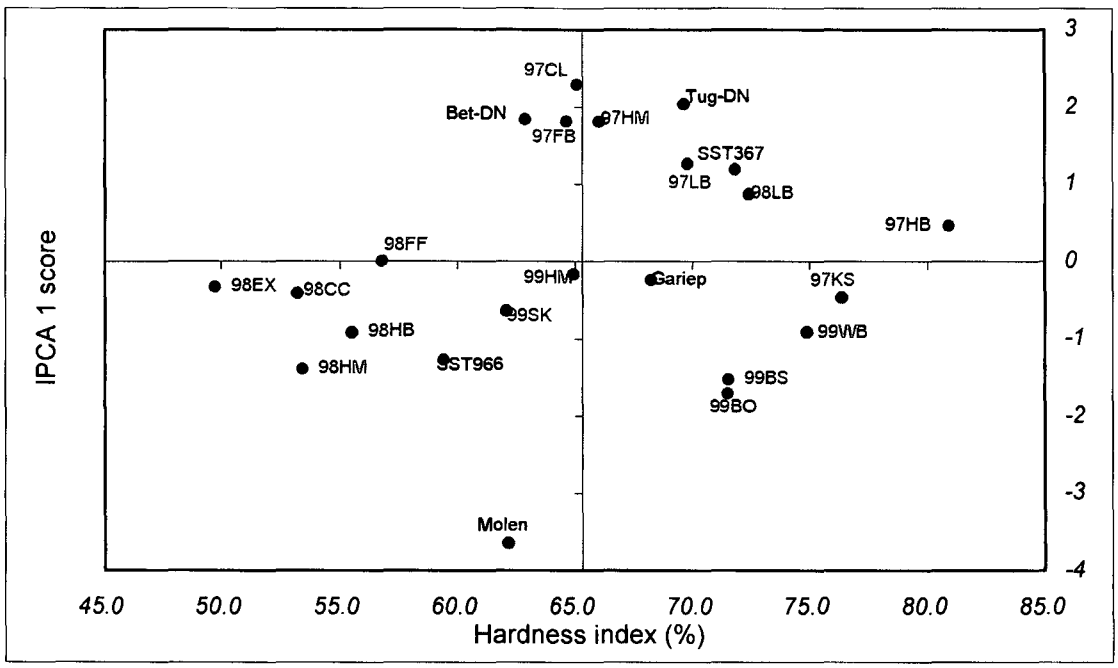

Figure 4.7 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the kernel hardness index means for six cultivars and 17 environments.

Cultivars: Bet-DN = Betta-DN, Gariep, Molen, SST 367, SST 966 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL = Clarens, 97FB = Ficksburg, 97KS= Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 9HM=Hennenman, 99SK=Senekal, 99WB=Wesselsbron

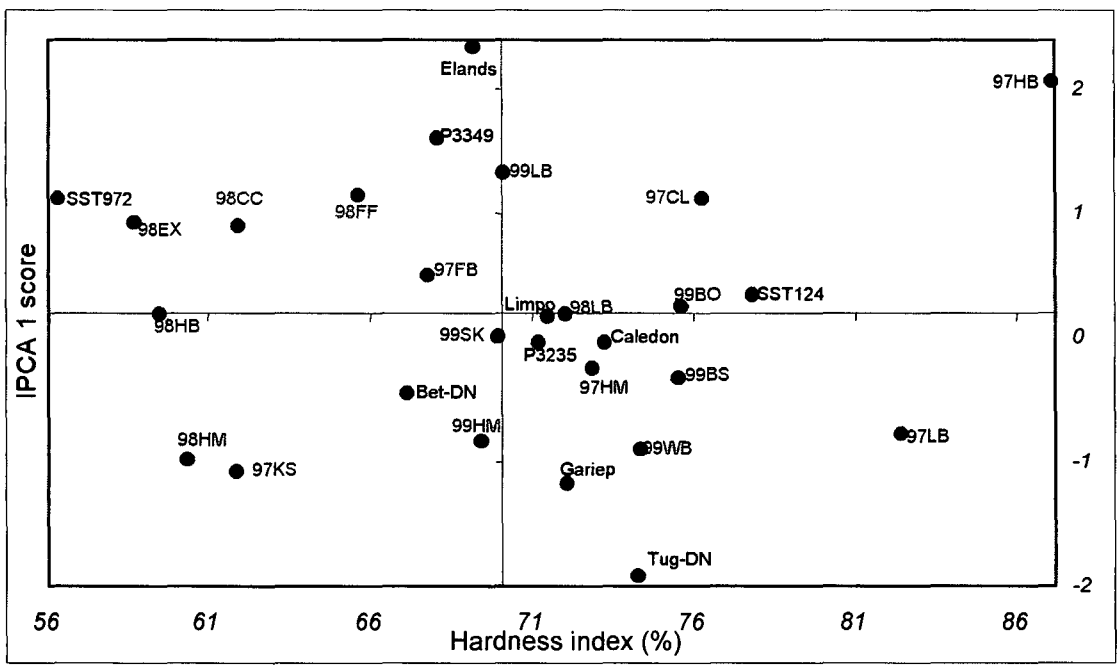

Figure 4.8 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the kernel hardness index for 10 cultivars and 18 environments.

Cultivars: Bet-DN=Betta-DN, Caledon, Elands, Gariep, Limpo=Limpopo, P3235=PAN 3235, P3349=PAN 3349, SST 124, SST 972 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL=Clarens, 97FB=Ficksburg, 97KS=Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 99HM=Hennenman, 99LB=Ladybrand, 99SK=Senekal, 99WB=Wesselsbron

The two hybrids, SST966 (Figure 4.7) and SST 972 (Figure 4.8) were the softest in kernel texture. All the other cultivars were very hard (indexes ranged between 62-77%) at the first and second planting dates. According to the IPCA 1 scores, Gariep was the only cultivar with stable HI values over the range of environments at the first planting date (Figure 4.7 and Table 4.6). The IPCA 1 scores of Limpopo, SST 124, Caledon, PAN 3235 and to a lesser extent that of Betta-DN, revealed stability towards HI in the second planting (Figure 4.8 and Table 4.7). This time Gariep as well as Tugela-DN (as in the first planting), Elands, PAN 3349, and SST 972 were very unstable for the hardness parameter.

Table 4.5 Ratios of variance components estimated for cultivars and their interaction for kernel and milling characteristics.

	Variance ratios: Genotype/(GXE interaction)									
	TW	TKW	DIAM	HI	MOIST	VK	BFLY	FLY	FCL	FPC
First planting	0.265	3.194	4.670	1.566	0.085	0.208	6.010	0.476	0.548	0.316
Second planting	0.350	2.625	3.500	10.854	0.214	0.496	4.773	0.830	0.500	0.113

4.3.1.5 Moisture content

MOIST of individual kernels was determined for each cultivar. The analyses indicated that the environment is by far the largest contributor to variation in MOIST, 93.5 and 92% of the total sum of squares. Genotype did not play a significant role in the variation at the first planting date, and contributed only 1.15% to the variation at the second planting date. The interaction's contribution was 4.8 and 4.6% for the respective planting dates and of this, the IPCA 1 scores of AMMI biplots (Figures 4.9 and 4.10) captured 68.9 and 60.14%.

Figure 4.9 indicates that for most environments grain MOIST was between 10 and 12%. Only 1998 Hebron, Hennenman and Excelsior had contents of less than 10% (9.5%, 9.2% and 9.6%). Ficksburg, 1997 and Wesselsbron, 1999 had contents of above the average, around 12%. The second planting date (Figure 4.10) revealed almost the same tendencies: 1998 Hebron, Hennenman and Excelsior had MOIST of less than 10% and this time only 99WB had a MOIST of 12.1%

The MOIST AMMI biplot indicated that all cultivars were stable and within the narrow range of 10.9 to 11.0% (Figures 4.9 and 4.10) around the averages of 10.97 and 11.02 of the two respective planting dates. According to the IPCA 1 scores (Tables 4.6 and 4.7), all the cultivars had stable MOIST. This is clearly in line with the fact that the MOIST of grain samples was not determined immediately after harvesting, but the grain was air-dried to prevent the risk of temperature rising to cause heat damage and mould development while in storage.

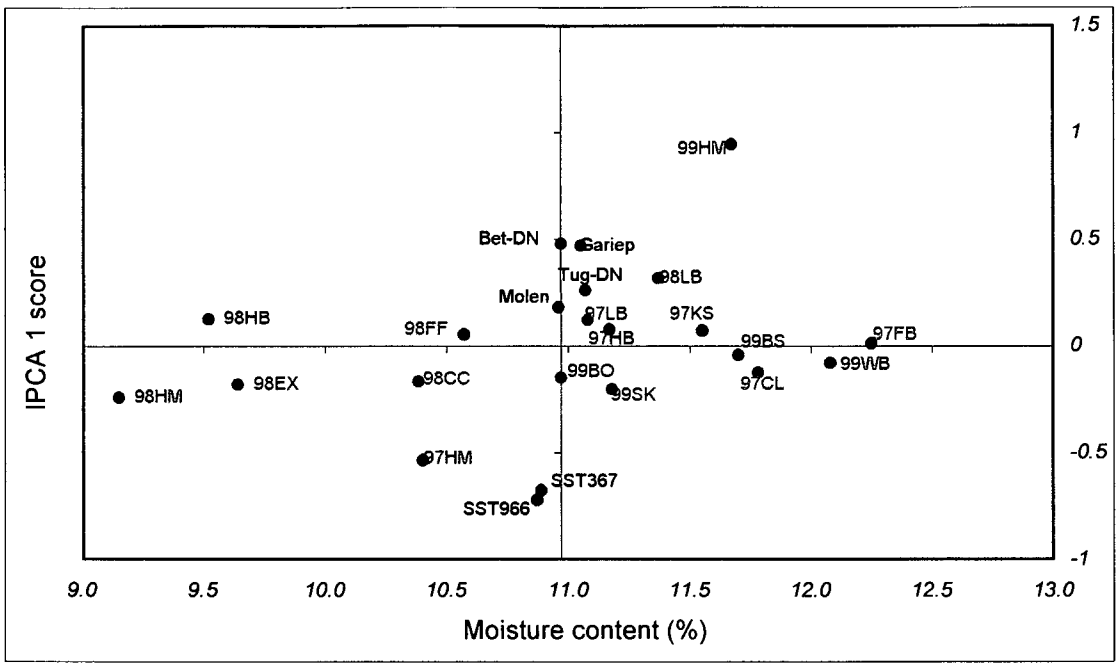

Figure 4.9 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the moisture content means for six cultivars and 17 environments.

Cultivars: Bet-DN = Betta-DN, Gariep, Molen, SST 367, SST 966 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL = Clarens, 97FB = Ficksburg, 97KS= Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 9HM=Hennenman, 99SK=Senekal, 99WB=Wesselsbron

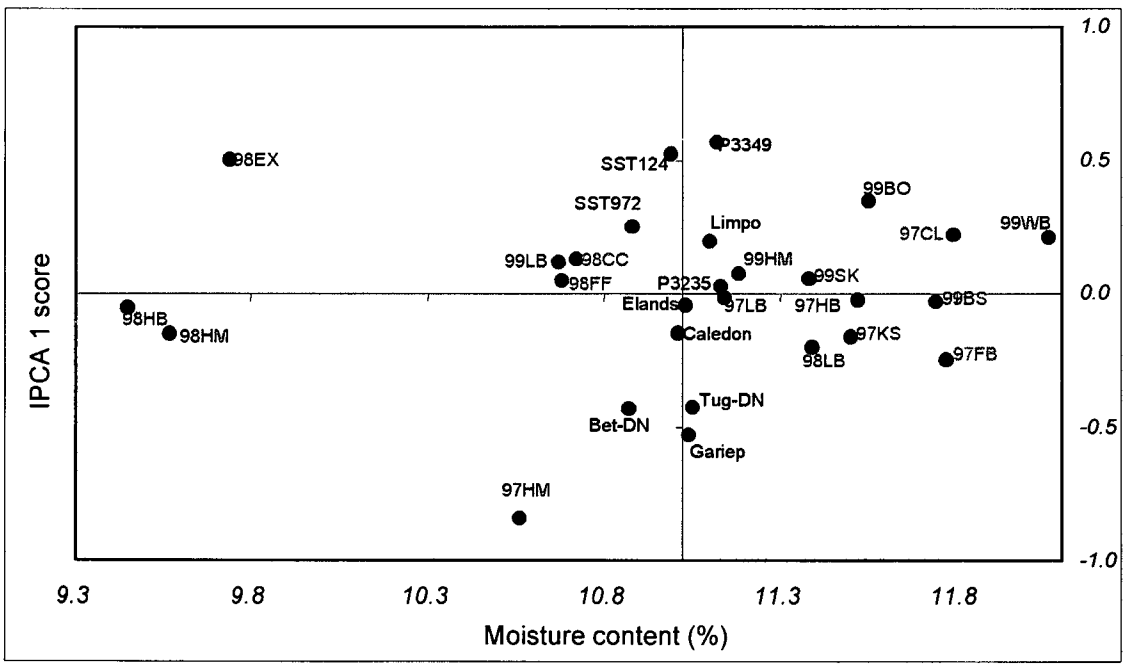

Figure 4.10 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the moisture content means for 10 cultivars and 18 environments.

Cultivars: Bet-DN=Betta-DN, Caledon, Elands, Gariep, Limpo=Limpopo, P3235=PAN 3235, P3349=PAN 3349, SST 124, SST 972 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL=Clarens, 97FB=Ficksburg, 97KS=Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 99HM=Hennenman, 99LB=Ladybrand, 99SK=Senekal, 99WB=Wesselsbron

4.3.1.6 Vitreous kernels

In the study of the percentage VK at the first planting date, most of the variation was due to environmental effects (58.4% of the sum of squares), variation in genotypes was responsible only for 2.9% and the interaction contributed a high 16.4%. The variance ratio of the genotype to interaction were 0.208 (Table 4.5), indicating that the interaction component played a much larger role than the genetic component. Analysis of the second planting date revealed the same contribution tendency, environment contributed 44.11%, genotypes 11.4% and the interaction 26.2% to the total variation in VK. The variance ratio (0.496) of cultivar to interaction again indicated that VK was highly influenced by the environmental interaction with cultivars.

VK was also among the milling characteristics that were highly susceptible to environmental effects, as reported by Van Lill and Smith (1997). Hoseney (1987) and Pomeranz and Williams (1990) also stated that vitreousness is largely determined and influenced by environmental conditions.

Figure 4.11 reveals that localities 98LB, 97KS, 99BO 99WB, 99BS, 97HM and 97HB resulted in environments with a high percentage VK. The percentage VK of 99HM, 97SK, 97LB, 97CL and 97FB were around 66%. The localities 98HM, 98CC, 98EX, 98FF and 98HB had less percentage VK, that of 98HM being only 48.3%. At the second planting date (Figure 4.12) 97LB, 99SK, 97CL, 99BO, 99WB, 99BS and 97HB had very high values. 98CC, 98LB, 99LB, 97KS and 99HM were around the average of 71% VK. The localities 98FF, 97FB, 98HM, 97HM and 98HB had relatively lower VK with that of 98EX the lowest at 54.9%.

Figures 4.11 and 4.12 indicate the AMMI biplots for VK of the two planting dates, in which the IPCA 1 score explained 57% and 65% of the above mentioned GXE interaction respectively for the two planting dates. The mean VK of cultivars planted at the first planting date was between 62.3 and 69.7% over all environments. Table 4.6 indicates instable percentage VK for all six cultivars (SST 966, Molen, SST 367, Betta-DN, Gariep and Tugela-DN), indicating high interaction with the environment. At the second planting date (Figure 4.12), some of the cultivars indicated higher stability to vitreousness, Gariep, Limpopo, Caledon, Elands, PAN 3235 and PAN 3349 had relatively stable VK over environments, but Betta-DN, Tugela-DN, SST 124 and SST 972 were inconsistent in percentage VK.

VK determination focuses on the percentage kernels that appear to be hard. Even within a soft wheat cultivar, a percentage of kernels might appear to be hard (Hoseney, 1987).

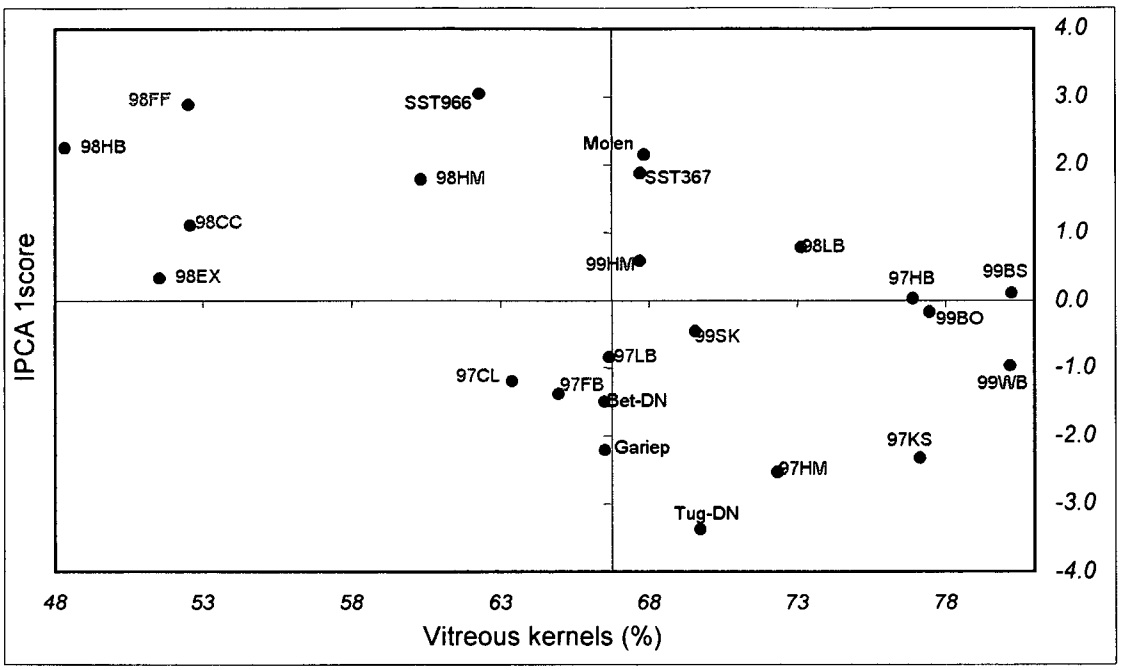

Figure 4.11 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the percentage vitreous kernels means for six cultivars and 17 environments.

Cultivars: Bet-DN = Betta-DN, Gariep, Molen, SST 367, SST 966 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL = Clarens, 97FB = Ficksburg, 97KS= Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 9HM=Hennenman, 99SK=Senekal, 99WB=Wesselsbron

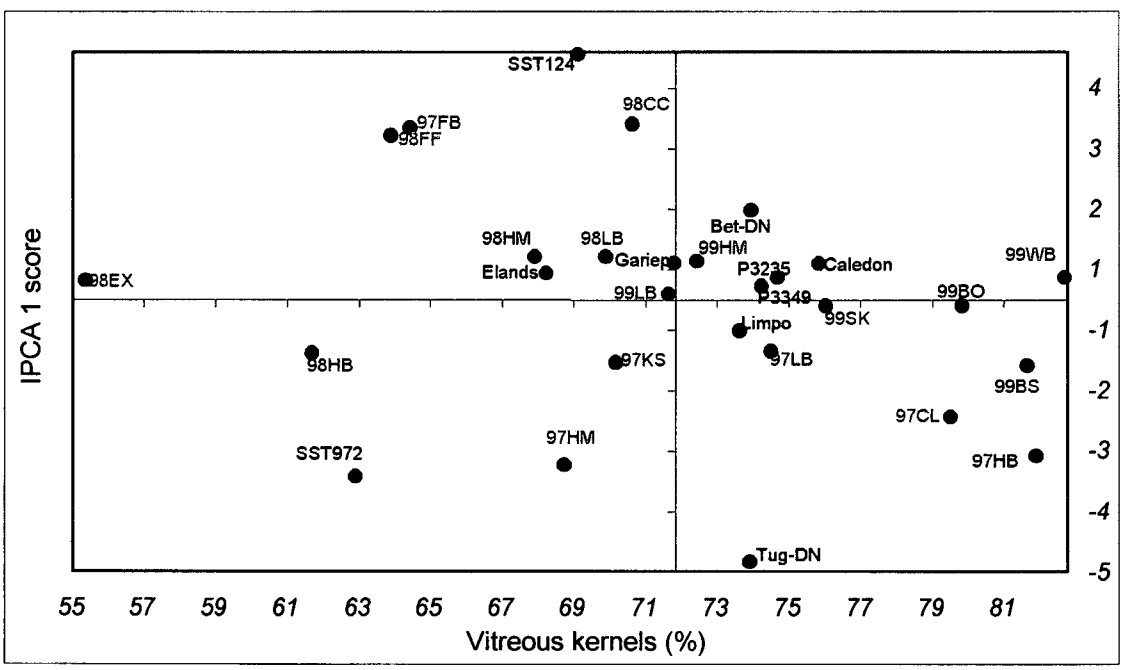

Figure 4.12 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the percentage vitreous kernels means for 10 cultivars and 18 environments.

Cultivars: Bet-DN=Betta-DN, Caledon, Elands, Gariep, Limpo=Limpopo, P3235=PAN 3235, P3349=PAN 3349, SST 124, SST 972 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL=Clarens, 97FB=Ficksburg, 97KS=Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 99HM=Hennenman, 99LB=Ladybrand, 99SK=Senekal, 99WB=Wesselsbron

4.3.1.7 Break flour yield

The AMMI analysis of variance of the first planting date, reveals significant variance for all three major components. Environments were responsible for 33.9%, genotypes for 48.6% and the GXE interaction for 10.2% of the variation in BFLY. The biplot (Figure 4.13) explained 56.3% of the observed interaction. The genotype to interaction variance ratio was 6.01, indicating that BFLY is primarily genetically determined. The same tendency is observed for the second planting date. Contributions to variation were distributed as follows: 23.7% from environments, 56% from genotypes and 13.7% were caused by the interaction between cultivars and the growth environment. The genotype to interaction variance ratio was 4.77 (Table 4.5), again indicating larger genotypic effects. For this planting the IPCA 1 interpreted 73.8% of the mentioned interaction. The results support the findings of Mamuya (2000) that BFLY is genetically controlled, but are in contrast with Van Lill and Smith (1997) that found BFLY to be largely affected by environmental effects.

Figure 4.13 and 4.14 indicate the AMMI biplots for BFLY of the first and second planting dates respectively. In the biplot of the first planting date's cultivars, a BFLY of less than the average of 24.4 was observed at 99BO, 99BS, 99WB, 99SK, 98LB, 97HM and 97KS. All these were characterised as hard environments, by the HI evaluation, and thus underline the negative correlation that exists between HI and BFLY. The localities 97KS, 97HB and 97CL had a BFLY of around the grand mean of 24.4. The following localities had a BFLY higher than 25: 97LB, 97FB, 98FF, 99HM, 98HB, 98HM, 98EX and 99CC. Of these, 98HB, 98HM, 98EX, 98CC and 98FF were also the localities producing grain of softer texture, again indicating the negative correlation between HI and BFLY. Environments of the second planting date formed two distinct groupings: those with above average (24.5) BFLY were 97HM, 97KS, 98EX, 98HB, 98HM, 99HM and 99WB. The BFLY of all the other localities were between 23 and 24.4, this included the eastern Free State localities (98FF, 98CC, 97CL, 97 FB) and Ladybrand 97, 98, 99, 97HB, 99BS, 99BO.

Figure 4.13 indicates that the cultivars Gariep, Betta-DN, SST 966 and Molen had a BFLY above 24. Tugela-DN with a BFLY of 21 and SST 367 at 23.7 were the two cultivars with the lowest BFLY and were also the two hardest cultivars in the first planting date. SST 966 had the softest kernel texture, but this was not reflected in its BFLY. At the second planting date Tugela-DN, SST 124 and SST 972 had a BFLY of less than 23. PAN 3349 had a BFLY around 24 and all other cultivars were between 25.5 and 26.7.

The major genetic contribution to variation in BFLY can be explained by the relationship between BFLY and grain hardness (also genetically controlled, Pomeranz *et al.*, 1985). BFLY and HI are

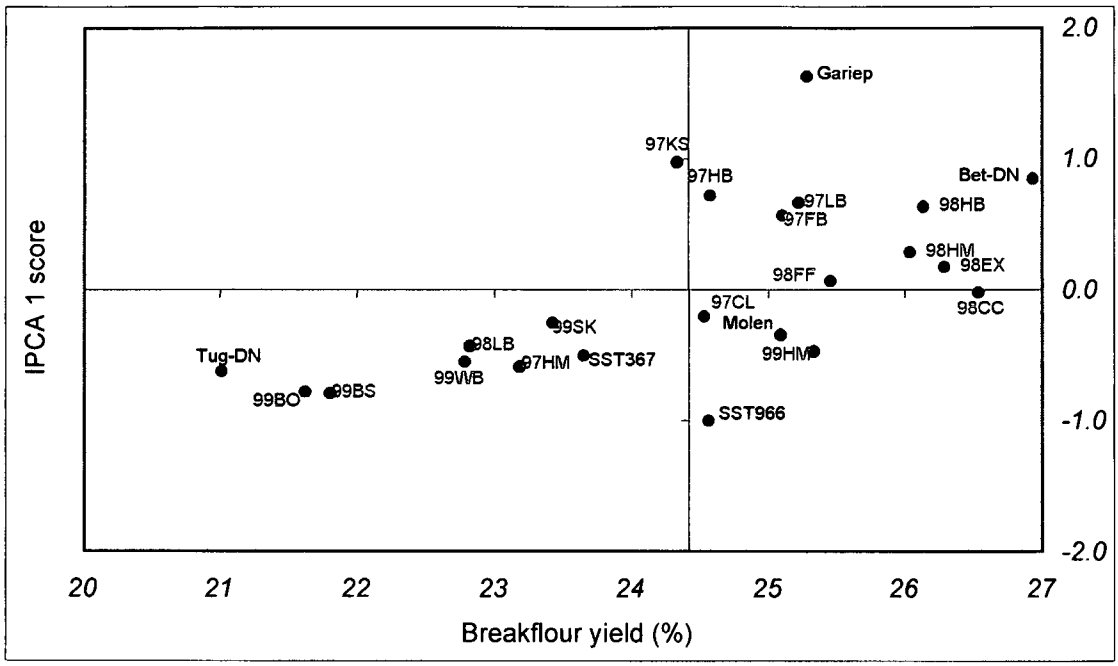

Figure 4.13 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the break flour yield means for six cultivars and 17 environments.

Cultivars: Bet-DN = Betta-DN, Gariep, Molen, SST 367, SST 966 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL = Clarens, 97FB = Ficksburg, 97KS= Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 9HM=Hennenman, 99SK=Senekal, 99WB=Wesselsbron

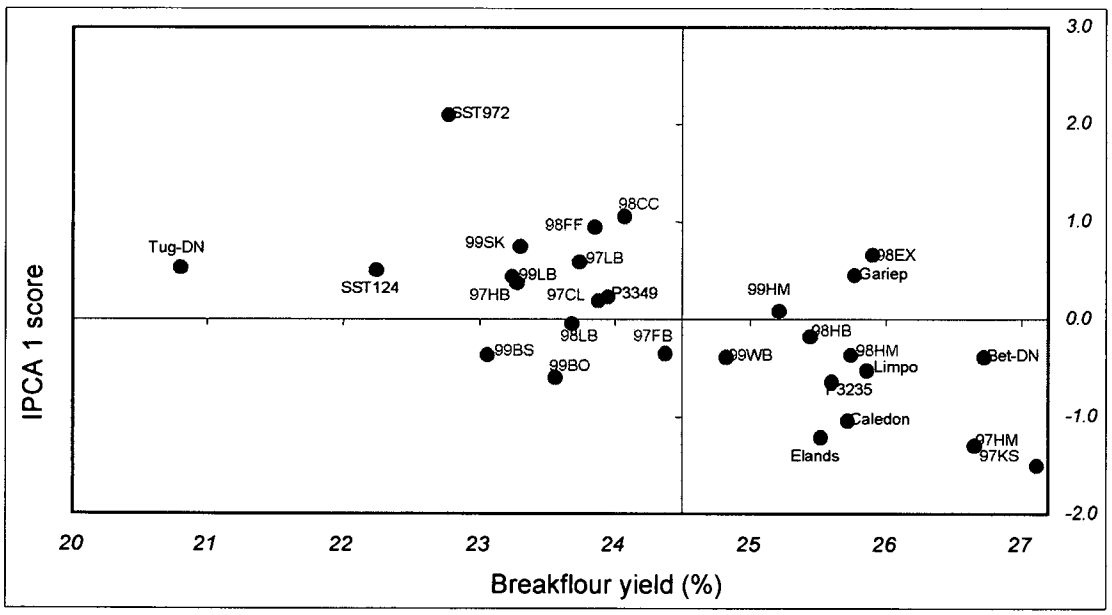

Figure 4.14 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the break flour yield means for 10 cultivars and 18 environments.

Cultivars: Bet-DN=Betta-DN, Caledon, Elands, Gariep, Limpo=Limpopo, P3235=PAN 3235, P3349=PAN 3349, SST 124, SST 972 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL=Clarens, 97FB=Ficksburg, 97KS=Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 99HM=Hennenman, 99LB=Ladybrand, 99SK=Senekal, 99WB=Wesselsbron

negatively correlated (Yamazaki and Donelson, 1983). This reveals why the wheat technical committee makes use of BFLY to judge the HI of a cultivar at release.

4.3.1.8 Flour yield

The AMMI ANOVA results of the first planting date indicate a high contribution of environments to the total variation in FLY (61.3%), followed by GXE interaction (19.5%) and genotype (9.1%). The IPCA 1 axis captured 65% of the mentioned GXE interaction. At the second planting date, the percentage contribution to variation were in the same order: environment 50.3%, GXE interaction 21.6% and genotypes 15.8% of the total sum of squares. The IPCA 1 axis explained 63.6% of the interaction component. This is in agreement with Nel *et al.* (1998) and Van Lill and Smith (1997) who reported FLY of spring and winter wheat in their respective studies, were highly sensitive to environmental effects. It is in contradictory to Mamuya (2000) and Collaku *et al.* (2002) who found genotypes to be the main contributor to variation in FLY.

The ratio values (0.476 and 0.83) of the variance components (genotype/ GXE interaction) is less than one and resembles greater interaction than main genetic variance components. Mamuya (2000) also observed high interaction contribution for the 1998 season on South African irrigation wheat cultivars. Significant GXE interaction was observed by Bhatt and Derera (1975) as well.

In the AMMI biplot (Figures 4.15 and 4.16) the percentage FLY of all cultivars ranged between 74.7 and 76.4, all close to the average of 75.5. According to the IPCA 1 scores only, Molen, Gariep and SST 367 had very stable FLY over environments of the first planting date (Table 4.6). SST 966, Tugela-DN and to a lesser extent Betta-DN revealed tremendous interaction and instability over environments. At the second planting date, all cultivars with the exception of SST 972 and SST 124, fell within 0.75% around the grand mean of a 75.95% extraction rate. SST 972 had the lowest and SST 124 the highest FLY over environments. At this planting date, all cultivars except the hybrid SST 972, Tugela-DN and Gariep, were stable with regard to FLY (Table 4.7).

By investigation of the first planting date environments, all localities except 98LB, 98EX, 98HM, and 98HB had extraction rates between 74.2 and 76.5%. The FLY at 98LB was very low and instable, averaging only 71.4%. High rainfall after ripening, delaying the harvesting process, might explain this. Weathering could affect kernel density and eventually, FLY (Czarneck and Evans, 1986). Other kernel characteristics (DIAM and TKW) were not affected, only FCL values were higher at this environment. Excellent flour extractions, that exceeded 77%, were produced at the localities 98EX, 98HM and 98HB. At the second planting date, most environments had flour extractions of between 74.8 and 76.6%. The FLY of 98EX (77.2%), 98HB (77.9%), 98HM (77.9%)

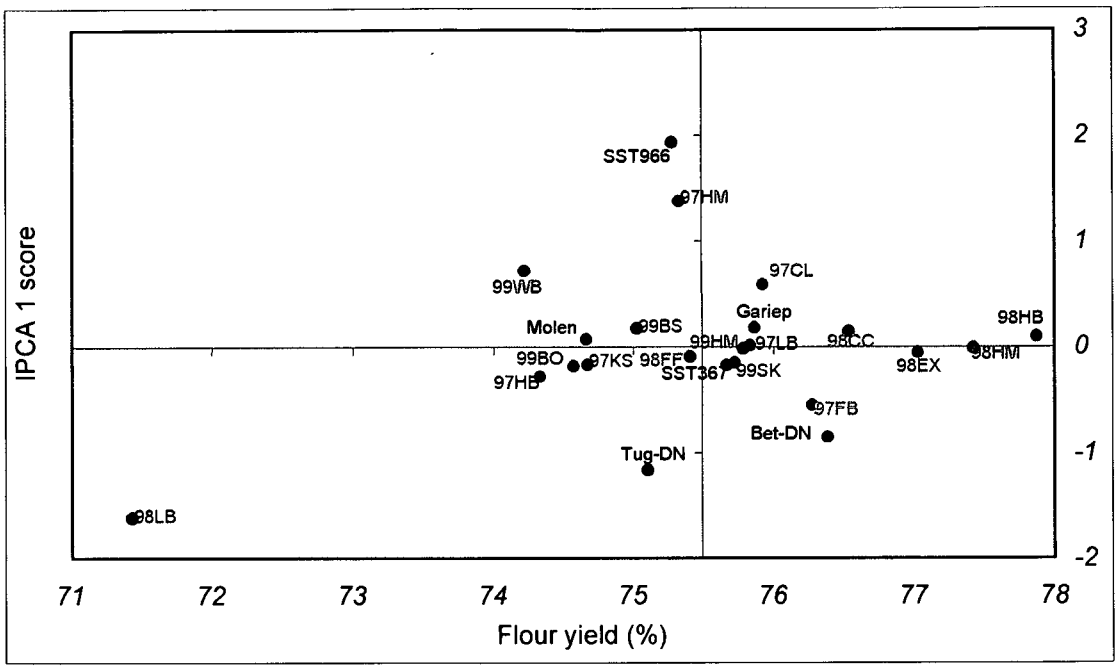

Figure 4.15 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the flour yield means for six cultivars and 17 environments.

Cultivars: Bet-DN = Betta-DN, Gariep, Molen, SST 367, SST 966 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL = Clarens, 97FB = Ficksburg, 97KS= Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 9HM=Hennenman, 99SK=Senekal, 99WB=Wesselsbron

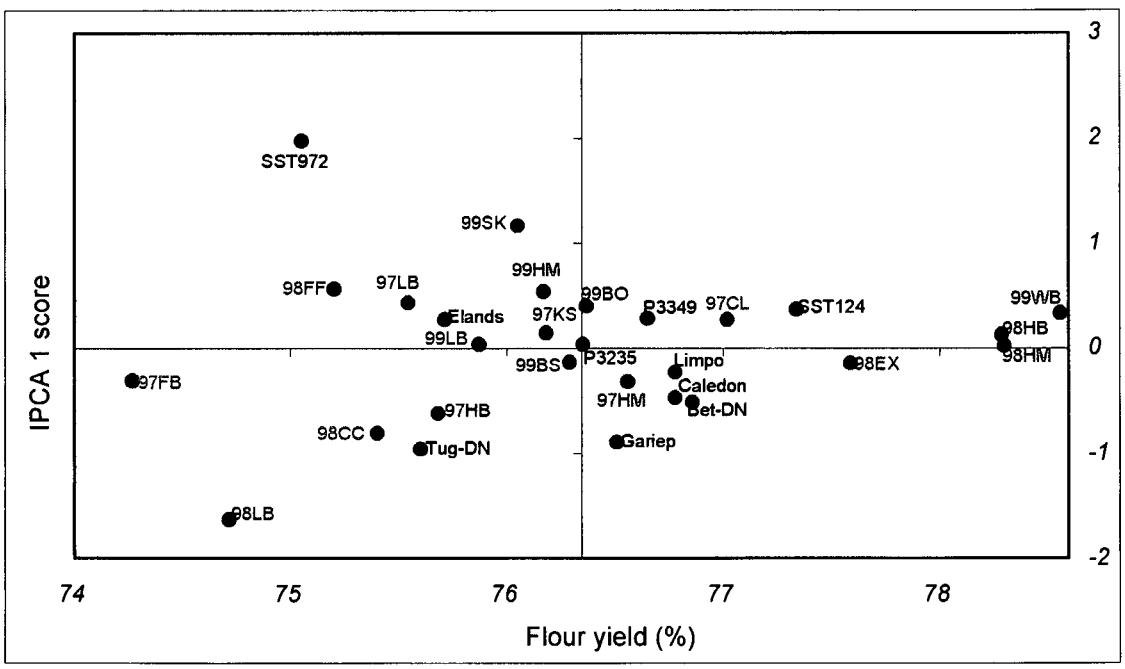

Figure 4.16 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the flour yield means for 10 cultivars and 18 environments.

Cultivars: Bet-DN=Betta-DN, Caledon, Elands, Gariep, Limpo=Limpopo, P3235=PAN 3235, P3349=PAN 3349, SST 124, SST 972 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL=Clarens, 97FB=Ficksburg, 97KS=Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 99HM=Hennenman, 99LB=Ladybrand, 99SK=Senekal, 99WB=Wesselsbron

and 99WB (78.2%) were excellent. Localities with a FLY of less than 74.5% were 97FB (73.9%) and 98LB (74.3%).

High flour extraction rates are of the most important quality trait to millers. The minimum for cultivar release in South Africa is 76% FLY.

4.3.1.9 Flour colour

The percentage environmental contributions to the total variation in FCL was 30.5% for the first and 40.9% for the second planting date. Cultivars contributed 17.1% and 14.6% to the variation in FCL, at the respective planting dates. The interaction was high, 32.7 and 29.7% at the first and second planting date respectively, the interaction component even dominates the environmental contribution. The AMMI biplots (Figures 4.17 and 4.18) respectively captured 71.9 and 72.5% of this very high interaction component.

The magnitudes of ratios of the variance components, genotype to GXE interaction, are less than one, reflecting the larger effect of the GXE interaction in comparison to the cultivar effect for both planting dates (Table 4.5).

Van Lill and Smith (1997) also found environmental contribution to variation in FCL to be high, the high interaction component was also evident in the work done by Mamuya (2000). Environmental effects that might be the reason for darkened FCL values are frost damage, immature harvested kernels and black point in wheat kernels (Bass, 1988). Particles of bran, dark millstreams and flour extraction rate might also influence FCL.

The AMMI biplots for FCL are presented in Figures 4.17 and 4.18. Lower FCL values indicate whiter FCL and in South Africa values between -3.0 and 2.5 are desirable for cultivar release. All cultivars delivered excellent FCL values at both planting dates. At the first planting date, Betta-DN and Gariep were the best and most stable cultivars, SST 966 produced good colour values, but were unstable over environments. At the second planting date SST 124, Caledon, Limpopo, Gariep and Betta-DN revealed very good FCL over environments. The FCL of Tugela-DN (both planting dates), PAN 3349 and SST 972 were very unstable over environments.

The only localities with mean FCL values above 2.0 were 97CL and 97HB at the first planting date and 97CL, 97FB and 98HM at the second planting date.

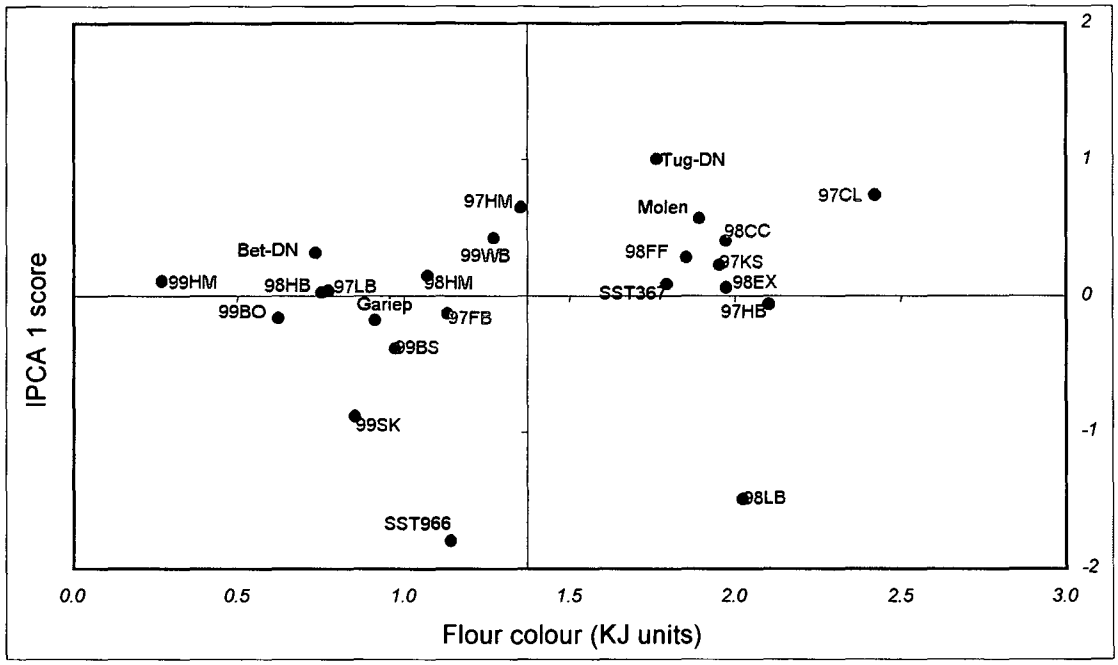

Figure 4.17 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the flour colour means for six cultivars and 17 environments.

Cultivars: Bet-DN = Betta-DN, Gariep, Molen, SST 367, SST 966 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL = Clarens, 97FB = Ficksburg, 97KS= Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 9HM=Hennenman, 99SK=Senekal, 99WB=Wesselsbron

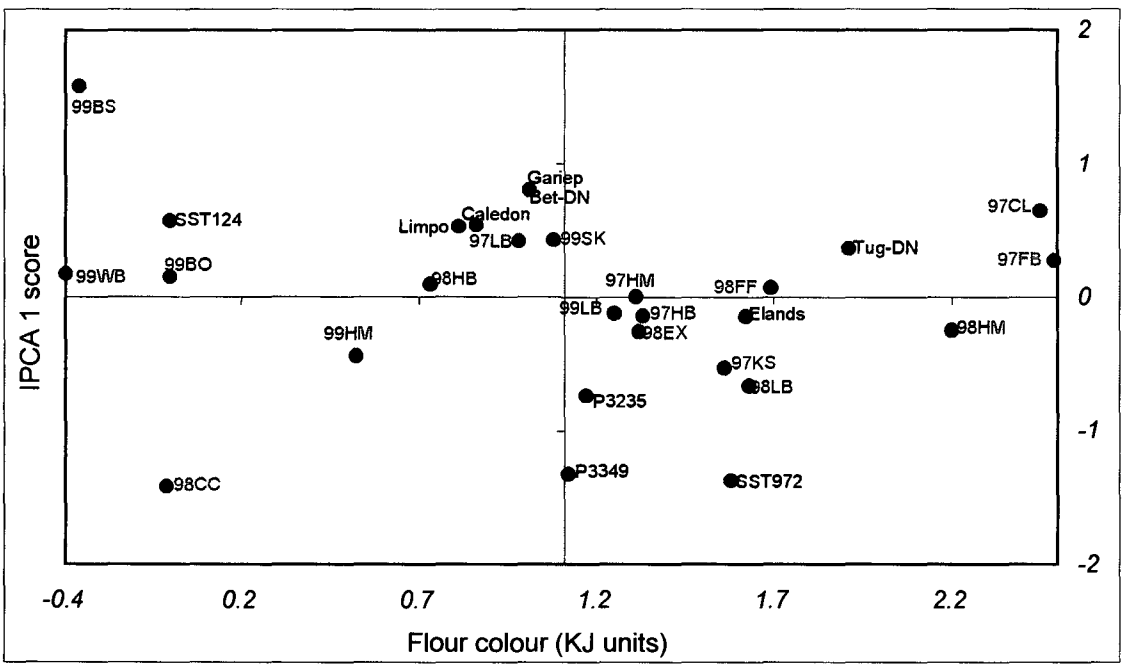

Figure 4.18 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the flour colour means for 10 cultivars and 18 environments.

Cultivars: Bet-DN=Betta-DN, Caledon, Elands, Gariep, Limpo=Limpopo, P3235=PAN 3235, P3349=PAN 3349, SST 124, SST 972 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL=Clarens, 97FB=Ficksburg, 97KS=Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 99HM=Hennenman, 99LB=Ladybrand, 99SK=Senekal, 99WB=Wesselsbron

4.3.1.10 Flour protein content

The AMMI analysis of variance at the first planting date reveals significant variance for all three major components. The environment was responsible for 38.1%, genotypes for 5.7% and the GXE interaction for 22.3% of the variation in FPC. The genotype to interaction variance ratio was 0.316 (Table 4.5), indicating larger interaction effects with the environment. The IPCA 1 axis (Figure 4.19) explained 66.9% of this GXE interaction. Almost the same tendency is observed for the second planting date, only the genotype contribution was even less. Contributions to variation were distributed as follows: 44.1% from environments, 2.6% from genotypes and 22.6% were caused by the interaction between cultivars and growing environment. The genotype to interaction variance ratio was 0.113 (Table 4.5), again indicating larger interaction effects. For this planting date, the IPCA 1 (Figure 4.20) accounted for 56.2% of the mentioned interaction. It is evident that the environment and its interaction to cultivars mainly affect protein content. This is confirmed by Pomeranz *et al.* (1985), Peterson *et al.*(1992) and Van Lill *et al.* (1995 a & b). Gaines (1991) found that the year, locality, cultivation practices, environmental and climatic conditions had tremendous effects on protein content. Bhatt and Derera (1975) also observed a significant GXE interaction for flour protein content.

As Figure 4.19 indicates, the first planting date produced FPC levels that ranged between 12% and 12.8%, all around the average of 12.4%. According to the IPCA 1 scores (Figure 4.19 and Table 4.6), Molen, Betta-DN and SST 367 were very stable in FPC over environments. Tugela-DN, Gariep and to a larger extent, SST 966, were very unstable for FPC. The second planting date cultivars (Figure 4.20) were all ± 0.4% around the average mean of 13% FPC and very stable. Instability was only observed for SST 972 and to a lesser extent for PAN 3349, Gariep and Elands (Figure 4.20 and Table 4.7).

As for the cultivars, most of the FPC of environments was centred around the average between 12 and 13%. Localities with FPC of less than 12%, were 98FB, 99BS, 99HM and 99BO. Those above 13% were 97CL, 97HB, and 97KS (Figure 4.19). In Figure 4.20, the localities 98EX and 97LB had FPC lower than 12%. The environments 98HB, 97CL, 97KS, 97FB, 98HM and 97HM had high FPC, above 13.7%.

FPC is one of the most important quality traits in wheat and flour trade. In the baking industries, protein content affects the mixing and fermentation quality of the dough.

Wheat producers need to pay attention to grain protein content and need to use nitrogen fertilisers to help maintain consistent quality in hard red winter wheat production (Lyon and Shelton, 1999).

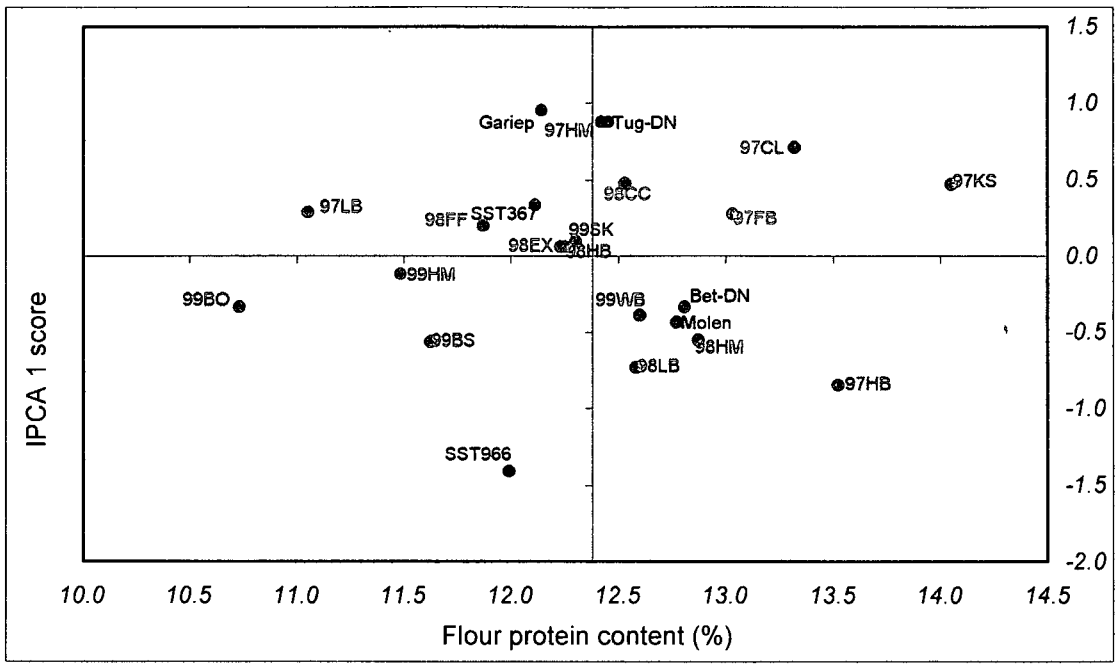

Figure 4.19 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the flour protein content means for six cultivars and 17 environments.

Cultivars: Bet-DN = Betta-DN, Gariep, Molen, SST 367, SST 966 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL = Clarens, 97FB = Ficksburg, 97KS= Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 9HM=Hennenman, 99SK=Senekal, 99WB=Wesselsbron

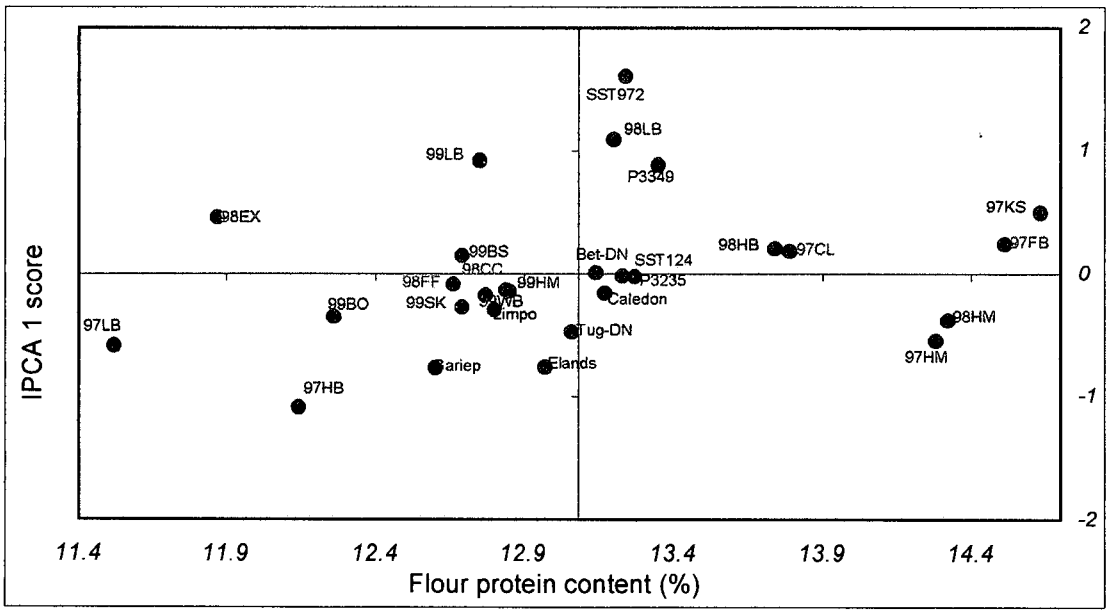

Figure 4.20 AMMI biplot of genotype and environment interaction of principal component analysis one (IPCA 1) scores plotted against the flour protein content means for 10 cultivars and 18 environments.

Cultivars: Bet-DN=Betta-DN, Caledon, Elands, Gariep, Limpo=Limpopo, P3235=PAN 3235, P3349=PAN 3349, SST 124, SST 972 and Tug-DN = Tugela-DN. ***Environments***: ***1997:*** 97CL=Clarens, 97FB=Ficksburg, 97KS=Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. ***1998:*** 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand. ***1999:*** 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 99HM=Hennenman, 99LB=Ladybrand, 99SK=Senekal, 99WB=Wesselsbron

4.3.2 AMMI stability values

Stability of wheat quality characteristics over environments and years is important to the milling and baking industries, whose processing technology requires consistent raw material in order to produce high quality end products.

IPCA 1 scores of a genotype in the AMMI analysis indicate the stability of the genotype over environments. The higher the relative IPCA 1 score (negative or positive) of a certain genotype, the more specifically adapted it is to certain environments. Genotypes are most stable over all environments when the IPCA 1 scores are close to zero. Purchase (1997) indicated that it is important to take not only the IPCA 1 score into consideration, because some genotypes were significantly affected by the IPCA 2 factor. He suggested the use of the AMMI stability value (ASV) formula. With this method, the distance from zero is determined in a two-dimensional scattergram of IPCA 1 scores against IPCA 2 scores (Purchase *et al.*, 2000b).

The AMMI stability values were calculated in the manner proposed by Purchase (1997) and presented in Tables 4.8 and 4.9, respectively, for the first and second planting date cultivars. Tables 4.8 and 4.9 indicate that kernel diameter was the most stable of all the measured characteristics over environments and planting dates. TKW, HI and VK were the most unstable traits, but all other characteristics also revealed high levels of instability at the first planting date. For the second planting date, DIAM and MOIST may be considered the most stable characteristics, FLY and FPC also indicated high stability levels.

If only considering the IPCA 1 scores, Molen was the cultivar most stable for the majority of the measured characteristics, followed by Gariep and then SST 367. SST 966 was the most unstable with regard to all traits, except DIAM. Tugela-DN and SST 966 revealed poor stability for the majority of characteristics, with SST 966 having the weakest stability. The AMMI stability value (ASV) in Table 4.8 confirmed that Molen was the most stable cultivar. Gariep, Betta-DN, SST 367, Tugela-DN and SST 966 were unstable for most of the kernel and milling characteristics, with SST 966 having the lowest stability. According to the ASV, Molen was stable for TW, DIAM, MOIST, BFLY, and FLY. Betta-DN had stable DIAM and FCL and SST 367 was stable for DIAM and FPC. Gariep was stable for DIAM, MOIST and FCL. Tugela-DN had stable DIAM and MOIST and SST 966 was stable only for DIAM values.

For the second planting date, according to the IPCA 1 values in Table 4.7, PAN 3235, followed by Limpopo, were the most stable cultivars, for the majority of kernel and milling traits. The cultivars Betta-DN, SST 124 and Caledon also possessed high stability values. SST 972 and Gariep had the poorest stability. With calculation of the ASV (Table 4.9), PAN 3235 again was prominent as

the most stable cultivar, followed by Limpopo. Gariep and SST 972 were again, with determination of the ASV, the most unstable cultivars. PAN 3235 had stable values for TW, TKW, DIAM, HI, MOIST, VK, FLY and FPC. Limpopo for the kernel characteristics DIAM, HI, MOIST and milling traits: FLY, FCL and FPC. Betta-DN was stable for TW, DIAM, MOIST, FLY and FPC. Tugela-DN revealed stability for DIAM, MOIST, BFLY, FCL and FPC. SST 124 had stable DIAM, MOIST, BFLY, FLY and FCL values and Caledon for DIAM, HI, MOIST, FLY and FPC. Elands's stability was for TW, DIAM, MOIST, FCL and FPC. PAN 3349 showed stability towards DIAM, MOIST, VK and FLY. Gariep was stable only for DIAM MOIST and FPC and SST 972 for TKW, DIAM and MOIST.

4.4 CONCLUSIONS

Cultivars, growth environment and their interaction (GXE) contributed significantly to the variation in kernel characteristics (TW, TKW, DIAM, HI and percentage VK) and the milling quality (BFLY, FCL, and FPC).

Environments were the most important contributor to variance in all traits, with the exception of BFLY. The effect was observed at both planting dates. This clarifies why millers often purchase grain by environment.

BFLY is under strong genetic control. Genotypes also played an important role in the variance of TKW, DIAM and HI. Cultivar choice is thus important for grain and milling quality.

Interaction between genotype and environment had a larger effect on test weight, percentage vitreous kernels, flour yield, flour colour and flour protein content than genotypes. This was true for both planting dates.

Molen was the most stable cultivar at the first planting date. Although this cultivar was removed from the industries preference list, because of its inherent low falling number and short mixing time, its milling characteristics and quality stability is good and should be utilised in breeding programmes. At the second planting date, PAN 3235 and Limpopo were the stable cultivars, the Betta types, Betta-DN, SST 124 and Caledon were also quite stable. These cultivars' milling quality is thus more stable over environments and would be a good choice to producers and millers for reaching their goals in terms of quality grain and flour.

Table 4.6 IPCA 1 scores and rankings for quality measurements of the cultivars planted at the first planting date.

IPCA 1 Scores of cultivars planted at the first planting date																			
	TW	Rank	TKW	Rank	DIAM	Rank	HI	Rank	MOIST	Rank	VK	Rank	BFLY	Rank	FLY	Rank	FCL	Rank	FPC	Rank
Betta-DN	0.870	4	0.888	4	-0.284	5	1.840	4	0.481	4	-1.496	1	0.850	4	-0.850	4	0.314	3	-0.333	1
Gariep	-0.559	2	0.608	3	-0.043	1	-0.239	1	0.472	3	-2.204	4	1.630	6	0.179	3	-0.179	2	0.956	5
Tugela-DN	0.797	3	-2.480	6	0.517	6	2.039	5	0.262	2	-3.369	6	-0.626	3	-1.167	5	1.004	5	0.881	4
SST 367	1.049	5	0.237	2	-0.052	2	1.266	2	-0.675	5	1.875	2	-0.506	2	-0.174	2	0.088	1	0.334	2
SST 966	-1.745	6	0.913	5	-0.197	4	-1.271	3	-0.719	6	3.049	5	-1.001	5	1.938	6	-1.793	6	-1.407	6
Molen	-0.413	1	-0.166	1	0.059	3	-3.636	6	0.181	1	2.145	3	-0.347	1	0.073	1	0.566	4	-0.432	3

Table 4.7 IPCA 1 scores and rankings for quality measurements of the cultivars planted at the second planting date.

IPCA 1 Scores of cultivars planted at the second planting date																			
	TW	Rank	TKW	Rank	DIAM	Rank	HI	Rank	MOIST	Rank	VK	Rank	BFLY	Rank	FLY	Rank	FCL	Rank	FPC	Rank
Betta-DN	0.297	3	0.577	4	-0.141	4	-0.643	5	-0.430	7	1.476	7	-0.391	2	-0.509	7	0.803	8	0.007	1
Gariep	-0.254	2	0.779	5	-0.097	3	-1.368	7	-0.528	9	0.613	6	0.449	3	-0.891	8	0.797	7	-0.768	8
Tugela-DN	0.598	5	-0.827	6	0.325	8	-2.115	9	-0.425	6	-4.329	10	0.527	5	-0.956	9	0.362	2	-0.474	6
SST 124	1.918	10	-1.126	8	0.230	7	0.149	2	0.525	8	4.054	9	0.507	4	0.369	5	0.568	5	-0.019	2
Limpopo	-1.167	8	0.453	3	-0.166	5	-0.026	1	0.198	4	-0.519	4	-0.529	6	-0.225	2	0.535	4	-0.293	5
Caledon	-1.174	9	1.549	9	-0.384	9	-0.236	3	-0.147	3	0.594	5	-1.040	8	-0.465	6	0.525	3	-0.160	4
Elands	-0.690	7	1.013	7	-0.229	6	2.144	10	-0.042	2	0.442	3	-1.211	9	0.272	3	-0.147	1	-0.761	7
PAN 3235	-0.305	4	0.017	1	-0.014	2	-0.237	4	0.028	1	0.369	2	-0.641	7	0.145	1	-0.742	6	-0.023	3
PAN 3349	0.622	6	-2.752	10	0.489	10	1.408	8	0.569	10	0.216	1	0.229	1	0.284	4	-1.326	9	0.885	9
SST 972	0.154	1	0.315	2	-0.012	1	0.924	6	0.251	5	-2.916	8	2.100	10	1.975	10	-1.375	10	1.606	10

Table 4.8 AMMI stability values and rankings of the cultivars planted at the first planting date.

	AMMI STABILITY VALUES																			
	TW	Rank	TKW	Rank	DIAM	Rank	HI	Rank	MOIST	Rank	VK	Rank	BFLY	Rank	FLY	Rank	FCL	Rank	FPC	Rank
Betta-DN	1.550	4	1.385	3	0.404	4	2.811	3	1.062	5	2.032	1	1.234	4	1.281	3	0.581	2	1.252	2
Gariep	1.451	3	1.080	1	0.198	1	1.710	1	0.721	3	2.727	3	1.922	6	1.216	2	0.357	1	1.361	5
Tugela-DN	1.586	5	3.526	6	0.736	6	3.316	5	0.576	2	3.960	4	1.753	5	1.593	4	1.660	5	1.283	3
SST 367	1.341	2	1.712	5	0.209	2	2.719	2	1.032	4	4.276	5	1.164	2	1.621	5	1.224	3	0.554	1
SST966	2.241	6	1.541	4	0.440	5	3.181	4	1.072	6	5.165	6	1.169	3	2.646	6	2.868	6	2.002	6
Molen	0.673	1	1.088	2	0.237	3	5.570	6	0.467	1	2.583	2	0.399	1	0.223	1	1.398	4	1.322	4

Table 4.9 AMMI stability values and rankings of the cultivars planted at the second planting date.

	AMMI STABILITY VALUE																			
	TW	Rank	TKW	Rank	DIAM	Rank	HI	Rank	MOIST	Rank	VK	Rank	BFLY	Rank	FLY	Rank	FCL	Rank	FPC	Rank
Betta-DN	0.612	1	1.053	3	0.262	3	1.477	5	0.532	6	2.132	5	1.115	4	0.933	6	1.311	7	0.485	4
Gariep	1.028	4	1.609	5	0.182	2	1.458	4	0.653	8	0.908	3	1.548	7	1.319	7	1.301	6	0.870	6
Tugela-DN	1.175	6	2.683	8	0.730	8	2.183	8	0.524	5	6.341	9	0.921	2	1.354	8	0.588	2	0.785	5
SST124	2.360	10	2.087	7	0.456	7	1.973	7	0.974	10	6.417	10	0.879	1	0.558	3	0.921	4	1.470	9
Limpopo	1.378	7	1.241	4	0.318	4	0.770	3	0.276	2	1.129	4	1.019	3	0.506	2	0.919	3	0.334	3
Caledon	1.411	9	2.758	9	0.738	9	0.269	1	0.298	3	2.548	6	1.754	8	0.618	5	1.007	5	0.265	2
Elands	0.798	2	1.803	6	0.426	6	2.212	9	0.338	4	3.337	7	2.058	9	1.625	9	0.405	1	0.994	7
PAN3235	0.987	3	0.448	1	0.041	1	0.437	2	0.063	1	0.591	2	1.334	6	0.393	1	1.427	8	0.100	1
PAN3349	1.164	5	4.923	10	0.911	10	1.794	6	0.823	9	0.476	1	1.153	5	0.605	4	2.327	9	1.281	8
SST972	1.388	8	0.850	2	0.329	5	2.683	10	0.537	7	4.024	8	3.546	10	2.750	10	2.659	10	1.986	10

Tugela-DN and PAN 3349 (also a Tugela type) were unstable cultivars. The hybrids SST 966 and SST 972 were the most unstable cultivars over environments with regard to milling quality. These cultivars are high-risk quality cultivars. Their quality is good in specific regions, but they were not adapted over environments. Their cultivation must be managed and restricted to high potential areas in order to reach maximum quality potential.

If the three cultivars Betta-DN, Gariep and Tugela-DN that were planted at both planting dates were compared, the overall kernel and milling quality stability was better at the second planting date. The intermediate growth type of these cultivars might explain this, the cultivars were ripe before the true winter types at the first planting date and were longer on the field. This might have influenced the grain quality.

The cultivar, environment and the GXE interaction play an important role in the milling quality of South African winter and facultative wheat. In future, breeders have to concentrate on quality stability in breeding programmes. The wheat technical committee has to consider stability evaluation during the three years of quality testing before release.

CHAPTER 5

CHARACTERISATION OF SOUTH AFRICAN WINTER WHEAT FOR MILLING PERFORMANCE

5.1 INTRODUCTION

The problem of predicting the milling behaviour of wheat by the use of simple laboratory tests has occupied cereal scientists for many years. Estimates of the overall milling value of a wheat sample may provide a useful guide to the future management of a breeding programme. From a miller's point of view, many factors in addition to flour extraction determine the milling value of wheat. For example, the lower the flour ash and the brighter the flour colour, the more desirable the wheat is for milling (Bass, 1988).

Flour yield is a key bread wheat quality trait, since higher flour yield from a certain amount of wheat means more profit to the miller, but the quality of the flour is just as important as the amount of the flour extracted from the grain.

Flour colour is regarded as one of the major criteria for quality of flour, playing an important role in the control of the flour production process. Flour colour from bran contamination is one of the most obvious effects of the quality characteristics of the flour particles, influenced by the grinding in the reduction action (Posner and Hibbs, 1997). The miller prefers the increase in potential for flour extraction, while maintaining the flour colour. The measurement of brightness (influenced by the dulling effect of bran particles) correlates strongly with ash content and flour extraction (Fowler and Priestley, 1991b; Posner and Hibbs, 1997). Li and Posner (1989) found a linear relationship (r=0.995) between flour colour and flour extraction. This relationship could be used to rank wheat cultivars in terms of colour degradation. A slower increase in flour colour as flour yield is increased, indicates a higher wheat quality.

Ash content of flour is defined as the residue remaining after controlled incineration of the wheat or flour. It is expressed as a percentage of the original sample and represents the mineral content of the flour, individual elements which may exist in various forms in combination with other flour constituents. There is a very high correlation between flour ash and fiber content. It is likely that near-infrared (NIR) calibrations are associated with cellulose components of bran fragments in the flour, rather than with the minerals themselves (AACC, 2000).

Millers use wheat ash as a quality factor to evaluate the product and prefer wheat that will produce low ash flours. The ash itself does not affect flour properties and thus, it can be

argued, that ash content should not be regarded as a flour quality parameter in bakers' specifications. Fowler and De la Roche (1975a) considered the use of flour ash useful as a measure of milling efficiency rather than of wheat quality. Ash values of wheat can be an important tool for the adjustments and control of mills (Posner and Hibbs, 1997).

Wheat has an ash content of about 1.5%. The ash is not distributed evenly in the wheat kernel. The gradient of ash content increases from the centre to the outer layers of the kernel. The inner endosperm is relative low in ash (~0.3%), whereas the bran is higher in ash content and may contain as much as 6%. Therefore ash is a convenient assay for the presence of bran in the flour (Hoseney, 1994). The ash content of flour is correlated with flour colour brightness and provides a rapid means of monitoring the milling process through the assessment of the grade value of flour streams (Fowler and Priestley, 1991b; Oliver *et al.*, 1993). Ash content alone is usually not an overriding quality factor, but when combined with other factors it can be useful in explaining performance (Dick and Matsuo, 1988).

Wheat varies in the amount of ash found in the endosperm, and therefore small variation in ash content does not always imply the presence of different amounts of bran in the flour (Hoseney, 1994). This variability of mineral content can be due to the environment, genetic factors and their interaction (Posner and Hibbs, 1997). Dick and Matsuo (1988) illustrated the genetic differences in ash content found in flour of different wheat classes milled to about 75% extraction. They indicated that flour milled from hard red spring wheat had an ash content of 0.45 to 0.50%, while flour, milled from durum wheat to the same extraction, had an ash content of about 0.75%. A larger proportion of the ash was removed by the debranning of durum and hard red spring wheat cultivars than with soft wheat cultivars. However, the wheat ash content is influenced more by the environment than by the genetic background. Ash appears not to be related to protein content, although a high positive correlation was observed between flour colour and protein content (Preston *et al.,* 1995).

Since the milling performance is a composite value of various factors, experimental millers use various methods to evaluate milling results and to determine the milling performance of the wheat. Bass (1988) and Posner and Hibbs (1997) indicated that milling performance can be evaluated by subtracting the flour colour value from the flour yield: Milling performance = Flour yield – Flour colour. Another method indicates the milling rating, based on the total flour ash where milling rating = flour extraction – (white flour ash x 100) (Bass, 1988), a higher milling rating is preferable. Milling value = (white flour ash)/(flour yield) x100. This value figure is also used in evaluating milling performance. The white flour ash to whole-wheat flour ash ratio was determined for each cultivar to further determine milling performance. When this ratio is related to flour extraction, the lower the ratio, the higher the milling performance, and hence the milling

quality of the wheat (Posner and Hibbs, 1997). Gaines *et al.* (1996a) used the following formula to calculate the milling performance: Milling score = 100 – {(80 – FLY) + 50 (flour ash – 0.3) + 0.48 (milling time – 12.5) + 0.5 (65 – %long patent) + 0.5 (16 – first tempering moisture)}. Another formula to calculate a milling score: Milling score = 100 – {(test weight – 60) + (82 – flour yield) + 100 x (flour ash content – wheat ash content / 3.9) + 10 x [(wheat protein content – 1) – flour protein content]} was utilised by Ohm *et al.* (1998). This milling score had significant negative correlations with test weight and kernel hardness. The negative correlation indicates that uniformity in hardness is desirable for good milling performance (Ohm *et al.,* 1998). All the above-mentioned suggestions to calculate the experimental milling performance of a wheat sample, involve ash contents or flour colour values.

From a miller's point of view, flour extraction and colour is very important, therefore milling performance of the South African winter and facultative cultivars was investigated.

5.2 MATERIAL AND METHODS

5.2.1 Field trials

Thirteen hard red winter and facultative bread wheat varieties were evaluated in the 1999 cropping season. Due to variation in growth period requirements, two planting dates were used to sample quality data from each cultivar. Betta-DN, Gariep, Molen, SST 367, SST 966 and Tugela-DN were planted at the first planting date. Betta-DN, Caledon, Elands, Gariep, Limpopo, PAN 3235, PAN 3349, SST 124, SST 972 and Tugela-DN were planted at the second date. Betta-DN, Gariep and Tugela-DN were therefore the only cultivars evaluated at both planting dates.

5.2.2 Environments

During 1999 the cultivars were planted at Hennenman, Wesselsbron, Bultfontein (fallow and monoculture), Senekal and Ladybrand (only second planting date). To sample the wide range of cultivars effectively, two independently randomised trials were planted at each test site, at a three week interval. The first planting date for Hennenman, Wesselsbron, Bultfontein fallow and monoculture was the last week of April and the second planting date was the third week of May. The first planting date for Senekal was during the third week of May. The second planting dates for Senekal and Ladybrand were the second week of June.

5.2.3 Experiment and cultivation practices

The experiment and cultivation practises, as described in Chapters 3 and 4, were applied.

5.2.4 Laboratory methods for quality analysis

All the material was evaluated for flour yield, ash content and flour colour. The quality analyses were conducted in triplicate.

5.2.4.1 Flour extraction

All the wheat samples were milled in a laboratory pneumatic mill, Bühler model MLU-202 (manufactured by Bühler Bros., Inc., Uzwil, Switzerland). The AACC method 26-21A for milling hard wheat was followed (AACC, 2000).

Wheat samples of 1.5 kg were weighed into airtight containers and conditioned 18 hours prior to milling. The wheat was milled and expressed as percentage extraction.

$$\text{Extraction \%} = \frac{\text{Total flour fraction}}{\text{Total (flour + bran fractions)}} \times 100$$

Flour yield, or extraction, is thus expressed as the percentage of flour obtained from a given amount of wheat (Bass, 1988).

5.2.4.2 Flour colour

The flour colour brightness was determined on a Martin series III flour colour grader. Calibration of the instrument against a standard flour sample (with a known colour value) preceded sample measurements. The higher the value the darker the flour. A more negative value indicates bright, white flour.

5.2.4.3 Ash content

An Inframatic, serial no. 1216, was used to determine the ash contents on the whole-wheat flour and white flour. In determining the ash content of a sample, this instrument works on the basis of near-infrared (NIR) reflectance. It is a relatively simple and reproducible technique.

5.2.5 Calculations and statistical analysis

5.2.5.1 Calculations

The following calculations were determined for each cultivar planted at the first and second planting dates, to obtain an indication of the milling performance of the wheat cultivars:

Milling performance = Flour yield – Flour colour. The higher the value the better the performance.

Milling rating = Flour extraction – (white flour ash x 100) (Bass, 1988). A higher milling rating is preferable.

Milling value = (white flour ash)/(flour yield) x100. A lower value indicates less ash content in the flour and is an indication of effective milling performance.
Ash ratio = (white flour ash)/(whole-wheat ash). When this ratio is related to flour extraction, the lower the ratio, the more effective the milling performance.

5.2.5.2 Analysis of variance (ANOVA)

Analysis of variance for flour yield, flour colour, the ash contents of the whole wheat and wheat flour, the ratio of flour ash to whole-wheat ash contents, milling performance, milling rating and milling value were performed across six and five environments of the two respective planting dates of 1999. Cultivar means were compared for each character. The AGROBASE 20 (Agrobase, 1999) computer programme was utilised to perform the analysis of variance.

5.3 RESULTS AND DISCUSSION

5.3.1 Analysis of variance

The analysis of variance was carried out across five environments (first planting date) and six environments (second planting date) for the two planting dates of 1999. The analysis indicates highly significant ($P< 0.01$ or $P< 0.05$) differences among genotypes for FLY, FCL, the whole-wheat ash content (ASHW), flour ash content (ASHFL), the (ASHFL)/(ASHW) ratio, milling performance, milling rating and milling value at one or at both planting dates (Tables 5.1 and 5.2). Environments indicated significant differences, at $P<0.01$ or $P<0.05$, at both planting

dates, for all the quality measurements (Tables 5.1 and 5.2). This indicated that there were various responses of the cultivars to the environments for milling performance.

5.3.2 Cultivar means

The results of the ANOVA were confirmed by the LSD (0.05) values that indicated significant differences among cultivars, except for the flour ash values and the milling value of cultivars planted at the first planting date. Although the ANOVA indicated significant differences ($P<0.05$) and ($P<0.01$), respectively, for these characteristics, but no significant differences were detected by the LSD values.

Tables 5.3 and 5.4 indicate the cultivar means for each of the milling performance values. At the first planting date, Betta-DN yielded significantly more flour than Molen and Tugela-DN, but did not differ significantly from Gariep, SST 367 and SST 966. On the other hand, there were no significant differences between Gariep, SST 367 and SST 966, Tugela-DN and Molen at the first planting date. SST 124 had significantly the highest flour yield at the second planting date, followed by PAN 3349, Betta-DN, Limpopo and Caledon that did not differ from each other. Cultivars with flour yields of less than 76% were PAN 3235, Gariep, SST 972, Elands and Tugela-DN. These cultivars did not differ significantly from Limpopo and Caledon.

Table 5.1 Analysis of variance for flour yield, flour colour, the whole-wheat and flour ash contents, ratios, milling performance, –rating and –values evaluated from material planted at the first planting date of 1999.

SOURCE	df	MEAN SQUARES							
		FLY	FCL	ASHW	ASHFL	Ashfl/Ashwl	Perform	Rating	Value
Total	89								
Genotype	5	4.101 **	3.254 **	0.075 **	0.003*	0.003**	11.479**	39.105**	0.006**
Reps	2	0.694	0.115	0.000	0.001	0.000	0.275	5.893	0.001
Environments	4	8.763 **	2.596 **	0.053 **	0.006**	0.002**	17.593**	37.885**	0.007**
Residual	78	0.720	0.606	0.004	0.001	0.001	1.793	10.471	0.002
Grand mean		75.057	0.791	1.746	0.608	0.349	74.266	14.268	0.810
R-squared		0.504	0.363	0.682	0.339	0.385	0.479	0.305	0.312
CV (%)		1.130	98.36	3.400	5.130	6.550	1.800	22.680	5.250

**Significantly different at $P<0.01$, *Significantly different at $P<0.05$, FLY=Flour yield, FCL=Flour colour, ASHW=whole-wheat ash, ASHFL=flour ash, Ashfl/Ashw=flour ash to whole wheat as ratio, Perform=milling performance, Rating=milling rating, Value=milling value.

Table 5.2 Analysis of variance for flour yield, flour colour, the whole-wheat and flour ash contents, ratios, milling performance, –rating and –values evaluated from material planted at the second planting date of 1999.

SOURCE	df	MEAN SQUARES							
		FLY	FCL	ASHW	ASHFL	Ashfl/Ashw	Perform	Rating	Value
Total	179								
Genotype	9	9.608 **	6.359 **	0.041 **	0.003	0.004**	29.275**	60.090**	0.009**
Reps	2	0.413	0.072	0.001	0.001	0.000	0.154	0.498	0.000
Environments	5	30.050 **	13.710 **	0.105 **	0.010*	0.004**	69.270**	115.777**	0.021**
Residual	163	0.534	0.678	0.003	0.003	0.000	1.334	7.783	0.001
Grand mean		76.150	0.332	1.749	0.608	0.350	75.827	15.014	0.803
R-squared		0.732	0.533	0.614	0.129	0.504	0.737	0.469	0.463
CV (%)		0.960	274.90	3.360	9.390	5.410	1.520	18.580	4.560

**Significantly different at P<0.01, *Significantly different at P<0.05, FLY=Flour yield, FCL=Flour colour, ASHW=whole-wheat ash, ASHFL=flour ash, Ashfl/Ashw=flour ash to whole wheat as ratio, Perform=milling performance, Rating=milling rating, Value=milling value.

The whole-wheat ash values of SST 367, Molen and Gariep did not differ from one another, but were significantly higher than the values of Betta-DN, Tugela-DN and SST 966. Betta-DN and Tugela-DN did not differ significantly from each other. SST 966 had the lowest whole-wheat ash values; significantly lower than all the other cultivars planted at the first planting date. At the second planting date, there were no significant differences in the whole wheat ash content of Gariep, PAN 3235, Elands, Tugela-DN, Limpopo, Caledon and SST 124. Betta-DN and PAN 3349 had lower whole-wheat ash contents, but did not differ significantly from Elands, Tugela-DN, Limpopo, Caledon or SST 124. The hybrid cultivar, SST 972 had (significantly) lower whole-wheat ash content. This variability of ash content can be due to the environment, genetic factors and their interaction. However, the wheat ash content is influenced more by the environment than by the genetic background (Posner and Hibbs, 1997). Although the whole-wheat ash contents indicated differences among cultivars, no significant differences were observed between any of the cultivars planted at both planting dates. This indicated that the different amounts of ash contained in the bran, were removed by the milling process and that the ash content of the endosperm did not differ between the cultivars.

As far as the flour ash to whole-wheat ash ratio in relation to a certain extraction level is concerned, a lower ratio is preferable, because it indicates less ash in the flour. Results indicated that Gariep, Molen and SST 367 had the best ratios, but did not differ significantly from Tugela-DN and Betta-DN, but differed significantly from SST 966 that had the poorest ratio. There were no significant differences between Gariep, Molen, SST 367, Betta-DN, and Tugela-DN with regard to the flour ash to whole-wheat ash ratio at the first planting date. For the second planting date, PAN 3235, Elands, Gariep, SST 124, Limpopo and Caledon had the most favourable ratios. Betta-DN and Tugela-DN had poorer ratios, but did not differ significantly from Elands, Gariep, SST 124, Limpopo and Caledon. PAN 3349 and SST 972

had the poorest ratios; SST 972 had a significantly higher ratio than all the other cultivars, except for PAN 3349 planted at the second planting date.

With regard to the milling performance, flour yield and flour colour are involved in this calculation. The higher the value the better the performance, indicating lower flour colour values at higher extraction rates. At the first planting date, Betta-DN was the most effective performer and Tugela-DN the poorest. However, Gariep, SST 966 and SST 367 did not differ from each other or Betta-DN. SST 966, SST 367 and Molen, on the other hand, did not differ from Tugela-DN. At the second planting date, SST 124 performed significantly higher than all the other cultivars, followed by PAN 3349, Betta-DN, PAN 3235 and Limpopo that did not differ from each other. PAN 3235, Limpopo, Caledon, Gariep, SST 972 and Elands did not differ significantly. At the second planting date Tugela-DN again performed the poorest, but its performance did not differ significantly from those of Gariep, SST 972 and Elands.

In the calculation of milling rating, flour yield and flour ash content are involved. Higher values are the best. If flour ash contents is used to measure flour colour, the ranking of cultivars obtained by the performance or rating methods, are supposed to be similar. At the first planting date, the milling rating of Gariep was significantly higher than the rating of Tugela-DN, but it did not differ significantly from Betta- DN, SST 966, SST 367 and Molen. At the second planting date, SST 124, PAN 3235, Limpopo, Betta-DN and Elands did not differ significantly in milling rating, but they differed significantly from Tugela-DN. Tugela-DN had the lowest ranking, but did not differ significantly from Caledon, Gariep, PAN 3349 and SST 972. With only minor variations in the ranking and significant differences, milling performance and rating calculations revealed similar results.

The milling value calculates the flour ash content as a percentage of the flour yield; therefore lower values reflect better milling performance. There were no differences in the milling values between the cultivars planted at the first planting date. At the second planting date, SST 124 differed significantly from Tugela-DN, SST 972, PAN 3349 and Gariep, but not from Caledon, Elands, Betta-DN, Limpopo and PAN 3235 in milling value. Other cultivar groupings with regard to the milling value were Caledon, Gariep, PAN 3349, SST 972 and Tugela-DN. SST 972, PAN 3349, Gariep, Caledon, Elands and Betta-DN did not differ in milling value from one another. PAN 3349, Gariep, Caledon, Elands, Betta-DN, Limpopo and PAN 3235 were not significantly different either.

Table 5.3 Mean ash values, ash ratios, milling performance, rating and values, cultivar rankings and differences for the respective milling quality measurements of the first planting date.

	FLOUR YIELD		FLOUR COLOUR		ASH BROWN		ASH WHITE		ASHW/ASHB		PERFORMANCE		RATING		VALUE	
Rank	Cultivar	Mean*	Cultivar	Mean*	Cultivar	Mean*	Cultivar	Mean*	Cultivar	Mean*	Cultivar	Mean*	Cultivar	Mean*	Cultivar	Mean*
1	Betta-DN	75.78 a	Betta-DN	0.20 a	SST 367	1.80 a	Gariep	0.59 a	Gariep	0.331 a	Betta-DN	75.55 a	Gariep	16.80 a	Gariep	0.777 a
2	Gariep	75.33 ab	Gariep	0.30 ab	Gariep	1.80 a	SST 966	0.60 a	Molen	0.342 a	Gariep	75.08 ab	Betta-DN	15.18 ab	SST 966	0.800 a
3	SST 367	75.28 ab	Molen	0.80 abc	Molen	1.80 a	Molen	0.61 a	SST 367	0.343 a	SST 966	74.12 abc	SST 966	14.83 ab	SST 367	0.802 a
4	SST 966	75.03 ab	SST 966	0.90 abc	Betta-DN	1.70 b	Betta-DN	0.61 a	Betta-DN	0.350 ab	SST 367	73.97 abc	SST 367	13.21 ab	Betta-DN	0.824 a
5	Tug-DN	74.54 b	Tug-DN	1.20 bc	Tug-DN	1.70 b	SST 367	0.62 a	Tug-DN	0.357 ab	Molen	73.57 bc	Molen	12.92 ab	Molen	0.826 a
6	Molen	74.38 b	SST 367	1.30 c	SST 966	1.60 c	Tug-DN	0.62 a	SST 966	0.373 b	Tug-DN	73.31 c	Tug-DN	12.67 b	Tug-DN	0.830 a
LSD		1.059		0.972		0.074		0.039		0.029		1.672		4.041		0.053

ASHW=whole-wheat ash, ASHFL=flour ash, ASHFL/ASHW= flour ash to whole wheat as ratio, PERFORMANCE= milling performance, RATING=milling rating, VALUE=milling value, Tug-DN= Tugela-DN,

* Means followed by the same letter did not differ significantly at P=0.05.

Table 5.4 Mean ash values, ash ratios, milling performance, rating and values, cultivar rankings and differences for the respective milling quality measurements of the second planting date.

	FLOUR YIELD		FLOUR COLOUR		ASH BROWN		ASH WHITE		ASHW/ASHB		PERFORMANCE		RATING		VALUE	
Rank	Cultivar	Mean*	Cultivar	Mean*	Cultivar	Mean*	Cultivar	Mean*	Cultivar	Mean*	Cultivar	Mean*	Cultivar	Mean*	Cultivar	Mean*
1	SST 124	77.70 a	SST 124	-1.00 a	Gariep	1.80 a	SST 124	0.59 a	PAN 3235	0.332 a	SST 124	78.64 a	SST 124	18.34 a	SST 124	0.764 a
2	Pan 3349	76.80 b	Pan 3235	0.00 ab	PAN 3235	1.80 a	Limpopo	0.60 a	Elands	0.338 ab	PAN 3349	76.75 b	PAN 3235	16.13 ab	PAN 3235	0.787 ab
3	Betta-DN	76.70 bc	Pan 3349	0.00 ab	Elands	1.77 ab	Elands	0.60 a	Gariep	0.339 ab	Betta-DN	76.61 bc	Limpopo	15.99 abc	Limpopo	0.790 ab
4	Limpopo	76.20 bcd	Betta-DN	0.10 b	Tug-DN	1.77 ab	PAN 3235	0.60 a	SST 124	0.342 ab	PAN 3235	75.88 bcd	Betta-DN	15.93 abc	Betta-DN	0.792 abc
5	Caledon	76.10 bcd	SST 972	0.40 bc	Limpopo	1.76 ab	PAN 3349	0.60 a	Limpopo	0.342 ab	Limpopo	75.75 bcd	Elands	15.58 abc	Elands	0.793 abc
6	Pan 3235	75.90 cd	Gariep	0.50 bc	Caledon	1.76 ab	Caledon	0.61 a	Caledon	0.348 abc	Caledon	75.42 cd	Caledon	14.96 bcd	Caledon	0.804 abcd
7	Gariep	75.70 d	Limpopo	0.50 bc	SST 124	1.74 ab	Gariep	0.61 a	Betta-DN	0.354 bc	Gariep	75.24 de	Gariep	14.79 bcd	Gariep	0.805 bcd
8	SST 972	75.60 d	Caledon	0.70 bc	Betta-DN	1.72 b	Betta-DN	0.61 a	Tug-DN	0.357 bc	SST 972	75.16 de	PAN 3349	13.42 bcd	PAN 3349	0.825 bcd
9	Elands	75.50 d	Elands	0.70 bc	PAN 3349	1.72 b	Tug-DN	0.63 a	PAN 3349	0.369 cd	Elands	74.74 de	SST 972	12.86 cd	SST 972	0.831 cd
10	Tug-DN	75.40 d	Tug-DN	1.30 c	SST 972	1.64 c	SST 972	0.63 a	SST 972	0.383 d	Tug-DN	74.07 e	Tug-DN	12.12 d	Tug-DN	0.839 d
LSD		0.816		0.920		0.066		0.064		0.021		1.290		3.116		0.041

ASHW=whole-wheat ash, ASHFL=flour ash, ASHFL/ASHW= flour ash to whole wheat as ratio, PERFORMANCE= milling performance, RATING=milling rating, VALUE=milling value, Tug-DN= Tugela-DN,

* Means followed by the same letter did not differ significantly at P=0.05.

5.4 CONCLUSIONS

Although no significant differences were observed between the flour ash values alone, differences in performance, as indicated by the various calculations, reflected the importance to evaluate ash content in relation to the flour extraction.

When focusing on the various calculations to determine the milling performance of a wheat sample (ash ratio, performance, rating and value), the results were more or less the same, indicating the reliability of all the calculations. The use of ash contents in most calculations gave an indication of flour contamination with bran particles.

At the first planting date, Gariep and Betta-DN were the best performing cultivars, while Molen and Tugela-DN reflected lower milling performances. However, there were not large differences between the six cultivars evaluated at the first planting date.

At the second planting date, the different milling evaluations resulted in more or less the same cultivar rankings. The best performing cultivars were SST 124, PAN 3235, Betta-DN and Limpopo. PAN 3349, SST 972 and Tugela-DN indicated lower milling performances.

When it is kept in mind that Betta-DN is the quality standard and new lines were released against this cultivar, it is no surprise that the cultivars did not deviate much from one another. The stable ranking order of the cultivars reflects the selection of cultivars with a milling performance close to that of Betta-DN, therefore cultivars in this study have milling values that do not vary widely.

CHAPTER 6

GENERAL CONCLUSIONS AND RECOMMENDATIONS

- The ANOVA indicated significant differences among genotypes, environments and GXE interaction for most of the milling characteristics measured in this study. Variation in break flour yield, kernel diameter, thousand kernel weight and kernel hardness were largely controlled by genotypic factors. The effect of environmental conditions had an influence on most of the measured kernel and milling characteristics.

- Wheat breeders need to identify the key quality components that are genetically controlled and serve the purpose of easy improvement through selection. This study indicated that break flour yield, kernel diameter, thousand kernel weight and kernel hardness is under genetic control. Therefore these characteristics are important in stable assessment and enhancement of milling quality of South African winter and facultative wheat breeding programmes.

- Identification of quality aspects that are highly influenced by environment, would assist in the development of wheat with enhanced quality stability over diverse environmental conditions. The environment had a significant effect on all the quality characteristics measured in this study, but some of the traits were more susceptible to environmental fluctuations than other traits. Environments had a large influence on test weight, moisture content, percentage vitreous kernels, flour yield, flour colour and the flour protein content.

- The interaction between genotypes and the environment were significant for most of the milling quality traits measured in this study. Interactions were investigated by means of the AMMI analysis. The interaction effects were the largest on test weight, percentage vitreous kernels, flour yield, flour colour and flour protein content. Many environments are required to accurately predict the value of a breeding line for these characteristics that exhibit large and significant GXE interaction. On the other hand, if interaction is very low or absent, only a few test sites are required to rank the cultivars.

- Some wheat cultivars have ideal growing regions where they produce the best milling quality or end products. Therefore, specific adaptation, with regard to quality characteristics, to the different parts of the Free State needs further assessment. Greater emphasis on GXE interaction of quality traits would be beneficial for a better differentiation of genotypes as well as, in the classification of the environments that are

useful in the selection of good quality attributes. Therefore, clustering of the Free State localities based on GXE interaction would be important in achieving resource efficiency. GXE interaction effects may be predictable or unpredictable and if test sites are not representative of the target environment, large GXE interaction to important quality traits may result and hinder the progress of the breeding programmes.

- The modern milling and baking industries are characterised by high volume, highly automated plants with little flexibility in processing methods and procedures. Consistency in quality and performance of wheat grain and flour is of critical value to the output of high-quality products. For the plant breeder this means wheat genotypes with optimal end use quality must be consistent across environments and have acceptable mean performance in milling and baking tests. Since the information on GXE interactions and quality stability of lines and cultivars are essential to wheat breeders, producers and the processing industries, data on the quality stability need to be generated and presented when new varieties are proposed for commercial release.

- Stability of quality characteristics and cultivars were determined by the AMMI biplots and AMMI stability values. Molen was the most stable cultivar at the first planting date. Although this cultivar was removed from the industry preference list, because of its inherently low falling number and short mixing time, its milling stability was good. At the second planting date PAN 3235 and Limpopo were the stable cultivars. Betta-DN, SST 124 and Caledon were also quite stable. These cultivars' milling quality is thus more stable over environments and would be a good choice to producers and millers to reach their goals in terms of quality grain and flour. Tugela-DN and PAN 3349 were unstable cultivars. The hybrids SST 966 and SST 972 were also unstable over environments. These cultivars are high-risk quality cultivars. Their quality is good in specific regions, but they were not adapted over environments. Their cultivation must be managed and restricted to high potential areas in order to reach their maximum quality potential. Betta-DN, Gariep and Tugela-DN were planted at both planting dates. The overall kernel and milling quality stability was better at the second planting date. The intermediate growth type of these cultivars might explain this, the cultivars were ripe before the true winter types at the first planting date. For the best quality results, these cultivars should be planted at later planting dates or they have to be harvested in time, in order that they are not subjected to weathering in the field.

- The cultivar, environment and the GXE interaction plays an important role in the milling quality of South African winter and facultative wheat. In future, breeders will have to concentrate on quality stability in breeding programmes. The wheat technical committee

has to consider stability evaluation during the three years of quality testing before commercial release and a database of cultivars' quality performance and stability after release, could also be of great value. The AMMI and AMMI stability values proved to be useful in accomplishing these recommendations.

- According to the canonical variate analysis, cultivars could be differentiated and grouped effectively, according to kernel size, kernel hardness, break flour yield and test weight. The groups that segregated from the cultivars planted at the first planting date, were Gariep with Betta-DN and Molen with SST 966. In the years that favoured similarity in kernel hardness, these four cultivars could be grouped together. Tugela-DN and SST 367 did not group with one another or with any of the other cultivar groupings. However, these cultivars are no longer available on the market. It might be that they are not grouping well with the other cultivars currently available on the market. For cultivars planted at the second planting date, the groups were Tugela-DN with SST 124 in two of the three years. Betta-DN, Caledon, Elands, Gariep, Limpopo and PAN 3235 formed a group and could be stored together. SST 972 and PAN 3349 were not similar to each other or to any of the other cultivars and should be stored separately whenever possible.

- These cultivar groupings could be of value to grain depot owners and the milling industries to enhance the value of the grain when similar cultivars are grouped together with regard to similar kernel size, test weight, kernel hardness and break flour yield. Despite the large variation in wheat quality supplied to the miller, milling industries aim to produce flour of consistent predetermined standards. Cultivars with the same kernel and milling characteristics will help to improve the quality of stored wheat grain. Higher milling performance obtained in this way, could help millers in realising their goals. This could be achieved by introducing the grouping of wheat based on their quality attributes at wheat reception.

- The canonical variate analysis further proved to be a useful tool in determining the milling quality and performance of new and unknown cultivars. A new line's grouping, with regard to the most widely produced cultivars of a region, could be determined beforehand, even before release in a production area by using this method.

- Understanding the relationships between different quality aspects and characteristics could help in quality determination and assisting quality breeding programmes. The relationships among the measured kernel and milling characteristics, indicated highly positive correlations between kernel characteristics, weight and size. TKW had positive correlations with kernel DIAM. TKW and DIAM had a positive correlation with MOIST. It

is a fact that higher moisture contents will influence the kernel weight and diameter. Therefore, TKW should be determined at optimum moisture contents and when cultivars have to be ranked, it should be done at the same moisture levels.

- TW correlated positively with HI. HI could be an indication of the kernel density, because harder kernels have higher endosperm density than softer kernels. HI correlated negatively with BFLY over years and seasons. HI correlated positively with the percentage VK. This positive correlation explains why VK is generally associated with kernel hardness and the use of VK to obtain an indication of the grain kernel hardness. VK correlated negatively with BFLY. The negative correlation between BFLY and HI just further explains correlation between the VK and HI, that correlated positively in this study and confirms the utilisation of VK as another measurement of kernel hardness, therefore also the negative correlation between VK an BFLY. These correlations confirmed the current use of VK and BFLY as kernel hardness indicators, but care should be taken with the use of VK, because this study also revealed that the environment might influence VK to a large extent.

- FLY correlated negatively with flour colour. The correlation indicates possible darker flour from too high extraction rates. Flour colour from bran contamination is one of the most obvious effects of darker flour colour, influenced by the grinding action. Therefore, this correlation could be used to ensure superior flour at optimum extraction rates.

- Selection of germplasm from cultivars with low correlation coefficients among most quality attributes, could yield progeny with overall more environmentally stable quality than the currently available cultivars.

- The stepwise multiple regressions indicated that only small percentages of the variation in TW, HI, BFLY, FLY and FLC could be explained by the other kernel and milling characteristics determined in this study. Some of the physical kernel characteristics normally used in predicting another characteristic failed to do so in this evaluation.

- HI explained the variation in the TW the most effectively. Kernel characteristics measured in this study contributed only 16.8 to 57.6% of the variation in TW over planting dates and years. However, it is not recommended to use indirect measurements for predicting TW. TW determination is a fast and simple test and should be used directly. It is important to compare the TW values of cultivars at equal moisture levels.

- The VK and MOIST could be regarded as the most important independent variance predictors for kernel hardness, interpreting up to 28.2 and 43.2%, respectively. HI had linear relationships with moisture content, therefore moisture content plays an important role in the variation of HI. Fully matured and dry grain with optimum moisture levels should be used during HI evaluation of cultivars.

- The most explanatory predictors for BFLY were kernel size (TKW and DIAM) and HI. These characteristics could define 41.6 to 63.3% of the variation in BFLY. The coefficient of determination was moderate to fairly strong, therefore not only the kernel hardness (generally considered as the most important trait in BFLY determination), but also the kernel size should be included in BFLY estimations.

- It became evident that the kernel hardness measurements, HI, BFLY and VK could be regarded as the most definable predictors for flour yield, these predictors interpreted up to 50% of the variation in FLY. TW explained less than 4% of the variation in FLY, indicating that TW is not always a reliable indicator of the amount of flour extraction. Flour yield is usually associated positively with kernel size. In this study, the regression analysis indicated that the kernel size characteristics, TKW and DIAM together, explained only 9.6 to 20.7% of the variation in FLY. This illustrates the difficulty in predicting flour yield by indirect calculations, therefore the ultimate and final test for flour yield prediction would be to mill a wheat sample on an experimental mill.

- The most important variable in predicting FCL was FLY. The measurement of colour brightness is influenced by the dulling effect of bran particles, darker flour at high extraction rates indicates the inclusion of more bran particles in the flour. Therefore, flour extraction could be used to explain the variation in flour colour values.

- From a miller's point of view, flour extraction and colour is very important, therefore milling performance of the South African winter and facultative cultivars was determined. At the first planting date, Gariep and Betta-DN were the best performing cultivars, while Molen and Tugela-DN reflected lower milling performances. At the second planting date, the different milling evaluations revealed similar cultivar rankings. The best performing cultivars were SST 124, PAN 3235, Betta-DN and Limpopo. PAN 3349, SST 972 and Tugela-DN indicated lower milling performances. However, it is a positive sign that differences between the evaluated cultivars were small. This indicates that the regulations for cultivar release serves its purpose.

CHAPTER 7

SUMMARY

The objectives of this research were to assess South African winter and facultative bread wheat cultivars for milling quality, to study the effect of genotype x environment interaction on the stability of the wheat quality and to characterise the cultivars for milling performance.

Thirteen hard red varieties were planted at six localities throughout the Free Sate at two planting dates, during 1997 to 1999. Betta-DN, Gariep, Molen, SST 367, SST 966 and Tugela-DN were planted at the first planting date. Betta-DN, Caledon, Elands, Gariep, Limpopo, PAN 3235, PAN 3349, SST 124, SST 972 and Tugela-DN were planted at the second date.

Material was evaluated for test weight, thousand kernel weight, kernel diameter, kernel hardness, moisture content, vitreous kernels, break flour yield, flour yield, flour colour and flour protein content.

Combined ANOVA's for the characteristics was performed over environments. Cultivar differences were determined by means of the least significant difference at individual localities. The analysis indicated highly significant differences among genotypes, environments and GXE interactions, for most of the measured traits. Genotypes contributed significantly to the variance in BFLY, DIAM, TKW and HI. Environment had a large effect on TW, MOIST, VK, FLY, FCL and FPC. Significant GXE interactions were present for most of the quality traits.

Canonical variate analysis was used to differentiate between cultivar groups and indicated that TKW, DIAM, HI, BFLY and TW could effectively differentiate between cultivars. The groups observed with regard to the mentioned characteristics were Gariep with Betta-DN and Molen with SST 966. Tugela-DN and SST 367 were not similar to any other cultivars. At the second planting date, Tugela-DN grouped with SST 124. Betta-DN, Caledon, Elands, Gariep, Limpopo and PAN 3235 formed a group. SST 972 and PAN 3349 were not similar to each other or to the other cultivars.

The correlation matrix was performed, to calculate phenotypic relationships between quality traits. TKW had positive correlations with DIAM and these two characteristics indicated positive correlations with MOIST. HI correlated positively to TW and also correlated positively to VK. HI and VK correlated negatively to BFLY. High negative correlations were found between HI and FLY. FLY had positive correlations with BFLY, but correlated negatively with FLC.

Stepwise multiple regressions indicated that only small percentages of the variation in TW, HI, BFLY, FLY and FLC could be explained by the other kernel and milling characteristics. HI explained the variation in the TW the most effectively. VK and MOIST could be regarded as the most important variance predictors for HI. Predictors for BFLY were kernel size and HI. These characteristics could define 41.6 to 63.3% of the variation in BFLY. Kernel hardness measurements, HI, BFLY and VK were the most definable for flour yield, together they interpreted up to 50.0% of the variation in FLY. TW explained less than 4% of the variation in FLY; therefore TW is not always reliable in predicting flour extraction. The kernel size explained less than 9.6 to 20.7% of the variation in FLY, illustrating the difficulty of predicting flour yield by indirect calculations. The most important variable in predicting FCL was FLY.

AMMI analysis of variance was performed to investigate the influence of the GXE interaction on milling quality. Every locality by year combination was treated as a separate environment. Analysis confirmed differences in genotype performance, that there were varying growth conditions among the localities and the presence of GXE interactions. Interaction effects on TW, percentage VK, FLY, FCL and FPC, were large. IPCA 1 stability scores were compared to the AMMI stability values. Molen was the most stable cultivar at the first planting date. At the second planting date, PAN 3235 and Limpopo were the stable cultivars. Betta-DN, SST 124 and Caledon were also quite stable. Tugela-DN, PAN 3349, as well as the hybrid cultivars SST 966 and SST 972, were unstable with regard to milling quality.

Milling performance, as calculated by flour extraction, ash contents and flour colour in various formulas, revealed Gariep and Betta-DN as the high performing cultivars (first planting date), while Molen and Tugela-DN reflected poorer performances. The most effective performing cultivars at the second planting dates were SST 124, PAN 3235, Betta-DN and Limpopo. PAN 3349, SST 972 and Tugela-DN indicated poorer milling performances.

Key words: bread wheat, correlations, environment, genotype, GXE interaction, kernel and flour characteristics, milling performance, milling quality.

OPSOMMING

Die doel van hierdie studie was om Suid Afrikaanse winter en fakultatiewe broodkoring kultivars te bestudeer ten opsigte van hul maalkwaliteit. Die effek van die kultivar x omgewing interaksie op die graan– en maalkwaliteit is ook ondersoek, gevolglik is die kultivars dan ook gekarakteriseer volgens maalprestasie.

Dertien kultivars is gedurende 1997 tot 1999 op ses lokaliteite, by twee plantdatums in die Vrystaat aangeplant. Betta-DN, Gariep, Molen, SST 367, SST 966 en Tugela-DN is ingesluit by die eerste aanplanting. Betta-DN, Caledon, Elands, Gariep, Limpopo, PAN 3235, PAN 3349, SST 124, SST 972 en Tugela-DN is ingesluit in die tweede aanplanting.

Die material is geëvalueer vir hektolitermassa, duisendkorrelmassa, korreldeursnit, hardheid, voginhoud, horingagtige korrels, breekmeelopbrengs, meelekstraksie, meelkleur en proteïen-inhoud van die meel.

Gesamentlike variansie analises vir al die eienskappe, oor die verslillende lokaliteite, is uitgevoer. Kultivar verskille op elke lokaliteit is bepaal met behulp van die kleinste betekenisvolle verskil tegniek. Die analise het verskille tussen genotipes, omgewings en genotipe x omgewing (GXE) interaksies vir die meeste eienskappe aangedui. Genotipes het grootliks bygedra tot die variasie in breekmeelopbrengs, korreldeursnit, duisendkorrelmassa en hardheid. Hektolitermassa, voginhoud, horingagtige korrels, ekstraksie, meelkleur en proteïeninhoud is hoofsaaklik deur die omgewing beïnvloed. Daar was ook betekenisvolle interaksie tussen die genotipes en die omgewing vir die meeste kwaliteitseienskappe wat bepaal is.

CVA analises is gebruik om verskille tussen kultivargroepe uit te wys. Hierdie analises het duisendkorrelmassa, korreldeursnit, breekmeelopbrengs, hardheid en hektolitermassa uitgesonder as die eienskappe wat effektief tussen groepe kultivars kan onderskei. Groepe wat hiervolgens aangedui is, was Gariep met Betta-DN en Molen met SST 966 by die eerste aanplanting. Tugela-DN en SST 367 het nie ooreenkomste met mekaar of enige van die ander kultivars gehad nie. By die tweede aanplanting het Tugela-DN en SST 124 saam gegroepeer, terwyl Betta-DN, Caledon, Elands, Gariep, Limpopo en PAN 3235 'n groep gevorm het. SST 972 en PAN 3349 het van mekaar en ook van al die ander kultivars verskil.

Korrelasiematrikse om die fenotipiese verwantskappe tussen die kwaliteitseienskappe te bepaal is uitgevoer. Duisendkorrelmassa het positief met korreldeursnit gekorreleer. Hierdie twee eienskappe het ook positiewe verwantskappe met voginhoud gehad. Hektolitermassa en

hardheid was positief gekorreleerd, so ook het hardheid en die persentasie horingagtige korrels positiewe korrelasies getoon. Hardheid en die persentasie horingagtige korrels was negatief gekorreleerd met breekmeelopbrengs. Daar was 'n hoë negatiewe korrelasie tussen ekstraksie en hardheid. Ekstraksie was positief gekorreleerd met breekmeelopbrengs en negatief met meelkleur.

Stapsgewyse meervoudige regressies is ingespan om die variasie in hektolitermassa, hardheid, breekmeelopbrengs, meelekstraksie en meelkleur te bepaal. Dit het aangedui dat die ander graan– en maaleienskappe slegs 'n klein persentasie van die variasie in die vaste eienskap kon verklaar. Hektolitermassa variasies is die beste deur hardheid beskryf. Horingagtige korrels en voginhoud kan beskou word as die belangrikste voorspellers vir variasie in die graan hardheid. Pitgrootte en hardheid het 41.6 tot 63.3% van die variasie in breekmeelopbrengs verklaar. Hardheidsbepalers, naamlik die horingagtige korrels, breekmeelopbrengs en hardheidsindeks, was die mees verklarende eienskappe vir die variasie in ekstraksie en het soveel as 50% van die variasie in ekstraksie verklaar. Hektolitermassa het egter minder as 4% van die variasie in meelopbrengs verklaar en wys dat hektolitermassa nie altyd 'n betroubare voorspeller van ekstraksie is nie. Pitgrootte het slegs 9.6 tot 20.7% van die variasie verklaar en dui verder op die ingewikkeldheid van ekstraksie bepalings d.m.v. indirekte metodes. Die belangrikste veranderlike in die bepaling van meelkleur was ekstraksie, maar minder as 32% van die variasie is só verklaar.

Die AMMI analise is uitgevoer om GXE interaksies se invloed op maalkwaliteit te ondersoek. Elke lokaliteit en jaar kombinasie is as 'n individuele omgewing beskou. Die analise het verskille tussen genotipes en omgewings bevestig en die teenwoordigheid van interaksies aangedui. GXE interaksies het 'n betekenisvolle invloed op hektolitermassa, horingagtige korrels, ekstraksie, meelkleur en meelproteïen gehad. Die IPCA 1 stabiliteitswaardes is met die AMMI stabiliteitswaardes vergelyk. Molen was die stabielste kultivar t.o.v. die meeste eienskappe, by die eerste aanplanting. By die tweede aanplanting was PAN 3235 en Limpopo die stabiele kultivars, Betta-DN, SST 124 en Caledon was ook betreklik stabiel. Tugela-DN en PAN 3349 het onstabiele kwaliteitseienskappe getoon, terwyl die basters, SST 966 en SST 972 ook onstabiel was.

Maalprestasies is bereken met formules wat meelopbrengs, as-inhoud en meelkleur bevat. Gariep en Betta-DN was die mees effektiewe presteerders (eerste aanplanting), terwyl Molen en Tugela-DN die laagste rangordes ingeneem het. Kultivars met die beste maalprestasies, by die tweede aanplanting, was SST 124, PAN 3235, Betta-DN en Limpopo. PAN 3349, SST 972 en Tugela-DN het laer prestasiewaardes getoon.

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Appendix 1

Genotype and environment means of individual localities planted during 1997-1999 at the first planting date

TEST WEIGHT

	1997												1998												1999											
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	Means
Betta-DN	75.7	4	79.1	1	79.1	2	78.8	2	77.8	5	79.7	1	**78.37**	77.6	2	79.5	2	78.6	2	75.1	3	75.7	4	76.6	2	**77.18**	79.4	3	76.9	2	78.8	2	77.4	5	77.8	5	**78.06**
Gariep	76.0	2	76.5	4	77.9	4	78.9	1	77.3	6	79.5	2	**77.68**	77.3	3	79.3	4	78.9	1	76.0	1	76.1	2	77.0	1	**77.43**	80.1	1	78.1	1	79.1	1	79.3	2	79.4	2	**79.20**
Tugela-DN	75.7	3	76.8	3	79.2	1	77.7	4	80.6	1	78.7	3	**78.12**	75.7	5	79.5	3	75.6	6	74.7	6	75.9	3	74.5	5	**75.98**	77.1	6	76.2	4	78.5	3	77.4	4	77.7	6	**77.38**
SST 367	76.4	1	78.5	2	78.6	3	78.1	3	80.1	2	78.3	4	**78.33**	77.7	1	79.5	1	77.8	3	75.1	2	74.9	6	75.5	4	**76.75**	78.0	4	75.5	5	77.6	6	77.2	6	78.1	4	**77.28**
SST966	75.2	5	75.6	6	77.3	5	75.4	6	79.2	3	78.1	6	**76.80**	76.6	4	76.7	6	77.2	4	74.9	5	76.8	1	75.5	3	**76.28**	79.5	2	76.6	3	77.7	5	80.2	1	80.4	1	**78.88**
Molen	75.0	6	76.3	5	76.2	6	76.8	5	78.4	4	78.2	5	**76.82**	74.8	6	77.7	5	76.4	5	75.0	4	75.6	5	74.3	6	**75.63**	77.4	5	75.1	6	78.2	4	78.1	3	78.7	3	**77.50**
Environment Mean	75.7		77.1		78.1		77.6		78.9		78.8		**77.69**	76.6		78.7		77.4		75.1		75.8		75.6		**76.54**	78.6		76.4		78.3		78.3		78.7		**78.05**
CV (%)	0.8		0.5		0.8		0.8		1.3		0.4			0.7		0.8		0.7		0.8		0.3		0.5			0.2		0.5		0.8		0.5		0.5		
LSD	2.3		1.5		2.3		2.3		3.9		1.2			1.9		2.2		1.9		2.3		0.7		1.3			0.6		1.3		2.3		1.5		1.6		

THOUSAND KERNEL WEIGHT

	1997												1998												1999											
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	Means
Betta-DN	34.0	4	37.8	3	32.3	3	32.5	3	27.0	6	33.6	4	**32.87**	43.9	2	38.3	2	41.3	3	33.8	5	33.0	5	37.5	4	**37.97**	36.7	3	33.6	3	34.2	4	32.0	4	32.6	4	**33.82**
Gariep	33.8	5	36.0	5	30.1	5	33.2	2	28.1	5	33.9	3	**32.52**	41.8	4	37.6	4	40.6	4	33.7	6	33.6	4	39.1	3	**37.73**	36.1	4	32.6	4	35.9	2	33.0	3	32.8	3	**34.08**
Tugela-DN	41.3	1	46.7	1	36.3	1	38.3	1	36.6	1	37.5	1	**39.45**	46.2	1	41.9	1	42.6	1	35.9	1	41.4	1	41.1	1	**41.52**	40.3	1	36.5	1	40.0	1	38.6	1	39.0	1	**38.88**
SST 367	36.2	2	37.1	4	31.6	4	32.2	4	29.6	3	33.3	5	**33.33**	41.5	5	38.1	3	38.8	5	35.3	4	32.5	6	37.4	5	**37.27**	35.5	5	31.7	5	30.8	6	30.8	6	30.7	6	**31.90**
SST966	33.7	6	38.1	2	33.1	2	29.5	6	30.9	2	34.2	2	**33.25**	43.9	3	37.4	5	41.4	2	35.7	3	33.7	3	39.4	2	**38.58**	37.2	2	34.1	2	34.6	3	34.9	2	34.7	2	**35.10**
Molen	34.5	3	35.5	6	29.3	6	31.3	5	29.3	4	33.2	6	**32.18**	40.0	6	35.1	6	37.5	6	35.8	2	34.0	2	35.4	6	**36.30**	34.9	6	31.2	6	33.0	5	31.8	5	31.8	5	**32.54**
Environment Mean	35.6		38.5		32.1		32.8		30.2		34.3		**33.93**	42.9		38.0		40.4		35.0		34.7		38.3		**38.23**	36.8		33.3		34.8		33.5		33.6		**34.39**
CV (%)	2.4		1.5		2.2		2.7		4.0		2.2			1.6		2.7		2.0		5.9		2.1		4.8			2.0		2.3		2.9		1.7		1.3		
LSD	3.2		2.1		2.6		3.3		4.6		2.8			2.5		3.9		2.9		7.7		2.7		6.9			2.7		2.9		3.7		2.1		1.6		

KERNEL DIAMETER

	1997												1998												1999											
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	Means
Betta-DN	2.41	4	2.50	4	2.32	4	2.27	5	2.05	5	2.20	4	**2.29**	2.78	3	2.36	6	2.75	3	2.44	6	2.44	6	2.61	3	**2.57**	2.50	5	2.35	5	2.33	5	2.29	6	2.38	4	**2.37**
Gariep	2.37	6	2.47	6	2.18	6	2.37	2	2.14	6	2.13	6	**2.28**	2.66	5	2.47	3	2.69	5	2.49	5	2.43	5	2.62	2	**2.56**	2.52	4	2.36	4	2.45	2	2.37	3	2.38	3	**2.42**
Tugela-DN	2.86	1	2.91	1	2.60	1	2.70	1	2.57	1	2.35	1	**2.67**	2.93	1	2.72	1	2.79	1	2.61	1	2.85	1	2.88	1	**2.80**	2.76	1	2.59	1	2.72	1	2.64	1	2.64	1	**2.67**
SST 367	2.45	3	2.58	2	2.41	2	2.35	3	2.29	2	2.22	2	**2.38**	2.74	4	2.52	2	2.69	4	2.62	2	2.54	3	2.59	4	**2.62**	2.56	2	2.40	2	2.32	6	2.30	5	2.33	6	**2.38**
SST966	2.46	2	2.56	3	2.34	3	2.15	6	2.23	4	2.20	5	**2.32**	2.79	2	2.42	5	2.76	2	2.48	3	2.60	2	2.54	5	**2.60**	2.56	3	2.39	3	2.43	3	2.45	2	2.43	2	**2.45**
Molen	2.39	5	2.48	5	2.25	5	2.35	4	2.21	3	2.21	3	**2.32**	2.63	6	2.43	4	2.59	6	2.55	4	2.50	4	2.50	6	**2.53**	2.48	6	2.27	6	2.39	4	2.33	4	2.33	5	**2.36**
Environment Mean	2.49		2.58		2.35		2.36		2.25		2.22		**2.38**	2.76		2.49		2.71		2.53		2.56		2.62		**2.61**	2.56		2.39		2.44		2.40		2.41		**2.44**
CV (%)	3.69		1.83		2.41		2.06		3.28		3.15			1.53		1.98		2.90		3.79		1.56		2.48			1.65		2.25		2.25		1.29		1.04		
LSD	0.34		0.18		0.21		0.18		0.28		0.26			0.16		0.18		0.29		0.36		0.15		0.24			0.16		0.20		0.21		0.12		0.09		

HARDNESS INDEX

	1997												1998												1999											
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	Means
Betta-DN	62.60	4	67.50	3	73.90	4	69.40	6	78.10	4	65.10	4	**69.43**	48.60	5	77.40	1	51.90	6	47.30	6	53.10	5	47.30	5	**54.27**	58.80	5	63.80	3	70.20	5	66.20	6	67.30	6	**65.26**
Gariep	69.40	2	67.10	4	75.20	3	78.50	3	84.50	3	65.70	3	**73.40**	56.80	3	74.40	4	55.60	3	55.90	2	58.90	1	52.30	3	**58.98**	64.20	3	71.00	2	83.40	1	73.30	2	73.40	2	**73.06**
Tugela-DN	76.10	1	71.30	2	75.60	2	84.30	1	87.50	1	72.70	2	**77.92**	59.60	1	76.10	2	61.90	2	53.80	4	56.30	3	54.20	1	**60.32**	64.90	2	71.20	1	77.90	2	69.80	5	69.80	5	**70.72**
SST 367	67.50	3	74.90	1	79.30	1	79.40	2	84.80	2	75.70	1	**76.93**	57.70	2	75.70	3	65.10	1	58.60	1	58.70	2	53.90	2	**61.62**	65.90	1	63.70	4	75.10	3	76.40	1	73.80	1	**70.98**
SST966	59.30	5	56.30	5	61.50	6	70.90	5	74.80	6	62.60	5	**64.23**	41.80	6	62.90	6	52.50	5	49.80	5	50.10	6	41.00	6	**49.68**	57.10	6	56.50	6	68.40	6	71.70	4	72.30	3	**65.20**
Molen	52.80	6	53.20	6	65.30	5	75.40	4	75.60	5	54.10	6	**62.73**	54.70	4	67.80	5	53.80	4	54.90	3	55.80	4	49.70	4	**56.12**	61.40	4	63.30	5	74.20	4	71.70	3	72.30	4	**68.58**
Environment Mean	64.6		65.1		71.8		76.3		80.9		66.0		**70.78**	53.2		72.4		56.8		53.4		55.5		49.7		**56.83**	62.1		64.9		74.9		71.5		71.5		**68.97**
CV (%)	5.4		2.5		3.8		2.8		3.1		5.8			2.8		2.1		5.8		9.0		3.5		4.3			1.4		1.6		1.6		1.3		3.0		
LSD	13.1		6.2		10.2		8.0		9.3		14.3			5.6		5.7		12.3		18.0		7.2		8.0			3.3		3.9		4.5		3.4		8.1		

MOISTURE CONTENT

	1997												1998												1999											
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	Means
Betta-DN	12.4	1	11.6	6	11.3	2	11.4	5	11.1	4	10.5	3	**11.38**	10.2	6	11.8	1	10.6	3	8.5	6	9.6	3	9.6	4	**10.05**	11.2	3	12.1	1	12.0	5	11.7	3	11.0	2	**11.60**
Gariep	12.2	4	11.7	5	11.3	1	11.8	1	11.2	3	10.0	6	**11.37**	10.4	3	11.6	2	10.7	2	9.3	3	9.7	2	9.7	2	**10.22**	11.2	2	12.1	2	12.2	1	11.8	2	11.0	3	**11.66**
Tugela-DN	12.3	2	12.0	1	11.2	3	11.7	2	11.4	1	10.2	5	**11.47**	10.6	1	11.4	3	10.8	1	9.5	1	9.7	1	9.6	3	**10.27**	11.1	6	12.0	3	12.1	2	11.7	5	10.9	4	**11.56**
SST 367	12.1	6	11.8	3	11.0	4	11.3	6	11.1	5	10.7	2	**11.33**	10.3	5	11.2	5	10.4	6	9.1	5	9.3	6	9.9	1	**10.04**	11.1	4	10.9	5	12.0	6	11.8	1	11.1	1	**11.38**
SST966	12.2	5	11.7	4	10.9	5	11.5	4	10.9	6	10.7	1	**11.32**	10.5	2	11.0	6	10.5	4	9.2	4	9.4	5	9.5	6	**10.01**	11.4	1	10.9	6	12.1	3	11.5	6	10.9	5	**11.36**
Molen	12.3	3	11.9	2	10.8	6	11.6	3	11.3	2	10.3	4	**11.37**	10.3	4	11.2	4	10.4	5	9.4	2	9.5	4	9.6	5	**10.05**	11.1	5	12.0	4	12.1	4	11.7	4	10.9	6	**11.56**
Environment Mean	12.3		11.8		11.1		11.5		11.2		10.4		**11.37**	10.4		11.4		10.6		9.2		9.5		9.6		**10.11**	11.2		11.7		12.1		11.7		11.0		**11.52**
CV (%)	0.9		0.5		1.6		0.6		0.6		1.3			0.7		0.7		0.6		1.7		2.2		1.0			0.6		0.2		1.1		0.3		0.3		
LSD	0.4		0.2		0.6		0.3		0.3		0.5			0.3		0.3		0.2		0.6		0.8		0.4			0.3		0.1		0.5		0.1		0.1		

Genotype and environment means of individual localities planted during 1997-1999 at the first planting date (continue)

VITREOUS KERNELS

	1997												1998												1999									
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	Means
Betta-DN	67.3	3	72.0	2	69.3	3	81.3	3	77.3	3	76.7	3	**73.98**	49.3	4	66.7	6	49.3	4	62.7	3	46.7	3	46.7	5	**53.57**	68.7	3	66.7	3	78.7	3	78.0	4	72.7	5	**72.96**
Gariep	70.7	1	57.3	5	67.3	4	82.7	2	74.0	5	82.0	1	**72.33**	47.3	5	68.7	5	48.0	5	59.3	5	42.7	6	51.3	4	**52.88**	73.3	1	70.0	2	83.3	2	76.7	5	76.0	4	**75.86**
Tugela-DN	70.7	2	70.0	3	70.7	2	87.3	1	82.7	1	79.3	2	**76.78**	52.7	3	79.3	1	42.7	6	51.3	6	43.3	5	54.7	2	**54.00**	73.3	2	66.0	6	88.0	1	88.0	1	85.3	1	**80.12**
SST 367	56.7	6	75.3	1	75.3	1	72.7	4	71.3	6	70.0	4	**70.22**	60.7	2	72.7	4	59.3	2	64.0	1	58.0	1	54.0	3	**61.45**	66.0	6	66.0	5	76.3	6	75.3	6	77.3	3	**72.18**
SST966	59.3	5	44.7	6	54.0	6	68.7	6	78.7	2	57.3	6	**60.45**	40.7	6	74.0	3	54.0	3	61.3	4	55.3	2	43.3	6	**54.77**	67.3	5	66.7	4	77.3	4	84.0	2	72.0	6	**73.46**
Molen	65.0	4	61.0	4	63.3	5	70.0	5	77.3	4	68.7	5	**67.55**	64.7	1	77.3	2	61.7	1	63.3	2	44.0	4	59.3	1	**61.72**	68.7	4	70.7	1	77.3	5	79.3	3	81.3	2	**75.46**
Environment Mean	64.9		63.4		66.7		77.1		76.9		72.3		**70.22**	52.6		73.1		52.5		60.3		48.3		51.6		**56.40**	69.6		67.7		80.2		80.2		77.4		**75.01**
CV (%)	11.8		9.1		11.2		7.4		6.8		10.4			24.0		5.9		19.3		19.6		11.8		16.9			6.7		8.2		9.7		5.5		6.8		
LSD	28.7		21.7		28.0		21.2		19.7		28.2			47.2		16.1		37.9		44.4		21.4		32.6			17.5		20.9		29.0		16.6		19.8		

BREAKFLOUR YIELD

	1997												1998												1999									
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	Means
Betta-DN	28.40	1	25.80	2	27.90	1	28.30	1	28.70	1	24.60	1	**27.28**	28.60	1	25.10	1	27.50	1	28.10	1	29.30	1	28.50	1	**27.85**	25.30	1	27.20	2	26.00	1	25.00	1	23.50	1	**25.40**
Gariep	26.60	2	25.90	1	27.30	2	26.50	2	25.80	2	23.60	3	**25.95**	28.00	3	22.60	3	26.80	2	27.80	2	27.90	2	27.80	2	**26.82**	24.00	3	25.40	5	22.10	4	20.50	5	21.10	5	**22.62**
Tugela-DN	20.10	6	21.60	6	22.00	6	19.20	6	20.40	6	18.70	5	**20.33**	23.30	6	20.30	6	23.40	6	24.20	6	22.20	6	23.00	6	**22.73**	20.70	6	21.00	6	19.50	6	18.60	6	19.00	6	**19.76**
SST 367	24.10	5	23.50	5	23.10	5	23.80	5	24.10	4	24.30	2	**23.82**	24.80	5	22.50	4	24.00	5	24.40	5	25.60	4	25.70	5	**24.50**	22.60	5	25.40	4	21.40	5	21.50	4	21.20	4	**22.42**
SST966	24.90	4	25.40	3	24.40	4	24.10	3	23.40	5	24.60	2	**24.47**	28.00	2	22.20	5	25.30	4	25.40	4	25.40	5	26.40	3	**25.45**	23.30	4	25.80	3	24.00	2	22.70	2	22.20	3	**23.60**
Molen	26.50	3	25.00	4	26.60	3	24.10	4	25.00	3	23.30	4	**25.08**	26.50	4	24.20	2	25.70	3	26.30	3	26.40	3	26.30	4	**25.90**	24.60	2	27.20	1	23.70	3	22.50	3	22.70	2	**24.14**
Environment Mean	25.1		24.5		25.2		24.3		24.6		23.2		**24.49**	26.5		22.8		25.5		26.0		26.1		26.3		**25.54**	23.4		25.3		22.8		21.8		21.6		**22.99**
CV (%)	1.6		3.4		3.8		1.7		4.3		4.1			3.0		3.7		3.4		8.1		1.6		2.2			1.0		1.2		3.6		1.5		2.2		
LSD	1.5		3.2		3.6		1.6		3.9		3.6			3.0		3.2		3.2		7.8		1.6		2.1			0.9		1.1		3.1		1.3		1.8		

FLOUR YIELD

	1997												1998												1999									
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	Means
Betta-DN	77.9	1	75.7	5	77.1	1	75.8	2	75.2	1	75.0	4	**76.12**	77.4	1	73.3	2	77.0	1	78.0	1	78.6	1	78.4	1	**77.12**	77.9	1	76.8	1	74.4	3	75.5	2	74.4	5	**75.80**
Gariep	77.1	2	75.7	4	76.5	2	76.3	1	74.8	2	75.1	3	**75.92**	77.3	2	69.9	5	76.6	2	77.7	2	78.5	2	77.5	2	**76.25**	76.3	2	76.2	2	74.2	5	75.0	4	74.9	2	**75.32**
Tugela-DN	76.3	4	76.1	2	75.5	4	73.8	5	74.5	4	72.7	6	**74.82**	76.4	4	72.7	3	74.6	5	77.3	4	77.5	4	76.6	5	**75.85**	74.9	5	75.9	3	72.2	6	74.7	5	75.0	1	**74.54**
SST 367	76.3	3	75.9	3	75.5	5	74.5	3	74.7	3	76.9	2	**75.63**	75.8	5	73.9	1	74.6	6	77.6	3	77.4	6	76.8	4	**76.02**	75.4	3	75.2	5	75.3	1	75.8	1	74.7	3	**75.28**
SST966	74.9	6	77.4	1	75.8	3	73.6	6	73.6	5	77.6	1	**75.48**	76.8	3	68.1	6	74.8	4	77.2	5	77.8	3	76.8	3	**75.25**	75.3	4	75.8	4	75.0	2	75.3	3	73.8	6	**75.04**
Molen	75.1	5	74.7	6	74.6	6	74.0	4	73.2	6	74.6	5	**74.37**	75.5	6	70.7	4	74.8	3	76.7	6	77.4	5	76.0	6	**75.18**	74.5	6	74.8	6	74.2	4	73.8	6	74.6	4	**74.38**
Environment Mean	76.2		75.9		75.8		74.7		74.3		75.3		**75.39**	76.5		71.4		75.4		77.4		77.9		77.0		**75.94**	75.7		75.8		74.2		75.0		74.6		**75.06**
CV (%)	0.4		0.8		0.8		0.4		0.4		1.0			0.6		2.8		0.9		0.8		0.5		0.4			0.6		0.5		1.5		0.3		0.5		
LSD	1.3		2.2		2.3		1.2		1.2		2.8			1.8		7.5		2.5		2.3		1.4		1.2			1.7		1.5		4.0		0.9		1.5		

FLOUR COLOUR

	1997												1998												1999									
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	Means
Betta-DN	0.7	5	1.6	5	0.3	5	1.2	6	1.7	5	0.5	5	**1.00**	1.4	5	0.5	6	1.0	6	1.0	3	0.5	5	0.8	6	**0.87**	-0.3	6	0.0	5	0.6	5	0.0	6	0.9	2	**0.24**
Gariep	0.4	6	2.2	4	-0.1	6	1.5	4	1.0	6	1.2	4	**1.03**	1.8	4	2.4	2	1.2	4	0.4	6	0.6	4	1.5	5	**1.32**	0.2	4	0.1	4	0.2	6	0.4	5	0.5	5	**0.28**
Tugela-DN	1.1	3	3.4	2	0.6	3	2.8	2	2.0	3	3.1	1	**2.17**	2.7	1	1.2	5	2.5	3	1.0	4	1.0	3	2.4	3	**1.80**	0.8	3	0.5	2	3.3	1	1.1	3	0.4	6	**1.22**
SST 367	2.3	1	2.7	3	2.0	1	1.7	3	1.9	4	1.8	2	**2.07**	2.4	3	1.2	4	2.7	1	1.3	2	1.2	1	2.8	1	**1.93**	2.3	1	0.5	3	1.2	3	2.0	1	0.5	3	**1.30**
SST966	1.0	4	0.8	6	0.3	4	1.5	5	2.2	2	0.0	6	**0.97**	0.9	6	4.6	1	1.1	5	0.5	5	0.3	6	1.6	4	**1.50**	2.2	2	-0.3	6	0.8	4	1.4	2	0.5	4	**0.92**
Molen	1.3	2	3.8	1	1.4	2	3.0	1	3.8	1	1.5	3	**2.47**	2.6	2	2.2	3	2.6	2	2.2	1	1.0	2	2.7	2	**2.22**	-0.1	5	0.8	1	1.5	2	0.9	4	0.9	1	**0.80**
Environment Mean	1.2	-9	2.4	-9	0.8	-9	1.9	-9	2.1	-9	1.3	-9	**1.62**	2.0		2.0		1.8		1.1		0.8		2.0		**1.61**	0.8		0.3		1.3		1.0		0.6		**0.79**
CV (%)	47.0		25.5		87.5		23.9		29.0		48.1			38.6		35.5		23.6		60.2		57.2		19.7			32.3		188.0		42.3		79.8		65.4		
LSD	2.0		2.3		2.5		1.7		2.3		2.4			2.9		2.7		1.6		2.4		1.6		1.4			1.0		1.9		2.0		2.9		1.5		

FLOUR PROTEIN CONTENT

	1997												1998												1999									
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	Means
Betta-DN	14.1	1	13.2	4	11.7	1	14.1	3	14.3	2	12.6	4	**13.33**	12.1	4	11.8	5	12.9	2	14.2	1	12.3	2	12.4	3	**12.62**	12.5	3	11.8	2	13.2	1	12.2	2	12.4	1	**12.42**
Gariep	13.5	2	13.1	5	11.6	2	14.4	2	12.8	5	13.1	1	**13.08**	12.9	3	12.0	4	12.1	3	11.9	5	12.0	5	11.8	4	**12.12**	11.9	5	11.1	5	11.5	6	10.4	6	10.3	5	**11.04**
Tugela-DN	13.3	3	14.6	1	10.4	5	14.9	1	12.9	4	13.0	2	**13.18**	13.1	2	11.7	6	11.7	4	11.5	6	12.8	1	12.5	2	**12.22**	12.5	2	11.1	6	13.0	3	12.1	3	10.6	4	**11.86**
SST 367	12.0	6	13.6	2	11.5	3	13.6	5	12.5	6	12.9	3	**12.68**	11.9	5	12.4	3	10.9	5	13.5	3	12.0	6	11.8	5	**12.08**	12.9	1	11.8	3	12.0	5	10.9	5	9.7	6	**11.46**
SST966	12.2	5	12.0	6	10.2	6	13.4	6	14.5	1	10.9	6	**12.20**	11.3	6	13.4	2	10.5	6	12.6	4	12.2	4	11.4	6	**11.90**	12.1	4	11.2	4	12.8	4	12.4	1	10.7	2	**11.84**
Molen	13.1	4	13.4	3	10.9	4	13.9	4	14.1	3	12.0	5	**12.90**	13.9	1	14.2	1	13.1	1	13.5	2	12.2	3	13.5	1	**13.40**	11.9	6	11.9	1	13.1	2	11.7	4	10.7	3	**11.86**
Environment Mean	13.0		13.3		11.0		14.0		13.5		12.4		**12.90**	12.5		12.6		11.9		12.9		12.2		12.2		**12.39**	12.3		11.5		12.6		11.6		10.7		**11.75**
CV (%)	5.3		4.1		5.0		4.4		7.7		9.4			5.0		6.5		4.6		14.5		5.1		5.7			3.6		5.1		4.1		7.1		4.7		
LSD	2.6		2.0		2.1		2.3		3.9		4.4			2.3		3.1		2.1		7.0		2.3		2.6			1.7		2.2		1.9		3.1		1.9		

Values for a characteristic, in the same colour, within a locality (column), do not differ significantly from each other. R=rank, LSD= Least significant difference, CV= Coefficient of variation

1997: 97CL = Clarens, 97FB = Ficksburg, 97KS= Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. 1998: 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand.

1999: 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 9HM=Hennenman, 99SK=Senekal, 99WB=Wesselsbron.

Appendix 2

Genotype and environment means of individual localities planted during 1997-1999 at the second planting date

TEST WEIGHT

	1997												1998												1999											
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	99LB	R	Means
Betta-DN	77.53	5	75.27	10	78.67	5	76.33	2	81.47	4	75.97	3	**77.54**	79.80	2	76.10	8	79.60	2	77.50	3	77.40	4	79.10	1	**78.25**	78.80	9	76.60	4	78.30	9	80.00	4	79.40	5	79.50	4	**78.77**
Gariep	78.83	1	76.33	8	78.17	7	75.40	4	80.00	9	74.17	6	**77.15**	78.60	6	80.00	1	78.60	5	77.40	4	78.60	1	78.40	2	**78.60**	80.50	2	77.60	2	79.00	4	79.10	7	79.30	7	79.80	3	**79.22**
Tugela-DN	75.40	8	77.70	6	79.30	3	75.10	5	81.30	5	77.60	1	**77.73**	77.40	7	77.90	6	76.20	9	75.50	8	77.00	6	78.10	4	**77.02**	78.10	10	75.30	9	78.40	6	80.00	3	79.50	4	77.40	8	**78.12**
SST124	77.87	3	75.30	9	81.60	1	76.97	1	83.30	1	77.03	2	**78.68**	77.10	8	79.50	4	77.60	8	76.80	5	77.90	2	75.80	9	**77.45**	81.50	1	79.30	1	78.10	10	80.80	1	81.00	1	80.30	1	**80.17**
Limpopo	76.50	7	80.23	1	78.57	6	74.03	7	79.97	10	74.50	5	**77.30**	78.70	5	79.90	2	79.00	4	76.30	7	76.50	9	77.60	6	**78.00**	79.60	5	76.40	6	79.20	2	78.80	9	78.30	10	77.80	7	**78.35**
Caledon	77.77	4	78.53	3	78.00	9	73.50	9	81.23	6	73.67	9	**77.12**	79.40	4	79.50	3	79.30	3	76.70	6	77.40	3	77.70	5	**78.33**	79.60	6	75.10	10	79.00	3	78.90	8	78.70	8	79.50	5	**78.47**
Elands	76.73	6	80.00	2	78.97	4	75.67	3	81.47	3	75.70	4	**78.09**	80.00	1	78.00	5	79.70	1	78.20	1	77.00	7	78.40	3	**78.55**	79.80	4	77.40	3	79.50	1	80.40	2	79.50	3	80.20	2	**79.47**
PAN 3235	78.63	2	78.10	5	79.67	2	74.83	6	81.50	2	73.53	10	**77.71**	79.60	3	77.50	7	78.10	6	77.50	2	77.30	5	74.80	10	**77.47**	79.80	3	76.40	7	78.90	5	79.80	5	79.60	2	79.40	6	**78.98**
PAN 3349	75.37	9	76.80	7	76.97	10	73.97	8	81.00	7	73.97	7	**76.35**	73.30	10	75.90	9	77.80	7	74.80	9	77.00	8	77.40	8	**76.03**	79.00	8	76.40	5	78.30	7	78.70	10	78.50	9	76.80	9	**77.95**
SST972	75.37	10	78.30	4	78.13	8	73.43	10	80.43	8	73.77	8	**76.57**	76.80	9	74.90	10	76.00	10	74.50	10	76.30	10	77.60	7	**76.02**	79.40	7	76.30	8	78.30	8	79.20	6	79.40	6	75.10	10	**77.95**
Env Mean	77.00		77.66		78.80		74.92		81.16		75.15		**77.42**	78.10		77.90		78.20		76.50		77.20		77.50		**77.57**	79.60		76.70		78.70		79.60		79.30		78.60		**78.74**
CV	0.81		0.82		0.99		0.96		0.89		2.23			0.70		1.75		1.02		0.50		0.31		0.71			0.48		0.58		0.79		0.59		0.50		0.96		
LSD	2.00		2.03		2.50		2.31		2.46		5.11			1.74		4.38		2.54		1.23		0.77		1.75			1.23		1.43		2.00		1.51		1.27		2.42		

THOUSAND KERNEL WEIGHT

	1997												1998												1999											
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	99LB	R	Means
Betta-DN	37.73	6	38.53	4	29.67	4	31.50	4	31.57	5	30.00	4	**33.17**	41.70	5	36.60	7	41.00	4	36.70	7	35.50	6	37.20	4	**38.12**	35.02	8	31.33	6	32.23	7	32.57	6	32.83	6	37.06	7	**33.51**
Gariep	39.80	4	35.10	9	28.83	7	30.77	7	30.23	9	28.63	8	**32.23**	40.20	6	38.30	4	40.10	7	34.90	8	35.00	8	35.60	6	**37.35**	36.61	4	31.47	5	31.57	8	31.27	7	31.17	7	37.28	6	**33.23**
Tugela-DN	44.03	1	46.70	1	34.07	1	34.50	2	41.30	1	34.85	2	**39.24**	44.90	2	41.70	2	41.60	2	40.40	2	41.70	1	39.40	2	**41.62**	39.49	1	35.08	2	36.33	2	38.50	1	39.30	1	41.86	1	**38.43**
SST124	36.33	8	35.07	10	27.77	10	28.20	10	30.57	8	28.17	9	**31.02**	33.80	10	32.40	10	34.60	10	31.70	10	31.90	10	32.40	9	**32.80**	32.98	10	29.78	10	34.57	4	30.17	9	**30.13**	9	33.82	10	**31.91**
Limpopo	35.83	10	36.20	8	29.10	6	29.83	8	28.17	10	28.87	7	**31.33**	35.00	8	36.90	6	38.70	9	34.00	9	33.30	9	35.20	7	**35.52**	34.14	9	29.86	9	30.10	10	29.70	10	28.30	10	35.13	9	**31.37**
Caledon	36.57	7	36.23	7	29.33	5	29.40	9	31.27	7	28.97	6	**31.96**	42.10	4	38.90	3	40.00	8	37.70	5	35.00	7	37.10	5	**38.47**	36.29	5	30.09	8	30.40	9	30.80	8	**30.50**	8	38.05	2	**32.69**
Elands	36.07	9	36.77	5	28.17	9	31.50	5	31.50	6	29.50	5	**32.25**	42.80	3	38.00	5	40.60	5	38.20	4	35.60	5	37.40	3	**38.77**	36.92	3	31.48	4	32.97	6	33.30	5	**33.67**	4	37.96	4	**34.38**
PAN 3235	38.40	5	36.33	6	30.40	3	31.03	6	31.73	4	27.80	10	**32.62**	39.90	7	36.00	8	40.20	6	37.10	6	36.20	4	34.60	8	**37.33**	36.08	7	30.85	7	32.97	5	33.57	4	33.03	5	38.05	3	**34.09**
PAN 3349	41.50	3	39.43	3	28.33	8	33.57	3	35.80	2	30.60	3	**34.87**	34.50	9	33.20	9	41.10	3	38.90	3	39.50	3	31.80	10	**36.50**	36.22	6	33.51	3	34.73	3	35.47	3	35.67	3	35.69	8	**35.22**
SST972	41.80	2	44.60	2	32.33	2	34.83	1	34.27	3	35.07	1	**37.15**	45.50	1	43.00	1	44.00	1	40.50	1	40.50	2	40.30	1	**42.30**	38.80	2	36.33	1	38.40	1	36.83	2	37.03	2	37.89	5	**37.55**
Env Mean	38.81		38.50		29.80		31.51		32.02		30.53		**33.58**	40.00		37.50		40.20		37.00		36.40		36.10		**37.88**	36.26		31.98		33.43		33.22		33.26		37.28		**34.24**
CV (%)	3.30		1.79		3.97		3.68		3.03		6.89			4.71		4.65		1.91		2.75		2.32		1.64			1.59		1.37		3.09		2.61		1.86		2.73		
LSD	4.10		2.21		3.79		3.71		3.30		6.40			6.04		5.58		2.45		3.26		2.71		1.90			1.85		1.40		3.31		2.78		1.98		3.26		

KERNEL DIAMETER

	1997												1998												1999											
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	99LB	R	Means
Betta-DN	2.51	7	2.61	4	2.18	5	2.26	5	2.27	5	2.25	6	**2.35**	2.68	5	2.40	8	2.70	3	2.48	7	2.54	5	2.59	4	**2.57**	2.42	9	2.21	6	2.24	7	2.31	5	2.32	6	2.48	9	**2.33**
Gariep	2.59	5	2.38	10	2.16	7	2.23	7	2.24	9	2.26	5	**2.31**	2.59	6	2.53	4	2.66	7	2.48	8	2.53	7	2.46	7	**2.54**	2.53	4	2.25	5	2.25	6	2.28	8	2.31	7	2.57	4	**2.36**
Tugela-DN	2.91	1	2.88	1	2.42	1	2.45	1	2.77	1	2.69	1	**2.69**	2.81	1	2.73	1	2.75	2	2.80	1	2.94	1	2.68	2	**2.79**	2.68	2	2.48	2	2.51	2	2.69	1	**2.69**	1	2.79	1	**2.64**
SST124	2.65	4	2.52	6	2.24	3	2.25	6	2.32	4	2.27	4	**2.38**	2.43	10	2.45	6	2.53	10	2.46	9	2.50	9	2.41	10	**2.46**	2.53	5	2.36	4	2.30	4	2.32	4	**2.36**	4	2.50	8	**2.40**
Limpopo	2.49	9	2.46	7	2.11	8	2.19	10	2.12	10	2.12	10	**2.25**	2.55	8	2.41	7	2.57	9	2.31	10	2.42	10	2.42	9	**2.45**	2.34	10	2.16	10	2.13	10	2.16	10	**2.15**	10	2.41	10	**2.22**
Caledon	2.51	8	2.45	9	2.11	9	2.19	8	2.26	7	2.23	8	**2.29**	2.77	3	2.58	3	2.70	4	2.51	5	2.54	6	2.60	3	**2.62**	2.44	7	2.16	9	2.19	8	2.20	9	2.23	9	2.57	3	**2.30**
Elands	2.42	10	2.54	5	2.08	10	2.28	4	2.26	6	2.23	7	**2.30**	2.69	4	2.52	5	2.70	5	2.57	4	2.52	8	2.54	5	**2.59**	2.47	6	2.21	7	2.27	5	2.29	7	2.36	4	2.54	5	**2.36**
PAN 3235	2.55	6	2.45	8	2.18	4	2.19	9	2.25	8	2.21	9	**2.31**	2.56	7	2.39	9	2.62	8	2.50	6	2.55	4	2.47	6	**2.52**	2.42	8	2.18	8	2.19	9	2.31	6	2.31	8	2.51	7	**2.32**
PAN 3349	2.78	2	2.66	3	2.18	6	2.35	3	2.46	2	2.44	2	**2.48**	2.46	9	2.32	10	2.69	6	2.70	3	2.75	3	2.45	8	**2.56**	2.59	3	2.39	3	2.38	3	2.50	3	2.40	3	2.53	6	**2.46**
SST972	2.73	3	2.78	2	2.36	2	2.44	2	2.38	3	2.40	3	**2.52**	2.78	2	2.67	2	2.84	1	2.75	2	2.87	2	2.77	1	**2.78**	2.69	1	2.58	1	2.56	1	2.55	2	**2.58**	2	2.64	2	**2.60**
Env Mean	2.61		2.57		2.20		2.28		2.30		2.33		**2.39**	2.63		2.50		2.68		2.56		2.62		2.54		**2.59**	2.51		2.30		2.30		2.36		2.37		2.55		**2.40**
CV (%)	3.31		1.67		2.73		2.83		2.21		1.66			1.92		3.26		1.91		2.44		2.30		1.80			1.95		1.64		2.39		2.18		2.09		2.12		
LSD	0.28		0.14		0.19		0.21		0.17		0.12			0.16		0.26		0.16		0.20		0.19		0.15			0.16		0.12		0.18		0.17		0.16		0.17		

Values for a characteristic, in the same colour, within a locality (column), do not differ significantly from each other. R=rank, LSD= Least significant difference, CV= Coefficient of variation, Env Mean= Environment mean
1997: 97CL = Clarens, 97FB = Ficksburg, 97KS= Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. 1998: 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand.
1999: 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 99HM=Hennenman, 99LB=Ladybrand, 99SK=Senekal, 99WB=Wesselsbron

Genotype and environment means of individual localities planted during 1997-1999 at the second planting date (continue)

HARDNESS INDEX

	1997												1998												1999											
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	99LB	R	Means
Betta-DN	65.36	9	69.20	9	80.59	7	63.10	5	82.41	9	71.76	7	**72.07**	57.50	9	66.80	9	63.10	8	54.30	9	54.30	9	55.20	9	**58.53**	66.07	9	65.30	9	70.10	8	73.53	8	73.50	8	67.08	9	**69.26**
Gariep	70.39	2	79.26	5	84.37	4	63.22	4	84.97	8	71.08	8	**75.55**	61.90	7	73.00	5	62.20	9	63.30	5	61.80	3	59.90	4	**63.68**	70.91	5	74.26	2	78.28	3	78.80	3	80.00	1	70.45	5	**75.45**
Tugela-DN	69.78	4	77.47	6	88.36	2	68.15	2	87.34	5	79.34	1	**78.41**	64.50	3	76.00	2	69.00	3	66.80	2	62.90	2	59.60	5	**66.47**	74.79	2	74.10	3	80.98	1	79.78	2	77.80	3	71.00	2	**76.41**
SST124	72.63	1	82.54	1	91.97	1	68.57	1	92.11	1	77.34	2	**80.86**	72.00	1	82.40	1	74.30	1	68.80	1	71.20	1	65.00	1	**72.28**	77.84	1	76.26	1	77.72	4	82.20	1	79.50	2	79.49	1	**78.84**
Limpopo	66.35	7	80.43	2	82.91	5	60.68	7	87.01	7	74.01	5	**75.23**	61.30	8	74.70	3	67.00	5	62.00	6	60.90	4	61.20	3	**64.52**	70.91	4	70.76	6	77.21	5	75.25	7	74.90	7	69.82	7	**73.14**
Caledon	69.85	3	80.15	3	84.96	3	64.11	3	89.19	2	75.86	3	**77.35**	64.50	2	74.00	4	69.50	2	64.40	3	60.20	5	62.40	2	**65.83**	72.38	3	72.23	4	78.40	2	78.31	4	77.70	4	70.75	4	**74.96**
Elands	65.64	8	79.82	4	78.01	9	55.10	9	87.12	6	73.12	6	**73.14**	62.00	6	69.40	8	67.40	4	57.30	7	57.30	8	58.70	8	**62.02**	68.53	7	65.84	7	69.50	9	75.56	6	75.00	6	70.81	3	**70.87**
PAN 3235	69.22	5	74.87	7	81.88	6	61.90	6	88.35	4	75.02	4	**75.21**	63.50	4	71.40	6	65.20	6	63.30	4	59.60	6	59.10	6	**63.68**	70.50	6	71.32	5	73.67	6	76.65	5	76.80	5	69.98	6	**73.15**
PAN 3349	66.80	6	71.80	8	80.40	8	58.86	8	88.44	3	63.68	9	**71.66**	62.90	5	70.20	7	64.30	7	55.40	8	57.70	7	58.80	7	**61.55**	66.48	8	65.70	8	73.63	7	69.06	9	72.90	9	68.80	8	**69.43**
SST972	56.53	10	61.86	10	65.62	10	49.90	10	78.87	10	62.21	10	**62.50**	44.10	10	57.20	10	49.40	10	42.90	10	43.90	10	42.10	10	**46.60**	55.67	10	53.34	10	58.93	10	61.06	10	63.00	10	57.80	10	**58.30**
Env Mean	67.25		75.74		81.91		61.36		86.53		72.78		**74.20**	61.40		71.50		65.10		59.80		59.00		58.20		**62.52**	69.41		68.91		73.84		75.02		75.10		69.60		**71.98**
CV (%)	3.78		1.79		6.98		3.73		2.84		5.07			2.65		3.78		2.84		2.33		2.50		2.65			3.63		1.61		1.87		1.77		2.27		2.39		
LSD	8.14		4.33		18.32		7.32		8.35		11.24			5.21		8.66		5.92		4.46		4.72		4.95			8.08		3.54		4.42		4.26		5.47		5.33		

MOISTURE CONTENT

	1997												1998												1999											
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	99LB	R	Means
Betta-DN	11.63	7	11.40	10	10.95	10	11.34	9	11.57	5	10.67	5	**11.26**	10.50	9	11.50	5	10.50	9	9.31	7	9.47	5	9.22	10	**10.08**	11.35	5	10.94	10	12.01	6	11.65	9	11.14	10	10.53	9	**11.02**
Gariep	11.91	3	11.70	8	11.19	4	11.69	2	11.51	7	10.92	1	**11.49**	10.60	7	11.50	3	10.70	5	9.72	6	9.66	1	9.41	9	**10.27**	11.44	3	11.22	4	11.90	9	11.69	7	11.34	9	10.68	4	**10.27**
Tugela-DN	11.99	2	11.78	4	11.24	2	11.65	3	11.36	9	10.92	2	**11.49**	10.80	4	11.60	2	10.80	4	9.73	5	9.32	8	9.48	8	**10.29**	11.29	8	11.18	5	11.93	8	11.68	8	11.58	6	10.62	8	**10.94**
SST124	11.89	4	11.71	7	11.16	5	11.41	6	11.47	8	9.69	10	**11.22**	10.40	10	11.50	4	10.60	8	9.87	1	9.47	6	9.94	4	**10.30**	11.35	6	11.17	6	11.96	7	11.73	5	11.69	3	10.75	2	**9.98**
Limpopo	11.38	10	12.11	1	11.31	1	11.40	7	11.58	4	10.57	7	**11.39**	10.70	5	11.60	1	10.80	3	9.83	3	9.33	7	10.00	3	**10.38**	11.64	1	11.34	1	12.10	5	11.87	3	11.58	5	10.67	6	**10.76**
Caledon	11.80	6	11.68	9	11.20	3	11.36	8	11.59	3	10.74	4	**11.40**	10.60	8	11.40	7	10.60	6	9.84	2	9.19	10	9.86	6	**10.25**	11.23	10	11.12	9	12.10	4	11.80	4	11.43	8	10.66	7	**10.78**
Elands	11.86	5	12.02	2	11.00	9	11.60	4	11.54	6	10.81	3	**11.47**	10.70	6	11.30	8	10.50	10	9.17	10	9.56	4	9.94	5	**10.20**	11.29	9	11.25	3	11.83	10	11.91	1	11.64	4	10.67	5	**10.49**
PAN 3235	12.07	1	11.77	5	11.07	8	11.77	1	11.64	1	10.64	6	**11.49**	10.90	3	11.20	9	10.80	2	9.83	4	9.62	2	10.00	1	**10.39**	11.32	7	11.14	8	12.19	2	11.90	2	11.71	2	10.74	3	**10.21**
PAN 3349	11.60	8	12.01	3	11.14	6	11.57	5	11.60	2	10.28	9	**11.37**	11.10	1	11.40	6	10.90	1	9.20	9	9.59	3	10.00	2	**10.37**	11.48	2	11.28	2	12.41	1	11.73	6	11.87	1	10.94	1	**9.96**
SST972	11.52	9	11.75	6	11.09	7	11.25	10	11.33	10	10.35	8	**11.22**	10.90	2	10.90	10	10.60	7	9.20	8	9.24	9	9.56	7	**10.07**	11.38	4	11.15	7	12.16	3	11.44	10	11.48	7	10.46	10	**11.27**
Env Mean	11.77		11.79		11.14		11.50		11.53		10.58		**11.38**	10.70		11.40		10.70		9.57		9.45		9.75		**10.26**	11.38		11.18		12.06		11.74		11.55		10.67		**10.57**
CV (%)	1.29		1.08		0.80		1.51		1.31		3.45			0.86		0.87		0.85		2.02		1.46		1.82			0.44		0.36		0.21		0.38		0.95		0.66		
LSD	0.49		0.41		0.29		0.56		0.51		1.11			0.29		0.32		0.29		0.62		0.44		0.57			0.16		0.13		0.08		0.14		0.35		0.23		

VITREOUS KERNELS

	1997												1998												1999											
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	99LB	R	Means
Betta-DN	72.67	3	76.00	7	78.67	3	66.67	8	78.00	8	68.00	6	**73.34**	74.70	5	75.30	2	70.00	3	69.30	4	65.30	3	51.30	7	**67.65**	76.00	5	74.67	3	82.00	6	84.67	2	80.00	7	78.67	1	**79.34**
Gariep	74.67	2	72.00	9	80.00	2	66.67	9	78.67	7	72.00	4	**74.00**	65.30	8	77.30	1	64.00	6	62.00	8	57.30	7	47.30	10	**62.20**	76.67	4	78.67	2	78.00	10	83.33	3	82.00	4	67.33	8	**77.67**
Tugela-DN	60.00	7	90.00	1	78.00	5	71.33	4	96.00	1	81.60	1	**79.49**	59.30	9	57.30	10	53.30	9	65.30	7	79.30	1	53.30	5	**61.30**	78.67	3	72.00	6	82.00	5	87.33	1	82.67	2	74.00	3	**79.45**
SST124	80.00	1	75.00	8	58.67	10	61.33	10	68.00	10	52.00	10	**65.83**	75.30	4	62.70	9	71.30	2	62.00	9	66.00	2	58.00	4	**65.88**	71.33	8	69.33	9	87.33	1	70.67	10	73.33	9	72.67	4	**74.11**
Limpopo	63.33	6	83.00	3	73.33	8	73.33	2	83.33	4	80.00	2	**76.05**	71.30	7	73.30	4	66.00	4	78.70	2	56.70	8	60.00	3	**67.67**	69.33	9	69.33	8	84.00	3	82.67	5	76.67	8	72.00	5	**75.67**
Caledon	59.33	8	82.00	4	78.67	4	78.00	1	81.33	5	72.67	3	**75.33**	80.00	1	74.00	3	74.00	1	75.30	3	58.00	6	65.30	1	**71.10**	84.67	1	74.00	4	83.33	4	82.67	6	81.33	5	71.33	6	**79.56**
Elands	48.00	9	68.00	10	75.33	6	71.33	5	80.00	6	53.33	9	**66.00**	75.30	3	64.00	8	60.00	8	66.70	5	52.70	9	50.70	8	**61.57**	75.33	6	70.00	7	81.33	7	82.67	7	81.33	6	62.67	10	**75.56**
PAN 3235	68.67	4	80.00	6	80.67	1	68.00	7	86.67	2	72.00	5	**76.00**	79.30	2	70.70	6	65.30	5	66.70	6	61.30	5	52.00	6	**65.88**	84.00	2	79.33	1	78.00	9	80.67	8	86.67	1	75.33	2	**80.67**
PAN 3349	66.00	5	83.33	2	74.00	7	72.00	3	84.67	3	66.67	7	**74.45**	72.70	6	72.00	5	63.30	7	80.00	1	63.30	4	60.70	2	**68.67**	72.00	7	73.33	5	87.33	2	82.67	4	82.00	3	71.33	7	**78.11**
SST972	46.67	10	80.67	5	62.67	9	68.00	6	77.33	9	64.00	8	**66.56**	48.00	10	67.30	7	46.70	10	48.00	10	52.00	10	50.00	9	**52.00**	67.33	10	58.67	10	78.67	8	74.00	9	67.33	10	66.00	9	**68.67**
Env Mean	63.93		79.00		74.00		69.67		80.36		69.06		**72.70**	70.10		69.40		63.40		67.40		61.20		54.90		**64.39**	75.53		71.93		82.20		81.13		79.33		71.13		**76.88**
CV (%)	10.05		5.36		10.47		10.82		7.05		8.49			10.00		9.67		10.90		7.05		9.01		9.78			6.89		5.54		3.51		4.98		4.76		8.55		
LSD	20.58		13.55		24.81		24.13		19.23		17.84			22.50		21.50		22.20		15.20		17.70		17.20			16.66		12.75		9.25		12.94		12.09		19.48		

Values for a characteristic, in the same colour, within a locality (column), do not differ significantly from each other. R=rank, LSD= Least significant difference, CV= Coefficient of variation, Env Mean= Environment mean
1997: 97CL = Clarens, 97FB = Ficksburg, 97KS= Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. 1998: 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand.
1999: 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 99HM=Hennenman, 99LB=Ladybrand, 99SK=Senekal, 99WB=Wesselsbron

Genotype and environment means of individual localities planted during 1997-1999 at the second planting date (continue)

BREAKFLOUR YIELD

	1997												1998												1999											
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	99LB	R	Means
Betta-DN	26.16	2	25.40	2	24.70	3	29.44	3	25.19	3	29.23	1	**26.69**	27.40	1	26.20	1	24.90	3	28.40	1	28.40	1	28.30	1	**27.27**	24.40	2	27.49	1	26.99	1	26.31	1	26.66	1	25.36	1	**26.20**
Gariep	23.63	8	24.63	5	24.41	6	28.51	6	25.98	1	28.48	6	**25.94**	27.20	2	25.20	2	26.40	1	26.70	5	26.90	3	28.00	2	**26.73**	24.22	3	25.06	6	24.99	6	24.60	4	24.45	6	24.56	3	**24.65**
Tugela-DN	20.55	10	21.00	10	18.85	10	22.82	9	18.25	10	21.53	10	**20.50**	19.80	10	20.30	10	21.00	10	21.50	10	21.50	10	24.70	8	**21.47**	19.85	10	21.54	10	21.17	10	19.32	10	19.86	10	20.81	10	**20.43**
SST124	23.78	6	22.40	8	20.99	9	23.71	8	21.13	9	23.17	8	**22.53**	22.30	9	21.70	8	21.70	9	22.90	9	23.00	9	23.90	10	**22.58**	21.65	9	22.58	9	22.60	9	20.55	8	21.05	8	21.17	9	**21.60**
Limpopo	25.98	3	24.30	6	24.32	7	28.89	5	25.92	2	28.67	5	**26.35**	24.70	3	24.90	3	25.10	2	27.60	2	26.20	6	26.70	3	**25.87**	23.87	5	25.91	5	26.83	2	24.73	3	25.92	2	24.88	2	**25.36**
Caledon	25.84	5	25.10	4	24.55	5	29.78	2	23.93	6	29.03	2	**26.37**	24.10	5	24.50	4	24.10	5	27.40	3	26.90	4	26.10	5	**25.52**	23.98	4	26.60	4	26.77	3	24.91	2	25.58	3	23.80	5	**25.27**
Elands	26.21	1	23.80	7	24.99	2	30.26	1	23.94	5	29.00	3	**26.37**	23.40	7	24.50	6	23.60	8	27.20	4	27.30	2	26.30	4	**25.38**	23.64	6	26.66	3	26.29	4	24.04	5	24.98	5	23.32	6	**24.82**
PAN 3235	25.85	4	25.43	1	25.76	1	29.15	4	24.02	4	28.93	4	**26.52**	24.00	6	24.10	7	24.10	4	26.60	6	26.40	5	25.90	6	**25.18**	24.46	1	27.00	2	26.19	5	23.88	6	25.02	4	23.93	4	**25.08**
PAN 3349	23.69	7	25.13	3	24.23	8	26.50	7	21.61	8	26.39	7	**24.59**	23.40	8	24.50	5	23.90	6	25.70	7	24.10	7	24.30	9	**24.32**	23.59	7	24.67	7	23.79	7	21.81	7	21.26	7	22.55	7	**22.95**
SST972	21.97	9	21.57	9	24.62	4	21.99	10	22.87	7	22.06	9	**22.51**	24.40	4	20.90	9	23.70	7	23.40	8	23.70	8	24.80	7	**23.48**	23.34	8	24.60	8	22.61	8	20.40	9	20.86	9	22.00	8	**22.30**
Env Mean	24.37		23.88		23.74		27.11		23.64		26.33		**24.84**	24.10		23.70		23.90		25.80		25.40		25.90		**24.78**	23.30		25.21		24.82		23.06		23.57		23.24		**23.87**
CV (%)	4.06		2.65		3.02		2.56		6.27		5.29			4.94		3.20		2.12		1.68		1.57		1.31			2.56		1.89		1.20		2.06		1.46		2.70		
LSD	3.17		2.02		2.30		2.22		5.03		4.24			3.81		2.43		1.62		1.39		1.28		1.08			1.91		1.53		0.95		1.52		1.10		2.01		

FLOUR YIELD

	1997												1998												1999											
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	99LB	R	Means
Betta-DN	75.49	1	77.20	3	74.64	8	75.58	8	75.81	5	76.77	4	**75.92**	77.00	1	75.10	5	73.90	9	78.30	4	78.30	5	78.00	2	**76.77**	76.23	3	76.36	3	78.76	2	76.66	2	76.34	3	75.83	5	**76.70**
Gariep	74.91	3	76.07	8	75.50	5	75.95	5	75.84	4	76.85	2	**75.85**	76.80	2	75.20	4	75.40	3	77.50	8	78.00	7	77.60	4	**76.75**	74.57	9	74.57	9	77.30	10	76.14	4	75.83	6	75.96	3	**75.73**
Tugela-DN	72.60	8	75.57	10	73.86	9	75.10	9	75.09	8	76.41	6	**74.77**	75.60	4	74.80	7	73.00	10	76.00	10	76.30	10	77.00	7	**75.45**	73.69	10	74.50	10	78.40	4	75.85	7	75.26	9	74.62	9	**75.39**
SST124	74.92	2	77.05	4	76.29	1	77.01	2	76.46	1	76.76	5	**76.42**	75.40	5	75.40	3	75.20	5	77.80	5	78.30	4	78.00	1	**76.68**	78.11	1	77.72	1	79.07	1	76.96	1	77.84	1	76.66	1	**77.73**
Limpopo	74.07	6	77.40	1	75.43	6	75.92	6	75.68	6	77.08	1	**75.93**	75.30	6	75.40	2	75.70	2	79.70	1	78.40	3	77.50	5	**77.00**	75.85	5	75.87	5	78.11	6	75.87	6	75.86	5	75.70	6	**76.21**
Caledon	74.46	5	77.30	2	75.83	3	75.80	7	76.01	3	76.82	3	**76.04**	75.70	3	75.60	1	74.90	6	79.30	2	78.60	1	77.70	3	**76.97**	75.96	4	75.32	7	77.79	7	76.06	5	75.75	7	75.88	4	**76.13**
Elands	72.36	9	76.23	7	73.41	10	77.01	1	73.62	9	76.04	7	**74.78**	72.50	10	73.80	9	74.30	8	78.90	3	77.70	8	76.90	8	**75.68**	74.63	8	75.96	4	78.59	3	74.71	9	74.11	10	74.79	8	**75.47**
PAN 3235	73.00	7	76.43	6	75.98	2	76.41	4	76.09	2	74.35	10	**75.38**	74.20	7	74.10	8	75.20	4	77.60	7	78.20	6	77.30	6	**76.10**	74.87	7	75.70	6	77.62	9	75.65	8	76.30	4	75.01	7	**75.86**
PAN 3349	74.79	4	77.03	5	75.55	4	76.84	3	75.67	7	75.52	8	**75.90**	74.00	8	74.90	6	75.80	1	77.60	6	78.50	2	75.80	10	**76.10**	75.73	6	77.00	2	78.29	5	76.51	3	76.95	2	75.99	2	**76.75**
SST972	72.08	10	75.93	9	74.91	7	73.86	10	72.51	10	74.95	9	**74.04**	73.50	9	68.90	10	74.60	7	76.30	9	76.60	9	76.10	9	**74.33**	76.83	2	74.70	8	77.67	8	74.52	10	75.50	8	74.28	10	**75.58**
Env Mean	73.87		76.62		75.14		75.95		75.29		76.17		**75.50**	75.00		74.30		74.80		77.90		77.90		77.20		**76.18**	75.65		75.77		78.16		75.89		75.97		75.47		**76.15**
CV (%)	1.20		0.37		0.98		0.87		1.98		1.21			0.90		1.45		0.71		0.84		0.36		0.36			0.92		0.58		0.67		0.31		0.43		0.85		
LSD	2.85		0.91		2.36		2.12		5.05		2.82			2.15		3.45		1.70		2.10		0.90		0.88			2.23		1.40		1.68		0.75		1.05		2.04		

FLOUR COLOUR

	1997												1998												1999											
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	99LB	R	Means
Betta-DN	2.47	6	3.10	3	1.97	1	1.47	6	1.33	5	1.43	5	**1.96**	-2.00	10	1.30	5	1.90	5	1.90	6	0.80	6	1.10	6	**0.83**	0.37	8	-0.10	9	-0.13	2	0.40	4	-0.10	6	0.17	9	**0.10**
Gariep	2.50	4	3.27	2	1.03	5	0.53	9	1.30	6	1.53	4	**1.69**	-1.40	8	1.00	6	1.20	7	1.50	8	0.80	7	1.10	7	**0.70**	1.47	4	0.63	6	-0.47	9	0.57	3	0.13	4	0.63	7	**0.49**
Tugela-DN	3.33	2	3.53	1	1.80	2	2.27	2	1.80	2	1.82	2	**2.43**	0.20	5	1.80	3	2.80	1	3.80	1	1.10	2	1.30	4	**1.83**	2.20	1	1.27	3	0.33	1	0.97	1	1.00	1	2.23	3	**1.33**
SST124	1.20	10	2.47	5	-0.57	10	-0.13	10	-0.40	10	0.17	10	**0.46**	-1.10	6	0.50	10	0.80	10	1.80	7	-0.50	10	0.40	10	**0.32**	-0.47	10	-2.23	10	-1.60	10	0.20	6	-1.07	10	-0.30	10	**-0.91**
Limpopo	2.50	5	1.37	10	0.77	7	1.60	4	0.70	8	0.77	9	**1.28**	-1.30	7	0.90	8	1.10	8	1.20	9	1.00	3	1.10	5	**0.67**	1.43	5	0.33	7	-0.27	5	0.63	2	-0.50	9	1.17	5	**0.47**
Caledon	1.90	8	2.10	7	0.63	8	1.27	7	0.53	9	0.90	8	**1.22**	-1.50	9	0.70	9	1.00	9	1.10	10	0.10	9	0.80	9	**0.37**	1.57	3	0.67	5	-0.30	6	0.17	7	-0.23	7	2.37	2	**0.71**
Elands	3.60	1	2.53	4	1.60	3	1.00	8	2.83	1	1.00	7	**2.09**	2.00	2	2.20	2	2.30	2	2.20	5	0.90	4	1.70	3	**1.88**	2.03	2	0.00	8	-0.13	3	0.33	5	0.37	2	1.73	4	**0.72**
PAN 3235	3.03	3	1.67	8	1.27	4	1.47	5	1.77	3	2.17	1	**1.89**	0.50	4	1.50	4	2.20	3	2.60	4	1.20	1	0.90	8	**1.48**	0.43	7	1.57	1	-0.13	4	-2.43	10	0.00	5	0.40	8	**-0.03**
PAN 3349	1.50	9	1.57	9	0.83	6	1.87	3	1.27	7	1.57	3	**1.43**	2.70	1	0.90	7	1.20	6	2.70	3	0.60	8	2.50	1	**1.77**	0.17	9	1.30	2	-0.43	8	-2.20	9	0.27	3	0.97	6	**0.01**
SST972	2.33	7	2.40	6	0.00	9	3.77	1	1.63	4	1.27	6	**1.90**	1.30	3	5.00	1	1.90	4	2.70	2	0.80	5	1.80	2	**2.25**	1.10	6	1.23	4	-0.33	7	-1.77	8	-0.33	8	2.67	1	**0.43**
Env Mean	2.44		2.40		0.93		1.51		1.24		1.30		**1.64**	-0.10		1.60		1.60		2.20		0.70		1.30		**1.21**	1.03		0.47		-0.35		-0.31		-0.05		1.20		**0.33**
CV (%)	33.14		20.76		47.34		39.68		63.06		45.85			-928.00		54.60		27.40		33.70		59.30		27.70			56.01		91.39		-92.30		-128.00		-1340.00		34.56		
LSD	2.59		1.60		1.42		1.92		2.65		1.81			2.20		2.80		1.40		2.30		1.30		1.10			1.85		1.37		1.03		1.28		2.00		1.33		

Values for a characteristic, in the same colour, within a locality (column), do not differ significantly from each other. R=rank, LSD= Least significant difference, CV= Coefficient of variation, Env Mean= Environment mean
1997: 97CL = Clarens, 97FB = Ficksburg, 97KS= Kroonstad, 97HB=Hebron, 97HM=Hennenman, 97LB=Ladybrand. 1998: 98CC=Clocolan, 98EX=Excelsior, 98FF=Frankfort, 97HB=Hebron, 98HM=Hennenman, 98LB=Ladybrand.
1999: 99BS=Bultfontein monoculture, 99BO=Bultfontein fallow, 99HM=Hennenman, 99LB=Ladybrand, 99SK=Senekal, 99WB=Wesselsbron

Genotype and environment means of individual localities planted during 1997-1999 at the second planting date (continue)

FLOUR PROTEIN CONTENT

	1997												
Cultivar	97FB	R	97CL	R	97LB	R	97KS	R	97HB	R	97HM	R	Means
Betta-DN	15.44	1	13.03	8	11.41	5	15.25	3	12.28	5	14.20	5	**13.60**
Gariep	13.77	9	12.90	9	11.31	6	13.65	10	12.95	2	14.17	7	**13.13**
Tugela-DN	13.90	8	14.17	3	11.19	8	13.77	9	13.36	1	14.40	4	**13.47**
SST124	14.97	3	15.47	1	11.02	9	13.97	7	11.22	9	14.64	3	**13.55**
Limpopo	13.43	10	12.77	10	11.21	7	14.47	5	12.48	4	14.18	6	**13.09**
Caledon	14.83	4	13.97	4	11.72	4	15.95	1	12.04	6	13.60	10	**13.69**
Elands	14.25	7	13.20	7	13.05	1	14.43	6	12.62	3	15.25	1	**13.80**
PAN 3235	14.73	6	13.80	5	11.79	3	13.95	8	11.95	7	14.73	2	**13.49**
PAN 3349	15.07	2	15.00	2	11.88	2	14.98	4	11.78	8	13.77	9	**13.75**
SST972	14.73	5	13.57	6	10.66	10	15.83	2	10.69	10	13.90	8	**13.23**
Env Mean	14.51		13.79		11.53		14.63		12.14		14.28		**13.48**
CV (%)	10.30		5.57		7.88		8.24		8.23		4.84		
LSD	4.79		2.46		2.91		3.86		3.20		2.21		

	1998												
Cultivar	98CC	R	98LB	R	98FF	R	98HM	R	98HB	R	98EX	R	Means
Betta-DN	12.70	6	13.80	3	12.90	3	14.30	7	13.30	7	11.00	8	**13.00**
Gariep	13.00	3	12.30	8	13.00	2	14.30	7	13.00	10	10.70	9	**12.72**
Tugela-DN	11.90	9	13.30	5	12.20	8	14.80	1	14.10	4	10.70	9	**12.83**
SST124	14.90	1	12.40	7	13.50	1	14.10	9	14.50	2	12.20	4	**13.60**
Limpopo	12.70	5	11.80	10	12.20	10	14.40	3	13.10	9	12.30	3	**12.75**
Caledon	12.60	7	11.80	9	12.70	5	14.50	2	13.60	5	12.70	2	**12.98**
Elands	12.00	8	12.90	6	12.20	9	14.40	3	13.30	8	11.50	7	**12.72**
PAN 3235	12.80	4	13.60	4	12.50	7	14.40	3	14.40	3	11.90	5	**13.27**
PAN 3349	14.00	2	14.80	2	12.60	6	13.60	10	13.60	6	13.80	1	**13.73**
SST972	11.80	10	15.30	1	12.80	4	14.40	3	14.50	1	11.90	5	**13.45**
Env Mean	12.90		13.20		12.70		14.30		13.70		11.90		**13.11**
CV (%)	9.86		9.84		6.97		7.00		3.24		4.54		
LSD	4.06		4.16		2.83		3.21		1.42		1.73		

	1999												
Cultivar	99SK	R	99HM	R	99WB	R	99BS	R	99BO	R	99LB	R	Means
Betta-DN	12.75	7	13.47	1	13.23	1	12.63	6	12.37	4	12.48	6	**12.82**
Gariep	11.47	10	12.13	9	12.47	8	12.27	9	11.90	9	11.59	10	**11.97**
Tugela-DN	13.06	3	13.08	4	13.13	3	13.33	2	12.20	7	12.57	5	**12.90**
SST124	13.06	2	12.54	7	12.20	10	12.60	7	12.57	3	12.35	8	**12.55**
Limpopo	13.23	1	11.75	10	12.30	9	12.47	8	12.27	5	13.39	2	**12.57**
Caledon	12.98	4	13.26	3	13.03	5	12.73	5	12.67	2	12.35	7	**12.84**
Elands	12.85	5	12.87	5	13.13	4	11.40	10	12.23	6	11.94	9	**12.40**
PAN 3235	12.79	6	13.40	2	13.17	2	13.47	1	12.70	1	12.76	4	**13.05**
PAN 3349	12.31	9	12.47	8	12.90	7	13.20	3	11.63	10	12.92	3	**12.57**
SST972	12.44	8	12.73	6	12.97	6	12.83	4	12.03	8	15.15	1	**13.03**
Env Mean	12.69		12.77		12.85		12.69		12.26		12.75		**12.67**
CV (%)	4.38		3.08		4.07		3.99		5.28		4.97		
LSD	1.78		1.26		1.67		1.62		2.07		2.03		

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