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THE UNIVERSITY OF ALBERTA

Studies of Grain Hardness and Functional Quality in the Early Generations of a Wheat Cross (*Triticum aestivum*, L.)

BY

Hongli Zhang

A Thesis

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **Studies of grain hardness and functional quality in early generations of a spring wheat cross (*Triticum aestivum*, L.)**, submitted by Hongli Zhang in partial fulfilment of the requirements for the degree of Master of Science in Plant Breeding.

Supervisor

Date 16/7/89

Dedication

To my grandmother and my parents

Abstract

Canadian Prairie Spring Wheat is a new category of wheat for Western Canada and the major quality breeding objectives have been harder grain kernels, higher protein content and stronger flour strength. The materials used in the present study were from four generations of plant progenies (F3--F6, derived from F2 single plants) of a cross between two parents, the Canadian Prairie Spring wheat HY 320, and the cultivar QT 8132 with harder kernels, higher protein content, stronger flour strength and lower grain yield than HY 320. The objectices were to examine the efficiency of hardness selection and how such selection affects the other quality measures, to examine the effects of site-year and different seed sources, and to estimate the correlations among, and the heritabilities of, the quality traits obtained from microprediction tests for wheat quality in Triticum aestivum, L..

The results obtained showed that the hardness grouping in F4 significantly affected the measures of hardness, flour yield, protein content, farinograph water absorption and arrival time in the later generations of F5 and F6. Wheats selected for harder kernels were shown in later generations to be harder and to have higher flour yield, higher protein content, higher water absorption and longer farinograph arrival time. Wheat in the softest group had significantly lower flour yield and protein content than the other groups. Thus hardness measures could be used to identify lines with low flour yield and low protein content. The hardness grouping did not affect the measures of sedimentation value, farinograph dough development time and stability; thus the selection for these characters, such as for stronger flour strength as measured by sedimentation and stability, should [illegible] carried out separately from the hardness selection. Site-years significantly influenced the quality measures of hardness, protein content and sedimentation value in F4 and F5, suggesting that for the true estimates of these values multi-site testing is necessary. It was also shown that significant correlations exist between the California winter nursery and Edmonton research station for hardness and sedimentation value, implying that site-years influenced the mean values of the population, but not the ranking of individual lines within the population. Thus testing on the winter nursery material for hardness and sedimentation values would be effective and resource saving strategy. In F4, F5 and F5 generations, hardness showed significant correlation with protein content, flour yield, farinograph water absorption and arrival time, while sedimentation value showed significant correlation with protein content, farinograph dough development time and stability. Thus it would appeared that testing of hardness, sedimentation value and protein content should present a reasonable overall estimates for quality improvement in the Canadian Prairie Spring wheat class. Inter-generation regression heritabilities showed that hardness and sedimentation value were significantly heritable, indicating that selection for these two traits would be effective in the early generations of breeding programs.

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1. Introduction

Good quality traits are major breeding objectives in most modern wheat breeding programs but wheat quality is defined in many different ways for different end products. Each type of wheat has its own typical grain and flour characteristics which can be specified in terms of quality measures such as grain hardness, protein quantity and quality, farinograph and extensograph properties, and other measures. (Finney and Yamazaki, 1967, 1987).

In plant breeding programs the limitations of seed supply, and the large number of early generation breeding lines that needs to be evaluated annually, restrict the type of quality evaluation that can be conducted using standard methods. Fortunately a number of micro-prediction tests for wheat quality have been developed in the past thirty years that require a relatively short time and small quantities of samples (Hehn and Barmore, 1965; Pomeranz, 1988). The results from those micro-prediction tests have been very similar to those obtained from standard large scale measures (Finney and Yamazaki 1967, 1987) and most of the prediction tests are also highly repeatable (de La Roche and Fowler, 1974). Plant breeders can now use these quick, small-scale tests to select wheats suited for each of the end-use categories.

Amongst the microprediction tests, grain hardness, protein content and protein quality have been proposed and accepted as being fundamental measures of the quality attributes of breadmaking wheat in most studies (Hehn and Barmore,1965; Fowler and de La Roche, 1975a; O'Brien and Ronalds, 1987). Differences in these traits have been associated with differences of the milling and baking characteristics of the breadwheat varieties (Symes, 1969; Baker and Dyke, 1975; Baker and Cambell, 1979; Tipples et al, 1981; Pomeranz et al, 1984). Hardness is of particular interest to wheat researchers, not only because of its importances in wheat classification but also because it is very easy to measure and is controlled by major gene(s) (Symes, 1965; Symes, 1969; Baker, 1978; Miller et al, 1984). It has been suggested that hardness is the easiest single test to carry out to best predict the possible potential baking quality, both in soft and hard wheat (Yamazaki and Donelson, 1983; Williams, 1986). Thus further knowledge concerning selection for hardness and its effects on the other quality traits would be of interest to plant breeders.

Many quality traits have been reported to be heritable and the heritabilities reported from the prediction tests have generally been moderate to high (Baker et al, 1968; Lofgren et al, 1968; Briggs and Shebeski, 1971; Bhatt and Derera, 1975; Baker, 1977; Pearson et al. 1981; O'Brien and Ronalds, 1987), and use of the strategy of early generation selection has been frequently suggested. Heyne and Finney (1965) suggested the use of the F2 progeny method to study early generation selction for quality. Shebeski (1967) proposed that selection for wheat breadmaking quality in a cross could start on a single plant basis as early as the F3 generation, and effective early generation testing has also been reported by others (Lebsock et al, 1964; Atkins et al, 1965; McNeal et al, 1969). The efficiency of early generation selection depends on the speed and accuracy with which the genotypic value can be measured on small and often unreplicated samples of the available plant material. As quality characteristics are phenotypic observations, the accuracy with which a particular test measures the genotypic value must be assessed by its heritability, and the knowledge of the inheritance of quality traits is important for predicting the progress that a plant breeder can make during selection.

It is commonly accepted that quality components are not independent from each other in their final contribution to breadmaking quality, and that the performance of one component is likely to be influenced by the variability of other components. An understanding of the interrelationships between the quality components would be an asset in any quality breeding program. Results of these interrelationship studies in the past were often controversial and hard to interpret because of confounded genotypic and environmental effects. The interrelationships among the quality components tend to be varietal specific, and clear relationships demonstrated in some studies are not repeatable in others. The influence of location and environmental effects on the quality parameters has long been recognized and is commonly reported (Ladd and Bailey, 1910; Baker et al, 1968). The high variation caused by location and environment effects mean that extensive year, location and climate testing is necessary. An efficient breeding program depends on the knowledge of possible site, year and location effects on the quality traits and their interrelationships. Relatively little is yet known about such effects in early generation wheat materials, especially for the Canadian Prairie Spring wheat class.

Most past studies (e.g. Baker et al,1968; Orth et al, 1972; Bhatt and Derera, 1975; Fowler and de La Roche, 1975b) used highly selected, advanced generation materials from regional trials or varieties with known difference in quality, and few studies (Briggs 1969; Borghi et al. 1975; Pearson et al. 1981; O'Brien and Ronalds, 1987.) have been conducted with grains from single plant derived rows or from the early generation plots in a breeding programme. It is these materials that are of the greatest interest for evaluating the efficiency of early generation selection and its practical usage in a breeding programme.

Canadian Prairie Spring (CPS) wheat is a new category of wheat for Western Canada. Some of the quality improvement objectives for this class include a harder wheat kernel, higher protein content and stronger flour. The present research was designed to get further understanding on the effects of hardness selection in CPS wheat progenies and how such selection affects other measures of quality. The material used was from a cross between two parents (one of which is a CPS wheat), differing substantially in grain hardness, grain yield, sedimentation value and protein content. There were three specific objectives in the present study:

1) To examine the impact of hardness selection in the F4 generation on the functional quality traits of the later generations (F5 and F6).

2) To study and describe the heritabilities of, and correlation among, the quality traits in the early generations of a Hard X Medium Hard wheat cross, using grains from the F3, F4, F5 and F6 generations derived from different seed sources.

3) To compare the quality traits of grains from samples grown in Edmonton and in the California winter nursery, to examine the site-year and seed source effects on the quality traits, and the effectiveness of quality measurements on the winter nursery material as compared with Edmonton materials, for the same population. Both F4 and F5 generations were used for this comparison.

2. Literature Review

2.1 Wheat Quality and Interrelationship of Quality Characters.

Wheat quality means different things to different people. Each segment of the wheat industry, made up from breeders, growers, traders, millers and bakers, has its own concept of what constitutes a good quality wheat. Nevertheless, it is generally accepted that good breadmaking quality means at least two things: First, the wheat must have the basic physical and chemical properties required by the milling and baking processes, and secondly, and maybe more importantly, the flour must possess the ability to produce a good quality bread (Tipples et al. 1982). Finney et al. (1967, 1987) reviewed these interests in detail and stated that a flour of good quality for breadmaking should have a high water absorption, a medium to medium long mixing requirement, satisfactory mixing tolerance and dough handling properties, good loaf volume potential and ability to produce good internal crumb grain and color.

Generally speaking, breadmaking quality is a complex physico-chemical character and a number of different physical and chemical tests have been developed to measure the individual components of wheat quality. These individual properties of wheat grain and flour play important roles in the overall quality performance. The components are not independent from each other in their final contribution to the breadmaking quality, and the contribution of each component is likely to be influenced by variability in the other. Thus the interrelationships of the quality components have frequently been studied.(Sunderman et al. 1965; Baker et al. 1968; Bushuk et al. 1969; de La Roche and Fowler 1975; O'Briens and Ronalds 1987).

Among the quality characters that have been studied, protein content has been one of the greatest interest. The major effect of protein content on breadmaking quality has been known for some time. In a review, Finney and Yamazaki (1967) concluded that all quality properties are a function of protein content in one way or another, although the protein content alone does not account for all the quality differences (Bushuk et al. 1969). Loaf volume measure is an effective means of assessing the final breadmaking quality. Finney and Barmore (1948), in a study on both hard winter and spring wheat varieties ranging in protein content from 8.5 to 18%, demonstrated a linear relation between protein content and loaf volume. Fifield et al. (1950) studied 589 wheat samples representing 10 varieties of hard red spring wheat grown in four crop years under a wide range of climatic and soil conditions and reported a similar linear relationship between flour protein and loaf volume. The relationship between loaf volume and flour protein for each variety was linear within the limits of protein content encountered from 8.5-18%. Regression lines for loaf volume on protein content for any variety were similar in all four crop years. Bushuk et al. (1969) investigated the effects of protein quality and quantity as factors in the evaluation of bread wheats. They reported that within bread wheat cultivars which differ in protein quality, the loaf volume was positively correlated with protein content. It is now recognized that the loaf volume is a function of both the quantity and the quality of the flour protein (Finney et al. 1987).

In two studies, Finney et al. (1948) and Fifield et al. (1950) suggested further that the examination of the protein/loaf volume regression lines can be used to separate the protein quality differences of cultivars, as the intercept and the slope of the regression lines of loaf volume on protein content for the varieties differed significantly. This relationship has been subsequently established by other researchers (Sunderman et al. 1965; Fowler and de La Roche 1975a).

Protein content also relates to many other quality traits. Bushuk et al. (1969) found that for the single variety Manitou, grown in the same location over two years, most of the standard breadmaking quality parameters were significantly correlated with protein content. Fowler and de La Roche (1975b) found a significant influence of variation in protein content on 1000 kernel weight, bushel weight and on baking quality. Tkachuk and Kuzina (1979) showed that wheat grain density was negatively correlated with protein content. These relationships can be expected for lines in a plant breeding programs.

Wheat protein content has frequently been reported to be correlated with farinograph characteristics (Sunderman et al. 1965; Fowler and de La Roche 1975b). High protein content can accompany an increase in farinograph water absorption (Finney and Yamazaki 1967) and stability (Lebsock et al. 1964). Orth et al. (1975) reported that protein content and farinograph water absorption both increased with flour extraction rate and suggested that optimum flour yield should be determined for each variety, or more practically for each wheat type, to allow realization of maximum breadmaking potential. They also reported that gluten strength decreased with increasing extraction rate by showing an increase in farinograph dough breakdown and a decrease in maximum extensograph resistance, accompanied by a depression of loaf volume potential at extraction rate above optimum. Shogren et al. (1986) concluded that water absorption and loaf volume potential (and indirectly, mixing time) are governed by protein content and quality, by extractability and by their interactions.

Flour strength has been recognized as a basic factor in determining flour breadmaking quality (Wrigley and Moss, 1968, Briggs and Shebeski 1972, Tipples et al. 1982) and it has been primarily a function of protein quality (Wrigley and Moss 1968; Tipples et al. 1982). Zeleny (1947) developed the sedimentation test as a measure of flour protein quality and significant positive correlations between sedimentation value and protein content have been frequently reported (Greenaway et al. 1966; Fowler and de La Roche 1975a; Pearson et al. 1981). This correlation simply describes a relationship between the two parameters and does not explain any functional relationship. Higher sedimentation values would not therefore guarantee higher protein contents. Hsu and Sosulski (1969) stated that based on phenotypic correlations obtained in F2 wheat populations the two quality traits (protein content and sedimentation value) showed no consistent relationship, positive or negative, depending on the cross. Thus it appears that the relationship is a property of the individual cross. In other studies, sedimentation value has been shown to correlate positively with many other quality traits, especially the dough consistency and handling properties (Fowler and de La Roche 1975b).

The physical properties of wheat grain also have effects on the overall quality, especially on milling quality. Among them hardness of the grain is of the greatest interest. Starch damage, which results from mechanical fracturing of the starch granule, increases with wheat endosperm hardness and is related to the rate and level of water absorption and dough development characteristics. Williams (1967) has shown that hardness, as measured by particle size index, is closely related to starch damage, diastatic activity, water absorption and gassing power for a wide range of varieties grown in Australia. Symes (1969) found that a single gene for hardness increased flour yield, thus harder wheat had higher flour yield. Baker and Dyck (1975) reported similar result in studies using a segregating population. Baker and Dyck (1975) also indicated that hardness as measured by the particle size index (PSI), or grinding time, was related to mixograph peak height and farinograph absorption. Furthermore, they indicated that grinding time may appear to be a more economical test than PSI, as it is simplier and easier to operate, in distinguishing hard and soft wheat within a segregating population.

The relationship between protein content and wheat hardness has been the subject of numerous investigations, with often conflicting results. Aamodt and Torrie (1935) first reported a positive relationship between protein content and grain hardness among a group of varieties and suggested that hardness was caused by the effect of the protein so that hardness could be used as an indicator for the protein content. Symes (1965) studied the genetics of hardness and protein content and reported that no relation could be found between the two traits in the Australian varieties used. Miller et al. (1984) studied the protein effects on grain hardness and concluded that for all varieties and across all locations, grain protein content was not correlated with hardness. Some varieties, however, showed significant negative or positive relationship between protein content and hardness. It herefore appeared that the relationship was variety specific. Davis et al. (1961), using a segregation population, also investigated this relationship and showed that correlation values were not significantly different from zero in two crosses, but were significant and positive in two other crosses(r=0.25, 0.61). Pomeranz et al. (1988) reported a positive relationship between protein content and hardness and indicated that when the hardness score was correlated with protein, it was only a reflection of the fact that the hard wheats were high in protein , rather than that protein and hardness were related.

Wheat quality is a complex factor, and the advent of a clear, simple test for the factors primarily responsible for breadmaking quality would present a clear advantage to those involved in the wheat industry, especially plant breeders. Greenaway et al. (1966) presented evidence to indicate that sedimentation is the test that singularly gives the best prediction of bread making quality and strength of a hard wheat. Baker and Campbell (1971) found that, in addition to sedimentation value, measures of nitrogen content and centrifuge absorption provided useful information on breadmaking quality (viz. remix loaf volume and mixing properties). The additional information provided by the centrifuge absorption was related to the degree of starch damage, which could in turn reflect kernel hardness (Williams, 1967; Barlow et al. 1973) and/or differences in milling damage of the starch itself (Collins 1971; Farrand 1972).

In another study, in an evaluation of eight tests to screen early generations of wheat for breadmaking quality, Baker et al. (1971) found that protein content, farinograph developing time and gassing power were the most useful in predicting loaf volumes in a selection program for quality. Orth et al. (1972) reported that residue protein content, Zeleny sedimentation value and Farinograph dough development time provided the most useful information for predicting baking quality by a single test. Fowler and de La

Roche(1975b) studied 29 basic grain and flour tests required for wheat quality assessment, and concluded that only measurements of kernel hardness, protein content and dough development are necessary to describe the baking quality of wheat.

Factor analysis has been used to suggest as many as three (Orth et al. 1976) four (Jardine et al. 1963; Wrigley and Moss 1968) or up to seven (Briggs and Shebeski 1972) groupings of related quality tests. These include measures of strength, stability, hardness, stiffness, 1000 kernel weight, bushel weight and flour ash. A logical interpretation of these factor analysis results would be that at least one test is needed for each of the quality factors to guarantee effective quality screening in a breeding program. Considering the large number of samples to be tested and the work that is involved, a wheat breeder must restrict himself to limiting the number of selection tests to the minimum number which could still properly represent the total correlation matrix. A review of literature showed that tests of grain hardness, protein content and protein quality are most commonly used to describe the overall quality package of a variety, especially in the early generations of a breeding program (Fowler and de La Roche, 1975a; Orth et al. 1976; O'Brien and Orth 1977).

2.2 Hardness, and its Significance in a Wheat Quality Breeding Program

Kernel hardness has become commonly recognized as a fundamental component of milling and baking quality of wheat (Triticum aestivum, L) (Symes 1965; Finney and Yamazaki 1967; Fowler and de La Roche 1975a; Pomeranz et al. 1984; Finney et al. 1987). In the process of flour milling, grain hardness has decisive effects on the cleanness of separation of endosperm from bran, moisture level tolerance, the resultant size of the endosperm fragments and the sieving behavior of the flours. These factors in turn influence the rate of mill through-put, and the quality and yield of the flour, as well as the final overall breadmaking quality. Thus kernel hardness was very often used in wheat classification. (Poser, 1988)

Differences in grain kernel hardness have been associated with many quality traits, such as flour yield, mixing characteristics, and loaf volume, etc. (Symes 1969; Baker and Dyck; 1975; Pomeranz et al. 1988). Williams (1967) showed that the physical hardness of wheat has a direct effect on its milling performance, and on water absorption, damaged starch content, and fermentation capacity of flours, and that there is a close relationship between kernel hardness and starch damage (Williams 1967). Simmonds (1974) reported that hard and soft wheat fracture differently during the milling process, which causes differences in starch damage levels and particle size. Hard wheat produced larger flour particles with higher starch damage levels, compared to soft wheat (Farrand 1972; Stenvert 1974). The hard wheat can tolerate high moisture levels during conditioning to give the optimum flour yield of flour consistent with an acceptable flour color.

Both the flour particle size and the starch damage level correlate with the final breadmaking quality of the flour (Pratt 1978). Nevertheless, starch damage level may appear to be more responsible for flour quality than particle size, especially for dough rheological characteristics (Kurimoto and Shelton 1988). In breadmaking, higher levels of starch damage result in higher water absorption of the dough and subsequently, higher bread yield and better crumb texture.

The biochemical nature of hardness is still unknown. Symes (1969) has suggested that "the effect of changing this gene (for hardness) is to change the type of the protein that is laid down within the grain" Thus, grain hardness may relate to the strength with which the protein matrix entraps the starch granules and also possibly to the structure of the granules themselves. On the other hand, the tightness of adhesion between the protein matrix and starch granules may be more important in determining the grain hardness than the composition of the protein matrix (Simmonds et al. 1973).

For an important character like hardness, controlled by a major gene, wheat breeders have long realized the relevance of measuring this character as a classifier of quality. In modern wheat breeding programs, breeder often intercross diverse types of wheat and produce crosses with wild relatives of wheat to improve agronomic and production performance. Innovative crosses may produce segregates with soft wheat characteristics and these should be removed from a hard wheat breeding program, or alternatively they may produce segregates with hard wheat characteristics, making them unsuitable for a soft breeding program. It has been suggested that if only one quality characteristic is to be chosen, hardness would be the one best able to predict the possible potential quality in baking, both in soft (Yamazaki and Donelson 1983) and hard wheat (Williams,1986). These suggestions have encouraged plant breeders, since the hardness test may be the easiest single test to carry out. This would be especially beneficial in early generations when relatively large numbers of small, often unreplicated samples need to be screened.

There have been many laboratory methods suggested for hardness testing and each one has been modified at least several times already.The most commonly used tests are: 1) Time to grind (Miller at al. 1981); 2) Particle size index (PSI) (Symes 1961); 3) Resistance to grinding (Stenvert 1971); and 4) Near Infra Red Reflectance (Williams 1979).

It would not be a surprise that varieties would respond differently to different testing methods. Factors like moisture and temperature of the grain, kernel size and shape, and sometimes even the protein content, would interact with different testing methods and the inherent hardness of the kernel, thus influencing the recorded values (Obuchuski and Bushuk 1980). This variation will be further enhanced when the year, location, cultivar and the effects of their interactions are taking into consideration. Nevertheless, effective discrimination between cultivars, and the consistency of the relationships that exist between hardness and other quality parameters still enable plant breeders to use hardness extensively to select new cultivars (Fowler and de La Roche, 1975a; Pomeranz and Mattern 1987). Pomeranz and Miller (1982) studied a range of hardness tests and concluded that time to grind can most effectively evaluate the hardness of plant breeders samples and distinguish hard and soft wheats in marketing channels, while Near-Infra Red Reflectance method (NIR) was the most effective for accurate ranking of varieties.

2.3 The Inheritance of Breadmaking Quality in Wheat.

Studies on the inheritance of breadmaking quality have been limited to examination of the inheritance of the individual components of

4.2 Hardness selection effects on the expression of other quality parameters:

4.2.1 ANOVA

Hardness selection was conducted in 1987 on the 360 F4 progeny lines. To estimate the effects of hardness grouping on the measures of other quality traits throughout the generations, the results of each quality traits were subjected to analysis of variance (ANOVA). The grouping effects were reported in Table 4.2.1.1 for prediction tests, and in Table 4.2.1.2 for farinograph testing and Buhler milling.

Hardness and flour yield measures were significantly influenced by selection according to seed source and generations. Grain protein content was also significantly affected by the selection pressure for all the seed sources except for cF5 (i.e. 1988 Edmonton F5, derived from 1987/88 California F4)

Sedimentation values were generally not significantly influenced by selection for hardness (Table 4.2.1.1), indicating an independence of sedimentation measures from hardness. Seed source of aF5 (i.e. 1987/88 California F5) was the only case where hardness grouping had significantly affected the sedimentation measurements.

Hardness selection showed no significant effects on 1000 kwt and hectolitre weight measures (Table 4.2.1.1).

Table 4.2.1.1 Effects of hardness selection on other quality parameters (Prediction tests)

	Rep #	Hard	Prot	Sedt	Flyd	Kwt	Hlwt
aF4	1	___	**	NS	**	NS	NS
bF4	1	**	**	NS	*	NS	___
aF5	1	**	**	**	**	NS	___
cF4	2	**	**	NS	*	NS	NS
bF5	2	**	**	NS	**	NS	NS
cF5	2	**	NS	NS	**	NS	NS
88 F6	2	**	**	NS	**	NS	NS

Note:
* Significant at 0.05 level.
** Significant at 0.01 level.
88 = 1988
Rep # = Number of replications.
NS = Not significant at 0.05 level.
___ = No test was performed.

Buhler milling and farinograph measures were conducted on the seed source of aF4 (i.e. 1987 Edmonton F4), bF5 (i.e. 1988 Edmonton F5, derived from 1987 Edmonton F4) and on the Edmonton 1988 F6. Hardness selection by group significantly affected the group quality traits farinograph water absorption (FAB), farinograph arrival time (FAT) and Buhler Experimental Milling Yield (Bflyd) for all three seed sources (Table 4.2.1.2).

With one exception of the farinograph stability measures (FST) in the bF5 sample, all other farinograph characteristics (FPT, FST, FDT, FMTI and F20) were not shown to be affected by slection for hardness (Table 4.2.1.2).

Table 4.2.1.2 **Effects of hardness selection on other quality parameters (Farinograph properties and Buhler milling tests)**

	Edm 87 F4	Edm 88 F5	Edm 88 F6
FAB	**	*	**
FAT	*	*	**
FPT	NS	NS	NS
FST	NS	**	NS
FDT	NS	NS	NS
FMTI	NS	NS	NS
F20	NS	NS	NS
Bflyd	*	*	*

1) * and ** are indicators for significance at 0.05 and 0.01 confidence levels.
2) 87 = 1987. 88 = 1988 Edm = Edmonton
3) NS = Not significant.

4.2.2 Comparison of means of the three hardness groups for the quality parameters of hardness, protein content and flour yield

Mean values for each of the three hardness groups were calculated for each of the seed and generation sources. Duncan's multiple mean comparison tests were conducted within each seed and generation source for hardness, protein and flour yield.

Results were reported in such a way that "normal plant breeding progression" (1987 Edmonton F4 --> 1987/88 California F5 --> 1988 Edmonton F6) was separated from the "1988 Edmonton all generation special case" where all generations (F3 to F6) were present in the one. Results are summarized in Tables 4.2.2.1a, 4.2.2.1b, 4.2.2.2a, 4.2.2.2b, 4.2.2.3a, and 4.2.2.3b, and graphically in Figures 4.2.2.1a, 4.2.2.1b, 4.2.2.2a, 4.2.2.2b, 4.2.2.3a, and 4.2.2.3b.

For hardness, the means of the three hardness groups differed significantly from each other throughout the seed source, location and generations except for the 1988 Edmonton F3 case, where the means of the medium and soft groups were not significantly different (Table 4.2.2.1a, Table 4.2.2.1b).

Among the three sample groups divided on the basis of hardness, means of protein content showed no significant difference between the hard and medium-hard groups for most of the seed sources, especially under the "normal plant breeding procedures" (Table 4.2.2.2a, Table 4.2.2.2b). However in the 1988 Edmonton conditions F4(cF4) and F5(bF5), means for protein content of each of the hardness groups were significantly different from each other (Table 4.2.2.2a, Table 4.2.2.2b).

Soft wheats usually have a lower protein content than hard wheat. Significant differences were observed between the soft group and the other hardness groups for protein level in most of the situations. In 1988 Edmonton F3 hill plots, no significant differences were found among the hardness groups for protein content (Table 4.2.2.2b).

The pattern of performance of the flour yield means was similar to that for protein. Means of flour yield in the soft group were usually significantly different from those for the other two groups. Exceptions were the 1987 Edmonton F4 and 1988 Edmonton F3, where no differences were found between the soft and medium-hard groups (Table 4.2.2.3a, Table 4.2.2.3b). In the 1988 Edmonton F3 hill plots, means of flour yield for hard, medium-hard and soft groups did differ from each other significantly (Table 4.2.2.3b).

Means of flour yield for the hard wheat group were generally not significantly different from those of the medium-hard group throughout all generation and seed sources (Table 4.2.2.3a, Table 4.2.2.3b).

Table 4.2.2.1a Duncan's Multiple Mean Comparison of Hardness measures in the Normal Plant Breeding Progression

Hardness Group	MEANS 1987 Edmonton F4	1987/88 California F5	1988 Edmonton F6
Hard	26.3a	23.3a	23.9a
Medium	32.1b	27.2b	28.9b
Soft	43.3c	32.6c	36.1c
Standard Error of Mean	0.40	0.65	0.52

Note: Means in each of the column following by different letters are significantly different at *p* = 0.05, using Duncan's Multiple range test.

Table 4.2.2.1b Duncan's Multiple Mean Comparison of Hardness measures in the 1988 All Generations Special Case

Hardness Group	MEANS 88 Edm F3	88 Edm F4	88 Edm F5	88 Edm F6
Hard	26.0a	24.2a	24.7a	23.9a
Medium	30.2b	30.7b	30.5b	28.9b
Soft	30.5b	38.6c	33.5c	36.1c
Standard Error of Mean	1.75	0.73	0.37	0.52

Note: Means in each of the column following by different letters are significantly different at *p* = 0.05, using Duncan's Multiple range test.

Table 4.2.2.2a Duncan's Multiple Mean Comparison of Protein Content (%) in the Normal Plant Breeding Progression

Hardness Group	MEANS		
	1987 Edm F4	1987/88 Calif F5	1988 Edm F6
Hard	13.1b	12.6b	12.5b
Medium	13.2b	12.2b	12.2b
Soft	12.3a	11.2a	11.2a
Standard Error of Mean	0.19	0.15	0.18

Note: Means in each of the column following by different letters are significantly different at $p = 0.05$, using Duncan's Multiple range test.

Table 4.2.2.2b Duncan's Multiple Mean Comparison of Protein Content (%) in the 1988 All Generations Special Case

Hardness Group	MEANS			
	88 Edm F3	88 Edm F4	88 Edm F5	88 Edm F6
Hard	12.8a	12.4c	12.7c	12.5b
Medium	12.6a	11.9b	12.2b	12.2b
Soft	12.7a	10.9a	11.1a	11.2a
Standard Error of Mean	0.26	0.14	0.15	0.18

Note: Means in each of the column following by different letters are significantly different at $p = 0.05$, using Duncan's Multiple range test.

Table 4.2.2.3a Duncan's Multiple Mean Comparison of Flour Yield (%) in the Normal Plant Breeding Progression

Hardness Group	MEANS 1987 Edm F4	 1987/88 Calif F5	 1988 Edm F6
Hard	71.0b	68.5b	72.5b
Medium	66.5a	65.9b	71.9b
Soft	67.7a	60.0a	63.2a
Standard Error of Mean	0.49	1.53	0.74

Note: Means in each of the column following by different letters are significantly different at $p = 0.05$, using Duncan's Multiple range test.

Table 4.2.2.3b Duncan's Multiple Mean Comparison of Flour Yield (%) in the 1988 All Generations Special Case

Harndess Group	MEANS 88 Edm F3	 88 Edm F4	 88 Edm F5	 88 Edm F6
Hard	64.3a	73.2b	72.0c	72.5b
Medium	64.4a	72.6b	69.9b	71.9b
Soft	64.3a	70.1a	67.3a	63.2a
Standard Error of Mean	0.93	0.65	0.69	0.74

Note: Means in each of the columns following by different letters are significantly different at $p = 0.05$, using Duncan's Multiple range test.

Figure 4.2.2.1a Means of Hardness Measures in Each of the Hardness Groups under the Normal Plant Breeding Progression (SE=Standard error)

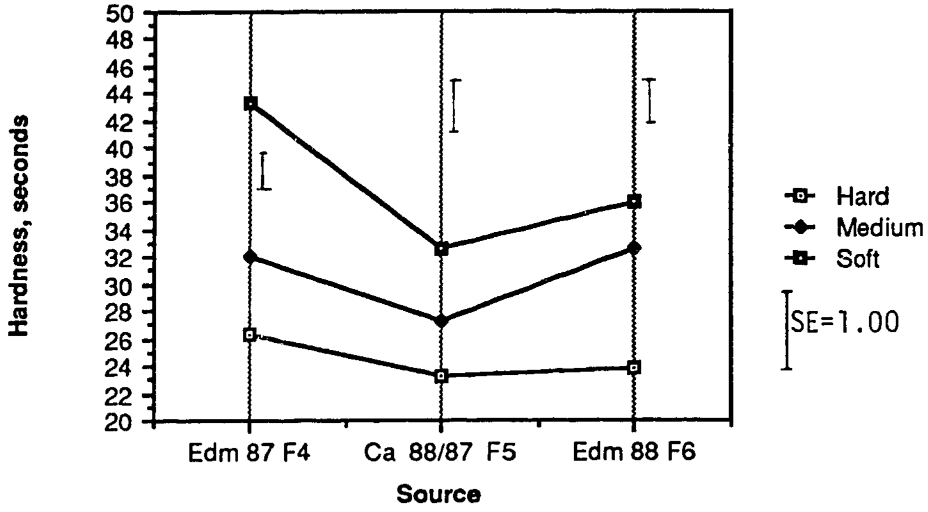


Figure 4.2.2.1b Means of Hardness Measures in Each of the Hardness Groups under the 1988 All Generation Speciai Case (SE= Standard error)

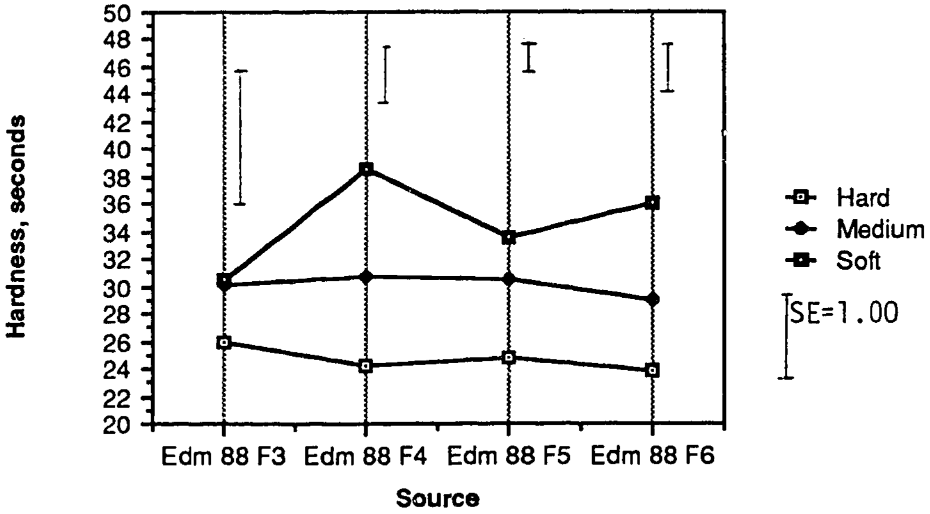


Figure 4.2.2.2a Means of Protein Content Measures in Each of the Hardness Groups under the Normal Plant Breeding Progression (SE= Standard error)

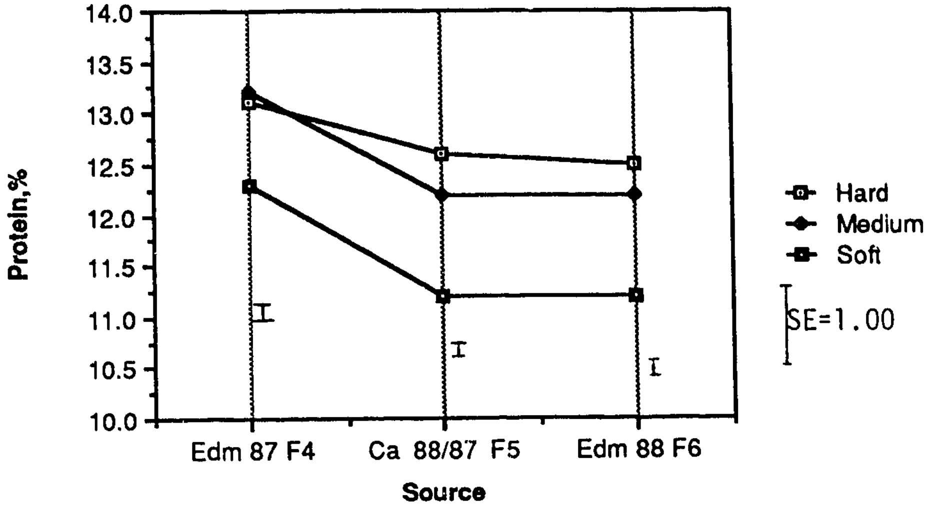


Figure 4.2.2.2b Means of Protein Content Measures in Each of the Hardness Groups under the 1988 All Generation Special Case (SE= Standard error)

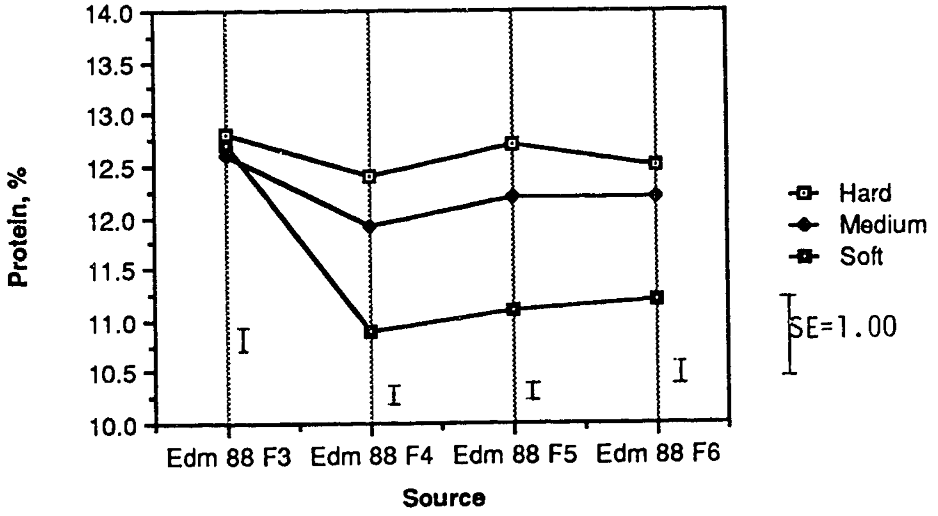


Figure 4.2.2.3a Means of Flour Yield Measures in Each of the Hardness Groups under the Normal Plant Breeding Progression (SE= Standard error)

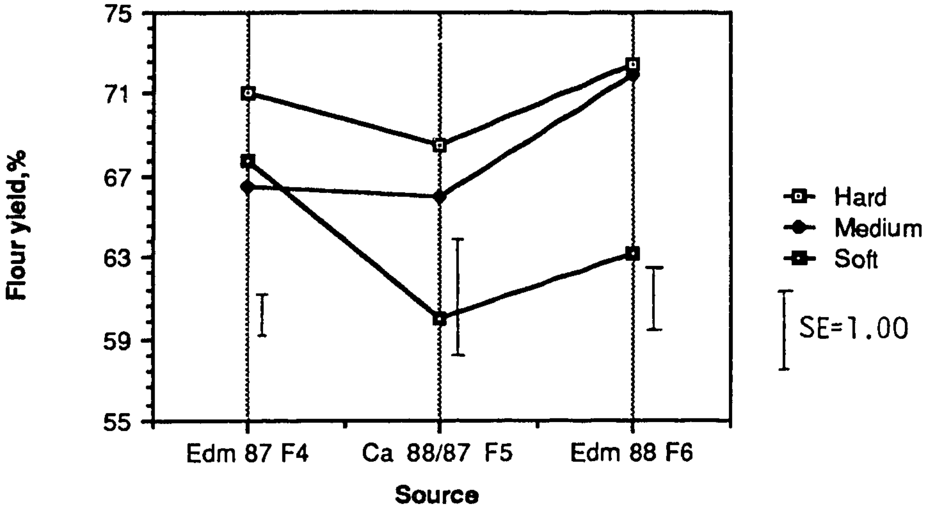
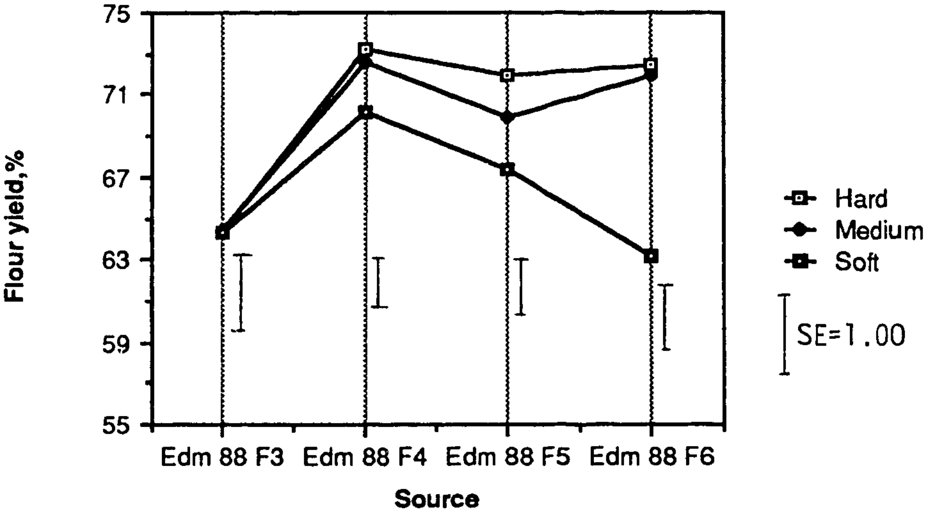


Figure 4.2.2.3b Means of Flour Yield Measures in Each of the Hardness Groups under the 1988 All Generation Special Case (SE= Standard error)



4.3 Correlations among, and Heritabilities of, Quality Characters

4.3.1 Correlations among the quality characters

Simple correlations were carried out among the 1987 Edmonton F4, 1988 Edmonton F5 and 1988 Edmonton F6 materials. 12 quality traits (prediction tests and farinograph properties) were tabulated in a matrix where 81 correlation pairs were formed for each of the three generations. Table 4.3.1.1., Table 4.3.1.2. and Table 4.3.1.3 summarize the results for the 1987 Edmonton F4, 1988 Edmonton F5, and 1988 Edmonton F6 respectively.

Hardness was significantly correlated with protein content, farinograph water absorption, farinograph arrival time and flour yield in each of the three generation sources. Harder wheats usually had higher protein content, higher water absorption ability and higher flour yield. Hardness was also correlated with sedimentation values in 1987 F4 samples and with mixing tolerance index in the 1988 F6 samples.

Protein content showed significant negative correlation with the sedimentation values for all seed sources. Higher protein content was correlated with higher sedimentation values. It was also shown to be positively correlated with other quality measures such as farinograph water absorption, farinograph arrival time, farinograph peak time and mixing tolerancece index in many cases. Sedimentation values correlated highly with farinograph stability (Table 4.3.1.1., Table 4.3.1.2., Table 4.3.1.3) for each of the generations, with correlation coefficients ranged from .76 to .85. Higher sedimentation values resulted in a more stable farinograph curve. Sedimentation value was shown to correlate with mixing tolerance index in

F6, with farinograph arrival time in F4 and F6, with farinograph peak time in F4 and F5 and with farinograph water absorption in F4.

Among the farinograph properties (Table 4.3.1.1., Table 4.3.1.2., Table 4.3.1.3), water absorption was significantly negative correlated with the arrival time. Samples with higher water absorbing capacity took longer to arrive at the 500 Brabender Units line. Farinograph stability is an important parameter to measure the strength of the flour and it was shown to be correlated significantly with the peak time in all generations. The slower the dough developed, the longer would be the stability of the dough. The 20 minute drop was shown to be correlated negatively with the departure time. The sooner the curve leaves the 500 BU line, the deeper would be the drop from the line.

Table 4.3.1.1. Simple Correlations between the Quality Traits (Prediction Tests and Farinograph Properties) in the F4 1987 Edmonton material

	A	B	C	D	E	F	G	H	I	J	K	L
A. Hard	---											
B. Prot	-.77	---										
C. Sedt	-.69	.83										
D. Flyd	-.67	.44	.36	---								
E. Kwt	-.23	.13	.20	.10	---							
F. FAB	-.75	.70	.73	.62	.12	---						
G. FAT	-.68	.80	.66	.56	<.01	.79	---					
H. FPT	.18	-.66	-.72	.44	<.01	.33	-.23	---				
I. FST	-.34	.44	.78	-.34	<.01	.52	.25	-.84	---			
J. FDT	.61	-.52	-.50	-.36	<.01	-.85	-.12	.70	.59	---		
K. FMTI	-.54	.42	.44	.36	.32	.60	.28	-.23	.53	-.39	---	
L. F20D	-.63	.58	.58	.51	.03	.43	.76	-.49	-.44	-.94	.69	---

> .64 = Significant at 0.05 level
> .77 = Significant at 0.01 level

Table 4.3.1.2. Simple Correlations between the Quality Traits (Prediction Tests and Farinograph Properties) in the F5 1988 Edmonton material

	A	B	C	D	E	F	G	H	I	J	K	L
A. Hard	---											
B. Prot	-.71	---										
C. Sedt	-.40	.80	---									
D. Flyd	-.83	.56	.45	---								
E. Kwt	-.28	.52	.38	.45	---							
F. FAB	-.75	.64	.58	.52	<.01	---						
G. FAT	-.71	.72	.53	.46	<.01	.74	---					
H. FPT	.25	-.66	-.78	.18	<.01	.18	.38	---				
I. FST	-.66	.51	.76	-.37	<.01	.30	.62	-.66	---			
J. FDT	.24	-.43	-.27	-.39	<.01	.00	-.54	.60	.51	---		
K. FMTI	-.18	.49	.28	.18	.02	.47	.18	.00	.16	.00	---	
L. F20D	-.32	.61	.50	.49	.03	.03	.54	-.67	-.54	-.96	.00	---

$>$ .64 = Significant at 0.05 level

$>$ .77 = Significant at 0.01 level

Table 4.3.1.3. Simple Correlations between the Quality Traits (Prediction Tests and Farinograph Properties) in the F6 1988 Edmonton material

	A	B	C	D	E	F	G	H	I	J	K	L
A. Hard	---											
B. Prot	-.65	---										
C. Sedt	-.59	.88	---									
D. Flyd	-.80	.51	.58	---								
E. Kwt	-.48	.43	.46	.46	---							
F. FAB	-.75	.62	.44	.50	<.01	---						
G. FAT	-.80	.62	.64	.62	<.01	.66	---					
H. FPT	.05	-.44	-.34	.11	<.01	.00	.48	---				
I. FST	-.12	.62	.85	-.37	<.01	.21	.17	-.76	---			
J. FDT	.18	-.27	-.29	.03	<.01	-.13	-.61	.87	.46	---		
K. FMTI	-.82	.84	.79	.44	.02	.50	.74	-.09	<.01	-.04.	---	
L. F20D	-.24	.32	.54	.11	.03	.20	.62	-.67	-.72	-.78	.34	---

> .64 = Significant at 0.05 level
> .77 = Significant at 0.01 level

4.3.2 Heritability of Quality Traits

In the present study, F6 plants in Edmonton 1988 constituted the most advanced generation, thus the measures on the F6 offered the best assessment of genetic progress in the plant breeding program. Heritabilities estimated for F6 on F3 (1988 Edmonton), on F4 (3 sources) and on F5 (3 sources) are listed on Table 4.3.2.1 for prediction tests.

Table 4.3.2.1 Heritability of Quality Traits for F6 on F3, F6 on F4 and F6 on F5 as measured by intergeneration regression

	Hard	Prot	Sedt	Flyd	Kwt	Hlwt
88 F6 on F3	.47	.16	.87	.36	<.01	---
88 F6 on aF4	.80	.82	.94	.27	.04	---
88 F6 on bF4	.85	.27	.94	.43	<.01	---
88 F6 on cF4	.85	.91	.82	.41	.08	.42
88 F6 on aF5	.72	.53	.74	.64	<.01	---
88 F6 on bF5	.83	.60	.78	.47	.04	.29
88 F6 on cF5	.90	.47	.91	.57	<.01	<.01

Note. > 0.41 = Significant at 0.05 level
> 0.59 = Significant at 0.01 level
aF4 = Edmonton 87 F4,
bF4 = 87/88 California F4,
cF4 = 88 Edmonton F4,
aF5 = 87/88 California F5,
bF5 = 88 Edmonton F5,
cF5 = 88 Edmonton F5 (derived from 87/88 California F4)

Heritabilities obtained for hardness and sedimentation values were generally high, showing that these two traits were less influenced by environment. All the heritabilities obtained for sedimentation value were significant at the 0.01 level. Heritability for protein content varied from 0.16 to 0.91, and for flour yield varied from 0.27 to 0.80.

No significant heritabilities were found for 1000 kwt and hectolitre weight.

Figures 4.3.2.1a, 4.3.2.1b, 4.3.2.2a, 4.3.2.2b, 4.3.2.3a, 4.3.2.3b illustrate the intergeneration progress of quality traits of individual random selected lines for hardness, protein content and sedimentation values.

Heritabilities for farinograph properties were very high. With the exception of departure time and 20 minutes drop, all the farinograph properties were significantly inherited.

Table 4.3.2.2 Intergeneration heritabilities of quality traits under normal plant breeding progression

	Hard	Prot	Sedt	Flyd	Kwt	Hlwt
aF5 on aF4	.91	.68	.73	.72	.23	---
bF5 on aF4	.88	.50	.73	.61	.38	---
88 F6 on aF4	.80	.82	.94	.27	.04	---
88 F6 on aF5	.72	.53	.74	.64	< .01	---

Note. > 0.41 = Significant at 0.05 level
> 0.59 = Significant at 0.01 level
aF4 = Edmonton 87 F4,
bF4 = 87/88 California F4,
cF4 = 88 Edmonton F4,
aF5 = 87/88 California F5,
bF5 = 88 Edmonton F5,
cF5 = 88 Edmonton F5 (derived from 87/88 California F4))

Table 4.3.2.3 Intergeneration heritabilities of quality traits under the 1988 Edmonton all Generation Special Case

	Hard	Prot	Sedt	Flyd	Kwt	Hlwt
cF4 on F3	.50	.46	.93	.76	< .01	---
bF5 on F3	.38	< .01	86	.80	< .01	---
cF5 on F3	.52	.27	.93	.49	< .01	---
88 F6 on F3	.47	.16	.87	.36	< .01	---
bF5 on cF4	.56	.47	.84	.77	.56	.32
cF5 on cF4	.61	.32	.91	.75	29	.34

Note. > 0.41 = Significant at 0.05 level
> 0.59 = Significant at 0.01 level
cF4 = 88 Edmonton F4,
bF5 = 88 Edmonton F5,
cF5 = 88 Edmonton F5 (derived from 87/88 California F4)

Table 4.3.2.4 Intergeneration heritabilities for farinograph quality traits (aF4 = Edmonton 87 F4, bF5 = 88 Edmonton F5)

	F6 on F4	F6 on F5	F5 on F4
FAB	.70	.60	.49
FAT	.64	.66	.76
FPK	.81	.67	.59
FST	.77	.82	73
FDT	< .01	.20	< .01
FMTI	.67	.79	.84
F20	.20	.24	< .01

Note. > 0.41 = Significant at 0.05 level
> 0.59 = Significant at 0.01 level

Figure 4.3.2.1a Progress of Individual Random Lines for the Quality Trait Hardness Under the Normal Plant Breeding Progression (SE= Standard error)

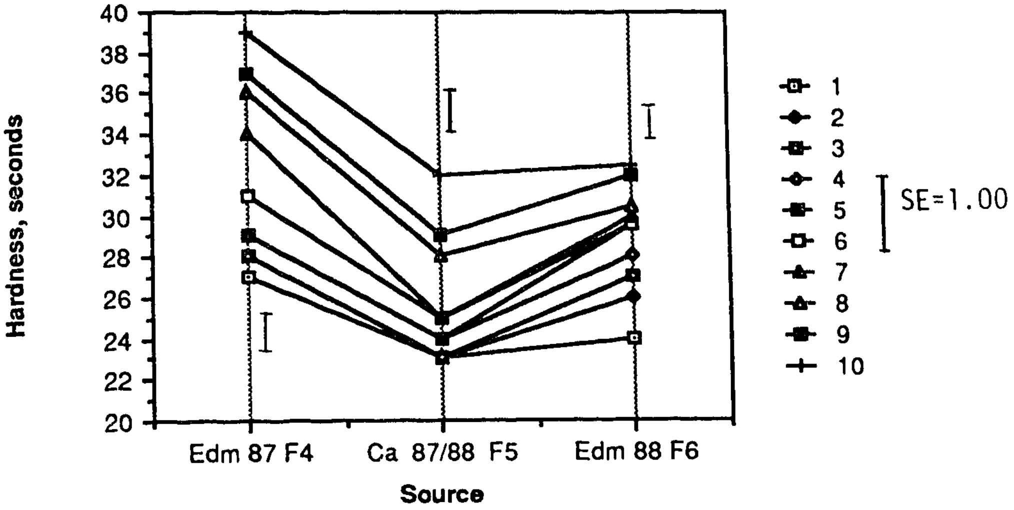


Figure 4.3.2.1b Progress of Individual Random Lines for the Quality Trait Hardness Under the 1988 All Generation Special Case (SE= Standard error)

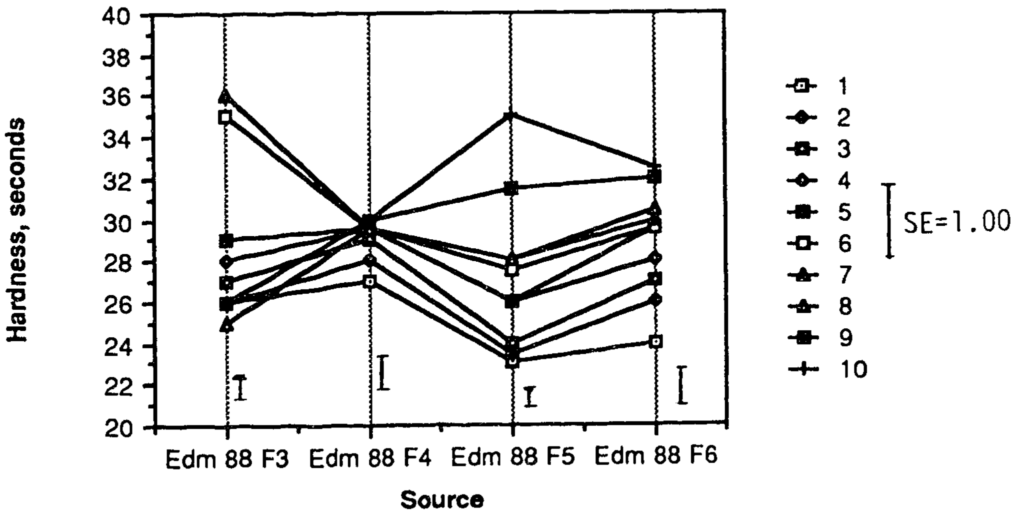


Figure 4.3.2.2a Progress of Individual Random Lines for the Quality Trait Protein Content Under the Normal Plant Breeding Progression(SE= Standard error)

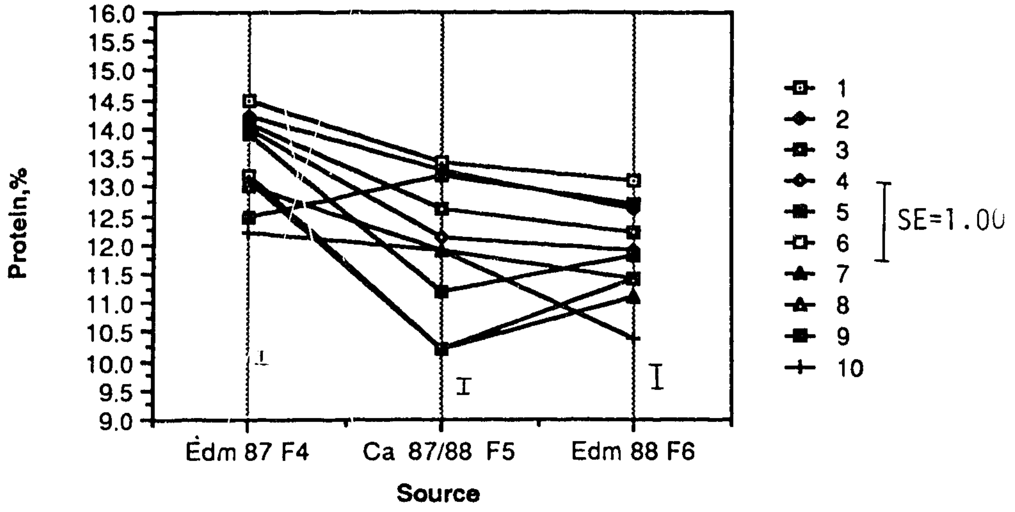


Figure 4.3.2.2b Progress of Individual Random Lines for the Quality Trait Protein Content Under the 1988 all Generation Special Case (SE= Standard error)

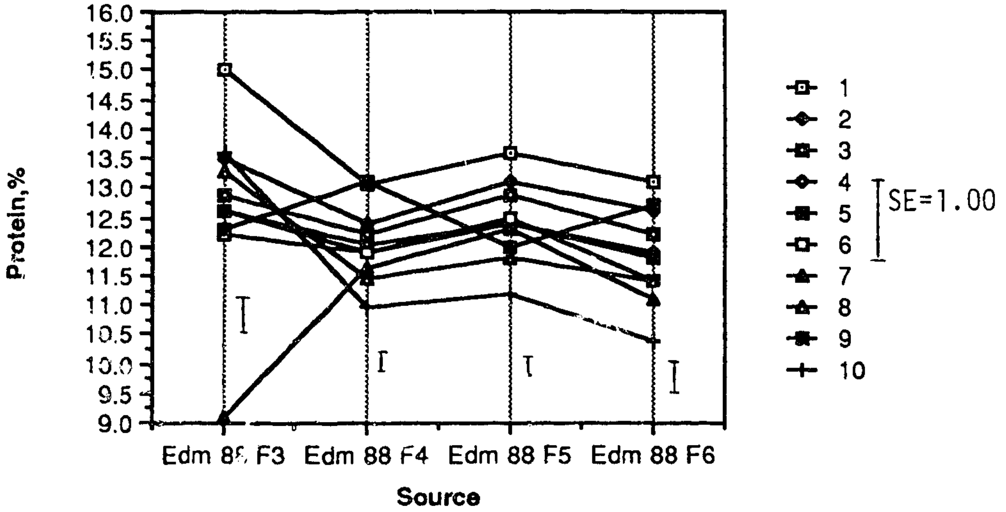


Figure 4.3.2.3a Progress of Individual Random Lines for Sedimentation Value Under the Normal Plant Breeding Progression (SE= Standard error)

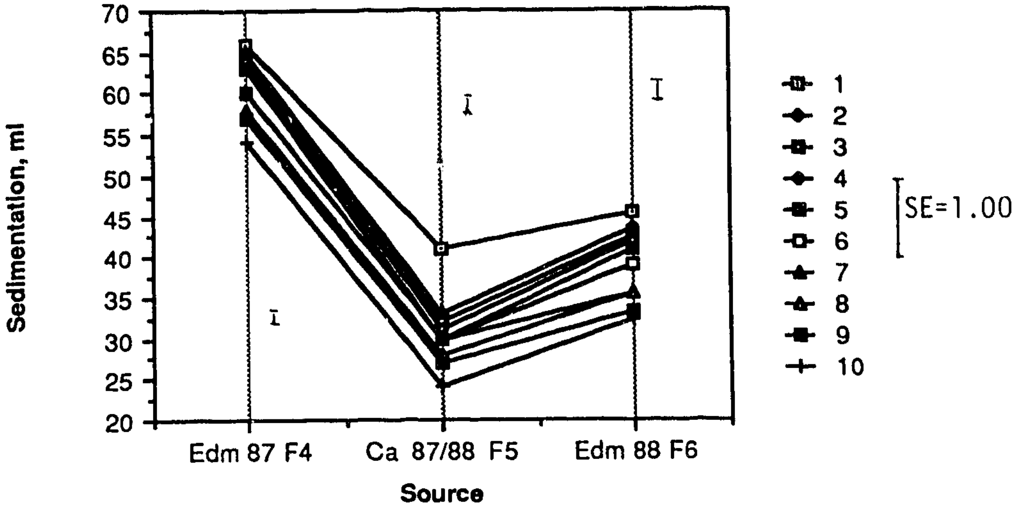


Figure 4.3.2.3b Progress of Individual Random Lines for Sedimentation Value Under the Normal Plant Breeding Progression (SE= Standard error)

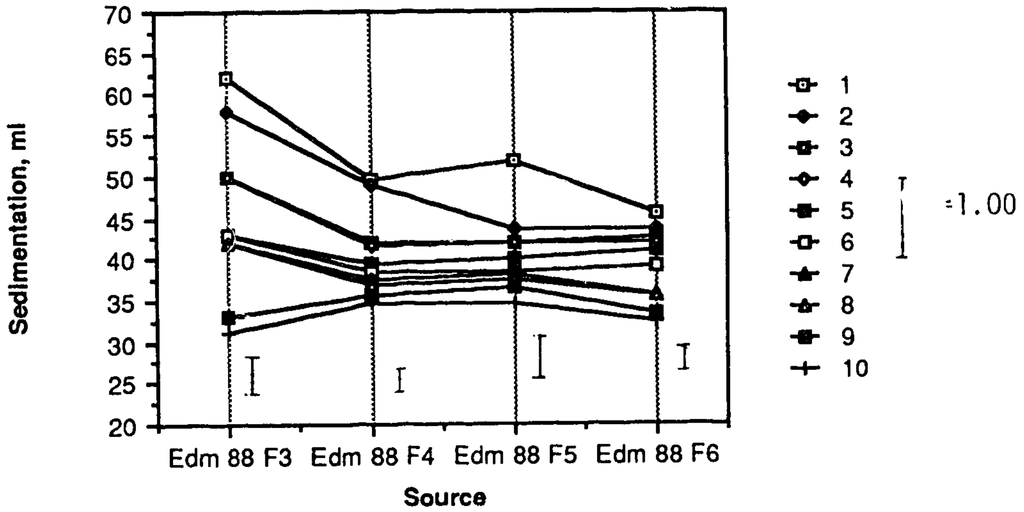


Table 4.3.2.5 Means and standard deviations of farinograph properties throughout generations F4, F5 and F6 in the random selected group

	F4		F5		F6	
	Mean	St.Dev.	Mean	St.Dev.	Mean	St.Dev.
FAB	32.5	1.38	32.0	0.62	32.0	0.75
FAT	3.0	0.47	2.8	0.63	2.5	0.37
FPT	4.4	0.52	3.9	0.82	3.9	0.67
FST	5.5	0.93	3.6	1.70	4.1	1.24
FDT	8.5	1.07	6.4	2.04	6.6	1.17
FMTI	56.0	8.43	60.0	20.5	62.0	14.80
F20	58.0	14.0	93.0	30.6	87.0	27.50

4.4 Site-year Effects on the quality traits as measured by prediction tests

4.4.1 Site-year effects in F4 and F5

Three sources of the F4 generation were planted in three different year-sites and three sources of the F5 generation were planted in two different year-sites. The effects of the site-year on the measured quality traits were subjected to the analysis of variance (Table 4.4.1.1, Table 4.4.1.2).

Hardness was significantly affected by site-year for both the F4 and the F5 generations. Protein content and sedimentation value were significantly influenced in the F4 where three site-years were involved, but not in the F5 case, where only two site-years were present.

Flour yield and 1000 Kwt measures were not significantly affected by the site-year.

4.4.2 Comparison of quality measures on samples from the California winter nursery and samples from the Edmonton location

Simple correlation analysis was carried out on F4 and F5 for five characters, comparing data from the California winter nursery with that from samples grown in 1988 at Edmonton (Table 4.4.2.1). 1988 Edmonton F4 (cF4) and F5 (bF5) had the same seed source as the California winter nursery material.

Hardness and flour yield were significantly correlated between the two locations for both the F4 and the F5 materials. Sedimentation values were also shown to be significantly correlated between the two sites in both F4 and F5. No significant correlation between the two seed sources was found for protein content either on the F4 or the F5 material (Table 4.4.2.1).

4.4.2.3 Duncan's multiple range comparisons of quality traits throughout the generations.

Means of the quality traits throughout the generations were compared for hardness, protein content and sedimentation values. The results were given in Table 4.4.3.1a. and 4.4.3.1b respectively for the " normal plant breeding progression " and "1988 all generations special case ".

In the " normal plant breeding progression " where multiple testing environments were involved, the means differed significantly for hardness, protein content, and sedimentation values (Table 4.4.3.1a), but to different extents. It appeared that the means for sedimentation values changed most dramatically (from 1987 Edmonton's 61.1 to 1987/88 California's 30.6), and the means were significantly different from each other in the three environments.

In the "1988 all generations special case " where only one environment was present, no significant differences between the generation means were observed for the quality traits hardness, protein content and sedimentation value throughout the generations (F3 to F6).

Table 4.4.1.1 Site-year and Seed Source Effects on Quality Traits for Three Sources of F4 (Edm 87 F4, Ca 87/88 F4, Edm 88 F4)

	Mean Squares					
	d.f.	Hard	Prot	Sedt	Flyd	Kwt
Site-year	2	53.5**	92.5**	2725**	172 ns	136.5 ns
Total Error[1]	37	10.8	0.7	44.6	29	33.5

1. Total error = Experimental error + Sampling error.

Table 4.4.1.2 Site-year and Seed Source Effects on Quality Traits for Three Sources of F5 (Cal 87/88 F5, Edm 88 F5, Edm 88 F5 (derived from Cal 87/88 F4))

	Mean Squares					
	d.f.	Hard	Prot	Sedt	Flyd	Kwt
Site-year	2	17.9*	0.595 ns	411.5 ns	193 ns	112 ns
Total Error[1]	47	13.3	1.1	148.2	217.5	9.5

1. Total error = Experimental error + Sampling error.

Table 4.4.2.1 Correlations of Quality Traits, between seed sources for prediction tests. 1) 87/88 California F4 (i.e. bF4) and 1988 Edmonton F4 (i.e. cF4). 2) 1987/88 California F5 (aF5) and 1988 Edmonton F5 (i.e.bF5)

	Correlation Coefficients	
	Between bF4 and cF4	Between aF5 and bF5
Hardness	0.78**	0.94**
Protein	0.59 ns	0.36 ns
Sedimentation	0.76*	0.69*
Flour Yield	0.72*	0.94**
1000 Kwt	0.13 ns	0.69*

* = Significant at 0.05 level
** = Significant at 0.01 level
ns = Non-significant

Table 4.4.3.1a Comparisons of the Means of Quality Traits Throughout the Generations in the Random Group (Normal Breeding Progression)

Site-year	MEANS		
	Hardness	Protein	Sedimentation
1987 Edm F4	31.8b	13.5b	61.1c
1987/88 Ca F5	25.6a	12.0a	30.6a
1988 Edm F6	28.9ab	11.9a	39.2b
Standard Error of the Means	1.09	0.30	1.37

Note: Means in each of the column following by different letters are significantly different at $p = 0.05$, using the Duncan's Multiple range test.

Table 4.4.3.1b Multiple Comparisons of the Means of Quality Traits Throughout the Generations for the Random Group (1988 All Generations Special Case F3-F6)

Site-year	MEANS		
	Hardness	Protein	Sedimentation
1988 Edm F3	28.4a	12.6a	45.4a
1988 Edm F4	29.1a	12.1a	40.7a
1988 Edm F5	27.2a	12.4a	40.6a
1988 Edm F6	28.9a	11.9a	39.2a
Standard Error of the Means	0.97	0.35	2.05

Note: Means in each of the column following by different letters are significantly different at $p = 0.05$, using Duncan's Multiple range test.

5. Discussion

The present study of various quality characteristics in different generations was limited by certain restrictions of the experimental designs which were used. For example, the materials in the 1987/88 California winter nursery were seeded in single rows while in Edmonton (1987 and 1988), the material was seeded in 4 - row plots. By contrast, the 1988 Edmonton F3 was seeded in hill plots. Nitrogen fertilization was applied at Edmonton in 1987 but not in 1988. These differences could have contributed to possible seeding method, fertility and genotype interaction effects. Estimates of any such interaction effects cannot be obtained from this study and thus the reported relationships are subject to possible bias from these sources of variability.

The climatic conditions in the three crop years of the present study were observed to be quite diverse, though the actual weather data was not available for report. Crop season 1987/88 in the California winter nursery was considered an average year for winter nursery (high temperature, long light hour situation). Both Edmonton crop years (1987 and 1988) deviated considerably from the average Edmonton weather pattern, with 1987 being a year of heavy spring frost and lower than average temperatures, and 1988 being a year of drought conditions. The hardness selections were made from samples grown under 1987 Edmonton conditions. Large differences between successive climatic environments are the common scene for plant breeders and thus the results obtained from this study are believed to nevertheless to have relevant implication to plant breeding programs.

breadmaking quality (Lebsock et al. 1964; Symes 1965; Sunderman et al. 1965; Baker 1977; O'Brien and Ronalds 1987). Studies of this nature have been commonly reported, but interpretation of the results is frequently complicated by the polyploid nature of wheat and also by the strong environmental influence, especially on protein content, and also due to the genetic specificity of individual crosses.

Protein content is probably the one character that has been studied the most, and a clear picture of the genetic mechanism of this character is still not elucidated. The genetics of protein control is complex, and estimates of gene numbers involved have ranged from a few to many (Hehn and Barmore 1965). The mode of gene action has been shown to be under polygenic control (Worzella, 1942; Haunold et al. 1962) with no dominance (Kaul and Sosulski 1965), to partial dominance (Lebsock et al. 1964; Hsu and Susulski 1969; Chapman and McNeal 1970).

Haunold et al. (1962) obtained heritability estimates as high as 65% for grain protein content by using parent offspring regression techniques for several selfed generations. They found that about 14% of F3 lines in the winter wheat cross Atlas 66 X Wichita overlapped the range of the high protein parent, suggesting a one- or two-gene pair difference with high protein recessive. Johnson et al. (1963) obtained F2 derived families from an 'Atlas 66 X Comanche' cross and they were more productive and had higher protein content than Comanche, the lower protein parent. This suggests significant potential for progress in selecting for high grain protein. Later they reported transgressive segregation for high protein in the cross 'Nap Hal' X Atlas 66 (Johnson et al. 1973).

McNeal et al. (1982) reported the tendency of transgressive improvement in quality of protein lines, reflecting complementary or additive effects of genes from parent which were of poor or mediocre quality. Davis et al. (1961), in studies of seed protein in the soft red winter wheat cultivar "Atlas 66", found protein content to be heritable and quantitatively controlled, and obtained broad sense heritability estimates of 54 to 69% for protein content. Schlehuber et al. (1967) studied protein content and sedimentation value in F5 and F4 lines of a Triumph x C.I. 12406 cross and reported heritabilities of 57% and 66% respectively. Sunderman et al. (1965), using the regression of F3 lines on F2 plants, obtained estimates of heritability of grain protein of from 15 to 26%. Low heritability for protein content was also reported in early generation materials by Pearson et al. (1981).

Inheritance studies have shown that both additive and non-additive gene action may influence grain protein content. Halloran (1975) indicated a generally additive nature of genetic control of protein content with evidence of dominance. Kraljevic-Balalic et al. (1982) found a preponderance of non-additive gene action in crosses of five divergent cultivars, with presence of partial dominance affecting the inheritance of protein content. Atlas 66 was found to possess mainly recessive genes for protein concentration, but the genetic control of protein content, whether by dominant or recessive genes, may change depending on the influence of environment on the segregating populations.

In many of the genetic studies of protein quality, sedimentation value has also been evaluated, and some degree of dominance for high sedimentation value has been reported (Hsu and Sosulski 1969).

Intergeneration regression was used by Lebsock et al. (1964) to demonstrate heritabilities of 56 and 60% for sedimentation value in the cross of P.I. 56219 X Conley, and they also demonstrated partial dominance for short mixing tolerance. For sedimentation value, Sunderman et al. (1965) reported values of 64% based on F2-F3 regression, and 44% with the components of variance method, in an Itana x Atlas 66 cross. Regressions of F5 on F4 , F7 on F4 and F7 on F5 lines gave heritability values for sedimentation value of 54, 44, and 63% respectively, in a Tascosa x 55C1304 cross (Atkins et al. 1965).

Lofgren et al. (1968) studied the progenies of four wheat crosses and reported that flour yield, 1000 kernel weight, and kernels per 30 ml were more heritable than test weight and protein content. Pearson et al. (1981) reported that hardness, dough stiffness and 1000 kernel weight had high standard unit heritabilities (72-80%) as measured by correlation of F3 single plant data on the F4 progeny row data. They also reported an intermediate heritability (57%) for flour yield, and low heritability for protein content (19%).

Chromosomal location of genetic control of wheat quality has been investigated by a number of research groups. Morris et al. (1966; 1968) developed a set of substitution lines of the donor Variety Cheyenne into the recipient Chinese spring. The chromosomes 7B and 5D were identified as carriers of control of high flour yield, and 5D was the only chromosome on which factors for kernel hardness were located (Mattern et al. 1973). Major factors for the strong dough mixing characteristics of Cheyenne were located on chromosome 4B, 7B and 5D (Morris et al. 1966; 1968). Important contributions to loaf volume, crust appearance and crumb texture were made by chromosome 1B, 4B, 7B and possibly 1A. A depression of general quality characteristics were observed in the 1D substitution line. Morris et al. (1978) also identified major and minor regulatory genes for protein content in the cultivar Atlas 66. The genes were located on the chromosomes 5D and 5A respectively.

Welsh et al. (1968) used the variety Chinese spring as the common genetic background and subjected three sets of hard red spring substitution lines to milling and baking tests. For the donor Timstein, the variety with strong flour and satisfactory flour yields, the authors reported quality differences in the case of 16 different chromosomes substitutions, with the most important effects coming from substituted chromosomes 3B and 5D (baking absorption), 1B, 3B and 6B (dough handling properties), and 3B (loaf volume). Chromosome 1D produced a loaf volume significantly smaller than Chinese spring. Doekes et al. (1976) investigate quality gene location using chromosome substitution lines of Cheyenne, Hope , and Timstein transferred into the recipient variety Chinese spring. Major factors for kernel hardness and increased baking absorption were found on chromosome 5D of Cheyenne and Hope, and on chromosomes 3B, 5D and 7D of Timstein. Law et al. (1978) conducted a detailed study of genetic variation associated with chromosomes 5D and showed that two genes, Pro1 and Pro2 were involved with the total protein content. Pro1 was identified on the long arm of 5D chromosome and Pro2 was not closely related or linked with Pro1 and was assigned to the short arm of 5D chromosome. None of researchers were able to find chromosomes which produced consistent effects in different varieties for the quality traits.

Starting from the 1980's, a number of researchers has presented strong evidence that the presence of certain high molecular weight (HMW) glutenin subunits are correlated positively with improved breadmaking quality (Payne 1980; Payne et al. 1983; Day et al. 1985), even though the high molecular weight subunits constitute only about 10% of the storage protein in the endosperm. By intercrossing aneuploid lines of wheats, Law and Payne (1983) determined that the high molecular weight glutenin subunits are controlled by a single complex locus positioned about 9 cM from the centromere, on each of the long arms of chromosomes 1A, 1B and 1D. These loci have been designated Glu A1, Glu B1 and Glu D1 respectively (Payne, 1983). Further analysis showed that each locus of 1A, 1B and 1D displays allelic variation and their combined effects are the main cause for the differences in the protein quality for breadmaking (Payne 1983; Sozinov 1988).

Hardness has long been considered as a varietal characteristic, although environmental factors exert a modifying effect (Pomeranz and Mattern 1987). Previous studies have reported high heritabilities for grain hardness (Bhatt and Derera 1975; Pearson et al. 1981; O'Brien and Ronalds 1987). Symes (1965) in a study of the particle size index of near isogenic lines of hard and soft wheat, reported that a single major gene and minor genes controlled wheat hardness. Mattern et al. (1973), using maltose values and flour granularity of flour milled from chromosomal substitution lines, found that hardness in wheat, for the variety Cheyene, was controlled by one major gene and one minor gene. Baker (1977) studied the inheritance of kernel hardness, and found that the difference between Pitic 62 (a soft wheat) and Neepawa (a hard wheat) was governed by two major genes and one or more minor genes, while the difference between Glenlea, a very hard wheat, and Neepawa was accounted for by one single major gene and one or more minor genes. Thus it appeared that different levels of hardness could be caused by different major genes. Greenwell and Schofield (1986) presented data for the presence of a Mr(molecular mass)-15k protein associated with the surface of starch granules from hexaploid bread wheat (Triticum aestivum L.), that controls hardness. This protein band is strong in soft wheat and faint in hard wheats when separated by gradient SDS-PAGE. When Mr-15k protein is present, it appears to eliminate the binding of endosperm storage proteins to starch granules. Greenwell and Schofield suggested that the gene coding for the 15k band is on the same chromosome of the major gene controlling endosperm texture, which is known to be on the D-genome (Mattern et al. 1973; Law et al. 1978). Durum wheat does not have the band at all as it does not have the D-genome. Though this pattern was widespread in 150 wheats of widely different genetic backgrounds, the mechanism by which the proteins cause this effect is not yet known (Greenwell and Schofield 1986)

Williams (1986) studied influence of chromosome number and species on the kernel hardness and reported that all the diploid wheats were very soft, whereas all the tetraploids were very hard, and a complete spectrum of hardness was displayed by hexaploid wheats. In hexaploid wheat, the combination of the DD chromosomes with the AABB chromosome assemblage resulted in a breakdown or unlocking of the restrictions in hardness displayed by diploid and tetraploid wheats, with the result that hexaploid wheat with the full range of hardness can be encountered in a wheat breeding program. The author proposed that the DD genome is the source for the softest wheats, the AABB (durum) genome provides the hardest wheats and the AABBDD hexploids have the widest range in hardness (Williams 1986).

2.4 Environmental Effects on Flour quality

The recognition that environment has a significant influence on wheat quality characters has been wide and has been established for a long time. Ladd and Bailey (1910) reported that variations in seasonal and local factors could result in significant differences in the protein content and baking quality of North Dakota wheat. Hehn and Barmore (1965), in their review of wheat quality breeding, strongly emphasized the influence of environment on wheat quality and pointed out that further knowledge of the environmental sensitivity of each of the quality factors under consideration would help to improve the success of breeding for quality.

Protein content is most easily affected by the environment, and since it is such an important component of the overall breadmaking quality, it secondarily influences other quality parameters quantitatively. Waldron et al. (1942) examined variations in the protein content and loaf volume of eight hard red spring wheat varieties grown at four North Dakota stations over a four year period. Significant differences were found from year to year in wheat protein content, but little variation was reported between stations. Also, marked varietal differences in wheat protein content, flour yield and loaf volume were reported. Sandstedt and Fortmann (1944) showed that extremely large differences in baking strength existed in six Nebraska hard red winter wheats grown at 14 locations in 1939-40. Baking properties of the flours were found to be greatly affected by the environment in which the wheats were grown.

Harris at al. (1947) also studied the effects of season, locality, and variety on the yield and quality of five hard red spring wheat varieties grown at five different locations in North Dakota over a period of five years. They reported that yield per acre, weight per bushel, protein content, flour yield, flour ash, water absorption, loaf volume and crumb color were all significantly affected by yearly variation in climate, by locality and by variety. Crop year and location exerted a very significant effect on protein quality. Harris et al. (1957) studied the effects of variety and environment on the quality of 56 samples of hard red spring wheat grown in 1954 at different locations in North Dakota. Significant differences were reported in flour yield(%), flour protein and loaf volume between different varieties and locations, the latter factor apparently having the major influence. Schlehuber and Tucker (1959) have suggested that the major factors responsible for grain protein percentage, in order of importance, are environment, soil and cultivar.

Baker et al. (1968) showed that the heritability of starch damage was low in a test at a single location in a single year (0.38) but increased significantly when tested at two locations in the same year (0.64). This result was reconfirmed further in a later study when 15 locations and 5 years were involved (Baker et al. 1971). Baenziger et al. (1985) conducted a genotype x environment (G x E) study on soft red winter wheat quality characters in 12 locations in the Southeastern U.S.A. and found that G x E interaction was significant for all variables. They also found that the cultivar means were closely related to the regional cultivar means, indicating that for preliminary quality evaluations, data from one environment was nevertheless sufficient for ranking cultivars. Pomeranz and Mattern (1987) showed that large environmental variance existed in the U.S. winter wheats for quality characters such as protein content and kernel density.

Obuchowski and Bushuk (1980) reported results for nine samples of one variety of hard red spring wheat from one location, but these samples had a range in protein content from 9.4-15.6%.

While the protein content depends largely on the weather conditions of the growing season, wheat protein quality under normal conditions is considered to be almost entirely an inherited character (Finney et al. 1987), though this might not be universally true. O'Brien and Orth (1977) studied the effect of location on flour yield, flour protein content, farinograph properties and the proportion of residue protein. By using 32 wheat varieties representing a wide range of grain hardness and dough rheological properties at 6 locations in Northwestern Victoria they found: 1) At each location, a highly significant correlation was obtained for dough breakdown and residue protein, suggesting that the residue test could be used as a selection tool in wheat breeding programs. 2) Residue protein and dough breakdown were least affected by the environment, whereas water absorption, flour protein content and flour yield were greatly influenced by environment. Moss et al. (1986) have shown that differences in mean maximum temperature during the grain filling provide possible causes of differences in dough strength of a cultivar. Arthur and O'Brien (1987) compared the quality data of the variety "Condor" in two different regions and found that significant dough property differences existed even at the same protein content. They concluded that the differences were associated with the nitrogen and sulphur ratio (N/S) and with residue protein content, arising from allelic variation.

Grain hardness has been shown to be a genetically controlled character (Symes 1965). Past studies have shown that variety had a much larger effect on its value than location (Symes 1969; Yamazaki and Miller 1982; Miller et al. 1984; Pomeranz et al. 1987), but the reverse result has also been reported. For example, Parish and Halse (1968) investigated the influence of temperature and relative humidity during ripening on grain hardness, and found that hard wheat becomes harder if the temperature during the ripening period is high. Miller et al. (1982) studied the variety Lancota in 9 locations and reported that hardness measurements were affected by the environmental factors. Finney et al. (1987) reported that environment slightly influenced flour yield, but greatly affected kernel hardness. Such variations in wheat hardness due to environment can cause considerable variation in certain milling or baking quality parameters. In breeding programs there is a need to identify any change in hardness ranking of varieties at different location, and to evaluate the extent of possible ranking changes.

While environmental variations are easily detected and quantified for most of the quality traits, some are more difficult to study. - amylase level in the grain kernel has been shown to have decisive effects on the overall breadmaking quality (Finney and Yamazaki 1967). Higher - amylase activity usually results in undesirable quality performance. For example, Lukow and Bushuk (1984) studied the effects of germination on the quality of the varieties Neepawa and Glenlea. Both varieties showed an increased deterioration of breadmaking quality as the germination treatments were prolonged and the -amylase level in the grain increased. Baker et al. (1971) measured various quality traits on composite samples of wheat grown in Western Canada. They considered that low inter-season correlations among quality traits were indicative of Genotype x Season interaction, and also concluded that measurements of - amylase activity were particularly subject to differential effects of environment. They suggested that difference in - amylase activity could only be detected when environment conditions were appropriate. Such dependency on environmental conditions for the effective differentiation of genotypes poses special problems in wheat breeding programs. Studies of environmental influence on the quality parameters do not agree with each other all the time. Genotype x Season and Genotype x Location interactions might not be present in some studies. Fowler and de La Roche (1975b) investigated the quality of wheat cultivars grown in 15 different locations in eastern Canada. By testing the same cultivar in different locations and in different seasons, they were able to measure the relative magnitude of the effects of season and location on wheat quality. For quality variables of hard red spring wheat, they found Genotype x Location and Genotype x Season interactions to be " relatively unimportant except in a few cases ". This finding may reflect the general lack of genetic variability in the genotype studied. A similar study on the Canadian Prairie Spring Wheats, with their wider genetic base, might lead to different results.

Most of the past studies of environmental effects on quality traits have been concentrated on pureline varieties. Studies on plant breeder lines have been less common, simply because of the large amount of the samples that need to be processed, and the complexities due to genetic segregation in early generations. Miezan et al. (1977) reported, by using 12 selection lines (F6 and F7) from two crosses tested at different environment over two years, that genetic effects influenced grain protein as effectively as environment. They also showed that grain protein content in wheat can be increased by breeding without decreasing the yield. Baker and Kosmolak (1977) studied two composite samples of 20-30 lines in each of four trials, representing different geographic areas in western Canada. Difference between the effects of environments was found in all traits. It was concluded that G x E interaction was most important in determining mixograph development time, falling number and remix loaf volume, less important in determining farinograph absorption, and least important in determining flour protein and flour yield, grinding time and sedimentation value. Because of the strong environmental influence that exists on some quality characteristics both with varieties and advanced lines, it seems that accurate determination of the milling and baking quality of a cultivar in the advanced stage of agronomic testing would benefit from multiple environment testing.

2.5 Early Generation Selection for Flour Quality

From a theoretical point of view, selection should start as early as in F3 generation (Shebeski 1967). However, besides the problems of segregation and heterozygosity within the lines during early generations (Spitters 1979), the biggest problem that plant breeders face is the actual identification of the superior lines. The first essential is to chose relevant quality parameter having a sufficiently high heritability. Heyne and Smith (1967) in fact suggested that the "proper factors" to select should be mainly based on the heritability of the character. If the heritability was high in early generations, testing should start as early as possible. In the early generations of wheat breeding program, these trials, because of the large number of lines and the relatively small amount of seed sample available to be tested, have to be fast and easy to measure on small lots of grain. Small samples of grain available in early generations of plant breeding programs do not permit measurements of loaf volume and baking strength index, etc. Therefore, it is necessary to use measurements from other tests to predict these important quality parameters. O'Brien and Orth (1977) summarized the major criteria for early generation tests for breadmaking quality as 1) small sample size, 2) high repeatability, 3) strong correlation with functional properties used for the final assessment, 4) wide genetic variance, and 5) the ability to rank wheats similarly at different locations where the selectable lines are grown.

Zeleny sedimentation value has long been considered and used as an index for quality screening in early generations of wheat because of its high heritability and close relationship with many other quality parameters. During the 1960's, various milling, baking and other predictive tests were developed, and an early generation screening evaluation program became available to breeders for testing F3 or F4 generations (Yamazaki et al. 1968).

It was recommended that the mixograph test in F3 could be used as an aid in selecting lines with desirable quality. In a study of F3, F5 and F6 lines from a cross of P.I.56219-12 with 'Conley'', Lebsock et al. (1964) found that sedimentation value was positively correlated at the highly significant level with mixing tolerance and protein content. Heritability values determined by the regression of F5 and F6 means on F3 line values were relatively high for mixing tolerance, somewhat lower for sedimentation value and relatively low for protein content. Heyne and Finney (1965) also suggested that in screening F3 wheat lines for breadmaking quality, use of the mixograph test would be a worthwhile approach, followed by milling and baking tests in the later generations. McNeal et al. (1964), in a report of the effectiveness of selection for flour absorption and dough mixing properties in the early generations (F4 and F5) of a Lemhi x Thatcher wheat cross, stated that flour protein showed a highly significant correlation with absorption, but the relationship of flour protein with peak stability was inconsistent. They indicated that selection was effective in improving farinograph characteristics, compared to no selection, and that selection was more effective in F3 than in F4. They suggested that selection in early generations for agronomic characteristics should be accompanied by selection for milling and baking quality to prevent loss of high quality lines. Lee et al. (1983) also suggested that effective quality improvement could be made when protein content was selected for at the same time as screening for yield in early generations.

Barlow et al. (1971) estimated the heritability of 25 different quality parameters and used these tests to predict loaf volume by multiple regression. They found that protein content, farinograph development time and gassing power were important measurements for assessing wheat quality in early generation of breeding programs. Briggs et al. (1971) reported that, based on the broad sense heritability of F2 derived F5 populations, many of the quality parameters could be selected effectively in F3. Baker and Campbell (1971) studied eight tests designed to screen early generation wheats, and concluded that nitrogen content, Zeleny sedimentation value, and centrifuge absorption were the most useful of the tests studied to predict remix loaf volume and mixograph properties. Orth et al. (1972) reported, from a single test, that residue protein content (as a measure of protein quality), Zeleny sedimentation value, and farinograph development time in that order were the most effective as the tests for prediction of the remix loaf volume. Orth et al. (1976), using factor analysis, reported that factors like protein quality, grain hardness and protein content were the minimum number of tests accounting adequately for the total test correlation matrix, and they concluded that these tests will provide sufficient information to allow selection for breadmaking quality during early generations in a breeding program. Kosmolak and Baker (1979), by studying 250 advanced lines in areas of western Canada, reported the effectiveness of using the linear function of flour protein content and mixograph development time in selecting those samples of spring wheat which would result in a loaf of bread with above average volume

Pearson et al. (1981) examined five micro-prediction tests (hardness, protein, dough stiffness, flour yield and 1000 kernel weight) for wheat quality in the early segregating generation (F3 and F4) of a genetically diverse wheat population and suggested that quality testing at the head row stage is highly effective for most of the traits considered, with the exception of protein content. Whan et al. (1982) showed that associations between consecutive generations were closer in later than in early generations, pointing to the suggestion that the degree of homozygosity influenced the correlation between generations. McNeal et al. (1982) compared the agronomic and quality characteristics of spring wheat lines selected for protein content and protein yield and suggested that protein yield might be a better selection criterion than protein percentage for plant breeders to use in improving protein productivity. O'Brien (1983) suggested that a good response could be expected for selection on a single plant basis and proposed an integrated two-step system in early generation selection for yield and good quality wheat. He stressed the high value of the F3 quality testing regime that requires only 20 g of seeds, and that selects wheat lines on the basis of their balance of grain hardness, protein content and quality properties.

3. Materials and Methods:

The materials used for this study were obtained from a cross between plants derived from a breeder seed lot of HY320[1], a registered Canadian Prairie Spring wheat, which has medium hardness, red seed, high yield and medium grain protein content, and QT8132[2] , an unregistered, putative hard, white seeded wheat line, with a lower yield but higher protein content than HY320. Table 4.1.1.1 summarize the quality data of the two cultivars.

In the fall of 1986, 360 individual plants from the F2 population of HY320 X QT8132 were randomly selected and were then increased as single plant derived rows in the Brawley Winter Nursery, California, in the winter of 1986/1987. The F4 seeds were returned from California and seeded in Edmonton in the spring of 1987. Each line was seeded in a 6 meter long, 4 row plot at a row spacing of 15cm, with a seeding rate of 400 seeds /m^2. Days to heading and maturity, lodging score and plant height data were collected in the fall before harvest. All four rows were harvested in the fall of 1987 to assure enough seed for all macro scale and microprediction quality tests (i.e. Buhler flour milling, Farinograph tests,1000 kernel weight, hectoliter weight, grain hardness, Brabender laboratory milling, grain protein, sedimentation value). Microprediction tests were conducted on the seed samples from all 360 F4 rows. Based on the hardness measurements, the 360 lines were then divided into three subgroups, hard, medium and soft

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[1] Pedigree: Tobari 66 X Romany; the cross was made in 1968. A line designated 7029-66-9, derived either from an F4 or F5 single plant, was selected in 1973. Later 122 uniform paired rows were selected as breeder lines.(De Pauw et al. 1987)

[2] Pedigree: An unregistered wheat of Australian origin, brought back by Dr. K. G. Briggs in 1983. QT stands for Queensland Territories. This line was originally obtained by Dr. Jim Syme from the 12th International Bread wheat Screening Nursery (number 109). The pedigree for this line is Ciano - Siette Cerrors X Kal - Blue Bird/PCI's'.

kernelled (Hard group, hardness is < 30, medium hardness is in the range of 31-35, and soft is > 36.) Ten individual lines were then selected at random to represent each of the three groups.and another 10 lines were selected at random from the entire 360 lines to represent the whole population. Buhler milling and Farinograph tests were carried out on all 40 selected lines.

F3 reserve seed and F4 seed of the 40 lines were sent to the 1987/1988 California Winter Nursery. The F4 and F5 seeds that were brought back from California were planted in the spring of 1988 in Edmonton, along with the reserve seed of the F2 (Edmonton, 1986), F3 (California, 1986/87), and F4 generations (Edmonton, 1987), for each of the 40 selected samples. All generations and sources except the F2 Edmonton, 1986 seed source, were seeded in two replicates. The plot design and seeding rates in 1988 was similar to those used in 1987. The F2 generation (Edmonton, 1986 source) was planted in hill plots, due to scarcity of seed.

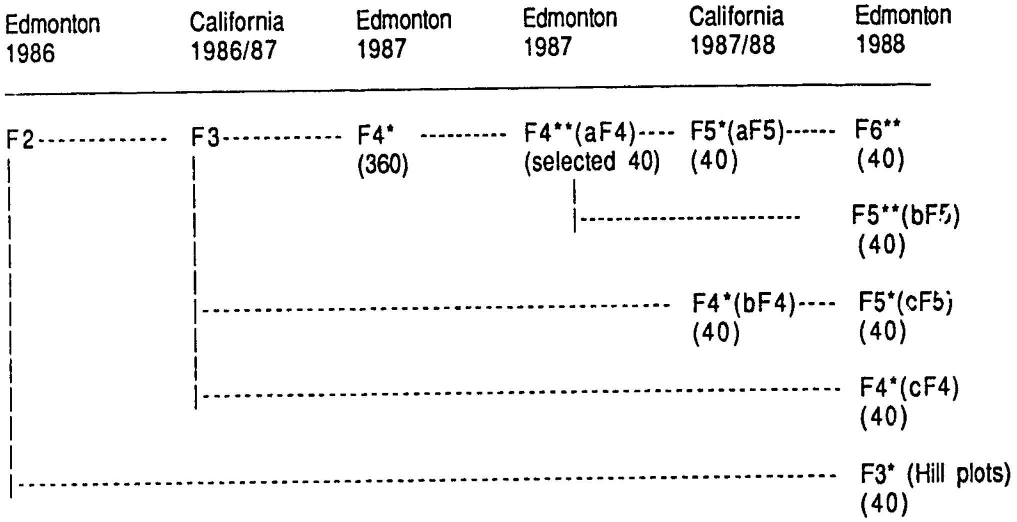
Five generations of the material were harvested and quality prediction tests were carried out on both replicates of the seeds of all generations and sources of the selected 40 lines. Buhler milling and Farinograph tests were conducted on the F5 and F6 (Edmonton, 1988, source), for which the replicates were composited.

While the cross was made and the current research was proceeding, DePauw (1987) showed that the breeders lines of the parent HY 320, were not uniform for hardness and that there was a bimodal distribution for hardness among the 128 breeder lines. Since breeder seed of HY 320 used for crossing was therefore a mixture for hardness, the variation for hardness among the parental HY 320 lines could account for some of the variability in hardness of the progeny. Approximately 30 individual HY320 plants were used at the time when the crossing was made (Kutchera, personal communication).

The source and disposition of seed over the generations and grown at different locations is summarized in Figure 1.

Figure 3.1.1.1. Flowchart of generations and seed sources, including locations used

(HY320 X QT8132)



* Only prediction tests were conducted on these samples.

** Complete quality analysis (microprediction tests and Farinograph) was carried out on these samples.

The following designation are used to refer to generation grown in different location and years:

aF4 = 1987 Edmonton F4
bF4 = 1987/88 California F4
cF4 = 1988 Edmonton F4
aF5 = 1987/88 California F5, derived from aF4.
bF5 = 1988 Edmonton F5, derived from aF4.
cF5 = 1988 Edmonton F5, derived from bF4.

Statistical analyses conducted:

Objective 1: To examine the impact of hardness selection in the F4 generation on the functional quality traits of later generations (F5 and F6).

Concepts of Anova A and Anova B used in the current study are defined as following:

Anova design A:

Sources	d.f.
Grouping	2
Experimental Error	27
Total	29

Anova Design B:

Sources	d.f.
Grouping	2
Replication	1
Experimental Error	56
Total	59

The following Anova were conducted:

a) Between F4 selection groups (hard, medium, soft; Anova design B) on 1988 Edmonton F6;(Replicated for all quality characteristics).

b) Between F4 selection groups (hard, medium, soft) Anova on F5, 3 sources:(California/1987/88, Anova design A; Edmonton/1988 F5c (Replicated, Anova design B); Edmonton/1988 (Replicated, Anova design B)). (All quality characteristics).

c) Between F4 selection groups (hard, medium, soft) Anova on F4, 3 sources: (Edmonton/1987, Anova design A; California/1987/88 Anova design A; Edmonton/1988(Replicated, Anova design B))
(All quality characteristics).

d) Duncan's multiple mean comparison tests were used among hardness groups throughout the generations, (for the quality characteristics Hardness, Protein, and Flour yield).

Objective 2: To compare the quality traits of materials grown in Edmonton and in the California winter nursery, to examine the site-year and seed source effects on the quality traits, and the effectiveness of quality measurements on the winter nursery material as compared with Edmonton materials, for the same population. Both F4 and F5 generations were used for this comparison.

The following analysis were conducted:

a) F4 Anova, 3 sources: (Edmonton 1987; California 1987/88; and Edmonton 1988).

Anova Design:

Sources	d.f.
Site-year	2
Experimental Error	1
Sampling Error	36
Total	39

b) F5 analysis of variance, 3 sources. (California 1987/88; Edmonton 1988 cF5; Edmonton 1988 bF5)

Anova Design:

Sources	d.f.
Site-year	2
Experimental Error	2
Sampling Error	45
Total	49

c) Simple Correlations between bF4 and cF4, and between aF5 and bF5.

d) Duncan's multiple mean comparison tests for hardness, protein and sedimentation throughout the generations for the random selected group (N = 10).

Objective 3: To study and describe the heritabilities of, and correlation among, the quality traits in the early generations of a Hard X Medium Hard wheat cross, using the F3, F4, F5 and F6 generations derived from different seed sources.

The following analysis were conducted:

a) Simple correlations between quality traits, amongst 360 F4 lines grown in 1987.

b) Within random selection groups, simple regression analyses were conducted between the same quality character through the generations for each of the seed sources. Coefficients of determination were used as a heritability measure (Sunderman et al, 1965). Means of the two replicates were used for 1988 Edmonton F6; 1988 Edmonton bF5, 1988 Edmonton cF5, and for the 1988 Edmonton cF4 in this analysis.

Regressions conducted were:

1. On F3: Edmonton 1988 F6, bF5 and cF5, cF4.
2. On aF4 and bF4: Edmonton 1988 F6 and 3 sources of F5.
3. On cF4: Edmonton 1988 F6, bF5 and cF5.
4. On 3 sources of F5: Edmonton 1988 F6

c)Within random groups, simple correlations were calculated among quality characters for different generation sources

a) aF4
b) bF5
c) 1988 Edmonton F6

Grain Quality Tests:

1) 1000 kernel weight (g)

1000 kernel weight was determined with a Count-A-Pak model electronic seed counter using approximately 35 g of wheat grain from which all the broken kernels and foreign materials were previously removed by hand picking. The weight of 500 seeds X 2 was recorded.

2) Test weight (g/hectoliter)

Test weight was determined using the standard method for hectoliter weight. An imperial pint measure and a Cox funnel were used, and a Grain Commission conversion chart. The moisture basis was 9.0 +/- 0.25%.

3) Kernel hardness (seconds)

For determination of hardness, the samples were dried in a dryer at 55 ^{0}C for 48 hours before they were threshed, so that the moisture content of the stored grain samples was 9.0 +/- 0.25% , The temperature of the storage and operation rooms was controlled at 12-14 ^{0}C by using air conditioning to minimize temperature fluctuations. Wheat hardness was measured by the time to grind 4g of wheat (Miller et al 1981). The procedure involved pouring approximately 6g of wheat into a Brabender micro hardness tester and automatically recording the time required to grind the 4g as it fell on the pan of a micro-balance. The larger the grinding time, the softer the wheat grain.

4) Grain protein content (%)

Wheat protein content measurements in this study were assessed in the Technicon Infra-Analyzer 300. This method operates on the principle that when near infra red light is shone on a finely ground sample (from a UDY mill) the intensity of light reflected from the surface of the sample relates to its chemical composition. The infra-analyzer measures the reflectance at multiple wavelengths so that the amount of several constituents, (e.g. moisture and protein), can be assessed with only one reading and the effect of one on the absorption of others can be corrected for. All the readings for protein content were expressed at 13.5% moisture basis.

5). Flour yield, (%)

Flour yield was measured with the small Brabender Jr. Laboratory mill, for 50 g samples, and with the big Buhler Jr. Experimental. Mill for 500 g samples. In both cases, the moisture content was calibrated to 14% according to AACC methods. (AACC, 1969)

6) Moisture Content (%)

Moisture content was measured using a Brabender Moisture Meter. Samples of wheat (minimum 12 g) were dried at 155 °C for one hour and water loss equated to moisture content.

Flour quality tests:

1) Sedimentation Value (cm^3)

AACC method 56-60, 1969.

2) Farinograph

AACC,1969. The following parameters were recorded:

1) Water absorption, Brabender Units, %

2) Arrival time, minutes

3) Peak time (dough development time) minutes

4) Departure time, minutes

5) Stability, minutes

6) Mixing tolerance index (MTI), Brabender Units

7) 20 minutes drop, Brabender Units

The prediction tests were carried out on all the seed sources and generations (except hectoliter weight measures on aF4, bF4, aF5 and the 1988 Edmonton F3. Buhler milling and Farinograph tests were carried out on aF4, bF5, and 1988 Edmonton F6 materials. Table 1 indicates the codes assigned for each of the quality traits.

Table 3.1.1.1 Codes used for Different Quality Testing Methods

Measurement	Code
Seed hardness	Hard
1000 Kernel weight	Kwt
Protein content	Prot
Hectoliter weight	Hlwt
Brabender flour yield	Flyd
Buhler flour yield	Bflyd
Sedimentation	Sedt
Farinograph properties	
Water absorption	FAB
Arrival time	FAT
Peak time	FPT
Departure time	FDT
Stability	FST
Mixing tolerance index	FMTI
20 minute drop	F20

4. Results

4.1 Quality analysis of 1987 Edmonton F4

Microprediction tests (hardness, protein content, flour yield, sedimentation and 1000 kwt) were carried out on all 360 F4 lines. Ranges, means, medians and coefficients of variability of the means for the lines and parents (HY 320 and QT 8132) in Table 4.1.1.1. Figure 4.1.1.1 illustrated the distribution of hardness values in the F4 progenies.

For all quality traits, median and mean values were almost identical and both values were relatively close to the mid-parent value. The range of the quality values for the 360 lines well exceeded the parental values in both directions for all prediction tests (Table 4.1.1.1).

Sedimentation value and hardness exhibited the greatest variation, as indicated by the coefficient of variation.

Simple correlations among the five quality traits were calculated for the 360 progeny lines (Table 4.1.1.2). Hardness was shown to be highly significantly correlated with protein, sedimentation value and flour yield. Grain protein content was also shown to be highly significantly correlated with sedimentation value and flour yield (Table 4.1.1.2).

Table 4.1.1.2 Correlations among quality traits of 360 F4 lines grown in 1987 at Edmonton

	Hard	Prot	Sedt	Flyd	Kwt
Prot	-0.55**	—			
Sedt	-0.16**	0.57**	—		
Flyd	-0.54**	0.24**	0.02	—	
Kwt	0.05	0.06	0.03	-0.12*	—

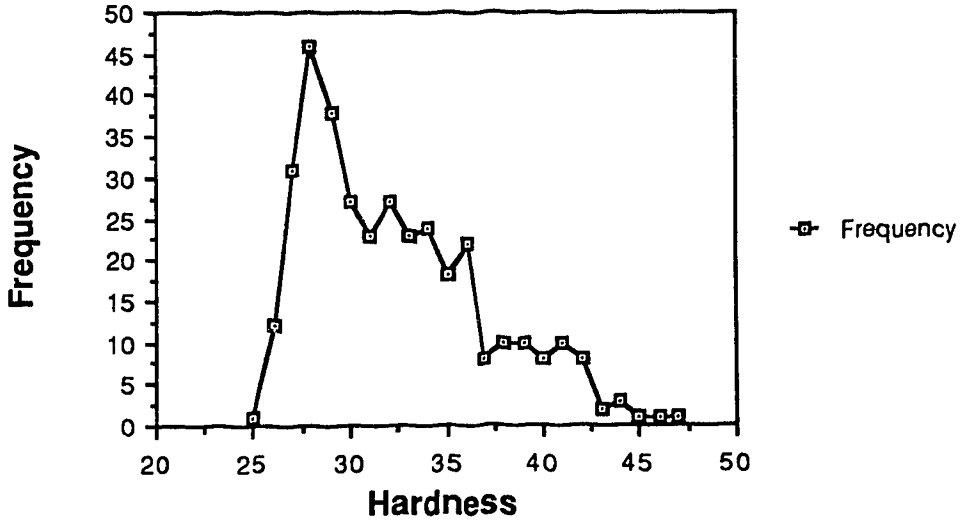
* Significant at 0.05 level.
** Significant at 0.01 level.

Table 4.1.1.1. Quality traits for 360 F4 lines, compared to parents (Standard errors are expressed in the brackets)

	Hard	Prot	Sedt	Flyd	Kwt
Parents[1]					
HY 320	36.0(1.3)	11.2(0.4)	48.0(1.3)	66.7(2.3)	40.6(1.3)
QT 8132	26.5(0.4)	13.1(0.2)	57.0(0.9)	70.5(1.7)	44.0(0.8)
Mid-Parent	31.3	12.1	52.3	68.6	42.3
Lines:					
Range:	25.0-47.0	10.7-17.1	25.0-70.0	56.8-75.1	26.2-55.4
Median:	32.0	12.8	55.0	69.3	40.0
Mean:	32.5	12.8	53.3	69.0	39.7
St. Dev.[2]	4.6	0.85	9.5	3.1	4.3
C.V.[3]	14.2	6.6	17.8	4.6	10.9

1. Average of 3 replicates.
2. St. Dev. = Standard Deviation.
3. C.V. = Coefficient of Variation.

Figure 4.1.1.1 Hardness Distribution for 360 F4 lines in Edmonton 1987



5.1 Hardness distribution of F4 progenies

360 progeny lines was a relatively large sample size and therefore provided a good representation of the complete F4 population. The ranges of values for the wheat and flour properties measured on the F4 progenies were typical of plant breeding programs where two parents of diverse genetic background for quality are crossed. Many of the quality traits measured on the segregating population were intermediate in value between the two parents, but some lines were obtained which exceeded both parents in selected quality traits. Genetic mechanisms were not studied in the present research but segregation in the cross created a wide range of genetic variation, and if the traits of the superior lines could be fixed, improved flour quality could be achieved through vigorous selection in F4.

The similarity of the estimates between the quality means of the F4 generation and the mid-parent values for the selected quality traits indicated that the the mid-parent values were an excellent indicator of the progeny quality means.

The distribution of hardness was skewed in the direction of softness. The softest line (Hardness value = 47) of the F4 progenies was about 2.5 standard deviations away from the softer parent (Hardness value: HY320 = 36). Since this study was initiated it has been determined that one of the parents (HY320) alone contributes significantly to the hardness distribution, since it has proven to be genetically non-uniform for hardness. DePauw (1987) showed that bulk lines of HY 320 were not uniform in their hardness and a bimodal distribution existed among the HY320 breeder lines. Thus, although the average hardness value for HY320 was 36, some softer lines may have been used during the time of crossing, since over 30 plants were used in the crossing procedure (Kutchera, personal communication). HY 320 is a representative varietyfor quality for the Canadian Prairie Spring Wheat class. One of the common complaints about this wheat class from the wheat industry is that the variety HY 320 is too soft. Thus breeding for a harder wheat kernel has become one of the more important breeding objectives for the Canadian Prairie Spring Wheat class. The hardness distribution obtained for the F4 progeny lines showed that the majority of the lines were harder than HY 320, one of the softer parents, suggesting that the harder lines could be selected from this cross.

5.2 Direct effects of hardness selection on the expression of other quality traits

Grain hardness has been shown previously to be simply inherited (Symes 1969; Baker 1977; O'Brien and Ronald 1987), and the manipulation of this character [illegible]vely easy. In the evaluation of quality potential, kernel hardness has usually been the prediction test of initial interest, due to the ease of measurement. The test is simple, rapid and can be conducted on as little as 4-5 grams of seed (Miller 1981). Given this measurement, an immediate decision can be made as to the bread (Williams 1986) and pastry (Yamazaki and Donelson 1983) quality potential of a line.

In the present study selection of hardness in F4 significantly affected the measurements of hardness, flour yield estimated both by the Brabender laboratory mill and the Buhler experimental mill, farinograph water absorption and farinograph arrival time, throughout the generations. Selection for hardness also influenced the protein content no matter which generation or seed source, with only one exception. Compared with the softer lines, and throughout generations and seed sources, the progeny of harder wheats generally had harder kernels and higher protein content, higher flour yield, higher farinograph water absorption, and longer farinograph arrival time.

The response of the hardness measures in the later generation to the F4 selection followed expectation from the literature. The hardness grouping patterns (hard, medium hard and soft) remained consistent throughout the generations. Thus lines selected for harder grain kernels in the F4 had harder grain kernels in the later generations of F5 and F6, no matter which years or locations were taking into account. This result has considerable implications for a plant breeding program, especially in the Canadian Prairie Spring Wheat class, where breeding for harder kernel is an objective. The only exception was the 1988 Edmonton F3 situation, where seeds were planted in hill plots and the medium and soft groups were not different in their hardness measures. Segregation in the F3 population, conbined with effect of the heavy green kernels from late tillers in the hill plots would be the possible reasons contributing to this lack of significant differences, not only in hardness, but also in flour yield and protein content.

Symes (1969) found that the hardness gene also increased flour yield. In the present study, the hard wheats also had higher flour yields, and selection for hardness increased the flour yield, both in the Brabender laboratory mill measure and for the Buhler experimental mill measure. This result agrees with previous studies (Baker and Dyck 1975; Pomeranz et al. 1988). The measure of flour yield has been well known for its lack of convincing repeatability (Baker and Cambell 1971). Stenvert (1974) stated that one reason for the higher flour yields of harder wheats was that the hard wheat can withstand a higher level of moisture content during the process of tempering and thus was able to give a higher flour yield. Mattern et al. (1973) found that the control of kernel hardness was located on chromosome 5D, and later a single gene was identified controlling the differences between hard and soft wheat milling (Law et al. 1978) for the variety Cheyenne. In several cases in the present study, the flour yield measures obtained from the hard group do not significantly differ from those of the medium hard group, indicating that the dependance of flour yield on hardness can also be variable. However, progenies of the soft group was found to have a significantly lower flour yield than those from the other selection groups consistently, so one may still use the hardness measure to discard the lines with the lowest flour yield in the Canadian Prairie Spring Wheat breeding program.

When a hard wheat has been identified, the protein quantity would be the next immediate concern with respect to evaluating the breadmaking or other quality potential (Finney and Barmore 1948; Bushuk et al. 1969). The effects of protein content on wheat hardness have been the subject of many investigations, with varied and often conflicting results. In the present study, where Canadian Prairie Spring wheat was used as one of the parents, hardness grouping showed significant effects on protein content in all generations, and for all seed sources except one. Wheat selected for harder kernels usually had a higher protein content than the wheats selected in the medium and soft groups, although in several cases the hard group did not show significant difference from the medium hard group. In the cF5 situation, hardness grouping did not affect the protein content and this indicated that the relationship between hardness and protein content can be inconsistent. Environmental factors might also contribute to this insignificance. Nevertheless, all progenies from the soft group were shown to have significantly lowered protein content, for every seed source and generation. This would indicate that plant breeders can use a simple hardness measure to identify the lines with lower protein content.

Farinograph water absorption is an important character for the baking industry and higher water absorption is desirable for bakers (Hadziyev, personal communication). In the process of milling, hard wheats will have higher starch damage than soft wheats (Williams 1967), consequently requiring more water to make a dough of proper consistency, than a soft wheat would require. Doeks and Belderok (1976) showed that the baking absorption of wheat is determined by the chromosome 5D. In the present study, hardness selection directly influenced the farinograph water absorption performance. The degrees of response to the hardness selection for FAB measures were different among the hardness groups but, generally, harder wheats required more water to reach the 500 line (Brabender Units) consistency. The simple hardness measure can therefore be used to predict FAB values.

Hardness grouping also influenced the farinograph arrival time. FAT is closely correlated with the farinograph water absorption. Harder wheats require longer to reach the 500 line (Brabender Units).

As Table 4.2.1.1 and 4.2.1.2 indicated, hardness selection did not influence the quality traits sedimentation value, farinograph dough development time, and farinograph stability. The independence of quality traits from the effects of hardness grouping showed that the hardness influence has its limitations, and that hardness measure alone cannot account for all important quality differences. Such limitations suggest that additional quality measures would be needed for the best prediction of the wheat quality potential of a breeding line.

5.3 Correlations among and heritabilities of the quality traits

In the present study, the interrelationships among the quality traits were generally similar throughout the F4, F5 and F6 generations. This indicated that the relationships among the quality traits were less influenced by environment and seed sources. Fowler and de La Roche (1975) also reported independence of these relationships from the environment, using hard red spring wheats.

In the present study, hardness, protein content, flour yield, farinograph water absorption and farinograph arrival time were significantly correlated with each other in all three generations. The F4 lines from this cross demonstrated a broad range of hardness values, thus representing a population of diverse hardness (hard, medium-hard, and soft), so that strong correlations of this nature were expected, and results are in close agreement with previous studies on other germplasm (Sunderman et al. 1965; Baker et al. 1975; Pomeranz et al. 1988). Orth et al. (1973) reported that both protein content and farinograph water absorption increase with flour extraction rate. Harder wheats have been shown to have higher starch damage after the milling process, compared to the soft wheats (Simmonds 1974). Water, absorbed by both starch and protein of the flour (hydrophobic gluten) is important and necessary for dough development, so significant correlations were observed between farinograph water absorption and farinograph arrival time. Undamaged starch absorbs less water than damaged starch granules, thus a significant correlations of FAB with flour yield might indicate that higher starch damage could have resulted from a higher extraction rate. The strong correlations reported here suggested that simple, easy measures such as hardness and protein content could be used in the screening of large numbers of breeding lines to predict the other less easy measured quality traits such as FAB, FAT and flour yield.

Zeleny sedimentation values, which reflect the protein quantity as well as the protein quality, showed highly significant correlations with protein content, farinograph development time and farinograph stability in the present study. FPT and FST have been shown to be good indicators of dough handling properties and final baking quality and are often used as final loaf volume indicators (Finney and Yamazaki 1967; Orth et al. 1972). The strong correlations of sedimentation value with FST and FPT obtained in the present study follow the expectation of the literature and further prove that both the quantity and quality of the protein play an important role for final quality in the Canadian Prairie Spring quality type.

Sedimentation value was significantly correlated with protein content. It was not correlated, or was not consistently correlated with hardness, FAT, FAB and flour yield. Thus, it appeared that the protein content was an intermediary influence, connecting hardness and sedimentation. The lack of correlation of sedimentation value with other quality traits and the known importance of the sedimentation value indicated that, for the best prediction of flour quality, sedimentation value should also be included in early generation testing and quality prediction, in addition to protein content and hardness. Generally speaking, the interrelationships among quality traits are complex and it is hard to make a clear, simple characterization of the factors responsible for baking quality. Some prediction tests are more reliable and accurate than others, and some can be more meaningful than others (Baker and Campbell 1971). In the present study of CPS wheat study, the correlations indicated that quality traits hardness, sedimentation value and protein content would be the best indicators of the flour quality, in agreement with the previous literatures, where good bread making and cake baking were as quality objectives.

In a selection program, a plant breeder can only exploit the genetic differences among lines. A screening test which cannot identify genetic differences is of little value in screening in plant breeding programs. Heritability of a test indicates the extent to which genetic differences are detectable. Heritability estimates obtained in the present study revealed that the traits hardness and sedimentation value were highly heritable, while the traits protein content and flour yield were only moderately heritable. The heritability values are in agreement with those reported by Baker et al. (1971), Davis et al. (1961), Bhatt and Derera (1975) and Pearson et al. (1981). Previous studies (Fowler and de La Roche 1975b; Bhatt and Derera 1975; Pearson et al. 1981; O'Brien and Ronald 1987) have all reported high heritability values for estimates of grain hardness. Given the report by Symes (1965) of a single gene difference for this trait, high heritability estimates are to be expected. With respect to the hardness reqirements for the Canadian Prairie Spring wheat class, the present study confirms availability of a suitable degree of genetic variance in this cross, combined with good heritability.

Sedimentation value was indicated as the singular flour test to give the best prediction of the strength of the flour and the breadmaking quality of a hard wheat (Greenaway et al. 1966; Bushuk et al, 1969). High heritabilities for this trait have been commonly reported (Lebsock et al. 1964; Atkins et al. 1965; Sunderman et al. 1965). Hsu and Sosulski (1969) further reported a high degree of dominance for high sedimentation value and suggested that only two genes were responsible for determination of sedimentation value in the cross of Selkirk X Gabo. In the present study, the number of genes involved in the inheritance of sedimentation value could not be determined, as a genetic design was not used. Nevertheless, high inter-generation regression heritability estimates obtained for this character in the present study implied that a relatively simple mode of inheritance existed. Inter-generation heritability estimates between different site-years further indicated that the environment, which was reported in the literature to significantly influence the sedimentation value, would not affect the relative performances of lines. Thus the high heritability for sedimentation value, along with its close relationship to other important quality parameters, makes this character very valuable for screening large samples of lines in a Canadian Prairie Spring wheat breeding program, to seek high quality potential.

Heritability estimates for protein content between different generations and site-years ranged in this study from 0.16 to 0.91. The variation is in close agreement with the past literature. Low correlations for protein content were reported between F3 and F2 plants of r= 0.41 to 0.58 (Haunold et al. 1962) and r= 0.24 (Sunderman et al. 1965). In contrast Lofgren et al. (1968) reported intergeneration correlations as high as r = 0.73, based on flour protein content. Samson et al. (1983) showed that inter-generation correlations for protein content between F6 to F4 ranged from r - 0.25 to r - 0.50. Some of the higher heritabilities reported in the present study reflect the strong correlations between hardness and protein present in this cross in different generations. Generally speaking, the varied heritabilities for protein content, along with the relative small variation in the F4 progeny lines as illustrated in the Table 4.1.1.1., would make this character less suitable as a main selection criteria in the early generations of the breeding program.

Lofgren et al. (1968) studied the progenies of four wheat crosses and reported that the flour yield was more heritable than protein content. Baker et al. (1971) reported heritabilities for flour yield that ranged from .46 to .81 in different years for hard red spring wheats. Because of the low repeatability of the flour yield measures (Baker and Cambell 1971), measurement of this character is usually considered of little value in the early generations of a breeding program. In the present study, inter-generation heritability measures for flour yield ranged from .27 to .80 in different generations and years. Some of the extreme high heritability estimates for flour yield are believed to have been caused by the tempering process in the current study, which brought up the grain moisture content to 14% before milling in a manner that favored hard wheats in the milling process, and which would thus discriminate against the soft wheats.

Farinograph properties (FAB, FAT, FPT, FST, FMTI) measured on lines from this CPS cross showed high to medium high heritabilities in the present study. These results agreed with previous studies. Baker et al. (1968) reported heritabilities for farinograph characteristics within a hard red spring wheat cross. Heritabilities for dough development time ranged from .38 to .59, and for mixing tolerance index ranged from .48 to .75. High heritabilities for the farinograph properties were also reported by Heyne and Finney (1965) in a series of crosses between hard red winter wheats. Effective selction for farinograph properties in F3 and F4 was reported to be effective (McNeal et al. 1964). Because relatively larger amounts of seed (minimum 200 g) are needed for farinograph tests, plant breeders have tended to stay away from this test in their breeding program, especially in early generations. However, the strong correlations obtained in the present study enable hardness, sedimentation value and protein content to be used as good indicators of farinograph properties. Heritability studies in this study further suggested that estimation of hardness and sedimentation value can be very effective for quality improvement in early generation selection.

Different environments influenced the magnitude of the heritability estimates for the quality traits, and amongst these traits protein content was the most influenced. Heritabilities for protein content of F6 on three different sources of F4 seed indicated that the location X year effects were bigger than the year effects alone. Results of regression heritabilities of F6 on three different sources of F5 further showed that location X year interaction caused more variation in heritability than did variation due to the effects of seed source or year alone. Thus, in the plant breeding program situation, multi-site testing is needed for a true estimate of the heritability of protein content. This result agrees with a previous study of Bhatt and Derera (1975).

5.4 Site-year effects on quality parameters in F4 and F5

The influences of environment on wheat quality were reviewed and specifically emphasized by Hehn and Barmore (1965). Information on the different types and magnitudes of genotype X environment interaction is necessary when allocating materials and other resources to a breeding program. In the present study, significant genotype X environment interactions were found for hardness in both the F4 and F5 generations. Protein content and sedimentation value were found to be significantly influenced by the environment in the F4 but not in the F5 generation. Significant geneotype X environment interaction would mean that evaluation of breeding lines over several environments would give a more accurate estimate of their quality potential.

Variety has been shown to have much larger effects than location on hardness (Williams 1967; Fowler and de La Roche 1975b; Pomeranz et al. 1984). Nevertheless, Parish and Halse (1968) studied the influence of temperature and relative humidity during ripening on grain hardness and reported that hard wheat becomes harder with a more humid atmosphere during the later stages of ripening, while all wheat becomes harder if the temperature during this period is higher. Miller et al. (1982) and Finney et al. (1987) also reported the significant influences of environment on hardness. The significant effect of site-year on hardness in the present study is believed to be primarily due to the differences in growing conditions of the California Winter Nursery and the Edmonton Research Station.

Effects of environment on protein content are believed to be manifested through the enzyme nitrate reductase which regulates nitrogen uptake by the plant (Eilrich and Hageman 1973). The level of the substrate, available soil nitrogen, is controlled by environmental factors such as moisture, temperature and niitrogen fertilizers (McNeal et al. 1972). Therefore the significant effect that environment has on protein level should not be unexpected. Sedimentation value, which measures the protein quantity as well as the protein quality. is also expected to show a certain response to the environmental factors that influence the protein content. In the present study, both the protein content and sedimentation value were significantly influenced by the environment in the F4 situation but not in the F5. In the F5 situation, there were only two site-years present and the Edmonton 1987 crop season, when nitrogen fertilization was performed, was missing. Thus it is believed that the nitrogen fertilization may have contributed, at least in part, to the variation for protein content and sedimentation values.

Significantly high correlations were observed for hardness, sedimentation value and flour yield between the California Winter Nursery and Edmonton conditions for both F4 and F5. These data suggested that selection for these three traits would be successful in the winter nursery materials, and this could be exploited as an effective resource saving strategy. So in a breeding program, plant breeders could use the Winter nursery not only as an increase site but also as a site for testing. Thus larger population of breeding materials could be sent to California winter nursery in the fall and the micro-prediction quality testing in the spring would disgard the ones with inferior quality. Fewer numbers of the qualified materials enable plant breeders to have less operations in the Edmonton field situations and keep the operation costs down. So larger amount of samples could be tested with less cost.

The high correlations also indicated that the G X E interaction was not important in determining the relative performance of individual lines for flour yield, grinding time and sedimentation value. Baenziger et al. (1985) studied 24 winter wheat cultivars in 12 locations and reported that significant influences of environment exist for hardness, protein content and flour yield, but that environment did not affect the ranking of the cultivars. The result was confirmed in the present study.

5.5 "Normal plant breeding progression" vs. the "1988 all generations special case".

In several cases of the present study, results were reported for the "normal plant breeding progression" (abbreviated normal progression) and the "1988 all generations special case" (abbreviated special case) separately. Under the special case of 1988, four generations of the wheat cross were present in the one environment at the same time. Theoretically, the special case data set should tend to maximise identification of genetical differences and minimise environmental influences and interactions, compared to the normal progression data set. Needless to say, results obtained from this comparison would have less direct apllication to a practical plant breeding program, compared to the results obtained from the normal progression. Nevertheless the results would give the actual relations under the "optimum" conditions.

As illustrated by Table 4.2.2.2a and 4.2.2.2b, the responses of protein content to selection for hardness groupings were not significantly different between the hard and medium-hard group under the normal progression situation for all the sources (F4, F5 and F6). Under the special case situation, where the possible envoronmental influences and their interaction are minimized, the protein contents between the hard and medium hard groups were significantly different for both F4 and F5. This result indicated that the different locations, different years and their interactions could have influenced the protein measures between the hard and the medium-hard groups. Thus, in the practical CPS breeding program, more than one site-year of testing would be appropriate for the evaluation of the protein content. The response of hardness and flour yield to the hardness grouping did not show significant difference between the two situations, implying that the differences between the mean values of the three hardness groups for these two characters were independent from the environment effects, further suggesting that effective hardness selection could be carried out in any environment.

With the exception of the heritability obtained on F3, the average heritabilities obtained between different generations under the special case were little higher than those under the normal progression for all the major prediction quality measures (protein content, hardness and sedimentation value), as indicated in Tables 4.3.2.2 and 4.3.2.3. The differences between the two situations are relatively small, and under both situations, heritability estimates are high and significant for hardness and sedimentation value. Since the heritability estimtes obtained in the present study were based on the inter-generation regressions, the heritability values representing, to a great extent, the ranking of the individual lines within the populations. Thus the result would further support that environment has relatively little effect on the relative performance of the individual lines within their generations.

Three site-years (1987 Edmonton, 1987/88 California, 1988 Edmonton) were present in the normal progression situation. As illustrated in Tables 4.4.3.1a and 4.4.3.1b and Figures 4.3.2.3a and 4.3.2.3b, site-years significantly affected the mean values of the quality traits hardness, protein content and sedimentation value among the generations, among the three sedimentation value was most dramatically influenced. Means for hardness and protein content were also influenced. By contrast, the means of all the quality traits under the special case did not differ from each other between the generations. These results showed that the environment had significant effects on the means of quality traits. Nitrogen fertilization treatment in the 1987 would contribute to the quality differences too, especially to protein content and sedimentation. Since the ranking of the individual lines within the population was shown to be not greatly influenced by the environment, so in the practical breeding program one would realize that the absolute values of the quality measure of one individual line would be of little meaning if not compared with values of other lines in the same population under the same growing conditions.

6. Summary

Canadian Prairie Spring wheat is a new class of wheat for Western Canada. Some of the breeding objectives for quality improvement for the CPS type include harder grain kernels, higher protein content and stronger flour strength. One of the objective of the current study was to examine the impact of hardness selection on the functional quality traits of later generations, in a cross designed for CPS wheat quality improvement. Results obtained in the present study showed that hardness selection in the F4 was effective in improving other quality traits in later generations. Hardness selection significantly affected the hardness, protein content and flour yield measures in later generations. Harder wheats selected in F4 resulted in harder wheats with higher protein content and higher flour yield in F5 and F6. One can at least use the hardness measure to identify soft lines so that lines with low protein and low flour yield lines can be identified and discarded.

Heritabilities of, and correlations among, the quality traits in the early generations in this cross of HY 320 and QT 8132 were also studied. Hardness and sedimentation value were shown to be highly heritable. Protein content showed moderate to low heritability. Significant correlations were found between hardness and protein content, and between protein content and sedimentation value. These three traits also showed significant relationships with the farinograph properties and thus are considered to be satisfactory predictors for flour quality in the CPS breeding program. High variability of hardness and sedimentation values in the F4 progeny lines together with high heritability estimates for these two traits offers excellent scope for early generation selection among lines, to improve quality.

Heritability levels of flour yield were shown to be intermediate. The strong response of flour yield measure to the hardness grouping and the significant correlations that flour yield had with other quality traits (especially hardness), is probably an indirect effect arising from the protocol used for tempering prior to milling. Both the tempering process and the setting of the mill would contribute to this significance, since the tempering and milling procedure were biased in favour of identifying hard wheat with higher flour yield.

Environment significantly influenced the means of quality traits such as hardness, sedimentation value and protein content, but the correlations of results obtained between samples from the California winter nursery and samples from the Edmonton Research Station showed that the ranking of the individual lines changed very little, confirming that selection for hardness and sedimentation value on samples from the winter nursery would be acceptable. Heritability studies further confirmed this conclusion.

One of the major limitations of the current study was that the material used were from one individual cross of the CPS wheat type. One might question the generality of these results, based on the degree of genetic variation that existed in the cross. Hardness values in the 360 F4 progeny lines indicated, however, that there were large variations for hardness, and thus the population represented a study covering a wide range of hardness categories. The relevance of the current results to practical breeding programs involving a wide range of hardness in the parent is therefore considered to be considerable.

References

1. Aamodt, O. S. and Torrie, J. H. 1935; Studies on the inheritance of and the relation between kernel texture and protein content in several spring wheat crosses. Can. J. Res. 13: 202-219.

2. American Association of Cereal Chemists. Approved methods of the AACC. 7th edition. The Association, St. Paul, MN, 1969.

3. Arther, M. L. and O'Brien L. 1987; A comparative study of the quality status of Condor wheat grown in Northern Victoria and Southern New South Whales. Aust. J. Agric. Res. 38: 465-471.

4. Atkins, I. M., E. C. Gilmore, P. Scottino, O. G. Merkle and Porter K. B. 1965; Evaluation of the sedimentation test in a wheat breeding program. Crop Science 5: 381-385.

5. Axford, D.W.E., E. E. McDermott, and Redman D.G. 1978; Small-scale tests of breadmaking quality. Milling Feed Fert. 66: 18-20.

6. Baenziger, P. S., R. L. Clements, M. S. McIntosh, W. ı. Yamazaki, T. M. Starling, D. J. Sammoms and Johnson J. W. 1985; Effect of cultivar, environment, and their Interaction and stability analysis on milling and baking quality of soft red winter wheat. Crop Science 25: 5-8.

7. Baker, R. J., V. M. Bendelow and Kaufmann M. L. 1968; Inheritance of and inter-relationship among yield and quality traits in common wheat. Crop Science 8: 725-728.

8. Baker, R. J. and Campbell, A. B. 1971; Evaluation of screening tests for quality of bread wheat. Can. J. Plant Sci. 51: 449-455.

9. Baker, R. J., K. H. Tipples and Campbell A. B. 1971; Heritabilities of and correlation among quality traits in wheat. Can. J. Plant Sci. 51: 441-448.

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

11. Baker, R. J. 1977; Inheritance of kernel hardness in spring wheat. Crop Science.17: 960-962.

12. Baker, R. J. and Kosmolak, F. G. 1977; Effects of genotype-environment interaction on bread wheat quality in Western Canada. Can. J. Plant Sci. 57: 185-191.

13. Barlow, K. K., Buttrose, M. S., Simmonds, D. H. and Vesk, M. 1973; The nature of the starch protein interface in wheat endosperm. Cereal Chem. 50: 443-454.

14. Bhatia, C. R. 1975; Criteria for early generation selection in wheat breeding program for improving protein productivity. Euphytica 24: 789-794.

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

16. Borghi, B., G. Boggini, and Corino, L. 1975; Breeding for quality in common wheat. 1. Early selection in F2 and F3 generations. Cereal Res. Commun. 3: 205-214.

17. Briggle, L. W., W. T. Yamazaki and Hanson W. D. 1968; Heritability of three soft wheat quality characters in the F2 and F3 generations. Crop Science 8: 283-287.

18. Briggs, K. G. 1969; The effectiveness of selection for yield and breadmaking quality in Triticum aestivum, L. in the F3 generation. Ph.D Thesis, University of Manitoba, Manitoba.

19. Briggs, K. G., W. Bushuk, and Shebeski, L. H. 1969; Variation in breadmaking quality of systematic controls in a wheat breeding nursery and its relationship to plant breeding procedures. Can. J. Plant Sci. 49: 21.

20. Briggs, K. G. and Shebeski, L. H. 1971; Early generation selection for yield and bread making quality of hard red spring wheat. Euphytica 24: 453-463.

21. Briggs, K. G. and Shebeski L. H. 1972; An application of factor analysis to some breadmaking quality data. Crop Science 12: 44-46.

22. Bushuk. W., K. G. Briggs. and Shebeski,.L. H. 1969. Protein quantity and quality as factors in the evaluation of bread wheat. Can. J. Plant Sci. 49: 113-122.

23. Busch, R. H., W. C. Shuey and Frohberg R. C. 1969; Response of hard red spring wheat (Triticum aestivum L.) to environments in relation to six quality characteristics. Crop Science 9: 813-817.

24. Chapman, S. R. and McNeal F. H. 1970. Gene Effects for grain protein in five spring wheat Crosses. Crop Science 10: 45-46.

25. Collins, T. H. 1971; The importance of damaged starch. Milling 153: 17-20.

26. Corpuz, I. M., G. M. Paulsen and Heyne E. G. 1983; Relationship between kernel color and protein content of hard red X hard white winter wheat progeny. Euphytica 32: 617-624.

27. Cowley, C. R. and Wells, D. G. 1980; Inheritance of seed protein in crosses involving "Hand": a hard red winter wheat. Crop Science 20: 55-58.

28. Davis, W. H., G. K. Middleton and Hebert T. T. 1961; Inheritance of protein, texture, and yield in wheat. Crop Science 1: 235-38.

29. Day, P. R., J. Bingham, P. I. Payne and Thompson R. D. 1985; The way ahead: wheat breeding for quality improvement. In: Chemistry and physics of baking; (Chapter 19). Eds: J. M. V. Blanshard, P. J. Frazier and Galiard, P. The Royal Society of Chemistry. London.

30. De La Roche, I. A. and Fowler, D. B. 1974; Wheat quality evaluation: 1. Accuracy and precision of prediction tests. Can. J. Plant Sci. 55:

31. Diehl, A. L., V. A. Johnson and Mattern P. J. 1977; Inheritance of protein and lysine in three wheat crosses. Crop Science 18: 391-395.

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

33. Eilrich, G. L. and Hageman, R. H. 1973; Nitrate reductase activity and its relationship with to accumulation of vegatative and grain nitrogen in wheat (Triticum aestivum, L.) Crop Science 13: 59-66

34. Farrand, E. A. 1972; Controlled levels of starch damaged in a commercial United Kingdom bread flour and the effects on absorption, sedimentation value and loaf quality. Cereal Chem. 49: 479-488.

35. Fifield, C. C., R. Weaver, and Hayves, J. F. 1950; Bread loaf volume and protein content of hard red spring wheats. Cereal Chem. 27: 283.

36. Finney K. F. and Barmore, M. A. 1948 Loaf volume and protein content of hard winter and spring wheat, Cereal Chem. 25: 291-312.

37. Finney, K. F. and Yamazaki, W. T. 1967; Quality of hard, soft and durum wheats. In: Wheat and wheat improvement, K. S. Quisenberry and L. P. Reitz ed.; 1st Ed. Agronomy 13: pp471-503.; ISSN Amer. Soc. Agron., Inc., Madison, Wisc.

38. Finney, K. F., W. T. Yamazaki, V. L. Youngs and Rubenthaler G. L. 1987 Quality of hard, soft, and durum wheats. In: wheat and wheat improvement; pp677-748.

39. Fowler, D. B. and De La Roche I. A. 1975a; Wheat quality evaluation. 2. Relationships among prediction tests. Can. J. Plant Sci. 55: 251-262.

40. Fowler, D. B. and De La Roche I. A. 1975b; Wheat quality evaluation. 3. Influence of genotype and environment. Can. J. Plant Sci. 55: 263-269.

41. Garcia-Olmedo, F., P. Carbonero and Jones B. L. 1982; Chromosomal locations of genes that control wheat endosperm proteins. Advances in Cereal Science and Technology 5: 3-47.

42. Gebre-Mariam, H., E. N. Larter, and Evans L. E. 1988; Selection for yield, kernel weight and protein content in early generations of six wheat Crosses. Can. J. Plant Sci. 68: 641-649.

43. Greenaway, W. T., N. S. Hurst, M. H. Neustad, and Zeleny, L. 1966; Microsedimentation test for wheat. Cereal Sci. Today. 11: 197-199.

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

45. Halloran, G. M., 1975; Genetic analysis of grain protein percentage in wheat. Theor. Appl. Genet. 46: 79-81.

46. Halloran, G. M. 1981; Grain yield and protein relationships in a wheat cross. Crop Science 21: 699-701.

47. Harris, R. H., L. D. Sibbitt, and Scott, G. M. 1945; Comparative effects of variety and environment on some properties of North Dakota hard red spring wheat flour. Cereal Chem. 12: 75.

48. Harris, R. H., L. D. Sibbitt, Waldron, L. R. and Stoa, E. 1947; Comparative effects of season, location and variety of the yield and quality of North Dakota hard red spring wheat. N.D. Agric. Expt. Sta. Bull.;

49. Haunold, A., V. A. Johnson and Schmidt, J. W. 1962; Genetic measurements of protein in the grain of Triticum aestivum, L. Agronomy J. 54: 203-206.

50. Hehn, E. R. and Barmore, M. A. 1965; Breeding wheat for quality. Advances in Agronomy 17: 85-114.

51. Heyne, E. G. and Finney, K. F. 1965; F2 progeny test for studying agronomic and quality characteristics in hard red winter wheats. Crop Science 5: 129-132.

52. Heyne, E. G. and Smith, G. S. 1967; Wheat breeding In: K. S. Quisenberry and L. P. Reitz (Eds), Wheat and wheat improvement. American Society of Agronomy, pp269-306.

53. Hsu, C. S. and Sosulski, F. W. 1969; Inheritance of protein content and sedimentation value in diallel crosses of spring wheat (Triticum aestivum L). Can. J. Gen. Cyt. 11: 967-976.

54. Jardine, R.; H. J. Moss, and Mullaly, J. A. 1963; Wheat quality: a factor analysis of some test data. Aust. J. Agric. Res. 14: 603-621

55. Johnson, V. A., P. J. Mattern, J. E. Stroike, and Schmidt, J. W. 1973; Genetic advances in wheat protein quantity and composition. Pages 547-556. In: E. R. Sears and L. M. S. Sears (Eds) Proc 4th Intl. Wheat Genet. Symp., Missouri, Columbia.

56. Johnson, V. A., P. J. Mattern, C. J. Peterson and Kuhr, S. L. 1985; Improvement of wheat protein by traditional breeding and genetic techniques. Cereal Chem. 62(5): 350-355.

57. Johnson, V. A. , J. W. Schmidt. P. J. Mattern and Haunold, A. 1963. Agronomic and quality characteristics of high protein F2 - derived families from a soft winter -hard red winter wheat cross. Crop Science 3: 7-10.

58. Kaul A. K. and Sosulski, F. W. 1964; Inheritance of two quality components in a spring wheat cross, Can. J. Gen. Cyt. 6: 240-244.

59. Kosmolak, F. G. 1978; Grinding time - a screening test for kernel hardness in wheat. Can. J. Plant Sci. 59: 415-.

60. Kosmolak, F. G. and Baker, R. J. 1978; Early generation screening For baking potential. Can. J. Plant Sci. 59: 21-26.

61. Kraljevic- Balalic, M., D. Stajner, and Gasic, O. 1982; Inheritance of grain proteins in wheat. Theor. Appl. Genet. 63: 121-123.

62. Kurimoto, Y. and Shelton, D. R. 1988; The Effect of flour particle size index on baking quality and other flour attributes. Cereal Foods World 33(5): 419-433.

63. Ladd, E. F., and Bailey, C. H. 1910; Wheat investigations - Milling, baking and chemical tests. N. D. Agric. Expt. Sta. Bull.; pp 95.

64. Law, C. N., C. F. Young, J. W. S. Brown, J. W. Snape, and Worland, A. J. 1978; The study of grain protein control in wheat using whole chromosome substitution lines. In: Seed protein improvement by nuclear techniques. International Atomic Energy Agency, Vienna. pp483-502.

65. Law, C. N. and Payne, P. I. 1983; Genetic aspects of breeding for improved grain protein content and type in wheat. Journal of Cereal Science 1: 79-93.

66. Lebsock, K. L., C. C. Fifield, G. M. Gurney, and Greenaway, E. T., 1964; Variability and evaluation of mixing tolerance, protein content and sedimentation value in early generations of spring wheat, Triticum aestivum, L., Crop Science 4: 171-174.

67. Lee, H. S., C. H. Cho, H. S. Song and Chang, H. G. 1983; Studies on the variation of quality traits and its selection efficiency in Triticum aestivum. Proc. 6th International Wheat genetics Symposium, Kyoto, Japan; pp835-841.

68. Lofgren, J. R., K. F. Finney, E. H. Heyne, R. C. Hoseney, and Shogren, M. D. 1968; Heritability estimates of protein content and certain quality and agronomic properties in bread wheats (Triticum aestivum,L.). Crop Science 8: 563-567.

69. Lukow, O. M. and Bushuk, W. 1984; Influence of germination on wheat quality. I. Functional (breadmaking) and biochemical properties. Cereal Chem. 61(4):

70. Mattern, P. J., R. Morris, J. W Schmidt, and Johnson, V. A. 1973; Locations of genes for kernel properties in the wheat variety 'Cheyenne' using chromosome substitution lines. Page 703-710 In: Proc. 4th Int. Wheat Genet. Symposium, University of Missouri: Columbia, MO.

71. Mattern, P. J. 1988; Wheat hardness: a microscopic classification of individual grains. Cereal Chem. 65(4): 312-315.

72. McGuire, C. F. and McNeal, F. H. 1974; Quality response of 10 hard red spring wheat cultivars to 25 environments. Crop Science 14: 175-178.

73. McNeal, F. H., M.A. Berg, R. K. Bequette, C. A. Watson, and Koch, E. J. 1964; Early generation selection for flour absorption and dough mixing properties in a Lemhi X Thatcher wheat cross. Crop Science 4: 105-108.

74. McNeal, F. H., M. A. Berg, C. A. Watson and Koch, E. J. 1969; Selection for baking quality in early generations of a Lemhi X Thatcher wheat Cross. Crop Science 9:

75. McNeal, F. H., M. A. Berg, McGuire, C. F., Stewart, V. R. and Baldridge, D. E. 1972; Grain and plant nitrogen relationships in eight spring wheat crosses , Triticum aestivum, L. Crop Science 12: 599-603.

76. McNeal, F. H., C.F. McGuire and Klindworth, D. L. 1982; Agronomic and quality characteristics of spring wheat lines selected for protein content and protein yield. Euphytica 31: 371-381.

77. McNeal, F. H. , M. A. Berg, R. K. Beguette, C. A. Watson, and Koch, E. J. 1964. Early generation selection for flour-absorption. and dough mixing properties in a Lemhi X Thatcher wheat cross. Crop Science 4: 105-108.

78. Miezan, K., E. G. Heyne and Finney, K. F. 1977; Genetic and environmental effects on the grain protein content in wheat. Crop Science 17: 591-593.

79. Miller, B. S., S. Afework, J. W. Hughes and Pomeranz, Y. 1981; Wheat hardness: time required to grind wheat with the Brabender automatic micro hardness tester. Journal of Food Science 46: 1863-1869.

80. Miller, B. S., S. Afework., Y. Pomeranz, B. L. Bruinsma,and Booth, G D. 1982; Measuring the hardness of wheat. Cereal Food World 27(2): 61-64.

81. Miller, B. S., Y. Pomeranz and Axfwork, S. 1984; Hardness (Texture) of hard red winter wheat grown in a soft wheat area and of soft red winter wheat grown in a hard area. Cereal Chem. 61(2): 201-203.

82. Morris, R., P. J. Mattern, J. W. Schmidt, and Johnson, V.A.1978. Studies on protein, lysine and leaf rust reactions in wheat cultivar, Atlas 66 using chromosome substitutions. Pages 447-454 In: Proc, 5th Int. Wheat Gen. Symp,. New Delhi, India, Feb,.1978. S. Ramanujam, ed, Indian Soc. Genetics and plant breeding, New Delhi.

83. Morris, R., J. W. Schmidt, P. J. Mattern and Johnson, V. A. 1966; Chromosomal location of genes for flour quality in the wheat variety 'Cheyenne' wheat chromosomes. Crop Science 6: 208-212.

84. Morris, R., J. W. Schmidt, P. J. Mattern and Johnson, V. A. 1968. Quality tests on six substitution lines involving 'Cheyenne' wheat chromosome. Crop Science 8: 121-123.

85. Moss, H. J. , P. J. Randall, and Pendleton, V. 1986. Growth temperature and grain quality. In 26th Ann. General meeting, Aust. Soc. Plant Physiol., Melbourne, Abstract.

86. O'Brien, L. and Orth, R. A. 1977; Effects of geographic location of growth on wheat milling yield, farinograph properties, flour protein and residue protein. Aust. J. Agric. Res. 28: 5-9.

87. O'Brien, L. 1983; Integrated system for breeding high yielding, good quality wheats. In: Proc. 6th. International wheat Genetic symposium, Kyoto, Japan; pp735-741.

88. O'Brien, L. and Ronalds, J. A. 1984; Yield and quality interrelationships amongst random F3 lines and their implications for wheat breeding. Aust. J. Agric., Res. 35: 443-51.

89. O'Brien, L. and J. A. Ronalds. 1987; Heritabilities of measures of wheat quality in early generations. Aust. Agric. Res. 38: 801-808.

90. Obuchowski, W. and Bushuk, W. 1980; Wheat hardness: comparison of methods of its evaluation. Cereal Chem. 57(6): 421-425.

91. Orth, R. A., R. J. Baker and Bushuk, W. 1972; Statistical evaluation of techniques for predicting baking quality of wheat cultivars. Can. J. Plant Sci. 52: 139

92. Orth, R. A., L. O'Brien and Jardine., R. 1976; A factor analysis of bread wheat quality tests. Aust. J. Agric. Res. 27: 575-582.

93. Orth, R. A. and O'Brien, L. 1976; A new biochemical test of dough strength of wheat flour. The Journal of the Australian Institute of Agricultural Science (June): 122-124.

94. Parish, J. A., and Halse, N. J. 1968; Effects of light, temperature and rate of desiccation on translucency in wheat grain. Australian J. Agric. Res. 19: 365

95. Payne, P. I. 1987; Genetics of wheat storage proteins and the effect of allelic variation on bread-making quality. Ann. Rev. Plant Physiology 38: 141-153.

96. Pearson, D. C., Rosielle, A. A. and Boyd, W. J. 1981; Heritabilities of five wheat quality traits or early generation selection. Aust. J. Exp. Agric. Anim. Husb. 21: 512-515.

97. Pomeranz, Y., and Miller, B. S. 1983. Wheat hardness: its significance and determination. Pages 399-403 In: Proc. 7th World Cereal and bread Congr.(Ptague), Developments in Food Science, 5. Elsevier: Amsterdam.

98. Pomeranz, Y., C. J. Peterson and Mattern, P. J. 1985; Hardness of winter wheat grown under widerly different climatic conditions. Cereal Chem. 62(6): 463-467.

99. Pomeranz, Y. and Mattern, P. J. 1987; Genotype and genotype X environment interaction effects on hardness estimates in winter wheat. Cereal Foods World 33(4): 371

100. Pomeranz, Y., Z. Czuchajowska, M. D. Shogren, G. L. Rubenthaler, L. C. Bolte, H. C. Jeffers and Mattern, P. J. 1988; Hardness and functional (Bread and cookie-making) properties of U. S. wheats. Cereal Foods World 33(3): 297-304.

101. Posner, E. S. 1988; Back to the Issue of wheat grading. Cereal Foods World 33(4): 362-365.

102. Reitz, L. P. 1957; Breeding wheat for quality. Cereal Science Today 2(6): 148-151.

103. Sampson, D. R., D. W. Flynn and Jui, P. Y. 1983; Inheritance of kernel protein Content in five spring wheat cross. Can. J. Gen. Cyt. 25: 398-402.

104. Sandstedt, R. M. , and Karl Fortmann. 1944. Effect of environment during the growth and development of wheat on the baking properties of its flour. Cereal Chem. 21: !72-188.

105. Schlehuber, A. M., Abbott, D. C., Jackson, B. R. and Curtis, B. C. 1967; Correlated inheritance of maturity and quality factors in a hard red winter wheat cross. Crop Science 7: 13-16.

106. Shebeski, L. H. 1967; Wheat and wheat breeding. In K.F. Nielson(ed.) Pro. Can. Centennial Wheat Symp. pp249-272, Modern Press.

107. Simmonds, D. H. 1974; Chemical basis of hardness and vistreosity in the wheat kernel. Baker's Digest.48: 16-

108. Simmonds, D. H., K. K. Barlow, and Wrigley, C. W. 1973; The biochemical basis of grain hardness in wheat. Cereal Chem. 50: 553-562.

109. Spitters, C. J. T. 1979; Competition and its consequences to selection in barley breeding. Agric. Res. Rep. Wageningen.

110. Stenvert, N. L. 1972; The measurement of wheat hardness and its effect on milling characteristics. Australian J. of Exp. Agri. and Animal Hus. 12: 159-164.

111. Sunderman, D. W., M. Wise and Sneed, E. W. 1965; Interrelationships of wheat protein content, flour sedimentation value, farinograph peak time, and dough mixing and baking characteristics in the F2 and F3 generations of winter wheat, Triticum aestivum,L. Crop Science 5: 537-540.

112. Symes, K. J. 1965; The Inheritance of grain hardness in wheat as measured by the particle size index. Aust. J. Agric. Res. 16: 113-123.

113. Symes, K. J. 1969; Influence of a gene causing hardness on milling and baking quality of two wheats. Aust. J. Agric. Res. 20: 971-979.

114. Symes, K. J. 1961; Classification of Australian wheat varieties based on the granularity of their wholemeal. Aust. J. Exp. Agric. Anim. Husb. 1: 18-23.

115. Payne, P. I., P. J. Corfield, and Blackman , J. A. 1979; Identification of a high-molecular-wight subunit of glutenin whose presence correlates with bread-making quality in wheats of related pedigree. Theor. Appl. Genet. 55: 153-159.

116. Payne, P. I., L. M. Holt, R. P. Thompson, D. Bartels, and Harberd, N. 1983; In: Proc. 6th Int. Wheat Genet. Symp. pp827-834. Kyoto; Univ. press.

117. Pomeranz. Y. and Afework, S. 1984; The effects of kernel size in plump and shrunken kernels and of sprouting, on kennel hardness in wheat. J. Cereal Sci 2: 119.

118. Tipples, K. H., K. R. Preston and Kilborn, R. H. 1982; Implications of the term "Strength" as related to wheat and flour quality. Baker's Digest; 1982: 16-20.

119. Tkachuk, R. and Kuzina, F. D. 1979; Wheat: relations between some physical and chemical properties. Can. J. Plant Sci. 59: 15-20.

120. Vogel, K. P, V. A. Johnson and Mattern, P. J. 1978; Protein and lysine contents of endosperm and bran of the parents and progenies of crosses of common wheat. Crop Science 18: 751-754.

121. Waldron, R. L., R. H. Harris, T. E. Stoa, and Sibbitt, L. D. 1942; Protein and quality in hard red spring wheat with respect to temperature and rainfall. N. D. Agric. Expt. Sta. Bull. pp311.

122. Welsh, J. R. and Hehn, E. R. 1964; The effect of chromosome 1D on hexaploid wheat flour quality. Crop Science 4: 320-323.

123. Welsh, J. R., C. A. Watson and Green, C. 1968; Chromosomal control of flour properties in three substitution sets of common wheat. Crop Science 8: 81-82.

124. Williams P. C. 1967; Relation of starch damage and related characteristics to hardness in Australian wheat varieties. Cereal Chem. 25: 383-391.

125. Williams, P. C. 1979; Screening wheat for protein and hardness by near infrared reflectance spectroscopy. Cereal Foods World 56(3): 169-172.

126. Williams, P. C. 1986; The influence of chromosome number and species on wheat hardness. Cereal Chem. 44: 56-57.

127. Williams, P. C. 1986; Relation of starch damage and related characteristics to kernel hardness in Australian wheat varieties. Cereal Chem. 44: 350-352.

128. Worzella, W. W. 1942. Inheritance and interrelationship of components of quality, cold resistance and morphological characters in wheat hybrids. J. Agric. Res. (Washington, D. C.) 65: 501-522.

129. Wrigley, C. W. and Moss, H. J. 1968; Selection for grain quality in wheat breeding. In: Proc. 3rd Int. Wheat Genet. Symp. Australia pp327-336.

130. Yamazaki, W. T., J. R. Donelson and Briggle, L. W. 1968; Micro-tests for soft wheat quality evaluation. Crop Science 8: 199-201.

131. Yamazaki, W. T. and Donelson, J. R. 1972; Evaluating soft wheat quality of early generation progenies. Crop science 13: 374-375.

132. Yamazaki, W. T., and Donelson, J. R. 1983; Kernel hardness of some U. S. wheats. Cereal Chem. 60: 344.

133. Yamazaki, W. T. and Andrews, L. C. 1982; Small-scale milling to estimate the milling quality of soft wheat cultivars and breeding lines. Cereal Chem. 59(4): 270

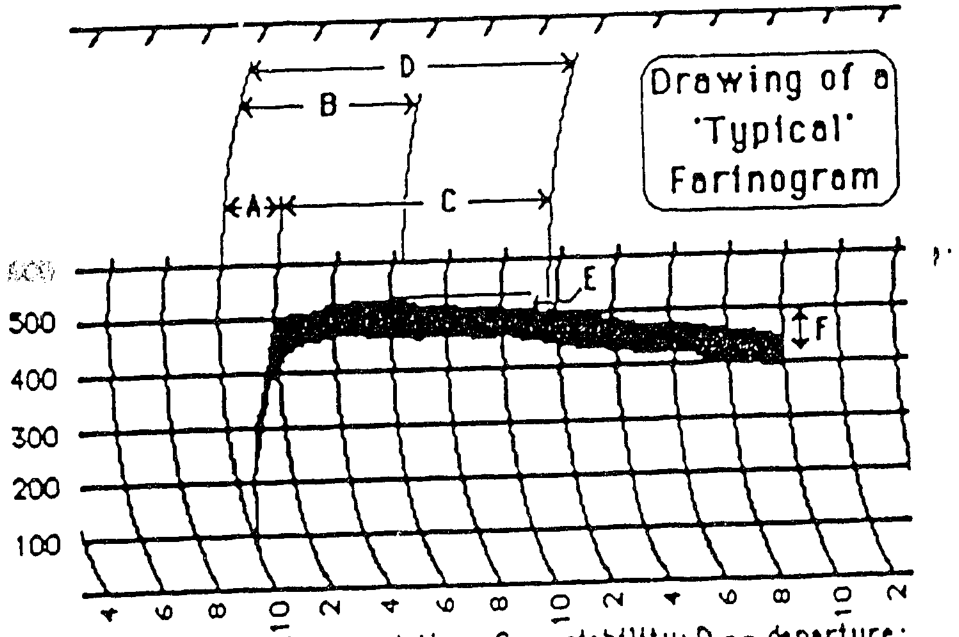
134. Zeleny, L., 1978. Criteria of wheat quality. In: Wheat chemistry and technology. pp19-49. Edited by Pomeranz. Y. ASA press.

135. Zeleny, L. 1947; A simple sedimentation test for estimating the bread-baking and gluten qualities of wheat flour. Cereal Chem. 24: 465

Appendix 1 Definitions of farinograph properties and illustration of typical farinographs for the three hardness groups

1. Definitions of Farinograph Properties:

Farinograph properties were measured by the constant flour weight method, utilizing a 50g mixing bowl (AACC, 1969). The shape of the farinograph curve gives a fair indication of the inherent strength of a flour. A 'weak' flour gives a curve indicating a rapid build up in dough consistency to a sharply defined peak, followed by a rapid breakdown . By contrast, strong flour usually gives a much slower build up in dough consistency, a relatively longer time to achieve peak consistency, a less sharply defined maximum, and a much more gradual drop in consistency level following peak development. The indices 'arrival time', 'dough development time', 'stability', 'mixing tolerance index' and '20 minutes drop' may be calculated from a finished curve. A schematic of a 'typical' farinograph curve is presented below:



A -- arrival time; B -- peak time; C -- stability; D -- departure; E -- mixing tolerance index; F -- twenty minute drop

Farinograph indices are defined as follows:

A. Arrival time: The time that it takes for the dough to arrive at the 500 Brabender Unit line.

B. Peak time, also called dough development time, is the time that it takes to reach the maximum mixing peak.

C. Stability: The time to the top of the curve intersection at the 500 Brabender Unit line.

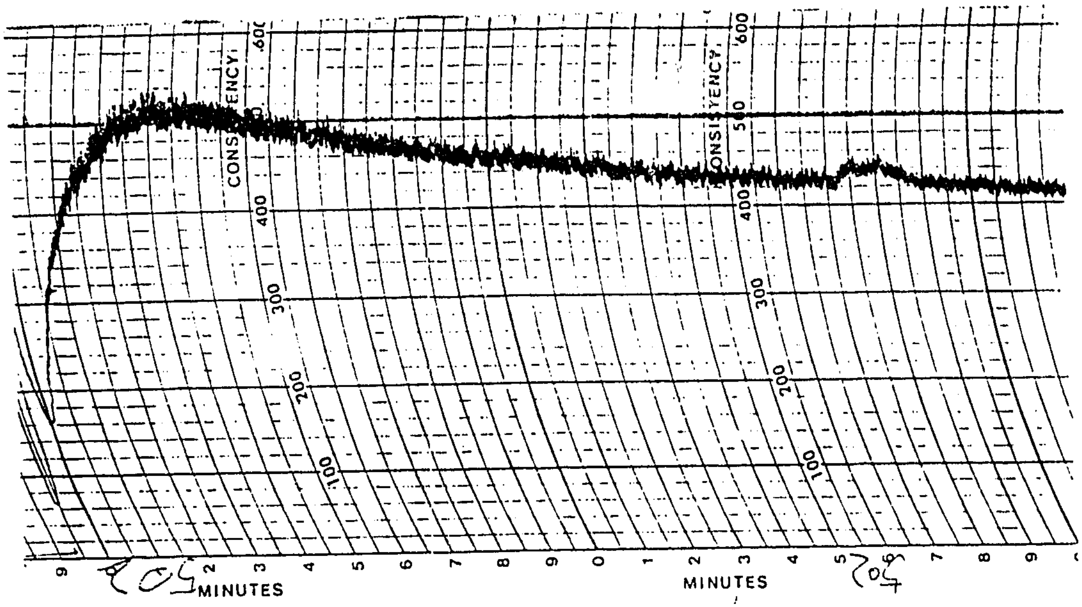
D. Departure time: The time that it takes to when the dough leaves the 500 Brabender Unit line.

E. Mixing tolerance index (MTI): The difference in Farinograph units from the top of the curve at the peak, to the curve means 5 minutes after the peak is reached.

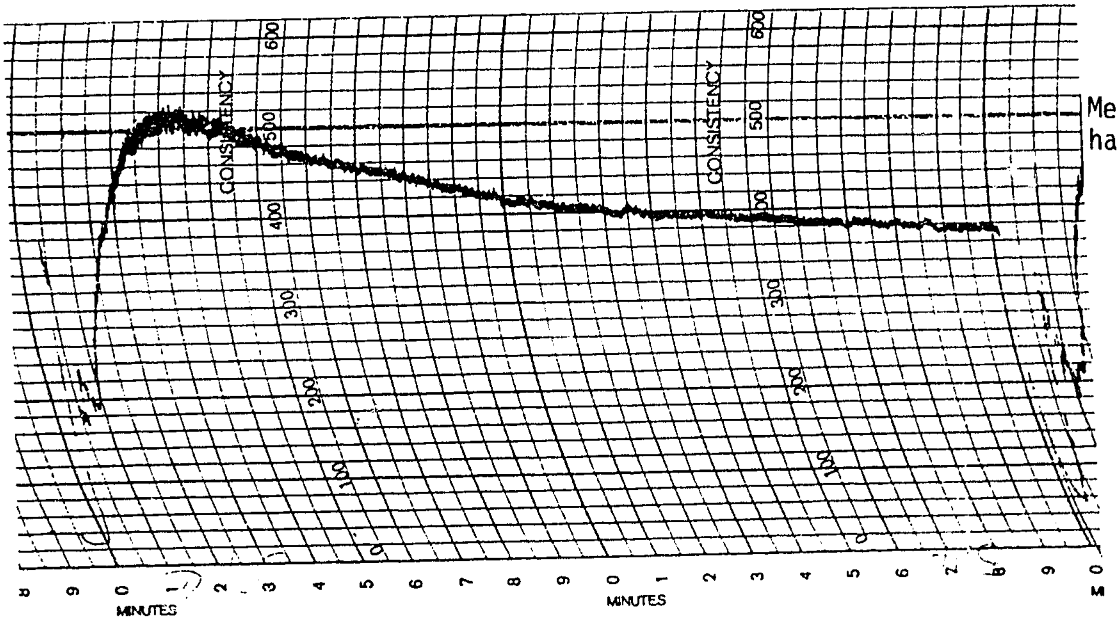
F. 20 minutes drop: The difference in units from the 500 Brabender Unit line to the center of the curve, measured at 20 minutes from addition of water (0-time)

G. Water absorption: The amount of water needed, based on 14% moisture content, to give the dough a consistency of 500 Brabender Units.

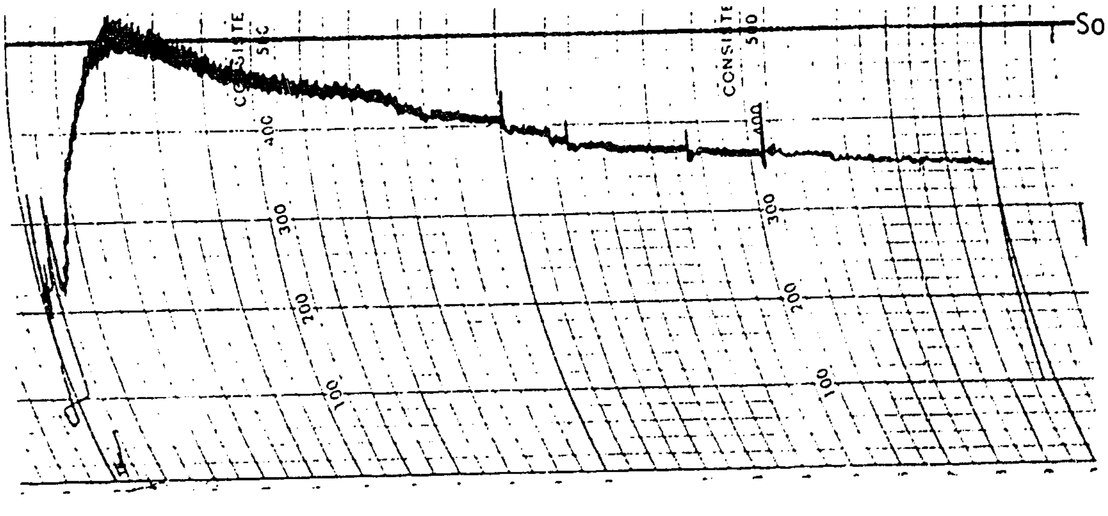
2. Typical farinographs of the three hardness groups



Hard



Medium hard



Soft