Factors Influencing Farinograph Absorption of Canada Western Red Winter Wheat Genotypes

by

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ABSTRACT

The main objective of this study was to investigate the nature of farinograph absorption (FA) in CWRW flours which is typically lower than CWRS wheats. FA for CWRW genotype samples ranged from 54 - 65%. Phloroglucinol assay of pentosan content (PC) proved to be accurate and precise. The most highly correlated parameters to FA were volume fractions of large (or small) flour particles determined by laser diffraction, protein content, starch damage and water soluble PC. Correlations to FA for these factors were in the range r = 0.40 to 0.68. A promising 4-variable regression model of FA prediction (R^2 = 0.64) was developed. CWRW wheats tended to be low in FA due to low levels of wheat hardness, protein content, or PC. Increasing the levels of these parameters by breeding would likely practically improve FA of future CWRW cultivars. An extended abstract is included at the end of this thesis.

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LIST OF ABBREVIATIONS

A	Arabinose
AACC	American Association of Cereal Chemists
AX	Arabinoxylan
BU	Brabender Unit
CNA	Combustion nitrogen analysis
CGC	Canadian Grain Commission
CV	Coefficient of variation
CWRS	Canada Western Red Spring
CWRW	Canada Western Red Winter
DS	Damaged starch
FA	Farinograph absorption
FAsh	Flour ash
FP	Flour protein
FTP	Flour total pentosan
FWEP	Flour water-extractable pentosan
FY	Flour yield
GLC	Gas liquid chromatography
HRW	Hard red winter
HRS	Hard red spring
HWW	Hard white winter
NIR	Near-infrared reflectance
NSP	Non-starch polysaccharide
PCA	Phloroglucinol colorimetric assay
PSI	Particle size index
ROM	Repeatability of measurement
SEE	Standard error of estimate
SRC	Solvent retention capacity
SRW	Soft white winter
SWW	Soft white winter
TKW	Thousand kernel weight
TW	Test weight
WAsh	Wheat ash
WE-AX	Water-extractable arabinoxylan
WP	Wheat protein
WTP	Wheat total pentosan
WU-AX	Water-unextractable arabinoxylan
WWEP	Wheat water-extractable pentosan
X	Xylose

CHAPTER 1: INTRODUCTION

Water absorption of wheat flour is one of the most important flour quality characteristics since it relates closely with proper dough formation, and the yield and quality of baked products. The Brabender Farinograph is the most common instrument that is used to determine flour water absorption. From a processor's perspective, water compared with flour and other ingredients, is an inexpensive ingredient. Flour with higher water absorption can increase bread yield and profitability (Tipples and Kilborn 1968; Puhr and D'Appolonia 1992). Accordingly, hard wheat cultivars and flour with relatively high absorption are preferred by millers and bread bakers. Canada Western Red Winter (CWRW) wheats (*Triticum aestivum* L.) typically have excellent milling quality but are generally deficient in farinograph absorption (FA) compared to Canada Western Red Spring (CWRS) wheats (~ 10% lower in absolute values on average). Since FA directly relates to the amount of bread manufactured from a given weight of flour, low FA values negatively affect demand and price for CWRW wheat compared to CWRS wheat. Therefore, a detailed understanding of intrinsic factors related to wheat flour FA is essential to improve the CWRW wheat class.

Extensive research has been done on factors related to FA of CWRS wheat flour, including damaged starch (DS), wheat kernel hardness, wheat kernel size, protein content and pentosan content. There is considerable information in general on the relationships between these factors and FA for many wheat classes. For example, DS and protein content are generally proposed as the most important factors related to FA (Farrand 1972; Meredith 1969; Kulp and Bechtel 1963). Other factors such as pentosan content, starch granule size distribution and wheat kernel size have also been shown to influence FA (Soh et al 2006;

Morgan et al 2000). Ultimately these factors are affected by genotype and wheat growing conditions (environment), but milling effects also can contribute to FA variation (Peterson et al 1992; Finlay et al 2007).

Although the literature suggests that DS is the most important factor related to flour absorption, pentosans are able to absorb considerably more water than DS on a unit mass basis, i.e. from 10 to 15 times their weight of water compared to 1.5 to 2 times for DS (Bushuk and Hlynka 1964; Kulp 1968). Accordingly, given the levels of DS (~5-8%) and the typical levels of pentosan content (~1.5-2%) in hard wheat flour, it is plausible that pentosans may be at least equal to or even more important than DS with respect to FA variation among different samples. While genotype by environment studies have identified variation in pentosan content that can be exploited by breeding, pentosan content has not been used as a selection trait to increase FA of CWRW wheats. FA itself is not a trait that can be easily manipulated by breeding as it is a multi-factor, i.e. multi-gene trait, and from a practical perspective has low testing throughput and requires amounts of flour unavailable in early generations. An alternative method to determine pentosan content is a colorimetric phloroglucinol assay (Douglas 1981), which is a small-scale test for pentosan quantification that has been applied in many studies.

So, while much is known about intrinsic and extrinsic factors related to FA of CWRS wheat flour, there is essentially no direct knowledge about the underlying factors that affect FA of CWRW wheat flour and especially its pentosan content.

The long-term goal of this research is to establish a basis to significantly improve FA of CWRW wheats for breeding and market development and identify genotypes with high (or

low) pentosan content that could be used as parental material in a breeding program. Another long term goal is to more precisely explain why CWRW wheat flour has low water absorption compared to CWRS wheat.

The objectives of the research are as follows:

- Establish the relationship between FA measured by 50 g and 10 g mixers.
- Demonstrate the effectiveness of the colorimetric phloroglucinol test of pentosan content in relation to FA.
- Evaluate relationships between pentosan content of CWRW wheat and flour measured by phloroglucinol assay and reference gas liquid chromatography (GLC) method.
- Determine the relative influence of factors traditionally associated with FA variation (e.g. DS, protein content, pentosan content, kernel size) and seek other plausible non-traditional factors related to FA, e.g. flour particle size by laser diffraction.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

Water absorption of wheat flour can be defined as the proportion of water per weight of flour required to produce a dough of standard consistency (Bushuk and Hlynka 1964). In industry, it is commonly measured using a Brabender farinograph (Greer and Stewart 1959; Holas and Tipples 1978). In general, soft wheat flours have lower water absorption compared to hard wheat flours which highlights kernel hardness and DS as two of the key contributing factors to be discussed later.

Among the cereal grains, only wheat flour forms a viscoelastic dough upon hydration and mixing. Hydration capacity of wheat flour is a critical factor in wheat flour quality because it contributes greatly to proper dough formation and the quality of baked products (Rasper and DeMan 1980; Berton et al 2002). From an economic perspective for the processor, water, compared with flour and other ingredients, is an inexpensive ingredient. Flour with higher water absorption can increase bread yield and profitability (Tipples and Kilborn 1968; Puhr and D'Appolonia 1992). Accordingly, wheat genotypes and flour with relatively high absorption are valued by millers and bread bakers.

The literature suggests that DS is the most important factor related to absorption (Tara et al 1972; Dexter et al 1985). However, pentosans per unit weight are able to absorb considerably more water than DS (Kulp 1968). Other factors, such as protein content, starch granule size distribution and wheat kernel size can also affect absorption (Farrand 1972; Meredith 1969; Kulp and Bechtel 1963). As well, both genotype and the growing environment from which the wheat derived can contribute to absorption variation among

different samples (Peterson et al 1992; Finlay et al 2007). Another extrinsic factor that can influence absorption is wheat flour milling which can affect the relative content of (damaged) starch and protein, level of DS and pentosans, depending on such factors as flour extraction, blending of millstreams, roll gap settings, etc. The literature lacks a clear picture of the relative importance of factors that affect absorption. This review provides a comprehensive assessment of the literature related to wheat flour absorption with a particular emphasis on the pentosan fraction of wheat and flour which is a focus of this research project.

2.2 Principle of Water Absorption by Wheat Flour

Water behaves like a weak dipole because of the uneven charge distribution caused by electrons that are more strongly attracted by the oxygen atom than by the two hydrogen atoms. This characteristic enables a water molecule to attract other water molecules through hydrogen bonding (Cauvain and Young 2012). Water via hydrogen bonding is also able to interact or dissolve other substances that do not ionise in water but have a polar nature such as hydroxyl (OH), carboxyl (COOH), carbonyl (C=O) and amino (NH_2) groups. Thus, the unique quality of water as a polar molecule enables it to interact via hydrogen bonding with other polar groups from various food components (Cauvain and Young 2012). In wheat flour, these polar groups are found in starch, protein and pentosans which are the three major chemical components that influence water absorption of flour (Bushuk and Hlynka 1964; Bushuk 1966; Cauvain and Young 2012).

Water interacts with starch by forming hydrogen bonds with hydroxyl groups. It also forms hydrogen bonds with oxygen molecules on the pyranose ring and those which bridge glucose units in the starch polymers (Bushuk 1966). Similarly in proteins, water forms

hydrogen bonds with peptide linkages, and also with the polar or ionic side chains of amino acids (Bushuk and Hlynka 1964). Non-starch polysaccharides (NSP) such as pentosans also contain hydroxyl groups, which interact with water through hydrogen bonding and absorb significantly more water per unit weight than starch and gluten (Bushuk and Hlynka 1964; Kulp 1968).

Sorption methodology provides some fundamental insights on water absorption of flour measured using empirical methods such as the farinograph. Bushuk and Winkler (1957) reported water-vapor sorption isotherms at 27 ℃ for Canada hard red spring (HRS) wheat flour and derived fractions of starch, freeze-dried and spray-dried gluten. For the flour materials, the isotherms were sigmoidal in shape (characteristic of polymers such as starch and protein) and showed considerable hysteresis between adsorption and desorption. Sorptive capacity of the material for water vapor was in the order starch > flour > freeze-dried gluten > spray dried gluten. Riganakos et al (1989) studied water sorption of wheat flour at temperatures between 25 ℃ and 55 ℃ with water activity (a_w) ranging from $0< a_w <0.8$. Wheat flour in Riganakos et al (1989)'s study also had sorption isotherms of sigmoidal shape which is typical for most food products. The authors explained wheat flour absorption occurring in three steps or phases. In the first phase, water is rapidly attracted to the polar or active sites of high binding energy on starch and gluten such as C=O, COO- or NH_4^+, forming a monolayer of water. The rate of this process slows in the second absorption phase as additional water binds to starch and gluten proteins. The authors suggested that, during this stage, there is less attraction between water molecules but higher attraction of water to other active sites. In the third phase, the accumulated water results in swelling of the food matrix, exposing more active sites that absorb more water, thereby increase the slope of the

sorption isotherm. Riganakos et al (1989) also attributed the ability of wheat flour to strongly absorb water to the non-crystalline structure of starch and gluten.

2.3 Flour Water Absorption Measurements

The water absorption capacity of wheat flour has been studied mainly though water addition or equilibration in controlled relative humidity. The Brabender farinograph is the most common instrument to determine flour water absorption. It measures the resistance encountered by the rotation of the special Z-shaped mixing blades during dough mixing (Cauvain and Young 2012; Schiraldi and Fessas 2012). While farinograph curves for different flours may have different shapes or profiles mainly due to differences in gluten strength (D'Appolonia 1984), the absorption has a common basis, i.e., the amount of water required to obtain a standard dough consistency, recorded on the vertical axis which is scaled in arbitrary Brabender units (BU) from 0 to 1000. The dough consistency target is generally 500 BU, i.e., the farinograph curve is centered on the middle value of the chart. In addition to use of the Brabender farinograph, several other techniques have been used to measure water absorption of flour, such as centrifugation and capillary methods. Table 1 provides a summary of techniques that have been used.

A few studies have compared different methods to evaluate flour water absorption. Sollars (1972) reported that results of a water retention capacity test of various types of wheat flour were closely related to results of the alkaline water retention capacity, and both tests were highly correlated with farinograph absorption. Berton et al (2002) found that the capillary suction method was more sensitive to the physical characteristics of flour, such as particle size distribution and bulk density than centrifugation method in determination of flour hydration capacity. Farinograph absorption of various types of wheat flour was found

to have a high correlation (r = 0.96) with ultracentrifuge absorption (Preston and Tipples 1978). These studies lead to the conclusion that different methods for evaluating flour water absorption are generally well correlated. However, for a proper interpretation of data, the technique used should be clearly specified.

2.4 Parameters that Affect Farinograph Absorption

2.4.1 Kernel Size

Morgan et al (2000) reported that based on 17 years of historical Canadian Grain Commission (CGC) harvest survey data, a strong positive relationship (r^2 = 0.59-0.70) existed between kernel weight and FA of CWRS wheat. Their further study of different kernel sizes, obtained by sieving of commercial samples of U.S. Dark Northern Spring and Australian Prime Hard wheat showed even stronger relationships (r^2 = 0.86-0.96) between kernel weight and FA. The reason for the strong positive relationship between kernel weight and FA could not be clearly explained in this study due to inconsistent trends between kernel size and DS and protein content across the sample sets. In other work, Bailey (1915) showed that wheat kernels of higher mass had higher percentage of endosperm compared to smaller kernels. This may explain the close relationship found between wheat kernel weights and milling yield (Sutton et al 1992). The same authors found a direct relationship between kernel weight, for one New Zealand wheat genotype, and protein content and loaf volume, but unfortunately no absorption results were reported. Posner (1997) reported that the germ and bran of wheat kernels of larger size took up more volume of the wheat kernel compared to smaller grains. However, it is not clear how this observation related to FA.

Table 1. Methods for evaluating flour water absorption.

Technique	Name	Description/parameter measured	References
Farinograph	Constant flour/ dough weight	Water required to give a farinogram with maximum resistance centered at 500 BU	AACC 54-21.02; AACC 54-22.01
Centrifugation	Alkaline water retention capacity	The amount of alkaline water held by flour at 14% moisture basis after centrifugation	AACC 56-10.02
	Solvent retention capacity profile (SRC)	The weight of solvent held by flour after centrifugation. Four solvents are independently used to produce four SRC values: water SRC, 50% sucrose SRC, 5% sodium carbonate SRC, and 5% lactic acid SRC.	AACC 56-11.02 Linlaud et al 2009
	Water hydration capacity of protein materials	The maximum amount of water that 1 g of material will imbibe and retain under low-speed centrifugation	AACC 56-30.01
	Ultracentrifugation	The maximum amount of water that 1 g of material will imbibe and retain under very high-speed centrifugation (145, 000g).	Preston and Tipples 1978
Sorption	Static desiccator (distilled water/saturated salt water)	Water sorption was measured gravimetrically on samples exposed to constant relative humidity of 100% and 75.6%	Elizalde et al 1996
	Controlled atmosphere microbalance	Changes of samples mass were measured under controlled successive relative humidity environment with a microbalance	Roman-Gutierrez et al 2002
Capillary suction	Baumann capillary apparatus	Volume of water absorbed by a thin layer of the tested material	Rasper and DeMan 1980; Elizalde et al 1996
	Tensiometer	Weight of water absorbed by flour placed on a glass cylindrical tube equipped with a sintered glass filter at one end	Berton et al 2002; Rasper and DeMan 1980

AACC = American Association of Cereal Chemists.

2.4.2 Damaged Starch

Starch is the major constituent of wheat comprising 63-72% of the wheat kernel (Pomeranz 1971) and 65-70% of flour at 14% moisture content. Damaged starch refers to the physical alteration of the native granular form of starch that occurs during milling, in which about 4 to 10% of the granules are damaged (Miralbés 2004). The proportion of DS depends on wheat hardness and the milling process. Flours from hard wheat normally have a higher degree of DS than that of soft wheat. Wheat of the same variety or sample could have different levels of DS depending on milling, e.g., by using a conventional roller mill which has more DS compared to a stone mill (Gelinas et al 2004), varying the number of reduction roll passes (Sapirstein et al 2007), varying roll gap settings (Hatcher et al 2008), or speed of reduction of coarse middlings (Dexter et al 1985).

2.4.2.1 Measurement of Damaged Starch

The degree of DS can be evaluated in several ways. The most common methods include enzyme treatments, e.g., AACC Approved method 76-30.02 (AACC International 11th Edition), which determines the percentage of starch granules in flour or starch preparations that is susceptible to hydrolysis by fungal α-amylase. In AACC Approved method 76-31.01 (AACC International 11th Edition), DS granules are hydrated and hydrolyzed to maltosaccharides and limit dextrins by fungal α-amylase. These sugars are then completely converted to glucose by amyloglucosidase, and glucose is determined spectrophotometrically by a color reaction after treatment with glucose oxidase/peroxidase. A different method (AACC Approved method 76-33.01, AACC International 11th Edition) uses an amperometric technique, and measures the decrease in free I^{3-} ions in solution due to the formation of an amylose-iodine complex with the DS. Results are given in an iodine

absorption index percentage (AI%) or they are calibrated to DS% values. The latter method has been adapted for an instrument-based determination by the Chopin company, and is referred to as the SDmatic test.

Compared with enzyme methods which are relatively complex and require a high level of operator skill, the SDmatic test is simpler, and more rapid. The relationship between methods for determining DS has been investigated in a few studies (Rogers 1994; Ranhotra 1993; Morgan and Williams 1995, McAllister et al 2011). In general, the SDmatic method and enzymatic approaches are closely correlated ($r^2 = 0.90$). Compared with enzymatic methods, the SDmatic test is affected more by amylose content variation (McAllister et al 2011). Thus the SDmatic is better suited to testing small batches of flour from hard conventional wheat samples, as opposed to special types of flours that contain both lower and higher amylose content.

2.4.2.2 Water Absorption of Damaged Starch

Damaged starch absorbs considerably more water than granular starch and is more susceptible to amylase attack. This was first discovered in the 1930s when milled starch granules showed differential absorption of dye compared to intact starch granules (Pulkki 1938). Undamaged starch granules absorb only 30% of its weight at 30 ℃ while damaged starch granules can absorb 2-3 times their weight of water (Farrand 1972; Miralbés 2004).

The hydration of damaged starch happens very quickly, the swelling generally completes in 0.5 s (Sandstedt and Schroeder 1960). In an intact starch granule, which is a semi-crystalline structure, water enters only through the amorphous zone because the crystalline zones have strong interchain bonds (Mao and Flores 2001). When starch is

damaged, the crystalline zones are disrupted and hence increase amorphous zone content through which water can enter the granule (Multon et al 1980). In the disrupted crystalline zone, the number of hydroxyl groups increases as well. Hydroxyl groups of glucose molecules in starch are the water binding sites and these sites increase when starch is physically damaged (Mok and Dick 1991). Mok and Dick (1991) studied the effects of mechanical damage on starch sorption characteristics of durum wheat varieties Vic and Ward and the HRS wheat variety Stoa. The isotherm of DS was steeper than that of undamaged starch. However, at low water activity (a_w = 0 to 0.6) undamaged starch had higher sorption capacity compared to slightly DS (2 h in a ball mill); while at a_w > 0.65, the damaged starch (24 h ball milled) absorbed more water. The authors suggested that at low water activity, the free hydroxyl groups in DS may have favoured forming intramolecular hydrogen bonds or bonds with amylose and amylopectin, hence reducing the number of polar sites. At higher water activities, the increase in absorption was caused by swelling of starch granules which exposed more polar sites to water.

Strong associations between DS and flour water absorption have been shown in many studies. Greer and Stewart (1959) and Mok and Dick (1991) concluded that differences in water absorption among flours were largely accounted for by variation in levels of DS. Tara et al (1972) studied the water absorption of 63 straight grade flours of Indian wheats that were milled in a Buhler Laboratory mill. They found that DS was highly correlated (r = 0.81 to 0.87) with FA and the correlation between protein content and FA was lower (r = 0.50). Dexter et al (1985) found a high correlation between DS and FA (r = 0.93) for five commercial CWRS wheats of varying protein contents milled to produce four DS levels. Sollars and Rubenthaler (1975) studied how different flour fractions affected FA of hard red

winter (HRW) wheat and soft white winter (SWW) wheat. Flours were separated into fractions of gluten, starch and tailings which contained higher amounts of NSP. The tailing fraction accounted for about 50% of the variation in absorption. Starch, which increased FA in blends of fractions and reconstituted flours by 2.1%, had a larger effect than water-solubles (1.2%) or gluten (1.1%). Berton et al (2002) stated that DS was the most correlated factor with water absorption among factors such as DS, protein and pentosan content for soft wheat flour from France.

Effects of DS on water absorption are also reflected in product development studies. Mao and Flores (2001) reported that increase in starch damage caused flour tortillas to become less stretchable, while firmness and rollability increased. They attributed these texture effects to high moisture content. While water is essential in dough formation, too much water can negatively affect dough properties and end-product quality. Increase in water absorption adversely affected the colour and textural characteristics of oriental noodles made from CWRS Wheat (Hatcher et al 1999). Also recovery resistance to compression and maximum cutting stress of the white salted noodles significantly declined with increasing absorption level.

Although many studies have concluded that FA is correlated with levels of DS, high levels of DS may not be better for breadmaking. This is due to α-amylase effects which can soften dough during fermentation. Although granular starch is resistant to α-amylase, damaged starch is susceptible to the enzyme (Farrand 1969). As a result, the water held initially is released, and the dough becomes softer. Accordingly, FA provides only an estimate of absorption required for baking, and baking absorption is determined by the handling properties of the dough at panning instead of at the initial stage of the mixing.

Long fermentation causes the dough to soften more due to the long-time reaction (Tipples 1969).

2.4.3 Starch Granule Size

Wheat starch is generally considered to have a bimodal size distribution with large lenticular A-type granules (25-40 μm) and small, spherical B-type granules (5-10 μm). Large granules represent about 3-10% of the total number of wheat starch granules, but they contribute 50-90% of the total weight of starch (Delcour and Hoseney 2010). Starch granule size distribution of different wheats and flour samples can be considerably different.

Park et al (2009) analyzed starch granule size distribution of 98 HRW and 99 HRS wheats by laser diffraction. The volume fraction of B-type granules in HRW and HRS wheats were 29.5-49.1% and 37.1-56.2%, respectively. HRW wheat had significantly smaller mean granule sizes of the distribution peaks of B-type granules (4.32 μm) than HRS (4.49 μm), but no significant difference existed for A-type granules (21.49 and 21.46 μm, respectively).

Starch granule size distribution showed some significant correlations with wheat and wheat flour properties. Park et al (2009) found that for both HRW and HRS, wheat and wheat flour protein content were negatively correlated with B-type granules in both size and volume fraction. B-type granules in HRS wheat showed weak but significant negative relationship ($r = -0.29$) between FA and volume of B-type starch granules. This could be because B-type granules had a negative relationship with flour protein content, but protein content had a positive relationship with FA. However, for samples with constant protein content, the increase in volume of B-type granules was associated with an increase in FA

(Soh et al 2006). D'Appolonia and Gilles (1971) reached the same conclusion in a study that separated the large and small starch granule fractions from a composite lot of HRS wheat flour, and tested their respective water binding capacities and FA. Their results indicated that the large starch granule fraction had lower water binding capacity and lower FA compared to small starch granules. Chiotelle and Lemeste (2002) also reported B-type granules had a higher water absorption rate compared to A-type granules. This result may be attributed to the relatively high amount of DS and larger specific surface area of small starch granules (Sahlstrom et al 1998). The aforementioned studies suggest that, for samples with varying protein contents, starch granule size distribution may not be an important variable contributing to FA.

Starch granule size distribution can also affect end-product quality. Park et al (2005) fractionated starch into large granules (>10 μm) and small granules (<10 μm), and then reconstituted the starch according to the following scheme: 0% small granules (100% large granules), 30, 60 and 100% (0% large granules). Reconstituted flours were evaluated for baking performance and bread quality. Baking absorption increased by almost 5% by interchanging all large granules with small granules. Sahlstrom et al (1998) suggested that for a Norwegian spring wheat, small A-type granules (diameter~12 μm) favourably affected bread weight. The size distribution of starch granules might be important in breadmaking at least in part owing to the different specific surface areas of A and B-type granules (Soulaka and Morrison 1985) and their shape differences (Eliasson 2012).

2.4.4 Protein Content

Wheat gluten protein is essential to breadmaking. Flour protein content influences dough rheological properties, and flour with high protein content generally denotes good

bread making potential (Mani et al 1992). Wheat proteins can be divided into four types according to solubility: albumins, globulins, gliadins and glutenins. The two main gluten protein fractions of wheat, gliadin and glutenin, have a unique ability to interact to form networks and films. Gliadins are responsible for viscosity and glutenins for strength and elasticity in dough (Toufeili et al 1999). When mixed with water, these two proteins in adequate amounts form a strong, cohesive dough, which can retain gas and produce aerated baked products (Delcour and Hoseney 2010; Cauvain and Young 2012). The amount of water added to wheat flour is critical in order to form dough with acceptable consistency and strength that is suitable for breadmaking. Conversely, the quantity and composition of gluten protein in wheat flour also affects the water absorption capacity of flour.

Greer and Stewart (1959) found that the differences in flour water absorption for two English wheat varieties were contributed largely by protein content. Tipples et al (1978) studied the water absorption capacity of commercial samples of CWRS wheat and found protein content and wet gluten content were positively correlated with baking absorption, but not significantly correlated with FA. In this study, damaged starch had a more important role in flour water absorption. Preston et al (2001) studied 14 CWRS wheat genotypes grown in 14 locations in Saskatchewan and found weak but significant correlation between protein content and FA ($r = 0.51$). In the same study, the correlation between FA and particle size index (PSI) was also weak but significant ($r = -0.46$). Meredith (1969) found that both protein content and damaged starch correlated positively with flour water absorption, but protein content was a more important factor. The literature lacks a clear consensus on whether protein content or damaged starch is a more important factor for farinograph absorption.

2.4.5 Arabinoxylan

Pentosans represent the major NSP fraction of both wheat and flour, and comprise about 2-3% of wheat flour (Gruppen 1992). Despite the low content of pentosans in wheat flour, they have a similar absolute level of water absorption compared to protein and starch which are present in flour in much higher proportions by weight (Kulp 1968, Table 2).

The term arabinoxylan (AX) is often used in reference to pentosans and vice-versa. AX is a NSP with a β-(1–4)-linked backbone of xylose (X) residues substituted with arabinose (A) side branches through O-2, O-3 or O-2, 3 linkages. Substituted side chains include arabinose, and glucuronic acid or its methyl derivative to a much lower extent. Ferulic acid, typically linked to O-5 of arabinose, is the mainly cross-linker of AX (Lempereur et al 1998). AX molecules have molecular weights from 22,000 to 5,000,000 (Perlin 1951). Structurally, AX can vary in ratio of A/X, content of ferulic acid and glucuronic acid, and in different relative proportions of unsubstituted, single and double substituted xylose residues (Hoffmann et al 1991). This diversity in AX structure has been reported to influence the ability of AX to absorb water.

Table 2. Water absorption capacity of flour constituents.*

Flour constituent	Weight (g/100 g flour)	Absorbed water (mL)
Starch	70	21
Gluten	12	24
Pentosans	2.5	26
Other	1.5	-
Water (moisture)	14	-

* Reported by Kulp (1968).

2.4.5.1 Quantification of Arabinoxylan

Methods of quantifying AX can be divided into two categories: chromatographic methods and colorimetric assays. The chromatographic approach traditionally uses GLC to separate a starch-free sample that is hydrolyzed to monomeric neutral sugars. Arabinoxylan is then quantified as the total of arabinose and xylose (Englyst and Cummings 1984; Slominski and Campbell 1990), multiplied by a polymerization factor of 0.88. The latter is used to correct for differences in the total molecular weight due to the loss of a water molecule that occurs for each condensation reaction when the polysaccharide is formed, i.e. 0.88 = (150 -18)/150 where 150 is the MW of xylose or arabinose, and 18 is the MW of water. The colorimetric phloroglucinol method (Douglas 1981) uses 12% HCl to hydrolyze pentosans to furfural and quantifies AX colorimetrically using xylose for calibration. In order to quantify pentosan content of higher fibre cereal products (whole wheat, shorts, bran), the method by Douglas (1981) was adapted by Bell (1985) to include a short pre-hydrolysis step using 0.5 M sulfuric acid to avoid underestimation of AX. Compared with the GLC approach, the phloroglucinol assay is faster and easier to implement and has a lower cost. With these advantages, the Douglas method has been widely used in many studies (Hashimoto et al 1987; Izydorczyk et al 1991; Biliaderis et al 1995; Wang et al 2006; Finnie et al 2006; Li et al 2009; Sapirstein et al 2012) producing accurate results, although that accuracy has been recently questioned (Kiszonas et al 2012).

The quantification of AX using the phloroglucinol assay has been assessed in a few studies. Douglas (1981) and Bell (1985) reported that the phloroglucinol method produced results comparable with other methods, such as Tollen's procedure (Fraser et al 1956) and

the GLC method. However, Kiszonas et al (2012) concluded that the glucose solution used to make up reaction solution was unnecessary, and the same authors did not incorporate acid pre-hydrolysis to solubilize bran particles as recommended by Bell (1985) for whole wheat analysis. Kiszonas et al (2012) found their application of the Douglas (1981) method underestimated AX content considerably (by 54% on average). Further, when using the pre-hydrolysis step with 0.5 M sulfuric acid (Bell 1985), the authors reported that preliminary experiments "resulted in an even greater underestimation of TAX levels". Careful evaluation of the Kiszonas et al (2012) paper reveals the use of different concentration of reagents compared to Douglas (1981), i.e. they increased the proportion of hydrochloric acid (from 1.7% to 14.5%) and phloroglucinol solutions (from 10 to 40%). It would appear that the application of the Douglas (1981) procedure by Kiszonas et al (2012) for wheat meal samples was incorrect.

2.4.5.2 Arabinoxylan Content in Wheat, Flour and Wheat Tissue Fractions

AX contents in wheat vary widely depending on wheat genotype and environmental conditions. Hong et al (1989) studied wheat meals of seven HRW and hard white winter (HWW) wheat cultivars, seven SWW wheat cultivars, and four soft white club wheat cultivars grown in a single Washington location; wheat total pentosans (WTP) ranged from 4.1-6.1% and wheat water-extractable pentosans (WWEP) ranged from 0.31-0.76%. Saulnier et al (1995) examined wheat meals of 22 wheat cultivars grown in France and found that WTP range was 5.5-7.8% and WWEP varied from 0.36-0.83%. Hartunian-Sowa (1997) reported that total AX of whole grain wheat ranged from 5.55% - 7.51% in a study encompassing 33 cultivars belonging to six U.S. wheat market classes (except durum wheat) that were grown in different locations. Interestingly, almost the same range of variation (5.7 -

7.0%) was reported (Coles et al 1997) for a single New Zealand bread wheat cultivar grown in one location under different experimentally induced drought regimens. Ordaz-Ortiz et al (2005) determined WTP content of 20 French wheat cultivars and WTP was 4.8-6.9%. Wang et al (2006) studied wheat meals of six commercially grown hard spring wheats, and found WTP ranged from 5.45-7.32% and WWEP ranged from 0.62-0.90%. Li et al (2009) reported that WTP and WWEP content of U.S. Pacific Northwest HRW wheat ranged 3.09–4.04% and 0.39-0.81%, respectively. Pritchard et al (2011) determined AX contents of several hundred genotypes of wheats, from diploid, to hexaploid including both primitive accessions and cultivars sourced from Australia, China and the International Maize and Wheat Improvement Center and found AX ranged 2.37-10.75%. Saeed et al (2014) investigated eight different spring wheats, and found WTP of whole wheat meals ranged from 2.93-5.02%.

AX contents in wheat flour also vary among genotypes. Shogren et al (1987) determined the flour total pentosan (FTP) content of 79 HRW wheats ranged from 1.27-2.09%. Tipples et al (1978) found that FTP increased with decreasing flour quality, which varied among milling streams and by adjusting roller gaps, from a low of 1.41% for the first middling fraction to a high 1.99% for fraction tailings. Water-soluble pentosans ranged from 0.43% for the 4th break roll flour to 0.65% for the 5th reduction roll stream. Ordaz-Ortiz et al (2005) determined FTP and flour water-extractable pentosan (FWEP) content of 20 French wheat cultivars; FTP ranged from 1.66-2.87%, and FWEP ranged from 0.26-0.75%. Wang et al (2006) studied flours of six commercially grown hard spring wheats, and found FTP ranged from 1.87-2.22% and FWEP ranged from 0.49-0.60%.

AX concentration appears to be different among different tissues and milling fractions of wheat as revealed by the considerable differences in A/X ratios (Delcour et al 1999;

Barron et al 2007; Wang et al 2006) and water solubilities of AX that have been reported. For example, the outer fibre-rich pericarp of wheat kernels prepared by dissection contained the highest concentration of AX (~40%) whereas lowest levels (~1.5% AX) occurred in starchy endosperm (Barron et al 2007). Similarly wheat bran and refined flour streams obtained by roller milling contained AX contents of 31% and 2%, respectively on average (Wang et al 2006). Clearly, wheat material with high fibre contents has high AX content and vice-versa. However, the relationship between A/X ratio and AX solubility is less clear, as the latter is complicated by issues of extractability and water access depending on the nature of the tissue or fraction. Arabinose side chains are reportedly responsible for the water solubility of AX, as xylan precipitates if arabinose is cleaved from the molecule, whether by mild acid treatment (Perlin 1951) or by enzyme hydrolysis (Neukom et al 1967). For wheat milling fractions, there appears to be a direct relationship between degree of arabinose substitution, i.e., A/X ratio and AX solubility (Wang et al 2006). For example, for refined flour from break and reduction roll streams (A/X~0.6) about 25% of total pentosan content was water-soluble. For fine bran and shorts (average A/X ~0.43) and coarse bran (A/X ~0.35) which contains mainly pericarp material, the corresponding solubilities were 6.5% and 2.7%, respectively.

2.4.5.3 Water Absorption of Arabinoxylans

Many studies have investigated the water absorption of water-extractable (WE)-AX and water-unextractable (WU)-AX. WE-AX and WU-AX are believed to have similar but different structures. The differences exist in slightly higher branching, higher A/X ratio and molecular weight of the insoluble AX (Courtin and Delcour 2001).This leads to different water absorption values for WE-AX and WU-AX that have been reported.

Jelaca and Hlynka (1971) studied pentosans isolated from commercially milled Canada HRS wheat flour, and reported that WE-AX was able to absorb 6.3 times its weight of water, while WU-AX could absorb 6.7 times its weight (dry basis). In another study (Courtin and Delcour 2001), WE-AX was reported to have a water holding capacity of 3.5-6.3 times its weight, while WU-AX held 6.7-9.9 times its weight in water. Wang et al (2003) determined the water holding capacity of water-unextractable pentosan of hard spring wheat flours to be 7.63 g/g. Girhammar and Nair (1992) measured the water holding capacity of WE-AX by determining the amount of non-freezable water by differential scanning calorimetry. They found that the amount of unfreezable water for wheat flour WE-AX was 0.41 g/g. Kulp and Bechtel (1963) isolated a pentosan rich fraction (55% pentosan content) from flour tailings and evaluated its role in breadmaking. They found that 1% of the flour fraction that contained 55% water-unextractable pentosans could increase the absorption by 5%-5.6%. It can be concluded from these studies that WU-AX has greater ability for water absorption compared to WE-AX. This might be due to the higher degree of branching of WU-AX (Courtin and Delcour 2001).

Unlike WE-AX and WU-AX, only a few studies have looked into the water absorption ability of total AX. Tipples et al (1978) found that pentosan content contributed strongly to FA of Canadian HRS wheat flours and was second in importance after damaged starch. Andrewartha et al (1979) found the degree of hydration of AX of wheat flour determined by a low-temperature NMR method, which measures the amount of water unfrozen at -30 ℃, was 0.38 g water/g dry matter. By comparison, Eliasson (2012) determined the water binding capacity of starch by DSC to be 0.30 g/g dry matter. Sollars and Rubenthaler (1975) studied how different flour fractions that were obtained by kneading

a mechanically mixed dough, e.g., water-extract, gluten, tailing, starch, affected FA by fractionation and reconstitution of HRW wheat and SWW wheat flour. One fraction at a time was interchanged between HRW and SWW flour. In the series that contained three SWW and one HRW fractions, the HRW tailings increased FA by 3%, water-extract and starch increased FA by 2% each, while gluten increased FA by 1%.

2.4.6 Environment and Genotype Factors

Finlay et al (2007) studied genotype and environmental effects on wheat quality of six adapted hard spring wheat genotypes that were grown under field conditions at widely scattered locations across western Canada. They reported that the growing environment as well as genotype and their interactions significantly affected FA with environment having a larger effect on the variance of FA compared with genotype. Preston et al (2001) studied 14 CWRS wheats that were grown at six stations in Saskatchewan and had the same conclusion.

Variables traditionally related to FA are also affected by environment and genotype. Peterson et al (1992) investigated 18 HRW wheat that were grown at seven locations for two years to determine relative contribution of genotype, environment and their interactions to variation in HRW wheat quality characteristics, e.g., flour protein content, mixing characteristics, and kernel hardness. They found that environment generally had a larger impact on the quality characteristics than genotype. Interaction of environment and genotype had similar magnitudes of impact on mixing tolerance and kernel hardness but had smaller impact on flour protein content and mixing time. Finlay et al (2007) reported that both environment and genotype had significant impact on CWRS FTP and DS contents. Flour protein (FP) was affected more by environment. Finnie et al (2006) studied the influence of cultivar and environment on AX in soft wheat. This study included seven spring and twenty

winter wheat cultivars grown in ten and twelve environments, respectively (each evenly split over two crop years). Both cultivar and environment were significant sources of variation in arabinoxylan contents determined by the Douglas (1981) method among the two cultivar sample sets (spring and winter). The cultivar-by-environment interaction was relatively unimportant in this study. Results indicated that the variation in AX content was primarily influenced by cultivar and secondarily influenced by environment. Within arabinoxylan fractions, WE-AX was primarily influenced by genotype, while WU-AX was more influenced by the environment.

2.4.7 Regression Modelling of Farinograph Absorption

Determination of FA requires wheat to be milled into flour. As several flour or wheat characteristics have been found to be correlated with FA, different researchers have tried to develop regression models, using known values of some parameters to predict FA and evaluate the relative influence of the independent variables (Table 3).

Tipples et al (1978) investigated six independent variables (protein, wet gluten, wet gluten/protein, DS, pentosans, 100/amylograph viscosity) of flours milled from CWRS wheat and developed equations for predicting FA. They suggested that the strongest single predictor of FA was DS, and the equation was FA = 58 + 0.207DS (r^2 = 0.897). Adding FP as a second variable considerably decreased the standard error of estimate (SEE). The equation was FA = 42.7 + 1.03FP + 0.248DS (r^2 = 0.993) for this two-variable model. Further addition of other variables only gave marginal reduction of SEE.

Some workers have attempted to devise predictive equations for FA based on theoretical considerations. For example, Farrand (1969) derived the following model: FA =

$57.3 + 1.4FP + 0.38DS - (1.6 \text{ moisture } (M)) + 0.004DS(FP + M)) + 12(6DS/FP^2-1)/FP$ based on replacing known variations in major flour components intrinsic properties with a model system, e.g., variations in conventional gluten quality attributes are replaced by a model protein, variations in damaged starch are replaced by a model starch. A few assumptions were additionally made for the purpose of developing the absorption models, e.g., variation in protein content corresponded with changes in starch (S) such that $FP + S = 81$, DS absorbed its own weight of water by definition. While the model developed by Farrand (1969) appears to be overly complex, it does include both protein content and DS which are the common variables in all the models in Table 3.

2.5 Wheat and Flour Particle Size

Flour comprises a range of particle sizes, as whole wheat does when it is ground into meal. That wheat hardness is the key variable affecting the granularity of wheat meal or flour, has been known for a long time (Cutler and Brinson 1935). For example, Biffen (1908) as reported by Symes (1961) found that when a few wheat kernels were crushed on an iron plate, the “weaker” (presumably soft) grain generated relatively fine powder while “stronger” (presumably hard) kernels produced angular fragments. These visual differences between hard and soft wheats were much later confirmed by microscopy of crushed wheat kernels (Greer and Hinton 1950, Mattern 1988); these papers both reported that soft wheat broke down with no apparent structure, whereas hard wheat fragmented along cell walls to produce angular pieces.

Table 3. Summary of prediction models of farinograph absorption.

Model	r^2	Wheat cultivar	Mill used	References
FA = 58 + 0.207DS	0.897	CWRS	Buhler Mill	Tipples et al 1978
FA = 42.7 + 1.03FP + 0.248DS	0.993	CWRS	Buhler Mill	
FA = 34.68 + 1.24FP + 1.56DS	n/a	63 Indian wheats		Tara et al 1972
FA = 39.44 + 1.30FP + 0.29DS	0.951	14 CWRS wheat, 2 Canada Eastern SWW wheat and 3 Alberta red winter wheat	Allis Chalmers Mill	Preston and Tipples 1978
FA = 28.0 + 2.48DS + 2.12FP+ 22.11FAsh	n/a	New Zealand wheat	Brabender Quadrumat Mill	Meredith 1966
FA = 37.51 + 0.48FP + 12.2DS	n/a	English wheat	Buhler Mill	Greer and Stewart 1959
FA = 52.4 + 0.46DS	n/a		Buhler Mill	Moss 1961
FA = 41.6 + 0.34DS + 1.32FP	n/a		Robinson Mill	
FA = 68.26 + 0.878FP + 0.334DS + 1.97M	n/a			Farrand 1969

FA = farinograph absorption; DS = damaged starch; FP = flour protein; FAsh = flour ash; M = moisture content; CWRS = Canada Western Red Spring; SWW = soft white winter; n/a = not reported.

Cutler and Brinson (1935) appear to be the first to quantify the degree of granularity by sieving ground wheat through two sieves (60 and 270 mesh) for an hour and calculating a granulation number which measured relative meal fineness using the yields of all three resulting fractions. Wheats with a lower granulation numbers (i.e. lower proportion of sieved product) were characterized as being harder. Worzella and Cutler (1939) found that the percentage of the meal passing through a single 270 mesh sieve (110 μm aperture), which was recorded as the particle size index, correlated well the granulation number developed by Cutler and Brinson (1935). The method of Cutler and Brinson (1935) was later modified by Symes (1961) who used a 75 μm aperture sieve and subsequently by Williams and Sobering (1986) who evaluated numerous types of grinders to establish the present version of the official particle size index test according to AACC International Method No. 55-30.01 (AACC International 11th Edition).

2.5.1 Measurement of Flour Particle Size Distribution

While the effects of wheat hardness on the particle size of wheat meal and flour, and on processing quality for breadmaking, is very well established in the literature, the particle size distribution of flour has been infrequently studied especially in relation to end-use quality, and FA in particular. Early research on flour particle size was limited by available techniques. Wichser and Shellenberger (1948) compared methods for determining flour particle size distribution using CWRS wheat flour. They reported that Tyler wire screens and the Ro-Tap shaker were able to generate accurate data for particle sizes larger than 37 μm. Flour particle size separation using the Roller Air Analyzer produced accurate particle size distribution data below 80 μm, whereas a sedimentation method using an Andreasen pipette sedimentation apparatus could only produce accurate data below 50 μm.

Compared with the above-noted methods, application of laser diffraction technology is a more comprehensive approach to quantify flour particle size (Gaines et al 1987). Computerized laser diffraction instruments cover a wider range of particle size (0.7–700 μm) and can generate results very quickly on parameters such as specific surface area, median particle diameter, volume fraction distribution, particle diameters of the 10^{th}, 50^{th} and 90^{th} percentile of volume fraction, etc. Also laser diffraction is an approved AACC method (55-40.01, AACC International 11^{th} Edition). Hareland (1994) evaluated flour particle size distribution by laser diffraction, sieve analysis and near-infrared reflectance (NIR) spectroscopy methods for flours derived from different wheat types and milling methods. High correlation (r = 0.95) was obtained between laser diffraction and sieve analysis for hard wheat flour particles smaller than 45 μm, but the correlation decreased (r = 0.77) when soft wheat flours were involved in the comparison. The correlations between laser diffraction and NIR methods for flour particle size ranges <10 μm, 10-41 μm and 41-300 μm were 0.96, 0.97 and 0.98, respectively.

2.5.2 Effect of Flour Particle Size on the Composition of Flour and Flour Quality

Sullivan et al (1960) air-classified a hard winter wheat patent flour into six particle size ranges (0-10, 10-20, 20-35, 35-60, 60-85, and 85-120 μm), which were analyzed for ash, protein, maltose value, gassing power and amylograph peak viscosity. Both ash and protein content fluctuated with particle size distribution, i.e., both increased with increasing flour particle size from 15 to 30 μm, decreased from 30 to 70 μm, and increased again above 70 μm. Amylograph viscosity increased to a peak for 20-30 μm particles, which had the highest concentration of starch and lowest protein content. Amylograph viscosity then dropped and increased again with increase of flour particle size.

Gracza and Norris (1961) air-classified a single parent hard wheat flour, and studied two fractions typically associated with B-type starch and pure protein containing particles (8.1 and 17.4 μm) that had the same protein content but different particle size. They found that flour with average particle size of 8.1 μm had higher FA than the 17.4 μm particles. Also, the bread made from the flour with the larger particles generated higher loaf volume. Harris (1955) studied six HRS wheats grown at six locations in U.S. to evaluate how flour particle size distribution was influenced by genotype and environment. Flour particle size distribution was determined using a Ro-Tap shaker and six fractions were obtained (0-38, 38-53, 53-61, 61-74, 74-105, and 105-125 μm). They found that flour protein content and loaf volume increased as flour particle size decreased, except for flour with particle size 0-38 μm. Flour water absorption also increased generally as particle size decreased. Flour particle size distribution was influenced by location of growth and to a lesser extent by genotype.

Wang and Flores (2000) air classified flours from U.S. HRW, HWW, and soft red winter (SRW) wheat into <38, 38–53, 53–75, and >75 μm fractions. They found that the protein content of intermediate particle size flour (38 –53 and 53 –75 μm) was higher than that of the finest and coarsest particle flours for HRW and HWW flours. In contrast, for the SRW wheat, protein content increased with increasing flour particle size. The same authors also evaluated relationships between flour particle size and FA and damaged starch content. For the hard wheat class samples, for the three fractions > 38 μm, FA and DS progressively decreased in moderate value with increasing particle size. For the soft wheat flours in this particle size range, FA increased considerably (by over 12% absolute) with increasing particle size, likely as a result of the large increase in protein contents for the flour fractions which ranged from 6.4 to 10.3%.

Devaux et al (1998), using laser diffraction, studied particle size distributions of flours milled from five hard wheats and four soft wheats grown in France for two harvest years. They found that the particle size distribution of soft wheat flours was bimodal with a small peak or distinct shoulder in volume fraction around 20 μm, which corresponded to the size associated with starch granules (Dengate and Meredith 1984), and a second large peak in volume fraction around 110 μm. In contrast, the hard wheat flour particle size distributions had only one large peak around 120 μm. An highly negative correlation ($r = -0.91$) was found across all samples between wheat meal PSI values and the average flour particle size, presumably measured as the mean volume diameter. A similar correlation ($r = -0.72$) was reported for U.S. soft wheat and flour particle size (Gaines 1985).

Scanlon et al (1988) studied the effect of roll gap and differential speed settings of a smooth reduction roll on the resulting particle size and composition of flours released from a relatively coarse farina sample (85% of which ranged from 132 – 247 μm) obtained in the milling of single commercial sample of CWRS wheat. The flour produced was sieved through 91 and 53 μm aperture sieves to produce three size fractions which were analyzed for DS, FP and water absorption. The finest flour fraction, regardless of roll gap or differential setting, had the lowest protein content and the highest degree of DS and water absorption.

2.6 Differences between Hard Red Spring and Hard Red Winter Wheat

HRW wheat on average typically has lower FA compared with HRS wheat, but the reason is not clear. Endo et al (1990) compared the quality characteristics and milling properties of 15 HRS and 15 HRW U.S. exported wheat samples. They divided the samples into three similar protein ranges (12.0-12.9%, 13.0-13.9% and 14.0-14.4%). The only

consistent differences between HRS and HRW across the protein ranges were observed for ratios of total amount of break flour to reduction flour (52.3 vs. 55.4%, 49.6 vs.50.0% and 47.8 vs. 53.7% for low, medium and high protein ranges, respectively) and DS (6.72 vs. 5.61%, 5.88 vs. 5.50% and 6.33 vs. 6.09% for low, medium and high protein ranges, respectively). Accordingly, within each protein range, the HRS flour had higher levels of damaged starch compared to HRW suggesting the former set of wheats had harder kernels on average.

Chung et al (2003) studied 12 cultivars each of hard winter wheat (11 red and one white) and HRS wheat that were grown in three crop years in California that allowed for synchronous grain development of all genotypes, thus removing a normally strong environmental component. Compared to HRW wheat, HRS wheat had significantly higher mean protein (13.0 vs. 12.0%) and wet gluten content (35.8 vs. 32.8%), harder kernels (SKCS hardness 90.9 vs. 84.1), higher baking water absorption (63.6 vs. 60.3%), higher loaf volume (88.4 vs. 81.7 cm^3), but lower gluten index (89.7 vs. 93.8%).

Maghirang et al (2006) evaluated 50 quality parameters of 100 HRW and 100 HRS wheats grown in the U.S., including milling properties, whole wheat grain parameters and wheat flour parameters. Both types of wheats were similar in test weight (TW), kernel size, polyphenol oxidase activity, gluten index, insoluble polymeric protein, free nonpolar lipids, loaf volume potential and mixograph tolerance index. HRS wheat had higher protein content (13.2 vs. 11.3%), flour yield (67.0 vs. 65.9%), wheat ash (1.67 vs. 1.54%), flour ash (0.45 vs. 0.43%), and FA (66.0 vs. 60.9%).

These results confirm the well-known technological differences in e.g., protein content, kernel hardness and starch damage, between HRS and HRW wheat in milling and

flour breadmaking quality, but offer no fundamental explanation why these two wheat classes significantly differ in FA.

CHAPTER 3: MATERIALS AND METHODS

3.1 Wheat Samples

The main focus of this thesis research was on HRW wheat genotypes with most belonging to the CWRW wheat class. A secondary study compared commercial samples of CWRW and CWRS wheats. It should be pointed out that not all the "CWRW" genotypes were in fact registered cultivars of the CWRW commercial class, as some were breeder lines, while others belong to the CW General Purpose (CWGP) class, as elaborated below (Tables 4 and 5). For purposes of naming efficiency, all are hereafter referred to as CWRW wheats. Samples consisted of a diverse set of advanced breeder lines and pure cultivars grown in 2011 and 2012 by Dr. Rob Graf of AAFC-Lethbridge. The 2011 CWRW wheat samples comprised 26 genotypes, grown in two close proximity sites and are herein referred to as 2011S1 and 2011S2, each having 13 genotypes (Table 4). The 2012 CWRW wheat samples consisted of 52 genotypes all grown in the same Lethbridge site. Eighteen of these genotypes were common to the 2011 sample set (Table 5). Commercial wheats (2013 crop year) comprised a total of 16 samples, eight each of CWRS and CWRW wheat classes (Table 6). Commercial wheats were provided by Richardson Pioneer, Paterson Grain, Viterra and Rogers Food Ltd. All samples for the thesis research were officially graded by the CGC Industry Services according to the CGC Official Grain Grading Guide.

Different samples sets were analysed to address the different objectives of this thesis project. The 2011 CWRW wheat samples were used to evaluate relationships between pentosan content of CWRW wheat and flour measured by phloroglucinol colorimetric assay (PCA) and the reference GLC method, and the relationship between FA measured using 50 g

and 10 g mixers. Both 2011 and 2012 CWRW wheat sample sets were used to determine relative influence of factors associated with FA variation, the effectiveness of the PCA method in relation to FA, and to develop and evaluate FA prediction models by multivariate regression. 2013 CWRW and CWRS commercial wheat samples were used to further probe underlying factors explains the low FA of flours of CWRW wheat compared to CWRS wheat.

Table 4. 2011 CWRW wheat genotypes in sample sets S1 and S2 (n=26).

2011S1	Radiant[a]	Flourish[a]	Tempest[a]	LJ1082	W511
(n=13)	CDC Buteo[a]	CDC Osprey[a]	AC Bellatrix[a]	LL066	
	LL611	LL163	LL532	W494	
2011S2	Jerry	DH00W3IN*34	CDC Falcon[b]	Accipiter[b]	W487
(n=13)	Broadview[b]	Peregrine[b]	CDC Raptor[b]	Norstar[a]	
	W460[b]	W486	W485	W478[a]	

CWRW = Canada Western Red Winter.
[a]CWRW wheat genotypes, W478 is now AAC Gateway; [b]Canada Western General Purpose wheat, W460 is now Pintail; all others are advanced lines or germplasm accessions.

Table 5. 2012 CWRW wheat genotype sample set (n=52).

Accipiter[b]*	AC Bellatrix[a]*	AC Tempest[a]*	Broadview[b]*	CDC Buteo[a]*
CDC Falcon[b]*	CDC Harrier[b]	CDC Osprey[a]*	CDC Raptor[b]*	DH99W19H*16[b]
DH00W31N*34[a]*	Emerson[a]	Flourish[a]*	Moats[a]	Peregrine[b]*
Radiant*	LH145	LH491	LJ1082P*	LJ1091P
LJ165	LJ168	LJ624	LK1114	LK1152Q
LK779	LK980	LL611*	LM814Q	1603-137-1[b]
W438	W455	W460[b]*	W472	W478[a]*
W481	W484	W486*	W489	W494*
W495[a]	W497	W499	W500	W501
W505	W506	W507	W508	W510
W511*	W512			

CWRW = Canada Western Red Winter.
* Genotypes in common with 2011 CWRW wheat sample set (n=19); [a]CWRW wheat genotypes, W478 is now AAC Gateway; [b]Canada Western General Purpose wheat, W460 is now Pintail; all others are advanced lines or germplasm accessions.

Table 6. Identity of 2013 Commercial CWRW and CWRS wheat samples (n =16).

	Name/Grade	Source	Location
CWRW	South Lakes	Richardson	MB
	Starbuck	Richardson	MB
	Mollard	Richardson	MB
	High RW	Paterson Grain	Winnipeg North Terminal
	A 1CWRW	Viterra	Winnipeg grain
	C 1CWRW	Viterra	Winnipeg grain
	2CWRW	Paterson	Morris
	N/A	Rogers Food Ltd	Lethbridge AB
CWRS	Shoal Lake	Richardson	MB
	Red River South	Richardson	MB
	Dixon	Richardson	SK
	Last Mountain	Richardson	SK
	Low RS	Paterson Grain	Winnipeg North Terminal
	A 1CWRS	Viterra	Vermilion grain
	B 2CWRS	Viterra	Weyburn grain
	C 2CWRS	Viterra	Grenfell grain

CWRW = Canada Western Red Winter; CWRS = Canada Western Red Spring.

3.2 Milling

3.2.1 Flour Milling

Wheat samples were milled using a tandem Buhler MLU-202 pneumatic laboratory mill (Martin and Dexter 1991) at the Grain Research Laboratory of the CGC. Prior to milling, wheat samples were cleaned using a Carter Dockage Tester. For each genotype sample of CWRW wheat, approximately 1 kg was tempered to 15.5% moisture. An electronic moisture meter (model CAE 919, Canadian Aviation Electronic Ltd.) was used to determine wheat moisture content according to the AACC Approved Method 44-11.01 (AACC International 11th Edition). Wheat samples with moisture contents lower than 10% required two-stage tempering: first to ~13% and then to 15.5%. For tempering, wheat samples were placed in 6 L plastic containers with airtight lids and were shaken by hand after the initial addition of

water and then inverted intermittently by a mechanical mixer for 6 h. Wheat samples were tempered overnight for 18 – 24 h.

After tempering, the moisture content of wheat samples was confirmed. In this procedure, approximately 10 g of tempered wheat was ground using a Break Mill (SM-3, C. W. Brabender, Duisburg, Germany), and moisture content determined with a Brabender Moisture Tester (MT-C, C. W. Brabender, Duisburg, Germany) at 130 ℃ for 1 h according to AACC Approved Method 44-15.02 (AACC International 11th Edition). Before milling, wheat samples were cleaned using a Cyclone Grain Scourer (Model 6, Forster and Son, Ada, OK) to remove any dust and damaged kernels. The following mill streams were generated: 4 break fractions (B1-B4), 1 quality fraction (Q1), one sizing fraction (S1), and 6 middling or reduction roll fractions (M1-M6). Shorts, bran and fine bran were also collected. The bran was passed through a bran finisher twice and rebolted on a box sifter over 180 μm nylon screen (PA-180 Nytal, Sefar) to collect bran flour. Mill streams from B1 - B4, M1 - M6, together with bran flour and flour from Q1 and S1 were collected, weighed and sieved with the same box sifter to remove any impurities. The sieved flour streams were combined and mixed in a tumbler for 10 min. The resulting straight grade flour was double bagged to avoid loss of moisture, and stored at 4 ℃ until required for analysis.

For the 2013 commercial wheat samples, 1.5 kg of each sample was milled in the same way, except that CWRS wheat was tempered to 16.5% moisture content. Flour steams were individually stored except for 38% by weight of each, that were blended as described above to make straight grade flour used for further analysis.

3.2.2 Whole Wheat Meal Preparation

Whole wheat meal samples were prepared using a Retsch ZM200 Centrifugal Mill (Retsch, Haan, Germany) fitted with a 0.75 mm sieve. Whole wheat meal was double bagged to avoid loss of moisture.

3.2.3 Wheat Flour Sieving

Straight grade flour of the commercial CWRW and CWRS wheat was shaken for 10 min on a Ro-Tap sieve shaker (model RX-29, W. S. Tyler, Mentor, OH) using a stack of seven sieves as specified in Table 7. This sieving procedure was triplicated for each sample. SAS GLM analysis showed no mean difference among replicates of sieved flour weights. Accordingly, flours of the triplicated samples for each sieve fractions were blended together for further analysis due to the need for adequate amount of material for these tests. These flour fractions were tested for moisture content, protein content, starch damage, total pentosan and water-extractable pentosan content.

Table 7. Sieves used for flour sieving of commercial CWRW and CWRS wheats.

Sieve U.S. No.	Tyler Equivalent Mesh No.	Estimated flour particle size μm
70	65	150-210
100	100	125-150
120	115	105-125
140	150	74-105
200	200	53-74
270	270	37-53
400	400	<37

CWRW = Canada Western Red Winter; CWRS = Canada Western Red Spring.

3.3 Physical Analysis of Wheat and Wheat Flour

3.3.1 Test Weight

Test weight of cleaned wheat was determined at the time of grading at CGC. A 0.5 L container was filled with wheat to be tested, by pouring through the pre-filled Cox funnel. A hardwood striker was used to scalp off any excess grain. Weight of the grain remaining in the 0.5 L container was determined in grams and was converted to kg/hL (CGC Official Grain Grading Guide). The average of two determinations was reported.

3.3.2 Particle Size Index

AACC International Method No. 55-30.01 (AACC International 11th Edition) was modified by grinding approximately 12 g of wheat through a laboratory cyclone grinder (Udy, model 3010-018, Fort Collins, CO) equipped with a feed rate regulator and a 0.75 mm screen. Exactly 10 g of wheat meal was weighed and processed for 10 min on a Ro-Tap sieve shaker (model RX-29, W.S.Tyler, Mentor, OH) using a U.S. No. 200 stainless steel wire screen with 75 µm opening. One film canister full of wheat was added on top of the sieve together with the meal before tapping to prevent clogging of the sieve. The PSI was recorded as the weight of material times 10 that passed through the sieve.

3.3.3 Thousand Kernel Weight

An electronic seed counter (Agriculex ESC-1, Agriculex Inc., Guelph, Ont.) was used to determine the weight per 1000 kernels (TKW). Approximately 10 g of wheat was loaded into the bowl of the instrument and 200 kernels were counted by an infrared detector and weighed. This weight multiplied by five was the TKW. Duplicate tests were performed and mean results reported.

3.3.4 Flour Particle Size Analysis

Wheat flour particle size was determined by laser diffraction using a Malvern Mastersizer 2000 (Malvern Instruments, Southborough, MA) with the Scirocco dry powder dispersion unit. Flour (10 g) was mixed and placed into the slit of the sample tray, and was presented to the instrument using a vibration feed rate of 65% and dispersion air pressure of 4 bars. Measurement time was 4 s and background time was 10 s. Three measurements were taken and the average was reported.

3.4 Chemical Analysis of Wheat and Flour

All analytical results are reported on a 14% moisture content basis, using at least two replicated determinations.

3.4.1 Moisture Analysis

Moisture content of flour and whole wheat meal was determined by air oven method at 130 ℃ for 1 h according to AACC Approved Method 44-15.02 (AACC International 11th Edition).

3.4.2 Ash Content

An electric muffle furnace at 600 ℃ was used to determine the ash content of whole wheat meal and wheat flour according to AACC Approved Method 08-01.01 (AACC International 11th Edition).

3.4.3 Protein Content

Total nitrogen of whole wheat meal and wheat flour was determined by combustion nitrogen analysis (CNA) using a Truspec N, CNA analyzer (LECO, St. Joseph, MI). A factor of 5.7 was used to convert nitrogen to protein content.

3.4.4 Damaged Starch Analysis

Damaged starch of wheat flour was determined using an amperometric method accommodated by a Chopin SDmatic instrument (Chopin Technologies, Villeneuve-la-Garenne, France) according to AACC Approved Method 76-33.01 (AACC International 11th Edition).

3.4.5 Farinograph Testing

Farinograph absorption was determined using a Farinograph-E instrument (Brabender GmbH & Co, Duisburg, Germany). Wheat flour was mixed in a 50 g or 10 g mixer bowl for 20 min at 63 rpm with optimized water to yield a maximum dough consistency centered at the 500 BU (Brabender Units) line according to AACC Approved Method 54-21.02 (AACC International 11th Edition). The average of duplicate determinations was reported on a 14% moisture basis.

3.4.6 Total Pentosan Content by the Phloroglucinol Colorimetric Assay

Total pentosans of wheat flours were analyzed using the PCA of Douglas (1981). About 5 mg flour sample was added to 2 mL deionized water in 15 mL test tube. 2 mL each of a dilution series of D-(+)-xylose (Sigma-Aldrich, St. Louis, MO) (0, 0.005, 0.01, 0.015 and 0.020 mg/mL) were likewise prepared in 15 mL test tubes and used to construct a

calibration curve for each analysis. A check sample was analyzed with each batch of flour or ground wheat samples. Colorimetric reagent was made fresh by dissolving 1.0 g of phloroglucinol into 5 mL ethanol (95% v/v) and mixed with 110 mL acetic acid, 2 ml HCL and 1 mL glucose standard solution (1.75% w/v). Colorimetric reagent (10 mL) was added, and the solution was heated in a water bath at 100 ℃ for 25 min and then quickly (within 1 min) cooled to room temperature in a cold water bath. The absorbance of aliquot was read as quickly as possible using a UV/Visible spectrophotometer (Biochrom Ultrospec 4300 pro, Biochrom, Cambridge, UK), with distilled water as the blank, first at 552 nm and then at 510 nm. Total pentosans of each test sample were calculated based on absorbance differences at 552 and 510 nm using the xylose calibration curve. Total pentosan values were calculated as 0.88 * % xylose to account for the water released when forming the polysaccharide.

Total pentosans of wheat meal were similarly handled, but analysis was based on extracts of acid hydrolyzed samples (Bell 1985) to solubilise bran particles that would otherwise interfere with absorbance measurement. Test tubes containing 200 mg ground wheat and 10 mL 0.5 M sulfuric acid were boiled in a water bath for 30 min at 100 ℃. These were then cooled to room temperature and centrifuged for 10 min at 8000 g. An aliquot (1 mL) of the supernatant was transferred into a 25 mL volumetric flask and the volume was made up to the 25 mL mark with distilled water. Diluted supernatant (2 mL) was analyzed using the Douglas (1981) method as described above.

3.4.7 Water-Extractable Pentosan Content

About 200 mg flour sample was weighed and added to 10 mL deionized water in 15 mL test tube cover with two layers of Parafilm. The mixture of flour and water was briefly dispersed using a vortex mixer and kept suspended with continuous rotation (40 rpm) using a

Rotamix mixer (Model RKVSD, ATR, Laural, MD) for 30 min at 23 ℃. After centrifugation for 5 min at 5000 g, the diluted supernatant (2 mL) was collected and analyzed using the PCA method described above. Preliminary experiments indicated 30 min extraction time was optimal for FWEP determination (see appendix Fig. A.1).

WWEP was determined by extracting the sample (200 mg) with deionized water (10 mL) with rotary shaking for 2 h at 30 ℃ (Wang et al 2006). After centrifugation (10 min, 8000 g), the extract (3 mL) was incubated with 1 M sulfuric acid (3 mL, 100 ℃, 30 min). After centrifugation (10 min, 8000 g), the diluted hydrolyzate (2 mL) was analyzed by the PCA method.

3.4.8 Assessment of Experimental Conditions of the Phloroglucinol Colorimetric Assay

3.4.8.1 Inclusion of Glucose

To determine if glucose is a required reagent in the Douglas (1981) method, five flour samples from the 2011 CWRW S1 set ranging in TP content (CDC Buteo, Tempest, LL611, LL532 and W494) were evaluated without and with glucose addition. The reaction reagent components were the same except that 1.0 mL of H_2O was used in place of the glucose solution.

3.4.8.2 Acid Hydrolysis of Wheat Meal Samples

Nine whole wheat meal samples from 2011S1 (AC Belatrix, CDC Buteo, LL163, LL532, LL611, W494, W511, Radiant, Tempest) were analyzed without and with pre-hydrolysis with 0.5 M sulfuric acid as described above.

3.4.8.3 Reaction Time with Sulfuric Acid

To determine the optimum acid hydrolysis time, eight whole wheat samples from 2011 CWRW wheats (AC Bellatrix, Accipiter, LL066, LL163, LL532, LL611, Radiant and W494) were analyzed for TP with acid hydrolysis times of 15, 30 and 45 min.

3.4.9 Determination of Alditol Acetates of Arabinose and Xylose by GLC

Both wheat meal and flour samples were analyzed by the classical method of Englyst and Cummings (1984) with modifications (Slominski and Campbell 1990; Meng and Slominski 2005). A sample (~ 50 mg) was weighed into a 50 mL screw-top centrifuge tube. After addition of 2 mL of dimethyl sulphoxide, the test tube was capped and heated in a boiling water bath for 1 h. The test tube cap was briefly opened to release pressure and was recapped. Then, without cooling, 6 mL of 0.1 M sodium acetate buffer, pH 5.2, at 50 ℃ was added and the mixture was immediately vortexed. The tube was cooled to 45 ℃ and starch was hydrolyzed to glucose by adding 0.1 mL of an enzyme solution containing 5000 units of α-amylase, 5 units of pullulanase and 120 units amyloglucosidase per ml of sodium acetate buffer at pH 5.2. Samples were placed in a shaking incubator at 45 ℃ for 16 h. Following the enzyme treatment, 42 mL of 95% ethanol (EtOH) was added and the test tube contents were mixed by inverting the tubes. After 1 h at room temperature, samples were centrifuged for 10 min at 200 ×g. The supernatant was discarded by decanting carefully, and test tubes were placed in a drying oven at 92 ℃. Samples were checked for cracking or shrinking away from the test tube wall after 15 min to ensure samples were properly dried, and if not, this was checked every 2-3 min thereafter. Subsequently, 1 mL of 12 M H_2SO_4 was added to the cooled test tube which was loosely capped with a glass marble and shaken for 1 h at 35 ℃ to dissolve the residue. After acid hydrolysis of the residue, 6 mL of water and 5 mL of internal

standard (1 mg myo-inositol per mL of saturated benzoic acid solution) was added and tubes were mixed for 2 h at 100 ℃.

To 1 mL of hydrolysates, 0.26 mL of 12 M freshly made ammonia solution and 5 μL of octan-2-o1 were added along with 0.1 mL of freshly prepared $NaBH_3$ solution (100 mg per mL of 3 M ammonia solution). Tubes were shaken manually and left to stand for 1 h at 40 ℃. Glacial acetic acid (0.1 mL) was added for neutralization. To 0.2 mL of the acidified solution, 0.2 mL of N-methyl imidazole and 2 mL of acetic anhydride was added, and the tubes were shaken manually and left to stand for 30 min at room temperature. Afterwards, 5 mL of water and 1 mL of dichloromethane (CH_2Cl_2) were quickly added, and tubes were capped and shaken by hand and reopened to release pressure. This procedure was repeated until no pressure was generated by shaking. Samples were then stored at -20 ℃ until analysis. Immediately before GLC analysis, the CH_2Cl_2 phase (bulk of the lower phase) was transferred to a GLC vial with a glass Pasteur pipette for injection into the chromatograph.

Arabinose (or xylose) standard for GLC analysis, was prepared as follows: 5 mL of arabinose solution (1 mg of arabinose per mL of saturated benzoic acid solution) was combined with 5 mL of inositol solution (1 mg of inositol per mL of saturated benzoic acid solution), 1 mL of water and 1 mL of 12 M H_2SO_4. Samples containing the standard sugar were handled as indicated above for experimental samples.

Alditol acetates of arabinose, xylose and sugar standards were analyzed with two GLC instruments. Initially, a Varian CP 3380 gas chromatograph was used with a glass column (1.8 m * 2 mm id) packed with 2% OV-7 on 100-120 Chromosorb W-HP, with helium gas at a flow rate of 40 mL min^{-1}. After sample injection, the oven temperature was

programmed from 180 to 330 ℃ at 3 ℃ min^{-1}. Injection port and detector temperatures were 275 and 300 ℃, respectively. Percent AX in sample was calculated as 0.88 * (%A + %X).

In later experiments, a Varian CP 3800 gas chromatograph was used with a Varian–sil 8 CB column (50 m * 0.2 mm * 0.33 μm) with helium gas at a flow rate of 1.5 mL min^{-1}. The oven temperature was programmed as follows: 100 ℃ for 2 min, and then increased to 265 ℃ at 50 ℃ min^{-1}, hold for 5 min, and increased from 265 ℃ to 275 ℃ at 50 ℃ min^{-1}, staying for 2 min. Injection port and detector temperatures were 265 and 285 ℃, respectively. Percent AX in sample was calculated as 0.88 * (%A + %X).

A and X results obtained for neutral sugars using the Varian CP 3380 GC were corrected with those obtained using the Varian CP 3800 GC using the following equations: $A = 0.9863A_{3800} - 1.2217$, and $X = 0.9301X_{3800} – 0.3546$, respectively (Fig.1). These equations were based on the regression between results obtained using the two instruments. This was needed to correct any inaccuracy (underestimation typically) in the computer – assigned baseline by the Varian CP 3380 system for A and X peaks that resolved on the descending slope of the solvent peak (Fig. A.2). When analyzing a wheat flour sample with relatively low amounts of A (~0.5-0.8%) and X (~0.6-1.2%), this underestimation was more apparent.

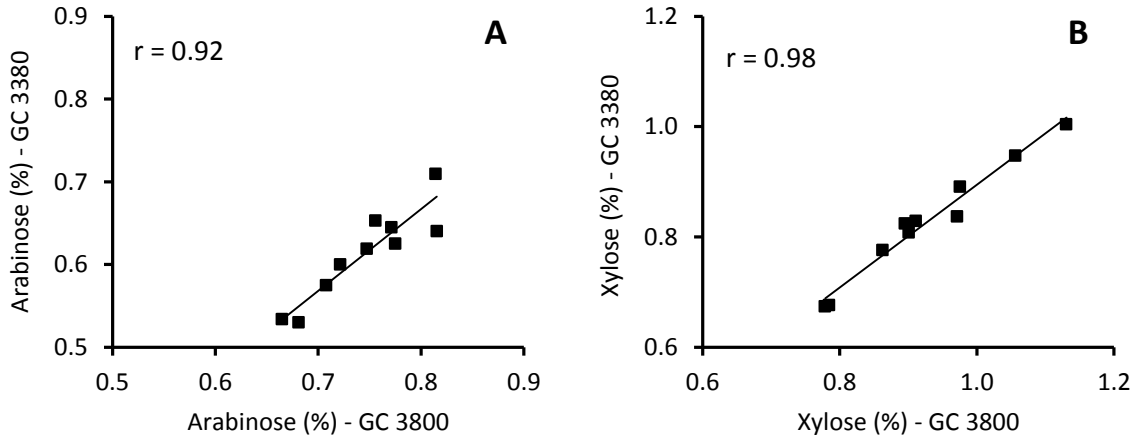


Figure 1. Relationships between arabinose (A) and xylose (B) obtained using Varian CP 3380 and CP3800 GC instruments.

3.5 Statistical Analysis

All statistical analyses were performed using procedures of the SAS software system version 9.3 (SAS Institute, Cary, NC). Treatment means were compared using Fisher's LSD test to determine significant differences ($p<0.05$). Relationships among test parameters were evaluated using Pearson's correlation analysis. Stepwise multivariate linear regression analysis was performed for prediction of FA using the R^2 Selection (RSQUARE) and Maximum R^2 Improvement (MAXR) procedures. The RSQUARE procedure was used to find subsets of independent variables that best predict FA by linear regression in a given sample set, i.e., the best one, or two, or three variable models. However, the RSQUARE procedure does not report on the statistical significance of the variables involved in a model. Accordingly, the MAXR procedure was used for this purpose and to develop the equations for a given combination of independent variables.

CHAPTER 4: RESULTS

4.1 Effectiveness of the Phloroglucinol Colorimetric Assay to Quantify Arabinoxylan Content of Wheat and Flour

4.1.1 Comparison of Phloroglucinol Colorimetric Assay vs. GLC Method

The AX contents of two sets of straight grade flour and wheat meal analyzed by PCA and GLC are reported in Table 8. The pentosan content of the flours ranged from 1.09-1.79% and 1.02-1.77% for PCA and GLC methods, respectively. These ranges overlapped with those determined by Shogren et al (1987) for 79 HRW wheat flours (1.27-2.09%), although Shogren et al (1987) used a different colorimetric assay procedure (Hashimoto et al 1987) based on the orcinol-hydrochloric acid method of Albaum and Umbreit (1947). The average pentosan content of the 26 flour samples determined by the phloroglucinol assay (1.47%) was slightly higher than that determined by GLC (1.43%). PCA results were also similar, but somewhat lower in range, to those obtained by Ordaz-Ortiz et al (2005) for flours of French wheats (most likely winter wheats) which ranged from 1.66-2.87%, and were determined by GLC. Results obtained by the PCA and GLC methods in this thesis research were highly correlated for flour ($r = 0.90$, Fig. 2). Results indicated satisfactory accuracy for the PCA method for wheat flour. The PCA method had excellent repeatability of measurement (ROM, 0.030%) for the 26 flour samples, which was very similar to results obtained for AX determined by GLC. The ROM value corresponds to a coefficient of variation (CV) of about 2%. FWEP ranged from 0.23-0.46%, which represented about 22% of FTP on average.

Table 8. Arabinoxylan contents by phloroglucinol colorimetric assay and GLC of flour and whole wheat.

Genotype	Flour %				Ground wheat%			
	FTP	AX	WE-AX	A/X	WTP	AX	WE-AX	A/X
Radiant	1.22 ± 0.03	1.27 ± 0.01	0.23 ± 0.003	0.75	4.50 ± 0.02	5.06 ± 0.21	0.23 ±0.011	0.54
Flourish	1.28 ± 0.04	1.16 ± 0.04	0.32 ± 0.007	0.77	4.56 ± 0.08	4.92 ± 0.15	0.36 ± 0.015	0.57
Tempest	1.66 ± 0.01	1.66 ± 0.01	0.38 ± 0.011	0.60	4.74 ± 0.01	4.86 ± 0.02	0.35 ± 0.011	0.56
CDC Buteo	1.28 ± 0.01	1.18 ± 0.02	0.29 ± 0.005	0.73	5.06 ± 0.08	5.16 ± 0.14	0.34 ± 0.007	0.54
CDC Osprey	1.27 ± 0.05	1.25 ± 0.04	0.24 ± 0.004	0.77	4.20 ± 0.04	4.77 ± 0.02	0.18 ± 0.001	0.56
LL611	1.72 ± 0.03	1.68 ± 0.01	0.46 ± 0.007	0.60	5.00 ± 0.15	5.57 ± 0.38	0.45 ± 0.013	0.56
LL163	1.57 ± 0.02	1.42 ± 0.02	0.43 ± 0.004	0.64	5.19 ± 0.20	5.39 ± 0.01	0.43 ± 0.005	0.56
LL532	1.43 ± 0.05	1.24 ± 0.05	0.30 ± 0.010	0.76	4.81 ± 0.16	4.86 ± 0.01	0.36 ± 0.004	0.61
LL066	1.31 ± 0.02	1.17 ± 0.02	0.25 ± 0.008	0.83	4.39 ± 0.05	4.59 ± 0.14	0.26 ± 0.017	0.58
W494	1.09 ± 0.03	1.02 ± 0.03	0.28 ± 0.008	0.72	4.43 ± 0.03	4.74 ± 0.25	0.38 ± 0.023	0.59
W511	1.62 ± 0.01	1.77 ± 0.02	0.36 ± 0.004	0.62	4.52 ± 0.01	5.14 ± 0.33	0.34 ± 0.024	0.58
AC Bellatrix	1.79 ± 0.03	1.61 ± 0.02	0.36 ± 0.004	0.61	5.31 ± 0.03	5.55 ± 0.45	0.46 ± 0.030	0.55
LJ1082	1.63 ± 0.02	1.70 ± 0.05	0.34 ± 0.001	0.74	4.95 ± 0.03	5.19 ± 0.35	0.42 ± 0.032	0.59
Jerry	1.70 ± 0.06	1.61 ± 0.04	0.31 ± 0.002	0.64	5.02 ± 0.14	5.33 ± 0.23	0.28 ± 0.010	0.54
Norstar	1.29 ± 0.05	1.25 ± 0.03	0.26 ± 0.007	0.74	4.08 ± 0.02	4.27 ± 0.22	0.24 ± 0.011	0.58
Broadview	1.62 ± 0.04	1.59 ± 0.02	0.38 ± 0.005	0.68	4.95 ± 0.11	5.07 ± 0.24	0.37 ± 0.011	0.55
W478	1.35 ± 0.00	1.31 ± 0.02	0.28 ± 0.002	0.76	4.66 ± 0.07	4.92 ± 0.20	0.27 ± 0.003	0.62
W487	1.51 ± 0.07	1.40 ± 0.01	0.24 ± 0.010	0.71	4.52 ± 0.10	4.65 ± 0.21	0.21 ± 0.016	0.59
DH00W3IN*34	1.49 ± 0.09	1.41 ± 0.00	0.31 ± 0.001	0.71	4.27 ± 0.01	4.36 ± 0.16	0.28 ± 0.016	0.55
W486	1.72 ± 0.01	1.67 ± 0.06	0.38 ± 0.003	0.60	4.70 ± 0.02	4.85 ± 0.35	0.29 ± 0.001	0.53
Peregrine	1.41 ± 0.02	1.44 ± 0.04	0.30 ± 0.003	0.71	4.14 ± 0.01	4.66 ± 0.32	0.29 ± 0.004	0.57
W485	1.42 ± 0.06	1.34 ± 0.04	0.30 ± 0.004	0.73	4.61 ± 0.07	4.87 ± 0.20	0.28 ± 0.008	0.60
Accipiter	1.58 ± 0.06	1.60 ± 0.01	0.35 ± 0.015	0.72	4.59 ± 0.01	4.81 ± 0.38	0.34 ± 0.024	0.56
CDC Raptor	1.54 ± 0.02	1.54 ± 0.06	0.30 ± 0.003	0.72	4.32 ± 0.13	4.60 ± 0.06	0.28 ± 0.010	0.52
W460	1.36 ± 0.01	1.44 ± 0.05	0.34 ± 0.001	0.72	5.00 ± 0.18	5.13 ± 0.43	0.31 ± 0.017	0.59
CDC Falcon	1.44 ± 0.01	1.50 ± 0.05	0.34 ± 0.002	0.74	5.42 ± 0.25	4.95 ± 0.11	0.33 ± 0.013	0.55
Min	1.09	1.02	0.23	0.60	4.08	4.27	0.18	0.52
Max	1.79	1.77	0.46	0.83	5.42	5.57	0.46	0.62
Average	1.47	1.43	0.32	0.70	4.69	4.95	0.32	0.57

FTP = flour total pentosan determined by phloroglucinol assay; WTP = wheat total pentosan determined by phloroglucinol assay; AX = arabinoxylan determined by GLC; A = arabinose; X = xylose; WE-AX = water-extractable arabinoxylan

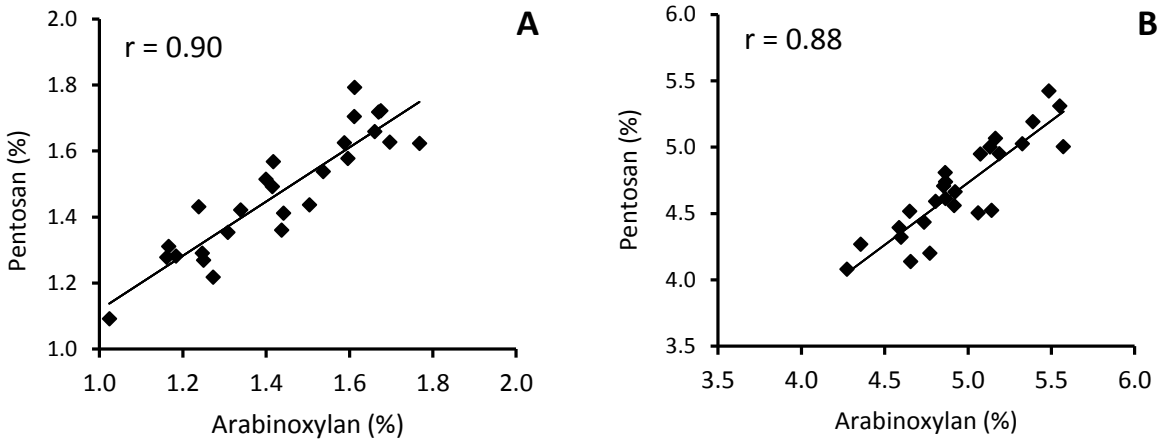


Figure 2. Total pentosan content of flour (A) and ground wheat (B) in relation to arabinoxylan content determined by GC-FID.

Wheat total pentosan content ranged from 4.08–5.42% and 4.27-5.57% for the PCA and GLC methods, respectively. Wheat water-extractable pentosan ranged from 0.18-0.46%, comprising about 7% of WTP (Table 8). Compared to AX results obtained by GLC, average WTP by the PCA were relatively lower by ~ 5%, which may be due to immediate loss of colored products or incomplete release of pentosan sugar constituents. The ROM for the PCA at 0.076% was considerably better than that for AX determination (0.214%) by GLC. This higher ROM for AX determination by GLC is likely due to the complex procedures used for preparing alditol acetate derivatives. Results obtained by the PCA and GLC methods were also highly correlated for wheat meal (r = 0.90, Fig.2). Results therefore confirmed the accuracy and precision of PCA method in determining WTP using the Bell (1985) pre-hydrolysis procedure. Results for wheat meals were similar to those reported in the literature.

4.1.2 Inclusion of Glucose

The Douglas (1981) method and forerunners (Cracknell and Moye 1970; Dische and Borenfreund 1957) included glucose as a reagent. Kiszonas et al (2012) questioned the use of

glucose in their approach to this method. Accordingly, the PCA procedure was evaluated without and with glucose using a subset of five flour samples selected at random from sample set 2011S1 (Tempest, CDC Buteo, LL611, LL532 and W494). The FTP of these samples determined without and with glucose ranged from 1.46-1.80% and 1.09-1.72%, respectively. Therefore, the PCA procedure used without glucose resulted in a significant ($p < 0.05$) increase of FTP by 13% on average for these samples.

In the PCA method, absorbance due to the presence of hexose sugars in the sample occurs at 552 nm as well as at 510 nm (Dische and Borenfreund 1957), but this interference is corrected by subtracting absorbance at 510 nm. Use of 510 nm to correct for interfering sugars was apparently first reported by Dische and Borenfreund (1957) without further explanation, although they showed that at equimolar concentrations compared to arabinose and xylose, hexose sugars like glucose and fructose have more than 90% lower absorbance at 552 nm and about 70% lower absorbance at 510 nm. Accordingly the absorbance of hexose sugars at these wavelengths is significant particularly at 510 nm. Cracknell and Moye (1970) noted that the calculated absorbance at 552 nm minus that at 510 nm was insignificant for hexoses and heptoses, whereas it was a linear function of the concentration of pentose sugars in solution. Results obtained in the present study indicate that the calculated absorbance difference is in fact sensitive to the presence of hexose sugars in a sample when extra glucose is not included as a reagent in the PCA procedure. In contrast, Kiszonas et al (2012) stated that inclusion of glucose when quantifying pentosans in wheat meal had no effect on the reaction and could be replaced with equal amounts of distilled water. However, as noted previously, Kiszonas et al (2012) did not apply the Douglas (1981) procedure as published

and did not subject their whole wheat meal samples to pre-hydrolysis as recommended by Bell (1985).

The nature of the need to add glucose in the PCA reagent appears to be explained by results (Fig. 3) which show the effects of excluding or including glucose on xylose calibration curves. It is important to point out the range of absorbances for the CWRW wheat samples used in this study (see Fig. 3 caption) lie in the lower concentration range of xylose below about 0.01 mg/mL in the standard curves. For the 552 nm curve (Fig. 3C) at this concentration point, there is essentially no effect of adding or excluding glucose on absorbance of xylose. However, at 510 nm (Fig. 3B) there is a considerable effect, i.e. the exclusion of glucose significantly reduced the absorbance, with the net effect ($A_{552} - A_{510}$) being a relative increase in xylose absorbance, hence calculated pentosan content for actual samples would be over-estimated, as was found.

Wheat flour has total sugar content in the range 1.2 – 1.6% (Naivikul and D'Appolonia 1978) the majority of which is sucrose. This range overlaps with the lower range of flour AX content. Whether the sugar is sucrose (which will hydrolyze to fructose and glucose in the PCA procedure) or other simple hexose sugars, the level is sufficient to contribute to a significant overestimation of pentosans without the presence of excess glucose in the PCA reagent.

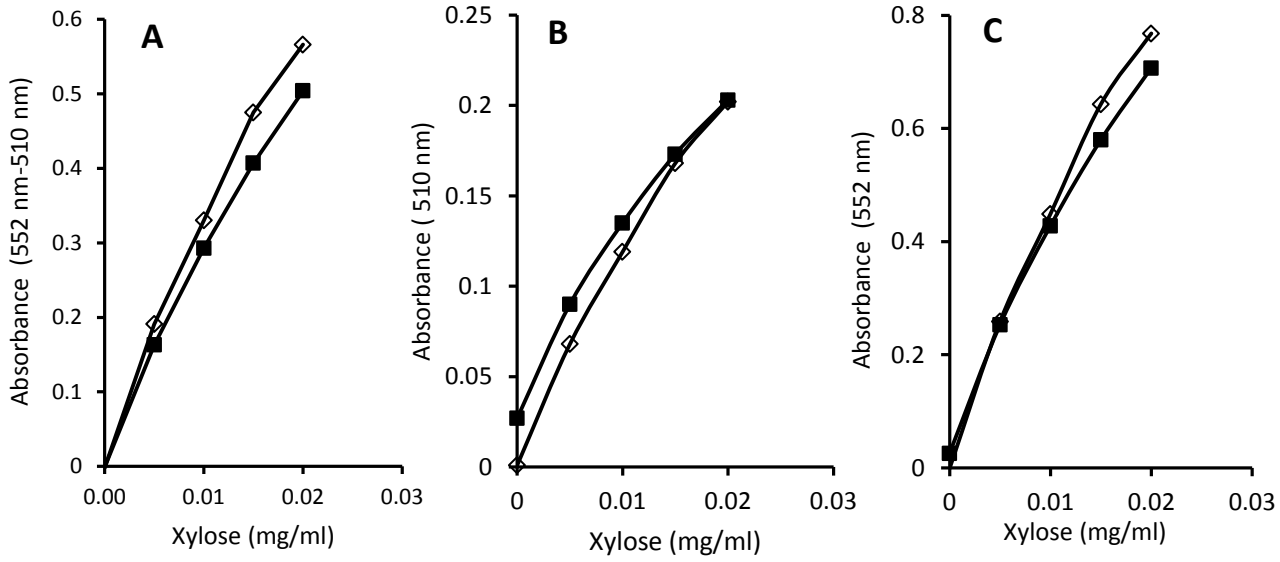


Figure 3. P hloroglucinol colorimetric reaction for xylose standard curves without (◇) and with (■) the inclusion of glucose, (A) absorbance difference, (B) absorbance at 510 nm, (C) absorbance at 552 nm. Typical ranges of absorbances for flour: 510 nm (0.102-0.125); 552 nm (0.190-0.360). For whole wheat: 510 nm (0.113-0.134), 552 nm (0.305-0.351).

4.1.3 Pre-hydrolysis of Wheat Meal Samples

Results of TP content of nine whole wheat meals determined by PCA without and with sulfuric acid pre-hydrolysis ranged from 3.45-4.28% and 4.43-5.31%, respectively. Without sulfuric acid pre-hydrolysis, the average WTP content was underestimated by 17% and resulted in relatively poor agreement with AX results determined by GLC (r = 0.34) compared with those obtained with pre-hydrolysis (r = 0.75, Fig.4, Table 9). Li et al (2009) reported that WTP contents of U.S. Pacific Northwest HRW wheats ranged from 3.09 to 4.04% by using a modified Douglas (1981) method developed by Finnie et al (2006) in which no pre-hydrolysis procedure was involved. Similarly, Kiszonas et al (2012) reported WTP results of twelve whole wheats (two soft white spring, seven SWW, two club, and one HRW wheat varieties) with no pre-hydrolysis ranging from 3.60-4.66%. This range of values is lower than those obtained in the present study (3.84-5.56%).

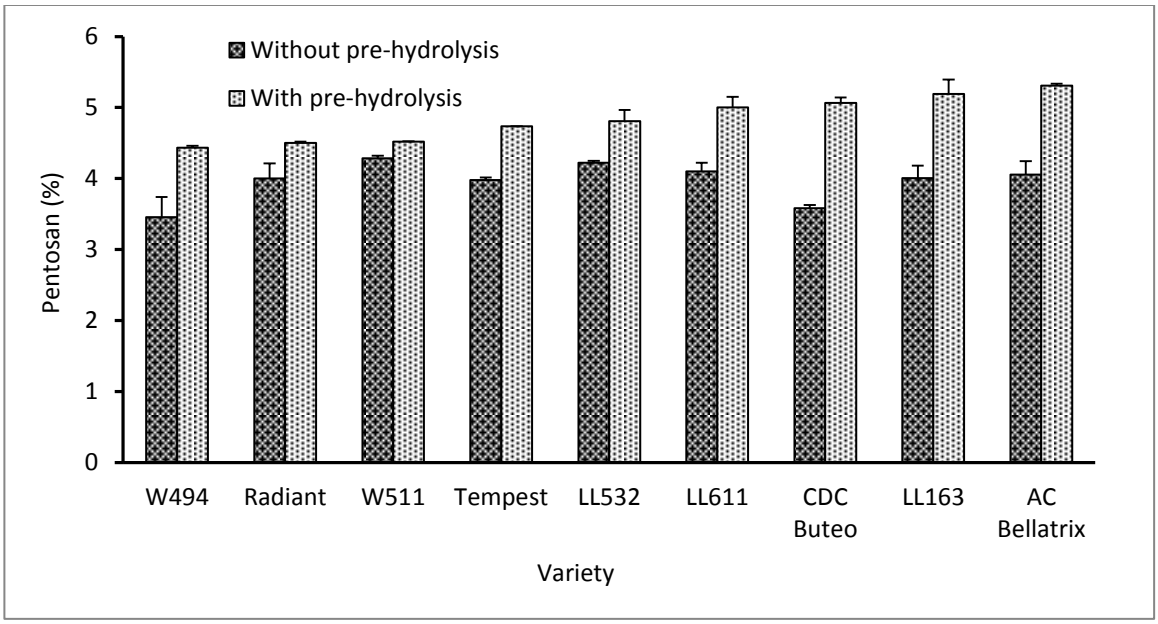


Figure 4. Total pentosan by the phloroglucinol procedure for different whole wheat samples without and with acid prehydrolysis.

Table 9. Correlations among total pentosan, arabinoxylan, arabinose and xylose without and with acid pre-hydrolysis of wheat meal.

	TP_P	TP_{NP}	AX	A	X
TP_P	1.00				
TP_{NP}	0.11	1.00			
AX	0.75	0.34	1.00		
A	0.71	0.56	0.89	1.00	
X	0.72	0.27	0.88	0.75	1.00

TP_P = total pentosan with acid pre-hydrolysis; TP_{NP} = total pentosan without acid pre-hydrolysis; AX = arabinoxylan; A = arabinose; X= xylose. TP results obtained using the phloroglucinol assay. A, X and AX results obtained by GLC.

4.1.4 Reaction Time of Acid Hydrolysis of Phloroglucinol Reagent

A preliminary experiment was performed to evaluate the acetic and hydrochloric acid hydrolysis times of 15 min, 30 min (recommended by Bell), and 45 min on pentosan content of eight genotype samples (2011 set). WTP results showed that the intermediate time of 30 min of acid hydrolysis produced significantly higher WTP contents for all eight samples (Fig. 5) and had the highest correlation with AX results (r = 0.96), compared to r = 0.86 and 0.79

for 15 min and 45 min, respectively.. An preliminary experiment was performed to evaluate the acetic and hydrochloric acid hydrolysis times of 15 min, 30 min (recommended by Bell), and 45 min on pentosan content of eight genotype samples (2011 set). WTP results showed that 30 min of acid hydrolysis produced the significantly higher WTP contents for all eight samples (Fig. 5) and had the highest correlation with AX results (r = 0.96), compared to r = 0.86 and 0.79 for 15 min and 45 min, respectively.

In light of this evaluation of the PCA procedure and experimental conditions, it can be concluded that the Douglas (1981) procedure to quantify pentosan content in flour and ground wheat displayed good accuracy and better repeatability compared with GLC of alditol acetates of AX for flour and whole wheat. The inclusion of glucose was shown to be essential in the PCA method along with the inclusion of a pre-hydrolysis step for wheat meal samples as originally demonstrated by Bell (1985).

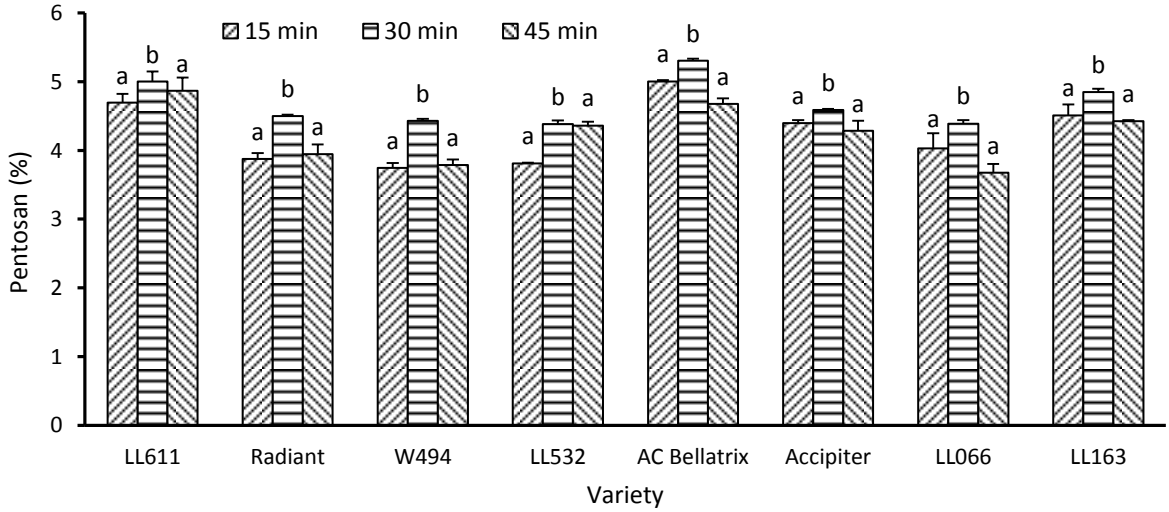


Figure 5. Total pentosan content of eight whole wheat samples with varying pre-hydrolysis times of 15 min, 30 min, and 45 min. Values in the same variety with the same letter are not significantly different (P<0.05).

4.2 Factors Related to Farinograph Absorption

4.2.1 Basic Properties of Wheat and Flour

All the 2011 and 2012 CWRW wheat samples were of milling grade, e.g. No.1 or No.2 CWRW. Results are summarized in Tables 10 and 11 for wheat and flour related properties, respectively. The range of values in these tables highlights the diverse nature of the genotypes used in this thesis research, which reflects in large part the diversity of the CWRW wheat germplasm (R. Graf, personal communication). As judged by the CV, some parameters varied widely (e.g. TKW, flour ash (FAsh), WWEP, FTP, FWEP) with CVs $\geqslant$ about 10%, and others apparently less so with CVs $\leqslant$6% (e.g. FP, FA). Of most importance to the thesis research was the variation in FA values. While CVs indicated that FA did not have relatively high variation among sample sets (FA CVs for 2011All and 2012 were 3.7 and 4.3%, respectively), the absolute range of FA values was considerable (~54-65%). More importantly, were the genotypes with relatively high FAs (> 62%), i.e., W494, LL611, W511, W486 in 2011All and LK779, AC Tempest, LL611, LJ624, W494 and W511 in 2012 (Table 12). Moreover, a few of these (W494, LL611, and W511) were common to both data sets, which highlight the genetic and heritable nature of FA and/or underlying factors.

ANOVA indicated that there were no significant differences among all the sample sets for TW, wheat ash (WAsh), WTP, FY and FWEP. 2011S1 and 2011S2 were significantly different for WWEP, FAsh, DS and d0.1. Results suggested that 2011S2 had harder kernels on average compared to 2011S1 but the differences attributable to a (AAFC Lethbridge field site) growing location effect may not be practically significant. There were considerably more differences on average between the sample sets grown in the

Table 10. CWRW wheat and wheat meal composition and technological characteristics of sample sets 2011S1, 2011S2, 2011All and 2012.

		TW (kg/hL)	PSI	TKW (g)	Wash (%)	WP (%)	WTP (%)	WWEP (%)
Mean	2011S1	81.8[a]	60.6[a]	30.6[ab]	1.38[a]	12.5[a]	4.64[a]	0.35[a]
	2011S2	81.0[a]	58.7[a]	28.8[a]	1.45[a]	12.2[a]	4.51[a]	0.29[b]
	2011All	81.4[a]	59.7[a]	29.7[a]	1.41[a]	12.3[a]	4.58[a]	0.32[ab]
	2012	82.3[a]	54.9[b]	32.6[b]	1.44[a]	13.1[b]	4.46[a]	0.25[c]
Range	2011S1	78.0-84.2	56.1-65.1	23.8-36.3	1.21-1.64	11.3-14.4	4.03-5.31	0.18-0.46
	2011S2	78.1-83.8	50.2-62.9	22.0-37.3	1.26-1.60	11.1-13.0	4.08-5.02	0.21-0.37
	2011All	78.0-84.2	50.2-65.1	22.0-37.3	1.21-1.64	11.1-14.4	4.03-5.31	0.18-0.46
	2012	76.5-86.5	47.6-61.8	25.8-40.0	1.22-1.72	12.0-15.1	3.84-5.56	0.17-0.38
CV	2011S1	2.27	4.37	10.71	8.61	6.51	8.56	24.5
	2011S2	2.80	5.54	17.0	7.45	4.76	6.45	14.1
	2011All	2.54	5.15	14.10	8.21	5.78	7.59	22.7
	2012	2.82	4.36	11.65	7.09	4.98	8.08	19.6

[a] Values followed by different letters in columns are significantly different ($p<0.05$).
TW = test weight; PSI = particle size index; TKW=thousand kernel weight; Wash = wheat ash; WTP = wheat total pentosan; WWEP = wheat water-extractable pentosan.

Table 11. CWRW wheat flour composition and technological characteristics of sample sets 2011S1, 2011S2, 2011All and 2012.

		FY (%)	FAsh (%)	FP (%)	DS (%)	FTP (%)	FWEP (%)	FA (%)	d0.1 (µm)	d0.5 (µm)	d0.9 (µm)
Mean	2011S1	76.4[a]	0.46[a]	12.1[a]	4.70[a]	1.45[a]	0.33[a]	60.2[a]	12.6[a]	56.5[a]	122.6[a]
	2011S2	75.4[a]	0.54[b]	12.0[a]	5.03[b]	1.50[a]	0.31[a]	59.7[ab]	15.5[b]	58.8[a]	125.4[a]
	2011All	75.9[a]	0.50[c]	12.1[a]	4.88[ab]	1.47[a]	0.32[a]	59.9[a]	14.0[ab]	57.7[a]	124.0[a]
	2012	75.8[a]	0.44[a]	12.5[b]	4.49[c]	1.29[b]	0.30[a]	58.3[b]	18.4[c]	65.7[b]	133.6[b]
Range	2011S1	74.8-77.7	0.35-0.55	11.1-13.7	4.1– 5.5	1.09 –1.80	0.23–0.46	55.6–64.7	11.3-15.7	50.3-64.8	113.3-132.3
	2011S2	72.6-78.0	0.45-0.62	11.0-13.0	4.56-5.44	1.29-1.71	0.24-0.38	57.2–62.6	13.8-20.5	53.3-69.1	119.2-136.7
	2011All	72.6-78.0	0.35-0.62	11.0-13.7	4.14-5.46	1.09-1.80	0.23-0.46	55.6-64.7	11.3-20.5	50.3-69.1	113.3-136.7
	2012	73.2-77.6	0.30-0.52	11.3-14.5	3.85-5.27	1.08-1.65	0.24-0.42	53.9-65.5	14.5-27.5	57.7-76.1	124.4-144.9
CV	2011S1	1.40	11.24	6.11	7.80	15.5	21.6	4.65	10.34	7.40	4.32
	2011S2	2.17	7.48	5.89	6.12	8.93	13.6	2.54	11.35	7.00	3.73
	2011All	1.89	12.61	5.89	7.50	12.37	17.93	3.70	14.97	7.33	4.12
	2012	1.46	12.9	5.47	7.51	9.24	15.4	4.34	13.69	6.26	4.17

[a] Values followed by different letters in columns are significantly different ($p<0.05$). FAsh = flour ash; FP = flour protein; DS = damaged starch; FTP = flour total pentosan; FWEP = flour water-extractable pentosan; FA = farinograph absorption; FY=flour yield; d0.1, d0.5 and d0.9 = the flour particle size of the 10^{th}, 50^{th} and 90^{th} percentile of the volume distribution determined by laser diffraction.

different crop years of 2011 and 2012. 2012 wheat was harder (lower PSI), had larger kernels (higher TKW) of higher FP, lower FAsh, lower FTP, slightly lower FA and had flour particle size distributions shifted in basic volume fractions (d0.1, d0.5, d0.9) toward higher values, suggestive of larger particles (Table 11).

Table 12. Genotypes in sample sets 2011All and 2012 with farinograph absorptions ⩾ 62%.

2011All	FA, %	2012	FA, %
W494	64.7	LK779	65.5
LL611	64.0	AC Tempest	64.1
W511	63.1	LL611	63.0
W486	62.6	LJ624	62.4
		W494	62.1
		W511	62.0

FA = farinograph absorption.

Fig. 6 illustrates that outcome in the particle size distributions for flours in the upper and lower 15% of damaged starch content (a parameter which is directly related to wheat hardness, and also to FA) for the 2012 wheat sample set. Compared to flours with relatively low levels of DS (average FA = 57.2%), flours with higher levels of DS (average FA = 60.2%) had a distribution of data points shifted towards particles of larger size. For purposes of regression analysis to FA, this type of data for individual flours, were distilled to points or ranges in particle size that provided “markers” or derived variables to complement the more traditional wheat and flour compositional factors that were studied. From this sort of analysis, a few particle size variables were selected (e.g., 26 μm and 140 μm) by the SAS stepwise multivariate analysis procedure as most discriminatory for FA prediction. In this latter respect, the result is analogous to PSI test values, however, the laser diffraction data clearly provides considerably more detail and, as will be shown later, was more useful and relevant to predict FA and explain the nature of its variation.

The difference between the 2011 and 2012 sample sets in wheat hardness properties PSI and DS, indicates a considerable growing location effect that is likely weather-related. Interestingly, while the 2012 wheat samples had significantly harder kernels on average (PSI 54.9 vs. 59.7, Table 10), the sample set had a significantly lower DS (4.49%) compared to 2011 samples (4.88%, Table 11, Fig. 7). It is plausible that the lower DS in 2012 is related to its higher average protein content (13.1% vs. 12.3%, Table 10), and presumed lower average starch content. Tipples et al (1978) reported a similar confounding effect of protein content on DS. Correlation results in this study do reveal a weak inverse relationship between FP and DS (r = -0.28 for 2011All, r = -0.32 for 2012, Table 15), supporting the view that FP (or starch content) can confound, at least partly, the direct influence of wheat hardness on DS values.

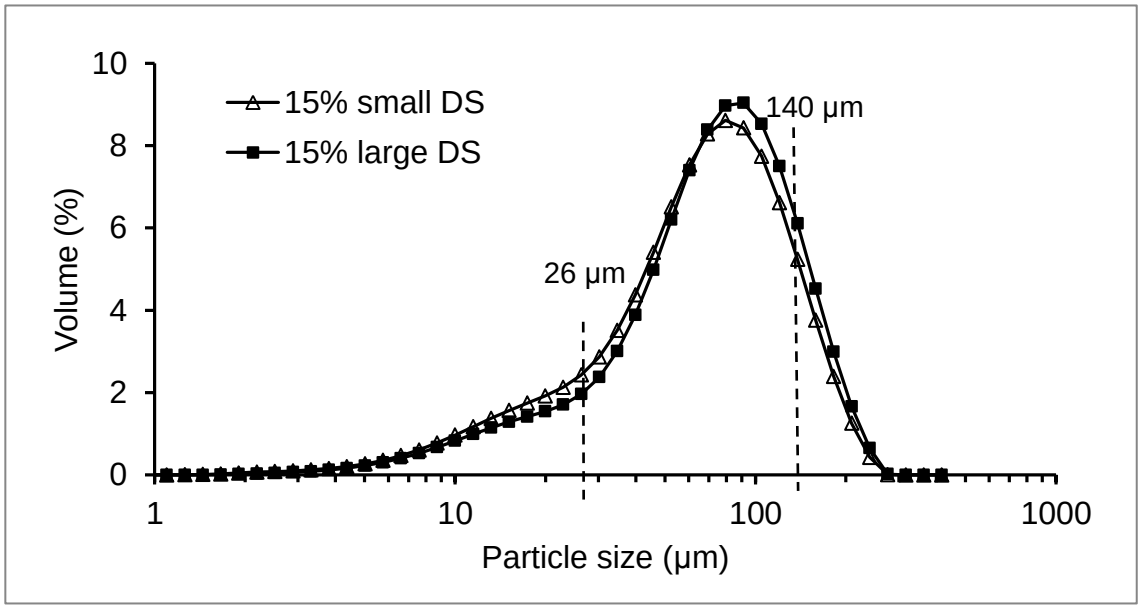


Figure 6. Flour particle size distributions by laser diffraction. Curves represent the average particle size distributions of flours in the bottom and top 15% of damaged starch content of the 2012 CWRW wheat sample set. Note: the x-axis is on a logarithmic scale. Flour particle size close to 26 and 140 µm were found to have the highest correlations to FA.

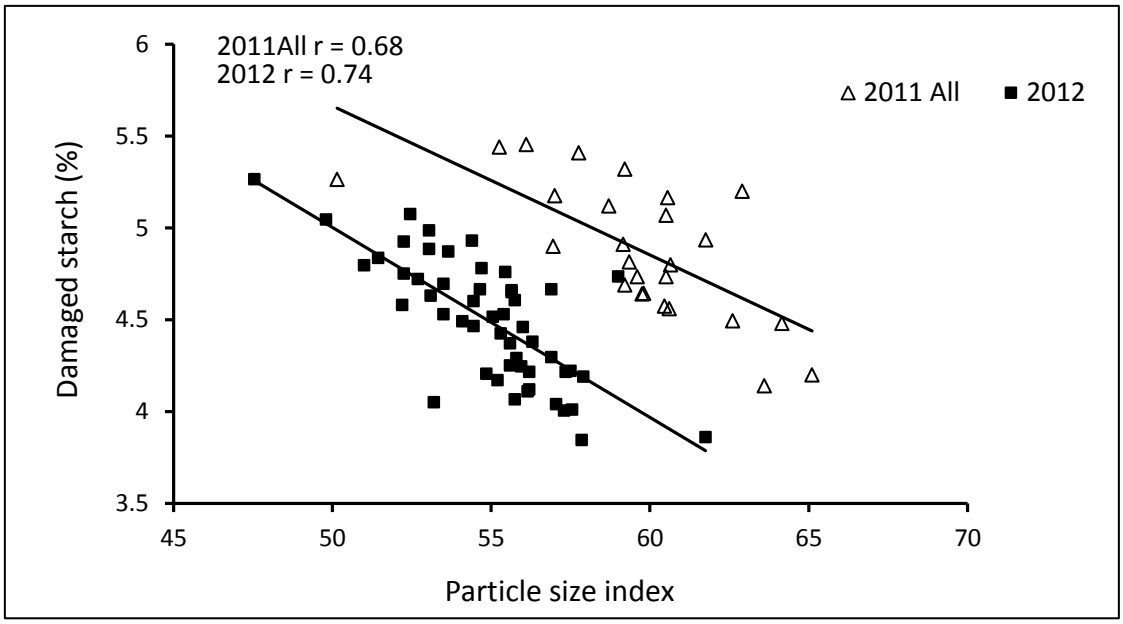


Figure 7. Correlation between flour damaged starch content and wheat particle size index of 2011All (△) and 2012 (■) wheat sample sets.

4.2.2 Correlation between Farinograph Mixing Bowls

Because of the limited amount of wheat available for this research, it was desirable to use a lower capacity mixing bowl (i.e. 10 g flour) instead of the standard 50 g bowl. Determination of FA typically requires at least three determinations to obtain the correct FA value, i.e. using the 50 g mixer generally requires 150 g flour, plus another 50 g for replication and statistical analysis if desired. In this study, FA for the 2011 sample set was determined using 50 g and 10 g mixing bowls. Results were highly correlated (r=0.97, Fig. 8) and absolute values closely agreed. For the 50 g bowl, FA ranged from 54.9-63.8%, with a mean of 59.1%, and ROM of 0.14%. For the 10 g bowl, FA values ranged from 55.6-64.7%, with a mean of 59.9% and ROM of 0.17%. Results indicated that the 10 g mixing bowl could generate accurate and precise FA values with a much lower flour requirement. The balance of the thesis research reflects outcomes using the 10 g farinograph mixer.

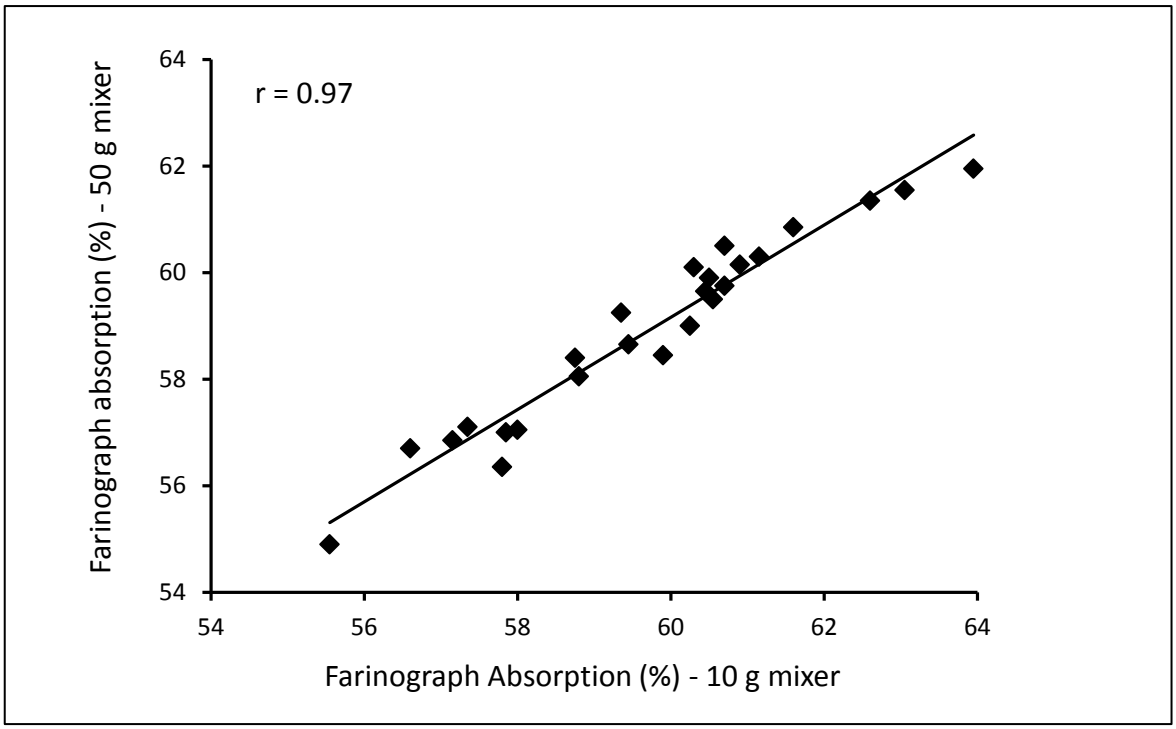


Figure 8. Relationship between farinograph mixing bowls – 50 g vs 10 g.

4.2.3 Relationship between Flour Quality Parameters and Farinograph Absorption

Tables 13-16 present simple correlations between FA and compositional parameters of the sample sets. Those results are graphically summarized in Figs. 9 and 10. Excluding flour particle size related properties (Fig. 9), the most highly and consistently correlated parameters for sample sets 2011All and 2012 were PSI (r = -0.41), FP (r = 0.40), DS (r = 0.40) and FWEP (r = 0.50). TKW and FTP had lower correlations of r = 0.32 and r = 0.30, respectively. For FP and PSI in 2011, there was apparently a considerable genotype effect as reflected by relatively different correlations to FA for FP of r = 0.59 (2011S1) and r = 0.09 (2011S2) and for PSI of r = -0.62 (2011S1) and r = -0.31 (2011S2). However, these two 2011 grown sample sets graded differently (Tables A.1. and A.2.), i.e. in 2011S1, 11 of 13 samples

graded No.1 CWRW and two graded No. 2 CWRW. However, for 2011S2, the grade distribution for the 17 samples originally received from Dr. Graf was 9 No.1 CWRW, 4 No. 2 CWRW, 1 No. 3 CWRW and 2 CW Feed. These grading results suggest a growing location effect for the neighbouring 2011 field sites. Correlation results between FA and flour particle size related parameters (Tables 13-16, Fig. 10) indicated that certain aspects of flour particle size distribution were relatively strongly related to FA. In fact, the parameters evaluated (d0.1, d0.5, d0.9, 26 μm and 140 μm) had the highest correlations to FA among all the whole wheat and flour properties that were studied. Perhaps more important was that the flour particle size correlation results obtained by the laser diffraction method were the most consistent across the sample sets (Fig.11).

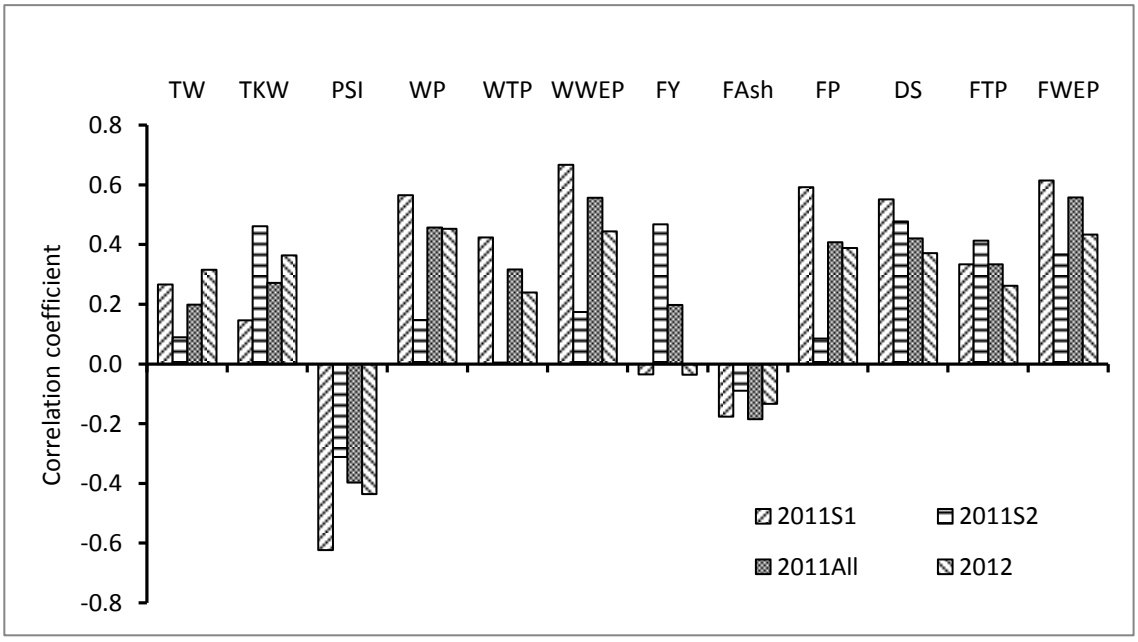


Figure 9. Correlations between farinograph absorption and wheat and flour parameters for sample sets 2011S1, 2011S2, 2011All and 2012. Refer to Table 13 for explanation of abbreviations.

Figure 11 shows the interesting and compelling pattern of variation for correlations between FA and the complete range of particle sizes. The result indicates that the volume fraction of flour particles of about 20 μm had the greatest negative impact on FA, whereas

the volume fraction of flour particle size ⩾ about 100 μm were maximally and consistently correlated to FA. Because the raw volume fraction data for a given flour sample is scaled to 100%, there should be an inverse relationship in the data between relatively small and large particle size fractions when different samples with different particle size distributions are compared (e.g., Fig. 6). In Fig. 6 for example, sample W494 has a higher volume fraction of particles larger than ~50 μm and a lower volume fraction of particles smaller than 50 μm. This inverse relationship between the volume fractions of small and large particles is also reflected in the highly negative correlation results for the variables "26 μm" and "140 μm" (r = -0.94/-0.95, Tables 13-16).

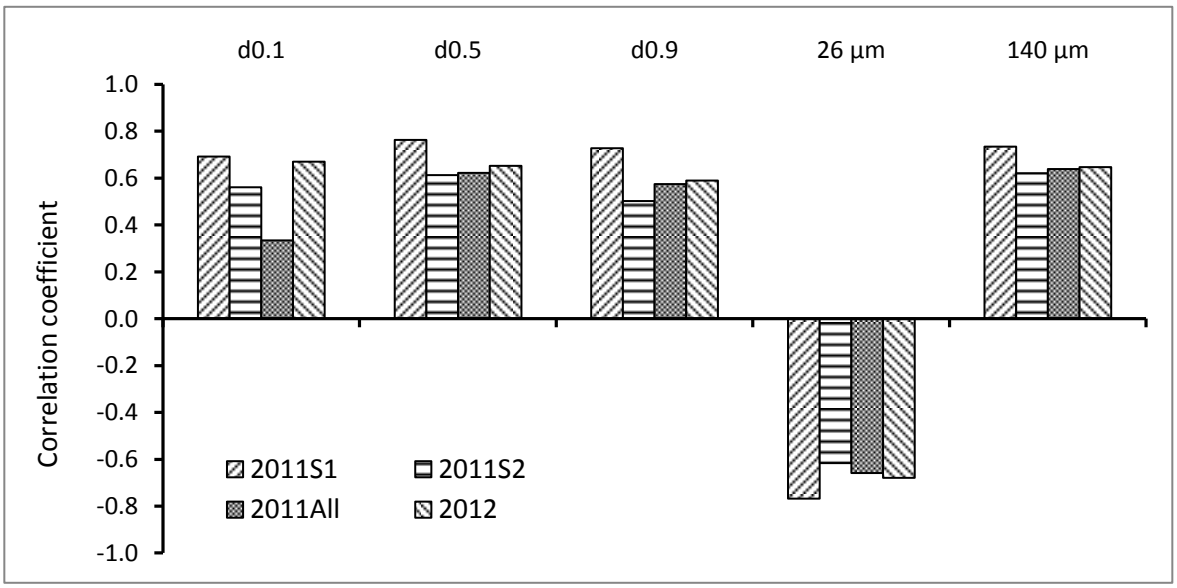


Figure 10. Correlations between farinograph absorption and flour particle size related parameters for sample sets 2011S1, 2011S2, 2011All and 2012. Refer to Table 13 for explanation of abbreviations.

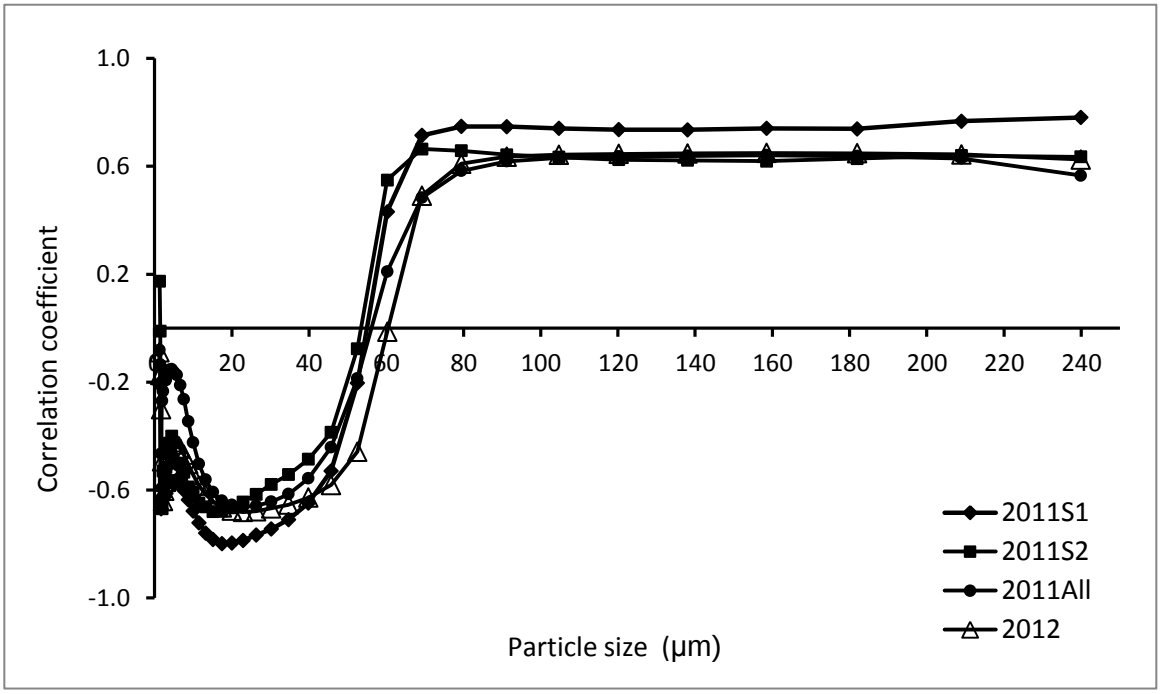


Figure 11. Correlation coefficients between farinograph absorption and flour particle size for sample sets 2011S1, 2011S2, 2011All and 2012.

This strong relationship between FA and flour particle size appears to be a novel result not previously described in the literature, although the underlying basis of this result, which is most likely wheat hardness variation among different samples is well known. The important question to be answered from this result (Fig.11) is whether there is a causal relationship between FA and the volume fractions of small (e.g. 26 μm) and/or large (140 μm) particles, or simply a statistical association. Results to be discussed later do indicate that a cause and effect relationship exists between FA and the proportion of large and small particles in different samples of wheat flours.

Table 13. Correlations between wheat and flour characteristics of sample set 2011S1.

	FA	TW	PSI	TKW	WP	WTP	WWEP	FY	FAsh	FP	DS	FTP	FWEP	d0.1	d0.5	d0.9	26 µm	140µm
FA	1.00																	
TW	0.27	1.00																
PSI	-0.62	-0.55	1.00															
TKW	0.15	0.75	-0.15	1.00														
WP	0.57	0.08	0.08	0.24	1.00													
WTP	0.42	-0.15	-0.42	-0.34	-0.02	1.00												
WWEP	0.67	0.17	-0.55	-0.10	0.35	0.64	1.00											
FY	-0.03	0.16	0.41	0.55	0.29	-0.65	-0.53	1.00										
FAsh	-0.18	-0.78	0.29	-0.61	-0.01	0.27	0.07	-0.37	1.00									
FP	0.59	-0.02	0.15	0.24	0.95	-0.04	0.35	0.40	0.03	1.00								
DS	0.55	0.28	-0.80	0.18	-0.14	0.39	0.33	-0.33	-0.08	-0.18	1.00							
FTP	0.33	-0.17	-0.39	-0.49	-0.20	0.80	0.63	-0.76	0.34	-0.19	0.43	1.00						
FWEP	0.62	0.34	-0.69	-0.12	0.03	0.68	0.80	-0.52	-0.12	0.00	0.49	0.79	1.00					
d0.1	0.69	0.36	-0.33	0.46	0.50	0.09	0.17	0.21	-0.37	0.48	0.46	-0.08	0.10	1.00				
d0.5	0.76	0.51	-0.55	0.48	0.30	0.11	0.27	0.25	-0.49	0.33	0.58	0.00	0.32	0.89	1.00			
d0.9	0.73	0.57	-0.59	0.51	0.24	0.12	0.30	0.19	-0.56	0.26	0.60	0.01	0.34	0.87	0.99	1.00		
26 µm	-0.77	-0.43	0.53	-0.41	-0.30	-0.09	-0.26	-0.31	0.37	-0.36	-0.54	0.00	-0.32	-0.80	-0.97	-0.93	1.00	
140 µm	0.74	0.57	-0.58	0.51	0.25	0.10	0.28	0.22	-0.56	0.27	0.59	0.00	0.34	0.87	0.99	1.00	-0.95	1.00

FA = farinograph absorption; TW = test weight; PSI = particle size index; TKW = thousand kernel weight; WP = wheat protein; WTP = wheat total pentosan; WWEP = wheat water-extractable pentosan; FY = flour yield; FAsh = flour ash; FP = flour protein; DS =damaged starch; FTP = flour total pentosan; FWEP = flour water-extractable pentosan; d0.1, d0.5 and d0.9 = the flour particle size of the 10^{th}, 50^{th} and 90^{th} percentile of the volume distribution determined by laser diffraction. The parameters 26 µm and 140 µm are the two flour particle size variables with the highest correlations to FA across all sample sets.

Table 14. Correlations between wheat and flour characteristics of sample set 2011S2.

	FA	TW	PSI	TKW	WP	WTP	WWEP	FY	FAsh	FP	DS	FTP	FWEP	d0.1	d0.5	d0.9	26 μm	140μm
FA	1.00																	
TW	0.09	1.00																
PSI	-0.31	-0.05	1.00															
TKW	0.46	0.61	0.17	1.00														
WP	0.15	0.48	-0.05	0.09	1.00													
WTP	0.01	-0.53	0.49	0.10	-0.25	1.00												
WWEP	0.17	-0.61	-0.20	-0.30	-0.61	0.25	1.00											
FY	0.47	0.63	0.13	0.75	0.33	-0.02	-0.63	1.00										
FAsh	-0.09	-0.73	-0.17	-0.60	-0.02	0.25	0.44	-0.72	1.00									
FP	0.09	0.45	0.03	0.02	0.95	-0.26	-0.59	0.33	-0.04	1.00								
DS	0.48	-0.55	-0.50	-0.07	-0.35	0.23	0.40	-0.05	0.40	-0.41	1.00							
FTP	0.41	-0.09	0.14	0.19	-0.08	0.40	0.31	0.03	0.15	-0.14	0.10	1.00						
FWEP	0.37	-0.44	-0.14	-0.09	-0.47	0.37	0.89	-0.36	0.24	-0.51	0.32	0.52	1.00					
d0.1	0.56	0.51	-0.65	0.53	0.12	-0.40	-0.12	0.47	-0.40	0.07	0.30	0.01	-0.07	1.00				
d0.5	0.61	0.39	-0.62	0.43	0.01	-0.41	-0.11	0.52	-0.43	0.01	0.38	-0.06	-0.08	0.94	1.00			
d0.9	0.50	0.48	-0.60	0.45	-0.02	-0.53	-0.13	0.50	-0.56	-0.03	0.28	-0.15	-0.11	0.92	0.94	1.00		
26 μm	-0.62	-0.37	0.56	-0.37	-0.07	0.39	0.13	-0.51	0.41	-0.09	-0.30	0.08	0.10	-0.88	-0.98	-0.87	1.00	
140 μm	0.62	0.32	-0.67	0.42	-0.05	-0.33	-0.06	0.49	-0.35	-0.07	0.49	-0.03	-0.02	0.93	0.98	0.90	-0.94	1.00

FA = farinograph absorption; TW = test weight; PSI = particle size index; TKW = thousand kernel weight; WP = wheat protein; WTP = wheat total pentosan; WWEP = wheat water-extractable pentosan; FY = flour yield; FAsh = flour ash; FP = flour protein; DS =damaged starch; FTP = flour total pentosan; FWEP = flour water-extractable pentosan; d0.1, d0.5 and d0.9 = the flour particle size of the 10^{th}, 50^{th} and 90^{th} percentile of the volume distribution determined by laser diffraction. The parameters 26 μm and 140 μm are the two flour particle size variables with the highest correlations to FA across all sample sets.

Table 15. Correlations between wheat and flour characteristics of sample set 2011All.

	FA	TW	PSI	TKW	WP	WTP	WWEP	FY	FAsh	FP	DS	FTP	FWEP	d0.1	d0.5	d0.9	26 μm	140μm
FA	1.00																	
TW	0.20	1.00																
PSI	-0.40	-0.17	1.00															
TKW	0.27	0.67	0.12	1.00														
WP	0.46	0.29	0.09	0.20	1.00													
WTP	0.32	-0.27	0.07	-0.06	-0.05	1.00												
WWEP	0.56	-0.01	-0.19	-0.05	0.20	0.55	1.00											
FY	0.20	0.49	0.31	0.71	0.35	-0.21	-0.28	1.00										
FAsh	-0.19	-0.65	-0.18	-0.56	-0.18	0.06	-0.18	-0.59	1.00									
FP	0.41	0.24	0.10	0.12	0.92	-0.11	0.07	0.35	-0.05	1.00								
DS	0.42	-0.20	-0.68	-0.06	-0.29	0.22	0.10	-0.28	0.36	-0.28	1.00							
FTP	0.33	-0.15	-0.19	-0.17	-0.18	0.63	0.45	-0.36	0.28	-0.17	0.34	1.00						
FWEP	0.56	0.03	-0.37	-0.07	-0.09	0.59	0.78	-0.34	-0.07	-0.18	0.35	0.70	1.00					
d0.1	0.33	0.18	-0.59	0.20	0.04	-0.23	-0.26	0.03	0.29	0.13	0.53	0.06	-0.05	1.00				
d0.5	0.62	0.36	-0.62	0.35	0.10	-0.15	0.01	0.27	-0.13	0.15	0.54	0.01	0.13	0.82	1.00			
d0.9	0.58	0.43	-0.62	0.37	0.06	-0.18	0.02	0.23	-0.19	0.10	0.53	-0.01	0.15	0.81	0.97	1.00		
26 μm	-0.66	-0.38	0.53	-0.36	-0.17	0.13	-0.08	-0.39	0.24	-0.21	-0.40	0.02	-0.14	-0.65	-0.95	-0.87	1.00	
140 μm	0.64	0.40	-0.63	0.41	0.09	-0.10	0.10	0.32	-0.25	0.09	0.53	0.01	0.18	0.72	0.97	0.94	-0.94	1.00

FA = farinograph absorption; TW = test weight; PSI = particle size index; TKW = thousand kernel weight; WP = wheat protein; WTP = wheat total pentosan; WWEP = wheat water-extractable pentosan; FY = flour yield; FAsh = flour ash; FP = flour protein; DS =damaged starch; FTP = flour total pentosan; FWEP = flour water-extractable pentosan; d0.1, d0.5 and d0.9 = the flour particle size of the 10^{th}, 50^{th} and 90^{th} percentile of the volume distribution determined by laser diffraction. The parameters 26 μm and 140 μm are the two flour particle size variables with the highest correlations to FA across all sample sets.

Table 16. Correlations between wheat and flour characteristics of sample set 2012.

	FA	TW	PSI	TKW	WP	WTP	WWEP	FY	FAsh	FP	DS	FTP	FWEP	d0.1	d0.5	d0.9	26 µm	140µm
FA	1.00																	
TW	0.32	1.00																
PSI	-0.44	-0.29	1.00															
TKW	0.36	0.59	-0.24	1.00														
WP	0.45	-0.16	-0.01	0.02	1.00													
WTP	0.24	-0.05	0.18	0.06	0.19	1.00												
WWEP	0.44	-0.13	-0.08	0.12	0.05	0.33	1.00											
FY	-0.04	0.50	-0.03	0.44	-0.12	0.06	-0.30	1.00										
FAsh	-0.13	-0.18	-0.10	-0.08	-0.13	-0.10	-0.06	0.03	1.00									
FP	0.39	-0.14	0.13	-0.08	0.90	0.25	-0.02	-0.10	-0.26	1.00								
DS	0.37	0.27	-0.74	0.36	-0.11	0.00	0.36	0.05	0.17	-0.25	1.00							
FTP	0.26	-0.22	0.01	-0.01	-0.02	0.49	0.59	-0.17	-0.01	0.02	0.19	1.00						
FWEP	0.43	-0.02	-0.26	-0.01	-0.04	0.23	0.73	-0.28	0.16	-0.11	0.32	0.59	1.00					
d0.1	0.67	0.50	-0.49	0.47	0.25	0.06	0.16	0.27	-0.03	0.19	0.41	-0.08	0.13	1.00				
d0.5	0.65	0.63	-0.56	0.56	0.19	0.01	0.10	0.36	-0.05	0.09	0.49	-0.11	0.11	0.94	1.00			
d0.9	0.59	0.60	-0.51	0.44	0.25	-0.03	0.07	0.33	-0.03	0.14	0.43	-0.11	0.08	0.87	0.93	1.00		
26 µm	-0.68	-0.59	0.50	-0.55	-0.27	-0.05	-0.10	-0.36	0.09	-0.18	-0.42	0.11	-0.08	-0.91	-0.98	-0.88	1.00	
140 µm	0.65	0.66	-0.59	0.61	0.07	0.01	0.14	0.36	-0.05	-0.01	0.54	-0.07	0.16	0.92	0.98	0.85	-0.95	1.00

FA = farinograph absorption; TW = test weight; PSI = particle size index; TKW = thousand kernel weight; WP = wheat protein; WTP = wheat total pentosan; WWEP = wheat water-extractable pentosan; FY = flour yield; FAsh = flour ash; FP = flour protein; DS =damaged starch; FTP = flour total pentosan; FWEP = flour water-extractable pentosan; d0.1, d0.5 and d0.9 = the flour particle size of the 10^{th}, 50^{th} and 90^{th} percentile of the volume distribution determined by laser diffraction. The parameters 26 µm and 140 µm are the two flour particle size variables with the highest correlations to FA across all sample sets.

Figures 12-23 present scatter plots, for all the data sets, of relations between FA and the most highly correlated wheat and flour properties, PSI (Fig.12), DS (Fig.13), FP (Fig.14), FTP (Fig.15 and Fig.16), FWEP (Fig.17 and Fig.18), d0.1 (Fig.19), d0.5 (Fig.20), d0.9 (Fig.21), 26 μm (Fig.22) and 140 μm (Fig.23). Visual inspection of these plots taken together leads to the conclusion that for the CWRW wheats under consideration, no single wheat or flour quality parameter was strongly related to FA.

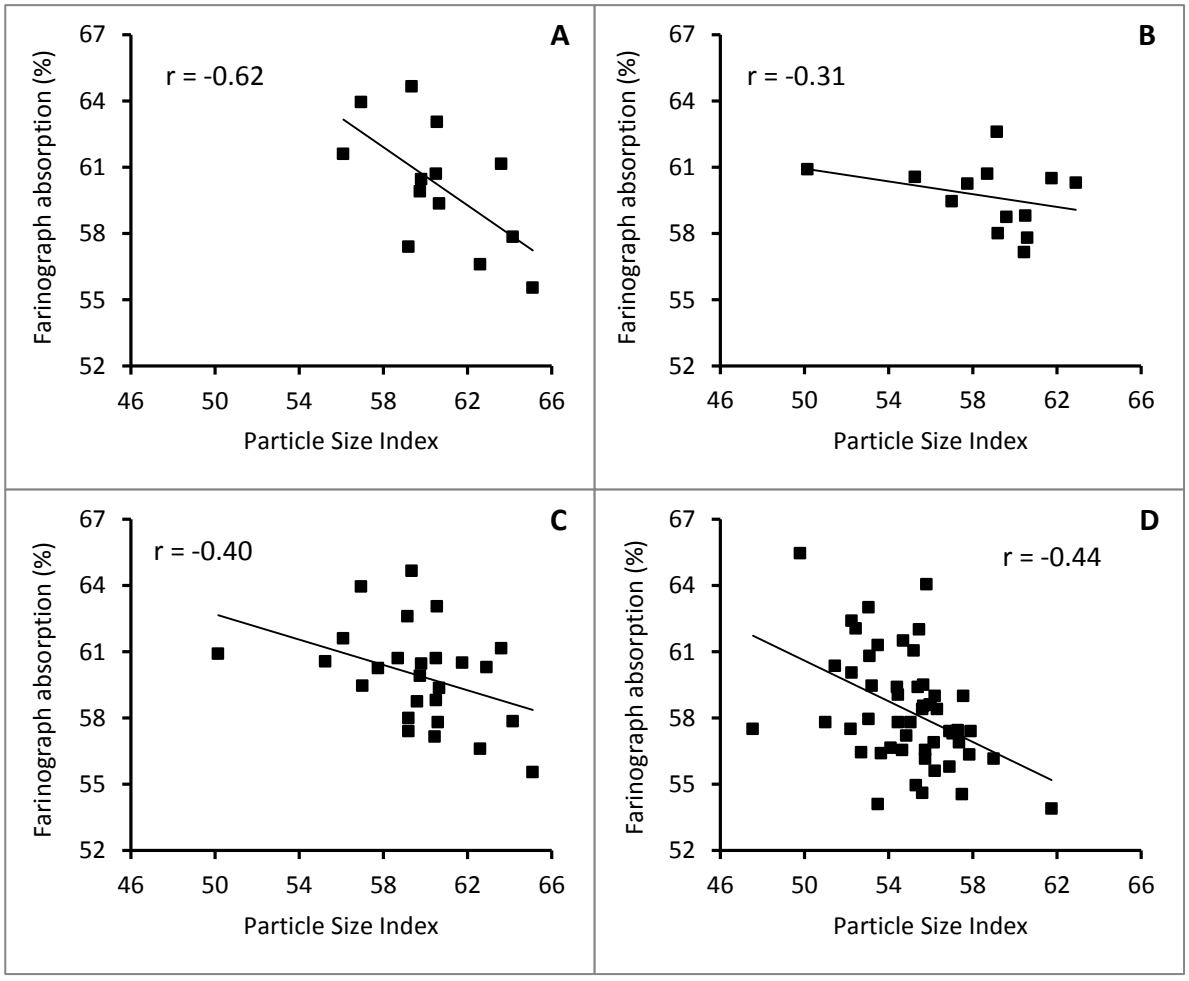


Figure 12. Relationships between farinograph absorption and particle size index of sample sets 2011S1 (A), 2011S2 (B), 2011All (C) and 2012 (D).

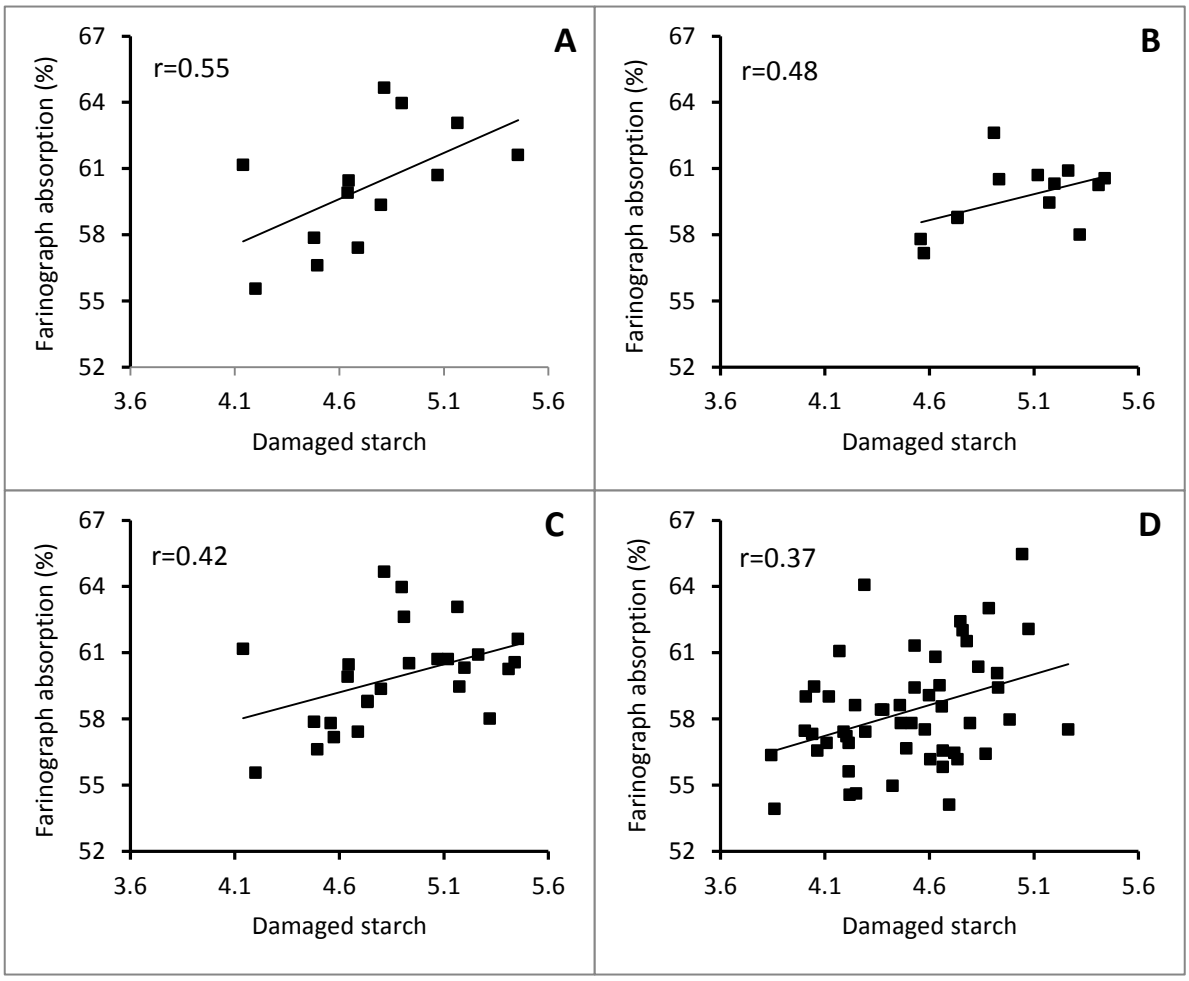


Figure 13. Relationships between farinograph absorption and damaged starch of sample sets 2011S1 (A), 2011S2 (B), 2011All (C) and 2012 (D).

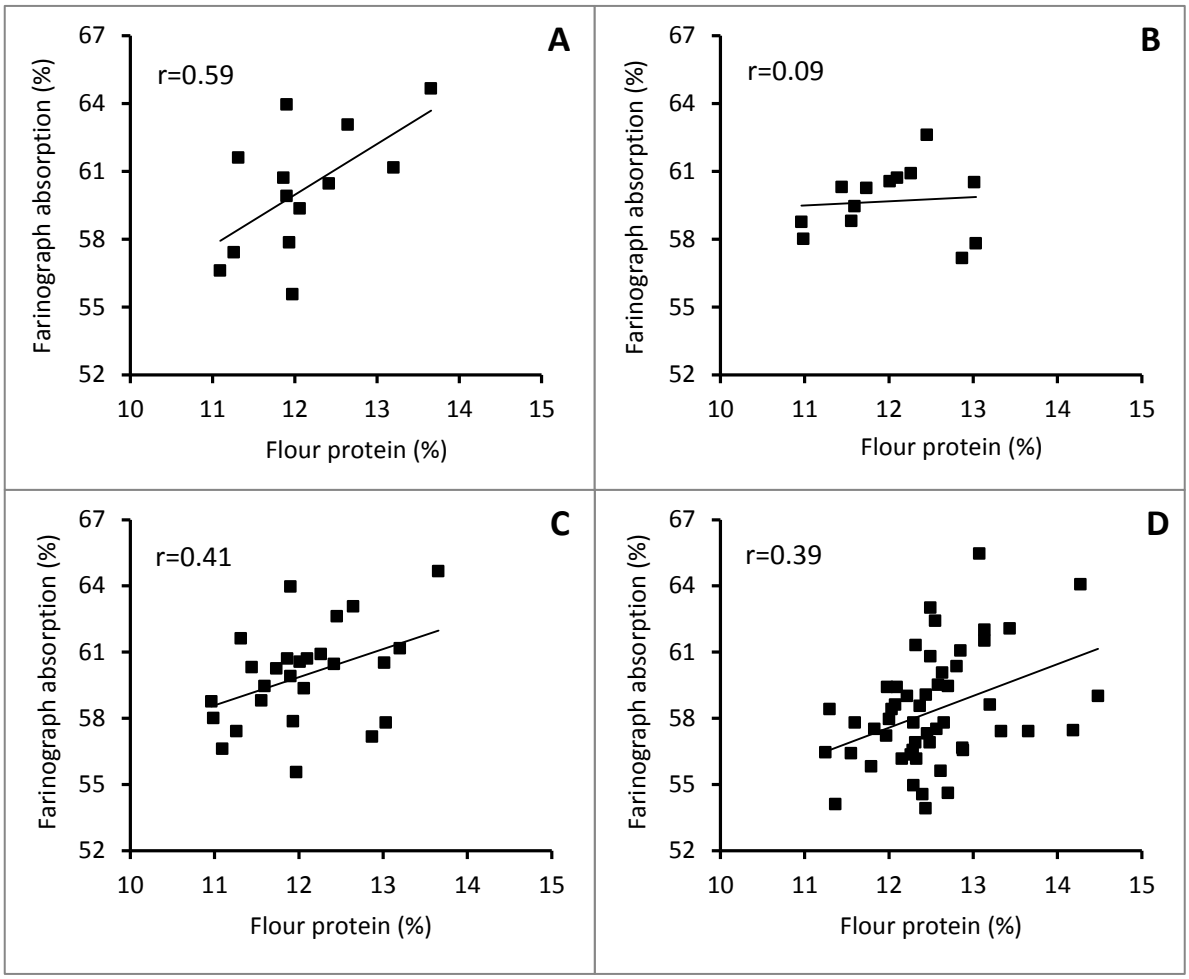


Figure 14. Relationships between farinograph absorption and flour protein of sample sets 2011S1 (A), 2011S2 (B), 2011All (C) and 2012 (D).

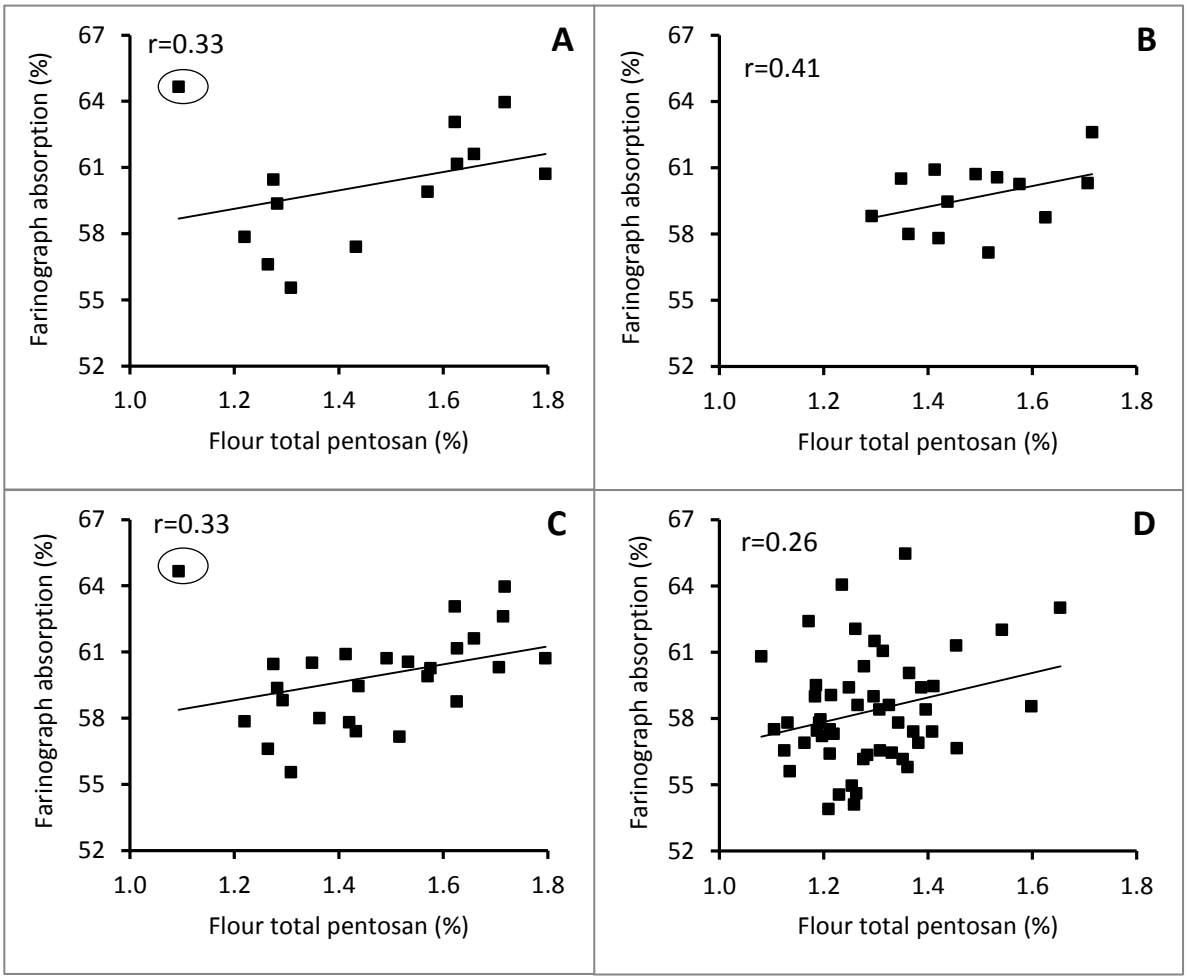


Figure 15. Relationships between farinograph absorption and flour total pentosans of sample sets 2011S1 (A), 2011S2 (B), 2011All (C) and 2012 (D), Circled point is genotype W494.

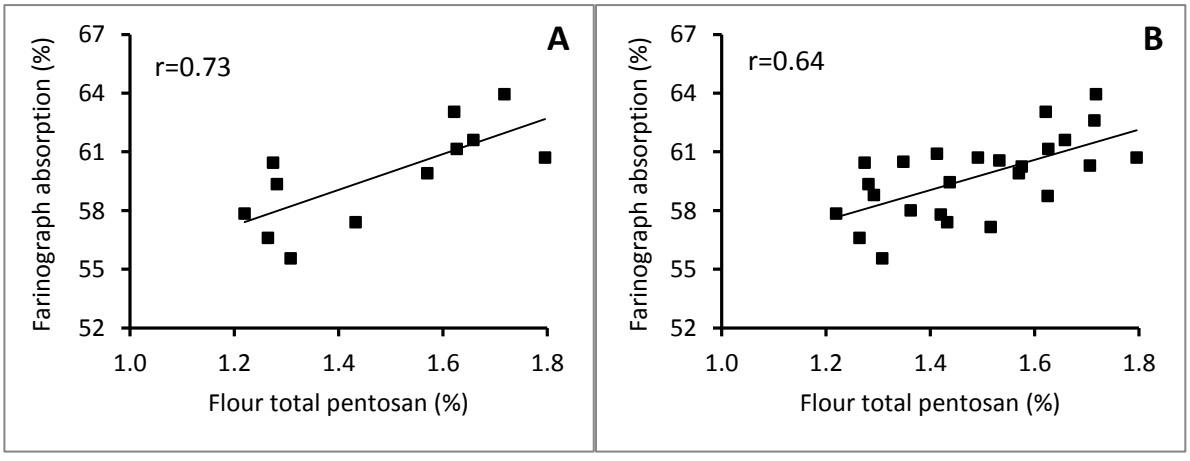


Figure 16. Relationships between farinograph absorption and flour total pentosans of sample sets 2011S1 (A) and 2011All (B), without genotype W494.

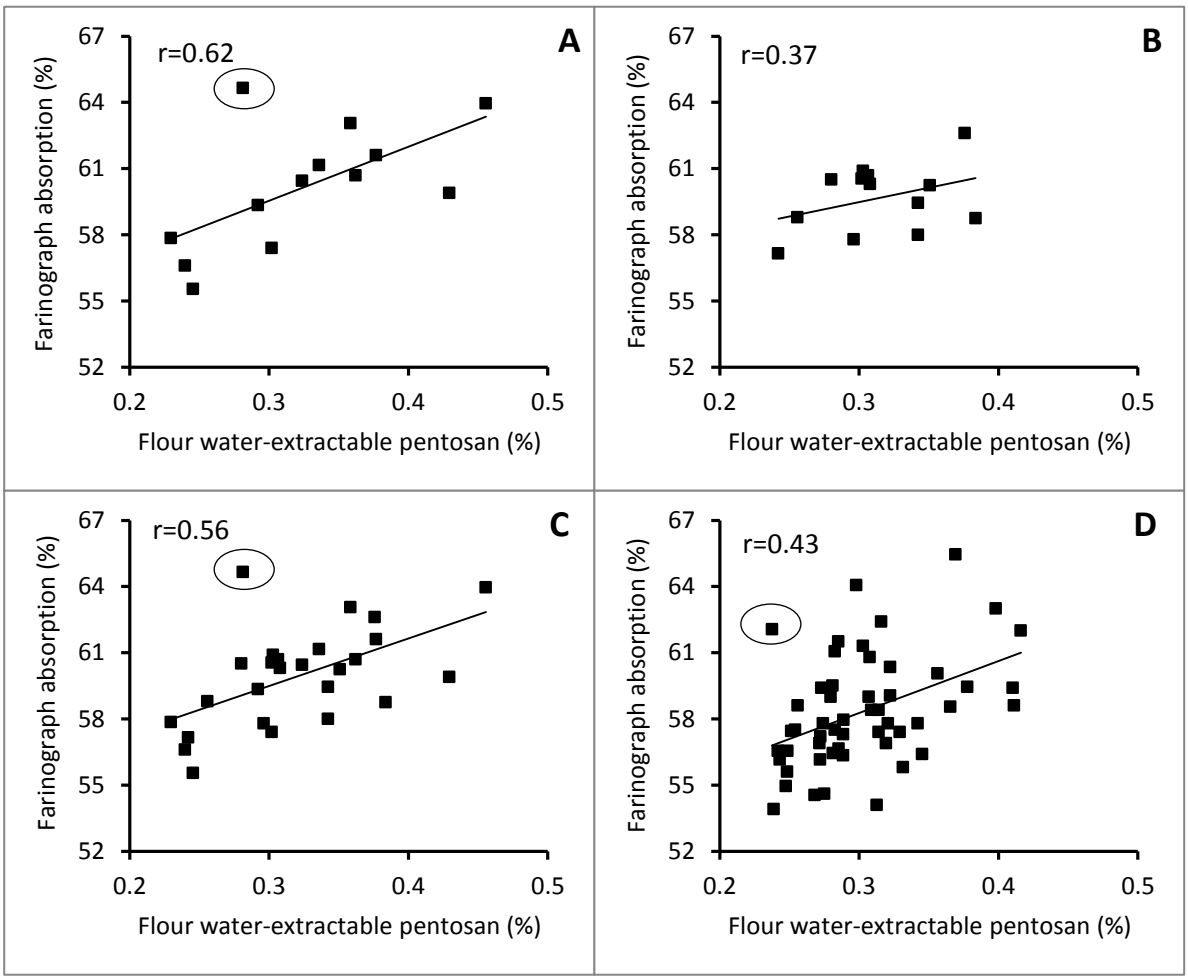


Figure 17. Relationships between farinograph absorption and flour water-extractable pentosan of sample sets 2011S1 (A), 2011S2 (B), 2011All (C) and 2012 (D). Circled point is genotype W494.

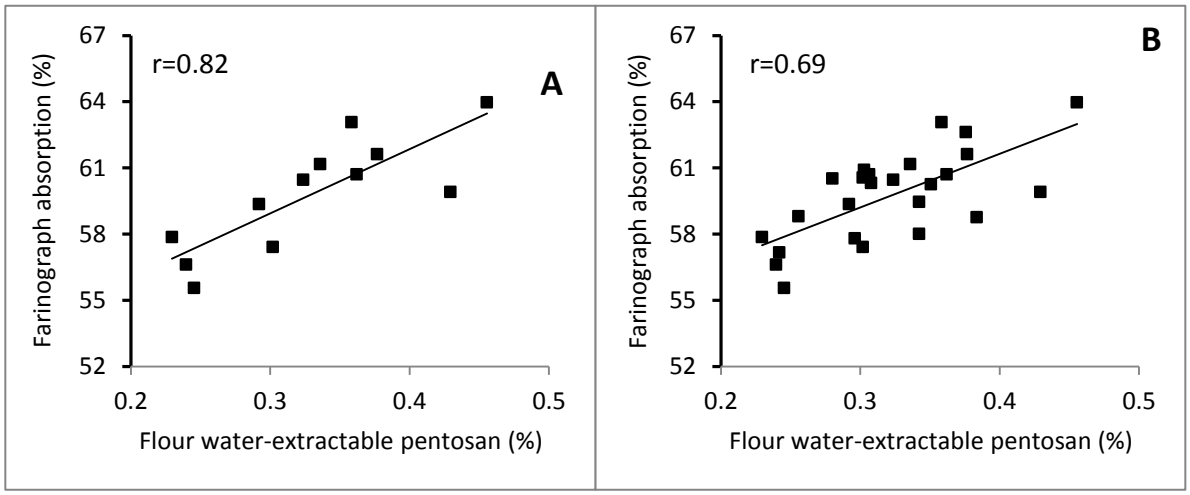


Figure 18. Relationships between farinograph absorption and flour water-extractable pentosan of sample sets 2011S1 (A) and 2011All (B) without genotype W494.

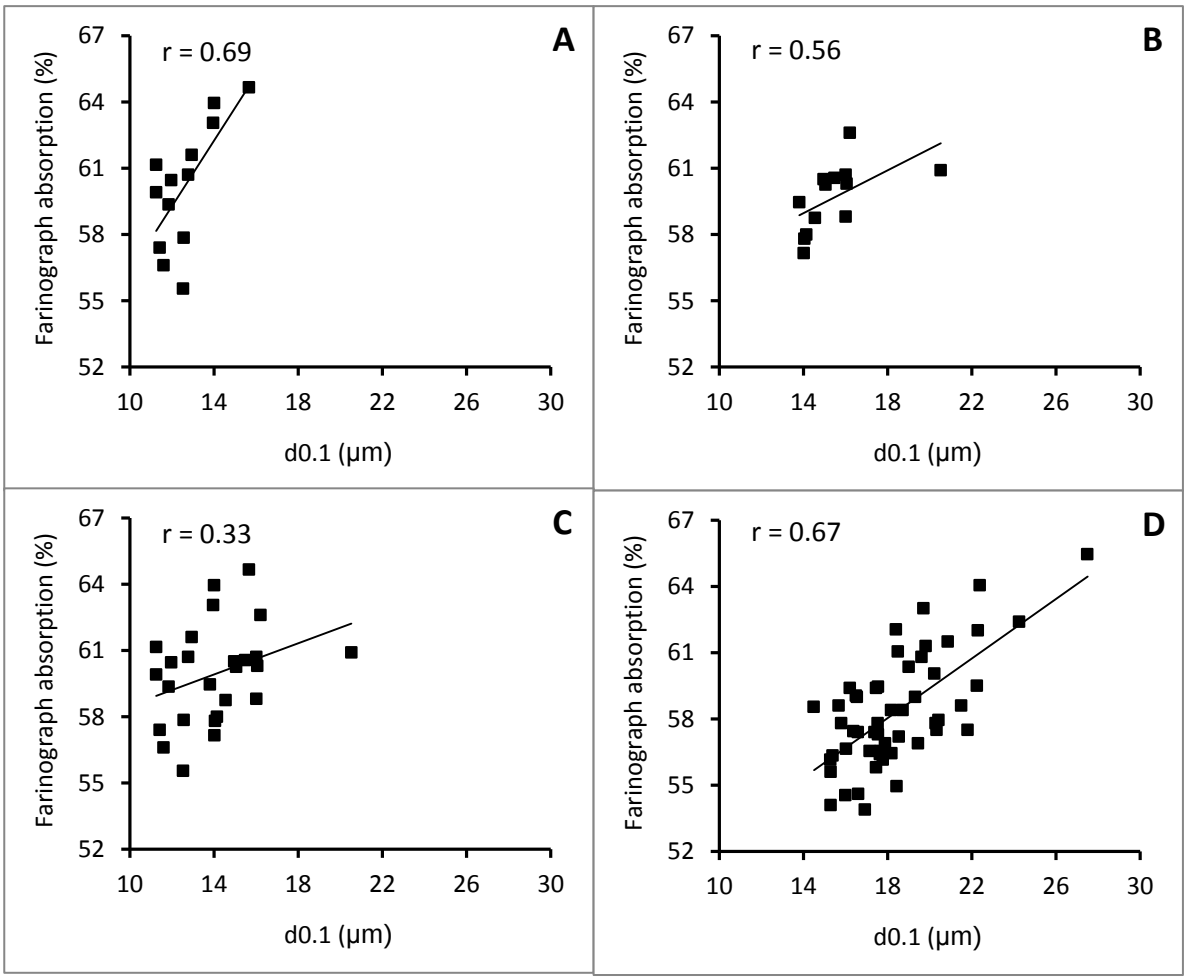


Figure 19. Relationships between farinograph absorption and flour particle size of the 10th percentile of the volume distribution determined by laser diffraction of sample sets 2011S1 (A), 2011S2 (B), 2011All (C) and 2012 (D).

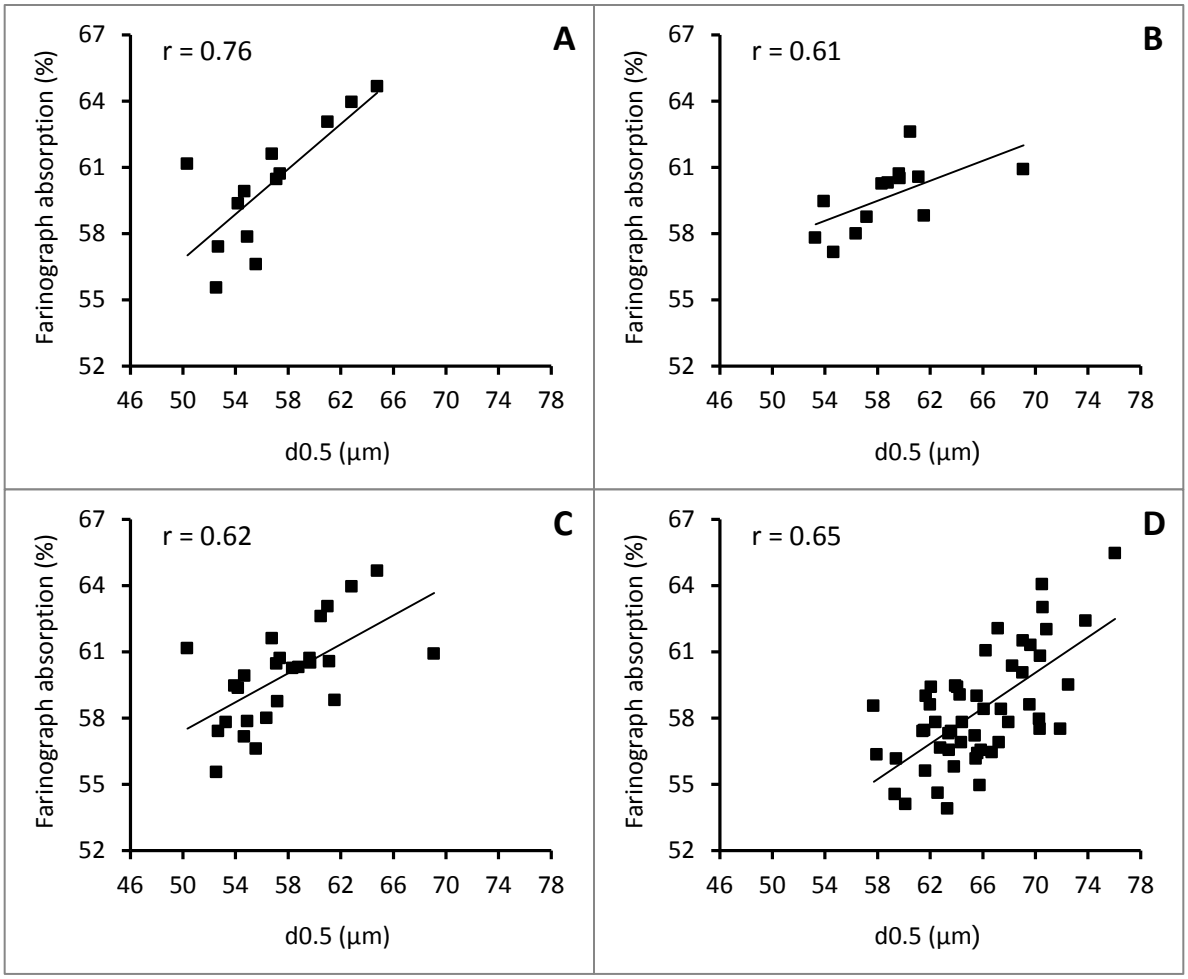


Figure 20. Relationships between farinograph absorption and flour particle size of the 50th percentile of the volume distribution determined by laser diffraction of sample sets 2011S1 (A), 2011S2 (B), 2011All (C) and 2012 (D).

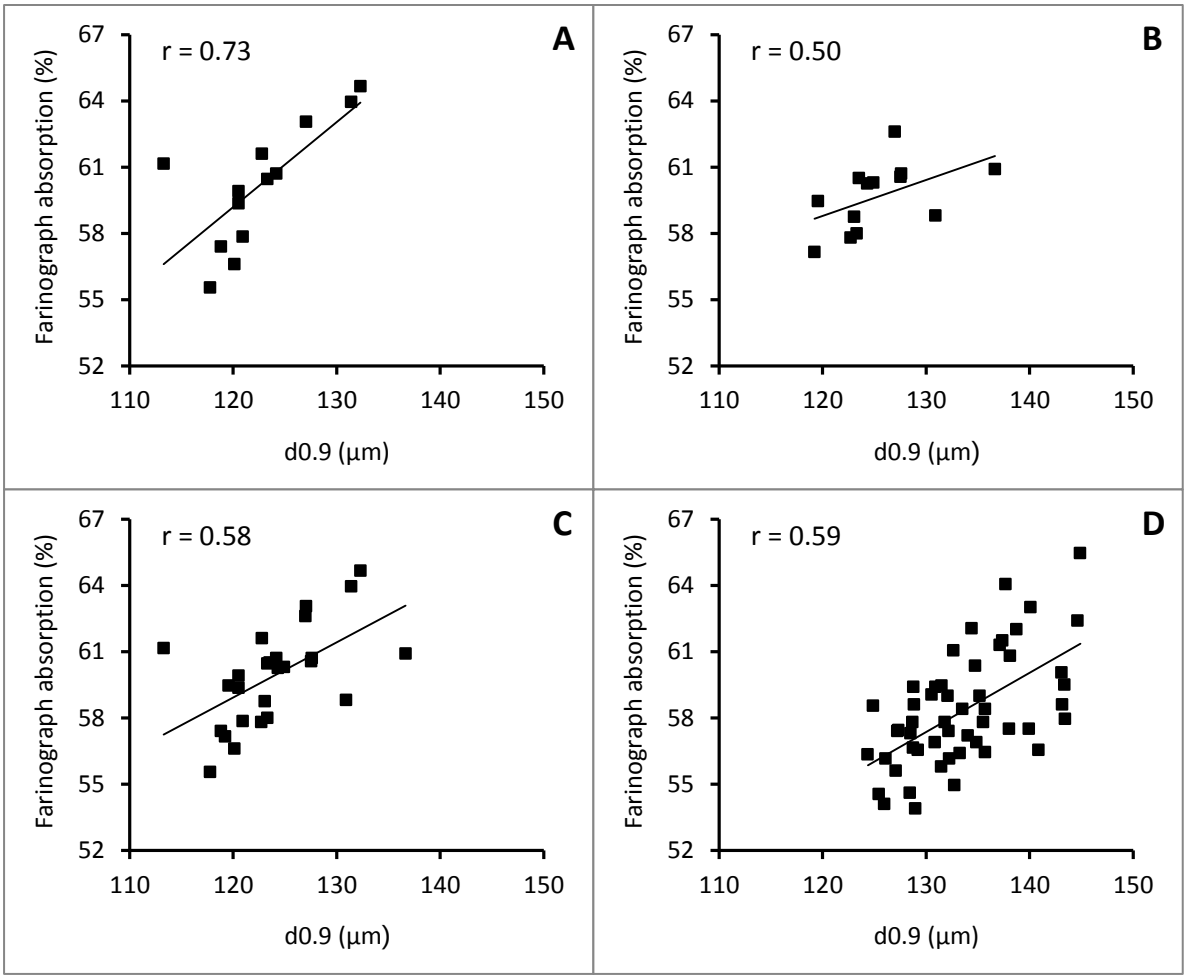


Figure 21. Relationships between farinograph absorption and flour particle size of the 90th percentile of the volume distribution determined by laser diffraction of sample sets 2011S1 (A), 2011S2 (B), 2011All (C) and 2012 (D).

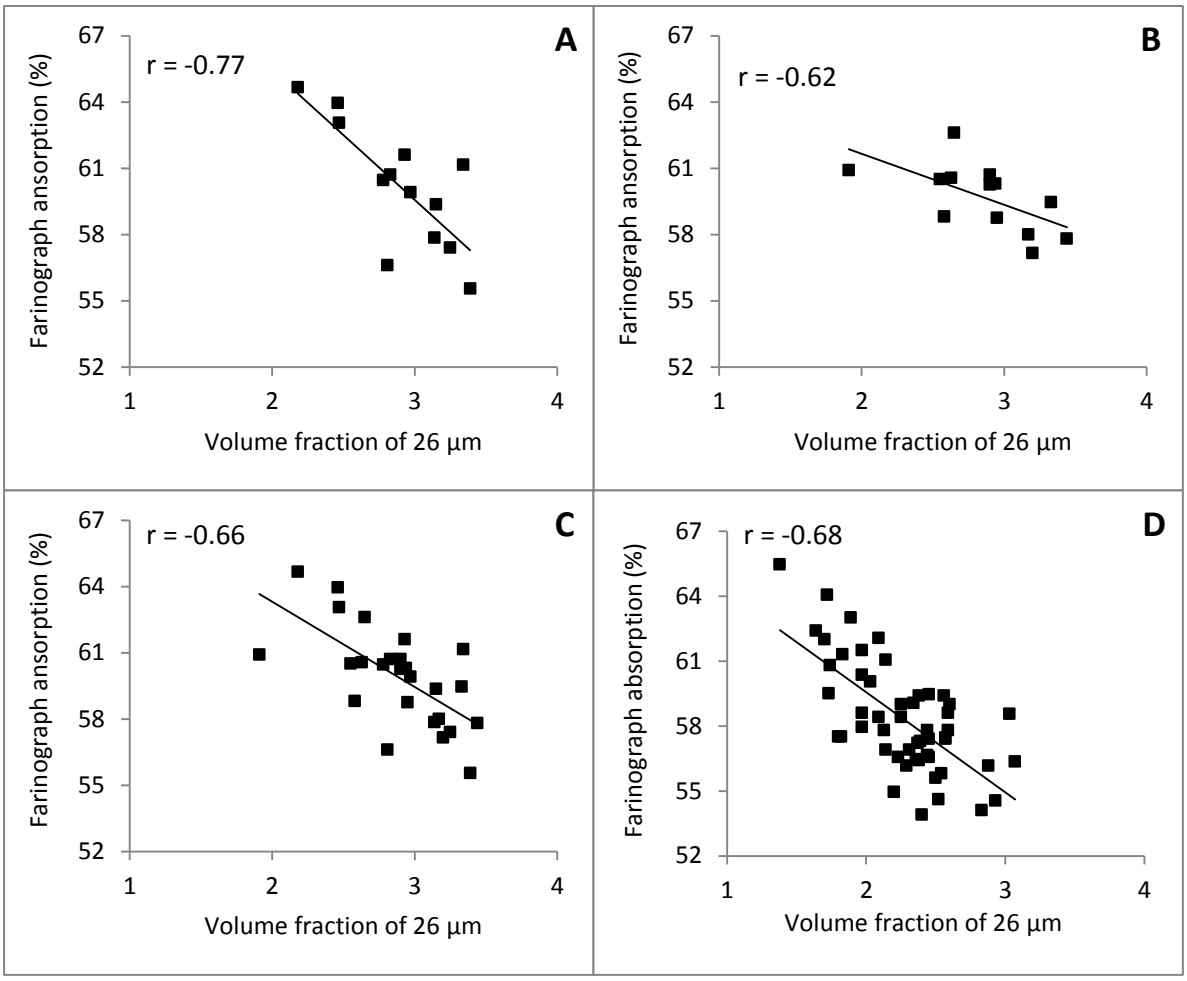


Figure 22. Relationships between farinograph absorption and volume fraction of flour particles of 26 µm of sample sets 2011S1 (A), 2011S2 (B), 2011All (C) and 2012 (D).

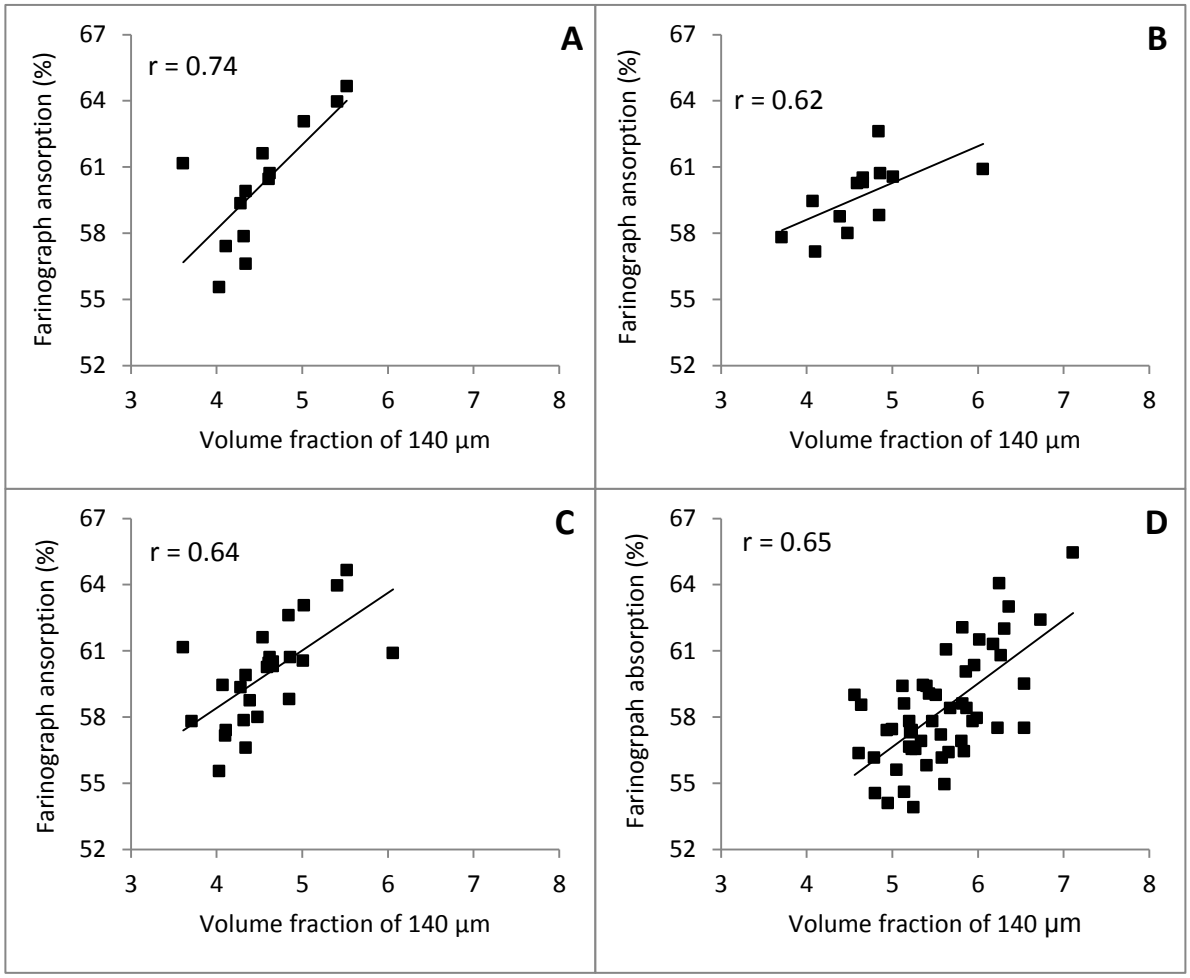


Figure 23. Relationships between farinograph absorption and volume fraction of flour particles of 140 µm of sample sets 2011S1 (A), 2011S2 (B), 2011All (C) and 2012 (D).

The degree of scatter in Figs. 12-23 also underscores the complexity of the nature of FA and how it can be influenced by both genotype and environmental effects. Perhaps the most interesting of these results were those related to pentosans. Figures 15C (sample set 2011All) and 17C (sample set 2011All) for FTP and FWEP parameters, respectively, contain a single outlier sample (W494) with very low pentosan content that was among the highest in FA. When this sample is removed, for purposes of correlation determination, the correlation coefficients for FTP and FWEP for the 2011 samples sets increase accordingly. Still, the low FTP and FWEP contents for sample W494 appear to cast some doubt on the significance of pentosan content as a determinant of FA. However, that significance, especially for FWEP content was affirmed upon multivariate regression analysis (next section) for prediction of FA. In that regard, it should be noted that WTP was completely unrelated to FTP (see correlations in Tables 13 - 16; r = -0.02 to 0.20). Interestingly, however, WWEP and FWEP were relatively highly correlated (r = 0.78 in 2011All and r = 0.73 in 2012 sample sets, Tables 15 and 16), and both these parameters had the highest correlations to FA among all conventional variables (excluding flour particle size by laser diffraction), i.e., r = 0.56 for 2011All and r = 0.44/0.43 for 2012 sample sets (Tables 15 and 16). The high correlation between water-soluble pentosan content in wheat (WWEP) and flour (FWEP) likely comes about because WWEP is measuring the soluble pentosans in the endosperm fraction of the whole wheat meal which is essentially the same as measuring soluble pentosans in straight grade flour. Wheat bran has been previously shown to contain very little content of water-extractable pentosans (Wang et al 2006).

Given the relevance of wheat hardness (via starch damage) and protein content as factors traditionally related to FA, this raises the question whether FA can be reliably

predicted from analytical data obtained from whole wheat, which would avoid the need for milling to flour. The answer to this question appears to be a qualified "yes" based on a multivariate model (to be presented later) that includes WWEP as well as PSI and WP. Results in Tables 15 and 16 do indicate that PSI (whole wheat based) and WP were, in addition to WWEP, among the highest correlated parameters to FA. As well, correlations among these three whole wheat parameters were very low (Tables 15 and 16), which is a requirement for robust multivariate analysis estimation of a dependent variable.

4.2.4 Multivariate Regression to Predict Farinograph Absorption

Figures 9 and 10 and Tables 13-16 indicate that FA is associated with individual wheat and flour compositional factors with moderate correlation values at best. A further complication is that several wheat and flour parameters co-vary (Tables 13-16), and this makes it difficult to determine, from simple correlations, the best or key independent factors related to FA. Accordingly, stepwise multivariate regression was applied to the various sample sets to determine the optimal combinations of parameters with minimal co-variation for prediction of FA. The analysis was performed in two phases, without and with the inclusion of flour particle size related parameters. For the former case, Table 17 presents the best 1-, 2-, 3- and 4-variable models for FA prediction (without flour particle size variables), with the relevant linear equations shown in Table 18. Tables 19 and 20 present the corresponding results for the same analysis that included flour particle size variables by laser diffraction.

By way of explanation, in Table 17 for the 2011All sample set, the best 2-variable combination of FP and FWEP explained ~ 58% (i.e. $R^2 = 0.575$) of the variation in FA. The next best 2-variable combination, WP (which is highly correlated to FP) and FWEP produced

a slightly lower R^2=0.571. By comparison, for the 2012 sample set, the best 2-variable model, WP and FWEP explained only 41% of the variation in FA. That the 2012 sample set contained 30 more different CWRW genotypes compared to the 2011 sample set (26 genotypes), at least in part explains the difference in FA prediction across sample sets using essentially the same 2-variable regression model. This result indicates that FA cannot be reliably predicted across wheat samples sets grown in different years containing different genotypes, based, essentially, on only protein and pentosan contents. However, when only the common 18 genotypes in the two sample sets are included in this type of analysis, much higher R^2 = 0.83 and 0.78 for FA prediction, were obtained for the best 2-variable model of WP and FWEP.

Tables 17 and 18 also illustrate a characteristic feature of stepwise multivariate regression, i.e., R^2 values increase with increasing number of independent variables, so long as variables entered into the model significantly complement variation in the independent variables already entered. For example, in Table 17, the progression of R^2 values for the best 1-, 2-, 3- and 4-variable models for the 2011All and 2012 samples sets were 0.32➞0.58➞0.74➞ 0.82, and 0.21➞ 0.41➞0.58➞0.66, respectively.

When flour particle size variables were included for FA prediction by stepwise multivariate regression, considerably higher R^2 values were obtained (Tables 19-20). For the 2011All and 2012 sample sets, the progression of R^2 values for the best 1-, 2-, 3- and 4-variable models was 0.43➞0.69➞0.82➞ 0.86, and 0.46➞ 0.61➞0.72➞0.74, respectively. The high levels of R^2 for FA prediction (e.g., for 3-variable models), averaging 0.76 across the two sample sets (2011All and 2012), and the commonality of variables selected, i.e., protein and (water-extractable) pentosan contents and either the “26 μm” and “140 μm”

particle size variables (which are essentially interchangeable as they are highly correlated inversely), indicates considerable progress in achieving a successful, practical and robust model for FA prediction. However, it is probably a fair observation that such a model will require for its development more site-years of data and more genotypes. Partly in that regard, Fig. 24 presents observed and predicted FA for a 4-variable linear regression model based on the data for all samples considered in this thesis research (i.e. 2011All + 2012). That model comprised WWEP, FP, DS and 140 μm, with all variables being highly significant. The result was promising with respect to the high $R^2 = 0.64$ attained for FA prediction, and the high prediction R^2 for the individual sample sets. The relevant equation for Fig. 24 provides some insight as to the relative influence of the factors on FA. Using average values for the independent variables (WWEP = 0.27%, FP = 12.36%, DS = 4.62% and 140 μm = 5.25%) across both sample sets 2011All and 2012, and ignoring the contribution of the constant or intercept value (18.5) towards FA, these four variables were ranked as follows in their contributing influence on FA: FP (30.4%) > DS (19.9%) > WWEP (8.95%) > 140 μm (8.91%).

Table 17. Summary of most promising variables (absent flour particle size) for predicting farinograph absorption by stepwise multivariate regression.*

Variables in model	R-Square	2011S1 Variables in Model	Variables in model	R-Square	2011S2 Variables in Model
1	**0.434**	**WWEP**	**1**	**0.228**	**DS**
1	0.388	PSI	1	0.225	FY
1	0.374	FWEP	1	0.213	TKW
2	**0.859**	**PSI FP**	**2**	**0.612**	**WWEP FY**
2	0.796	FP DS	2	0.543	FY FWEP
2	0.765	PSI WP	2	0.473	FY DS
3	**0.909**	**FP DS FWEP**	**3**	**0.757**	**WP WWEP FY**
3	0.903	PSI FP FTP	3	0.754	WWEP FY FAsh
3	0.888	PSI FP DS	3	0.693	WWEP FY FP
4	**0.946**	**PSI FY FP FTP**	**4**	**0.860**	**WTP WWEP FY FAsh**
4	0.940	PSI WWEP FP FTP	4	0.846	WP WWEP FY DS
4	0.927	PSI FP DS FWEP	4	0.836	WTP FY FAsh FWEP
Variables in model	R-Square	2011All Variables in Model	Variables in model	R-Square	2012 Variables in Model
1	**0.316**	**FWEP**	**1**	**0.205**	**WP**
1	0.302	WWEP	1	0.195	WWEP
1	0.209	WP	1	0.192	FWEP
2	**0.575**	**FP FWEP**	**2**	**0.408**	**WP FWEP**
2	0.571	WP FWEP	2	0.391	PSI WP
2	0.544	WP DS	2	0.390	PSI FP
3	**0.736**	**WP DS FWEP**	**3**	**0.584**	**TW WP WWEP**
3	0.729	FP DS FWEP	3	0.573	TW WP FWEP
3	0.696	WWEP FP DS	3	0.563	PSI WWEP FP
4	**0.820**	**WP FY DS FWEP**	**4**	**0.663**	**TW PSI WWEP FP**
4	0.819	FY FP DS FWEP	4	0.661	TW PSI WP WWEP
4	0.812	FAsh FP DS FWEP	4	0.630	PSI TKW FP FWEP
Variables in model	R-Square	2011Common Variables in Model	Variables in model	R-Square	2012Common Variables in Model
1	**0.519**	**WP**	**1**	**0.683**	**WP**
1	0.426	FP	1	0.640	FP
1	0.311	WWEP	1	0.268	TKW
2	**0.832**	**WP FWEP**	**2**	**0.775**	**WP FWEP**
2	0.815	FP FWEP	2	0.766	FP FWEP
2	0.725	WP FTP	2	0.764	WP FTP
3	**0.883**	**TW WP FWEP**	**3**	**0.835**	**TKW FP FWEP**
3	0.878	WP DS FWEP	3	0.828	PSI FP FWEP
3	0.872	FP DS FWEP	3	0.816	TW FP FWEP
4	**0.933**	**FAsh FP DS FWEP**	**4**	**0.890**	**TKW FAsh FP FWEP**
4	0.928	TW WP DS FWEP	4	0.884	PSI TKW FP FWEP
4	0.921	TW FP DS FWEP	4	0.872	TKW FAsh FP FTP

* Rows in boldface are the best 1-, 2-, 3- and 4-variable combinations for predicting farinograph absorption. Abbreviations: TW = test weight; PSI = particle size index; TKW = thousand kernel weight; WP = wheat protein; WTP = wheat total pentosan; WWEP = wheat water-extractable pentosan; FY = flour yield; FAsh = flour ash; FP = flour protein; DS =damaged starch; FTP = flour total pentosan; FWEP = flour water-extractable pentosan

Table 18. Summary of most promising equations (absent flour particle size) for predicting farinograph absorption by stepwise multivariate regression.

Sample set	#	Const	WWEP	PSI	TW	FP	TKW	WP	WTP	FTP	DS	FWEP	FY	FAsh	R^2
2011S1	1	52.5	21.8*												0.434
	2	74.9		-0.77***		2.63***									0.859
	3	6,22				2.58***					3.76**	15.1**			0.909
	4	-3.64		-0.73***		2.43***				5.76**			0.92*		0.946
2011S2	1	47.8									2.36				0.228
	2		29.5*										0.91**		0.612
	3	-38.6	40.8**					1.25*					0.94***		0.757
	4	-66.4	35.2***						-1.89*				1.46***	25.9**	0.860
2011All	1	53.0										21.6**			0.316
	2	32.4				1.62***						25.0***			0.575
	3	16.9						1.95***			2.72**	17.9***			0.736
	4	-19.6						1.65***			2.93***	21.2***	0.50**		0.820
2012	1	35.3						1.76***							0.205
	2	27.3						1.81***				24.2***			0.408
	3	-14.6	24.9***		0.50***			1.96***							0.584
	4	20.5	24.3***	-0.39***	0.37***	1.82***									0.663
2011 Common	1	37.0						1.92***							0.519
	2	28.6						2.04***				21.1***			0.832
	3	13.5			0.23*			1.82***				19.4***			0.883
	4	20.8				2.52***					2.04***	19.6***		-7.94**	0.933
2012 Common	1	10.9						3.67***							0.683
	2	7.67						3.66***				15.3*			0.775
	3	13.0				2.69***	0.21*					18.0**			0.835
	4	-1.02				3.20***	0.26**					14.7**		15.7*	0.890

Signficance at $p < 0.05$, 0.01 and 0.001 levels indicated by one, two and three asterisks, respectively. Refer to Table 18 for explanation of abbreviations.

Table 19. Summary of most promising variables (with flour particle size) for predicting farinograph absorption by stepwise multivariate regression.*

Variables in model	R-Square	2011S1 Variables in Model	Variables in model	R-Square	2011S2 Variables in Model
1	**0.588**	**26 µm**	**1**	**0.387**	**140 µm**
1	0.581	d0.5	1	0.379	26 µm
1	0.541	140 µm	1	0.376	d0.5
2	**0.859**	**PSI FP**	**2**	**0.612**	**WWEP FY**
2	0.825	WWEP 26 µm	2	0.591	FTP 26 µm
2	0.816	WWEP d0.5	2	0.588	FWEP 26 µm
3	**0.909**	**FP DS FWEP**	**3**	**0.757**	**WP WWEP FY**
3	0.903	PSI FP FTP	3	0.754	WWEP FY FAsh
3	0.903	FP FWEP d0.5	3	0.723	WP FWEP 140 µm
4	**0.962**	**PSI FP FTP d0.5**	**4**	**0.869**	**FY FAsh FWEP 26 µm**
4	0.961	PSI FP FTP 26 µm	4	0.860	WTP WWEP FY FAsh
4	0.956	PSI FP FTP 140 µm	4	0.855	FY FAsh FWEP d0.9
Variables in model	R-Square	2011All Variables in Model	Variables in model	R-Square	2012 Variables in Model
1	**0.433**	**26 µm**	**1**	**0.461**	**26 µm**
1	0.408	140 µm	1	0.450	d0.1
1	0.386	d0.5	1	0.426	d0.5
2	**0.692**	**WWEP d0.5**	**2**	**0.610**	**WWEP 26 µm**
2	0.684	WWEP 26 µm	2	0.605	FWEP 26 µm
2	0.662	FWEP 26 µm	2	0.586	WP 140 µm
3	**0.824**	**WP FWEP 26 µm**	**3**	**0.724**	**FP FWEP 140 µm**
3	0.822	WP FWEP d0.5	3	0.716	WWEP FP 140 µm
3	0.819	WP FWEP 140 µm	3	0.713	WP FWEP 140 µm
4	**0.862**	**WP DS FWEP 26 µm**	**4**	**0.743**	**WWEP FP FWEP 140 µm**
4	0.850	TW WP FWEP 140 µm	4	0.737	FY FP FWEP 140 µm
4	0.846	TW WP FWEP 26 µm	4	0.732	PSI WWEP FP 140 µm
Variables in model	R-Square	2011Common Variables in Model	Variables in model	R-Square	2012Common Variables in Model
1	**0.519**	**WP**	**1**	**0.683**	**WP**
1	0.426	FP	1	0.640	FP
1	0.322	26 µm	1	0.573	26 µm
2	**0.832**	**WP FWEP**	**2**	**0.825**	**WP 140 µm**
2	0.815	FP FWEP	2	0.824	FP 140 µm
2	0.725	WP FTP	2	0.816	WP d0.5
3	**0.947**	**WP FWEP d0.9**	**3**	**0.888**	**FP FWEP 140 µm**
3	0.947	WP FWEP 140 µm	3	0.881	FP FWEP d0.5
3	0.946	WP FWEP d0.5	3	0.874	WP FY 140 µm
4	**0.959**	**WP FWEP d0.1 d0.5**	**4**	**0.916**	**WP FY d0.1 d0.5**
4	0.956	WP FWEP d0.1 d0.9	4	0.913	FP FWEP d0.1 140 µm
4	0.953	PSI WP FWEP d0.9	4	0.910	FP FWEP d0.1 d0.5

* Rows in boldface are the best 1-, 2- 3- and 4-variable combinations for predicting farinograph absorption.
Abbreviations: TW = test weight; PSI = particle size index; WP = wheat protein;
WWEP = wheat water-extractable pentosan; FY = flour yield; FAsh = flour ash; FP = flour protein; DS = damaged starch; FTP = flour total pentosan; FWEP = flour water-extractable pentosan; d0.1 and d0.5 = the flour particle size of the 10^{th} and 50^{th} percentile of the volume distribution determined by laser diffraction. The parameters 26 µm and 140 µm are the two flour particle size variables with the highest correlations to FA across all sample sets.

Table 20. Summary of most promising equations (with flour particle size) for predicting farinograph absorption by stepwise multivariate regression.

Sample set	#	Const	26 µm	140 µm	PSI	FP	WP	FTP	d0.1	d0.5	d0.9	DS	FWEP	WWEP	FY	FAsh	R^2
2011S1	1	77.2	-5.86**														0.588
	2	74.9			-0.77***	2.63***											0.859
	3	6.22				2.58***						3.76**	15.1**				0.909
	4	41.4			-0.44***	2.24***		3.61**		0.23**							0.962
2011S2	1	52.0		1.67*													0.387
	2	-17.3												29.5*	0.91**		0.612
	3	-38.6					1.25*							40.8**	0.94**		0.757
	4	-9.59	-1.88**										20.9**		0.75**	21.0*	0.869
2011All	1	71.0	-3.86***														0.433
	2	35.6								0.33***				17.0***			0.692
	3	46.4	-3.03				1.28***						20.3***				0.824
	4	34.9	-2.41***				1.54***					1.47*	18.0***				0.862
2012	1	68.8	-4.63***														0.461
	2	63.2	-4.41***											20.2***			0.610
	3	17.0		2.63***		1.62***							20.9***				0.724
	4	17.4		2.62***		1.58***							12.9*	10.5			0.743
2011 Common	1	37.0					1.92***										0.519
	2	28.6					2.04***						21.1***				0.832
	3	14.3					1.87***				0.14***		18.8***				0.947
	4	20.5					1.77***		-0.21	0.26***			19.1***				0.959
2012 Common	1	10.9					3.67***										0.683
	2	6.53		2.24**			3.02***										0.825
	3	10.1		2.10***		2.63***							13.2*				0.888
	4	34.6					3.36***		-0.98*	0.94***					-0.84**		0.916

Signficance at $p < 0.05$, 0.01 and 0.001 levels indicated by one, two and three asterisks, respectively. Refer to Table 20 for explanation of abbreviations.

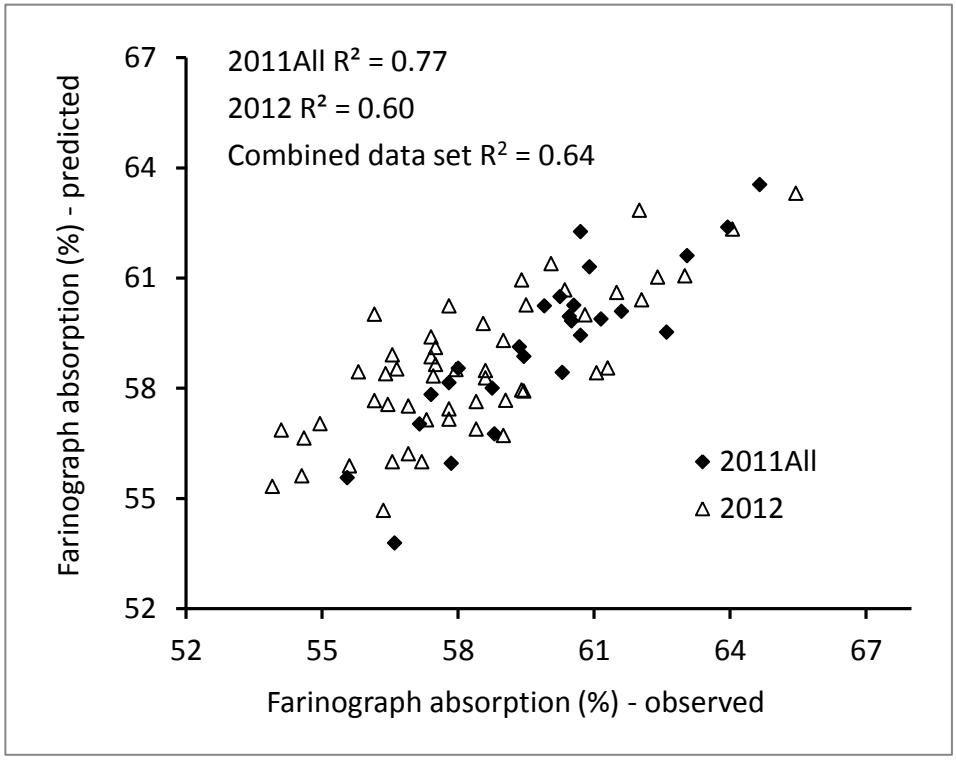


Figure 24. Observed and predicted farinograph absorptions (FA) for combined 2011All and 2012 sample sets. Result is based on a 4-variable linear regression model comprising wheat water extractable pentosan (WWEP) content ($p < 0.0001$) , flour protein (FP) ($p < 0.001$) , damaged starch (DS) content ($p < 0.0001$), and the volume fraction of particles of size 140 μm (140 μm) ($p < 0.001$). The following equation was used:

FA% = 18.50+19.51*WWEP+1.45*FP+2.54*DS+1.00*140μm.

4.3 Analysis of Commercial CWRW and CWRS Wheat Samples

The final set of experiments that were pursued in this thesis research involved a comparison of wheat and flour from a set of 16 commercial CWRS and CWRW wheats. One objective was to identify physical and chemical factors that could differentiate CWRW and CWRS flours with respect to FA variation, and compare results to factors related to FA for the CWRW wheat samples. Another objective was to seek a fundamental understanding of why certain flour particle size parameters, e.g., the proportion or volume fraction of large flour particles (e.g., the "140 μm" variable) was so strongly and positively associated with FA. As noted previously, the commercial wheat samples were milled and the straight grade flours were sieved into eight particle size fractions, using a Ro-Tap test sieve shaker and a stack of seven sieves with openings ranging from about 20 – 200 μm.

Wheat and flour properties of the eight CWRW and eight CWRS commercial wheat are presented in Table 21. Not surprisingly, CWRS wheat was significantly harder on average compared to CWRW, as reflected by significantly higher values for PSI, DS and the percentile volume fraction values (d0.1, d0.5 and d0.9) obtained by laser diffraction analysis. Higher values for CWRS flour for the latter parameters basically reflect coarser granularity for the CWRS flours compared to CWRW flours. Also, CWRS wheats had larger kernels (36.1 vs. 29.8 mg), marginally (but significantly) higher wheat and flour protein contents, but were similar in wheat and flour ash, and wheat total and water soluble pentosan contents. Compared to CWRW flour, CWRS flour was significantly higher in FTP and FWEP by a small amount. Not surprisingly, CWRS wheat flours had much higher FA (average FA = 64.6%) compared to CWRW (average FA = 55.4%).

Table 21. Wheat and flour properties of 2013 commercial CWRW and CWRS wheat samples.

	Variable	CWRW Crop		CWRS Crop	
		Range	Average	Range	Average
Wheat	PSI	56.5-59.1	57.6 ± 0.8 [a]	49.4-52.6	50.4 ± 1.1 [b]
	TKW	26.9-34.9	29.8 ± 2.4 [a]	35.4-37.0	36.1 ± 0.6 [b]
	WAsh (%)	1.37-1.56	1.49 ± 0.06 [a]	1.46-1.60	1.52 ± 0.05 [a]
	WP (%)	12.3-13.0	12.7 ± 0.3 [a]	12.4-13.9	13.3 ± 0.5 [b]
	WTP (%)	4.01-5.48	4.72 ± 0.56 [a]	4.15-5.09	4.62 ± 0.26 [a]
	WWEP (%)	0.24-0.42	0.34 ± 0.06 [a]	0.25-0.38	0.30 ± 0.05 [a]
Flour	FY (%)	73.0-77.4	74.4 ± 1.4 [a]	75.1-76.1	75.5 ± 0.4 [b]
	FAsh (%)	0.45-0.49	0.47 ± 0.02 [a]	0.46-0.48	0.47 ± 0.01 [a]
	FP (%)	11.3-12.3	11.9 ± 0.3 [a]	11.5-13.0	12.5 ± 0.50 [b]
	FTP (%)	1.30-1.46	1.40 ± 0.05 [a]	1.32-1.57	1.48 ± 0.09 [b]
	FWEP (%)	0.26-0.35	0.31 ± 0.03 [a]	0.27-0.47	0.34 ± 0.05 [b]
	DS (%)	4.13-4.66	4.35 ± 0.20 [a]	4.88-5.34	5.14 ± 0.18 [b]
	FA (%)	54.3-57.4	55.4 ± 0.9 [a]	63.1-67.0	64.6 ± 1.30 [b]
	d0.1	14.5-19.6	15.6 ± 1.7 [a]	22.7-27.5	24.8 ± 1.8 [b]
	d0.5	59.1-69.8	62.3 ± 3.4 [a]	77.7-80.4	79.1 ± 0.8 [b]
	d0.9	125.5-138.5	129.7 ± 3.9 [a]	147.2-150.5	148.9 ± 1.3 [b]

Values in rows followed by the same superscripts are not significantly different ($p < 0.05$)
FA = farinograph absorption; TW = test weight; PSI = particle size index; TKW = thousand kernel weight; WP = wheat protein; WTP = wheat total pentosan; WWEP = wheat water-extractable pentosan; FY = flour yield; FAsh = flour ash; FP = flour protein; DS =damaged starch; FTP = flour total pentosan; FWEP = flour water-extractable pentosan; d0.1, d0.5 and d0.9 = the flour particle size of the 10^{th}, 50^{th} and 90^{th} percentile of the volume distribution determined by laser diffraction; CWRW = Canada western red winter; CWRS = Canada western red spring.

With respect to the flour granularity difference between the CWRW and CWRS wheats, particle size distribution curves (by laser diffraction analysis) for CWRW and CWRS flours (Fig. 25) clearly reveal that difference; CWRS flours contained a considerably lower volume fraction or proportion of small particles (especially within the range 10 – 50 μm) and a higher volume of large particles. This result is similar to the comparison of flour particle

size for the lower and upper 15% of CWRW sample's classified by PSI (Fig. 6), except that the degree of difference between CWRW and CWRS flours (Fig. 25) was much greater.

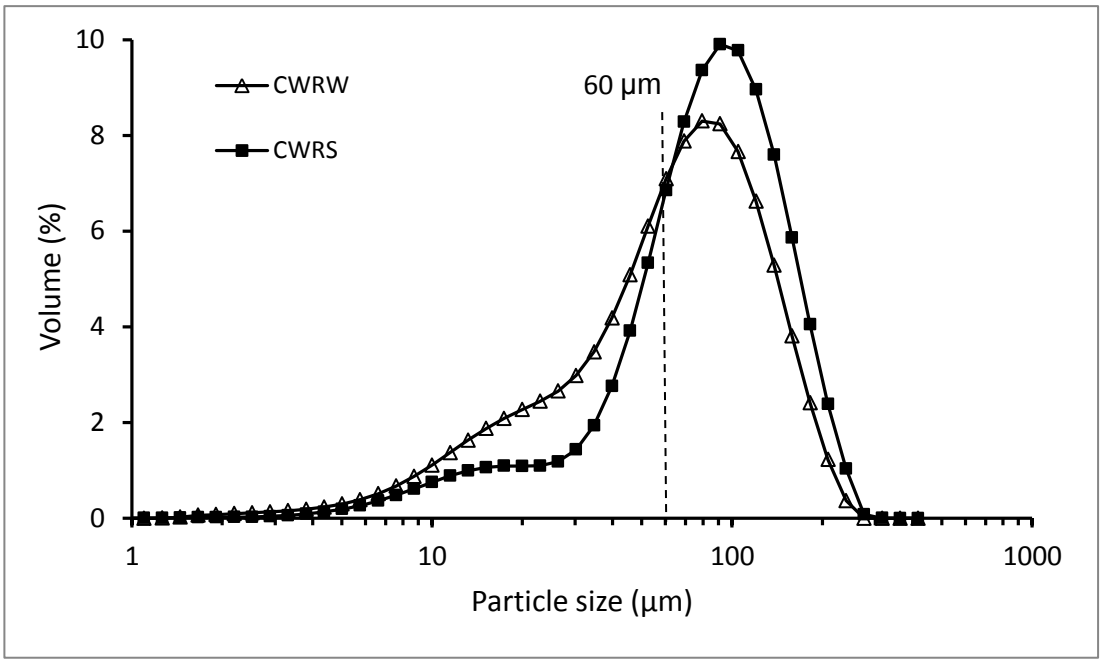


Figure 25. Average flour particle size distributions by laser diffraction of eight commercial Canada Western Red Winter (CWRW) wheats and eight Canada Western Red Spring (CWRS) wheats. The curves cross at about 60 µm.

Mechanical sieving of the straight grade flours also produced a result (Fig. 26) analogous to that generated by laser diffraction analysis of the straight grade flours (Fig. 25). For example, CWRS flours generated higher yields of larger particles (74-105 µm and 105-125 µm) and lower yields of smaller particles (37-53 µm and 53-74 µm). Flour fraction yield values used to generate Fig. 26 are presented in Table 22.

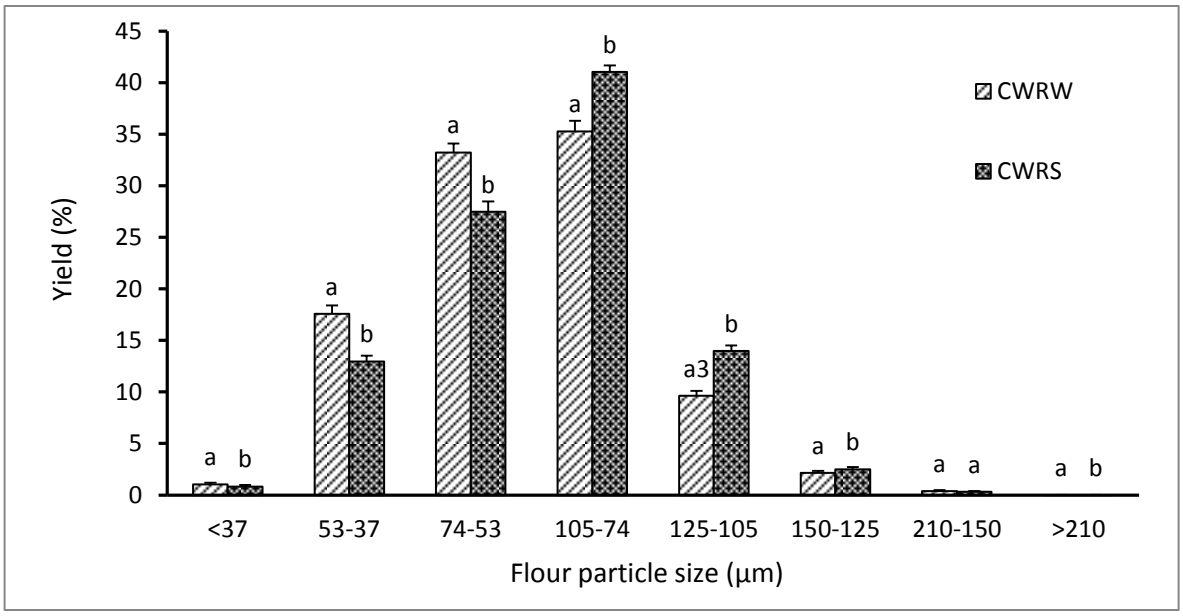


Figure 26. Flour yields of mechanically sieved straight grade flours of eight commercial Canada Western Red Winter (CWRW) wheats and eight Canada Western Red Spring (CWRS) wheats.

Table 23. Yields of sieved flour fractions of Commercial CWRW and CWRS wheats.

Sieve (µm)	CWRW	CWRS
<37	1.0 ± 0.2	0.8 ± 0.0
53-37	17.6 ± 0.8	13.0 ± 0.5
74-53	33.2 ± 0.9	27.5 ± 1.0
105-74	35.3 ± 1.0	41.0 ± 0.6
125-105	9.6 ± 0.5	14.0 ± 0.5
150-125	2.2 ± 0.2	2.5 ± 0.2
210-150	0.4 ± 0.1	0.3 ± 0.1
>210	0.01 ± 0.01	0.01 ± 0.01

Chemical analysis of the sieved flour fractions (DS, FP, FTP and FWEP) of the CWRW and CWRW wheats are shown in Table 23. Regardless of wheat type, with increasing flour particle size, the concentration of DS decreased, whereas concentrations of FP, FTP and FWEP increased. Comparing mean results for the different wheat classes, CWRS wheat flours compared to CWRW counterparts for all size fractions, had significantly

higher DS. For FP, CWRS flours had higher FP for flour particle size fractions below 105 μm, and lower FTP contents above 105 μm. CWRS flours had slightly higher FWEP contents across all flour size fractions.

Table 24. DS, FP, FTP and FWEP concentration of sieved flour fractions of CWRW and CWRS wheats.

	DS (%)		FP (%)	
Sieve (μm)	CWRW	CWRS	CWRW	CWRS
<37	6.3 ± 0.26 [a]	7.7 ± 0.23 [b]	7.1 ± 0.32 [a]	7.7 ± 0.25 [b]
53-37	5.9 ± 0.23 [a]	7.2 ± 0.18 [b]	8.9 ± 0.33 [a]	10.4 ± 0.35 [b]
74-53	4.5 ± 0.18 [a]	5.2 ± 0.19 [b]	10.5 ± 0.46 [a]	11.6 ± 0.32 [b]
105-74	3.4 ± 0.14 [a]	4.3 ± 0.21 [b]	10.0 ± 0.47 [a]	10.4 ± 0.29 [b]
125-105	2.8 ± 0.16 [a]	3.8 ± 0.30 [b]	10.4 ± 0.52 [a]	10.3 ± 0.29 [a]
150-125	2.5 ± 0.16 [a]	3.3 ± 0.33 [b]	11.0 ± 0.35 [a]	11.1 ± 0.47 [a]
210-150	N/A	N/A		
	FTP (%)		FWEP (%)	
Sieve (μm)	CWRW	CWRS	CWRW	CWRS
<37	0.73 ± 0.09 [a]	0.92 ± 0.08 [b]	0.24 ± 0.00 [a]	0.26 ± 0.02 [b]
53-37	0.98 ± 0.04 [a]	1.23 ± 0.08 [b]	0.25 ± 0.00 [a]	0.29 ± 0.03 [b]
74-53	1.26 ± 0.03 [a]	1.26 ± 0.05 [a]	0.31 ± 0.01 [a]	0.32 ± 0.02 [a]
105-74	1.52 ± 0.10 [a]	1.49 ± 0.09 [b]	0.32 ± 0.02 [a]	0.34 ± 0.02 [b]
125-105	1.79 ± 0.12 [a]	1.72 ± 0.10 [b]	0.34 ± 0.00 [a]	0.37 ± 0.03 [b]
150-125	2.49 ± 0.17 [a]	2.25 ± 0.16 [b]	0.34 ± 0.00 [a]	0.35 ± 0.01 [a]
210-150	3.57 ± 0.35 [a]	2.93 ± 0.40 [b]	N/A	N/A

[a-b] row values followed by the same superscripts are not significantly different ($P<0.05$).
DS = damaged starch; FP = flour protein; FTP = flour total pentosan; FWEP = flour water-extractable pentosan; CWRW = Canada Western Red Winter; CWRS = Canada Western Red Spring.

Whereas Table 23 presents concentration data for DS, FP, FTP and FWEP parameters by particle size, these data do not represent the functional contribution of these factors in straight grade flour. To that end, Table 24 reports corresponding values of the amount of each factor weighted by the fraction yield of flour (Table 22) according to the following calculation: factor quantity = concentration x yield% of flour fraction.

Table 25. Yield of DS, FP, FTP and FWEP of sieved flour fractions of CWRW and CWRS wheats.

	DS (%)		FP (%)	
Sieve (μm)	CWRW	CWRS	CWRW	CWRS
<37	0.07 ± 0.01 [a]	0.06 ± 0.01 [a]	0.07 ± 0.01 [a]	0.06 ± 0.01 [a]
53-37	1.04 ± 0.04 [a]	0.93 ± 0.04 [b]	1.56 ± 0.12 [a]	1.35 ± 0.08 [b]
74-53	1.50 ± 0.06 [a]	1.43 ± 0.05 [b]	3.49 ± 0.19 [a]	3.18 ± 0.19 [b]
105-74	1.18 ± 0.06 [a]	1.78 ± 0.09 [b]	3.52 ± 0.13 [a]	4.28 ± 0.11 [b]
125-105	0.27 ± 0.02 [a]	0.53 ± 0.04 [b]	1.01 ± 0.05 [a]	1.44 ± 0.04 [b]
150-125	0.05 ± 0.01 [a]	0.08 ± 0.01 [b]	0.24 ± 0.02 [a]	0.28 ± 0.02 [b]
210-150	N/A	N/A	NA	NA
Total	4.10 ± 0.13	4.82 ± 0.19	9.89 ± 0.39	10.59 ± 0.29
	FTP (%)		FWEP (%)	
Sieve (μm)	CWRW	CWRS	CWRW	CWRS
<37	0.01 ± 0.00 [a]	0.01 ± 0.00 [a]	0.002 ± 0.00 [a]	0.002 ± 0.00 [a]
53-37	0.17 ± 0.01 [a]	0.16 ± 0.01 [b]	0.043 ± 0.00 [a]	0.037 ± 0.00 [b]
74-53	0.42 ± 0.01 [a]	0.35 ± 0.02 [b]	0.102 ± 0.01 [a]	0.088 ± 0.01 [b]
105-74	0.54 ± 0.03 [a]	0.61 ± 0.04 [b]	0.113 ± 0.02 [a]	0.139 ± 0.01 [b]
125-105	0.17 ± 0.01 [a]	0.24 ± 0.01 [b]	0.033 ± 0.00 [a]	0.052 ± 0.00 [b]
150-125	0.05 ± 0.01 [a]	0.06 ± 0.01 [a]	0.007 ± 0.00 [a]	0.009 ± 0.00 [b]
210-150	0.01 ± 0.00 [a]	0.01 ± 0.00 [a]	N/A	N/A
Total	1.38 ± 0.05	1.43 ± 0.05	0.30 ± 0.02	0.33 ± 0.02

Value = actual value * fraction yield. N/A due to limited flour amount.
Refer to Table 22 for abbreviations.

Yield values reported in Table 24 should add up to the values of DS, FP, FTP, and FWEP in straight grade flour (Table 21). This was the case for all except for FP. For DS, FTP and FWEP, total yields of all flour fractions were slightly lower than those for straight grade flour by 6.3%, 2.4% and 3.1%, respectively and could be explained by the absent results for the 210-150 μm fraction for which there was insufficient quantity of flour for analysis. However, the sum of FP for all the flour fractions of CWRW and CWRS samples were 19% lower than those of straight grade flour. The reason for this discrepancy for FP was determined to be inaccurate determination of nitrogen content for these mechanically sieved flour fractions, and the correct values could not be supplied before this thesis document was finalized. Nevertheless, the relative differences in FP among the different

flour fractions and between CWRW and CWRS wheats can be considered to be correct. Those results indicate that large flour particles (> 105 μm) of CWRS wheat flours compared to CWRW counterparts, contained significantly higher content of DS, FP and pentosans (both total and water-soluble), all factors positively associated with FA. The opposite finding was the case for smaller flour particles. This result is novel as it has not been previously reported in the literature. The result explains why stepwise multivariate regression analysis identified the volume fraction (by laser diffraction) of relatively large (and small) flour particles as useful parameters to predict FA for the CWRW wheat sample sets that were studied.

More importantly, the result (Table 24) provides an explanation of the nature of the widely recognized difference in FA between HRW and HRS wheats or, for that matter, wheat samples that differ in kernel hardness. A wheat milling outcome with higher yield of larger flour particles and lower yield of smaller particles, will lead to higher FA, and vice versa, because those larger particles have higher levels of DS, FP and pentosans. The result also suggests that wheat hardness is the key factor underlying these differences in the composition of relatively small and large flour particles. However, as stated previously, FA is a complex trait, as kernel size (TKW) is also positively and negatively correlated with large and small flour particles (Tables 15 and 16) to a greater extent (e.g. for CWRW sample set 2012, correlations between TKW and 26 μm and 140 μm particles were r= -0.55 and r=0.61, respectively) than the relationship between TKW and wheat hardness (Tables 15 and 16, r = 0.27 and r = 0.36, for samples sets 2011All and 2012, respectively).

5 GENERAL DISCUSSION AND CONCLUSIONS

The basic objective of this thesis research was to develop a better understanding of the nature of the variation in FA of the CWRW wheat class by focusing on pentosan content and composition and other plausible factors. With that objective in mind, the goal of this research was to establish a basis to significantly improve FA of CWRW wheats which would go far to improve the marketability of this wheat class and increase revenue for producers. To address this objective and goal, a genotypically diverse set of samples of CWRW wheat cultivars and advanced breeding lines were obtained for the studies that were carried out. These wheats were grown at AAFC-Lethbridge in 2011 (26 genotypes) and 2012 (52 genotypes). 18 of these wheat samples were common to both data sets. In addition, several commercial CWRW and CWRS wheat samples were also included towards the end of the research as a means to explain why certain factors (i.e. flour particle size distribution related) were showing up as being particularly significant to FA variation of the CWRW wheats.

The research first dealt with two methodology related problems or questions. One was to establish the relationship between FA measured by 50 g and 10 g mixers, as it was preferable to use the latter mixer due to anticipated limited supply of wheat and flour for the samples to be studied. A second potential problem for the research arose from a recent publication (Kiszonas et al 2012) that questioned the accuracy of the phloroglucinol colorimetric assay, which was planned to be used in the research to measure pentosan or AX content of wheat. These authors reported that wheat pentosan content was underestimated by as much as 50% with the PCA procedure compared to values obtained by a conventional GLC method which measures alditol acetates of neutral sugars, e.g., arabinose and xylose.

Regarding the determination of FA, results showed that a 10 g mixer was a satisfactory substitute for the traditional 50 g mixer, as FA values were very highly correlated ($r = 0.97$), and both mixers achieved excellent repeatabilities of 0.14% (50 g) and 0.17% (10 g). On an aside, farinograph develop time, stability and mixing tolerance index were all well correlated between the two mixers ($r = 0.83$, 0.95 and 0.82, respectively). Some observations about using the 10 g mixer are worth noting. FA curves obtained from the 10 g mixer were less smooth than those obtained with the 50 g mixer, and this may have arisen due to the higher sensitivity of the 10 g mixer. Also, for the 50 g mixer, a self-zeroing 50 mL burette was used and the amount of water added into the mixing bowl is read at about 1min after initial water is released, to ensure that water on the inner wall of burette settles properly, thus reducing any error. In contrast, the 10 g mixer uses a 10 mL burette (read to 0.02 mL), which had a much smaller internal diameter than that used for 50 g mixer, and it needed to be filled and zeroed manually, so it was less convenient to use. The narrow internal diameter of the 10 mL burette sometimes lead to water flow issues due to some air trapped inside the burette column, resulting in a small difference between the amount of water read off the burette and that added to flour. Clearly, the major advantage of using the 10 g mixer was saving of flour, as typically 30 g was used including duplicates, compared to the 150 g of flour (or more) needed to obtained duplicate FA determinations using the 50 g mixing bowl.

The second and more important methodology matter to be resolved concerned the accuracy of the PCA procedure of Douglas (1981) which was modified for analysis of wheat meal by subjecting samples to prehydrolysis with 0.5 M sulfuric acid as recommended by Bell (1985). The 2011All CWRW sample set (26 samples) was used for these experiments which included determination of pentosan content in both wheat meal and flour. It was found

that the average FTP (flour total pentosan) content of the 26 flour samples determined by the PCA method (1.47%) was slightly higher than that determined by GLC (1.43%) and the ROM (repeatability of measurement) were essentially identical (PCA 0.030%, GLC 0.028%). High correlations between PCA and GLC were found for both flour (r = 0.90) and wheat meal (r = 0.88) pentosan content. FTP ranged from 1.09-1.79% and 1.02-1.77% for the PCA and GLC methods, respectively. These ranges of FTP of the 26 samples overlapped with those determined by Shogren et al (1987) for 79 hard red winter wheat flours (1.27-2.09%), although these workers used a different colorimetric assay procedure (Hashimoto et al 1987) based on the orcinol-hydrochloric acid method of Albaum and Umbreit (1947).

For whole wheat material, WTP (wheat total pentosan) content ranged from 4.08–5.42% and 4.27-5.57% for the PCA and GLC methods, respectively. The average WTP determined by PCA was relatively lower by ~ 5% compared to average WTP by GLC, which may be due to loss of colored products or incomplete release of pentosan sugar constituents. The ROM for the PCA (0.076%) was considerably better than that for AX determination by GLC (0.214%) which was likely due to the much more complex procedures leading to, and including, preparation of alditol acetate derivatives from NSP isolated from wheat meal after extensive enzymatic hydrolysis of starch. Results supported the accuracy and precision of the PCA method in determining WTP content using the Bell (1985) prehydrolysis modification, without which the average WTP content was underestimated by 17% and resulted in relatively poor agreement with AX results determined by GLC (r = 0.34) compared with those obtained with prehydrolysis (r = 0.75, Fig.4, Table 9). Also, this range of wheat meal pentosan contents were higher than those reported by Kiszonas et al (2012) and related publications from the same laboratory (Finnie et al 2006, Li et al 2009). Kiszonas et al (2012)

commented that “in preliminary studies, inclusion of the pre-hydrolysis step produced dramatically lower total AX levels”, which is contrary to results obtained in this thesis research. As well, Kiszonas et al (2012) refer to the “highly heterogeneous and particulate nature of ground whole wheat meals, which must be sampled from aqueous suspension. The samples were vigorously vortexed, and an aliquot was withdrawn as quickly as possible, always at the same height within the tube.” Evidently, the authors discarded the use of pre-hydrolysis with sulfuric acid in their basic procedure and commented that the error of total AX measurement was “a notable weakness” of the method. Indeed, if they followed the Douglas (1981) procedure without (dry) sample pre-hydrolysis, 5 mg of whole wheat meal samples would definitely create issues of error in AX determination. Incorporation of a pre-hydrolysis step removes this issue as the digest is centrifuged, and an aliquot from a homogeneous supernatant is used in the remaining steps of the (Douglas 1981) procedure. This view is supported by the highly repeatable results obtained in the current study as evidenced by the CV for pentosan contents of wheat meal which was <1.5% for the sample set. Furthermore, the present research (section 4.1.2) showed that inclusion of glucose in the phloroglucinol reagent solution was necessary so as not to further underestimate pentosan content. This finding was also contrary to that reported by Kiszonas et al (2012), who questioned the use of glucose in the method. However, as discussed previously, Kiszonas et al (2012) did not apply the Douglas (1981) procedure as published.

The balance of the experimental work of the thesis research was focused on the basic objective which was to evaluate the nature of FA variation in the CWRW wheat via determination of the relative influence of factors found in the literature to be more or less associated with flour water absorption or FA specifically, including kernel size (Morgan et al

2000), wheat hardness and starch damage (traditionally the most important factor per Greer and Stewart 1951, Meredith 1969, Tara et al 1972, Tipples et al 1978, Mok and Dyck 1991, Berton et al 2002), protein content (Greer and Stewart 1959, Meredith 1969, Tipples et al 1978, Preston et al 2001), pentosan content and composition (Bushuk and Hlynka 1964, Jelaca and Hlynka 1971, Tipples et al 1978, Courtin and Delcour 2001, Wang et al 2003, Finlay et al 2007). In addition, flour particle size was evaluated by laser diffraction analysis as another possible factor related to FA. While flour particle size has not been previously investigated in relation to FA, flour granularity, and in particular wheat meal granularity, in relation to wheat hardness or a related property, vitreousness, has been known for a long time (Cutler and Brinson 1935, Worzella and Cutler 1939, Berg 1947, Greer 1950, Symes 1961). Also, Hareland (1994) applied laser diffraction analysis to wheat flours of durum, and hard and soft common wheats, and observed shifts in the particle size distribution consistent with wheat hardness differences. All these papers indicate essentially, that the harder the wheat, the coarser the granularity of the milled product.

Results in this thesis study showed that wheat sample sets used in the research had a considerable range of FA values (~54-65%, for 2011 and 2012 material). More importantly, were the genotypes with relatively high FAs (>62%), i.e., W494, LL611, W511, W486 in sample set 2011All, and LK779, AC Tempest, LL611, LJ624, W494 and W511 in sample set 2012 (Table 12). However, only a few of these (W494, LL611, and W511) were common to both data sets. Accordingly, some germplasm with intrinsically high FA, albeit limited in number, does exist in CWRW wheats.

Results also showed the most highly correlated parameters to FA (excluding flour particle size related) were protein content, wheat hardness indices (PSI and DS), and WWEP

and FWEP. Simple correlations to FA for these factors tended to vary in the range 0.40 to 0.50, with the water-extractable pentosan compositional factors of wheat or flour (WWEP or FWEP) having the highest correlations of r = 0.56 and ~ 0.43 for data sets 2011All and 2012, respectively. Interestingly, flour particle size by laser diffraction had the highest and most consistent correlations to FA with the median volume fraction (variable d0.5), and the volume fraction of large (140 μm, VFL140) and small (26 μm) flour particles producing correlations in the range, r = -0.62 to 0.68 across both data sets. These simple correlation results indicate that FA is a complex property of wheat flour that is moderately influenced by a number of related and unrelated compositional factors, some of which can vary considerably due to growing conditions. The latter was shown by significant differences between the 2011All and 2012 samples sets for hardness related properties (PSI and DS), kernel size, protein content, and WWEP (Tables 10 and 11). In that regard, a very interesting and compelling feature of the flour particle size distribution results (Fig. 11) was the consistency in achieving relatively high correlations across sample sets between FA and the volume fraction of flour particles between 20-30 μm, and above 100 μm.

Because no single wheat or flour property was highly correlated with FA, multivariate regression analysis was pursued to determine whether a satisfactory relationship could be found for FA based on a few relatively uncorrelated variables, a process readily achievable in principle by the technique of stepwise multivariate regression analysis (SMRA). An overview of results for the various sample sets (Tables 17 – 20) revealed that factors such as wheat or flour protein, PSI or DS, WWEP or FWEP, and the volume fraction of flour particles of 26 or 140 μm, when combined in different ways according to computed regression equations, could generate potentially effective models for practical FA prediction.

One of the best such models, incorporating WWEP, FP, DS and VF140 (volume fraction associated with the 140 μm particle size), yielded an $R^2 = 0.64$ based on SMRA of data that combined results for all 78 CWRW genotype samples considered in this thesis research. Whether this or a related model is in fact reliable for FA prediction of other CWRW samples is unknown. However, given that the present research was based on sample sets, albeit diverse genetically, acquired from the same location over two growing seasons, it is probably fair to conclude that a reliable model for predicting FA will require for its development considerably more site years-worth of data.

The final aspect of this thesis research concerned the flour particle size analysis results noted above which appear to be novel, i.e., not previously described in the literature, although the underlying nature of the result, which is probably related to wheat hardness variation of the samples, is well known. However, it is not clear why direct and inverse relationships should exist between FA and the volume fraction of large or small flour particles, respectively. In an attempt to gain some fundamental insight into these relationships, wheat samples that differed widely in hardness (i.e., commercial CWRW and CWRS wheats) were sourced, milled to straight grade flour, and the latter were mechanically sieved to produce a wide range of flour fractions whose composition could be studied. This was done because laser diffraction analysis of flour only provides descriptive information about flour particle size distribution, i.e., no actual fractions are generated. Chemical analysis of the sieved flour fractions showed a clear trend, i.e. increasing flour particle size was associated with a decrease in DS and increase in FP, FTP and FWEP for both CWRW and CWRS flours. This trend for DS and FP appears to be similar to results reported by Scanlon et al (1988), and for DS (Pulkki 1938), except that in both of these studies, source material

comprised a single sample of relatively coarse farina or middlings which was subjected to different degrees of grinding by smooth reduction rolls. Not surprisingly both authors found for example, starch damage to be higher in the finer and more heavily ground farina derived flours.

In the present research, the functional contribution of the various mechanically sieved fractions to the straight grade flour (for 16 samples of CWRW and CWRS wheats) was evaluated in a way not previously reported, i.e. the concentrations of DS, FP, FTP and FWEP of the flour fractions were multiplied by their respective flour yields. Results showed that the coarser flour fractions (> 105 μm) contained significantly higher contents of protein, damaged starch and pentosans, i.e. all factors positively associated with FA, whereas the opposite was the case for relatively fine flour fractions. This result appears to explain why the volume fraction of large or small flour particles was found by SMRA for CWRW wheats to be most strongly associated with FA. The result also points to wheat kernel hardness differences among samples (whether CWRW wheats considered as a stand-alone class or between CWRS and CWRS wheats in general) as the key factor underlying roller milling outcomes wherein relatively large and small flour particles are clearly different in chemical composition.

Results as a whole indicated that CWRW wheats tend to be low in FA due to low levels of wheat hardness, or protein content, or pentosan content, and that increasing these parameters by plant breeding could significantly and practically improve FA of future CWRW cultivars. Results also point to laser diffraction analysis of flour particle size as a new and potentially useful method to screen lines towards that end.

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7 APPENDIX A

Table A.1. Grading results of sample set 2011S1 CWRW wheats.

Lab #	Genotype	Amount rcvd (g)	Grade	Reason for grade	Other Remarks	TW kg/hL	WP (%)	BP	S	FD	Con Cl	Midge	Ergot	Damage (Insect)
1	Radiant	1550	1 CWRW			79.7				0.26				
2	Flourish	1545	1 CWRW			84.0								
3	Tempest	1515	1 CWRW			81.1				0.03				
4	CDC Buteo	1550	1 CWRW			81.4				0.29	0.05			0.12
5	CDC Osprey	1535	1 CWRW			80.1				0.04				
6	LL611	1530	1 CWRW			84.2		7.20	0.27	0.05				
7	LL163	1550	1 CWRW			83.4								
8	LL532	1555	1 CWRW			82.6								
9	LL066	1535	1 CWRW			82.4								
10	W494	1545	1 CWRW		Low MIL	83.2				0.04				
11	W511	1535	1 CWRW			82.2								
12	AC Bellatrix	1550	2 CWRW	0.96% FD		78.7				0.96				
13	LJ1082	1235	2 CWRW	77.7 TW		77.7				0.06				

CWRW = Canada Western Red Winter; TW = test weight; WP = wheat protein; BP = blackpoint; S = smudge; FD = fusarium damage; Con Cl = contrasting classes; MIL = mildew

Table A.2. Grading results of sample set 2011S2 CWRW wheats.

Lab #	Genotype	Amount rcvd (g)	Grade	Reason for grade	Other Remarks	TW kg/hL	WP (%)	BP	S	FD	Con Cl	Midge	Ergot	Damage (Insect)
14	Jerry	730	1 CWRW			80.1				0.11	0.06			0.38
15	Norstar	735	1 CWRW			83.4								
16	Broadview	730	1 CWRW			80.1				0.05				
17	W478	745	1 CWRW			80.3		2.21	0.09	0.03		0.12		
18	W487	735	1 CWRW			83.2								
19	DH00W3IN*34	730	1 CWRW			84.0				0.03			0.002	
20	W486	735	1 CWRW			82.8				0.04				
21	Peregrine	730	1 CWRW			83.6								
22	W485	750	1 CWRW		Low MIL	81.8				0.04				
23	Accipiter	745	2 CWRW	78.3 TW		78.3								
24	CDC Raptor	740	2 CWRW	78.7 TW		78.8							0.001	
25	DH99W18I*45	750	2 CWRW	78.7 TW		78.7				0.03	0.04			
26	W460	725	2 CWRW	78.5 TW		78.5				0.07				
27	CDC Falcon	720	2 CWRW	78.5 TW		78.5								
28	DH99W19H*16	730	3 CWRW	75.5 TWT	Frost	75.5				0.03				
29	CDC Harrier	730	CWF	73.7 TWT		73.7				0.09				
30	W482	735	CWF	73.3 TWT		73.3				0.04				

Refer to Table A.1 for explanations of abbreviations

Table A.3. Grading results of sample set 2012 CWRW wheats.

Lab #	Genotype	Amount rcvd (g)	Grade	Reason for grade	Other Remarks	TW kg/hL	WP (%)	BP	S	FD	Con Cl	Midge	Ergot	Damage (Insect)
1201	Radiant	1500	1 CWRW			82.6	12.1							
1202	CDC Osprey	1503	1 CWRW			82.4l	12.6							
1203	AC Bellatrix	1491	1 CWRW			84.0	12.9				0.008		0.002	
1204	CDC Buteo	1500	1 CWRW			84.6	12.4							
1205	Flourish	1502	1 CWRW			83.6		0.18	0.16	0.02	0.07			
1206	Moats	1500	1 C WRW			83.8	12.7			0.03		0.04	0.003	
1207	Emerson	1497	1 CWRW			83.6	13.0							
1208	AAC Gateway	1496	1 CWRW			85.2	13.4	1.74					0.008	
1209	CDC Falcon	1495	1 CWRW			80.5	12.4							
1210	Broadview	1491	1 CWRW			82.0	12.2							
1211	CDC Harrier	1497	1 CWRW			80.1	12.0			0.02				
1212	CDC Raptor	1495	1 CWRW			83.0	12.0							
1213	Accipiter	1502	1 CWRW			83.6	11.7							
1214	Peregrine	1498	1 CWRW			83.2	11.8							
1215	Pintail (W460)	1496	2 CWRW	78.5TW		78.5	11.8							
1217	DH99W19H*16	1504	1 CWRW		Low MIL	79.1	12.1			0.04				
1218	DH00W3IN*34	1501	1 CWRW			85.5	11.6			0.06				
1219	1603-137-1	1505	1 CWRW			82.2	12.0			0.06				
1220	W495 (LJ 083)	1501	1 CWRW			82.0	12.3		0.10					
1221	W497 (LJ460)	1504	1 CWRW			81.2	13.0			0.05		0.1		
1222	W505 (LJ388)	1496	1 CWRW			86.5	12.4	0.07	0.07					
1223	W506 (LK 088)	1500	1 CWRW			84.2	12.6			0.07				
1224	W507 (LK 221)	1499	1 CWRW			82.2	12.2	0.07				0.08	0.079	
1225	W508 (LK640)	1500	1 CWRW			82.0	13.0							

Table A.3. Grading results of sample set 2012 CWRW wheats (continued).

Lab #	Genotype	Amount rcvd (g)	Grade	Reason for grade	Other Remarks	TW kg/hL	WP (%)	BP	S	FD	Con Cl	Midge	Ergot	Damage (Insect)
1226	W510 (LK976)	1499	1 CWRW			83.8	13.0		0.07	0.06			0.050	
1227	W512(LK1064)	1505	1 CWRW			81.0	12.4			0.08				
1228	AC Tempest	1506	1 CWRW			83.8	14.1	0.20	0.06	0.07			0.001	
1229	LE2411 (W438)	1513	2 CWRW	Light Weight		78.1	14.3			0.06				
1230	LF1318 (W455)	1507	1 CWRW			81.8	13.4					0.21		
1231	LG194 (W472)	1501	1 CWRW			80.1	13.9							
1232	LG237 (W481)	1504	1 CWRW			85.6	12.7						0.002	
1233	LH113 (W484)	1504	1 CWRW			83.8	13.3			0.06		0.17		
1234	LH145	1506	1 CWRW			81.0	12.2			0.15				
1235	LH188 (W486)	1502	1 CWRW			83.2	12.7			0.08				
1236	LH491	1445	1 CWRW			80.5	13.1			0.10		0.13		
1237	LH504Q (W494)	1504	1 CWRW			83.8	13.3			0.06			0.023	
1238	LH564Q (W489)	1502	1 CWRW			83.2	13.1			0.09		0.06	0.001	
1239	LJ1082P	1501	1CWRW			79.3	12.6	0.43				0.24		
1240	LJ1091P	1503	2 CWRW	Midge Low TW		76.7	13.3			0.15		1.1		
1241	LJ165	1501	1 CWRW			84.0	11.6			0.03		0.12		
1242	LJ168	1503	1 CWRW			83.4	12.1			0.03			0.001	
1243	LJ624	1501	1 CWRW			85.6	12.5	0.12						
1244	LJ 901 (W499)	1501	1 CWRW			80.1	13.5			0.15				
1245	LJ902(W500)	1500	1 CWRW			79.7	13.7							
1246	LJ913 (W501)	1497	2 CWRW	LW		78.3	13.5			0.12			0.002	
1247	LK1061(W511)	1502	1 CWRW			82.4	13.3					0.03		
1248	LK1114	1500	1 CWRW			85.6	12.5	0.17						
1249	LK1152Q	1414	1 CWRW			85.0	12.4					0.1		

Table A.3. Grading results of sample set 2012 CWRW wheats (continued).

Lab #	Genotype	Amount rcvd (g)	Grade	Reason for grade	Other Remarks	TW kg/hL	WP (%)	BP	S	FD	Con Cl	Midge	Ergot	Damage (Insect)
1250	LK779	1504	1 CWRW			83.4	14.2			0.04				
1251	LK980	1501	1 CWRW			79.7	12.3							
1252	LL611	1500	2 CWRW	0.67% SM		84.8l	12.7	4.82	0.47					
1253	LM814Q	1502	1 CWRW			82.8	13.3							

Refer to Table A.1 for explanations of abbreviations

Table A.4. Grading results of commercial CWRW and CWRS wheats.

Lab #	Name/Grade	Label Name	Province	Type	WP (%)	Grade	TW (kg/hL)	Primary Degrading Factor
1301	South Lakes	South lake	MB	CWRW	12.4	1 CWRW	81.6	
1302	Starbuck	starbuck	MB	CWRW	11.7	1 CWRW	82	
1303	Mollard	mollard	MB	CWRW	12.1	1 CWRW	81.4	
1304	High RW	wpg north	Winnipeg North Terminal	CWRW	11.7	1 CWRW	81.4	
1305	A 1CWRW	wpg VitA	Winnipeg grain	CWRW	12.1	1 CWRW	82.2	
1306	C 1CWRW	wpg VitC	Winnipeg grain	CWRW	12.1	1 CWRW	81.6	
1307	2CWRW	morris	Morris	CWRW	12.2	1 CWRW	82.4	
1308	N/A	Lethbridge	Lethbridge AB	CWRW	11.5	1 CWRW	82	
1311	Shoal Lake	Shoal lake	MB	CWRS	13.3	1 CWRS	84.2	
1312	Red River South	Red river south	MB	CWRS	13.2	1 CWRS	84.8	
1313	Dixon	Dixon	SK	CWRS	12.8	2 CWRS	84.4	0.36% FUS DMG
1315	Last Mountain	Last mountain	SK	CWRS	13.2	1 CWRS	84.4	
1316	Low RS	wpg north rs	Winnipeg North Terminal	CWRS	12.1	1 CWRS	84.8	
1317	A 1CWRS	vermilion	Vermilion grain	CWRS	12.4	1 CWRS	84.4	
1318	B 2CWRS	weybwrn	Weybwrn grain	CWRS	12.7	2 CWRS	82.2	0.38% FUS DMG
1319	C 2CWRS	grenfell	Grenfell grain	CWRS	13.2	1 CWRS	83	

Refer to Table A.1 for explanations of abbreviations, CWRS = Canada western red spring

Table A.5. Wheat and Wheat Meal Composition and Technological Characteristics of sample set 2011S1.

Lab No.	Genotype	FA	TW	PSI	TKW	WP	WTP	WWEP	FY	FAsh	FP	DS	FTP	FWEP
1	Radiant	57.85	80.3	64.15	31.50	12.00	4.50	0.23	77.6	0.42	11.9	4.48	1.22	0.23
2	Flourish	60.45	83.8	59.80	36.25	12.51	4.56	0.36	77.6	0.41	12.4	4.65	1.27	0.32
3	Tempest	61.60	82.0	56.10	29.50	12.08	5.26	0.35	74.8	0.47	11.3	5.46	1.66	0.38
4	CDC Buteo	59.35	81.6	60.65	30.00	12.68	4.03	0.34	76.5	0.43	12.1	4.80	1.28	0.29
5	CDC Osprey	56.60	80.1	62.60	27.25	11.26	4.20	0.18	77.4	0.48	11.1	4.50	1.26	0.24
6	LL611	63.95	84.2	56.95	29.75	12.26	5.00	0.45	75.5	0.35	11.9	4.90	1.72	0.46
7	LL163	59.90	83.4	59.75	31.00	12.51	4.85	0.43	76.3	0.44	11.9	4.64	1.57	0.43
8	LL532	57.40	82.6	59.20	30.30	11.54	4.39	0.36	75.1	0.48	11.3	4.69	1.43	0.30
9	LL066	55.55	82.4	65.10	32.75	12.77	4.39	0.26	76.4	0.45	12.0	4.20	1.31	0.25
10	W494	64.65	83.2	59.35	34.75	14.35	4.43	0.38	77.7	0.43	13.7	4.82	1.09	0.28
11	W511	63.05	82.2	60.55	33.25	12.85	4.47	0.34	77.2	0.47	12.6	5.17	1.62	0.36
12	AC Bellatrix	60.70	79.3	60.50	28.00	12.03	5.31	0.46	74.9	0.53	11.9	5.07	1.80	0.36
13	LJ1082	61.15	78.0	63.60	23.75	13.56	4.95	0.42	75.8	0.55	13.2	4.14	1.63	0.34

FA = farinograph absorption; TW = test weight; PSI = particle size index; TKW = thousand kernel weight; WP = wheat protein; WTP = wheat total pentosan; WWEP = wheat water-extractable pentosan; FY = flour yield; FAsh = flour ash; FP = flour protein; DS =damaged starch; FTP = flour total pentosan; FWEP = flour water-extractable pentosan.

Table A.6. Wheat and Wheat Meal Composition and Technological Characteristics of sample set 2011S2

Lab No.	Genotype	FA	TW	PSI	TKW	WP	WTP	WWEP	FY	FAsh	FP	DS	FTP	FWEP
14	Jerry	60.30	80.3	62.90	37.25	11.78	5.02	0.28	76.5	0.54	11.4	5.20	1.71	0.31
15	Norstar	58.80	83.6	60.50	31.75	11.87	4.08	0.24	76.8	0.45	11.6	4.74	1.29	0.26
16	Broadview	58.75	80.1	59.60	25.75	11.07	4.48	0.37	72.9	0.55	11.0	4.74	1.63	0.38
17	W478	60.50	80.3	61.75	29.25	12.68	4.66	0.27	76.5	0.55	13.0	4.94	1.35	0.28
18	W487	57.15	83.2	60.45	26.00	12.96	4.52	0.21	75.6	0.55	12.9	4.58	1.52	0.24
19	DH00W3IN*34	60.70	83.6	58.70	34.50	12.18	4.27	0.28	77.0	0.53	12.1	5.12	1.49	0.31
20	W486	62.60	83.0	59.15	34.75	12.71	4.70	0.29	78.0	0.49	12.5	4.91	1.71	0.38
21	Peregrine	60.90	83.8	50.15	32.50	12.46	4.14	0.29	76.1	0.52	12.3	5.27	1.41	0.30
22	W485	57.80	81.8	60.60	25.50	12.80	4.36	0.28	74.2	0.54	13.0	4.56	1.42	0.30
23	Accipiter	60.25	78.1	57.75	22.00	12.04	4.59	0.34	73.7	0.58	11.7	5.41	1.58	0.35
24	CDC Raptor	60.55	78.5	55.25	22.50	12.01	4.32	0.28	75.3	0.58	12.0	5.44	1.53	0.30
26	W460	58.00	78.3	59.20	27.00	11.24	5.00	0.31	75.3	0.53	11.0	5.32	1.36	0.34
27	CDC Falcon	59.45	78.3	57.00	25.75	12.19	4.56	0.33	72.6	0.62	11.6	5.18	1.44	0.34

Refer to Table A.5 for explanations of abbreviations

Table A.7. Wheat and Wheat Meal Composition and Technological Characteristics of sample set 2012.

Lab No.	Genotype	FA	TW	PSI	TKW	WP	WTP	WWEP	FY	FAsh	FP	DS	FTP	FWEP
1201	Radiant	57.20	82.6	54.85	33.25	12.89	3.84	0.20	76.44	0.45	11.97	4.21	1.20	0.27
1202	CDC Osprey	55.60	82.8	56.20	29.25	13.09	4.76	0.17	77.06	0.39	12.62	4.22	1.14	0.25
1203	AC Bellatrix	60.05	84.0	52.25	35.75	13.64	4.80	0.32	76.52	0.48	12.63	4.93	1.36	0.36
1204	CDC Buteo	57.80	84.6	55.05	31.00	13.05	4.46	0.20	76.47	0.45	12.29	4.52	1.13	0.27
1205	Flourish	59.05	83.8	54.45	35.00	13.07	3.94	0.21	76.63	0.47	12.44	4.60	1.21	0.32
1206	Moats	57.80	83.4	51.00	34.50	13.12	4.67	0.27	75.55	0.36	12.65	4.80	1.19	0.34
1207	Emerson	56.55	83.8	55.75	29.00	13.49	4.21	0.17	77.56	0.43	12.88	4.07	1.13	0.24
1208	AAC Gateway (W478)	60.80	85.2	53.10	35.50	13.56	4.05	0.27	76.90	0.48	12.49	4.63	1.08	0.31
1209	CDC Falcon	56.15	80.7	55.75	28.00	12.83	4.64	0.25	73.21	0.44	12.33	4.61	1.28	0.27
1210	Broadview	58.60	82.2	56.00	31.50	12.60	4.31	0.30	73.77	0.42	12.08	4.46	1.33	0.41
1211	CDC Harrier	57.80	80.1	54.45	31.50	12.47	4.26	0.29	75.66	0.51	11.60	4.47	1.34	0.32
1212	CDC Raptor	57.95	83.2	53.05	27.75	12.51	4.12	0.20	75.69	0.52	12.00	4.99	1.19	0.29
1213	Accipiter	56.40	83.6	53.65	28.50	12.18	4.03	0.26	75.01	0.48	11.55	4.87	1.21	0.35
1214	Peregrine	57.50	82.8	47.55	32.75	12.45	4.22	0.18	76.51	0.48	11.83	5.27	1.21	0.28
1215	Pintail (W460)	54.10	78.3	53.50	27.00	12.38	4.12	0.26	74.34	0.48	11.37	4.70	1.26	0.31
1217	DH99W19H*16	59.40	79.7	54.40	30.75	12.95	4.71	0.38	74.76	0.51	11.98	4.93	1.39	0.41
1218	DH00W31N*34	56.45	85.5	52.70	38.25	12.26	4.14	0.25	76.04	0.46	11.25	4.72	1.33	0.28
1219	1603-137-1	55.80	82.0	56.90	35.25	12.48	4.84	0.29	76.14	0.48	11.79	4.67	1.36	0.33
1220	W495 (LJ083)	54.95	81.8	55.30	37.75	12.93	4.24	0.20	76.29	0.48	12.29	4.43	1.25	0.25
1221	W497 (LJ460)	54.60	78.5	55.60	36.00	13.64	4.59	0.19	77.00	0.46	12.70	4.25	1.26	0.28
1222	W505 (LJ388)	57.50	86.5	52.20	35.50	12.80	3.98	0.21	76.89	0.43	12.56	4.58	1.11	0.25
1223	W506 (LK088)	56.90	84.0	56.15	34.00	13.03	3.87	0.19	75.39	0.43	12.32	4.11	1.16	0.27
1224	W507 (LK221)	59.45	82.6	53.20	27.75	12.67	4.14	0.28	74.17	0.30	12.70	4.05	1.41	0.38
1225	W508 (LK640)	56.65	82.0	54.10	27.75	13.02	4.88	0.24	77.27	0.36	12.87	4.49	1.46	0.29
1226	W510 (LK976)	60.35	83.8	51.45	38.25	13.57	4.42	0.28	75.01	0.49	12.80	4.84	1.28	0.32
1227	W512 (LK1064)	58.55	81.2	55.65	32.00	12.68	4.63	0.35	75.09	0.42	12.37	4.66	1.60	0.37

Table A.7. Wheat and Wheat Meal Composition and Technological Characteristics of sample set 2012 (continued).

Lab No.	Genotype	FA	TW	PSI	TKW	WP	WTP	WWEP	FY	FAsh	FP	DS	FTP	FWEP
1228	AC Tempest	64.05	84.0	55.80	36.50	14.42	4.91	0.31	75.10	0.32	14.27	4.29	1.24	0.30
1229	LE2411 (W438)	59.00	77.7	56.20	25.75	15.12	4.52	0.25	74.11	0.46	14.48	4.12	1.30	0.28
1230	LF1318 (W455)	56.35	81.2	57.85	26.75	12.40	4.35	0.21	75.49	0.49	12.26	3.85	1.28	0.29
1231	LG194 (W472)	57.45	80.5	57.30	32.25	14.30	4.46	0.21	74.81	0.37	14.19	4.01	1.19	0.25
1232	LG237 (W481)	59.50	85.6	55.65	34.75	12.66	4.30	0.27	77.18	0.38	12.58	4.65	1.19	0.28
1233	LH113 (W484)	58.60	83.6	55.95	32.25	14.05	4.29	0.22	76.19	0.37	13.20	4.25	1.27	0.26
1234	LH145	54.55	80.7	57.50	30.50	12.32	4.10	0.19	77.46	0.51	12.40	4.22	1.23	0.27
1235	LH188 (W486)	56.15	82.4	59.00	38.50	12.62	4.65	0.32	77.46	0.31	12.16	4.74	1.35	0.24
1236	LH491	59.40	80.7	55.40	29.75	12.89	4.15	0.26	73.41	0.30	12.10	4.53	1.25	0.27
1237	LH504Q (W494)	62.05	83.6	52.45	37.50	14.01	4.14	0.19	75.77	0.43	13.43	5.08	1.26	0.24
1238	LH564Q (W489)	61.50	83.4	54.70	38.50	13.61	4.83	0.25	76.55	0.48	13.13	4.78	1.30	0.29
1239	LJ1082P	61.05	79.5	55.20	31.00	13.37	4.67	0.26	75.03	0.42	12.85	4.17	1.31	0.28
1240	LJ1091P	57.30	76.5	57.05	28.00	13.14	4.26	0.26	75.70	0.46	12.45	4.04	1.22	0.29
1241	LJ165	58.40	83.6	56.30	37.50	12.00	4.69	0.26	75.97	0.43	11.30	4.38	1.31	0.31
1242	LJ168	58.40	83.2	55.60	35.75	12.10	4.27	0.25	76.18	0.48	12.04	4.37	1.40	0.31
1243	LJ624	62.40	85.6	52.25	40.00	13.35	4.03	0.28	75.80	0.47	12.55	4.75	1.17	0.32
1244	LJ901 (W499)	57.40	80.3	57.90	29.00	13.62	4.74	0.29	74.97	0.49	13.33	4.19	1.37	0.33
1245	LJ902 (W500)	56.90	79.1	57.35	28.75	13.23	4.46	0.25	74.37	0.52	12.49	4.22	1.38	0.32
1246	LJ913 (W501)	57.40	78.3	56.90	27.50	13.93	4.80	0.24	74.29	0.50	13.65	4.30	1.41	0.31
1247	LK1061 (W511)	62.00	82.4	55.45	33.50	13.86	4.34	0.35	76.45	0.44	13.13	4.76	1.54	0.42
1248	LK1114	53.90	85.6	61.75	31.25	12.53	4.94	0.19	76.46	0.45	12.43	3.86	1.21	0.24
1249	LK1152Q	61.30	85.0	53.50	36.25	12.79	4.82	0.23	77.45	0.42	12.32	4.53	1.45	0.30
1250	LK779	65.45	83.0	49.80	32.00	13.69	4.95	0.30	76.02	0.49	13.07	5.05	1.36	0.37
1251	LK980	56.55	79.1	54.65	29.50	12.51	4.51	0.28	74.77	0.46	12.28	4.67	1.31	0.25
1252	LL611	63.00	84.8	53.05	36.50	13.16	5.56	0.29	76.17	0.43	12.49	4.89	1.65	0.40
1253	LM814Q	59.00	83.4	57.55	34.00	12.84	5.18	0.25	76.96	0.45	12.22	4.01	1.18	0.31

Refer to Table A.5 for explanations of abbreviations

Table A.8. Wheat flour particle size characteristics by laser diffraction of sample set 2011S1.

Lab No.	Genotype	d0.1	d0.5	d0.9	26 µm	140 µm
1	Radiant	12.56	54.90	120.94	3.14	4.32
2	Flourish	11.98	57.11	123.33	2.78	4.61
3	Tempest	12.95	56.78	122.80	2.93	4.54
4	CDC Buteo	11.85	54.20	120.52	3.15	4.28
5	CDC Osprey	11.60	55.55	120.13	2.81	4.34
6	LL611	14.01	62.84	131.40	2.46	5.41
7	LL163	11.25	54.68	120.54	2.97	4.34
8	LL532	11.43	52.70	118.83	3.25	4.11
9	LL066	12.54	52.55	117.78	3.39	4.03
10	W494	15.68	64.77	132.31	2.18	5.52
11	W511	13.96	61.01	127.06	2.47	5.02
12	AC Bellatrix	12.79	57.40	124.20	2.83	4.62
13	LJ1082	11.25	50.34	113.30	3.34	3.61

CWRW = Canada western red winter; d0.1, d0.5 and d0.9 = the flour particle size of the 10^{th}, 50^{th} and 90^{th} percentile of the volume distribution determined by laser diffraction. The parameters 26 µm and 140 µm are the two flour particle size variables with the highest correlations to FA across all sample sets.

Table A.9. Wheat flour particle size characteristics by laser diffraction of sample set 2011S2.

Lab No.	Genotype	d0.1	d0.5	d0.9	26 µm	140 µm
14	Jerry	16.06	58.8	124.94	2.94	4.66
15	Norstar	16.02	61.5	130.91	2.58	4.85
16	Broadview	14.55	57.2	123.06	2.95	4.39
17	W478	14.97	59.7	123.55	2.55	4.66
18	W487	14.03	54.7	119.23	3.2	4.1
19	DH00W3IN*34	16.02	59.7	127.61	2.9	4.86
20	W486	16.22	60.5	126.98	2.65	4.84
21	Peregrine	20.53	69.1	136.66	1.91	6.06
22	W485	14.06	53.3	122.75	3.44	3.71
23	Accipiter	15.06	58.3	124.35	2.9	4.59
24	CDC Raptor	15.49	61.1	127.55	2.63	5.01
26	W460	14.15	56.4	123.31	3.17	4.48
27	CDC Falcon	13.81	53.9	119.58	3.33	4.07

Refer to Table A.8. for explanations of abbreviations

Table A.10. Wheat flour particle size characteristics by laser diffraction of sample set 2012.

Lab No.	Genotype	d0.1	d0.5	d0.9	26 µm	140 µm
1201	Radiant	18.54	65.42	134.04	2.37	5.57
1202	CDC Osprey	15.30	61.63	127.08	2.50	5.05
1203	AC Bellatrix	20.23	69.04	143.11	2.03	5.86
1204	CDC Buteo	17.54	64.44	131.83	2.44	5.47
1205	Flourish	16.51	64.28	130.55	2.34	5.43
1206	Moats	20.29	67.97	135.52	2.13	5.94
1207	Emerson	17.16	65.89	140.87	2.23	5.27
1208	AAC Gateway (W478)	19.63	70.38	138.13	1.74	6.27
1209	CDC Falcon	15.29	59.43	126.11	2.88	4.79
1210	Broadview	15.69	62.02	128.86	2.59	5.14
1211	CDC Harrier	15.80	62.41	128.71	2.59	5.20
1212	CDC Raptor	20.42	70.30	143.46	1.97	5.99
1213	Accipiter	17.65	65.61	133.26	2.38	5.66
1214	Peregrine	21.82	71.91	139.96	1.80	6.54
1215	Pintail (W460)	15.31	60.12	125.98	2.83	4.95
1217	DH99W19H*16	16.22	62.08	128.79	2.56	5.12
1218	DH00W31N*34	18.19	66.70	135.73	2.36	5.84
1219	1603-137-1	17.47	63.83	131.49	2.54	5.40
1220	W495 (LJ083)	18.44	65.79	132.74	2.20	5.61
1221	W497 (LJ460)	16.61	62.59	128.44	2.52	5.14
1222	W505 (LJ388)	20.34	70.36	138.04	1.82	6.23
1223	W506 (LK088)	19.46	67.24	134.88	2.14	5.81
1224	W507 (LK221)	17.56	63.93	131.52	2.45	5.36
1225	W508 (LK640)	16.04	62.79	128.75	2.44	5.20
1226	W510 (LK976)	19.02	68.26	134.75	1.97	5.96
1227	W512 (LK1064)	14.51	57.71	124.90	3.03	4.64
1228	AC Tempest	22.39	70.52	137.68	1.72	6.25
1229	LE2411 (W438)	16.55	61.70	135.19	2.60	4.56
1230	LF1318 (W455)	15.40	57.95	124.38	3.07	4.61
1231	LG194 (W472)	16.39	61.58	127.33	2.57	5.00
1232	LG237 (W481)	22.26	72.53	143.38	1.73	6.54
1233	LH113 (W484)	21.52	69.56	143.17	1.97	5.82
1234	LH145	16.00	59.33	125.44	2.93	4.80
1235	LH188 (W486)	17.79	65.49	132.25	2.29	5.58
1236	LH491	17.46	64.08	130.93	2.38	5.40
1237	LH504Q (W494)	18.41	67.17	134.40	2.09	5.82
1238	LH564Q (W489)	20.87	69.05	137.38	1.97	6.02
1239	LJ1082P	18.50	66.24	132.66	2.14	5.63

Table A.10. Wheat flour particle size characteristics by laser diffraction of sample set 2012 (continued)

Lab No.	Genotype	d0.1	d0.5	d0.9	26 µm	140 µm
1240	LJ1091P	17.56	63.41	128.52	2.39	5.21
1241	LJ165	18.73	67.41	135.72	2.09	5.87
1242	LJ168	18.18	66.09	133.51	2.25	5.68
1243	LJ624	24.27	73.83	144.64	1.64	6.73
1244	LJ901 (W499)	17.39	63.61	132.20	2.45	5.23
1245	LJ902 (W500)	17.89	64.36	130.85	2.31	5.34
1246	LJ913 (W501)	16.60	61.44	127.23	2.57	4.94
1247	LK1061 (W511)	22.30	70.87	138.73	1.70	6.31
1248	LK1114	16.93	63.33	128.99	2.40	5.25
1249	LK1152Q	19.82	69.64	137.14	1.83	6.18
1250	LK779	27.51	76.07	144.90	1.38	7.11
1251	LK980	17.67	63.44	129.22	2.45	5.23
1252	LL611	19.72	70.58	140.12	1.89	6.36
1253	LM814Q	19.32	65.56	132.09	2.25	5.51

Refer to Table A.8. for explanations of abbreviations

Table A.11. Validation of multivariate regression model (absent flour particle size) of sample set 2011All, 2012, 2011 Common and 2012 Common

	Model developed from	Validated with	R^2
1 Variable	2011All	2012	0.188
	2012	2011All	0.209
	2011Common	2012Common	0.683
	2012Common	2011Common	0.518
2 Variable	2011All	2012	0.382
	2012	2011All	0.571
	2011Common	2012Common	0.685
	2012Common	2011Common	0.721
3 Variable	2011All	2012	0.493
	2012	2011All	0.425
	2011Common	2012Common	0.720
	2012Common	2011Common	0.724
4 Variable	201 All	2012	0.476
	2012	2011All	0.320
	2011Common	2012Common	0.745
	2012Common	2011Common	0.561

Table A.12. Validation of multivariate regression model (with flour particle size) of sample set 2011All, 2012, 2011 Common and 2012 Common

	Model developed from	Validated with	R^2
1 Variable	2011All	2012	0.461
	2012	2011All	0.4328
	2011Common	2012Common	0.683
	2012Common	2011Common	0.518
2 Variable	2011All	2012	0.572
	2012	2011All	0.688
	2011Common	2012Common	0.685
	2012Common	2011Common	0.680
3 Variable	2011All	2012	0.692
	2012	2011All	0.805
	2011Common	2012Common	0.757
	2012Common	2011Common	0.793
4 Variable	201 All	2012	0.675
	2012	2011All	0.810
	2011Common	2012Common	0.788
	2012Common	2011Common	0.761

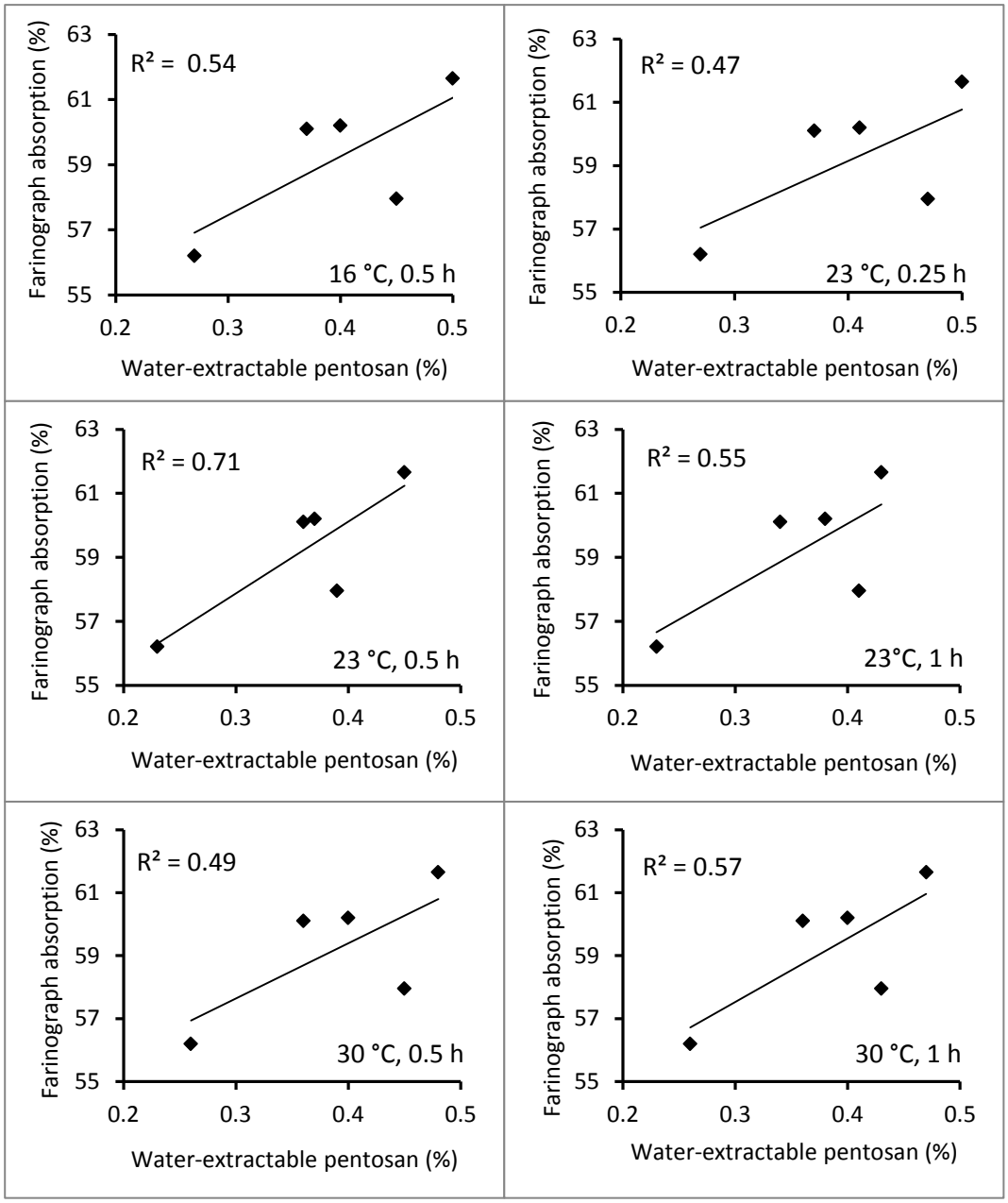


Figure A.1. Evaluation of experimental conditions to determine flour water-extractable pentosans by phloroglucinol assay. Water extraction at 16 ℃, 0.5 h; 23 ℃, 0.25 h; 23 ℃, 0.5 h; 23 ℃, 1 h; 30 ℃, 0.5 h and 30 ℃, 1 h.

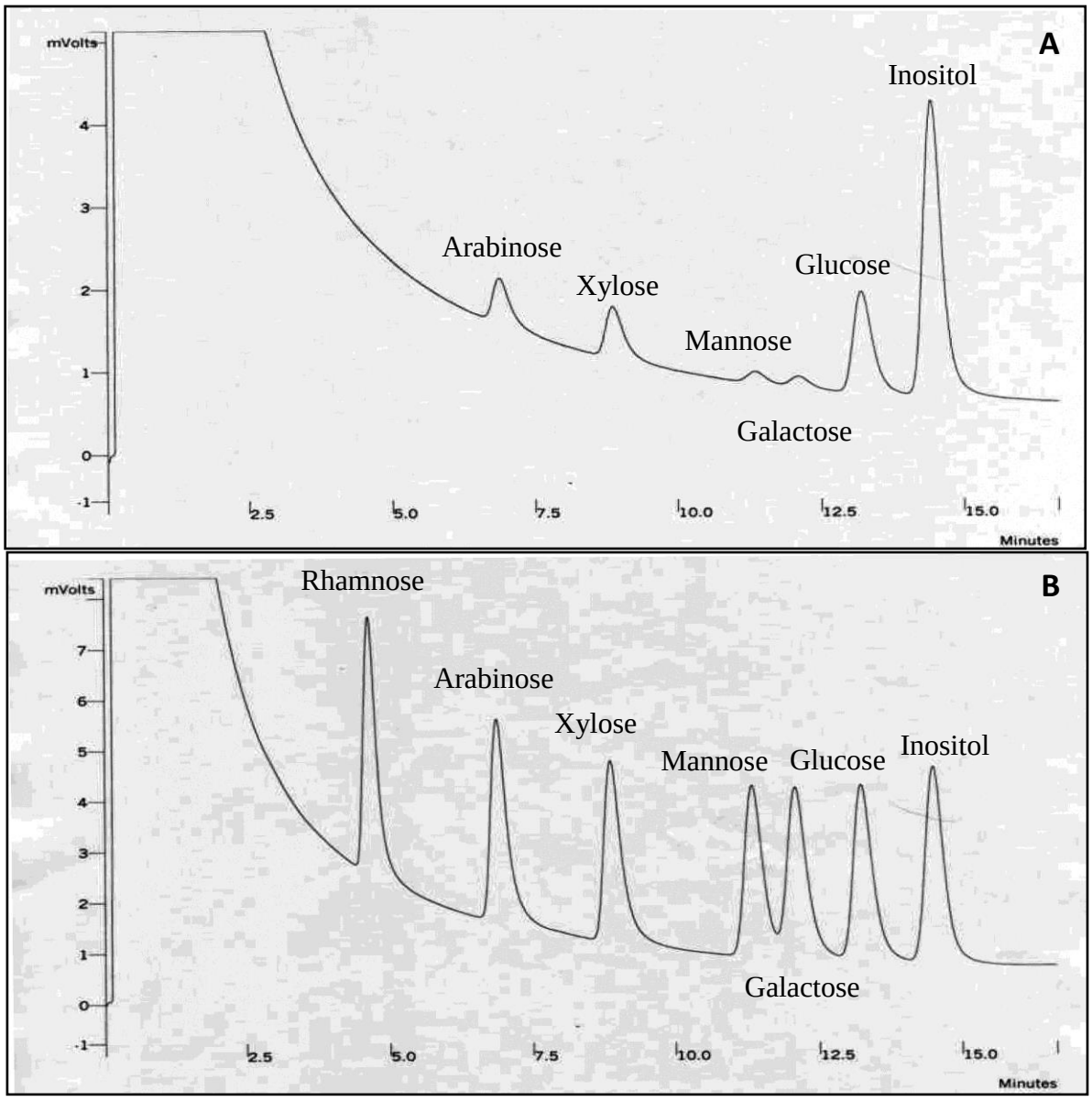


Figure A.2. Varian CP 3380 GLC analysis of neutral sugars in the non-starch polysaccharides fraction of a representative wheat flour sample (A) and sugar standards (B)

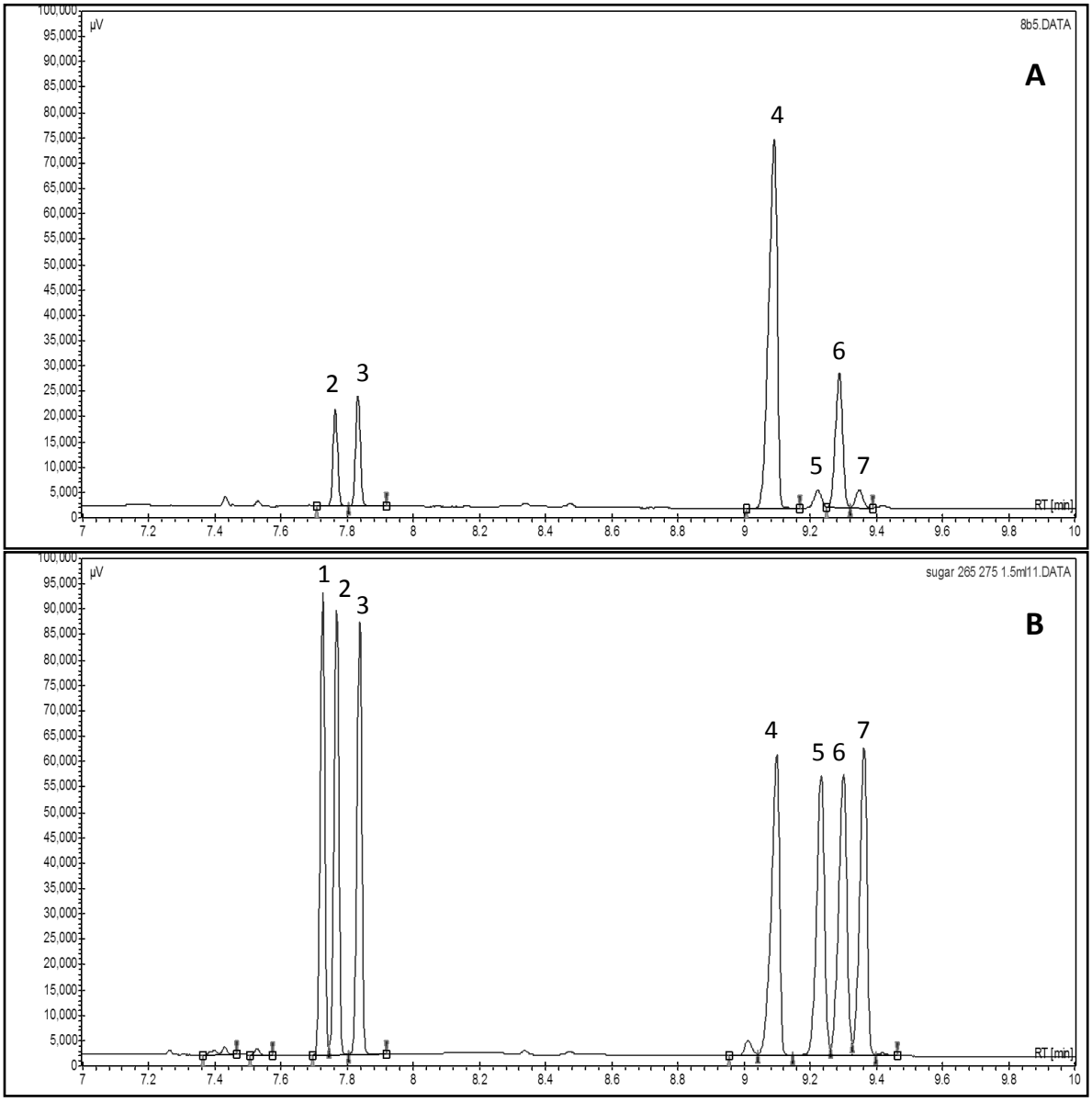


Figure A.3. Varian CP 3800 GLC analysis of neutral sugars in the non-starch polysaccharides fraction of a representative wheat flour sample (A) and sugar standards (B). 1-rhamnose; 2-arabinose; 3-xylose; 4-inositol; 5-mannose; 6-glucose; 7-galactose.

```
data one;
input trt $ T    D40 D27;
datalines;
RW    0.0025 0.0483 0.1187 0.0819 0.0325 0.0073
RW    0.0031 0.0398 0.0964 0.1197 0.0328 0.0067
RW    0.0024 0.0433 0.1164 0.1265 0.0303 0.0081
RS    0.0021 0.0330 0.0961 0.1518 0.0464 0.0088
RS    0.0023 0.0415 0.0922 0.1426 0.0567 0.0088
RS    0.0017 0.0336 0.0761 0.1307 0.0490 0.0078

;
proc glm data=one;
class trt;
model T=trt;
lsmeans trt/stderr;
means trt/scheffe;
run;
proc glm data=one;
class trt;
model D40=trt;
lsmeans trt/stderr;
means trt/scheffe;
run;
proc glm data=one;
class trt;
model D27=trt;
lsmeans trt/stderr;
means trt/scheffe;
run;

quit;
```

Figure A.4. SAS analysis Fisher's LSD procedure.

```
data parameter;
input FA     TW     PSI    TKW    WP     WTP    WWEP   FY     FAsh   FP     DS     FTP    FWEP   d1     d5     d9     d26    d140
     ;
datalines;


57.20  82.6   54.85  33.25  12.89  3.84   0.20   76.44  0.45   11.97  4.21   1.20   0.27   18.54  65.42  134.04 2.37   5.57
55.60  82.8   56.20  29.25  13.09  4.76   0.17   77.06  0.39   12.62  4.22   1.14   0.25   15.30  61.63  127.08 2.50   5.05
60.05  84.0   52.25  35.75  13.64  4.80   0.32   76.52  0.48   12.63  4.93   1.36   0.36   20.23  69.04  143.11 2.03   5.86
57.80  84.6   55.05  31.00  13.05  4.46   0.20   76.47  0.45   12.29  4.52   1.13   0.27   17.54  64.44  131.83 2.44   5.47
59.05  83.8   54.45  35.00  13.07  3.94   0.21   76.63  0.47   12.44  4.60   1.21   0.32   16.51  64.28  130.55 2.34   5.43
60.80  85.2   53.10  35.50  13.56  4.05   0.27   76.90  0.48   12.49  4.63   1.08   0.31   19.63  70.38  138.13 1.74   6.27
56.15  80.7   55.75  28.00  12.83  4.64   0.25   73.21  0.44   12.33  4.61   1.28   0.27   15.29  59.43  126.11 2.88   4.79
58.60  82.2   56.00  31.50  12.60  4.31   0.30   73.77  0.42   12.08  4.46   1.33   0.41   15.69  62.02  128.86 2.59   5.14
57.95  83.2   53.05  27.75  12.51  4.12   0.20   75.69  0.52   12.00  4.99   1.19   0.29   20.42  70.30  143.46 1.97   5.99
56.40  83.6   53.65  28.50  12.18  4.03   0.26   75.01  0.48   11.55  4.87   1.21   0.35   17.65  65.61  133.26 2.38   5.66
57.50  82.8   47.55  32.75  12.45  4.22   0.18   76.51  0.48   11.83  5.27   1.21   0.28   21.82  71.91  139.96 1.80   6.54
54.10  78.3   53.50  27.00  12.38  4.12   0.26   74.34  0.48   11.37  4.70   1.26   0.31   15.31  60.12  125.98 2.83   4.95
56.45  85.5   52.70  38.25  12.26  4.14   0.25   76.04  0.46   11.25  4.72   1.33   0.28   18.19  66.70  135.73 2.36   5.84
64.05  84.0   55.80  36.50  14.42  4.91   0.31   75.10  0.32   14.27  4.29   1.24   0.30   22.39  70.52  137.68 1.72   6.25
56.15  82.4   59.00  38.50  12.62  4.65   0.32   77.46  0.31   12.16  4.74   1.35   0.24   17.79  65.49  132.25 2.29   5.58
62.05  83.6   52.45  37.50  14.01  4.14   0.19   75.77  0.43   13.43  5.08   1.26   0.24   18.41  67.17  134.40 2.09   5.82
61.05  79.5   55.20  31.00  13.37  4.67   0.26   75.03  0.42   12.85  4.17   1.31   0.28   18.50  66.24  132.66 2.14   5.63
62.00  82.4   55.45  33.50  13.86  4.34   0.35   76.45  0.44   13.13  4.76   1.54   0.42   22.30  70.87  138.73 1.70   6.31
63.00  84.8   53.05  36.50  13.16  5.56   0.29   76.17  0.43   12.49  4.89   1.65   0.40   19.72  70.58  140.12 1.89   6.36


proc print data=parameter;



proc reg data = parameter;
   Model FA=TW    PSI   TKW   WP    WTP   WWEP  FY    FAsh  FP    DS    FTP   FWEP  d1    d5    d9    d26   d140
 / selection=rsquare sle=0.05 sls=0.05 best=3 stop=4;
run;
```

Figure A.5. SAS analysis R^2 selection procedure.

```
data parameter;
input FA     TW     PSI    TKW    WP     WTP    WWEP   FY     FAsh   FP     DS     FTP    FWEP   d1     d5     d9     d26    d140  ;
datalines;

57.20  82.6   54.85  33.25  12.89  3.84   0.20   76.44  0.45   11.97  4.21   1.20   0.27   18.54  65.42  134.04 2.37   5.57
55.60  82.8   56.20  29.25  13.09  4.76   0.17   77.06  0.39   12.62  4.22   1.14   0.25   15.30  61.63  127.08 2.50   5.05
60.05  84.0   52.25  35.75  13.64  4.80   0.32   76.52  0.48   12.63  4.93   1.36   0.36   20.23  69.04  143.11 2.03   5.86
57.80  84.6   55.05  31.00  13.05  4.46   0.20   76.47  0.45   12.29  4.52   1.13   0.27   17.54  64.44  131.83 2.44   5.47
59.05  83.8   54.45  35.00  13.07  3.94   0.21   76.63  0.47   12.44  4.60   1.21   0.32   16.51  64.28  130.55 2.34   5.43
60.80  85.2   53.10  35.50  13.56  4.05   0.27   76.90  0.48   12.49  4.63   1.08   0.31   19.63  70.38  138.13 1.74   6.27
56.15  80.7   55.75  28.00  12.83  4.64   0.25   73.21  0.44   12.33  4.61   1.28   0.27   15.29  59.43  126.11 2.88   4.79
58.60  82.2   56.00  31.50  12.60  4.31   0.30   73.77  0.42   12.08  4.46   1.33   0.41   15.69  62.02  128.86 2.59   5.14


proc stepwise data = parameter;
 Model FA=  TW    PSI   TKW WP    WTP   WWEP FAsh  FP    DS    FTP   FWEP d1    d9    d26   d140

 / maxr sle=0.1 sls=0.1 stop=4
;
run;
```

Figure A.6. SAS analysis Maximum R^2 Improvement procedure.

8 APPENDIX B - EXTANDED ABSTRACT

Canada Western Red Winter (CWRW) wheats typically have excellent milling quality but are generally deficient in farinograph absorption (FA) by 8-10% on average compared to wheats of the CWR Spring (CWRS) class. The main objective of this study was to develop a better understanding of the nature of the variation in FA of this wheat class by focusing on pentosan content and composition among other plausible factors using a genotypically diverse set of CWRW wheat cultivars and advanced breeding lines grown at AAFC-Lethbridge in 2011 (26 genotypes) and 2012 (52 genotypes). Several commercial CWRW and CWRS wheat samples were also included to address this main objective using mechanical sieving of flours into eight fractions ranging in granularity from about 20 – 200 μm.

Wheat samples were officially graded and were then milled on a tandem Buhler mill to obtain straight grade flour. Numerous wheat and flour compositional factors were evaluated including thousand kernel weight, wheat particle size index (PSI), wheat and flour protein (WP and FP), wheat and flour total and water-extractable pentosan contents (WTP, FTP, WWEP, FWEP), damaged starch (DS) content, and flour particle size distribution by laser diffraction. Simple correlation and stepwise multivariate regression analysis (SMRA) were used to study the relative influences of factors and their combinations on FA which ranged from 54 - 65%.

From a methodology standpoint, a rapid method for measuring pentosan content of wheat and flour, i.e. the phloroglucinol colorimetric assay (PCA), was shown to produce good accuracy and better repeatability compared to a classical and much more complex GLC

method which directly measures alditol acetates of the arabinose and xylose sugar components of pentosans. Also for determining FA, results showed that a 10 g farinograph mixer bowl was a satisfactory substitute for the traditional 50 g bowl, which is particularly useful when flour is limited.

Excluding flour particle size factors, the most highly correlated parameters to FA were protein content, wheat hardness indices (PSI and DS), and WWEP and FWEP. Correlations to FA for these factors tended to vary in the range r = 0.40 to 0.50, with WWEP or FWEP having the highest values. Interestingly, flour particle size by laser diffraction generated the highest and most consistent correlations to FA with the median volume fraction, and the volume fraction of large ($\geqslant$140 μm, VFL140) and small ($\leqslant$ 26 μm) flour particles producing correlations in the range, r = 0.62 to 0.68. SMRA yielded a promising model of FA prediction (R^2 = 0.64) based on a model incorporating WWEP, FP, DS and VFL140 variables. Chemical analysis of sieved flour fractions of commercial CWRW and CWRS wheats showed that large flour particles of CWRS flours compared to CWRW counterparts contained significantly higher contents of protein, DS and pentosans, whereas the opposite was the case for small flour particles. This result appears to explain why the VF of large and small flour particle sizes were found by SMRA to be most strongly associated with FA. Results as a whole indicated that CWRW wheats tend to be low in FA due to low levels of wheat hardness, or protein content, or pentosan content, and that increasing these parameters by plant breeding could significantly and practically improve FA of future CWRW cultivars. Results also point to laser diffraction analysis of flour particle size as a new and potentially useful method to screen lines towards that end.