Breadmaking Quality of Durum Wheat: Effects of Semolina Particle Size, Fermentation Time and Glutenin Molecular Size

BY

PRATIBA DAVID

A Thesis
Submitted to the Faculty of Graduate Studies
In Partial Fulfillment of the Requirements
for the Degree of

MASTER OF SCIENCE

Department of Food Science
University of Manitoba
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FACULTY OF GRADUATE STUDIES

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DEDICATION

To my father, Samuel Ratnaraj, for your confidence in me and your continued affirmation of my qualities. You are a remarkable father, ... even in old age they will still produce fruit and be vital and green. Thank you for your unconditional love.

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LIST OF ABBREVIATIONS

2R	mill product – twice reduced
6R	mill product – six times reduced
A-PAGE	Acid-Polyacrylamide gel electrophoresis
BR	breakdown resistance
BS	total bread score
BW	bandwidth
CC	crumb color
CS	crumb structure
CV	coefficientof variation
DIA	digital image analysis
DSL	dough sheet length
DTT	Dithiothreitol
Fabs	Farinograph absorption
FDDT	Farinograph dough development time
G	mill product – granulars
GRL	Grain Research Laboratory
HMW-GS	High molecular weight glutenin subunits
IG	insoluble glutenin in 50% - 1- propanol
IG/SP	insoluble glutenin to soluble protein ratio
Itl.	Italian durum wheats
L	Alveograph extensibility

LA	loaf appearance
LMW-GS	Low molecular weight glutenin subunits
LV	loaf volume
MT	Mixograph mixing time
MTI	mixing tolerance index
N.A.	North American durum wheats
OR	oven rise
P	Alveograph tenacity
P/L	Alveograph tenacity to extensibility ratio
PDR	peak dough resistance
PF1	peak force
RP	residue protein in 50% - 1- propanol
RTPT	remix-to-peak time
SDS-PAGE	Sodium dodecyl sulfate-Polyacrylamide gel electrophoresis
SP	soluble protein in 50% - 1 – propanol
SV	specific volume
W	Alveograph deformation strength
WIP	Mixograph work input

ABSTRACT

Durum wheat is used for production of pasta, couscous and speciality breads. There has been extensive research done in understanding the various components of durum wheat and their effects on pasta quality. At the same time there has been relatively limited research on the factors associated with durum wheat breadmaking quality. Compared to common wheat, durum wheat typically demands a higher price in the world market, and considerable amounts of Canadian durums are exported to countries that utilize semolina for bread products. Therefore, the goal of this thesis research was to develop a better understanding of durum wheat for breadmaking. This was accomplished by investigating the effects of semolina particle size on dough mixing properties and breadmaking performance, the relationship between protein composition and breadmaking properties, effects of varying fermentation time on baking quality, bread scoring by both subjective (GRL method) and instrumental (digital image analysis, DIA) approaches, and the keeping quality of durum bread.

Eleven durum and two common wheat genotypes were milled to obtain three products: G (granular semolina), 2R (twice reduced semolina) and 6R (6-times reduced semolina). As expected, the particle size distribution was substantially affected by the milling treament; semolina reduction resulted in a substantial decrease and increase in the proportion of particles $\geq$ 250 μm and $\leq$ 150 μm, respectively. Minimal genotypic differences were found in milling yield and particle size distribution for each mill product. Starch damage and flour gassing power were significantly affected by the milling treatment; the average starch damage of G, 2R and 6R products was 4.1%, 5.7%

and 6.4%, respectively. The average gassing powers of the corresponding samples were 11.8, 13.6 and 14.2 PSI, respectively.

Results of protein composition analysis by solubility fractionation of G material showed that there were considerable genotypic differences in propanol soluble protein (SP), insoluble glutenin (IG) and residue protein (RP). Most notably, IG content was highly correlated with numerous indices of durum breadmaking quality, i.e. dough strength and loaf volume. These results indicate that many of the key technological properties of durum wheat for breadmaking are dependent upon its content of large polymeric glutenin.

Dough mixing properties were significantly affected by the milling treatment; Mixograph mixing time, Mixograph work-input to peak development, and Farinograph development time were all significantly higher for G compared to 2R or 6R mill products. Farinograph absorptions were also significantly different among G, 2R and 6R material with values of 58.2, 62.3 and 64.1%, respectively. Differences in particle size and starch damage of the mill products explain these dough mixing results.

Baking quality was initially evaluated using the GRL Remix-to-Peak method at the standard 165 min (i.e. long) fermentation time. Bread loaf volume (LV) was not significantly different between mill products G and 6R. Significant genotypic differences were observed within the mill products. For G material, the common wheats (especially AC Barrie) had relatively poor baking performance due to their low levels of starch damage. There was a significant effect of fermentation time (15, 90 and 165 min) on breadmaking quality for evaluation of mill product G only; the shorter the fermentation time, the higher the LV on average. These results indicate that durum wheat doughs lack

fermentation tolerance, which may be a reflection of the distinct glutenin subunit composition of durums compared to common bread wheats. Interestingly, dough sheet length was negatively correlated to LV ($r = -0.80$, for 15 min fermentation) for mill product G; this result is contrary to the common view that low dough extensibility of strong durums is a negative attribute for breadmaking.

Subjective bread scoring results indicated no significant difference between mill products G and 6R at 165 min fermentation. At short (15 min) fermentation time, all bread scores improved compared to corresponding scores at longer fermentation times. Results of DIA of crumb grain indicated that this objective method was very effective to predict bread scores determined subjectively ($R^2 = 0.87$).

The keeping quality of durum wheat at ambient temperature for 5 days was comparable to that of common wheats for different mill products and fermentation times. Bread slices were more firm and less resilient for G than 6R after 5 days of storage. Shorter fermentation times yielded bread slices that were significantly less firm and more resilient for mill product G.

Overall, strong North American durums AC Melita, DT 369 and Durex were the best genotypes for breadmaking, with LV at 15 min (average 800 cc) and 165 min fermentation (average 730 cc), 13% and 1% less than corresponding results for common wheat Glenlea. The basis for the improved baking performance of these durum genotypes appears to be their higher contents of IG which leads to improved gas retention in baking.

1. INTRODUCTION

Durum wheat has been used mainly to produce pasta products. Certain unique characteristics of durum wheat; kernel hardness, semolina granularity, protein composition and viscoelastic properties, predispose the wheat to produce superior pasta. There has been extensive research done in understanding the various components of durum wheat and their effects on pasta quality, with relatively limited research on the factors associated with breadmaking quality. The interest in durum wheat stems from a growing desire in developing durum cultivars suitable for both pasta and bread production (Liu et al, 1996).

Durum wheat (*Triticum turgidum var. Durum*) is a tetraploid species possessing the genomic composition AABB (4n = 28) while lacking the D genome, which is present in hexaploid (AABBDD) common wheats (*Triticum aestivum*). Therefore durum wheat lacks certain key polypeptides especially D-genome encoded high molecular weight glutenin subunits, that are normally possessed by common wheats and confer common wheats with the potential for superior breadmaking. Durum kernels have the hardest texture among all wheat species, and are susceptible to excessive starch damage under severe roller milling conditions. Breadmaking results can be affected by the milling technique (Dexter et al, 1994). It has long been postulated that good breadmaking flour requires a strong gluten capable of producing an extensive viscoelastic matrix during dough formation, with good handling properties, i.e. moderate extensibility (MacRitchie 1984). Improved breadmaking quality of durum wheat has been suggested to be achievable by having gluten that is less elastic and more extensible (Boggini and Pogna 1989). It has been suggested that lack of adequate dough extensibility is an attribute of

durum semolina that could reduce the loaf volume (LV) potential by limiting oven spring (Rao et al, 2001). Although strong gluten is expected to generally improve breadmaking quality, recent research indicates that durum doughs with dough strength (by Extensigraph measurements) similar to common wheat doughs can still result in low LV (Edwards et al, 2001). Despite its low LV, durum wheat bread has been reported to have "....a fine and uniform porosity, characteristic flavor and taste, a long shelf life of over a week" (Quaglia, 1988).

Test baking procedures, whether using short or long fermentation times affect the LV (Dexter et al, 1994); strong Canadian durum cultivars had higher LV than weak durum counterparts using relatively long fermentation time (165 min). This is indicative of greater fermentation tolerance of strong cultivars. Considerable genotypic variability at the *Glu-B1* loci (Boggini and Pogna 1989; Ammar et al, 2000) and *Glu-B3* loci (Pena et al, 1994) associated with durum wheat breadmaking performance has been reported. However, a clear relationship remains hard to establish among protein content, protein composition, dough viscoelastic properties and baking quality.

On the world market, durum wheat often demands a higher price than bread wheat, making it an attractive crop for producers. Considerable amounts of Canadian durum wheat is exported to countries in the Mediterranean region that utilize semolina for bread products. Therefore, improved durum wheat cultivar development activities and enhanced market opportunities for producers could be derived from an increased understanding of durum wheat utilization quality. Limited information on the protein quality and other determinants of the breadmaking potential of durum wheat cultivars likely restricts the use of durum wheat for bread to its full potential.

The research was initiated to explore the area of breadmaking with durum wheat and to assist in better understanding its efficacy for the production of bread. Hence, there was a need to evaluate the effects of both extrinsic (semolina particle size and fermentation times) and intrinsic (protein quality) factors for their influence on dough rheological properties, LV, the bread crumb properties and bread textural characteristics. The specific objectives of this study were to investigate the following:

- Effect of semolina particle size on durum wheat breadmaking performance (dough mixing strength, dough fermentation, LV and bread crumb grain characteristics).
- Relationship between protein composition and breadmaking properties.
- Effect of fermentation time on dough extensibility, LV, and crumb grain.
- The keeping quality of durum wheat bread compared to that of common wheat bread.
- Subjective bread scoring versus bread scoring achieved by objective digital image analysis of crumb grain and other bread slice characterisitcs.

2. LITERATURE REVIEW

2.1 Introduction

Durum wheat is used for production of pasta, couscous and speciality breads. Bread is consumed widely around the world, though its use varies from country to country and within a country. Bread (unleavened) is a staple food item in the Middle Eastern diet (Sidhu et al, 1997), while hearth bread (leavened) and non-hearth breads are widely consumed in Italy. All semolina constituents, including protein, starch and lipids, contribute to the final loaf of bread, though some contribute more than others to the breadmaking quality of durum wheat. It has long been established that protein content and quality are the most important determinants of the breadmaking potential of wheat cultivars. A strong linear relationship between breadmaking performance, as measured by loaf volume (LV), and common wheat protein content, has been clearly demonstrated (Finney and Barmore 1948). Similarly, the various uses of durum wheat depend on the unique biochemical characteristics of gluten proteins. Gluten proteins, during mixing, form a viscoelastic network in dough. The quality of gluten and its rheological properties are substantially explained by the quantity and quality (composition) of gliadin and glutenin proteins, and their interaction. It is well established that the protein content and composition of durum wheat is responsible for the rheology of durum doughs from different genotypes and the cooking quality of pasta products (Dexter and Matsuo 1980). The literature review presented here expands on the technological quality and protein composition of durum wheat for breadmaking.

2.2 Milling

The main aim of durum wheat milling for pasta production continues to be to produce semolina with uniform granulation, bright yellow color, and relatively free of dark specks (Matsuo and Dexter 1980). Flour is generally a lower value by-product. Hard, vitreous and sound durum wheat is readily reduced to granular semolina with minimal production of flour. Non-vitreous kernels are softer than vitreous kernels with lower protein content and this affects the particle size (granulation) of mill products significantly. Dexter et al. (1988) reported that with an increasing proportion of starchy kernels, semolina yield decreased ($r = -0.51$), but not milling yield. Hard wheats are more susceptible to starch damage during roller milling than soft wheats. In hard wheats, starch granules are firmly bound in a strong protein matrix, whereas in soft wheat, starch granules are more loosely bound and are easily released during milling (Tipples 1969).

Hareland (1994) asserted that particle size distribution of flour of different wheat types could be affected by the mechanical setup: number of break and reduction rolls, variations in roll gap settings, roll speed differentials, and roll configurations. The milling method was also found to affect particle size distribution of hard wheat flours, but not soft wheats. This, in turn, would affect water absorption, on account of the increased surface area and finer particle sizes allowing water to more rapidly hydrate the core, and thereby affecting the dough development time. Milling conditions used to produce semolina are controlled to limit starch damage levels. Semolina may be reground to achieve a higher level of starch damage for breadmaking. Increased starch damage increases the baking absorption and the gassing power of the dough (Tipples 1969). Characteristic differences in dough rheology obtained by different dough testing methods

appear to be related to damaged starch content, not so much to flour particle size in common wheat (Kurimoto and Shelton 1988).

2.3 Protein Content

It has long been established that protein content and quality are the most important determinants of the breadmaking potential of wheat cultivars. As mentioned earlier, a strong linear relationship between breadmaking performance as measured by LV and common wheat protein content has been demonstrated (Finney and Barmore 1948). Durum protein contents are affected by cultivar and/or growing regions. An early study by Vogel and Bailey (1927) reported an average protein content of 13%, which was 1% less than that observed in common wheats grown in the same region, as influenced by climatic conditions. They observed early on that compared to common wheat, durum wheat exhibited decreased extensibility (Alveograph, L) accompanied by lower LV. In the more recent past, Dexter et al. (1981) observed that differences between Canadian durum and common wheat classes with similar average protein contents (12.3%), were attributed to variations in protein quality and not protein content.

However, an increase in protein content was viewed as a possibility to improve the quality of durum wheat cultivars for baking. Dexter et al. (1994) established that increasing protein content (range 10.2 –17.8%) in Canadian durum wheat, regardless of the length of fermentation increased LV, but not on a unit protein content basis. This indicated no protein quality effect. Pasqui and co-workers (1994) increased protein content of Italian durums with supplemental gluten (0, 1.5, 3.5 and 4.5 %) and found no linear relationship to LV. At an addition of 1.5%, (optimum) gluten, the LV was

augmented significantly ($p \leq 0.05$). The same authors, (Pasqui et al, 1995), followed up their earlier study by manipulating the protein content of the semolina of Italian durum cultivars to constant protein contents by addition of starch. For each cultivar, higher protein content (11%) had no significant ($p \leq 0.01$) improving effect on LV compared to lower protein contents (7 and 9%). But, Ammar et al. (2000) found that for a wider range of protein contents (11-14%), LV was strongly correlated ($r = 0.72$) to protein content for durums, as similarly observed in common wheats. Thus it appears that durum wheat LV is strongly correlated to protein content when the range is wide, but content alone does not fully explain how protein influences baking performance. Presumably as protein content increases, protein composition changes as well.

2.4 Technological Quality

Physical dough tests (Farinograph, Mixograph, Alveograph and Extensigraph) are rapid and useful evaluators of the baking performance of semolina/flour. Long Farinograph mixing stability (Stab) time and low mixing tolerance index (MTI) are characteristic of strong wheat flours (Bloksma and Bushuk 1988); for 37 Italian durum wheats, Farinograph dough development time (FDDT) and Stab were positively correlated ($r = 0.54$ and $r = 0.80$, respectively) to the LV of durum flours (Boggini and Pogna 1989). Boyacioglu and D'Appolonia (1994a) compared the performance of durum wheats (flour and semolina) and bread wheat flour. Durum flour had lower Stab (3.5 min) and a distinctly higher MTI (70 Brabender Units, BU) than bread wheat flour. On the other hand, durum semolina had a longer Stab (4.5 min), but the softening index (MTI) of the dough was only slightly higher than durum flour (10 BU).

Farinograph absorption (Fabs) is widely used as an estimate for determination of water addition to dough during baking. Durum flour generally give higher Fabs values than bread wheat flours. Higher Fabs values for durum flours are attributed to higher damaged starch content (Boyacioglu and D'Appolonia 1994a). Dexter et al. (1994) reported an increase in absorption and lower stability values for durum wheat doughs with high starch damage. FDDT became shorter with reduced granularity (semolina) consistent with rapid water uptake by damaged starch. The difference in FDDT of durum flour (4 min) and semolina (5.5 min) (Boyacioglu and D'Appolonia 1994a) was magnified by the extent of starch damage. Pasqui et al. (1994) found FDDT was consistently high for high semolina protein contents. Pasqui et al. (1995) found at high (11%) compared to lower (7 and 9%) protein contents, that starch damage increased (19 to 25 Farrand Units, FU), Fabs (57 to 58 %) was higher, and MTI (50 to 90 BU) was lower.

The water-binding capacity of durum wheat flour has been largely ascribed to its protein content (Quaglia 1988). Pasqui et al. (1991) reported on average lower Fabs (52 – 57%) for durums with low protein contents (11.1% ± 0.8), and higher Fabs (60 – 68%) for high protein contents (14.9% ± 0.7). Dexter et al. (1994) found Fabs increased (≈ 5%) with increasing (10 – 18 %) protein content.

Baking absorption is determined by handling properties of the dough at the moulding and sheeting stage of the baking process. For durum wheats, Bakhshi and Bains (1987) found that baking absorptions (60%) were considerably lower than Fabs (70%) of durum flour to compensate for the sticky dough during long fermentation. This was influenced by the higher (14.6%) starch damage of durum flour compared to bread

wheats (9.2%). Similarly, at high starch damage Dexter et al. (1994) found baking absorption was less than Fabs.

Fermentation is a key step for modifying the dough to produce a good LV. Two interrelated factors at this stage are fermentation time and fermentation tolerance (Mattern 1961). Fermentation tolerance is the ability of the semolina/flour to produce an acceptable loaf of bread over a period of fermentation time (Mattern 1961; Mailhot and Patton 1988). There are no studies that have exclusively looked at the effect of varying fermentation times on durum bread baking quality.

Durum hearth bread in Italy, is typically manufactured using a lean formula (no shortening) with a long fermentation time (Spina et al, 1998). Shortening has been shown to increase LV and improve dough handling properties, crumb grain, and retention of freshness (Pomeranz, 1988). Lukie (2001) found that the removal of shortening in baking formulation decreased the LV, and negatively affected crumb properties of common wheat bread.

Dough strength can be practically determined with either a Mixograph or Farinograph. In a Mixograph, dough is vigorously developed mainly by a "pull-fold-re-pull" action of planetary rotating pins moving through a dough partially fixed in a bowl by a pair of stationary pins (Shogren 1990). In a Farinograph, mixing is accomplished by shearing a dough by two Z-shaped blades rotating at different speeds. Quick and Crawford (1983) reported Mixograph dough development time (MT) of strong durum varieties were within the range (3.0 – 3.5 min) of common wheats. Boggini and Pogna (1989) reported that Mixograph indices for durum wheat were weakly correlated, Mixograph peak height ($r = 0.55$) and band width ($r = 0.44$) to LV. A possible source of

the poor correlations might be related to the absorption levels used calculated according to protein content (% absorption = (1.5 * Flour Protein Content) + 43.6) for each cultivar. Also the bake tests used a different mixer for dough development. Difference in MT between durum and common wheats has been reported to be similar to FDDT (Boyacioglu and D'Appolonia 1994a).

The Alveograph is extensively used as an indicator of durum wheat dough properties (Dexter et al, 1994). The standard Alveograph test is run at 50% fixed absorption and 2% salt, to evaluate the strength of the dough (work of deformation until rupture, W) and the ratio of tenacity (maximum peak height, P) to extensibility (length of the curve, L) following the ICC (1980) method. Durum wheat breadmaking quality has been found to improve with increased gluten strength (Quick and Crawford 1983; Boggini and Pogna 1989; Pena et al, 1994). Quaglia (1988) concluded that to make leavened durum bread from durum flour the Alveograph P/L ratio should be >1.5 with Alveograph W values of about 200. This would again indicate that durum varieties with higher strength have improved baking performance. Pasqui et al. (1991) evaluated the genotype Creso known to possess a tenacious elastic gluten at high (14.5%) or low (10.8%) protein levels. The Alveograph P/L ratios were >1.5 at both protein levels. A statistically significant ($p < 0.05$) increase in LV (716 – 889 cc) was found with decreasing P/L values (0.7 – 2.1) for a wide selection of Italian durums at the two protein levels (14.5 and 10.8 %). There was no statistically significant relationship between Alveograph W (in the range 47 – 270) and LV, but there was a weak trend of decreasing W accompanied by an increase in LV, especially at higher protein levels. They

concluded that durum doughs with lower W and P/L values (< 1.0) give higher LV (Pasqui et al, 1991; 1994).

Dough rheological tests using fixed absorption, e.g. the Alveograph test, results in the dough becoming stiffer resulting in reduced extensibility (L) and increased peak height (P) as starch damage increases (Dexter et al, 1994). Consequently, the Alveograph W value also increases (Faridi and Rasper 1987). This may explain why durum wheats are found to have P/L values higher than that of bread wheats. Boyacioglu and D'Appolonia (1994a) found durum flour and semolina had high P/L values of 2.2 and 1.6, respectively and, bread wheat flour had P/L value as low as 0.93. Overall durum wheat LV was lower than bread wheat, despite P/L values > 1.5. In contrast, Boggini et al. (1995) found that LV was positively correlated with Alveograph W values. A negative correlation between LV and P/L values was found; durum doughs with P/L values < 1.0 gave high LV. This is in agreement with the results of Pasqui et al. (1991, 1994), but contrary to Quaglia (1988).

Starch damage influences water absorption levels, and this is of concern when doughs are mixed at fixed absorption levels. It would be more relevant to evaluate the physical dough characteristics at optimum water absorption, reducing the influence of lack of sufficient water for absorption. Ammar et al. (2000) used optimum water absorption and found high Alveograph W values for durum genotypes did not necessarily correspond to increased LV ($r = 0.34$). However, dough extensibility (Alveograph L) was the most highly correlated parameter to LV ($r = 0.80$). Gluten strength of durum wheat was characterised by lower Alveograph L ($\approx$ 63.0 mm) value and higher P/L values (> 1.0), indicative of a more tenacious dough than for bread wheat (L = $\approx$ 91.0

mm; P/L = < 1.0) of comparable strength. Marchylo et al. (2001) found no significant correlation between dough extensibility and LV, but alveograph W was weakly correlated (r = 0.56) to LV. The contrary results of Ammar et al. (2000) and Marchylo et al. (2001) may be due to the different bake tests that were used. Ammar et al. (2000) used a long fermentation procedure (AACC method 10-10B), while Marchylo et al. (2001) used a very short fermentation method (Canadian Short Process).

Another means of measuring extensibility is with the aid of an Extensigraph. Extensigraph measurements with high maximum resistance (R_{max}) to extension and moderate extensibility (length, L) are desirable for good breadmaking flour. A high R_{max}, results in a nonsticky and elastic dough, whereas large L values result in a larger LV (Liu 1996). Durum wheats normally have a higher gliadin to glutenin ratio compared to common wheats, which contributes to an extensible but inelastic dough (Feillet 1988). Furthermore, durum doughs gave lower LV than bread wheat doughs with similar strength as evaluated by the Extensigraph (Edwards et al, 2001). Boyacioglu and D'Appolonia (1994a) reported that semolina had higher extensibility (L) and R_{max} values than durum wheat flours; at 180 min, L = 17.0 and 15.9 cm and R_{max} = 4.1 and 3.1 cm, respectively. Based on the literature reviewed above, the technological quality of durum wheat for breadmaking is clearly different compared to common wheats. Lower baking absorption and lower LV is the expectation for durum wheat, with LV being moderately positively correlated to dough strength. On the other hand, varying results have been reported on the relationship between durum dough extensibility and LV, possibly as a result of the many different test baking procedures that were used by different researchers.

2.5 Effects of Blending

The use of durum wheat alone for breadmaking limits the LV. Blending durum wheat with common wheat often has been studied with the objective to improve the quality of bread produced.

Amarjeet et al. (1993) blended durum wheat with common wheat prior to milling into straight grade flour. Bread and durum wheat possessed moderate protein contents; 8.4 and 9.2%, respectively. A 60:40 blend of common wheat to durum wheat produced bread with 95% of the LV (530 cc) found for 100% common wheat bread. In contrast, 100% durum flour produced a loaf with the lowest LV (423 cc) with significantly ($p < 0.05$) lower starch damage (62%) compared to common wheat bread (66%). Particle size distribution results showed a 66.7% of particles >114 μm for 100% durum flour, whereas the corresponding value was only 42% for 100% common wheat. The 60:40 blend had 56% of the particles >114 μm. The authors concluded that the 60:40 blend gave the best quality bread (good loaf appearance, crumb texture, crumb color), better than 100% bread wheat.

Boyacioglu and D'Appolonia (1994b) studied, among other factors, the effect of blending common wheat flour with either durum wheat semolina or flour. In contrast to the research of Amarjeet et al. (1993), the authors milled the wheats separately and then blended the mill products. With increasing semolina proportions LV decreased, but corresponding durum flour blends had higher LV. The blending of durum flour with common wheat flour increases the overall gliadin content of the latter (Dexter and Matsuo 1980), which yields an extensible but inelastic dough. Boyacioglu and D'Appolonia (1994b) found durum flour blends had higher extensibility, an increase in

loaf size during fermentation and baking, producing a higher LV (700 – 775 cc) than durum flour bread (605 cc). The consistently lower LV (570 – 670 cc) of semolina blends suggest an influence of lower starch damage and/or larger particle size, as protein contents of durum flour and semolina were similar at, 15% and 14.4%, respectively. The starch damage of durum flour was three times the starch damage of semolina, indicating insufficient starch damage for gas production in the latter. The high starch damage of durum flour is indicative of the severe milling effect of the smooth reducing rollers used in the Boyacioglu and D'Appolonia (1994b) study. Typically durum semolina is produced using corrugated rolls. The authors concluded that a blend with 25% durum flour produced bread with acceptable characteristics. Bread made with 25% durum flour produced higher LV (775 cc) than 25% semolina (670 cc), although all other bread characteristics were equal. In both the above studies (Amarjeet et al, 1993; Boyacioglu and D'Appolonia 1994b) a higher proportion of common wheat to durum wheat produced optimal breadmaking results.

Depending on the baking procedure, the optimum ratio of durum flour/semolina to bread flour can be variable. Hareland and Puhr (1998) studied the optimal percentage of durum flour in a sponge and dough baking process. A blend of 60% durum flour with 40% common wheat at the dough stage of the baking process, produced a bread with good (700 cc) LV, and external loaf characteristics similar to those of 100% common wheat flour bread. The authors noted that, in preliminary studies, the sponge and dough method (long bulk fermentation) produced larger LV than the straight-dough (short fermentation) procedure. This difference could not be ascribed solely to the influence of fermentation time. The two methods differed in formula, and the time of flour and

ingredient incorporation. The authors hypothesised that the strong common wheat flour added in the dough stage, would adjust for the weak durum flour used in the preceding sponge stage. Strong flours have carrying power when added to weak flours, and can produce loaves of acceptable volume (Tipples et al, 1982). The amount of durum wheat blended with common wheat to produce acceptable bread can be influenced by many factors including the extent of starch damage, the type of baking process (long or short fermentation) employed and the intrinsic strengths of the durum and common wheats.

2.6 Effect of Textural Changes

The reportedly longer shelf-life and delayed staling of durum wheat flour breads compared to common wheat flour breads have been partly attributed to the higher water-binding capacity of durum flour (Luraschi, 1955, cited in Quaglia, 1988). Quaglia (1988) reported that durum wheat bread had a long shelf-life of over a week. One of the major changes in bread as it ages is crumb staling. It is generally agreed that the staling mechanism is caused by retrogradation of starch (Pomeranz 1988), and is manifested by an increase in bread firmness.

Pasqui et al. (1991) found that wheats with protein content at 10.8 and 14.5 % had no effect on durum wheat bread crumb firmness at 24 and 96 hr after baking. However, there was a varietal effect ($p < 0.001$) on the rate of firmness, one day and four days after baking. Breads from reduced semolina with dough P/L values ≤ 1.0 had higher LV, and were softer after day four than doughs with higher P/L values. In follow up work, Pasqui et al. (1994), found adding 4.5% supplemental gluten made the slices significantly ($p < 0.05$) less firm on day one, i.e. softer. The slices were firmer when less than 4.5%

gluten was supplemented. On day four there was no significant difference in firmness attributable to the amount of added gluten (1.5, 3.0 and 4.5%). At constant protein content (achieved by diluting flour with starch), the crumb texture was significantly ($p<0.01$) firmer at 7% protein content than at 9 and 11% (Pasqui et al, 1995). It is evident that at higher protein contents, fresh bread slices are less firm, as a result of the higher LV.

Amarjeet et al. (1993) reported a decrease (0.65 kg/g) in the firmness of fresh bread with an increase in proportion of durum wheat to common wheat. With increasing proportions of durum wheat (0 to 80%), there was a corresponding decrease from 543 to 435 cc. The compression force was 0.35 kg/g for 100% durum wheat bread, compared to 3 times the load for 100% bread wheat. The reduced firmness of durum wheat breads may partly be explained by the higher starch damage and increased Fabs levels, which contribute to higher crumb moisture levels. It is known that less bound water in the crumb structure causes an increase in crumb firmness, and a rapid recrystallization of the starch complex (Hareland and Puhr 1998).

In contrast, Boyacioglu and D'Appolonia (1994c) found that crumb firmness of durum flour and semolina bread was higher (4.6 and 6.9 Newtons) than common wheat bread (4.1 Newtons). Crumb firmness of common wheat bread on day one after baking was significantly ($p < 0.05$) lower than durum flour bread; 1.03 and 1.57 Newtons, respectively. On day four, the crumb firmness was not significantly different between the two breads. The significantly greater ($p < 0.05$) LV of the common wheat bread would explain the firmness difference for fresh bread seen on day one. The level of soluble starch can also used as a measure of the rate of staling, for as the storage time increases,

there is a decrease in the amount of extractable soluble starch (Kim and D'Appolonia 1977). Boyacioglu and D'Appolonia (1994c) found that soluble starch was not different between common wheat flour and durum wheat flour breads over the span of four days of storage. Bread from 100% durum semolina had the highest firmness value and lowest LV. The firmness of bread made with 25% semolina, or 25% durum flour blended with common wheat flour was not significantly ($p < 0.05$) different from 100% common wheat flour bread, over the storage period of four days. The LV (an important factor affecting firmness) of the blend was also comparable to that of 100% common wheat flour.

The structure of bread crumb cells is a significant determinant of the textural property of fresh bread. The structure of leavened bread is influenced by the viscosity of the dough and the carbon dioxide produced during fermentation (Bloksma 1990). There are two approaches to scoring bread, qualitatively and quantitatively. Qualitatively, bread can be scored visually, e.g. by the GRL bread score (Kilborn and Tipples 1981), and Mohs scale (Calucci 2003) which involves assigning a score to the bread sample compared to a control sample. The second approach is objective; i.e. to quantitatively measure crumb grain parameters by digital image analysis. This method has the advantage of measuring the details of the bread structure that might vary due to ingredient or process variations that could not be quantified subjectively (Sapirstein 1999).

Pasqui et al. (1991) found on average, durum wheat loaves with a high protein content (14.9% ± 0.7) had a finer bread crumb structure than lower protein content bread. In contrast, another study (Pasqui et al, 1994) found crumb grain was unaffected by higher protein content (added supplemental gluten), and the crumb structure (fineness)

did not improve. In both studies, the evaluation of bread was done qualitatively (Mohs scale). Boyacioglu and D'Appolonia (1994a) reported that the crumb structure of durum wheat bread was coarse, dense and rough, in the absence of an oxidising agent (potassium bromate). However, Dexter et al. (1994) found omission of potassium bromate had no deteriorating effect on the durum bread crumb properties.

2.7 Protein Composition

Common wheats developed for breadmaking have been researched extensively. The breadmaking potential of bread wheat is well established and a high volume white pan bread is generally accepted as the benchmark of acceptable bread. Identification of the chromosomal location of genes and the expressed subunits has been well established for common wheats. As there is a close genetic relationship between bread and durum wheats the same arrangement of storage protein genes is very likely to occur in durum wheat (Payne et al, 1984), except for the latter's absence of the D-genome.

The storage proteins can be divided into two classes: gliadins and glutenins (MacRitchie 1992). Gliadins are considered to be responsible for viscosity and extensibility, glutenins for elasticity. Gliadins are encoded by six *Gli* loci mapped on the short arm of the group 1 and 6 chromosomes, *Gli-1* and *Gli-2*, respectively (MacRitchie 1992). Gliadins are monomeric (single-chain molecules) proteins, which can be separated into groups on the basis of their electrophoretic mobility at low pH by acid polyacrylamide gel electrophoresis (A-PAGE) (Sapirstein and Bushuk 1985).

Gliadins are divided into ω-gliadins, which are sulfur-deficient, and α-, β- and γ-gliadins which are sulfur-rich and characterised by intramolecular disulfide bonds

(MacRitchie and Lafiandra 1997). Gliadins can associate by hydrogen bonds and hydrophobic interactions (Masci et al, 1991). α-, β- and γ-gliadins have similar amino acid compositions and molecular weights ranging from 30 to 50 kDa. ω-gliadins have the lowest elctrophoretic mobility and have higher molecular weights (44-74 kDa), and a distinctive amino acid composition, which lacks the sulfur-containing amino acids cysteine and methionine (Masci et al, 1991).

Polymeric glutenins comprise subunits linked by inter-chain disulfide bonds (Carrillo et al, 1990; Masci et al, 1991). On the basis of their sodium dodecyl sulfate – polyacrylamide gel electrophoresis (SDS-PAGE), these subunits can be classified into two main groups, the high molecular weight glutenin subunits (HMW-GS) and the low molecular weight glutenin subunits (LMW-GS) (Gupta et al, 1995). HMW-GS, or A subunits, are coded by *Glu-1* loci located on the long arm of the group 1 chromosome (Payne 1987) and LMW-GS, i.e. the B, C and D subunits, coded by the *Glu-3* locus which have been subdivided according to mobility in SDS-PAGE and relative isoelectric point (Payne and Corfield 1979; Jackson et al, 1983; Carrillo et al, 1990). The HMW-GS can be further subdivided according to allelic composition into a higher molecular x-type subunit and a lower molecular weight y-type subunit (Payne et al, 1987). All glutenin subunits differ in the number of cysteine residues and the size and composition of the repetitive domain (Shewry et al, 1992). In bread wheats, all HMW-GS have a single cysteine residue in the C-terminal domain. While at the N-teminal, x-type and y-type subunits typically have three and five cysteines, respectively. The y-type gene present at the *Glu-A1* is always silent in cultivated hexaploid and tetraploid wheats. In common wheats there are typically 5 HMW-GS expressed, but in durum wheats, the x-type gene at

Glu-A1 and the y-type gene at the *Glu-B1* are expressed infrequently, resulting in durum wheat having between two to three HMW-GS (Lafiandra et al, 2000). HMW-GS 20 lacks 2 cysteine residues in the N-terminal region (Buonocore et al, 1996) which could have an effect on glutenin polymer formation and its molecular size.

The distribution of cysteine residues is of interest in relation to potential covalent cross-linking in gluten. The presence of at least 2 cysteine residues in different subunits would be the minimal requirement to form intermolecular bonds in polymeric glutenin. The number of cysteine residues and their position in glutenin subunit sequences are considered to affect dough strength in both bread and durum wheats by forming a polymeric network (Lafiandra et al, 1984; Troccoli et al, 2000). Glutenin proteins with sequences characteristic of gliadins (Lafiandra et al, 1984) are termed D-subunits. D-subunits are considered to have arisen from mutation of genes encoding ω-gliadins, resulting in a change from none to one cysteine residue capable of forming disulfide bonds (Masci et al, 1999). D subunits are the most acidic. Gliadin-type glutenin subunits generally have an odd number of cysteine residues (D'Ovidio et al, 1995), i.e. both C and D group LMW-GS (Kasarda 1989; Lafiandra et al, 1999). A growing glutenin polymer is believed to be terminated when a glutenin subunit with only one cysteine residue available is incorporated into the polymer (Masci et al, 1999). One cysteine residue in one polypeptide subunit is likely to be involved in intermolecular disulfide bonding with another cysteine residue of a different subunit, thereby acting as chain terminators preventing further development of the glutenin polymer. This would result in a decrease in the average molecular weight of the glutenin fractions and consequently have a negative effect on dough strength and viscoelastic properties (Masci et al, 1999). LMW-

GS, B and C subunits are encoded mainly by the *Glu-3* locus of the group 1 chromosome (Payne 1987), but some are encoded by the *Gli-1* locus (Lafiandra et al, 1984). Both loci are located on the short arms of the group 1 chromosome. The B group comprises the greatest number of subunits, having slightly lower SDS-PAGE mobilities than for α-, β- and γ-gliadins, and being more basic than the other storage proteins. Among LMW-GS, C subunits have the highest SDS-PAGE mobilities, and have a wide range of isoelectric points and overlap in SDS-PAGE with α-, β- and γ-gliadins (Carrillo et al, 1990).

Further two allelic genes in durum wheat related to polypeptides belonging to LMW-GS, i.e. LMW-1 and LMW-2, have been characterised (Payne et al, 1984). Furthermore, Carrillo et al. (1990) showed that there are different LMW-1 and LMW-2 types: LMW-1, LMW-1^{-}, LMW-2, LMW-2^{-} and LMW-2*. LMW-2 and LMW-1 glutenin groups were marked by the presence of 2 bands each. The size and mobility of the narrow, fast moving band of LMW-2 was the same as the slow band of the LMW-1. Subunit patterns of LMW-2 without the faster band were named LMW-2^{-}. The LMW-1 band pattern, missing the faster band was called LMW-1^{-}. LMW-2* had a slightly slower wide band corresponding to LMW-2 pattern. This large variation lead to the conclusion that the majority of B subunits were inherited as 2 groups, controlled at *Glu-A3* and *Glu-B3*, which are tightly linked with *Gli-A1* and *Gli-B1* (Ruiz and Carrillo 1993; Nieto-Taladriz et al, 1997).

γ-gliadins are under the genetic control of the *Gli-B1* locus, which also contains the genes that code for some ω-gliadins and LMW-GS (Payne et al, 1984; Shewry et al, 1986). At the *Gli-B1* locus, 2 major γ-gliadins and corresponding *Glu-3* loci LMW-GS are associated with durum wheat gluten strength: the allele '42', that codes for γ-gliadin

42, ω-gliadins 33-35-38, and LMW-1, are associated with gluten weakness; and allele '45', that codes for γ-gliadin 45, ω-gliadin 35, and LMW-2, are associated with gluten strength (Damidaux et al, 1980; Feillet et al, 1989). Damidaux et al. (1980) discovered that some durum wheat gliadin proteins were related to pasta cooking quality. Gliadin band 45 was associated with high elastic recovery of pasta and band 42 with poor elastic recovery. Further work on the relationship of the γ-42 and γ-45 bands to superior pasta cooking quality confirmed earlier findings (Kosmolak et al, 1980). In contrast, HMW-GS patterns do not appear to be related to viscoelastic properties of durum gluten. DuCros (1987) found that HMW-GS appeared to have a less crucial effect on pasta cooking properties, but this was not clearly established because of the limited genetic variability of *Glu-1* genes present in modern durum wheat cultivars. It was later established that gliadin γ-bands were genetic markers, and the corresponding LMW-GS strongly contributed to pasta firmness and elasticity. LMW-GS are the predominant fraction of durum wheat glutenin and the content in durum wheat of gliadin γ-45 type is higher (28%) than in γ-42 type (15%) (Feillet et al, 1989). Durum wheat carrying γ-45 can exhibit 6 different LMW-GS alleles (a,c,d,e,f,g) at the *Glu-B3* locus (Nieto-Taladriz et al, 1997), and this has been considered as a possible explaination for the range in pasta quality for gliadin γ-45 types. Further studies of LMW-GS encoded at the *Glu-3* locus (Pogna et al, 1988; Ruiz and Carrillo 1995), and tightly linked to the *Gli-1* loci were found to be responsible for differences in quality, rather than gliadin bands.

The LMW-GS class of proteins are diverse in numbers yet similar in electrophoretic mobility, making it difficult to identify specific contributions. The presence of LMW-2 is considered beneficial to pasta cooking quality. The quality-

related differences, whether quantitative and/or structural between wheats carrying LMW-1 and LMW-2, are still being debated. Masci et al. (2000) noted that it was likely the higher amounts of LMW-GS associated with LMW-2, that was more responsible for quality differences.

Hexaploid wheat (common wheat) has three genomes denoted as A, B and D. Durum wheat is a tetraploid wheat and has two genomes (A and B), lacking the D genome. The missing D-genome in durum wheat, particularly chromosome 1D which carries important determinants of dough strength and baking quality in hexaploid wheat (Welsh and Hehn 1964), would provide a genetic basis for the difference in quality between common and durum wheat. The absence of the D chromosome in durum wheat was observed to negatively affect breadmaking quality (Orth and Bushuk 1973). Microscopic study of glutenin of hexaploid wheat showed a fibrous structure with several thick strands intertwined with thin strands. In contrast tetraploid (derived) wheat was characterised by flat ribbonlike structures (Orth et al, 1973); the loss of fibrous structure appears to affect the structure of glutenin in tetraploids. Vensel et al. (1997) stated that it was likely that differences between durum and bread wheat cultivars result mainly from the differences in the proportions of the various glutenin subunits, rather than from the general absence in durum wheat of components coded by the D genome.

Pogna et al. (1996) demonstrated the *Gli-D1/Glu-D3* loci encoding for some HMW-GS of the chromosome 1D influenced the breadmaking properties of a bread wheat cultivar (Perzivan) crossed with durum wheats. Progenies with *Gli-D1/Glu-D3* occurring on chromosome 1AS translocated from chromosome 1DS caused an 18%

increase in Alveograph W value and a 66% decrease in P/L ratio. Accordingly, the allele at *Gli-D1/Glu-D3* corrected the tenacious dough characteristics of durum wheat.

HMW-GS in durums generally have a null allele at the *Glu-A1* locus and have limited variability at *Glu-B1*. Bread wheats have a greater allelic variability at *Glu-B1* and *Glu-A1* (Branlard et al, 1989). HMW-GS are believed to affect the breadmaking quality of bread wheats. Durum wheats lack the D genome, and thus have far less HMW-GS than hexaploids (Shewry et al, 1997), which in turn affects the breadmaking quality.

The glutenin to gliadin ratio has been suggested to influence dough viscoelastic properties as a change to a higher ratio can result in stronger doughs (MacRitchie and Lafiandra 1997). Although a flour could have a higher ratio of glutenin to gliadin, if the glutenin polymers were of lower 'quality', the expected relationship might not be seen. The ratio of HMW-GS:LMW-GS is also an important factor that affects extensibility and Mixograph dough development time (MacRitchie 1992). On mixing dough to peak development, the protein strands form a continuous network. The strength of the dough depends on entanglement points between the long chains. During mixing the entanglements loosen, reducing the points of support when the dough is subjected to stress and covalent bonds are broken causing the large molecules to break down (MacRitchie 1992).

Many solubility methods are derived from the Osborne (1907) classification of wheat proteins based on sequential extraction with water, salt solution and 70% ethanol. Osborne (1907) classified wheat proteins into four fractions: water-soluble albumins, salt-soluble globulins, alcohol-soluble gliadins and alcohol-insoluble glutenins. The overlapping solubility of gliadin and glutenin proteins have made clean isolation of each

protein fraction difficult, and have confounded efforts to demonstrate their functionality in breadmaking quality. In studies of bread wheat flour of different baking quality, having greater levels of insoluble proteins correlated to stronger flours possessing better baking performance (Orth and Bushuk 1972; MacRitchie 1992; Sapirstein and Fu 1998). Curioni et al. (2000) studied the importance of unextractable glutenin polymers in determining the quality characteristics of durum wheat. The unextractable fraction had a low proportion of HMW-GS and a high proportion of LMW-GS. The LMW-GS seemed to be the fraction with a relatively high degree of intermolecular bonding. The high level of networking resulted in a lack of elasticity and high tenacity of durum doughs, characteristics beneficial for the production of pasta, but detrimental to the baking performance of durum wheats.

Durum wheats have protein contents comparable to common wheat. But, the key difference is that durum wheats have a higher amount of LMW-GS to HMW-GS, and a lower ratio of polymeric to monomeric prottein content.

2.8 Durum Wheat Breadmaking and Technological Quality in Relation to Protein Composition

The breadmaking quality of durum wheat, particularly LV, improves with increased dough strength. Early studies showed, that baking performance of durum wheats was established to be similar to weak common wheats (Dexter et al, 1981). The fundamental properties of weak common wheats and durum wheats (dough mixing time, loaf volume per unit protein content) appeared to be similar. Durum wheats possessed weaker dough strength than common wheats based on SDS-sedimentation values. Quick and Crawford (1983) found durum wheat dough to be less elastic, less pliable and

weaker than hard red spring wheat dough, although doughs from strong gluten durums were more elastic than those from weaker durums. The strong durums produced greater LV than the weak cultivars and approached breadmaking quality of bread wheats.

With the numerous reports of the close relationship in common wheats of specific HMW-GS and baking quality, the same relationship was identified to be possible for durum wheats. DuCros (1987) found HMW-GS (via aggregation: disulfide bonding and non-covalent interactions) to be important to the dough strength but, concluded they were poor predictors of strength.

Boggini and Pogna, (1989) evaluated the particular HMW-GS associated with improved breadmaking quality of durums. They found a clear difference between γ-45 lines producing loaves with higher LV than γ-42 types. The accompanying HMW-GS compositions appeared to affect the breadmaking quality. Cultivars having subunit pair 7+8 produced the highest LV, and while 6+8 types had lower LV. Subunit 20 resulted in slightly poorer LV compared to subunits 7+8. LV was affected by HMW-GS in the following order: 7+8>20>6+17>13+16>6+8. The additive effect of γ-gliadin 42/45 and HMW-GS compositions was further studied; the cultivars with γ-45 and HMW-GS 7+8 had the highest LV. All HMW-GS compositions with γ-45 were better performing cultivars than those cultivars with γ-42. Cultivars Arcangelo and Grazia, both carrying γ-45 gliadin and HMW-GS 20, produced varying LV of 495 and 730 cc, respectively. This variation was not explained by the HMW-GS 20. The benefits of LMW-2 glutenin subunits to the baking performance of the two cultivars was likely the strong contributing factor to LV variation. The HMW-GS 6+17 is rare in durum wheat cultivars and LMW-2 is usually associated with γ-45. The authors speculated that other combinations such as

γ-42 (LMW-2)/7+8, γ-45/6+17, and γ-42 (LMW-2)/6+17 might favourably increase the baking quality of durum wheat.

Pena et al. (1994) examined the interrelationship between HMW-GS (*Glu-B1* locus) and LMW-GS (*Glu-B3* locus) composition and the breadmaking properties of Mexican durum cultivars. The cultivars carrying HMW-GS 7+8 had a significantly ($p < 0.05$) higher LV, while those with HMW-GS 6+8 had LV comparable to cultivars with HMW-GS 20. The higher LV associated with HMW-GS 6+8 was contrary to the results found by Boggini and Pogna (1989). Pena et al. (1994) also found that LMW-2 was associated with higher LV and Alveograph W values than LMW-1 types. Due to the imbalance of samples with LMW-1 (n=5) and LMW-2 (n=21), these conclusions should be accepted with caution. The effect of genetic linkage of γ-42 and LMW-1, and γ-45 and LMW-2, on LV results have been reported (Boggini and Pogna 1989; Pena et al, 1994). This indicates that gliadin and/or LMW-GS composition could also be influencing breadmaking quality confounding the contribution of HMW-GS (Pena et al, 1994). The combination of LMW-2 and HMW-GS 7+8 had significantly ($p < 0.05$,) higher LV compared to HMW-GS 6+8 and 20. Variation at the *Glu-B1* (HMW-GS) locus was identified as the most important factor in determining the bread-making quality of the durum wheat used.

In contrast, Carrillo et al. (1990) found HMW-GS to be poor indicators of durum wheat dough strength based on SDS-sedimentation results; HMW-GS 20 had a strong negative effect on the strength parameter with no significant ($p < 0.05$) difference between HMW-GS 6+8 and 7+8. On the other hand, LMW-GS patterns showed a significant difference for the evaluated patterns. Gluten strength decreased in the order

LMW-2 > LMW-2$^-$ > LMW-2* ≅ LMW-1 >LMW-1$^-$. LMW-2$^-$ is missing a protein subunit, compared to LMW-2. The study concluded that HMW-GS composition is not a good indicator of strength, compared to LMW-GS patterns.

The work of Pogna et al. (1990) suggests that allelic variation at *Glu-B3* and *Glu-B1* would have a major effect on durum quality as determined by SDS-sedimentation and the viscoelastograph. The close genetic linkage between *Gli-B1* and *Glu-B3* posed the question at the time as to whether the effects on quality were due to the glutenin subunits or gliadin protein. ω-gliadins encoded at *Gli-B1* and LMW-GS encoded at *Glu-B3* are closely linked genetically, but a LMW-2 subunit was responsible for improved gluten strength by SDS-sedimentation volume. The allelic variation at *Glu-B1* (7+8, 6+8 or 20) had a smaller effect than variation at *Glu-B3* (LMW-2/LMW-1) for gluten elastic recovery. The effect of HMW-GS 7+8 and LMW-2 was additive, being characterised by better gluten elastic recovery and SDS-sedimentation volume. Progeny crosses with Creso (γ-gliadin 45 and HMW-GS 6+8) resulted in no correlation of the allelic gliadins and HMW-GS with SDS-sedimentation volumes. They concluded that LMW-2 rather than ω-gliadin 35, was responsible for effects on quality.

Ciaffi et al. (1995) evaluated among others the effect of allelic variation at *Glu-A1*, *Glu-B1* and *Glu-B3* on durum wheat quality. Protein content, extensibility (Alveograph L) and dough development time (Mixograph) were not significantly affected by allelic variation at *Glu-1* and *Glu-3* loci. Positive influences of LMW-2 and the presence of x-and y-type HMW-GS at *Glu-A1* on the LV were found. The presence of both *1Ax* and *1Ay* subunits, increased the proportion of polymeric protein by 4%, and correspondingly resulted in an increase in breadmaking properties.

Ammar et al. (2000) evaluated the baking performance of durum genotypes and bread wheat genotypes. All durum cultivars expressed the LMW-2 allele at *Glu-B3* locus, with varying allelic composition at the *Glu-B1* locus. Genotypes with HMW-GS 6+8 were characterised by the best overall breadmaking quality (greater extensibility, P/L=1.2, high LV). The better baking performance was not explained by the amount of total polymer in flour, or the differences in the ratio of polymeric to monomeric protein among the different allelic compositions at the *Glu-B1* locus. Interestingly, Alveograph W, was not significantly different between HMW-GS 6+8 and 20. HMW-GS 7+8 and 20 was related to high Alveograph W values, due to high Alveograph P, with no concomitant increase in extensibility (Alveograph L). The difference in baking performance between HMW-GS 6+8 and 7+8 was attributed to differences in extensibility. The authors suggested that HMW-GS 6+8 possessed better secondary interactions between adjacent gluten polymers than HMW-GS 7+8. The improved performance of HMW-GS 6+8 over 20 was ascribed to the combination of greater dough strength and dough extensibility. The conflicting results of the Ammar et al. (2000) study and earlier work (Boggini and Pogna, 1989; Pena et al, 1994) suggest that *Glu-B1* is not a reliable indicator of breadmaking quality. Palumbo et al. (2002) found a negative relationship between Alveograph P/L and LV of durum cultivars. Higher LV was achieved for cultivars with lower Alveograph P.

There is strong agreement on the selection of γ-45 as markers for varieties with improved breadmaking quality, but the contribution of HMW-GS or LMW-GS individually is disputed. It is evident that the specific composition and proportion of glutenin subunits are the main determinants of the breadmaking quality of durum wheat.

The dissimilarity in results are likely influenced by the allelic variation among durum wheat cultivars of differing glutenin proportions.

3. MATERIALS AND METHODS

3.1 Wheat Samples and Milling

The sample set consisted of 13 genotypes grown under similar conditions in Regina, Saskatchewan in 1998. The sample set comprised of 11 durum wheat genotypes and 2 common wheat genotypes. The durum genotypes were chosen for their diverse gluten strength and the CWRS and CWES class cultivars were included to compare their performance against the durums. CWRS has excellent baking quality and CWES was a good check against the strongest durum genotypes. All samples appeared sound.

Table 1. Class, genotype and high molecular weight glutenin subunit (HMW-GS) properties of sample set.

Sample Number	Class	Genotype	HMW-GS
1	Canada Western Amber Durum (CWAD)	AC Melita	6+8
2	CWAD	AC Morse	6+8
3	CWAD	Kyle	6+8
4	Canadian breeding line	DT 674	6+8
5	Canadian breeding line	DT 369	6+8
6	U.S. Desert Durum	Durex	6+8
7	Italian Durum	Ofanto	20
8	Italian Durum	Grazia	20
9	Italian Durum	Simeto	7+8
10	Italian Durum	Creso	6+8
11	Italian Durum	Arcangelo	20
12	Canada Western Red Spring (CWRS)	AC Barrie	7+8/7+9; 2 biotypes
13	Canada Western Extra Strong (CWES)	Glenlea	(7)*+8

* (7) denotes over expressed subunit.

Samples were tempered to 16% moisture overnight at room temperature and milled into straight grade semolina (for durum) or farina (for common wheat hereafter collectively referred to as semolina), on an Allis-Chalmers Laboratory Mill incorporated with modified Grain Research Laboratory (GRL) sifter units and a laboratory purifier,

following the mill flow details as outlined by Dexter et al. (1990). Milling and sizing were done on corrugated rolls. For each of the 13 samples the following milling and blending steps were followed:

1) In step one of the milling step, one third the semolina was blended with ⅓rd the flour to give a straight-run granular mill product (G). The remaining ⅔rd portion of flour was set aside. In further treatments the particle size of the semolina was reduced to increase the starch damage and in turn increase gassing power as described in the next two steps.
2) In step two, ⅔rd semolina was gently reground twice, on sizing rolls to give twice reduced mill product (2R). One half of the 2R semolina was set aside.
3) In step three, the remaining 2R semolina was further re-ground four times to give six times reduced mill product (6R).

Finally, the 2R and 6R fractions were blended with ⅓rd flour from the first milling step to give the final products. This approach assured that the degree of refinement of the three final products for each genotype was the same, and that differences in processing properties were solely related to particle size and starch damage.

3.1.1 Sieve Analysis

One hundred grams of semolina was shaken for two min on a Ro-tap sieve shaker and the fractions separated were weighed. Semolina granulation was determined on a series of US standard sieves: #40 (420 μm), #60 (250 μm), #80 (180 μm) and #100 (150 μm).

3.2 Chemical Tests

3.2.1 Moisture Content of Grain and Semolina

A HalRoss moisture meter (Model No. 919, Labtronics, Canadian Aviation Electronics Ltd., Winnipeg, Manitoba) was used to determine the moisture content of whole grain. The moisture content of semolina samples was determined on a semi-automatic moisture tester (Brabender Corporation) by the air oven method according to the AACC approved method 44-15A (AACC, 2000).

3.2.2 Ash Content of Semolina

An electric muffle furnace was used to determine the ash content of semolina samples according to the AACC approved method 08-01 (AACC, 2000).

3.2.3 Protein Content of Semolina

Total nitrogen of semolina samples was determined by combustion nitrogen analysis using a Dumas (LECO Model FP-428, St. Joseph, MI) CNA Analyser (Sweeney and Rexroad, 1987). A factor of 5.7 was used to convert total nitrogen to protein content.

3.2.4 Starch Damage of Semolina

Starch damage of semolina samples was determined using a Megazyme kit according to the AACC approved method 76-31 (AACC, 2000), and GRL modified; hexokinase was substituted in place of the glucose oxidase/peroxidase enzyme (GOPOD) system.

3.3 Technological Analysis

3.3.1 Mixograph Test

Semolina (2 g, 14% moisture basis) was mixed at constant absorption (50%), temperature (25 °C) and mixer speed (88 rpm) on a 2 g direct-drive computerized Mixograph (National Manufacturing Company, Lincoln, NE), utilizing Mixsmart software version 3.73. Data acquisition and analysis was performed with the following settings: 160 for top, middle and bottom filters; 3 filter stages; minimum and maximum torque standard readings of 63 and 900, respectively; peak fit windows of 10% was set for top and middle curves. The mixogram envelope middle-line curve was used for all analyses. Figure 1 shows a sample mixogram.

Mixogram parameters were evaluated as follows: Mixograph mixing time to peak dough development (MT, min), band width at peak dough resistance (BW, %Torque), peak dough resistance (PDR, %Torque), peak dough resistance at 2 min past peak (MP+2, %Torque) and work input to peak dough development (WIP). WIP was determined as %Torque*min, which is a measure of power consumption of the Mixograph. Breakdown Resistance (BR, %) was calculated as [100*(PDR-DR_{TX})/PDR], where DR_{TX} denotes dough resistance at 2 min past MT. Figure 1 descriptors: MP, denotes peak mixing time (i.e. MT) and TX, denotes break down resistance (i.e. MP+2).

3.3.2 Farinograph Test

Semolina (50 g, 14% moisture basis) was mixed in a 50 g 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 the AACC approved method 54-21 (AACC, 2000).

3.3.3 Alveograph Test

Alveograph curves were obtained using the constant pressure Model MA82 (Chopin SA, Villeneuve-la-Garenne, France) according to the ICC (1980) standard no. 121 method. Maximum peak height (P, mm), length of the curve (L, mm) and work of deformation until rupture (W, $*10^{-4}$ J) were automatically calculated by the interfaced computer.

3.3.4 Gassing Power Test

Gassing power of a slurry was measured according to the AACC method 22-11 (AACC, 2000). The formula included 3% sucrose and 10 ml of 3% suspension of compressed yeast. The equipment used was a GasSmart computerized pressuremeters system (National Manufacturing Division, Lincoln, NE, USA), using GasSmart software version 3.31. The amount of carbon dioxide produced was measured as gas pressure (PSI) at 300 min. A sample GasSmart curve is shown in Figure 2.

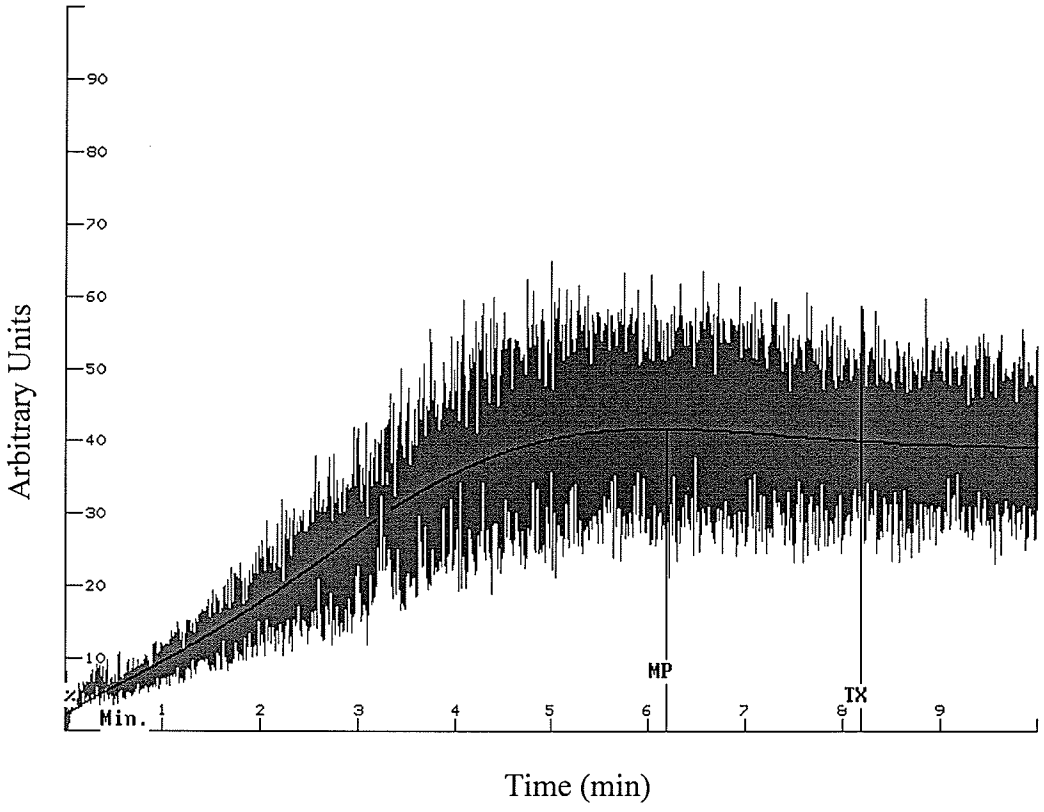


Figure 1. Representative Mixograph curve.

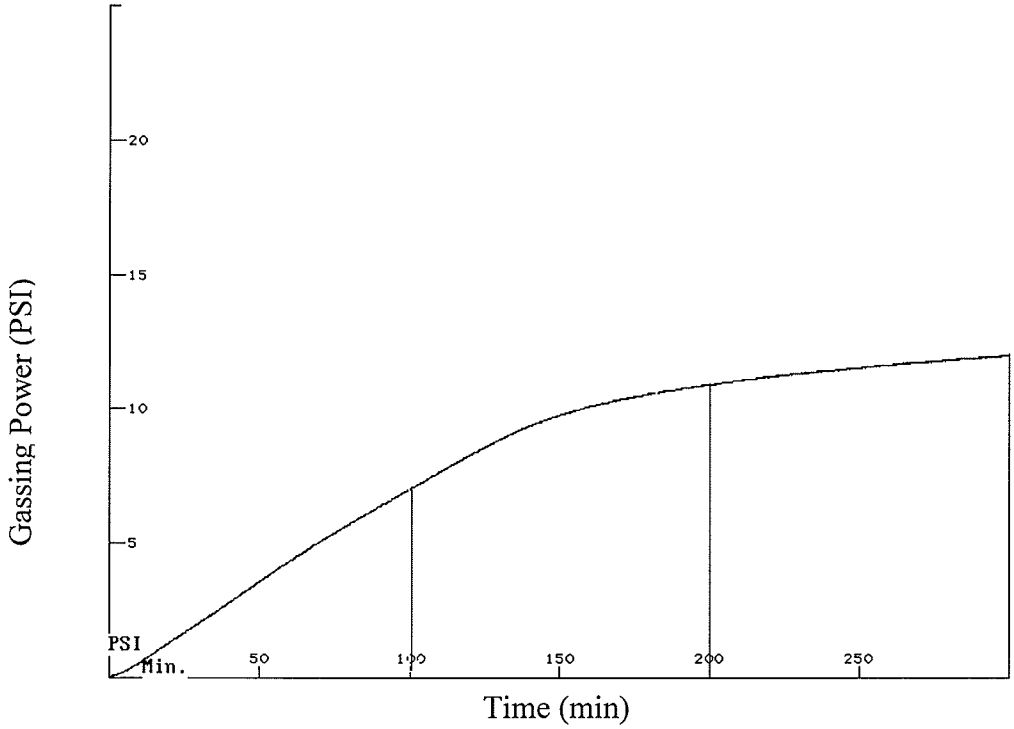


Figure 2. Representative gassing power curve.

3.4 Protein Fractionation and Analysis

Protein fractionation was done according to the method of Sapirstein and Johnson (2000), which quantified 3 fractions: 50% 1-propanol soluble protein (SP), 50% 1-propanol insoluble glutenin (IG) and residue protein (RP) by difference between flour protein content and (SP+IG). For each of the 13 genotypes, 100 mg of the sample and 1 ml of 50% 1-propanol (solution 'A') were mixed in a microfuge tube and vortexed at 10 min intervals. After 30 min extraction at room temperature, the mixture was centrifuged for 3 min at 2,200 x g with a tabletop centrifuge (Canlab Biofuge A, Manufactured for American Scientific Products, Model 1302). The supernatant was decanted and saved to quantify SP. The residual pellet was resuspended with the aid of a micro spatula in another 1 ml of solution 'A'. After 30 min extraction the second mixture was centrifuged for at room temperature 3 min at 15,000 x g. The supernatant was decanted and any remaining liquid in the tube was extracted by Pasteur pipette.

Afterwards the supernatants were pooled and the combined supernatants correspond to the SP fraction which contained monomeric and soluble glutenin protein (Fu and Sapirstein 1996). The SP fraction was diluted 100-fold, and quantified by UV-spectrophotometry (214 nm) which measured the peptide bond absorbance. A 1 ml aliquot of solution 'A' provided the blank for the spectrophotometry. Soluble protein content of the samples was subsequently determined using a calibration curve of UV absorbance to protein concentration.

To extract IG protein, the remaining 50% propanol insoluble protein pellet mentioned above, was extracted with 1 ml solution 'A' containing 0.1% (w/v) dithiothreitol (DTT). The concentration of DTT was adequate to solubilize the propanol insoluble glutenin by

partial reduction. A micro-spatula was used to disrupt and resuspend the dense pellet. The mixture was extracted for 30 min at 55°C in a heating block and vortexed at 10 min intervals. All samples were vortexed after being heated for 2 min of initial extraction to ensure complete suspension of the pellet. After 30 min, the mixture was centrifuged at room temperature for 3 min at 15,000 x g. The microfuge tube was inverted to obtain a homogeneous mixture of IG. The supernatant was then diluted 100-fold and analysed spectrophotometrically at 214 nm to determine IG content.

3.5 Baking Tests

3.5.1 Formulation, Fermentation, Sheeting and Process

The 13 genotypes of this study were investigated for baking quality. The Remix-to-peak bake test (Kilborn and Tipples 1981) was used to produce 100 g pup loaves, using the following formula: flour (14% moisture basis, 100%), yeast (Fleischman's compressed, 3%), salt (1%), sugar (2.5%), potassium bromate (0.0015%), ammonium phosphate (0.10%), malt syrup (60L, 0.60%), water (to optimum amounts). Depending on flour moisture, Farinograph absorption, and handling properties at the time of panning, the amount of water added was determined. Optimum baking absorption levels was determined, before the experimental set was baked. Baking absorption was dependent on the mill product (G versus 6R) and varied considerably from that of Farinograph absorptions.

In preparation for mixing, flour samples were weighed into 100 gm portions, sugar-salt solution and yeast water solution were stored in a warming cabinet set at 30 ± 0.5 °C. The ingredients were added into a GRL200 Mixer mixing bowl in the

following order: flour, salt-sugar solution, dough water with potassium bromate and ammonium phosphate and finally the yeast suspension. The mixture was mixed at 135 rpm at 30 °C for 3.5 min. Doughs were fermented for 2 hr and 45 min at 30 °C and relative humidity (RH) of 83%, and were subsequently remixed to 10% past peak dough development time. Doughs were then allowed an intermediate proof of 24 ± 1 min in the fermentation cabinet, at 83% RH and 30 °C.

After fermentation, the dough was successively passed through sheeting rolls three times at roll gaps of 11/32", 3/16" and 1/8", respectively on a National sheeter (National Manufacturing, Lincoln, NE, USA). The dough sheet length (DSL, cm) was measured after the final pass and then the dough sheet was moulded for 30 ± 2 sec on a GRL moulder (Kilborn and Irvine, 1963). Panned dough was proofed for 25 min in the fermentation cabinet (30 °C and 83% RH) and then baked for 25 min at 220 °C and cooled for 25 min before further assessment. Loaf height was measured before entering the oven and after baking and the difference was recorded as oven rise (OR).

After cooling, the loaves were assessed for LV by rapeseed displacement using a volumeter, and loaf weight on an analytical balance. Subsequently, the loaves were sliced on the day following baking to 12 mm thick slices on an Oliver Commercial Bread Slicer (Model 797G, Oliver Machinery Company, Grand Rapids, MI, USA, Serial No. 118356) and evaluated over a five-day period, subjectively and instrumentally. On the first day (day after baking), the loaves were appraised visually (subjectively) and assigned a score for loaf appearance, crumb structure and crumb color (see below for details). On the second day, the same loaves were double-bagged in polyethylene bags

for 24 hrs and appraised instrumentally by a line scan digital imaging system in the Department of Food Science (see section 3.7 for details).

3.5.2 Fermentation and Baking Treatments

The standard initial fermentation time of 165 min was varied to include 15 min (no time) and 90 min treatments. The samples were baked in duplicate.

3.6 Subjective Bread Scoring

Bread scoring comprised a visual appraisal of the loaf appearance, crumb structure and crumb color. Fluorescent 40 watt lamps were set up on a specially designed table for bread scoring (Kilborn and Tipples 1981). The breads were scored on a scale of 0.5 to 10 and when appropriate, letters were added to identify undesirable features not covered by the numerical values. A total bread score was determined from LV, loaf appearance and crumb properties. The scores for each visual factor first were adjusted by deducting downward when an undesirable trait was present. The designated deductions were as follows; for loaf appearance: very old (vo=1.5), old (o=1.0), slightly old (slo=0.5), and very slightly old (vslo=0.2); for crumb structure: very open (vo=1.0), open (o=0.5), slightly open (slo=0.2), very close (vcl=1.0), and close (cl=0.5); for crumb color: grey (0.5 to 1), dull (0.2 to 0.5), and yellow (0). As a standard of comparison, one bread wheat flour control sample was baked each day along with the other varieties and used as a reference.

The total bread score was calculated with the formula [(loaf volume x corrected loaf appearance x corrected crumb structure x corrected crumb color)/5000].

3.7 Line Scan Digital Image Analysis

3.7.1 Imaging System

The digital image analysis system encompassed the following components: digital line-scan camera, quartz halogen light source and camera power supply, end-drive conveyor and DC motor and digital tachometer (Figure 3.). The camera was a high performance EG&G Reticon LD2020 featuring a 2048 pixel line sensor, pixel size of 14 x 14 μm, with a maximum pixel rate of 33 MHz. Focus was provided by a 50 mm F-mount lens, using an aperture of f/11. The lighting system comprised dual 25 cm fiber optic light lines with a quartz halogen light source to ensure uniform illumination.

The fiber optic lighting was a cool light, which minimized drying of the product during image acquisition. The geometry of the lighting was 0/30 ° angle. The conveyor system was comprised of four components: conveyor belt, DC end-drive motor, integrated solid–state motor controller, digital tachometers and encoder and pulse counter. The conveyor system was set at a constant sample transport rate of 35 on the tachometer. The encoder wheel controled the image acquisition rate to obtain precise images with the desired aspect ratio (i.e. in square pixels) to eliminate spatial distortions of the image. The gray level (GL) threshold for image segmentation (Sapirstein et al, 1994) was set at 160 ± 1. Overall, the system produced images with excellent clarity and contrast.

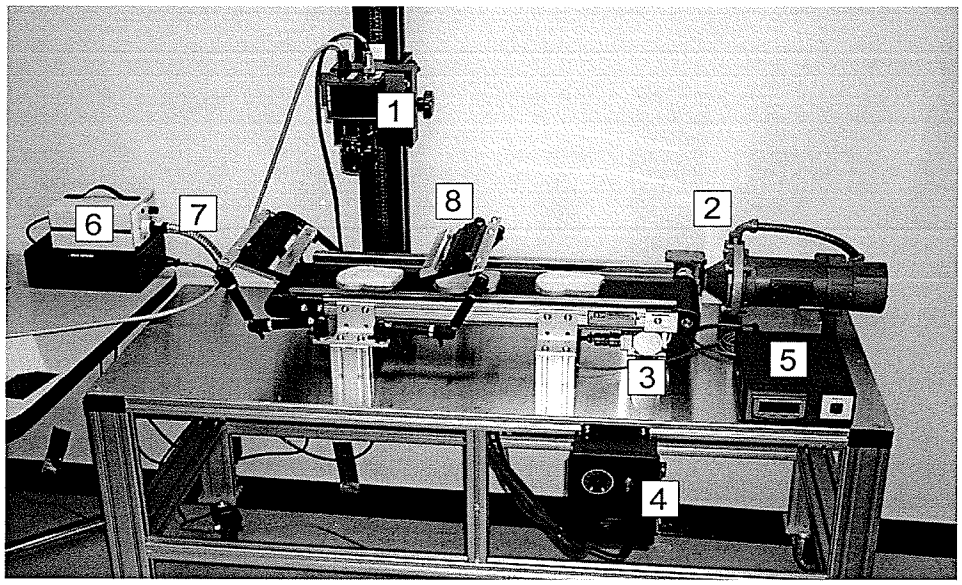


Figure 3. Digital imaging system.

(1) digital line-scan camera, (2) end-drive conveyor and DC motor, (3) encoder, (4) digital tachometer, (5) pulse counter, (6) quartz halogen light source and camera power supply, (7) fiber-optic cable, (8) fiber-optic light line w/cylindrical lens.

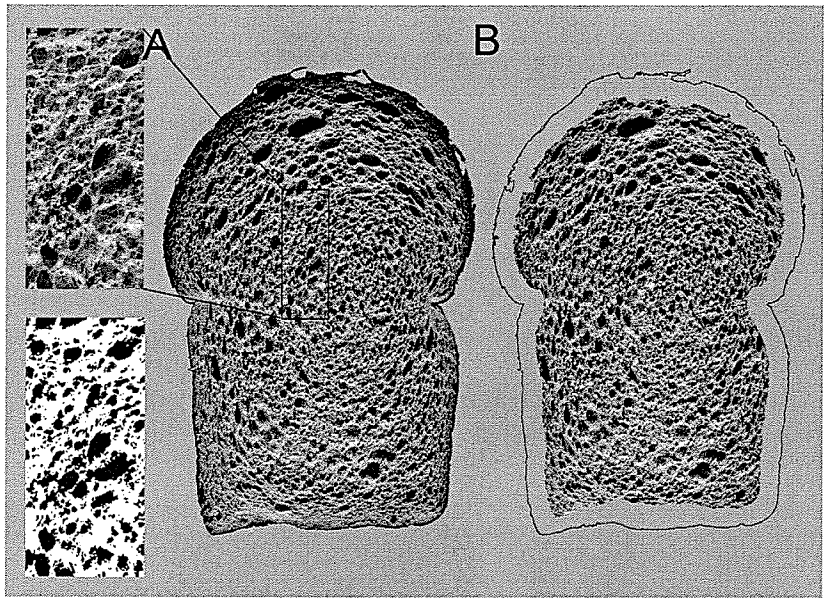


Figure 4. Representative digital image of a bread slice from the imaging system.

(A) illustrating overall image quality as well as "erosion" processing result for crust elimination (B), and binary image segmentation of a rectangular section of the crumb by the K-means algorithm.

3.7.2 Image Acquisition and Processing

Digital imaging of the crumb grain was performed to objectively evaluate the slices. Loaves were sliced on the day following baking to 12 mm thick slices as described earlier. This typically resulted in generating 8 slices per loaf, of which the 6 central slices were used for image analysis. The slices were visually scored on the day after baking and were stored overnight in the incubator at room temperature in closed polyethylene bags. Digital images of bread slices were always acquired on day two after baking. A digitally imaged Canadian ten cent coin was used to monitor the precise analysis of the systems integrity. The slices were placed on the conveyor belt and scanned in rapid succession. These images were saved and analyzed on the imaging computer. Small adjustments to the intensity of the light source were made to ensure a constant level of illumination using a gray-level working standard. A gray-level value of 160 on a scale of 0-255, was designated as the target reflection for the working standard. Figure 4 shows a representative area of a bread slice for analysis

Crumb grain parameters computed by DIA used in this study were:

- AREA_ALL (area of the slice in mm^2)
- AREA_GT_25 (total area of cells greater than 25 mm^2)
- CELL_DENSITY (Cell density (cells/ mm^2))
- CWT (Average cell wall thickness, μm)
- VOID_FRACTION (Ratio of cell area divided by area of the slice)
- LESS_7 (Number of cells smaller in area than 7.0 mm^2)
- AVG_GL (Average crumb gray level) and

- NO_CELLS (Number of cells in a slice).
- AVG-Area (average cell area, mm^2)
- S_L Ratio (Number of cells < 4.0 mm^2 divided by number of cells > 4.0 mm^2)
- BET_7_25 (Number of cells between 7.0 and 25.0 mm^2 in area)
- GREATER_25 (Number of cells greater in area than 25.0 mm^2)
- SC_AVG_AREA (Average area of cells smaller than 4.0 mm^2)
- SC_EQU_DIA (Equivalent diameter o cells smaller than 4.0 mm^2)
- CELL_AREA (Total area of cells in a slice mm^2)
- AREA_LT_7 (Total area of cells < 7.0 mm^2)
- AREA_BT_7_25 (Total area of cells between 7.0 and 25.0 mm^2)
- POR_AREA_GT_25 (Area proportion of cells > 25.0 mm^2)
- POR_AREA_LT_7 (Area proportion of cells < 7.0 mm^2)
- POR_AREA_BT_7_25 (Area proportion of cells between 7.0 and 25.0 mm^2)

Stepwise regression analysis to subjectively determine bread score by DIA:

The MAXR (maximum R^2 improvement option) was performed using SAS procedure stepwise (SAS/STAT User's Guide Version 6.03, SAS Institute, Cary, NC). This was performed to find and select the best linear regression model for prediction of the bread score, correlated to the subjectively (GRL method) determined scores. The MAXR stepwise regression method begins by finding the one-variable model producing the highest R^2. Followed by adding another variable, that yields a higher R^2. Once the two variable model is obtained, each variable in the model is compared to each variable not in the model. For each comparison, MAXR determines if replacing the variable in the model for the other would increase the R^2. On comparing all variables, MAXR

switches to the variable that produce the largest increase in R^2. Thus, the two-variable model achieved is considered the "best" model the technique can find.

3.8 Texture Analysis

A modified compression test based on (AACC- 74-10A) was used to measure the bread firmness and crumb resilience using the TA.XT2i texture analyzer (Texture Technologies Corp., New York). A 12mm thick slice was placed on the platform with a ¾ inch diameter steel ball probe screwed onto a probe carrier. Test program parameters were set to compress the slice to a 1mm/s to a 4 mm depth i.e. 25% of slice thickness, and return the probe to its start point at 1mm/s. The test was repeated twice with a pause distance of 1 mm at the end of the first stress compression before proceeding with the second compression. This test allowed measurement of recovery of the crumb structure to compression.

The Texture Expert software was used to measure the force peaks of both compressions (PF_1 and PF_2), gradient of PF1 (measure of crumb fragility/stiffness). Resilience was calculated as [(Area2 / Area1)*100] (Figure 3.)

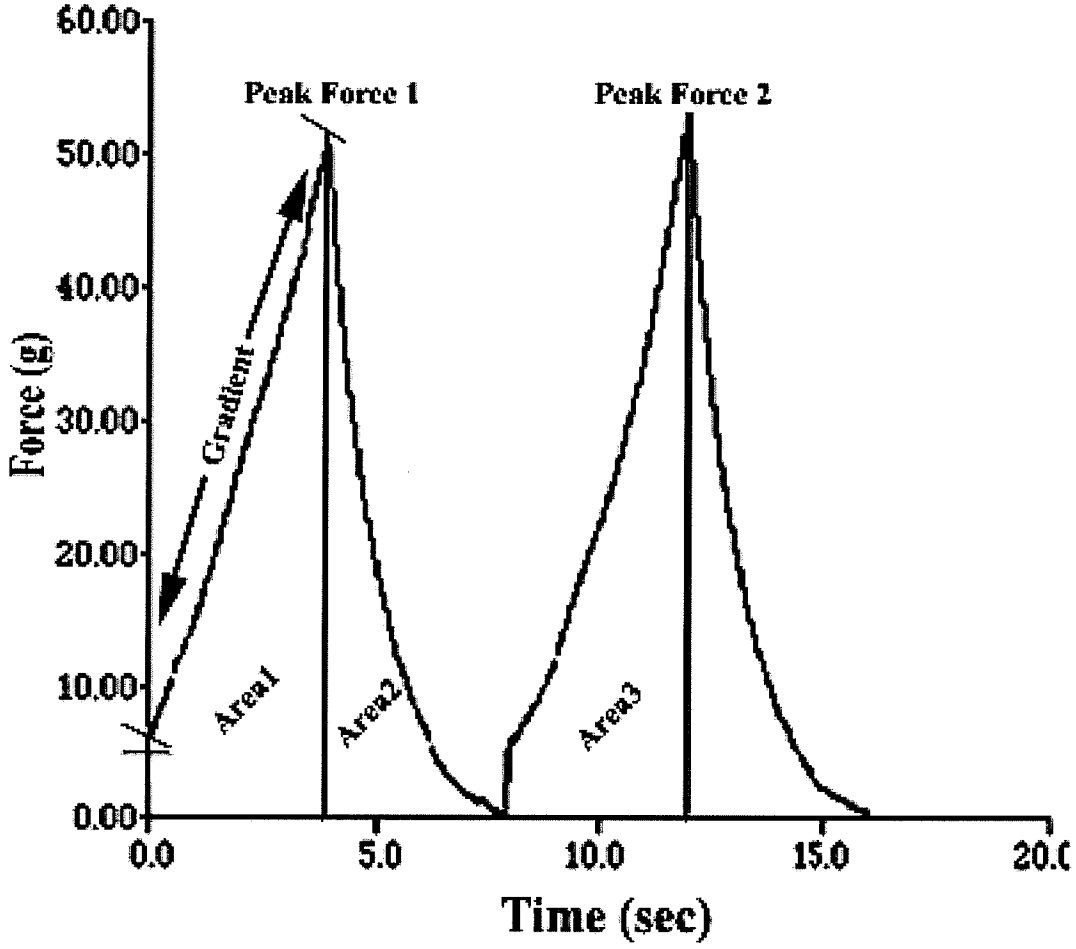


Figure 5. Representative curve of texture analysis.

3.9 Statistical Analysis

All experiments were completely randomized designs and tests carried out at least in duplicate, with a few exceptions. Except, milling yields, sieve analysis, moisture content of grain and Farinograph tests were performed in single determination. All statistical analyses were done by SAS (version 8.2, SAS Institute, 1999-2001). Analysis of variance (ANOVA) and least significant difference (LSD) tests were performed to

determine significant differences. Coefficient of variation (CV, %) measured the magnitude of variation among genotypes. Within an experiment, high CV values indicate a greater discrimination of variation among genotypes compared to low CV values.

4. RESULTS AND DISCUSSION

4.1 Milling and Chemical Analysis of Semolina

The test weight, semolina yield, flour yield, total extraction rate and ash content of the two common wheats and eleven durum samples of mill product G are reported in Table 2. Semolina moisture contents for mill product G, 2R and 6R are reported in Table 3. Test weight measures the bulk density of the wheat expressed as kilograms per hectoliter and is a rough index of semolina and flour yield (Cubbada 1988), and this relationship is more evident in a broad range of test weights. Matsuo and Dexter (1980a) found a significant ($r = 0.52$) trend towards higher milling yield (semolina and flour) with increasing test weights. In the current study, the range of test weights was relatively narrow for durums (78.8 to 84.6 kg/hl) and for common wheats; AC Barrie and Glenlea; 83.0 and 80.8 kg/hl, respectively. Semolina and flour yield was in the range; 58.8-69.4% and 6.0-16.3%, respectively. Total milling yield was 73.3-76.2% for all samples. On average, North American durums yielded 67.6% and Italian durums produced slightly more (68.7%) semolina. Consequently, the reverse was observed in flour yields of North American and Italian durums, with values of 7.3 and 6.5%, respectively. In durum wheat milling for pasta production, flour is a lower value by-product (Matsuo and Dexter, 1980b), but this is not an issue when durum wheat is used for baking purposes.

Ash content is an index of semolina contamination by bran. Common wheats had values ≤ 0.50, within the acceptable range for straight-grade bread wheat flours (Mailhot and Patton 1988) used for leavened bread. Ash contents for durum wheats were higher (0.64-0.76), which is typical for durum wheats.

Table 2. Comparison of test weight, semolina yield, flour yield, total extraction and ash content of durum and common wheat samples for G.

Genotypes	Test Weight kg/hl	Semolina Yield %	Flour Yield %	Total Extraction %	Ash Content %
AC Melita	82.2	66.6	7.4	74.0	0.71
AC Morse	81.3	65.8	7.5	73.3	0.64
Kyle	82.8	67.6	7.7	75.3	0.66
Durex	82.6	68.0	7.8	75.8	0.69
DT 674	82.5	68.9	7.3	76.2	0.68
DT 369	81.5	68.6	5.9	74.5	0.69
Ofanto	78.8	68.3	6.4	74.7	0.76
Grazia	84.6	69.4	6.4	75.8	0.66
Simeto	82.7	68.7	7.0	75.7	0.67
Creso	83.2	68.2	6.9	75.1	0.75
Arcangelo	81.8	68.8	6.0	74.8	0.69
AC Barrie	83.0	58.8	16.3	75.2	0.43
Glenlea	80.8	63.8	10.2	74.0	0.50
Averages	82.1	67.0	7.9	75.0	0.66
Mean of N.A.[1]	82.2	67.6	7.3	74.9	0.68
Mean of Itl.[2]	82.2	68.7	6.5	75.2	0.71

Table 3. Comparison of moisture content (%) of durum and common wheat samples for G, 2R and 6R.

Genotypes	G	2R	6R
AC Melita	14.1	13.7	13.5
AC Morse	14.2	13.7	13.5
Kyle	14.3	13.6	13.5
Durex	14.3	13.6	13.5
DT 674	14.2	13.6	13.5
DT 369	14.3	13.7	13.6
Ofanto	13.9	13.6	13.3
Grazia	14.0	13.5	13.4
Simeto	14.3	13.6	13.6
Creso	14.5	13.5	13.5
Arcangelo	14.1	13.5	13.6
AC Barrie	14.4	13.9	13.8
Glenlea	14.0	13.1	13.3
Mean of N.A.[1]	14.2	13.7	13.5
Mean of Itl.[2]	14.2	13.5	13.5

[1] North American Durums.
[2] Italian Durums.
All values reported on a 14% moisture basis

Table 4. Comparison of particle size distribution (% of total) of durum and common wheat samples for G and 6R.

Genotypes	G			6R		
	≥ 250 µm	180 µm	≤ 150 µm	≥ 250 µm	180 µm	≤ 150 µm
AC Melita	64.9	14.8	20.0	0.7	28.2	70.6
AC Morse	63.0	15.7	20.8	0.6	22.6	76.5
Kyle	63.5	16.2	20.1	0.8	27.8	71.2
Durex	64.0	15.5	19.9	0.8	31.1	67.5
DT 674	63.1	15.4	21.4	0.8	25.0	73.9
DT 369	67.1	14.8	17.6	0.8	25.9	72.9
Ofanto	65.2	15.8	18.7	0.9	26.3	72.7
Grazia	64.9	15.5	19.4	0.7	29.8	69.2
Simeto	65.6	15.7	18.2	1.3	29.3	69.3
Creso	64.8	15.7	19.2	0.5	25.7	73.6
Arcangelo	66.2	15.5	18.2	1.4	34.7	63.6
AC Barrie	52.0	13.8	34.9	0.6	12.3	86.7
Glenlea	59.7	15.5	24.3	0.7	15.0	84.0
Averages	63.2	15.3	21.3	0.8	25.7	73.2
Mean of N.A.[1]	64.2 ± 1.6	15.4 ± 0.6	20.0 ± 1.3	0.8 ± 0.1	26.8 ± 3.0	72.1 ± 3.1
Mean of Itl.[2]	65.4 ± 0.6	15.6 ± 0.1	18.7 ± 0.6	1.0 ± 0.4	29.2 ± 3.6	69.7 ± 3.9
CV	6.1	3.9	21.6	31.3	24.0	8.6

[1]North American Durums.
[2]Italian Durums.

The milling method affects the particle size distribution of hard wheats, such as durums (Hareland 1994). Semolina regrinding to 2R reduced the proportion of large particles, ≥ 250 μm seen in G to produce a much larger proportion of smaller particles (≤ 150 μm). The proportion of the small particles in 6R (≤ 150 μm) was substantially increased. Particle size distribution was within a narrow range for all durums (Table 4). Compared to durums, common wheats on average had a higher proportion of particles ≤ 150 μm and a lower proportion of particles ≥ 250 μm, for G, 2R and 6R (Table 4).

4.2 Protein Content

A strong relationship has been reported ($r = 0.72$) between loaf volume (LV) and a wide range of protein contents (11-14%) for durum wheats (Ammar et al, 2000). Protein content of durums for this study was within a relatively narrow range of 11.1 to 12.8% (Table 5) and did not vary across mill products. AC Melita, AC Morse, Kyle, Ofanto, Grazia and Simeto were in the higher range of 12.0 to 12.7%. While DT674, DT369, Creso and Arcangelo, were in the lower range of 11.1 to 11.9%. Common wheat genotype AC Barrie had the highest protein content (13.9%) while Glenlea (12.3%) was within the higher range of protein contents for durum wheats (Table 5). No differences were seen in protein content among G, 2R and 6R (Table 5). More importantly, the narrow range of protein contents among genotypes minimized the effect of protein content on LV and facilitated interpretation of results due to differences in protein quality.

4.3 Starch Damage

The extent of starch damage is a reflection of kernel hardness and the compactness of endosperm microstructure. Durum wheat is extremely hard, and starch granules that are

very firmly bound in the endosperm protein matrix are, therefore, more susceptible to damage during milling (Tipples 1969). Starch damage differences between G, 2R and 6R were significant ($p \leq 0.05$) (Table 5). On average, the level of starch damage for Italian genotypes was higher than that for North American genotypes (Table 6). Starch damage was substantially higher for durum wheats than those for common wheat genotypes, AC Barrie and Glenlea (Table 6). Glenlea starch damage was higher than that for AC Barrie for all mill products (Table 6).

4.4 Gassing Power

The gassing power of semolina/flour slurries of dough is a measure of the gas produced, which is normally highly correlated with starch damage. This relationship was also found in this thesis research (Figure 6). During fermentation, gassing power is partly limited by the amount of readily available damaged starch. Gassing power of G was positively correlated with starch damage ($r = 0.69$); the corresponding correlation for 6R ($r = 0.78$) was higher in keeping with the higher range of gassing power for 6R product (Figure 6). These results indicate that the gassing power of G was limited

Table 5. Comparison of protein content (%) of durum and common wheat samples for G, 2R and 6R.

Genotypes	G	2R	6R
AC Melita	12.7	12.7	12.8
AC Morse	12.7	12.6	12.8
Kyle	12.4	12.4	12.5
Durex	11.9	12.0	12.0
DT 674	11.9	12.1	12.0
DT 369	11.6	11.6	11.6
Ofanto	12.5	12.4	12.5
Grazia	12.0	12.1	12.2
Simeto	12.0	12.0	11.9
Creso	11.4	11.5	11.4
Arcangelo	11.1	11.0	11.0
AC Barrie	13.9	14.0	14.0
Glenlea	12.3	12.3	12.3
Averages	12.2	12.2	12.2
Mean of N.A.[1]	12.2	12.2	12.3
Mean of Itl.[2]	11.8	11.8	11.8
CV	5.8	5.9	6.1

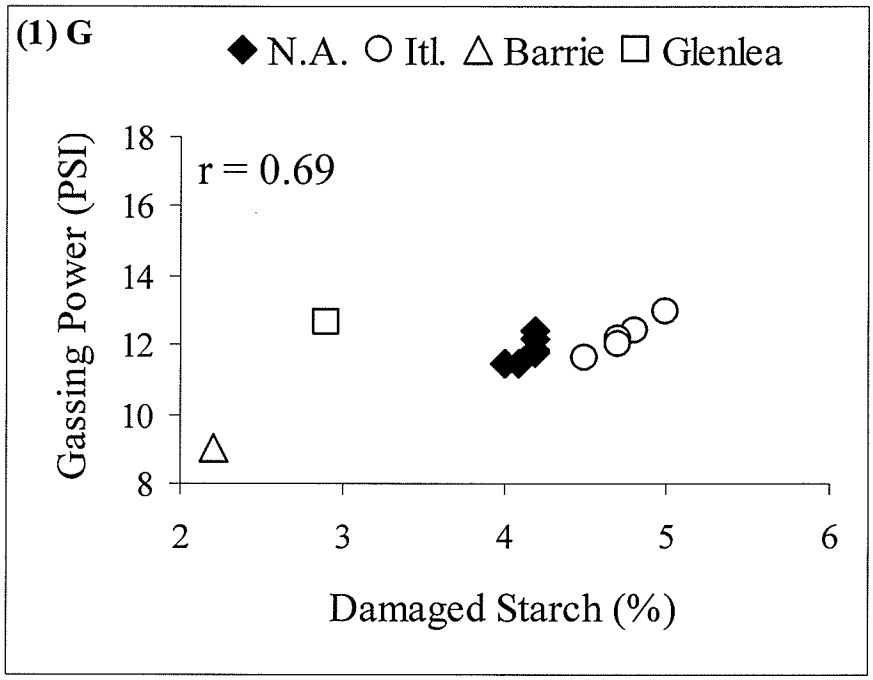
[1] North American Durums.
[2] Italian Durums.
All values reported on a 14% moisture basis

Table 6. Comparison of starch damage (%) of durum and common wheat samples for G, 2R and 6R.

Genotypes	G	2R	6R
AC Melita	4.2	5.8	6.7
AC Morse	4.0	5.5	6.3
Kyle	4.2	5.7	6.3
Durex	4.1	5.6	6.3
DT 674	4.2	5.8	6.2
DT 369	4.2	5.8	6.7
Ofanto	5.0	6.7	7.9
Grazia	4.5	5.9	7.1
Simeto	4.8	6.9	7.8
Creso	4.7	7.2	7.7
Arcangelo	4.7	6.4	7.2
AC Barrie	2.2	2.8	3.0
Glenlea	2.9	3.8	4.2
Averages	4.1 [C]	5.7 [B]	6.4 [A]
Mean of N.A.[1]	4.2	5.7	6.4
Mean of Itl.[2]	4.7	6.6	7.5
CV	18.8	21.1	21.9

[1] North American Durums.
[2] Italian Durums .
Means with the same letter are not significantly different at $p < 0.05$ level; upper case letters are different among averages of mill products G, 2R and 6R.

Figure 6. Relationship between starch damage (%) and gassing power (PSI) of mill products G (1) and 6R (2) of all genotypes.


(1) G
◆ N.A. ○ Itl. △ Barrie □ Glenlea
r = 0.69
Gassing Power (PSI)
18
16
14
12
10
8
2
3
4
5
6
Damaged Starch (%)

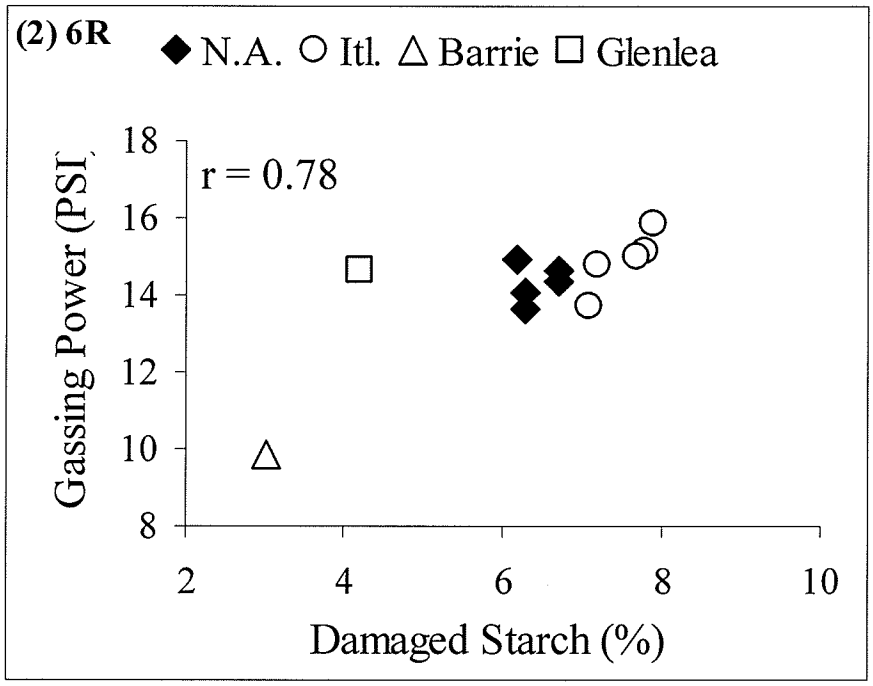
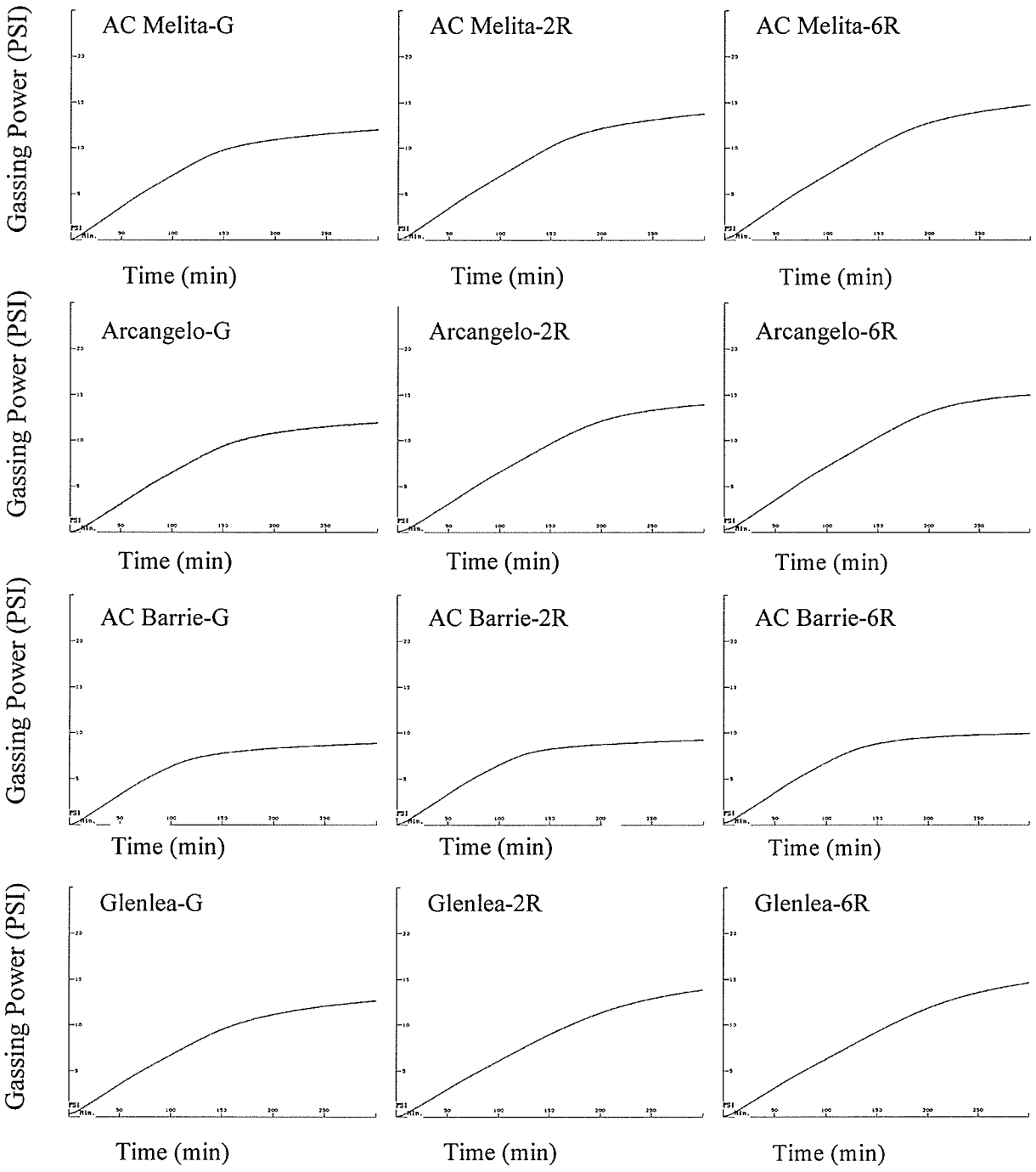

(2) 6R
◆ N.A. ○ Itl. △ Barrie □ Glenlea
r = 0.78
Gassing Power (PSI)
18
16
14
12
10
8
2
4
6
8
10
Damaged Starch (%)

Table 7. Comparison of gassing power (PSI) of durum and common wheat samples at 300 min for mill products G, 2R and 6R.

Genotypes	G	2R	6R
AC Melita	12.15 ± 0.13 cde	13.80 ± 0.17 def	14.67 ± 0.25 cde
AC Morse	11.50 ± 0.04 h	13.20 ± 0.17 gh	13.63 ± 0.40 h
Kyle	11.90 ± 0.07 efg	13.63 ± 0.21 ef	14.07 ± 0.21 fg
Durex	11.46 ± 0.09 h	12.97 ± 0.12 h	13.63 ± 0.06 h
DT 674	12.40 ± 0.09 bc	14.33 ± 0.06 bc	14.90 ± 0.20 bcd
DT 369	11.76 ± 0.20 fg	13.53 ± 0.15 fg	14.40 ± 0.10 ef
Ofanto	12.98 ± 0.38 a	14.90 ± 0.40 a	15.83 ± 0.12 a
Grazia	11.65 ± 0.15 gh	13.17 ± 0.15 h	13.73 ± 0.29 gh
Simeto	12.44 ± 0.18 b	14.43 ± 0.15 b	15.17 ± 0.12 b
Creso	12.15 ± 0.05 cd	14.60 ± 0.17 ab	15.00 ± 0.10 bc
Arcangelo	12.01 ± 0.14 def	13.97± 0.06 de	14.80 ± 0.26 cd
AC Barrie	8.99 ± 0.09 i	9.63 ± 0.31 i	9.90 ± 0.17 i
Glenlea	12.61 ± 0.09 b	14.07 ± 0.25 cd	14.63 ± 0.15 de
Averages	11.8 [A]	13.6 [B]	14.2 [C]
F value	122.2**	130.6**	134.1**
Mean of N.A.[1]	11.86 ± 0.37	13.57 ± 0.48	14.21 ± 0.53
Mean of Itl. [2]	12.25 ± 0.50	14.21 ± 0.67	14.92 ± 0.76
LSD-A[3]	0.26	0.34	0.36
LSD-M[3]	0.13		
CV	8.2	9.8	10.2

[1]North American Durums.
[2] Italian Durums.
[3] Least Significant Difference; A is among genotypes and M is between mill products.
Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within mill products G, 2R or 6R and upper case letters, are different among averages of mill products G, 2R and 6R.
n=3±SD
** Significant at $p<0.01$

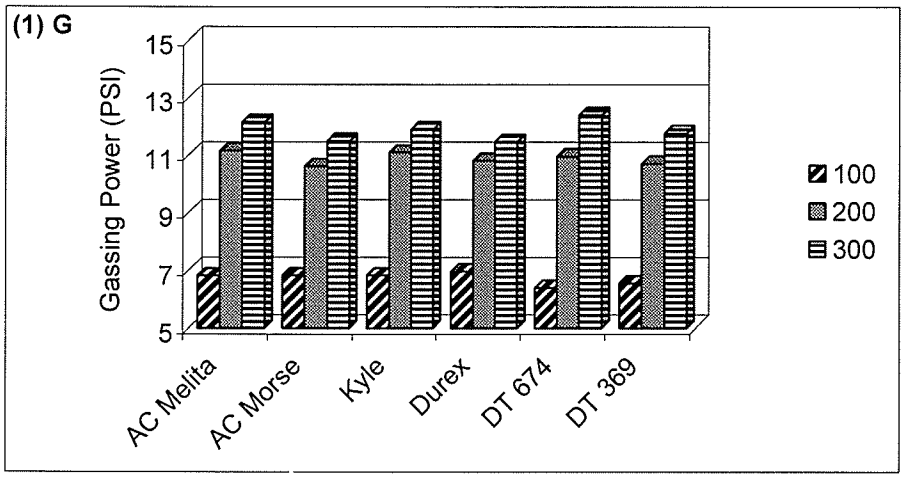
Figure 7. Representative gassing power curves of mill products G, 2R and 6R for genotypes, AC Melita, Arcangelo, AC Barrie and Glenlea.

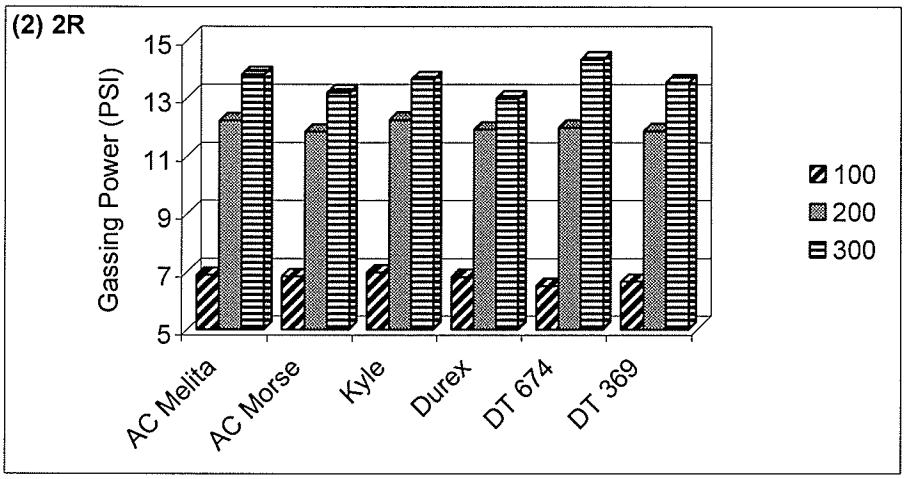

AC Melita-G
AC Melita-2R
AC Melita-6R
Arcangelo-G
Arcangelo-2R
Arcangelo-6R
AC Barrie-G
AC Barrie-2R
AC Barrie-6R
Glenlea-G
Glenlea-2R
Glenlea-6R
Gassing Power (PSI)
Time (min)

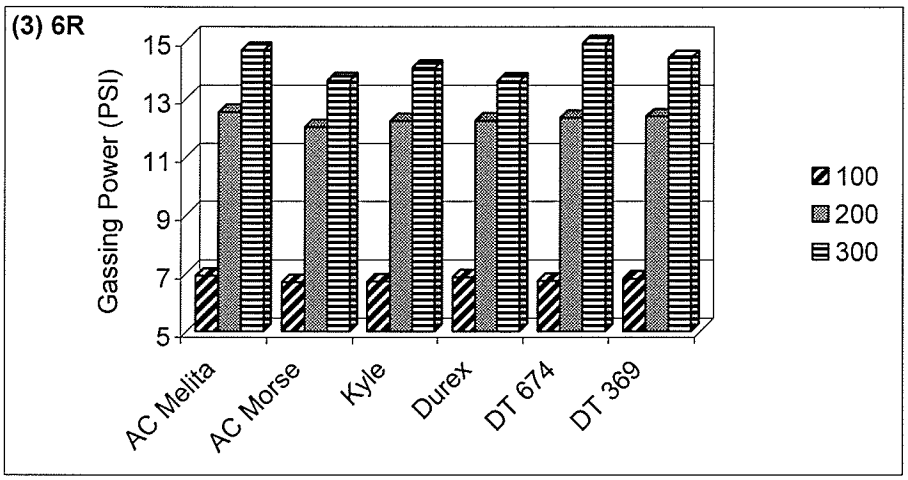
by the lower levels of starch damage of this mill product, and therefore gassing power could be a limiting factor during dough fermentation of G material.

Gassing power among G, 2R and 6R were significantly ($p \leq 0.05$) different (Table 7). Representative gassing power curves of AC Melita, Arcangelo, AC Barrie and Glenlea demonstrate the increase in gassing power with increasing starch damage (Figure 7). For G the rate of increase in gas production was substantial up to about 150 min and was minimal thereafter (Figure 8). For 6R mill product the corresponding rate of gas production after 150 min remained relatively high except for AC Barrie (Figure 8), reflecting higher starch damage for 6R product. But, there was an increase throughout for G. These results confirm that the amount of damaged starch was abundant in 6R compared to G, resulting in more gas production arising from higher levels of fermentable sugars produced by the action of yeast on damaged starch. Among all samples, Ofanto had the highest average gassing power for G, 2R and 6R (Table 7). Arcangelo a weak Italian genotype and AC Melita a strong North American genotype were not significantly different in gassing power within each of the three mill products G, 2R and 6R (Table 7). Glenlea and DT 674 were also not significantly different for all mill products (Table 7). Glenlea values were within the range of the durums. However, AC Barrie had the lowest gassing power; 9.0, 9.6 and 9.9 (PSI) for G, 2R and 6R, respectively. The average gassing power for G, 2R and 6R among Italian durum was 12.3, 14.2 and 15 PSI. For North American durums, the corresponding gassing power for G, 2R and 6R was 12.0, 14.0 and 14.2 PSI, respectively (Table 7).

Figure 8. Effect of time (min) on the gassing power (PSI) of milling treatments G (1), 2R (2) and 6R (3).


(1) G
Gassing Power (PSI)
15
13
11
9
7
5
AC Melita
AC Morse
Kyle
Durex
DT 674
DT 369
100
200
300


(2) 2R
Gassing Power (PSI)
15
13
11
9
7
5
AC Melita
AC Morse
Kyle
Durex
DT 674
DT 369
100
200
300


(3) 6R
Gassing Power (PSI)
15
13
11
9
7
5
AC Melita
AC Morse
Kyle
Durex
DT 674
DT 369
100
200
300

4.5 Protein Fractionation of Semolina into Soluble, Insoluble and Residue Protein

Sapirstein and Fu (1998) fractionated wheat proteins into soluble protein (SP) (albumins, globulins, gliadins and low molecular weight polymeric glutenin), insoluble glutenin (IG), and residue protein (RP) and differences in dough strength among genotypes were well demonstrated by the IG fraction. The same fractionation procedure was used in this study. The ratio of IG to SP (IG/SP) was also calculated. As protein content did not vary across mill products (G, 2R and 6R) (Table 8) there was no basis to expect a difference in protein quality among mill products, therefore protein fractionation analysis was done with only G.

SP content was significantly ($p \leq 0.01$) different among genotypes; ranging from 6.3 to 8.7 %semolina (weight basis of semolina). AC Barrie and DT 369 were the genotypes with the highest and lowest contents of SP, respectively. Among durum genotypes Kyle had the highest SP content (7.6%semolina), 61.1% of semolina protein. SP content of Glenlea (6.8%) was not significantly different from Durex and Arcangelo. The average SP content among North American durums and Italian durums was 7.1% and 6.8%, respectively. SP when expressed as % protein (semolina), resulted in Arcangelo being significantly higher values than Glenlea and Durex. This shift was due to the lower protein content of Arcangelo (Table 9). AC Barrie had the highest SP content among all genotypes (8.7%semolina and 62.8%protein), but was not significantly different from Kyle and Grazia (Table 9).

Correlation between protein content and SP content was higher when expressed as % semolina ($r = 0.90$) compared to % protein ($r = 0.49$). As SP mainly contains gliadins

which are the predominant storage proteins of wheat, a high correlation between SP and protein content was expected.

IG content was significantly ($p \leq 0.01$) different among genotypes; ranging from 1.9 to 3.1%semolina. AC Barrie and Glenlea were not significantly different and both had the highest IG contents; 2.9 and 3.1%, respectively (Table 8). AC Melita had the highest IG content among durum wheats (2.8%semolina)and was not significantly different from AC Barrie. Arcangelo had the lowest IG content (1.9%semolina). North American durums on average had a marginally higher IG content (2.5%) than Italian durums (2.3 %). IG content expressed as % protein reduced the degree of difference of AC Barrie (Table 9), likely due to its high protein content. When expressed as % protein Glenlea remained the genotype with significantly the highest ($p \leq 0.05$) IG content. The ranking of IG (% protein) among durum wheat genotypes was essentially not changed compared to rankings when expressed as %semolina due to the narrow range of protein contents. A weak correlation was established ($r = 0.52$) for IG (% semolina) and protein content. This indicates that the ranking of the genotypes by dough strength is strongly influenced by factors other than protein content, i.e. protein quality, which is well measured by IG content (Sapirstein and Fu 1998). The genotypes can be separated into two groups according to IG content; strong genotypes ($\geq$ 2.5%) and weak genotypes ($<$ 2.5%). As will be shown later, IG content was highly correlated with many indices of breadmaking quality indicating dough strength and LV are related.

RP was the protein fraction that was unextractable in 50%-1-propanol with and without the reducing agent DTT. Sapirstein and Fu (1998) did not find any trace of LMW-GS in this fraction in extractions done on common wheat flour, but found a small

amount of HMW-GS encoded by the *Glu-D1* loci. Durum wheat lacks the D-genome and this would reduce the amount of HMW-GS remaining in the RP fraction. Accordingly it can be assumed that RP of durum wheat samples was mainly non-gluten proteins, with negligible amounts, if any, of HMW-GS.

RP was significantly ($p \leq 0.05$) different among genotypes; ranging from 2.2 to 3.0%semolina. AC Barrie had the lowest proportion of RP, but was not significantly different from Glenlea, Grazia, Durex, AC Melita, DT 369 and Creso. Simeto had the highest RP content, but was not significantly different from AC Morse, Ofanto and Kyle (Table 8). RP expressed as % protein was reduced in its variation among genotypes. AC Barrie was significantly lower than all genotypes, while Glenlea was not significantly different from all durums except, Simeto and Arcangelo, which were significantly higher. The correlation between RP content (%protein) and ash content was $r = 0.66$, for the entire sample set.

It has long been proposed that stronger bread wheats should be related to a higher ratio of glutenins to gliadins (MacRitchie 1992), thus influencing the final LV. To investigate the effect of protein composition on the strength of the doughs in this study, the ratio of IG/SP provided an interesting separation of genotypes by strength. This parameter is more specifically the ratio of HMW polymeric glutenin content to a mixture of monomeric proteins and LMW glutenin polymers.

Table 8. Comparison of soluble (SP), insoluble (IG) and residue (RP) protein and the ratio of IG/SP expressed as % semolina of durum and common wheat samples for mill product G.

Genotypes	SP	IG	RP	IG/SP
AC Melita	7.4 ± 0.06 bc	2.8 ± 0.05 bc	2.5 ± 0.01 cd	0.38 ± 0.01 bc
AC Morse	7.3 ± 0.02 c	2.5 ± 0.01 ef	2.9 ± 0.04 ab	0.34 ± 0.00 d
Kyle	7.6 ± 0.01 b	2.2 ± 0.02 g	2.7 ± 0.01 abc	0.29 ± 0.00 f
Durex	6.7 ± 0.03 e	2.7 ± 0.01 cde	2.5 ± 0.04 cd	0.40 ± 0.00 b
DT 674	7.1 ± 0.24 d	2.2 ± 0.05 g	2.6 ± 0.29 bc	0.31 ± 0.00 ef
DT 369	6.3 ± 0.04 g	2.7 ± 0.06 bcd	2.5 ± 0.10 bcd	0.43 ± 0.01 a
Ofanto	7.5 ± 0.13 bc	2.3 ± 0.08 g	2.7 ± 0.21 abc	0.30 ± 0.00 f
Grazia	7.3 ± 0.17 c	2.3 ± 0.00 g	2.5 ± 0.17 cd	0.31 ± 0.01 f
Simeto	6.4 ± 0.08 fg	2.5 ± 0.13 def	3.0 ± 0.21 a	0.39 ± 0.02 bc
Creso	6.4 ± 0.08 fg	2.4 ± 0.19 fg	2.6 ± 0.28 bcd	0.37 ± 0.02 c
Arcangelo	6.6 ± 0.04 ef	1.9 ± 0.02 h	2.6 ± 0.02 bc	0.29 ± 0.01 f
AC Barrie	8.7 ± 0.08 a	2.9 ± 0.22 ab	2.2 ± 0.30 d	0.34 ± 0.02 de
Glenlea	6.8 ± 0.20 e	3.1 ± 0.08 a	2.5 ± 0.28 cd	0.46 ± 0.00 a
Mean of N.A.[1]	7.07 ± 0.47	2.52 ± 0.29	2.61 ± 0.15	0.36 ± 0.06
Mean of Itl. [2]	6.84 ± 0.51	2.26 ± 0.24	2.69 ± 0.21	0.33 ± 0.05
F Value	87.6**	24.4**	2.7*	45.0**
LSD-A[3]	0.22	0.22	0.38	0.03
CV	9.3	13.9	7.8	4.8

Table 9. Comparison of SP, IG and RP expressed as % protein content, of durum and common wheat samples for mill product G.

Genotypes	SP	IG	RP
AC Melita	58.1 ± 0.4 def	22.3 ± 0.4 bc	19.6 ± 0.1 c
AC Morse	57.6 ± 0.2 ef	19.8 ± 0.1 de	22.6 ± 0.3 abc
Kyle	61.1 ± 0.1 ab	17.5 ± 0.2 fg	21.5 ± 0.1 bc
Durex	56.6 ± 0.2 fg	22.8 ± 0.1 b	20.7 ± 0.4 c
DT 674	59.4 ± 2.0 bcd	18.4 ± 0.4 efg	22.2 ± 2.4 abc
DT 369	54.5 ± 0.3 h	23.6 ± 0.5 b	21.9 ± 0.9 bc
Ofanto	59.9 ± 1.1 bc	18.2 ± 0.6 efg	21.9 ± 1.7 bc
Grazia	60.8 ± 1.4 ab	18.8 ± 0.0 ef	20.4 ± 1.4 c
Simeto	53.7 ± 0.6 h	21.0 ± 1.1 cd	25.3 ± 1.8 a
Creso	56.3 ± 0.7 fg	20.8 ± 1.7 cd	22.9 ± 2.4 abc
Arcangelo	59.2 ± 0.4 cde	17.0 ± 0.2 g	23.8 ± 0.2 ab
AC Barrie	62.8 ± 0.6 a	21.1 ± 1.6 cd	16.1 ± 2.2 d
Glenlea	55.0 ± 1.6 gh	25.0 ± 0.7 a	20.0 ± 2.3 c
Mean of N.A.[1]	57.9 ± 2.3	20.7 ± 2.5	21.4 ± 1.1
Mean of Itl. [2]	58.0 ± 2.9	19.2 ± 1.7	22.9 ± 1.8
CV	4.8	12.2	10.5

[1]North American Durums.
[2] Italian Durums.
[3] Least Significant Difference; A is among genotypes
Means with the same letter are not significantly different at $p < 0.05$ level within each (column) protein fraction.
n=2 ± SD.
** Significant at p<.01; *Significant at p <.05.

IG/SP was significantly ($p \leq 0.01$) different among genotypes. Glenlea and DT 369 had the highest values (0.46 and 0.43, respectively) and were not significantly different from each other. AC Barrie, AC Morse and DT 674 were not significantly different. The lowest IG/SP values in the decreasing order were, Grazia (0.31) > Ofanto (0.30) > Arcangelo and Kyle (0.29). Overall the IG/SP ranking closely corresponded to differences in dough rheology and breadmaking performance (as described in the following sections).

4.6 Technological Analysis of Semolina

4.6.1 Mixograph Test

The Mixograph was used to assess rheological properties of semolina. In preliminary work, absorption levels higher than 50% (i.e. 55-60%) resulted in doughs that were sticky for 6R samples of weak dough strength (particularly Kyle and Arcangelo). To maintain a common basis to compare the mixing properties of G, 2R and 6R material, constant absorption (50%) was used. The narrow range of protein contents reduced the effect of constant absorption influencing Mixograph parameters.

Mixing time (MT) to peak dough development was found to discriminate samples in relation to dough strength, and was also influenced by particle size. Significant differences ($p \leq 0.01$) were observed among genotypes for each mill product G, 2R and 6R. MT on average was significantly higher for G (5.4 min) compared to 2R (4.2 min) and 6R (4.1 min) among all genotypes (Table 10). For G, genotypes could be grouped into strong (> 5.4 min) and weak (< 4.6 min) durum wheats. The genotypes could be further classified into strong (4.3 – 4.9 min), moderate (3.8 – 4.1 min) and weak (3.1 –

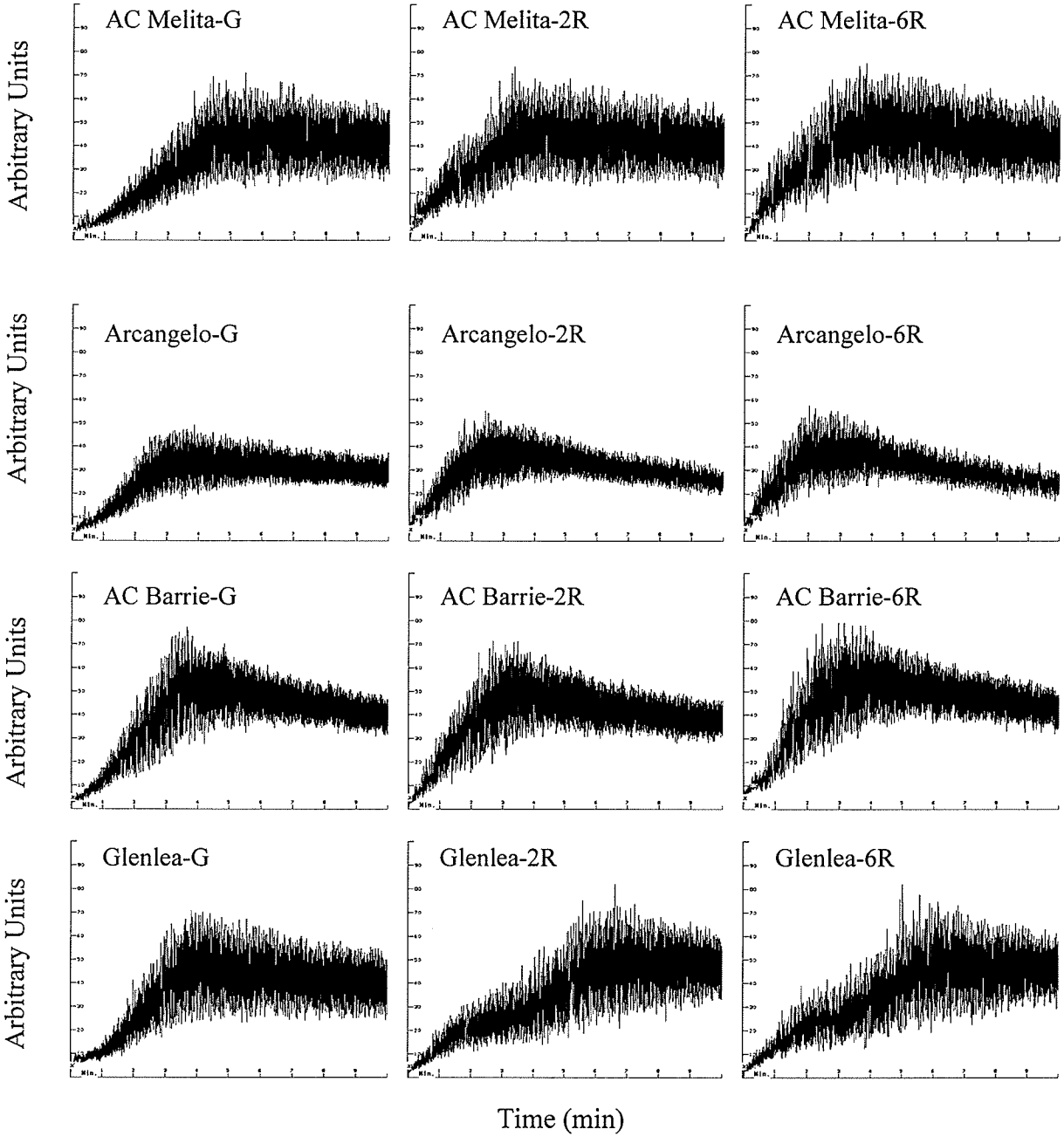
3.5 min), mixing types for mill product 6R. These results indicate that at constant absorption, MT was affected by particle size of semolina. The differences in particle size distribution between durum wheat genotypes and common wheats are due to kernel hardness differences of these two wheat classes. In mill products 2R and 6R with an increase in finer particle sizes (≤ 150 μm), there will be a concomitant increase in surface area, and it would be expected that the reduced mill products would absorb more water, and that absorption will be faster (hydration) to the core of the particles, affecting dough development time. Glenlea was the strongest mixing genotype for G, 2R and 6R (according to MT) and AC Barrie (Figure 9) was not significantly different to the weak durum wheats (Kyle, Ofanto, Grazia and Arcangelo) for the three mill products. On average North American durums had longer mixing times than Italian durums for all three mill products.

Table 10. Comparison of mixing time (MT, min) of durum and common wheat samples for G, 2R and 6R.

Genotypes	G	2R	6R
AC Melita	5.81 ± 0.34 cd	4.52 ± 0.14 b	4.26 ± 0.03 cd
AC Morse	5.43 ± 0.23 de	4.14 ± 0.21 c	4.07 ± 0.51 de
Kyle	4.60 ± 0.19 f	3.68 ± 0.23 de	3.50 ± 0.16 fg
Durex	5.83 ± 0.34 cd	4.61 ± 0.12 b	4.56 ± 0.18 bc
DT 674	5.18 ± 0.03 e	3.94 ± 0.10 cd	3.84 ± 0.01 ef
DT 369	5.98 ± 0.19 c	4.77 ± 0.11 b	4.90 ± 0.12 b
Ofanto	4.40 ± 0.22 f	3.34 ± 0.15 f	3.43 ± 0.10 gh
Grazia	4.40 ± 0.10 f	3.50 ± 0.11 ef	3.50 ± 0.11 g
Simeto	6.75 ± 0.52 b	4.73 ± 0.24 b	4.33 ± 0.19 cd
Creso	5.56 ± 0.23 cde	4.18 ± 0.03 c	4.09 ± 0.10 de
Arcangelo	4.17 ± 0.29 f	3.28 ± 0.05 f	3.10 ± 0.11 h
AC Barrie	4.45 ± 0.10 f	3.74 ± 0.18 de	3.65 ± 0.30 fg
Glenlea	8.28 ± 0.70 a	6.72 ± 0.29 a	6.62 ± 0.23 a
Averages	5.3 [A]	4.1 [B]	4.0 [B]
F Value	47.0 **	97.7 **	59.8 **
Mean of N.A.[1]	5.47 ± 0.52	4.28 ± 0.43	4.19 ± 0.50
Mean of Itl. [2]	5.05 ± 1.09	3.80 ± 0.63	3.69 ± 0.50
LSD-A[3]	0.49	0.27	0.34
LSD-M[3]	0.10		
CV	21.1	21.3	21.7

[1]North American Durums.
[2] Italian Durums.
[3] Least Significant Difference; A is among genotypes and M is among mill product.
Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within mill products G, 2R or 6R and upper case letters are different among averages of mill products G, 2R and 6R.
n=3±SD
** Significant at p<.01

Figure 9. Representative mixograms of milling treatments G, 2R and 6R for genotypes, AC Melita, Arcangelo, AC Barrie and Glenlea.


AC Melita-G
AC Melita-2R
AC Melita-6R
Arcangelo-G
Arcangelo-2R
Arcangelo-6R
AC Barrie-G
AC Barrie-2R
AC Barrie-6R
Glenlea-G
Glenlea-2R
Glenlea-6R
Arbitrary Units
Time (min)

Work input (WIP) is a measure of the energy required to reach peak dough development. Genotypic differences were highly significant ($p < 0.01$) for G, 2R and 6R. WIP was on average higher for G (129 %torque*min) and significantly ($p < 0.05$) different from 2R and 6R (121 %torque*min) (Table 11). This decrease in WIP corresponded to an increase in starch damage for 2R and 6R and the corresponding decrease in MT (4.2 ad 4.1, respectively) as previously noted. MT was highly correlated to WIPfor: G, $r = 0.90$; 6R, $r = 0.95$ (Appendix 3 and 4). As expected Glenlea had the highest WIP and was significantly different than all other genotypes for G, 2R and 6R (Table 11). As was found for corresponding IG contents of mill products, North American durums had higher WIP values than Italian durums.

Peak dough resistance (PDR) measured as %torque at MT, was significantly different between G, 2R and 6R ($p < 0.05$) (Table 12). The results showed a relatively small increase in PDR with an increasing percentage of smaller particle size; G, 2R, 6R with values of 38.8, 41.9 and 42.8 %torque, respectively. This increase can be explained by the increased surface area of the smaller 2R and 6R particles, thus increasing the dough resistance during mixing, presumably due to more complete hydration of the mill products leading to higher dough consistencies at constant absorption. AC Barrie had the highest PDR for G, 2R and 6R: with values 49, 49.6 and 52 %torque, respectively. This corresponded to the distinctly proportion of particles ≤ 150 μm for G, 2R and 6R; 34.9, 60.4 and 86.7%, respectively (Table 4). North American and Italian durums were comparable in PDR values for all three mill products.

Table 11. Comparison of work input (WIP, %Tq*min) of durum and common wheat samples for G, 2R and 6R.

Genotypes	G	2R	6R
AC Melita	150.63 ± 9.5 c	136.10 ± 6.5 b	130.07 ± 4.6 b
AC Morse	129.67 ± 4.6 d	118.23 ± 5.5 de	121.93 ± 24.2 bcd
Kyle	103.23 ± 2.4 f	102.57 ± 7.7 g	98.30 ± 4.6 f
Durex	134.23 ± 7.3 d	132.57 ± 3.5 bc	134.63 ± 6.1 b
DT 674	111.00 ± 3.8 f	99.90 ± 2.9 g	101.83 ± 2.9 ef
DT 369	127.90 ± 8.2 d	123.20 ± 1.5 d	131.03 ± 3.9 b
Ofanto	112.20 ± 12.7 ef	100.27 ± 4.9 g	102.83 ± 3.0 ef
Grazia	114.07 ± 4.4 ef	107.70 ± 2.2 fg	110.73 ± 2.5 def
Simeto	167.87 ± 19.1 b	137.17 ± 9.7 b	130.97 ± 7.6 b
Creso	125.43 ± 5.6 de	113.37 ± 1.1 ef	114.27 ± 6.9 cde
Arcangelo	87.33 ± 9.9 g	79.83 ± 4.1 h	79.30 ± 1.5 g
AC Barrie	131.17 ± 3.3 d	124.20 ± 7.5 cd	127.60 ± 8.3 bc
Glenlea	184.10 ± 8.5 a	198.23 ± 4.1 a	198.47 ± 10.6 a
Averages	124.0 [A]	114.2 [B]	114.0 [B]
F Value	31.8 **	83.4**	36.4**
Mean of N.A.[1]	126.11 ± 16.9	118.76 ± 15.03	119.63 ± 15.75
Mean of Itl. [2]	121.38 ± 29.5	107.67 ± 20.81	107.62 ± 18.87
LSD-A[3]	13.6	9.1	13.7
LSD-M[3]	3.39		
CV	20.4	23.6	23.3

[1]North American Durums.
[2] Italian Durums.
[3] Least Significant Difference; A is among genotypes and M is among mill product.
Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within mill products G, 2R or 6R and upper case letters are different among averages of mill products G, 2R and 6R.
n=3±SD
** Significant at p<.01

Table 12. Comparison of peak dough resistance (PDR, %) of durum and common wheat samples for G, 2R and 6R.

Genotypes	G	2R	6R
AC Melita	42.70 ± 0.8 b	44.53 ± 0.9 c	45.80 ± 0.9 c
AC Morse	37.50 ± 0.9 de	40.10 ± 0.4 ef	40.80 ± 0.7 ef
Kyle	36.73 ± 1.1 ef	40.40 ± 0.8 e	40.03 ± 0.3 ef
Durex	39.30 ± 1.2 c	42.50 ± 0.8 d	43.57 ± 1.2 d
DT 674	33.73 ± 0.7 g	36.20 ± 0.6 g	37.40 ± 0.7 g
DT 369	35.83 ± 0.2 f	38.47 ± 1.4 f	39.37 ± 0.2 f
Ofanto	38.53 ± 1.9 cd	42.40 ± 0.7 d	43.17 ± 1.5 d
Grazia	43.97 ± 1.3 b	47.00 ± 0.2 b	47.53 ± 1.4 b
Simeto	35.97 ± 0.6 ef	39.67 ± 0.6 ef	41.40 ± 1.6 e
Creso	35.33 ± 1.1 fg	39.97 ± 0.8 ef	40.03 ± 1.3 ef
Arcangelo	32.03 ± 0.8 h	35.03 ± 0.6 g	36.33 ± 0.7 g
AC Barrie	49.00 ± 1.0 a	49.60 ± 2.2 a	52.27 ± 0.7 a
Glenlea	43.67 ± 1.3 b	48.33 ± 1.2 ab	48.07 ± 2.2 b
Averages	37.4 [C]	40.6 [B]	41.4 [A]
F Value	70.6**	59.5**	64.3**
Mean of N.A.[1]	37.63 ± 3.1	40.37 ± 2.9	41.16 ± 3.0
Mean of Itl. [2]	37.17 ± 4.5	40.81 ± 4.4	41.69 ± 4.1
LSD-A[3]	1.7	1.7	1.7
LSD-M[3]	0.46		
CV	12.4	10.7	10.8

[1]North American Durums.
[2] Italian Durums.
[3] Least Significant Difference; A is among genotypes and M is among mill product.
Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within mill products G, 2R or 6R and upper case letters are different among averages of mill products G, 2R and 6R.
n=3±SD
** Significant at p<.01

Bandwidth (BW), measured the thickness of the mixogram envelope at MT and is a key characteristic used for assessing dough strength. Bandwidth is a measure of extensional viscosity occurring during mixing of the dough (Gras et al, 2000). BW on average was significantly ($p < 0.05$) different between G, 2R and 6R; 22.2, 24.3 and 25.0%, respectively (Table 13). Grazia had significantly higher BW compared to all genotypes for G and 2R, but was not different from Glenlea for 6R. A strong genotype like AC Melita had a wide BW, while Arcangelo a weaker genotype, had a narrow BW (Figure 9). This reflects a strength difference among genotypes as reflected in their IG contents, AC Melita (2.8 %) and Arcangelo (1.9 %), strong and weak, respectively. BW was highly correlated ($r = 0.74$) to IG %semolina.

The rate of breakdown two minutes past peak, is a common measure of a doughs tolerance to overmixing using the Mixograph (Khatkar et al, 1996). Breakdown resistance (BR) was lower for G (3.3%) and was significantly different ($p < 0.05$) than that of 2R and 6R; 5.3% and 5.9%, respectively (Table 14). As expected, stronger genotypes had lower BR values than weaker counterparts. Weaker genotypes like Arcangelo had better tolerance to overmixing for G (3.7%), and poor tolerance compared to 2R and 6R mill product (8.2% and 9.7%, respectively).

Table 13. Comparison of bandwidth (BW, %) of durum and common wheat samples for G, 2R and 6R.

Genotypes	G	2R	6R
AC Melita	26.23 ± 0.6 b	27.10 ± 0.4 b	28.33± 0.6 bc
AC Morse	22.17 ± 1.2 e	24.00 ± 0.5 cd	24.37± 0.4 de
Kyle	18.03 ± 0.3 g	20.50 ± 0.3 f	20.57± 0.4 f
Durex	25.33 ± 0.9 cd	26.63 ± 0.4 b	27.23± 0.7 c
DT 674	17.87 ± 0.7 g	20.13 ± 0.6 f	20.50± 0.4 f
DT 369	22.93 ± 0.2 e	24.27 ± 1.1 c	24.73± 0.7 d
Ofanto	18.73 ± 0.6 g	22.53 ± 0.8 e	23.50± 1.7 e
Grazia	27.73 ± 0.8 a	29.63 ± 0.4 a	29.47± 0.9 ab
Simeto	20.30 ± 0.7 f	22.97 ± 0.4 de	24.87± 0.9 d
Creso	21.03 ± 0.6 f	24.17 ± 0.5 c	24.13± 0.9 de
Arcangelo	16.63 ± 0.6 h	18.13 ± 0.2 g	19.67± 0.3 f
AC Barrie	24.90 ± 0.2 d	26.07 ± 1.5 b	27.67± 0.8 c
Glenlea	26.43 ± 0.4 b	29.30 ± 0.8 a	29.80± 1.2 a
Averages	22.2 ^{C}	24.3 ^{B}	25.0 ^{A}
F Value	100.0 **	72.1**	65.3**
Mean of N.A.[1]	22.09 ± 3.5	23.77 ± 2.9	24.29 ± 3.3
Mean of Itl. [2]	20.89 ± 4.2	23.49 ± 4.1	24.33 ± 3.5
LSD-A[3]	1.1	1.2	1.2
LSD-M[3]	0.33		
CV	16.8	14.3	13.6

[1]North American Durums.
[2] Italian Durums.
[3] Least Significant Difference; A is among genotypes and M is among mill product.
Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within mill products G, 2R or 6R and upper case letters are different among averages of mill products G, 2R and 6R.
n=3±SD
** Significant at p<.01

Table 14. Comparison of breakdown resistance (BR, %) of durum and common wheat samples for G, 2R and 6R.

Genotypes	G	2R	6R
AC Melita	2.75 ± 1.2 def	3.21 ± 1.0 gh	4.07 ± 0.3 d
AC Morse	0.79 ± 0.7 g	2.24 ± 0.9 hi	2.03 ± 1.6 ef
Kyle	6.37 ± 0.8 b	5.93 ± 1.1 cd	7.33 ± 1.9 b
Durex	3.55 ± 0.6 cde	4.07 ± 0.7 fg	5.03 ± 1.3 cd
DT674	3.46 ± 0.8 cde	9.31 ± 1.5 a	10.60 ± 0.1 a
DT369	2.04 ± 0.4 efg	2.86 ± 0.4 ghi	3.64 ± 0.5 de
Ofanto	4.99 ± 0.9 bc	6.99 ± 0.4 bcd	7.43 ± 1.0 b
Grazia	4.25 ± 0.3 cd	4.11 ± 0.7 efg	4.63 ± 0.5 d
Simeto	2.29 ± 2.3 efg	5.37 ± 0.7 def	4.99 ± 0.2 cd
Creso	2.44 ± 0.7 efg	5.76 ± 0.3 de	4.98 ± 1.2 cd
Arcangelo	3.74 ± 0.3 cde	8.20 ± 1.9 ab	9.74 ± 1.7 a
AC Barrie	8.31 ± 1.0 a	7.46 ± 0.2 bc	6.76 ± 1.5 bc
Glenlea	1.65 ± 1.5 fg	1.22 ± 1.2 i	0.97 ± 0.7 f
Averages	3.3 [C]	5.3 [B]	5.9 [A]
F Value	31.8 **	83.4**	36.4**
Mean of N.A.[1]	3.16 ± 1.87	4.60 ± 2.64	5.45 ± 3.1
Mean of Itl. [2]	3.54 ± 1.16	6.09 ± 1.57	6.35 ± 2.2
LSD-A[3]	1.7	1.7	1.9
LSD-M[3]	0.46		
CV	57.0	47.6	49.9

[1] North American Durums.
[2] Italian Durums.
[3] Least Significant Difference; A is among genotypes and M is among mill product.
Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within mill products G, 2R or 6R and upper case letters are different among averages of mill products G, 2R and 6R.
n=3±SD
** Significant at p<.01

4.6.2 Farinograph Test

There was a significant effect of particle size on Farinograph properties. Farinograph absorption (Fabs) is used to estimate the amount of water to be added to dough for baking. Fabs was significantly different among G, 2R and 6R with values of 58%, 62% and 64%, respectively (Table 15). This closely corresponds to the increasing starch damage of mill products. Clearly, the reduction of durum granularity (Figure 10) increases the absorption of the mill product.

Boggini and Pogna (1989) reported that Farinograph dough development time (FDDT) ($r = 0.58$) and stability ($r = 0.52$) were positively correlated to LV. Similar to Mixograph MT, FDDT of G material was significantly ($p < 0.05$) higher than that of 2R and 6R (Table 15 and Figure 11). As previously mentioned, presumably the increased starch damage and reduced particle size of 2R and 6R material results in an increased rate of hydration of the doughs giving shorter mix times compared to G. Dexter and coworkers (1994) also found, reduced granulars had shorter mixing times. FDDT was negatively correlated ($r = - 0.61$) to starch damage, and highly correlated ($r = 0.87$) with Mixograph MT and ($r = 0.82$) WIP. FDDT was also correlated similarly to IG and IG/SP; $r = 0.79$ for G.

Farinograph stability values were significantly higher for G (15.3 min) compared to those of 6R (10.9 min). However, 2R (13.0 min) stabilities were intermediate, but not significantly ($p < 0.05$) different than G and 6R (Table 15 and Figure 12). Boyacioglu and D'Appolonia (1994a) similarly found durum semolina (4.5 min) had longer stability than durum flour (3.5min). This indicates that particle size distribution of the samples influence the mixing stability, which is a measure of dough strength; lowering the

average particle size by milling results in weaker doughs. These "weaker doughs" probably reflect a rapid absorption of water by damaged starch, followed by release of water upon further mixing, resulting in a plasticizing effect due to excess free water, thus lowering the dough consistency. Stability was highly correlated to IG content and IG/SP value; r = 0.84, r = 0.85, respectively.

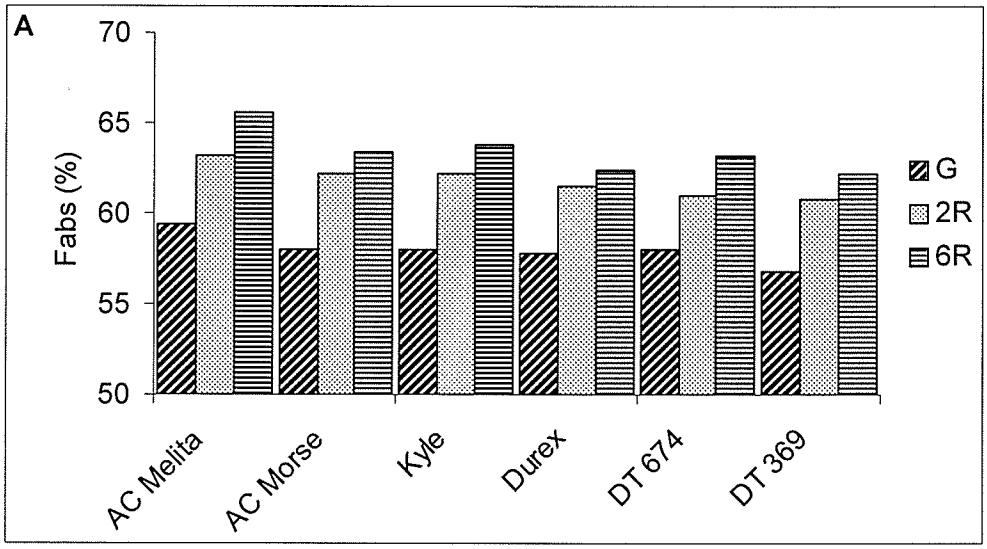
Mixing tolerance index (MTI) was significantly different between G and 2R, but not between G and 6R (Table 15 and Figure 13). MTI was negatively correlated (r = 0.63) to FDDT. MTI was also negatively correlated to other dough strength measures, i.e. Mixograph MT and WIP; r = 0.75, r = 0.77, respectively. IG content and IG/SP ratio was also negatively correlated to MTI; r = 0.72, r = 0.78, respectively.

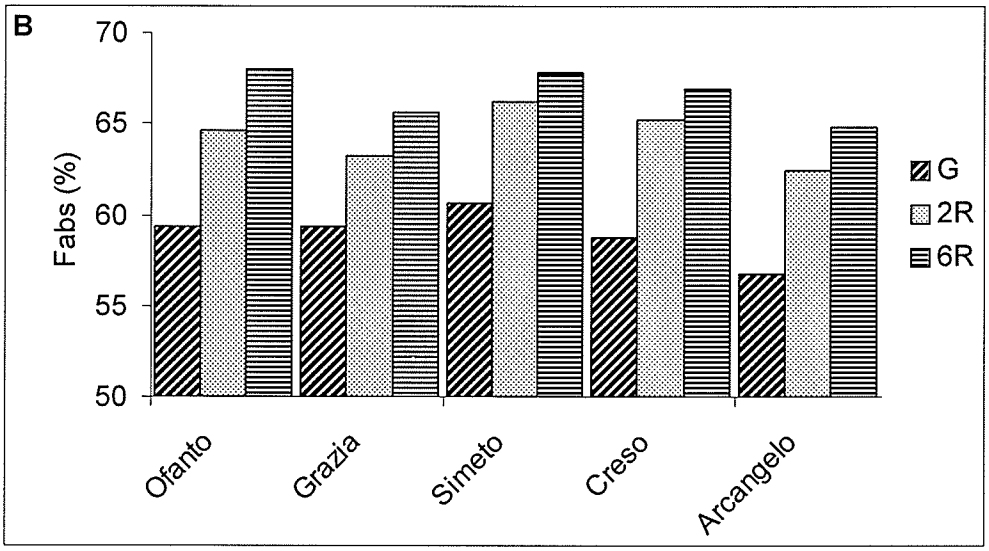
Table 15. Comparison of average Farinograph absorption (Fabs, %), dough development time (FDDT, min), stability (min) and mixing tolerance index (MTI, BU), of durum and common wheat samples for G, 2R and 6R.

All Genotypes	G	2R	6R
Fabs (%)	58.21 ± 1.5 ^{A}	62.30 ± 2.3 ^{B}	64.10 ± 2.8 ^{C}
FDDT (min)	5.19 ± 2.1 ^{A}	4.55 ± 1.9 ^{B}	4.30 ± 1.9 ^{B}
Stability (min)	15.27 ± 8.3 ^{A}	13.04 ± 6.3 ^{AB}	10.86 ± 6.5 ^{B}
MTI (BU)	27.31 ± 13.2 ^{A}	32.31 ± 13.0 ^{B}	31.54 ± 14.2 ^{AB}

Means with the same letter are not significantly different at $p < 0.05$ level; upper case letters are different among averages of mill products G, 2R and 6R, for each parameter.

Figure 10. Effect of milling treatments on Farinograph absorption (Fabs, %) of North American durum (A), Italian durum (B) and common wheat (C) samples.


A
70
65
60
55
50
Fabs (%)
G
2R
6R
AC Melita
AC Morse
Kyle
Durex
DT 674
DT 369


B
70
65
60
55
50
Fabs (%)
G
2R
6R
Ofanto
Grazia
Simeto
Creso
Arcangelo

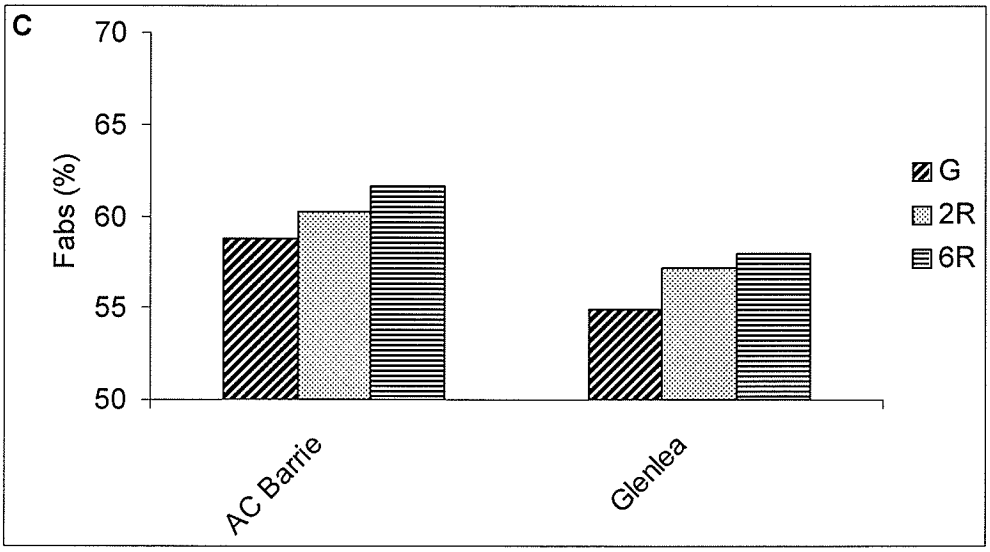
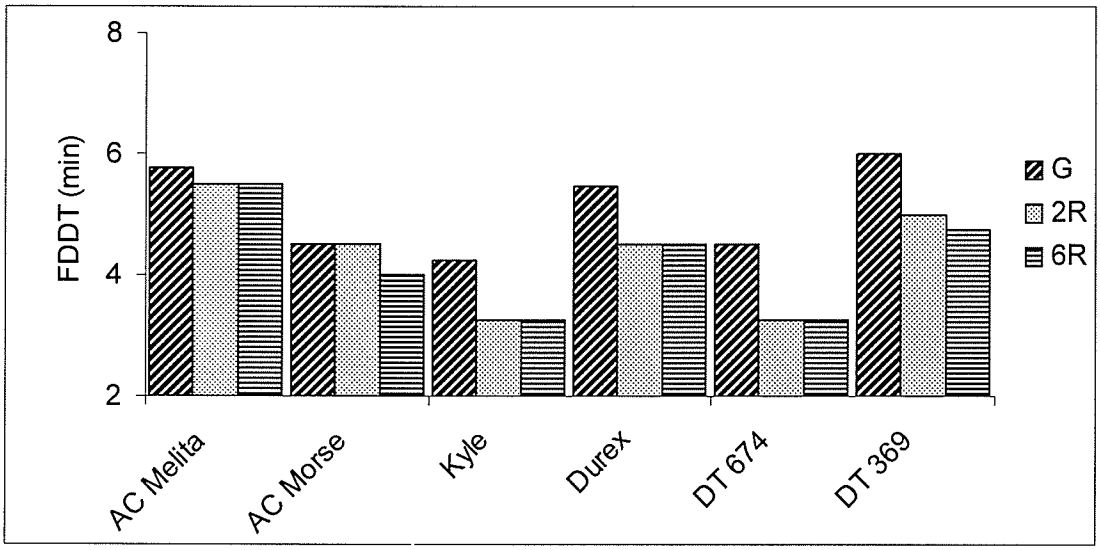
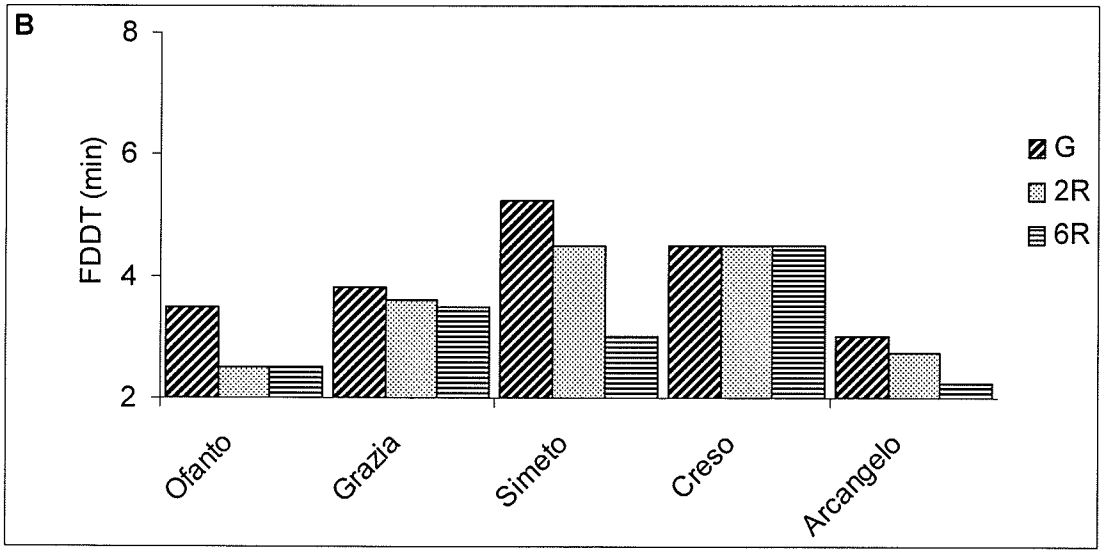

C
70
65
60
55
50
Fabs (%)
G
2R
6R
AC Barrie
Glenlea

Figure 11. Effect of milling treatment on Farinograph dough development (FDDT) of North American durum (A), Italian durum (B) and common wheat (C) samples.


8
6
4
2
FDDT (min)
G
2R
6R
AC Melita
AC Morse
Kyle
Durex
DT 674
DT 369


B
8
6
4
2
FDDT (min)
G
2R
6R
Ofanto
Grazia
Simeto
Creso
Arcangelo

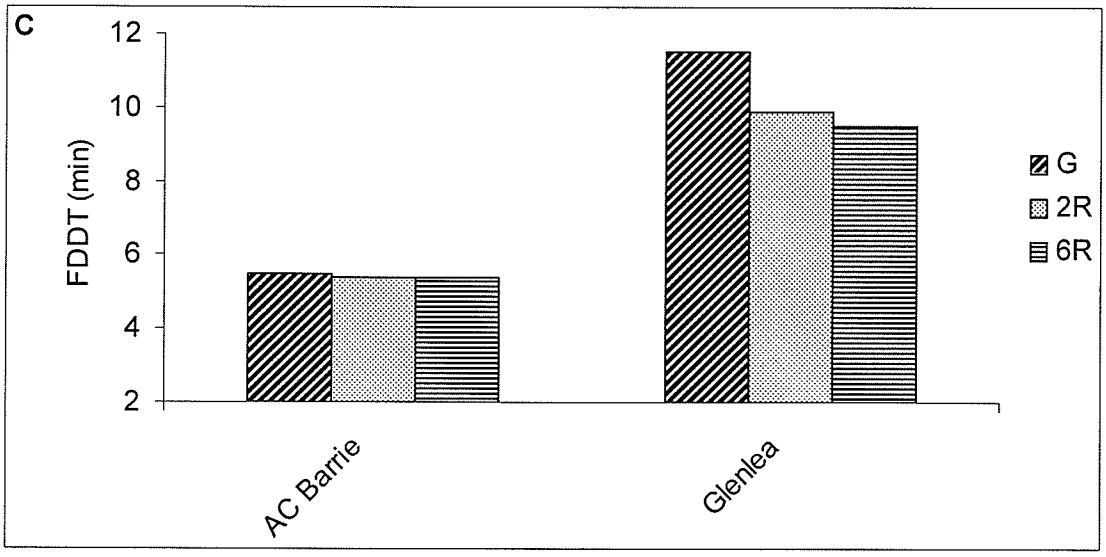
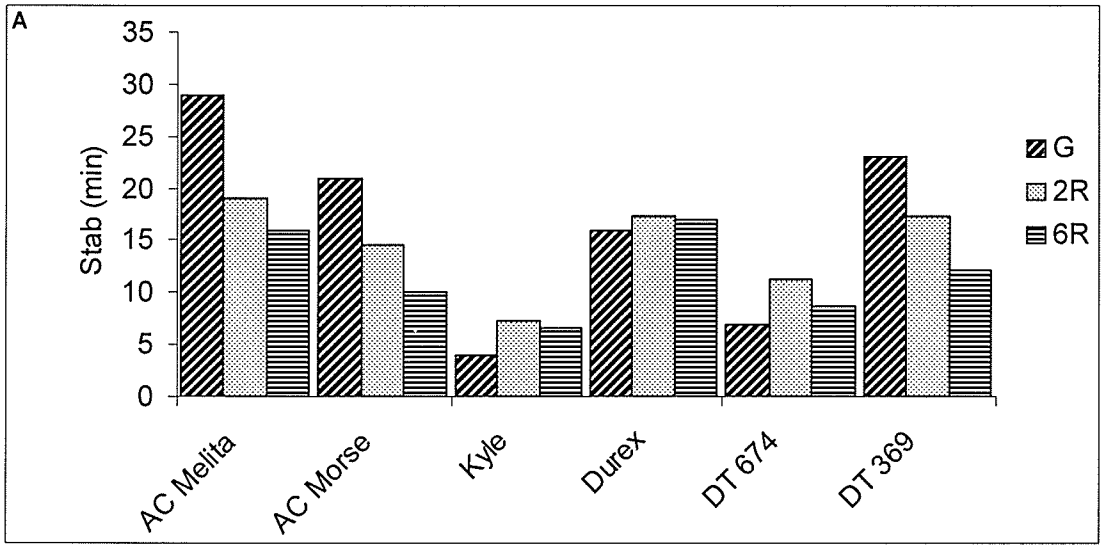
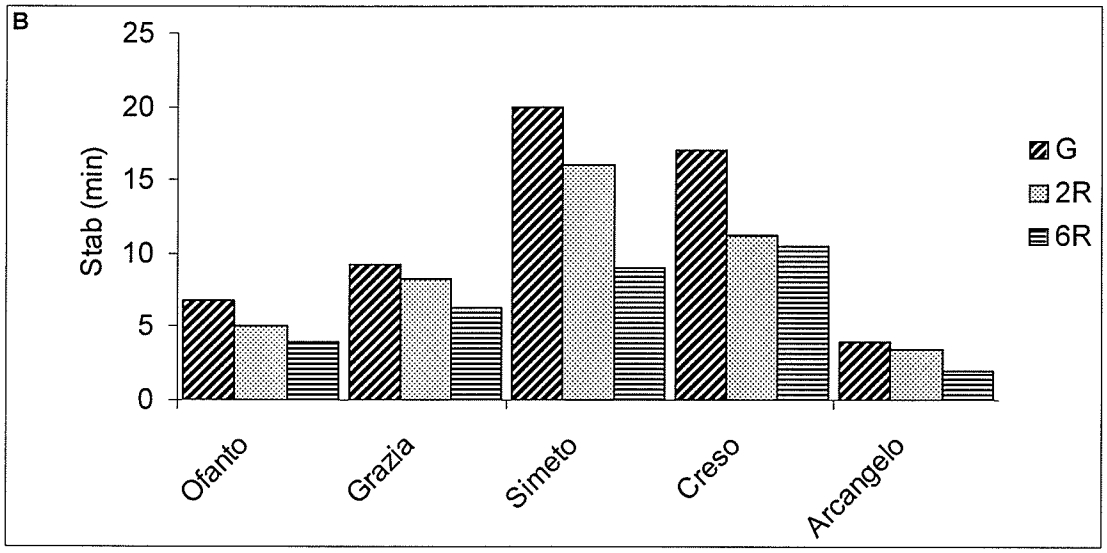

C
12
10
8
6
4
2
FDDT (min)
G
2R
6R
AC Barrie
Glenlea

Figure 12. Effect of milling treatments on Stability (Stab, min) of North American durum (A), Italian durum (B) and common wheat (C) samples.


A
35
30
25
20
15
10
5
0
Stab (min)
G
2R
6R
AC Melita
AC Morse
Kyle
Durex
DT 674
DT 369


B
25
20
15
10
5
0
Stab (min)
G
2R
6R
Ofanto
Grazia
Simeto
Creso
Arcangelo

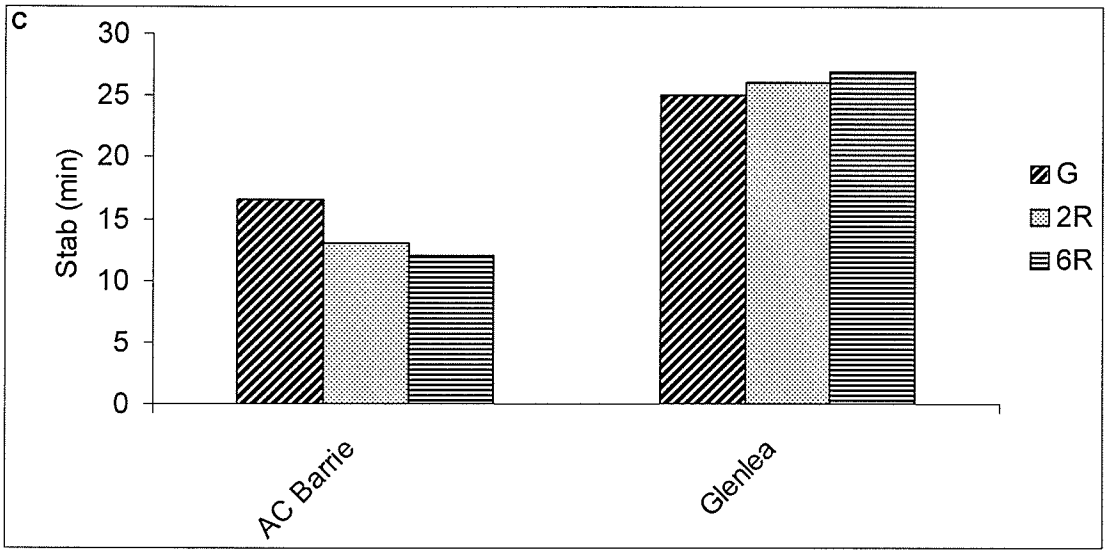
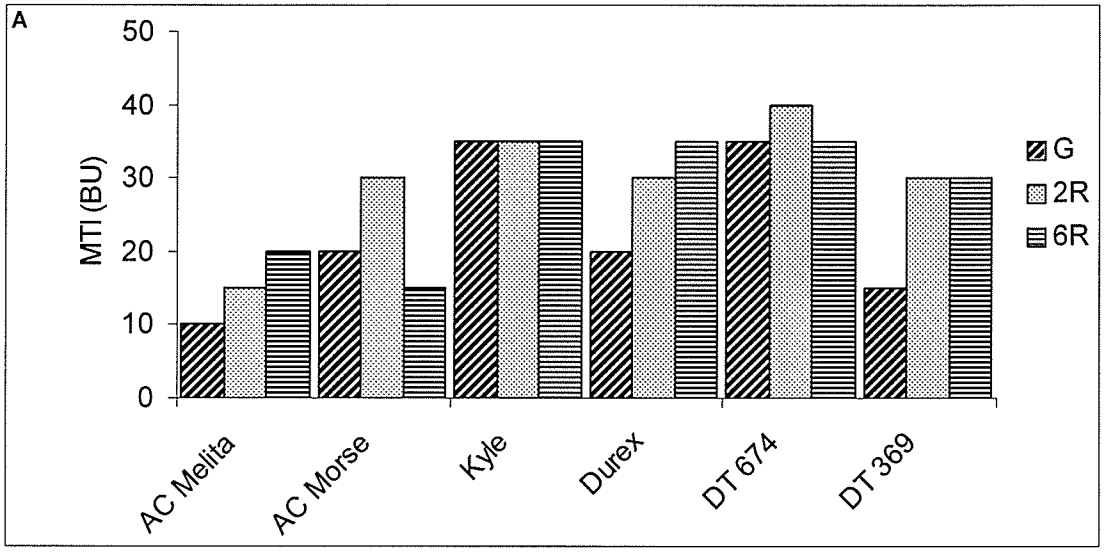
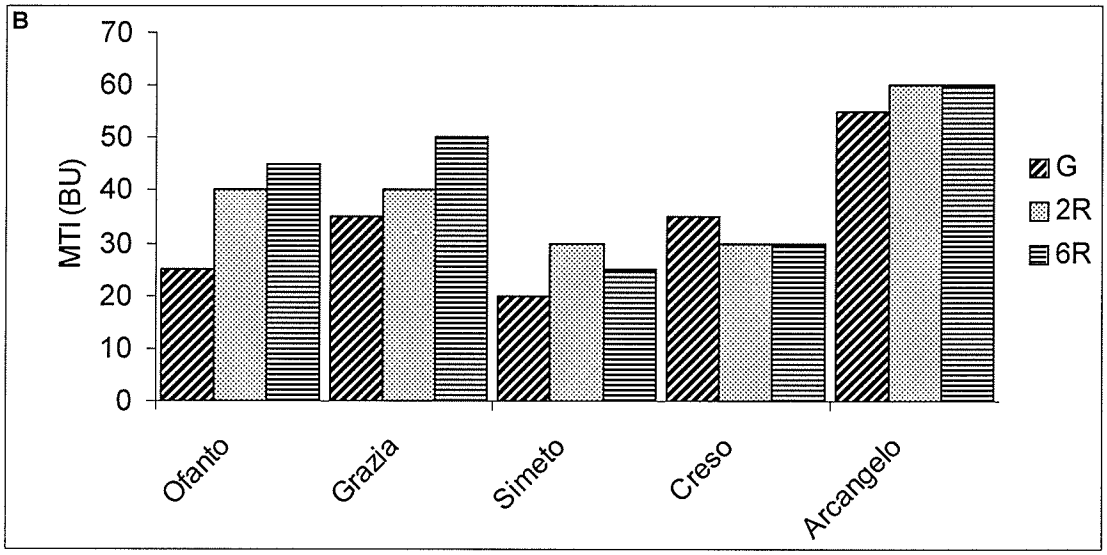
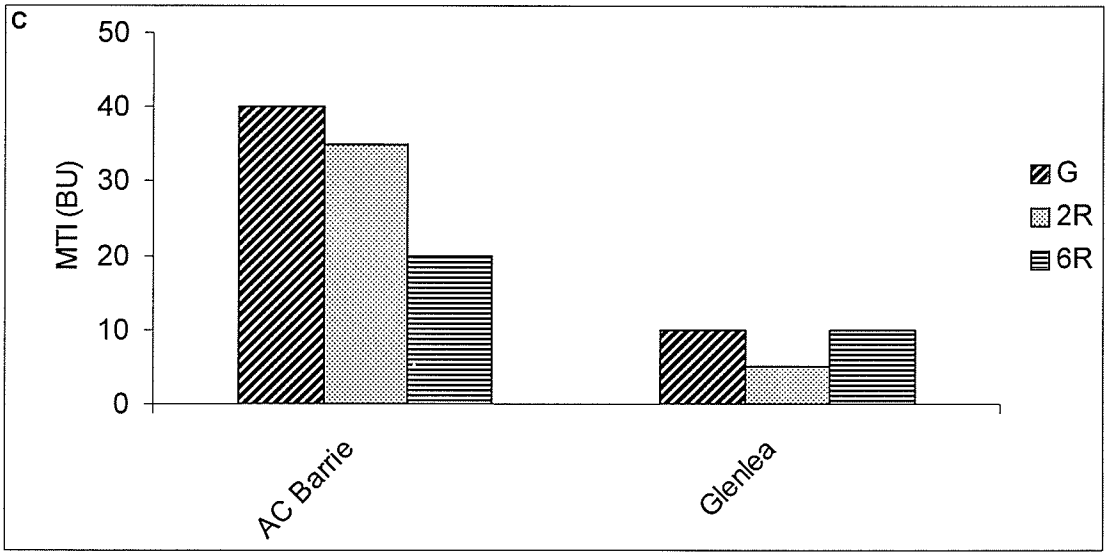

C
30
25
20
15
10
5
0
Stab (min)
G
2R
6R
AC Barrie
Glenlea

Figure 13. Effect of milling treatments on Mixing Tolerance Index (MTI, BU) of North American durum (A), Italian durum (B) and common wheat (C) samples.


A
MTI (BU)
50
40
30
20
10
0
AC Melita
AC Morse
Kyle
Durex
DT 674
DT 369
G
2R
6R


B
MTI (BU)
70
60
50
40
30
20
10
0
Ofanto
Grazia
Simeto
Creso
Arcangelo
G
2R
6R


C
MTI (BU)
50
40
30
20
10
0
AC Barrie
Glenlea
G
2R
6R

4.6.3 Alveograph test

Quaglia (1988) noted that leavened durum bread production required P/L values > 1.5 and W (deformation energy) values of about 200. In the current study, for only mill product G, P/L values were generally < 1.5, although 6 of 11 durum samples had W values > 200 (Table 16), P/L values were moderately correlated (r = 0.59) to W. Protein content despite its narrow rangewas moderately correlated to extensibility (r = 0.62) as measured by L (Figure 14). A very high correlation was found between IG content (% semolina) and W (r = 0.93). Deformation energy (W) is a well recognized measure of dough strength. Alveograph P is a measure of tenacity and was found to be correlated to IG content (r = 0.72) Therefore this strong inter-relationship further confirms the importance of glutenin protein quality as measured by IG as a key determinant of dough strength. Alveograph P/L and W were weakly correlated to LV (Appendix 3).

4.6.4 Dough sheet length (DSL)

It is widely accepted that good breadmaking performance requires extensible gluten (MacRitchie 1984; Ammar et al, 2000). It has been established that during fermentation, gluten undergoes a phenomenon referred to as "gluten mellowing", allowing the gluten to have improved extensibility (Dubois 1984). In this study, dough sheet length (DSL) was used as a practical measure of extensibility of the full formula dough.

DSL between G and 6R was significantly ($p \leq 0.05$) different (Table 17). The range of DSL for G was 37.3 to 53.8 cm, and shifted slightly to a higher, but comparable

range for 6R; 38.3 to 54.2 cm. There was a small but significant effect of particle size on DSL of AC Melita, Durex, DT 369 and Simeto and were not significantly different from those of common wheats for both G and 6R (Table 17). Those genotypes with the shortest DSL, also had the strongest doughs. Correlations between DSL and other measures of dough strength are shown in the appendices. DSL at 165 min was highly correlated to IG ($r = -0.91$) and to Alveograph W ($r = -0.91$). These results indicate that DSL is very closely related to dough strength. For mill product G, the durum genotypes can be grouped by extensibility (DSL) as high (Arcangelo, DT 674 and Kyle), moderate (AC Morse, Grazia, Creso and Ofanto) and minimally (Durex, DT 369, AC Melita and Simeto) extensible.

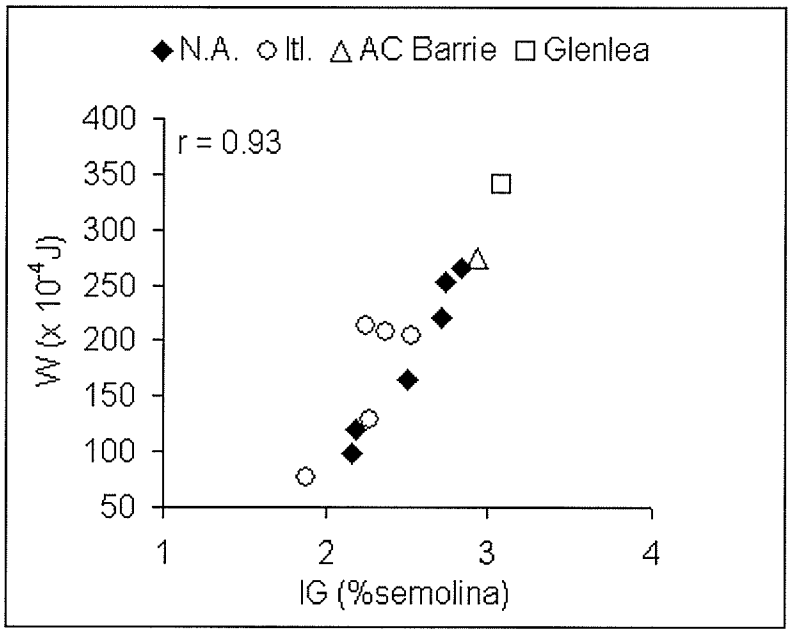
The effect of shorter fermentation times (15 and 90 min, compared to 165 min), were evaluated. DSL at fermentation times 15 and 90 min were not significantly different from each other but, were slightly but significantly lower than that of 165 min (Table 18). This parameter is a rough estimate of dough extensibility, as handling of the dough by the baker, can readily affect the DSL. Therefore, these results should be interpreted with caution. DSL at 15 min was highly correlated to IG content ($r = -0.87$) and Alveograph W ($r = -0.91$). There were large genotype differences, but there was a small effect of processing on the extensibility parameter.

Table 16. Comparison of tenacity (P, mm), extensibility (L, mm), deformation strength of the dough (W *10^{-4} J) and ratio of tenacity to extensibility (P/L) for G.

Genotypes	P	L	P/L	W
AC Melita	78	97	0.80	266
AC Morse	50	106	0.47	165
Kyle	34	102	0.33	99
Durex	63	96	0.66	220
DT 674	40	109	0.37	120
DT 369	76	93	0.82	252
Ofanto	52	90	0.58	129
Grazia	65	113	0.58	213
Simeto	89	62	1.44	204
Creso	82	76	1.08	208
Arcangelo	40	75	0.53	77
AC Barrie	64	123	0.52	274
Glenlea	101	78	1.29	340
Mean of N.A.[1]	56.8	100.5	0.60	187.0
Mean of Itl.[2]	65.6	83.2	0.80	166.2
CV	32.0	18.5	38.9	47.6

[1]North American Durums.
[2]Italian Durums.

Figure 14. Relationship between Alveograph, W and IG (% semolina) (A) and Alveograph, L and protein content (B).


◆N.A. ○ltl. △AC Barrie □Glenlea
r = 0.93
W (x 10⁻⁴J)
400
350
300
250
200
150
100
50
1
2
3
4
IG (%semolina)

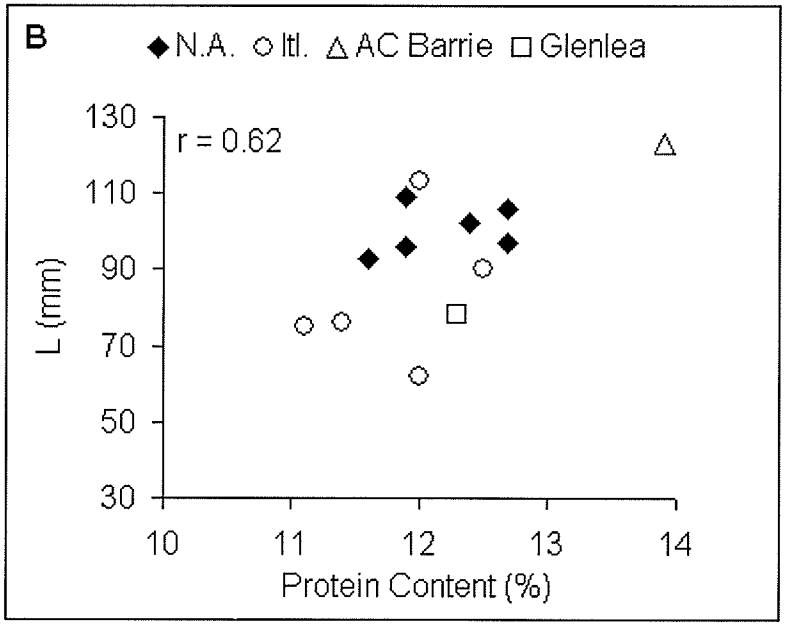

B
◆N.A. ○ltl. △AC Barrie □Glenlea
r = 0.62
L (mm)
130
110
90
70
50
30
10
11
12
13
14
Protein Content (%)

Table 17. Comparison of dough sheet length, DSL (cm) of durum and common wheat samples for G and 6R at 165 min fermentation time.

Genotypes	G	6R
AC Melita	40.60 ± 2.6 def	41.00 ± 1.9 cd
AC Morse	43.00 ± 2.3 cde	41.50 ± 1.4 cd
Kyle	49.90 ± 4 8 ab	45.70 ± 0.9 b
Durex	38.15 ± 2.5 f	39.85 ± 1.6 d
DT 674	53.40 ± 6.9 a	54.20 ± 1.7 a
DT 369	39.80 ± 0.9 ef	38.60 ± 3.7 d
Ofanto	46.70 ± 0.1 bc	43.80 ± 2.1 bc
Grazia	43.30 ± 2.4 cde	38.50 ± 0.9 d
Simeto	40.75 ± 0.4 def	38.45 ± 1.5 d
Creso	44.30 ± 0.9 cd	44.55 ± 0.4 bc
Arcangelo	53.75 ± 1.5 a	46.95 ± 2.8 b
AC Barrie	38.55 ± 2.5 f	38.55 ± 2.1 d
Glenlea	37.25 ± 1.9 f	38.30 ± 0.7 d
Averages	43.8 [A]	42.3 [B]
F Value	17.2**	16.3**
Mean of N.A.[1]	44.1 ± 6.1	43.5 ± 5.8
Mean of Itl. [2]	45.8 ± 4.9	42.5 ± 3.8
LSD-A[3]	4.2	3.6
LSD-M[3]	1.1	
CV	12.8	11.1

[1]North American Durums.
[2] Italian Durums.
[3]Least Significant Difference; A is among genotypes and M is between mill products.
Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within mill products G and 6Rand fermentation times 15, 90 and 165 min and upper case letters are different among averages of mill products and fermentation times. n=2±SD; ** Significant at p<.01

Table 18. Comparison of dough sheet length, DSL (cm) of durum and common wheat samples of G for 15, 90 and 165 min fermentation times.

Genotypes	15 min	90 min	165 min
AC Melita	38.70 ± 1.1 def	37.58 ± 2.2 efg	40.43 ± 1.6 def
AC Morse	41.03 ± 0.9 d	41.98 ± 1.7 cde	43.75 ± 3.8 cde
Kyle	50.58 ± 0.8 b	51.40 ± 2.1 a	49.08 ± 3.5 ab
Durex	35.05 ± 1.3 efg	36.25 ± 0.9 g	38.65 ± 2.2 f
DT 674	50.30 ± 0.9 bc	51.35 ± 1.6 ab	52.05 ± 4.3 a
DT 369	35.48 ± 1.5 fg	37.90 ± 1.7 fg	39.33 ± 0.8 ef
Ofanto	51.38 ± 1.4 b	47.00 ± 1.4 bc	46.83 ± 0.2 bc
Grazia	40.73 ± 1.7 d	41.95 ± 2.7 def	43.00 ± 2.4 cde
Simeto	44.83 ± 2.3 c	39.90 ± 1.4 efg	40.10 ± 0.9 def
Creso	41.03 ± 2.3 de	44.28 ± 1.4 cd	45.20 ± 1.9 cd
Arcangelo	54.25 ± 4.5 a	51.15 ± 3.4 ab	53.10 ± 1.1 a
AC Barrie	37.70 ± 1.1 defg	38.00 ± 0.9 efg	39.35 ± 1.7 f
Glenlea	34.83 ± 2.5 g	34.80 ± 0.6 g	37.40 ± 1.4 f
Averages	42.8 [B]	42.6 [B]	43.7 [A]
F Value	32.9**	13.9**	17.2**
Mean of N.A.[1]	41.9 ± 7.0	42.9 ± 7.0	43.9 ± 5.6
Mean of Itl.[2]	46.4 ± 6.1	44.9 ± 4.4	45.6 ± 4.9
LSD-A[3]	4.1	5.3	4.2
LSD-M[3]	0.8		
CV	15.9	14.0	11.9

[1]North American Durums.
[2] Italian Durums.
[3]Least Significant Difference; A is among genotypes and M is between mill products.
Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within mill products G and 6Rand fermentation times 15, 90 and 165 min and upper case letters are different among averages of mill products and fermentation times.
n=2±SD; ** Significant at p<.01

4.7 Baking Tests

4.7.1 Effect of Granularity (G and 6R)

Remix-to-peak time (RTPT) at 165 min fermentation was significantly higher ($p \leq 0.05$) for mill product 6R compared to G (Table 19). Genotypic differences within each mill product varied significantly ($p \leq 0.01$). RTPT was higher for Glenlea (4.8 min) and Simeto (4.6 min) for G, while for 6R, Glenlea (4.9 min), AC Melita (4.3 min) and DT 369 (4.8 min) had high values. Increased starch damage resulted in an increase in RTPT for 6R mill product at long fermentation (165 min). Accordingly, the effect of particle size was opposite to that found for other dough mixing time parameters (MT, FDDT). This result is partly influenced by dough fermentation time.

Loaf volume (LV) on average was not significantly ($p \leq 0.05$) different between G and 6R for durum wheats (results not shown). But, evaluation of both common and durum wheats resulted in a small though significant difference, between G (648 cc) and 6R (679 cc) on average (Table 19). This variation was due to the increased LV of common wheats for 6R. LV was significantly ($p \leq 0.01$) different among genotypes for both G and 6R. LV of AC Melita was significantly higher than that of all genotypes for G. For 6R, AC Melita LV was not significantly different from Durex, DT 369 and AC Morse. Glenlea was not significantly different from DT 369 and Durex for G, but for 6R Glenlea LV was significantly higher than all genotypes. AC Melita, DT 369 and Durex were collectively the best breadmaking durum genotypes. Arcangelo was the poorest performing genotype for both G and 6R. AC Barrie LV was low for G (515 cc) but LV improved substantially for 6R (685 cc). This poor performance of AC Barrie was likely as a result of insufficient starch damage in G.

The specific volume (SV) of bread can provide important information with regard to breadmaking performance as both LV and loaf weight are important factors in research and commercial baking. SV accounts for fermentation loss during the breadmaking process.

SV was significantly different between G and 6R for all genotypes but, not significantly different between G (5.1 cc/gm) and 6R (5.1 cc/gm) for durum wheats. Accordingly the large difference in SV between G and 6R for the two common wheats accounted for this result (Table 19). Among the durum wheats, AC Melita had the highest SV and Arcangelo had the lowest for both G and 6R. For G mill product, AC Barrie which performed poorly, was not significantly different from Arcangelo. For 6R mill product, Glenlea was significantly higher in SV compared to all other genotypes. Intermediate performance was shown by AC Barrie, Creso, Kyle, Grazia and Simeto.

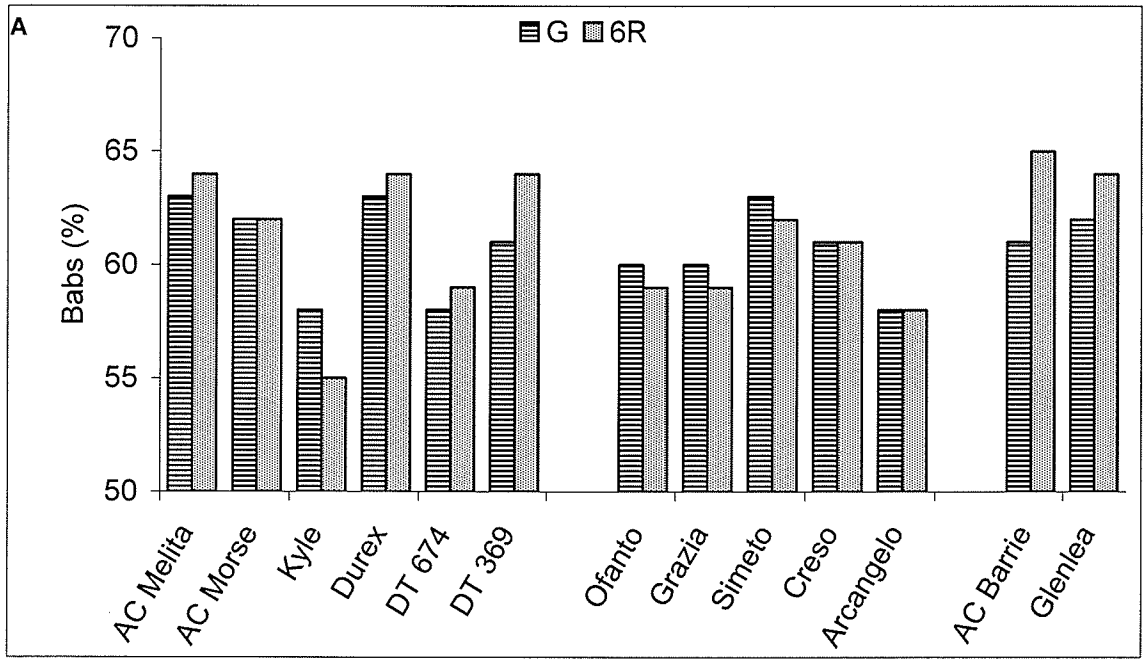
Baking absorption was comparable between the two mill products; G (60.8%) and 6R (61.2%) (Figure 15). The range of baking absorptions for G and 6R were 58-63% and 58-65%, respectively The effect of higher starch damage was evident in the higher baking absorption for 6R.

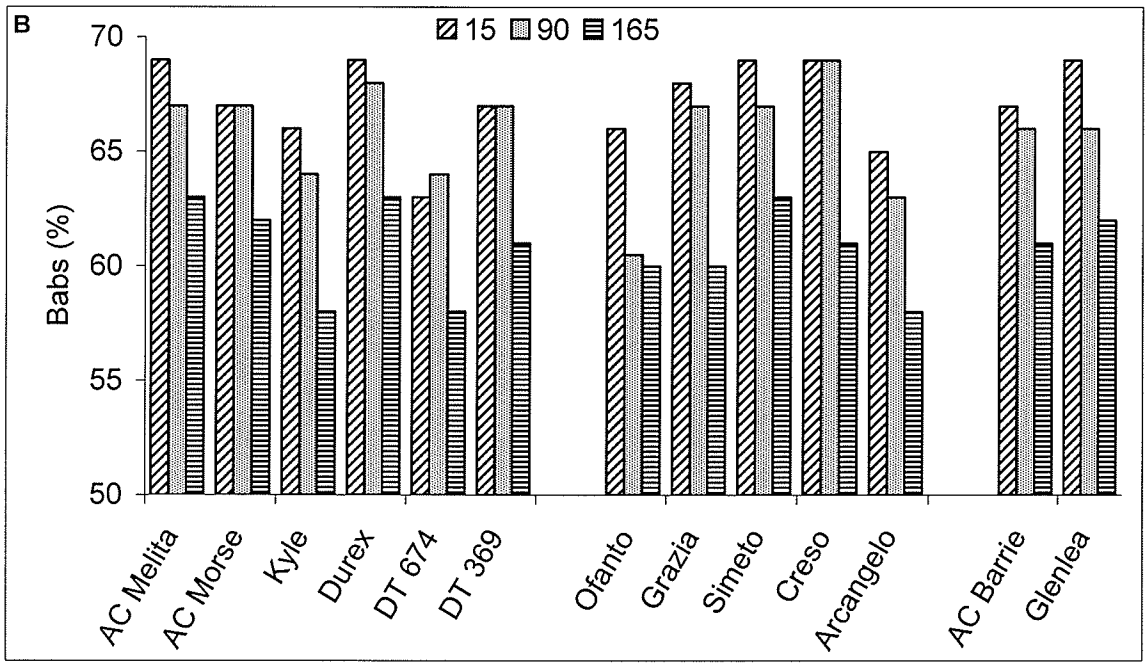
Table 19. Comparison of remix-to-peak time (min), loaf volume (cc), specific volume (cc/g) and oven rise (cm) of durum and common wheat samples for G and 6R at standard 165 min fermentation.

Genotypes	Remix-to-Peak Time		Loaf Volume		Specific Volume		Oven Rise	
	G	6R	G	6R	G	6R	G	6R
AC Melita	3.4 ± 0.30 c	4.3 ± 0.85 bc	760 ± 12 a	780 ± 14 b	5.9 ± 0.12 a	6.1 ± 0.07 b	29 ± 0.58 b	28 ± 0.00 b
AC Morse	2.8 ± 0.19 de	2.8 ± 0.14 def	675 ± 13 d	740 ± 00 b	5.2 ± 0.10 d	5.8 ± 0.07 b	25 ± 0.96 c	24 ± 1.41 c
Kyle	2.3 ± 0.08 fg	2.4 ± 0.28 ef	658 ± 15 de	620 ± 14 de	5.2 ± 0.13 d	5.0 ± 0.07 cd	22 ± 2.94 d	16 ± 0.71 e
Durex	3.6 ± 0.21 bc	3.7 ± 0.21 cd	705 ± 06 c	750 ± 28 b	5.5 ± 0.06 c	5.8 ± 0.28 b	26 ± 0.58 c	26 ± 0.71 bc
DT 674	2.6 ± 0.17 ef	2.5 ± 0.14 ef	593 ± 15 f	575 ± 07 f	4.6 ± 0.13 f	4.4 ± 0.07 e	13 ± 1.41 f	10 ± 1.41 f
DT 369	3.9 ± 0.29 b	4.8 ± 0.14 ab	723 ± 10 bc	750 ± 00 b	5.7 ± 0.06 b	5.8 ± 0.00 b	25 ± 2.22 c	25 ± 0.71 c
Ofanto	1.9 ± 0.15 h	2.3 ± 0.35 f	603 ± 10 f	600 ± 14 ef	4.6 ± 0.10 f	4.7 ± 0.14 de	13 ± 1.15 f	9 ± 0.71 f
Grazia	2.2 ± 0.25 g	2.5 ± 0.07 ef	665 ± 06 d	665 ± 07 c	5.2 ± 0.06 d	5.2 ± 0.07 c	21 ± 1.50 d	21 ± 2.12 d
Simeto	4.6 ± 0.25 a	5.7 ± 1.27 a	673 ± 05 d	670 ± 14 c	5.1 ± 0.10 d	5.2 ± 0.14 c	17 ± 0.50 e	16 ± 1.41 e
Creso	3.0 ± 0.27 d	3.5 ± 0.35 cde	638 ± 24 e	645 ± 21 cd	4.9 ± 0.22 e	5.0 ± 0.21 cd	16 ± 3.92 e	15 ± 0.00 e
Arcangelo	2.3 ± 0.19 g	2.9 ± 0.28 def	518 ± 19 g	495 ± 07 g	4.0 ± 0.13 g	3.8 ± 0.00 f	5 ± 2.06 g	4 ± 2.83 g
AC Barrie	2.4 ± 0.15 fg	2.6 ± 0.07 ef	515 ± 13 g	685 ± 07 c	3.8 ± 0.10 h	5.1 ± 0.14 c	33 ± 0.82 a	38 ± 0.71 a
Glenlea	4.8 ± 0.26 a	4.9 ± 0.64 ab	738 ± 38 b	855 ± 49 a	5.7 ± 0.29 ab	6.7 ± 0.49 a	33 ± 5.44 a	35 ± 1.41 a
Averages	3.1 [B]	3.4 [A]	648 [B]	679 [A]	5.0 [B]	5.3 [A]	21 [A]	20 [A]
Mean of N.A.[1]	3.1 ± 0.7	3.4 ± 1.0	688 ± 61	703 ± 84	5.3 ± 0.5	5.4 ± 0.6	23 ± 5.5	21 ± 6.9
Mean of Itl.[2]	2.9 ± 1.1	3.4 ± 1.4	615 ± 65	615 ± 73	4.7 ± 0.5	4.8 ± 0.6	14 ± 6.0	13 ± 6.5
LSD-A[3]	0.29	1.06	20.6	41.3	0.18	0.39	2.73	2.75
LSD-M[3]	0.22		9.9		0.10		1.1	
CV	28.2	29.3	12.1	14.1	13.0	14.6	41.2	49.5

[1]North American Durums.
[2] Italian Durums.
[3]Least Significant Difference; A is among genotypes and M is between mill products.
Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within mill products G and 6R and upper case letters are different among averages of mill products G and 6R. n=2±SD.

Figure 15. Effect of milling treatment and fermentation times on baking absorption (Babs, %) of (A) milling treatment G versus 6R and (B) fermentation times 15, 90 and 165 min of mill product G.


A
G
6R
70
65
60
55
50
Babs (%)
AC Melita
AC Morse
Kyle
Durex
DT 674
DT 369
Ofanto
Grazia
Simeto
Creso
Arcangelo
AC Barrie
Glenlea


B
15
90
165
70
65
60
55
50
Babs (%)
AC Melita
AC Morse
Kyle
Durex
DT 674
DT 369
Ofanto
Grazia
Simeto
Creso
Arcangelo
AC Barrie
Glenlea

During fermentation at 30 °c, only damaged starch is the contributing factor for gassing power. Gassing power increases many fold at the onset of starch gelatinization in the oven and, at this stage, all the starch contributes to gassing power by its breakdown to fermentable sugars. Ovenrise on average was not statistically different between G and 6R for all genotypes, but was different when only durum wheat genotypes were compared. On average for durum genotypes ovenrise for mill product G was (18.7 cm) compared to 6R (17.4 cm) for long fermentation (165 min) bake test (Table 19). This corresponds to the higher baking absorption of G mill product. Fermentation losses (Tipples, 1969) are high at long fermentation and would be expected to drop for no-time and short fermentation times.

4.7.2 Baking Treatments – Effects of Varying Fermentation Times

Preliminary baking studies showed that the loaf collapsed after extended fermentation times (60–180 min) for some durum genotypes indicating a lack of fermentation tolerance for those genotypes. Fermentation time is a critical baking process parameter, and little information has been published on its effects in durum wheat breadmaking. Accordingly, the effect of fermentation time on baking performance was studied in more detail.

Table 20. Comparison of remix-to-peak time (min), loaf volume (cc) of durum and common wheat samples for G at fermentation times 15, 90 and 165 min.

Genotypes	Remix-to-Peak Time			Loaf Volume		
	15 min	90 min	165 min	15 min	90 min	165 min
AC Melita	5.2 ± 0.5 de	4.2 ± 0.3 cd	3.4 ± 0.30 c	820 ± 22 b	808 ± 19 b	760 ± 12 a
AC Morse	4.1 ± 0.3 fg	4.0 ± 0.3 d	2.8 ± 0.19 de	805 ± 21 bc	773 ± 05 c	675 ± 13 d
Kyle	2.8 ± 0.3 hi	2.7 ± 0.0 f	2.3 ± 0.08 fg	763 ± 10 e	738 ± 13 e	658 ± 15 de
Durex	7.6 ± 0.6 b	4.8 ± 0.1 c	3.6 ± 0.21 bc	785 ± 10 cde	743 ± 10 de	705 ± 06 c
DT 674	2.9 ± 0.5 hi	3.0 ± 0.4 ef	2.6 ± 0.17 ef	693 ± 10 g	665 ± 13 f	593 ± 15 f
DT 369	8.5 ± 1.5 b	5.7 ± 0.6 b	3.9 ± 0.29 b	793 ± 13 cd	763 ± 15 cd	722 ± 10 bc
Ofanto	2.2 ± 0.2 i	1.9 ± 0.8 g	1.9 ± 0.15 h	735 ± 13 f	663 ± 17 f	603 ± 10 f
Grazia	3.4 ± 0.1 gh	2.8 ± 0.2 f	2.2 ± 0.25 g	770 ± 08 de	735 ± 10 e	665 ± 06 d
Simeto	6.0 ± 0.4 cd	5.5 ± 1.1 b	4.6 ± 0.25 a	720 ± 14 f	675 ± 17 f	673 ± 05 d
Creso	6.3 ± 1.0 c	3.6 ± 0.5 de	3.0 ± 0.27 d	735 ± 10 f	735 ± 13 e	638 ± 24 e
Arcangelo	2.4 ± 0.2 hi	2.5 ± 0.3 fg	2.3 ± 0.19 g	618 ± 25 h	603 ± 13 g	518 ± 19 g
AC Barrie	4.7 ± 0.4 ef	3.7 ± 0.2 de	2.4 ± 0.15 fg	818 ± 26 b	835 ± 19 a	515 ± 13 g
Glenlea	24.9 ± 1.0 a	10.1 ± 0.6 a	4.8 ± 0.26 a	918 ± 31 a	833 ± 30 a	738 ± 38 b
Averages	6.2 [A]	4.2 [B]	3.1 [C]	767 [A]	736 [B]	651 [C]
Mean of N.A.[1]	5.2 ± 2.4	4.1 ± 1.1	3.1 ± 0.6	777 ± 45	748 ± 48	686 ± 58
Mean of Itl.[2]	4.1 ± 2.0	3.3 ± 1.4	2.8 ± 1.1	716 ± 58	682 ± 55	619 ± 63
LSD-A[3]	0.71	0.71	0.29	24.3	20.9	20.6
LSD-F[3]	0.19			6.4		
CV	46.8	34.0	28.0	7.7	8.3	10.2

[1]North American Durums.
[2] Italian Durums.
[3]Least Significant Difference; A is among genotypes and F is among fermentation times
Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within fermentation times 15, 90 or 165 min and upper case letters are different among averages of fermentation times 15, 90 and 165 min. n=4±SD.

As the preceding baking experiments indicated that there was no significant difference in LV between G and 6R for durum wheat genotypes, the effects of fermentation were studied on G mill product only. The treatment varied fermentation times to include a 15 min (no-time) and 90 min (moderate), in addition to the standard 165 min (long) fermentation time.

Remix-to-peak time was significantly different among all three fermentation times (Table 20). In general, RTPT decreased with increasing fermentation times. On average, RTPT at 15 min fermentation (6.2 min) was twice as long as that the time at 165 min (3.1 min). This suggests that gluten proteins were being adversely affected by fermentation, an outcome which likely explains the negative response of LV to increased fermentation time.

LV was significantly ($p \leq 0.01$) different among genotypes for all three fermentation times (Table 18). The overall rankings of the genotypes at 15 min fermentation was similar to 165 min with two exceptions. Glenlea (G) was different ($p < 0.05$) from all genotypes with the highest LV at 15 min fermentation, with low starch damage but with gassing power comparable to durum genotypes. But, Glenlea was not different from AC Barrie and DT 369; for 90 and 165 min fermentation, respectively. At 15 min fermentation, AC Barrie and Simeto ranked higher and lower, respectively (Table 20). Among durum genotypes, Arcangelo had significantly the lowest LV. AC Barrie was not significantly different from AC Melita and AC Morse at 15 min and Arcangelo at 165 minutes. The lack of sufficient starch damage for AC Barrie, particularly for the 165 min fermentation time, was the reason for its reduced LV.

Generally, higher LV would be expected with increasing long fermentation time associated with higher gas production as fermentation proceeds. With longer fermentation time there is sufficient time for production of fermentable sugars due to yeast action on the substrate. However LV is a function of both gas production and gas retention by gluten films in dough (Dubois 1984). Clearly, extended fermentation had adverse effects on the ability of both durum and common wheat granular product to retain gas. This result is likely due to depolymerization/disaggregation of glutenin.

SV was significantly different among all three fermentation times and mirrored LV results, i.e. SV was higher for shorter fermentation times (Table 21). However, differences between fermentation times were relatively small compared to LV differences, likely due to lower fermentation losses associated with lower fermentation time treatments. These results indicate that at short fermentation times, when baking absorptions are higher the resulting LV, loaf weight and SV is higher. Benefits of long fermentation times were not found for G using the Remix-to-peak test baking procedure.

Baking absorption on average was within a small range for mill product G; 15 min (67.2%), 90 min (65.8%) and 165 min (60.8%) (Figure 15). The range of baking absorptions for all genotypes at 15 min (63-69%) and 90 min (63-69%) was comparable but the range was lower at165 min (58-63%). The low baking absorption at 165 min is due to reduced water-holding capacity of starch during long fermentation.

Average oven rise was significantly lower at short time though small (LSD = 0.7 cm) for 15 min (18 cm) compared to 90 and 165 min; 20 cm and 21 cm, respectively (Appendix 14). This variation is very small and cannot be explained with the available data recorded. Further study of ovenrise in a maturograph under controller

conditions might aid in confirming/explaining the differences observed in this experiment.

Table 21. Comparison of specific volume (cc/g) of durum and common wheat samples for G at fermentation times 15, 90 and 165 min.

Genotypes	Specific Volume		
	15 min	90 min	165 min
AC Melita	6.0 ± 0.1 b	6.1 ± 0.1 b	5.9 ± 0.12 a
AC Morse	5.9 ± 0.1 bc	5.7 ± 0.1 c	5.2 ± 0.10 d
Kyle	5.6 ± 0.0 e	5.5 ± 0.1 d	5.2 ± 0.13 d
Durex	5.8 ± 0.1 cd	5.6 ± 0.1 d	5.5 ± 0.06 c
DT 674	5.1 ± 0.1 g	5.0 ± 0.1 e	4.6 ± 0.13 f
DT 369	5.9 ± 0.1 bc	5.8 ± 0.1 c	5.7 ± 0.06 b
Ofanto	5.3 ± 0.1 fg	5.0 ± 0.1 e	4.6 ± 0.10 f
Grazia	5.6 ± 0.1 de	5.5 ± 0.1 d	5.2 ± 0.06 d
Simeto	5.2 ± 0.1 fg	5.0 ± 0.1 e	5.1 ± 0.10 d
Creso	5.3 ± 0.1 f	5.5 ± 0.1 d	4.9 ± 0.22 e
Arcangelo	4.5 ± 0.2 h	4.5 ± 0.1 f	4.0 ± 0.13 g
AC Barrie	6.0 ± 0.2 b	6.3 ± 0.1 a	3.8 ± 0.10 h
Glenlea	6.8 ± 0.2 a	6.4 ± 0.2 a	5.7 ± 0.29 ab
Averages	5.6 [A]	5.5 [B]	5.0 [C]
Mean of N.A.[1]	5.7 ± 0.3	5.6 ± 0.4	5.3 ± 0.5
Mean of Itl.[2]	5.2 ± 0.4	5.1 ± 0.4	4.8 ± 0.5
LSD-A[3]	0.18	0.18	0.18
LSD-F[3]	0.05		
CV	8.2	8.5	10.7

[1]North American Durums.
[2] Italian Durums.
[3]Least Significant Difference; A is among genotypes and F is among fermentation times
Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within fermentation times 15 , 90 or 165 min and upper case letters are different among averages of fermentation times 15, 90 and 165 min.
n=4±SD.

4.8 Subjective bread scoring

4.8.1 Effect of granularity (G and 6R)

It has been claimed that durum bread generally has a fine and uniform crumb structure (Liu et al, 1996). Bakers of common wheat pan bread prefer a fine crumb grain (Hayman et al, 1998).

Mill product granularity did not significantly affect external loaf appearance (LA), i.e. for G and 6R were not significantly different (5.0 and 5.2, respectively) (Table 22). The range of LA scores for G (3.5-6.1) was narrower than that for 6R (2.8-7.0). Weaker durum genotypes (Arcangelo, DT 674 and Kyle) had higher scores assigned for G than 6R. Between the two common wheats, Glenlea was scored higher than AC Barrie for both mill products. For G, the weaker durum genotypes (DT 674, Arcangelo and Ofanto) scored low for LA due to several faults in break and shred, symmetry, top crust structure and side crust structure. The loaves had scores further deducted for "old" and "slightly old" maturity.

Likewise mill product granularity did not significantly affect crumb structure scores assessed visually between G and 6R were found at standard 165 min fermentation time (Table 22). The range of values were similar for G and 6R; 4.0-6.3 and 4.3-6.3, respectively. The weaker durum wheats such as Arcangelo, DT 674, Ofanto and Kyle had coarser and open structure (thicker cellwalls) as reflected by the lower crumb structure values (4.0-5.5) for both mill products. For 6R product, Glenlea was not significantly different from strong and moderate strength durum wheats (Grazia, Durex, Simeto, AC Morse, AC Melita, Creso and DT 369). AC Barrie had low crumb structure

scores for both G and 6R, this is due to inadequate gassing power and the resulting low LV.

The amber yellow color in durum wheats is a result of the high xanthophyll content of the endosperm (Joppa and Williams, 1988; Boyacioglu and D'Appolonia, 1994b). The subjective scoring method used for crumb color was related to relate to visual brightness. The higher the value the brighter the bread crumb (Kilborn and Tipples 1981).

Averaged over all genotypes, crumb color scored similarly (5.1) for G and 6R (Table 22). Glenlea and AC Barrie were not significantly different for 6R, but were different for G; AC Barrie scored lower (4.9) than Glenlea (6.4). This difference was likely influenced by AC Barrie's low LV, resulting in a dense loaf with a coarse open crumb which reflects less light and is thus a duller crumb grain.

Total bread scores which is heavily influenced by LV results were not significantly different between G and 6R; 18.9 and 21.5, respectively (Table 22). However there appeared to be a large difference for common wheats. The range of values were narrower for G (6.8-31.0) than for 6R (5.0-43.8). AC Melita and Glenlea had the highest total scores for G (31 and 28, respectively) and 6R (31 and 44, respectively). Arcangelo had the lowest total bread score for both mill products, but was not significantly different from the low scores of Ofanto and DT 674. AC Barrie was not significantly different from the weakest durum genotypes for G. This was due to the low LV of AC Barrie. It is evident that the crumb characteristics between G and 6R are equivalent, with the exception of AC Barrie and very weak genotypes (such as, DT 674 and Arcangelo).

Table 22. Comparison of loaf appearance, crumb structure, crumb color and total bread score of durum and common wheat samples for G and 6R at long fermentation 165 min.

Genotypes	Loaf Appearance		Crumb Structure		Crumb Color		Total Bread Score	
	G	6R	G	6R	G	6R	G	6R
AC Melita	6.1 ± 1.3 a	6.5 ± 0.7 ab	6.3 ± 0.4 a	5.9 ± 0.5 ab	5.3 ± 0.4 bc	5.3 ± 0.4 bc	31.0 ± 10.7 a	31.1 ± 4.5 b
AC Morse	5.5 ± 0.0 abc	5.5 ± 0.7 bcd	6.0 ± 0.0 ab	5.9 ± 0.5 ab	5.0 ± 0.0 bc	5.0 ± 0.0 cd	22.6 ± 0.2 ab	23.7 ± 1.1 bcd
Kyle	5.5 ± 0.7 abc	5.2 ± 0.5 bcd	5.5 ± 0.0 bc	5.4 ± 0.9 abc	5.3 ± 0.4 bc	5.0 ± 0.0 cd	20.9 ± 1.7b	17.4 ± 4.8 de
Durex	5.0 ± 0.0 bcd	6.3 ± 1.1 abc	6.2 ± 0.0 ab	6.1 ± 0.1 a	5.0 ± 0.0 bc	5.0 ± 0.0 cd	21.9 ± 0.2 b	28.8 ± 6.6 bc
DT 674	4.0 ± 0.0 def	3.5 ± 0.7 e	4.9 ± 0.1 de	4.5 ± 0.0 cd	4.5 ± 0.0 c	4.3 ± 0.4 e	10.3 ± 0.7 c	7.8 ± 2.1 f
DT 369	5.3 ± 0.4 abc	5.3 ± 0.4 bcd	6.3 ± 0.4 a	5.5 ± 0.0 ab	5.0 ± 0.0 bc	5.0 ± 0.0 cd	24.0 ± 3.0 ab	21.7 ± 1.5 cd
Ofanto	3.8 ± 0.4 ef	4.2 ± 0.9 de	5.1 ± 0.1 cd	5.0 ± 0.0 bcd	4.9 ± 0.1 bc	4.8 ± 0.4 d	11.2 ± 0.8 c	12.0 ± 3.8 ef
Grazia	5.0 ± 0.0 bcd	5.0 ± 0.0 cd	5.8 ± 0.4 abc	6.3 ± 0.4 a	5.3 ± 0.4 bc	4.9 ± 0.1 cd	20.0 ± 0.1b	20.4 ± 1.5 cde
Simeto	5.1 ± 0.1 abc	5.0 ± 0.0 cd	6.3 ± 0.4 a	6.0 ± 0.0 a	4.8 ± 1.1 bc	4.8 ± 0.4 d	20.3 ± 5.1 b	19.1 ± 1.0 de
Creso	5.0 ± 0.0 bcd	5.8 ± 1.1 abc	5.8 ± 0.4 abc	5.8 ± 0.4 ab	5.5 ± 0.0 b	5.5 ± 0.0 b	19.9 ± 0.8 b	23.5 ± 5.0 bcd
Arcangelo	3.5 ± 0.7 f	2.8 ± 0.4 e	4.3 ± 0.4 ef	4.3 ± 0.4 d	4.5 ± 0.4 c	4.3 ± 0.4 e	6.8 ± 1.7 c	5.0 ± 1.5 f
AC Barrie	4.8 ± 0.4 cde	6.0 ± 0.0 abc	4.0 ± 0.0 f	5.0 ± 0.0 bcd	4.9 ± 0.6 bc	6.1 ± 0.1 a	9.6 ± 2.1 c	25.1 ± 0.8 bcd
Glenlea	6.0 ± 0.0 ab	7.0 ± 0.0 a	5.0 ± 0.7 d	5.6 ± 0.9 ab	6.4 ± 0.1 a	6.5 ± 0.0 a	27.6 ± 5.3 ab	43.8 ± 9.1 a
Averages	5.0 [A]	5.2 [A]	5.5 [A]	5.5 [A]	5.1 [A]	5.1 [A]	18.9 [A]	21.5 [A]
Mean of N.A.[1]	5.2 ± 0.7	5.4 ± 1.1	5.9 ± 0.6	5.5 ± 0.6	5.0 ± 0.3	4.9 ± 0.3	21.8 ± 6.7	21.7 ± 8.4
Mean of Itl.[2]	4.5 ± 0.8	4.5 ± 1.1	5.4 ± 0.8	5.5 ± 0.8	5.0 ± 0.4	4.8 ± 0.5	15.7 ± 6.3	16.0 ± 7.5
LSD-A[3]	1.1	1.4	0.71	0.94	0.83	0.41	8.5	9.2
LSD-M[3]	0.34		0.23		0.20		2.8	
CV	16.1	22.9	14.1	11.3	9.6	12.6	38.7	47.3

[1]North American Durums.
[2] Italian Durums.
[3]Least Significant Difference; A is among genotypes and M is between mill products.
Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within mill products G and 6R and upper case letters are different among averages of mill products G and 6R. n=2±SD.

4.8.2 Effect of Fermentation Times on Bread Scores

No significant ($p \leq 0.05$) difference in LA was found between 15 and 90 min fermentation times. However, significantly lower LA scores were assessed for 165 min fermentation (Table 23). Average LA scores for 15, 90 and 165 min were 5.5, 5.5 and 5.0, respectively.

For G material there was no significant difference in average crumb structure among the three fermentation times; 15 min (5.5), 90 min (5.6) and 165 min (5.5) (Table 23). Cell wall thickness is affected partly by the corresponding LV; lower volumes are often associated with thicker cell walls and a coarser crumb grain (Sapirstein 1999). In this case however, LV was significantly different among the 15, 90 and 165 min fermentation time treatments; 766, 736 and 648 cc, respectively. The order of ranking of the genotypes within each fermentation time changed from 15 to 165 min but not significantly.

At varying fermentation times, crumb color at 165 min was not significantly different from that obtained at 15 and 90 min (Table 24). But, there were significant differences between 15 min and 90 min for some genotypes. However those differences were very small. Glenlea consistently scored highest for crumb color at all three fermentation times, having a fine crumb and a brighter crumb color. AC Barrie scored significantly higher in crumb color for 15 (6.1) and 90 min (6.0) than at 165 min (4.9), while DT 674 had the lowest crumb color score (4.4 average score) for all three fermentation times.

Significant differences were observed between 165 min and, 15 and 90 min fermentation times for total bread score (Table 24). On average, the highest and lowest

total bread score were assigned to the 15 min (26.0) and the 165 min (18.9). Arcangelo had the lowest score at all three fermentation times and Glenlea had the highest scores at the two shorter fermentation times.

4.9 Digital Image Analysis of Crumb Grain

4.9.1 Comparative Study

Digital image analysis (DIA) can provide accurate and precise instrumented measurement of bread crumb grain (Sapistein 199). The effects of mill products (G and 6R) and fermentation times have been determined by the subjective GRL bread scoring method. These results were reported in the preceding section.

The GRL bread scoring procedure is a relatively old but established method . However it requires visual assessments done by an expert evaluator. Subtle differences might go noticed and not be discriminated by the assessor. Compared to the subjective approach, instrumental measurements are more rapid, consistent from day to day, more precise and comprehensive and can be performed with minimal instruction. Whether the instrumental measurements are related to subjective bread scores was addressed by this thesis research.

Table 23. Comparison of loaf appearance, crumb structure of durum and common wheat samples for G at fermentation times 15, 90 and 165 min.

Genotypes	Loaf Appearance			Crumb Structure		
	15 min	90 min	165 min	15 min	90 min	165 min
AC Melita	6.3 ± 0.4 abc	6.0 ± 0.7 ab	6.10 ± 1.3 a	6.3 ± 0.4 a	6.1 ± 0.1 a	6.25 ± 0.4 a
AC Morse	6.5 ± 0.7 ab	6.0 ± 0.0 ab	5.50 ± 0.0 abc	6.3 ± 0.4 a	6.5 ± 0.0 a	6.00 ± 0.0 ab
Kyle	5.3 ± 0.4 cd	6.3 ± 0.4 ab	5.50 ± 0.7 abc	5.5 ± 0.0 abc	5.0 ± 0.0 bcd	5.50 ± 0.0 bc
Durex	5.5 ± 0.7 bc	5.5 ± 0.7 abc	5.00 ± 0.0 bcd	5.8 ± 0.4 abc	6.3 ± 0.4 a	6.20 ± 0.0 ab
DT 674	4.3 ± 1.1 d	4.5 ± 0.7 c	4.00 ± 0.0 def	5.0 ± 0.0 bc	4.5 ± 0.0 cd	4.90 ± 0.1 de
DT 369	6.4 ± 0.8 ab	6.0 ± 1.4 ab	5.25 ± 0.4 abc	6.1 ± 0.1 ab	6.0 ± 0.7 ab	6.25 ± 0.4 a
Ofanto	6.0 ± 1.4 abc	5.3 ± 1.1 bc	3.75 ± 0.4 ef	4.8 ± 0.4 cd	5.0 ± 0.0 bcd	5.10 ± 0.1 cd
Grazia	5.3 ± 0.4 cd	5.5 ± 0.7 abc	5.00 ± 0.0 bcd	6.0 ± 0.0 ab	6.0 ± 0.7 ab	5.75 ± 0.4 abc
Simeto	5.3 ± 0.4 cd	5.5 ± 0.7 abc	5.10 ± 0.1 abc	5.5 ± 0.7 abc	5.8 ± 0.4 ab	6.25 ± 0.4 a
Creso	5.3 ± 0.4 cd	5.5 ± 0.7 abc	5.00 ± 0.0 bcd	5.8 ± 1.1 abc	6.3 ± 0.4 a	5.75 ± 0.4 abc
Arcangelo	3.8 ± 0.4 e	3.3 ± 0.4 d	3.50 ± 0.7 f	4.0 ± 0.0 d	4.0 ± 0.7 d	4.25 ± 0.4 ef
AC Barrie	5.5 ± 0.7 bc	6.3 ± 0.4 ab	4.75 ± 0.4 cde	5.0 ± 0.0 bcd	5.5 ± 0.7 abc	4.00 ± 0.0 f
Glenlea	6.8 ± 0.4 a	6.5 ± 0.7 a	6.00 ± 0.0 ab	5.8 ± 1.1 abc	5.9 ± 0.5 ab	5.00 ± 0.7 d
Averages	5.5 [A]	5.5 [A]	5.0 [B]	5.5 [A]	5.6 [A]	5.5 [A]
Mean of N.A.[1]	5.7 ± 0.9	5.7 ± 0.6	5.2 ± 0.7	5.8 ± 0.5	5.7 ± 0.8	5.9 ± 0.5
Mean of Itl.[2]	5.1 ± 0.8	5.0 ± 1.0	4.5 ± 0.8	5.2 ± 0.8	5.4 ± 0.9	5.4 ± 0.8
LSD-A[3]	1.1	1.1	1.1	1.1	1.0	0.71
LSD-F[3]	0.31			0.24		
CV	15.7	15.6	16.1	12.0	13.5	14.1

[1]North American Durums.
[2] Italian Durums.
[3]Least Significant Difference; A is among genotypes and F is among fermentation times
Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within fermentation times 15, 90 or 165 min and upper case letters are different among averages of fermentation times 15, 90 and 165 min. n=2±SD.

Table 24. Comparison of crumb color and total bread score of durum and common wheat samples for G at fermentation times 15, 90 and 165 min.

Genotypes	Crumb Color			Total Bread Score		
	15 min	90 min	165 min	15 min	90 min	165 min
AC Melita	5.5 ± 0.0 bcd	5.1 ± 0.1 c	5.25 ± 0.4 bc	35.8 ± 4.6 abc	29.9 ± 4.0 bc	31.0 ± 10.7 a
AC Morse	5.6 ± 0.6 bc	5.0 ± 0.0 cd	5.00 ± 0.0 bc	37.8 ± 10.6 ab	30.2 ± 0.3 bc	22.6 ± 0.2 ab
Kyle	5.0 ± 0.0 cde	5.0 ± 0.0 cd	5.25 ± 0.4 bc	22.1 ± 1.3 cde	22.8 ± 1.7 cde	20.9 ± 1.7 b
Durex	4.8 ± 0.4 de	5.0 ± 0.0 cd	5.00 ± 0.0 bc	23.3 ± 2.3 cde	25.3 ± 1.3 cd	21.9 ± 0.2 b
DT 674	4.5 ± 0.0 e	4.3 ± 0.4 f	4.50 ± 0.0 c	13.3 ± 3.5 ef	11.5 ± 0.7 fg	10.3 ± 0.7 c
DT 369	5.0 ± 0.0 cde	5.1 ± 0.1 c	5.00 ± 0.0 bc	30.8 ± 3.4 bcd	28.3 ± 10.1 bc	24.0 ± 3.0 ab
Ofanto	4.8 ± 0.4 de	4.5 ± 0.0 ef	4.90 ± 0.1 bc	20.5 ± 8.1 def	15.7 ± 3.8 ef	11.2 ± 0.8c
Grazia	5.3 ± 0.4 de	5.0 ± 0.0 cd	5.25 ± 0.4 bc	25.4 ± 3.6 bcde	23.9 ± 0.2 cd	20.0 ± 0.1 b
Simeto	5.0 ± 0.7 cde	4.7 ± 0.2 de	4.75 ± 1.1 bc	20.9 ± 6.9 def	20.2 ± 2.3 de	20.3 ± 5.1 b
Creso	5.6 ± 0.6 bc	5.4 ± 0.2 e	5.50 ± 0.0 b	25.1 ± 8.2 bcde	27.0 ± 3.1 cd	19.9 ± 0.8 b
Arcangelo	4.5 ± 0.7 e	4.3 ± 0.4 f	4.50 ± 0.4 c	8.3 ± 2.3 f	6.6 ± 1.4 g	6.8 ± 1.7 c
AC Barrie	6.1 ± 0.1 ab	6.0 ± 0.0 b	4.90 ± 0.6 bc	27.6 ± 5.1 bcd	35.0 ± 3.1 ab	9.6 ± 2.1 c
Glenlea	6.7 ± 0.2 a	6.5 ± 0.0 a	6.40 ± 0.1 a	47.3 ± 13.7 a	40.7 ± 5.4 a	27.6 ± 5.3 ab
Averages	5.2 ^{A}	5.1 ^{B}	5.1 ^{AB}	26.1 ^{A}	24.4 ^{A}	18.9 ^{B}
Mean of N.A.[1]	5.1 ± 0.4	4.9 ± 0.3	5.0 ± 0.3	27.2 ± 9.3	24.7 ± 7.0	21.8 ± 6.7
Mean of Itl.[2]	5.0 ± 0.4	4.8 ± 0.4	5.0 ± 0.4	20.0 ± 7.0	18.7 ± 8.0	15.7 ± 6.3
LSD-A[3]	0.76	0.38	0.83	13.7	7.7	8.5
LSD-F[3]	0.18			2.6		
CV	12.1	12.6	9.6	39.5	38.2	38.7

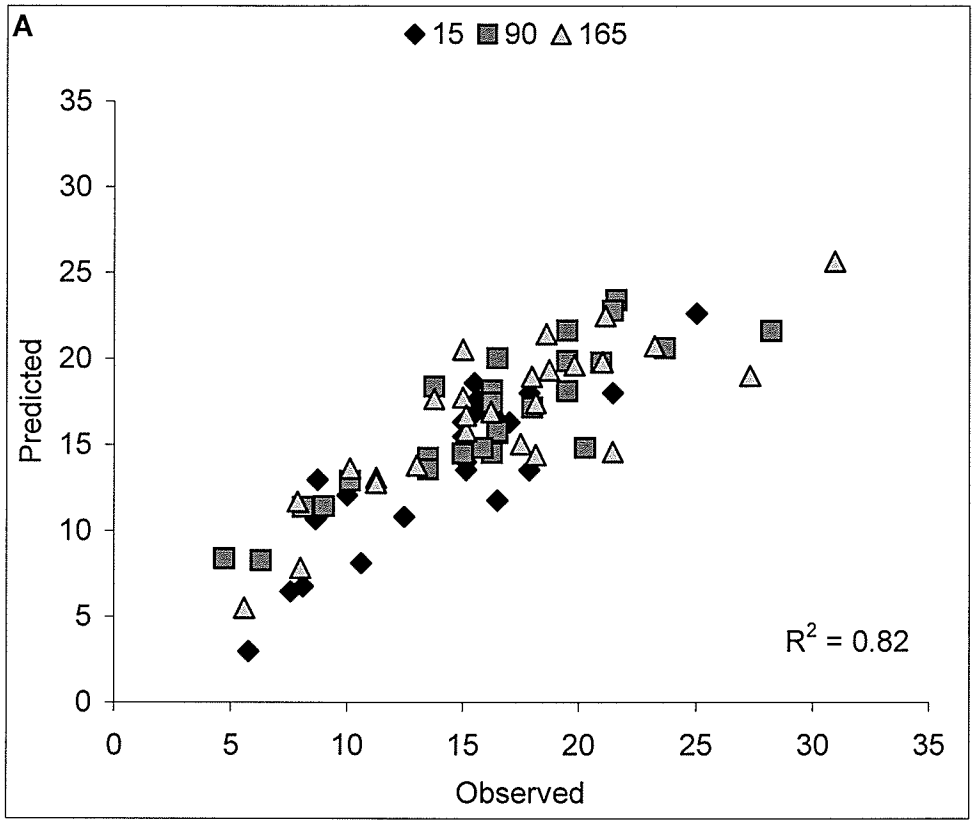
[1]North American Durums.
[2] Italian Durums.
[3]Least Significant Difference; A is among genotypes and F is among fermentation times
Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within fermentation times 15 , 90 or 165 min and upper case letters are different among averages of fermentation times 15, 90 and 165 min. n=2±SD.

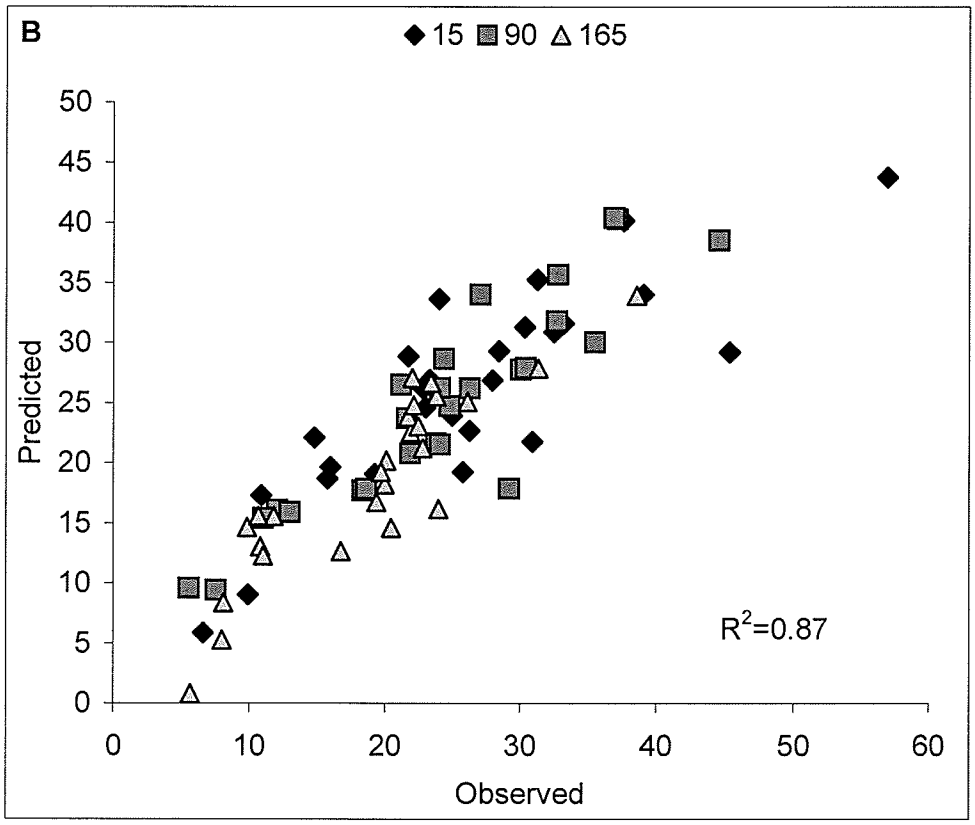
The relationship between subjective breadscore (calculated excluding LV); loaf appearance, crumb structure and crumb color and objective measurements was optimally achieved by a two variable model as there is no increase in the model R^2 beyond 2-variables. The DIA method was applied in two stages. First, DIA models were computed by stepwise regression analysis to bread scores calculated without LV, as the latter has a very large influence on the total bread score. The two best DIA variables were; number of cells smaller in area than 7.0 mm^2 (LT_7) and the void fraction which is the ratio of the total cell area divided by the area of the slice. The observed scores (GRL method) and the predicted (DIA) values were highly correlated, $R^2 = 0.82$ (Figure 16A).

There was an improved relationship ($R^2 = 0.87$) between GRL total bread score and the predicted total score by DIA (Figure 16B). The predicted total bread score was calculated with total number of cells in a slice (NO_CELLS) and total area of cells greater than 25 mm^2 (AREA_GT_25). These results confirm the possibility of using an image analysis system to predict the crumb grain quality of bread comparable to the subjective method, using the above mentioned parameters.

The LV of bread is widely determined by a volumeter by rape seed displacement. The LV was computed by using one variable, i.e. AREA_ALL (area of the slice in mm^2). A fixed area is eroded away on the outside of the slice and the remaining area on the inside is used to compute the LV. The predicted LV (DIA) was near perfectly ($R^2 = 0.98$) correlated to the observed LV (volumeteric method) (Figure 17). This is particularly interesting and is a useful tool for measuring LV simultaneously while assessing bread crumb grain.

Figure 16. Observed and DIA predicted bread subscore (LV excluded) – Model: 0.00905*LT_7 + 77.659*CTA – 53.154 (A) and total bread score – Model: 0.01462*NO_CELLS + 0.02549*AREA_GT_25 – 39.1644 (B) at fermentation times 15, 90 and 165 min.


A
15 90 165
Predicted
Observed
0
5
10
15
20
25
30
35
R^2 = 0.82


B
15 90 165
Predicted
Observed
0
5
10
15
20
25
30
35
40
45
50
60
R^2=0.87

4.9.2 Objective Crumb Grain Properties at Varying Fermentation Times (DIA)

In the case of evaluating bread crumb grain there are many factors considered, some of the parameters evaluated are: cell density, cell wall thickness (CWT), ratio of small to large cells, void fraction, average cell area (AVG AREA) and average gray level (AVG GL).

Cell density (cells/mm^2) is a measure of the number of cells per unit area. This provides a measure of crumb fineness. The cell density was not significantly different between North American and Italian durums at 90 and 165 min but number of cells per unit area was lower for Italian durums at 15 min fermentation (Table 25). The higher score of North American durums denotes a finer crumb structure compared to Italian durums.

CWT a measure of the intercellular distance between cells was not significantly different between North American and Italian durums at all three fermentation times and between the shorter (15 and 90 min) and longer (165 min) fermentation times for each group, i.e. N.A. and Itl. (Table 26).

Figure 17. Relationship between volumetric method and DIA of loaf volume at fermentation times 15, 90 and 165 min – Model: 0.2243*AREA_ALL – 83.752

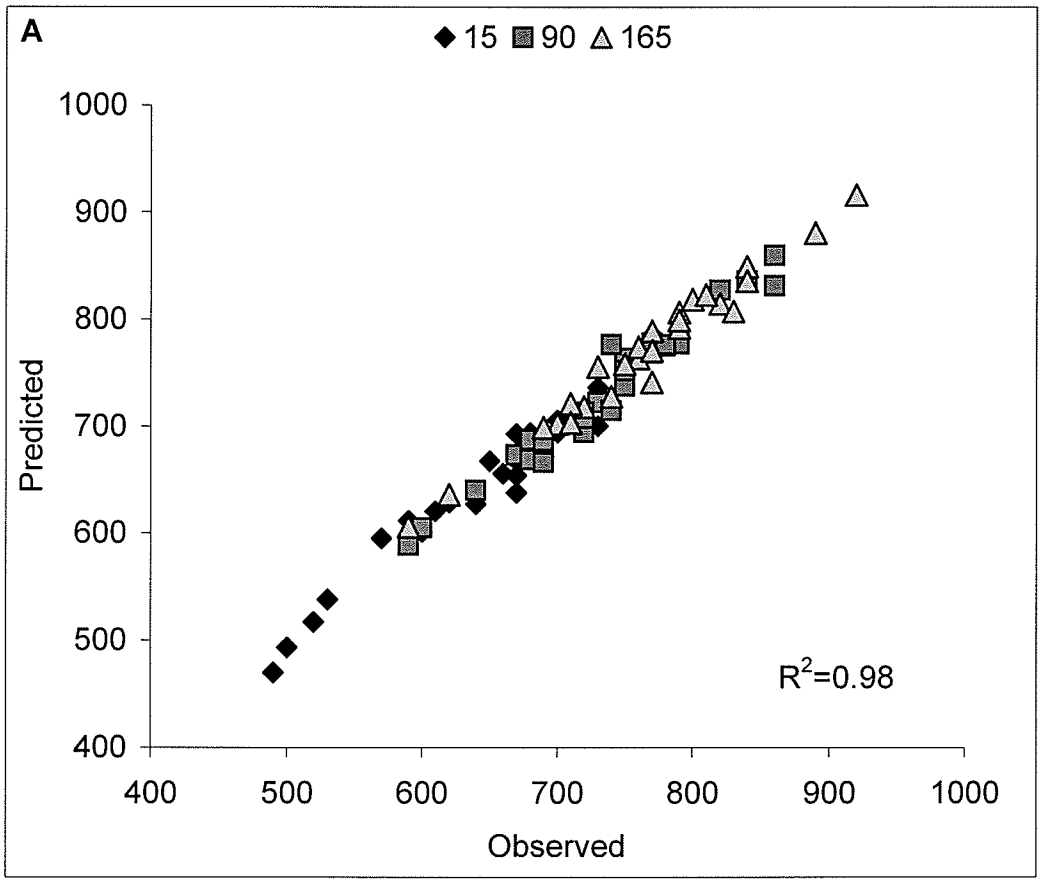

A
15
90
165
1000
900
800
700
600
500
400
Predicted
400
500
600
700
800
900
1000
Observed
R2=0.98

Table 25. Comparison of cell density of durum and common wheat samples for G at fermentation times 15, 90 and 165 min

Cell Density	15	90	165
AC Melita	93.2 ± 2.0 abc	97.1 ± 2.6 bcde	105.2 ± 3.4 ab
AC Morse	94.2 ± 1.3 abc	96.9 ± 0.8 bcde	108.2 ± 1.5 ab
Kyle	92.3 ± 5.8 abc	94.2 ± 2.9 cdef	104.6 ± 5.6 abc
Durex	94.6 ± 0.9 abc	96.7 ± 0.5 bcde	107.0 ± 2.4 ab
DT 674	89.3 ± 1.4 bcd	89.1 ± 2.5 f	101.1 ± 4.1 bc
DT 369	95.1 ± 0.9 ab	101.7 ± 3.4 ab	100.3 ± 1.1 bc
Ofanto	86.9 ± 0.5 cd	97.6 ± 3.4 bcd	104.8 ± 2.7 abc
Grazia	92.6 ± 6.9 abc	92.0 ± 1.3 ef	106.0 ± 3.7 ab
Simeto	88.7 ± 0.2 bcd	93.7 ± 0.1 def	95.5 ± 2.3 c
Creso	88.8 ± 0.1 bcd	94.3 ± 1.9 cdef	102.8 ± 6.9 abc
Arcangelo	83.4 ± 0.8 d	91.8 ± 0.9 ef	99.2 ± 2.5 bc
AC Barrie	97.8 ± 4.0 a	99.4 ± 3.4 abc	112.0 ± 7.3 a
Glenlea	97.8 ± 5.5 a	103.5 ± 0.2 a	108.9 ± 1.8 ab
Averages	91.9	96.0	104.3
Mean of N.A.	93.1 ± 2.8 b	95.9 ± 4.3 b	104.4 ± 3.9 b
Mean of Itl.	88.1 ± 3.9 c	93.9 ± 2.6 b	101.7 ± 5.1 b
C.V.	4.6	4.2	4.3

[1]North American Durums.
[2] Italian Durums.

Table 26. Comparison of cell wall thickness of durum and common wheat samples for G at fermentation times 15, 90 and 165 min

CWT	15	90	165
AC Melita	654.7 ± 2.8 c	678.4 ± 34.4 c	686.6 ± 70.8 b
AC Morse	697.1 ± 25.1 bc	658.5 ± 43.3 c	711.9 ± 31.7 b
Kyle	740.6 ± 29.3 b	713.8 ± 2.1 abc	719.6 ± 6.4 b
Durex	704.2 ± 44.3 bc	657.4 ± 10.3 c	695.2 ± 37.4 b
DT 674	760.6 ± 53.1 b	750.9 ± 5.8 ab	740.7 ± 23.4 ab
DT 369	659.1 ± 28.4 c	670.1 ± 29.4 c	687.9 ± 29.2 b
Ofanto	740.6 ± 45.1 b	695.0 ± 3.0 bc	723.6 ± 2.4 ab
Grazia	690.9 ± 11.2 bc	689.2 ± 23.7 c	707.3 ± 2.0 b
Simeto	717.3 ± 48.5 bc	676.9 ± 16.7 c	704.7 ± 39.5 b
Creso	711.9 ± 28.5 bc	691.1 ± 54.2 c	717.1 ± 9.5 b
Arcangelo	833.1 ± 29.7 a	763.3 ± 11.2 a	795.9 ± 7.1 a
AC Barrie	718.1 ± 29.1 bc	685.6 ± 9.2 c	797.7 ± 30.8 a
Glenlea	681.7 ± 1.2 bc	688.9 ± 22.3 c	718.4 ± 42.4 b
Averages	716.1	693.8	723.6
Mean of N.A.	702.7 ± 47.8 a	688.2 ± 40.2 a	706.9 ± 34.8 b
Mean of Itl.	738.8 ± 58.7 a	703.1 ± 38.5 a	729.7 ± 38.2 ab
C.V.	6.5	4.6	4.9

[1]North American Durums.
[2] Italian Durums.

Ratio of small to large cells was calculated by dividing the number of cells less than 4.0 mm^2. This is a measure of the crumb grain uniformity, a larger value denotes a more uniform cellular structure. There was no significant difference due to fermentation times for North American durums (Table 27). Ratio was lower for Italian durums at 15 min compared to 90 and 165 min, indicative of irregular cells.

Void fraction is a measure of the ratio of total cell area divided by area of the slice. This parameter is influenced by the LV. The parameter was not significantly different between North American and Italian durums at each fementation time and among fermentation times for each group of durums; N.A. and Itl. (Table 28).

Average area (mm^2) is a measure of cell size. The average cell size was significantly higher for Italian durums compared to North American durums at 15 min fermentation (Table 29). This implies that short fermentation resulted in larger gas cells. For North American durums the cell size was significantly smaller at 165 min fermentation compared to 15 min.

Average gray level (AVG GL) is a measure of reflectance of the bread slice. Bread slice with a relatively fine crumb grain, i.e. numerous small cells would have a higher reflectance compared to a bread slice with a coarse crumb grain. Average gray level was not significantly different among fermentation times for both North American and Italian durums (Table 30). But reflectance was significantly lower for Italian durums, this corresponds to the larger cells measured in average area (Table29). Gray level should be interpreted cautiously due to the influence of the yellow color in durum wheat breads.

Table 27. Comparison of small to large cells of durum and common wheat samples for G at fermentation times 15, 90 and 165 min

SMALL TO LARGE CELLS	15	90	165
AC Melita	39.1 ± 1.9 bc	44.1 ± 0.4 abc	42.2 ± 2.3 ab
AC Morse	40.3 ± 2.6 ab	39.8 ± 3.1 bcd	43.1 ± 2.9 ab
Kyle	39.6 ± 4.2 bc	42.4 ± 3.1 bcd	43.5 ± 4.7 ab
Durex	41.3 ± 2.0 ab	44.3 ± 1.3 ab	43.8 ± 2.9 ab
DT 674	37.6 ± 2.0 bcd	36.8 ± 2.1 d	41.9 ± 1.1 abc
DT 369	40.6 ± 1.3 ab	39.3 ± 2.1 bcd	37.4 ± 2.2 bc
Ofanto	36.7 ± 1.9 bcd	37.1 ± 1.7 cd	40.9 ± 0.8 bc
Grazia	37.1 ± 2.2 bcd	37.3 ± 0.3 bcd	39.7 ± 3.6 bc
Simeto	34.6 ± 3.2 cd	39.7 ± 1.2 bcd	35.1 ± 1.2 c
Creso	35.9 ± 1.1 bcd	37.4 ± 6.4 bcd	40.2 ± 4.9 bc
Arcangelo	33.2 ± 1.8 d	35.8 ± 0.1 d	39.2 ± 0.2 bc
AC Barrie	40.0 ± 1.5 b	42.7 ± 2.6 bcd	48.7 ± 4.5 a
Glenlea	45.4 ± 0.1 a	50.3 ± 5.2 a	44.4 ± 0.5 ab
Averages	38.6	40.5	41.5
Mean of N.A.	39.8 ± 2.2 b	41.1 ± 3.3 b	41.9 ± 3.1 b
Mean of Itl.	35.5 ± 2.2 c	37.5 ± 2.6 b	39.0 ± 3.0 b
C.V.	8.3	10.1	8.3

[1]North American Durums.
[2] Italian Durums.

Table 28. Comparison of void fraction of durum and common wheat samples for G at fermentation times 15, 90 and 165 min

VOID FRACTION	15	90	165
AC Melita	0.51 ± 0.01 a	0.50 ± 0.00 a	0.48 ± 0.02 a
AC Morse	0.50 ± 0.01 ab	0.50 ± 0.01 a	0.47 ± 0.01 ab
Kyle	0.49 ± 0.02 ab	0.49 ± 0.01 ab	0.47 ± 0.01 ab
Durex	0.49 ± 0.01 ab	0.50 ± 0.00 a	0.48 ± 0.00 a
DT 674	0.49 ± 0.02 ab	0.49 ± 0.01 ab	0.47 ± 0.01 ab
DT 369	0.50 ± 0.01 a	0.49 ± 0.01 a	0.49 ± 0.01 a
Ofanto	0.50 ± 0.01 ab	0.49 ± 0.01 ab	0.47 ± 0.00 ab
Grazia	0.50 ± 0.02 a	0.50 ± 0.01 a	0.47 ± 0.01 ab
Simeto	0.50 ± 0.01 ab	0.50 ± 0.00 a	0.48 ± 0.01 a
Creso	0.50 ± 0.01 ab	0.49 ± 0.02 a	0.47 ± 0.01 ab
Arcangelo	0.47 ± 0.02 b	0.47 ± 0.01 b	0.45 ± 0.00 bc
AC Barrie	0.50 ± 0.02 ab	0.50 ± 0.01 a	0.44 ± 0.02 c
Glenlea	0.50 ± 0.01 ab	0.50 ± 0.01 a	0.47 ± 0.01 ab
Averages	0.50	0.49	0.47
Mean of N.A.	0.50 ± 0.01 a	0.50 ± 0.01 a	0.48 ± 0.01 a
Mean of Itl.	0.49 ± 0.02 a	0.49 ± 0.01 a	0.47 ± 0.01 ab
C.V.	1.9	1.8	2.7

[1]North American Durums.
[2] Italian Durums.

Table 29. Comparison of average cell area of durum and common wheat samples for G at fermentation times 15, 90 and 165 min.

AVG AREA	15	90	165
AC Melita	0.55 ± 0.02 a	0.52 ± 0.01 abc	0.46 ± 0.00 ab
AC Morse	0.53 ± 0.02 a	0.52 ± 0.01 abc	0.43 ± 0.02 bc
Kyle	0.53 ± 0.05 a	0.52 ± 0.03 abc	0.45 ± 0.03 bc
Durex	0.52 ± 0.00 a	0.52 ± 0.01 abc	0.45 ± 0.01 bc
DT 674	0.54 ± 0.03 a	0.55 ± 0.03 a	0.47 ± 0.03 ab
DT 369	0.53 ± 0.00 a	0.49 ± 0.01 c	0.48 ± 0.01 ab
Ofanto	0.57 ± 0.01 a	0.50 ± 0.03 bc	0.45 ± 0.01 bc
Grazia	0.55 ± 0.06 a	0.55 ± 0.00 a	0.45 ± 0.02 bc
Simeto	0.56 ± 0.01 a	0.54 ± 0.01 ab	0.51 ± 0.00 a
Creso	0.56 ± 0.01 a	0.53 ± 0.03 abc	0.46 ± 0.04 ab
Arcangelo	0.56 ± 0.02 a	0.52 ± 0.01 abc	0.45 ± 0.01 bc
AC Barrie	0.51 ± 0.04 a	0.50 ± 0.03 abc	0.40 ± 0.04 c
Glenlea	0.51 ± 0.04 a	0.48 ± 0.01 c	0.43 ± 0.00 bc
Averages	0.54	0.52	0.45
Mean of N.A.	0.53 ± 0.02 b	0.52 ± 0.02 a	0.46 ± 0.02 a
Mean of Itl.	0.56 ± 0.02 a	0.53 ± 0.02 a	0.46 ± 0.03 a
C.V.	3.8	3.9	5.9

[1]North American Durums.
[2] Italian Durums.

Table 30. Comparison of average grayscale (GL) of durum and common wheat samples for G at fermentation times 15, 90 and 165 min

AVG GL	15	90	165
AC Melita	124.1 ± 1.8 abc	123.7 ± 0.4 ab	127.1 ± 0.4 ab
AC Morse	124.3 ± 1.5 ab	124.2 ± 0.1 ab	129.1 ± 0.4 a
Kyle	122.8 ± 2.4 abcd	120.8 ± 6.4 bcd	129.8 ± 0.7 a
Durex	122.1 ± 1.1 abcd	122.2 ± 1.7 bc	129.4 ± 3.1 a
DT 674	121.5 ± 0.5 abcd	121.1 ± 0.5 bcd	126.9 ± 3.7 ab
DT 369	125.1 ± 1.1 a	127.8 ± 3.4 a	130.0 ± 1.4 a
Ofanto	116.2 ± 0.7 efg	122.3 ± 0.5 bc	124.9 ± 3.4 abc
Grazia	120.5 ± 2.1 bcde	118.0 ± 0.7 cde	127.1 ± 2.5 ab
Simeto	115.8 ± 1.2 fg	114.8 ± 0.5 e	120.9 ± 0.3 c
Creso	118.5 ± 2.1 defg	121.8 ± 0.9 bc	125.0 ± 2.6 abc
Arcangelo	114.8 ± 2.7 g	117.9 ± 1.9 cde	122.8 ± 2.0 bc
AC Barrie	114.3 ± 2.8 g	116.4 ± 0.9 ed	127.3 ± 0.7 ab
Glenlea	119.8 ± 2.5 cdef	123.9 ± 0.5 ab	130.2 ± 2.6 a
Averages	119.9	121.1	126.9
Mean of N.A.	123.3 ± 1.7 a	123.3 ± 3.3 a	128.7 ± 2.0 a
Mean of Itl.	117.2 ± 2.6 b	118.9 ± 3.0 b	124.1 ± 2.9 b
C.V.	3.1	2.9	2.3

[1]North American Durums.
[2] Italian Durums.

4.10 Texture analysis of bread slices

4.10.1 Effect of granularity (G and 6R)

Significant differences on day one and day five were observed for all textural traits for both G and 6R (Table 31, 32).

One of the marked physicochemical changes during bread staling is crumb firming. This process of crumb firming involves starch retrogradation, i.e. the reorganization of starch polymers by partial gelatinization and re-crystallization. It is assumed that reorganization of amylose and amylopectin polymers contribute to the increased firming during staling of bakery products (Hug-Iten et al, 2001).

Peak force (PF1) provides a measure of the firmness, rigidity and/or flexibility of the bread crumb. G had significantly higher PF1 values compared to 6R on both day one and day five after baking (Table 31, 32). LV was negatively corelated to PF1 for day one and day five; G, $r = 0.88$ and $r = 0.80$ and 6R, $r = 0.83$ and $r = 0.88$, respectively. For mill product G, AC Barrie with the lowest LV had the firmest crumb on day one (162 g) and day five (320 g) compared to all other genotypes on average; 90 and 181 g for day one and five, respectively. Several genotypes PF1 was not significantly different for day one and day five, i.e. Glenlea, DT 369, Simeto, Durex (strong genotypes) and Kyle and Grazia (weak genotypes).

Table 31. Comparison of peak force (g), gradient (g*s) and resilience (%) of durum and common wheat samples for G and 6R on day one at 165 min fermentation time.

Day 1	Peak Force		Gradient		Resilience	
Genotypes	G	6R	G	6R	G	6R
AC Melita	63.5 ± 8.0 g	58.2 ± 6.8 gh	14.6 ± 1.9 g	13.3 ± 1.7 gh	49.2 ± 2.0 a	51.51 ± 1.8 a
AC Morse	82.6 ± 10.0 def	69.8 ± 8.1 efgh	19.4 ± 2.5 def	16.2 ± 2.0 efgh	45.7 ± 2.6 cde	47.78 ± 3.1b
Kyle	77.2 ± 12.8 ef	104.8 ± 23.8 c	18.0 ± 3.2 ef	24.9 ± 5.9 c	44.3 ± 3.7 cf	42.26 ± 2.3 f
Durex	73.2 ± 6.7 fg	57.6 ± 7.2 h	17.0 ± 1.7 fg	13.1 ± 1.9 h	48.1 ± 3.9 ab	51.85 ± 1.6 a
DT 674	96.2 ± 16.6 c	90.7 ± 14.3 cd	22.7 ± 4.2 c	21.4 ± 3.5 cd	46.4 ± 2.9 bcde	50.46 ± 2.8 a
DT 369	81.7 ± 8.9 def	71.8 ± 11.4 efgh	19.1 ± 2.2 def	16.6 ± 2.9 efgh	43.0 ± 3.3 fg	47.19 ± 2.9 b
Ofanto	71.4 ± 5.3 fg	78.8 ± 6.7 de	16.6 ± 1.3 fg	18.4 ± 1.7 de	47.0 ± 2.2 abcd	46.44 ± 2.4 bc
Grazia	85.3 ± 5.8 cde	72.0 ± 5.1 efg	20.0 ± 1.5 cde	16.7 ± 1.3 efg	45.9 ± 2.3 bcde	50.06 ± 1.0 a
Simeto	80.2 ± 6.1 ef	73.1 ± 13.7 ef	18.7 ± 1.5 ef	17.0 ± 3.4 ef	45.4 ± 2.4 cde	47.00 ± 3.0 b
Creso	92.4 ± 12.9 cd	77.9 ± 12.7 def	21.8 ± 3.2 cd	18.1 ± 3.2 def	44.7 ± 3.6 def	47.96 ± 3.7 b
Arcangelo	123.4 ± 25.6 b	138.2 ± 12.2 a	29.5 ± 6.3 b	33.1 ± 3.0 a	41.2 ± 3.1 g	42.61 ± 1.7 ef
AC Barrie	162.3 ± 16.7 a	120.4 ± 36.8 b	39.1 ± 4.2 a	28.6 ± 9.1 b	47.5 ± 1.9 abc	44.75 ± 3.2 cd
Glenlea	74.9 ± 6.7 ef	64.5 ± 16.8 fgh	17.4 ± 1.6 ef	14.8 ± 4.2 fgh	41.5 ± 1.9 g	44.45 ± 2.6 de
Averages	89.6 [A]	82.9 [B]	21.1 [A]	19.4 [B]	45.4 [B]	47.3 [A]
Mean of N.A.[1]	79.06 ± 10.9	75.48 ± 18.7	18.46 ± 2.7	17.57 ± 4.7	46.09 ± 2.3	48.51 ± 3.6
Mean of Itl.[2]	90.54 ± 19.9	88.00 ± 28.2	21.31 ± 4.9	20.69 ± 7.0	44.85 ± 2.2	46.82 ± 2.7
LSD-A[3]	11.3	14.2	2.8	2.0	2.4	2.0
LSD-M[3]	4.4		1.1		0.73	
CV	29.4	29.4	31.1	31.2	5.4	6.7

[1] North American Durums.
[2] Italian Durums.
[3] Least Significant Difference; A is among genotypes and M is between mill products.
Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within mill products G and 6R and upper case letters are different among averages of mill products G and 6R. n=6±SD.

Table 32. Comparison of peak force (g), gradient (g*s) and resilience (%) of durum and common wheat samples for G and 6R on day five at 165 min fermentation time.

Day 5	Peak Force		Gradient		Resilience	
Genotypes	G	6R	G	6R	G	6R
AC Melita	153.87 ± 14.3 ef	112.71 ± 8.9 e	37.01 ± 3.5 ef	26.82 ± 2.2 e	38.53 ± 3.1 bc	43.16 ± 2.9 bc
AC Morse	141.00 ± 25.5 fg	132.47 ± 7.6 de	33.79 ± 6.3 fg	31.74 ± 1.9 de	40.10 ± 5.5 ab	39.42 ± 2.9 ab
Kyle	164.51 ± 12.5 de	210.27 ± 28.8 b	39.69 ± 3.2 de	51.01 ± 7.1 b	34.68 ± 2.7 de	34.21 ± 2.4 de
Durex	153.48 ± 9.6 ef	114.79 ± 7.9 e	36.97 ± 2.3 ef	27.30 ± 2.0 e	41.91 ± 1.7 ab	45.19 ± 2.5 ab
DT 674	194.80 ± 17.0 c	177.48 ± 35.1 bc	47.16 ± 4.2 c	42.94 ± 8.8 bc	38.37 ± 4.1 bcd	44.46 ± 4.5 bcd
DT 369	161.22 ± 20.2 ef	147.40 ± 14.1 cde	38.80 ± 4.9 ef	35.43 ± 3.5 cde	32.25 ± 2.8 e	36.14 ± 3.3 e
Ofanto	121.04 ± 21.3 g	166.19 ± 20.6 cd	28.86 ± 5.3 g	40.11 ± 5.2 cd	43.75 ± 7.5 a	38.08 ± 3.1 a
Grazia	174.43 ± 7.6 cde	160.58 ± 9.0 cd	42.10 ± 1.9 cde	38.62 ± 2.2 cd	35.83 ± 3.9 cde	39.82 ± 2.7 cde
Simeto	164.49 ± 16.1 de	144.56 ± 9.5 cde	39.60 ± 4.0 de	34.70 ± 2.4 cde	35.47 ± 3.6 cde	39.96 ± 4.1 cde
Creso	186.69 ± 14.7 cd	166.80 ± 42.0 cd	45.26 ± 3.7 cd	40.19 ± 10.4 cd	35.39 ± 3.6 cde	41.10 ± 5.3 cde
Arcangelo	240.50 ± 25.8 b	263.22 ± 46.4 a	58.54 ± 6.4 b	64.18 ± 11.5 a	32.10 ± 4.0 e	37.13 ± 4.0 e
AC Barrie	320.53 ± 45.7 a	208.18 ± 107.7 b	78.37 ± 11 a	50.50 ± 26.6 b	41.27 ± 3.3 ab	42.05 ± 7.6 ab
Glenlea	171.03 ± 9.7 de	142.62 ± 33.9 cde	41.26 ± 2.5 de	34.25 ± 8.4 cde	34.22 ± 3.1 e	36.46 ± 3.9 e
Averages	180.6 [A]	165.2 [B]	43.6 [A]	39.8 [B]	37.2 [B]	39.8 [A]
Mean of N.A.[1]	161.48 ± 18.2	149.19 ± 38.3	38.90 ± 4.5	35.87 ± 9.5	37.64 ± 3.6	40.43 ± 4.6
Mean of Itl.[2]	177.43 ± 43.0	180.27 ± 47.2	42.87 ± 10.7	43.56 ± 11.7	36.51 ± 4.3	39.22 ± 1.6
LSD-A[3]	23.1	40.8	5.7	10.1	0.04	4.09
LSD-M[3]	11.2		2.8		1.2	
CV	28.1	25.5	28.9	26.2	10.0	8.4

[1]North American Durums.
[2] Italian Durums.
[3]Least Significant Difference; A is among genotypes and M is between mill products.
Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within mill products G and 6R and upper case letters are different among averages of mill products G and 6R. n=6±SD.

Among durum wheats, for day one and day five, Arcangelo had the firmest crumb (e.g. G on day one and five, 123 g and 241 g, respectively). On day five the other durum genotypes were not distinctly separated.

With mill product 6R compared to all other genotypes, Arcangelo had the firmest crumb on both day one and day five. AC Barrie was significantly softer than Arcangelo but was firmer than all other genotypes on both days. On day one and five, the crumb firmness of bread from 6R product was not was not significantly different among other genotypes.

Overall genotypes for G and 6R, AC Barrie and Arcangelo had the firmest crumb. A plausible explanation for this difference between Arcangelo and AC Barrie, and the other genotypes is as a result of their low LV for both G and 6R mill products. The remaining genotypes were significantly better performers. The percentage increase in PF1 over a five day period was similar between G and 6R, 105 and 102%, respectively (Table 33).

The slope (gradient) of the curve was the measurement of the rate of rupture of the crumb during the probe's first compression of the product. This value can be considered to be a measure of the fragility of the crumb grain. There was a significant ($p < 0.05$) difference in the gradient parameter between G and 6R on both day one and day five (Table 31, 32). The gradient was higher for G on day one and day five, 21 and 44 (g*s), respectively. The crumb grain ruptured under less force on day one. Arcangelo was significantly the least fragile among durums. For mill product G, AC Barrie was significantly higher than all genotypes on day one and five. Glenlea was not significantly

different from several durum genotypes on both days of evaluation: Kyle, Durex, DT 369, Grazia and Simeto.

For mill product 6R, Arcangelo was significantly higher than AC Barrie on day one and day five. This switch can be explained by the significantly lower LV of Arcangelo (495 cc) compared to AC Barrie (684 cc) (Table 17).

On day one and day five all other genotypes were not distinguishable (other than AC Barrie and Arcangelo) from each other. LV was negatively related to gradient on day one and day five; G, $r = 0.88$ and $r = 0.80$ and 6R, $r = 0.83$ and $r = 0.88$, respectively. The average increase in gradient was similar between G and 6R; 112 and 110 %, respectively (Table 31, 32). The similarity in response between PF1 and gradient, among genotypes was expected and was confirmed by the high correlation. PF1 and gradient were perfectly correlated ($r = 1.0$) on day one and day five for both G and 6R.

Consumers measure the freshness of a loaf of bread by squeezing the loaf. In an attempt to duplicate, this 'squeeze test', the ball probe simulates a human thumb. Resilience is a measure of how well the crumb can recover from compression of the first penetration. Significant differences between resilience of mill products G and 6R on day one were noted. Mill product 6R (47%) was more resilient than G (45%) on day one and, though the value was reduced (40%) on day five but remained higher (Table 29, 30). In contrast to PF1, Arcangelo was not significantly different to Glenlea for mill product G and 6R on both days of storage. AC Barrie was not significantly different to several durum wheat genotypes for both mill products on day one and day five. This result points to the good keeping quality of durum wheat bread. But, the extent of loss of resilience was lower for AC Barrie, G (13%) and 6R (6%) compared to other genotypes

(Table 32). There was no correlation of resilience to LV and PF1. The difference observed between AC Barrie and Arcangelo cannot be explained with the limited information available from this study.

Table 33. Comparison of percent increase in peak force (g) and gradient (g*s) and decrease in resilience (%) from day 1 to day 5 of durum and common wheat samples for G and 6R at 165 min fermentation time.

	% Increase in Peak Force		% Increase in Gradient		% Decrease in Resilience	
Genotypes	**G**	**6R**	**G**	**6R**	**G**	**6R**
AC Melita	145.0 a	97.0 ab	157.1 a	105.7 abc	21.7 a	16.1 ab
AC Morse	71.5 cd	91.5 ab	75.2 de	98.5 abc	12.4 bc	17.3 ab
Kyle	117.9 ab	105.8 a	127.0 abc	111.4 ab	21.4 a	18.8 ab
Durex	111.0 b	101.8 a	119.0 bc	111.5 ab	12.5 bc	12.7 bc
DT 674	106.2 b	98.2 ab	112.1 bc	103.9 abc	17.2 ab	11.8 bc
DT 369	101.4 bc	108.4 a	107.4 bcd	117.3 ab	24.6 a	23.4 a
Ofanto	68.5 d	110.5 a	72.7 e	117.1 ab	7.1 c	18.1 ab
Grazia	105.2 b	123.8 a	111.3 bc	132.0 ab	22.1 a	20.5 ab
Simeto	105.5 b	102.6 a	112.3 bc	109.7 ab	21.9 a	14.6 abc
Creso	107.1 b	115.0 a	113.4 bc	122.5 ab	20.5 ab	14.4 bc
Arcangelo	101.1 bc	91.3 ab	105.3 bcde	94.5 bc	22.1 a	13.0 bc
AC Barrie	100.4 bcd	64.2 b	103.6 cde	67.2 c	13.0 bc	6.3 c
Glenlea	130.1 ab	124.0 a	139.0 ab	135.7 a	17.3 ab	18.1 ab
Averages	105.4	102.6	111.9	109.8	18.0	15.8

Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within mill products G and 6R
n= 6±SD

4.10.2 Effect of Fermentation Times

Results obtained in the earlier experiment, confirmed that there were differences between mill products at long fermentation (165 min). The following study was undertaken to evaluate the effect of storage time on crumb grain characteristics at three fermentation times; 15, 90 and 165 min. With the lack of significant differences in LV between G and 6R, established earlier, textural characterisitics were evaluated on only G. Differences ($p \leq 0.05$) among fermentation times were observed on day one after baking for all traits.

But, the differences were narrowed (insignificant) for PF1 between the two shorter fermentation times; 15 and 90 min on day five of storage (Table 34). PF1 at 15 min (48 g) was lowest and highest at 165 min (73 g). AC Barrie and Glenlea were not significantly different from each other and other durum genotypes on day one and five, but at 165 min AC Barrie had the firmest crumb compared to all other genotypes. On day one and day five the genotypes were not distinctly separated. LV was negatively correlated to firmness values at all three fermentation times; 15 ($r = 0.56$), 90 ($r = 0.94$) and 165 ($r = 0.89$) on day one. The correlation was weaker on day five, 15 ($r = -0.23$), 90 ($r = -0.64$) and 165 min ($r = -0.87$) for the 3 fermentation times. The significant difference between short and long fermentation time is likely influenced by water diffusion and redistribution among protein-starch and crumb-crust factions.

The average percentage increase in PF1 was similar between 15 min (247%) and 165 min (247%) over the five day storage time (Table 37). This lack of difference is very interesting as the extent of starch damage was identical and the effect of fermentation times had no influence on starch retrogradation. The baking absorption was

higher at 15 min (67 %) and it has been reported that water content influences the rate of starch retrogradation in common wheat bread crumb (Zeleznak and Hoseney, 1986).

The gradient is perfectly correlated to PF1 (r = 1.0) for all three fermentation times. Gradient was significantly different among all three times on day one, 15 min (11 g*s), 90 min (13.0 g*s) and 165 min (17.0 g*s) (Table 35). On day five the difference between 15 and 90 min were insignificant. But, together were significantly different from 165 min. The average percentage increase in gradient from day one to day five was highest at 15 min (274 %) and lower at 165 min (265 %). Table 37, shows the distribution of average increases for all genotypes. The increased crumb firmness contributed to the increased slope of the curve at 15 min.

Although not so prominent, significant differences in resilience (LSD = 0.54 g*s) was observed among all three fermentation times on day one (Table 36). The differences were not present between 15 and 90 min but were different from 165 min. On average resilience was highest at 15 min on day one and day five. Among all genotypes Glenlea was the genotype with significantly the lowest resilience at all three fermentation times on day one. But on day five the variation was minimal from other genotypes. This difference in resilience on day one is not clear as the LV of Glenlea was significantly higher and baking absorption was comparable to other genotypes.

Resilience was moderately correlated to baking absorption at all three fermentation times; 15 min (r = 0.60), 90 min (r = 0.51) and 165 min (r = 0.62). Resilience was negatively correlated from weak to none for the three times (Appendix 10).

Overall PF1 and gradient was lowest and resilience was highest at 15 min. Higher the baking absorption and higher the LV the more improved were the textural characteristics of all genotypes at 15 min.

Table 34. Comparison of peak force (g) of durum and common wheat samples for G at fermentation times 15, 90 and 165 min.

	Peak Force – Day 1			Peak Force – Day 5		
Genotypes	**15 min**	**90 min**	**165 min**	**15 min**	**90 min**	**165 min**
AC Melita	52.7 ± 13.4 bc	47.6 ± 7.9 def	45.4 ± 3.7 g	195.2 ± 33.5 ab	147.0 ± 10.0 cde	166.2 ± 14.5 f
AC Morse	56.7 ± 3.9 ab	47.6 ± 5.8 def	71.0 ± 7.1 de	195.8 ± 27.6 ab	161.6 ± 28.7 bcd	236.8 ± 24.3 cd
Kyle	45.3 ± 4.4 cdef	54.5 ± 10.5 cd	66.5 ± 9.9 ef	126.7 ± 24.3 e	130.4 ± 53.9 de	225.0 ± 27.5 de
Durex	44.0 ± 5.4 def	49.8 ± 3.3 cdef	61.0 ± 8.1 ef	160.2 ± 19.3 cd	179.1 ± 32.0 b	199.0 ± 16.0 ef
DT 674	57.9 ± 13.5 ab	70.5 ± 19.5 a	81.5 ± 9.5 cd	191.8 ± 34.9 ab	162.1 ± 16.4 bcd	289.4 ± 31.7 ab
DT 369	52.5 ± 6.6 bcd	51.4 ± 8.6 cdef	55.5 ± 4.1 fg	157.0 ± 24.6 cd	119.1 ± 17.1 e	218.8 ± 29.8 de
Ofanto	47.1 ± 7.7 cde	66.7 ± 5.9 ab	85.0 ± 17.4 c	159.1 ± 26.7 cd	243.0 ± 26.9 a	266.6 ± 34.0 bc
Grazia	37.5 ± 2.1 f	50.9 ± 9.3 cdef	59.2 ± 2.3 f	134.8 ± 19.3 de	143.2 ± 20.8 cde	228.0 ± 14.0 de
Simeto	45.9 ± 2.8 cdef	57.9 ± 3.8 bc	59.7 ± 4.9 ef	137.5 ± 23.7 de	166.2 ± 30.9 bc	221.2 ± 18.0 de
Creso	40.4 ± 4.4 ef	53.2 ± 14.6 cde	60.8 ± 3.1 ef	154.1 ± 11.9 cde	138.8 ± 22.0 cde	250.9 ± 35.0 cd
Arcangelo	64.2 ± 9.5 a	75.3 ± 19.0 a	107.4 ± 21.8 b	205.9 ± 26.7 a	231.8 ± 31.8 a	286.1 ± 61.2 ab
AC Barrie	45.0 ± 8.0 cdef	44.9 ± 8.6 ef	131.6 ± 16.9 a	172.5 ± 28.7 bc	148.8 ± 13.5 bcde	313.7 ± 20.7 a
Glenlea	39.7 ± 3.5 ef	43.5 ± 5.2 f	64.0 ± 6.9 ef	158.9 ± 14.1 cd	150.0 ± 15.1 bcde	238.9 ± 26.2 cd
Averages	48.4 ^{C}	54.9 ^{B}	73.0 ^{A}	165.3 ^{B}	163.2 ^{B}	241.6 ^{A}
Mean of N.A.[1]	51.5 ± 5.8	53.6 ± 8.7	63.5 ± 12.5	171.1 ± 28.0	149.9 ± 22.3	222.5 ± 41.1
Mean of Itl.[2]	47.0 ± 10.4	60.8 ± 10.1	74.4 ± 21.4	158.3 ± 28.6	184.6 ± 49.5	250.5 ± 26.9
LSD-A[3]	8.6	8.8	11.5	29.3	31.8	33.0
LSD-F[3]	2.8			8.6		
CV	16.4	18.2	32.3	15.3	22.4	16.5

[1]North American Durums.
[2] Italian Durums.
[3]Least Significant Difference; A is among genotypes and F is among fermentation times
Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within fermentation times 15, 90 or 165 min and upper case letters are different among averages of fermentation times 15, 90 and 165 min. n=6±SD.

Table 35. Comparison of gradient (g*s) of durum and common wheat samples for G at fermentation times 15, 90 and 165 min.

	Gradient – Day 1			Gradient – Day 5		
Genotypes	**15 min**	**90 min**	**165 min**	**15 min**	**90 min**	**165 min**
AC Melita	11.9 ± 3.3 bc	10.7 ± 2.0 efg	10.2 ± 0.9 g	47.3 ± 8.3 ab	35.3 ± 2.4 bcde	40.1 ± 3.6f
AC Morse	12.9 ± 1.0 ab	10.7 ± 1.3 efg	16.5 ± 1.8 de	47.3 ± 6.8 ab	38.9 ± 7.0 bcd	57.6 ± 6.1 cd
Kyle	10.1 ± 1.2 cde	12.4 ± 2.6 de	15.4 ± 2.4 ef	30.2 ± 6.0 e	31.2 ± 13.4 de	54.6 ± 6.8 de
Durex	9.9 ± 1.3 cde	11.3 ± 0.8 defg	14.0 ± 2.0 ef	38.6 ± 4.8 cd	43.2 ± 7.9 b	48.2 ± 3.9 ef
DT 674	13.3 ± 3.3 ab	16.3 ± 4.8 ab	19.1 ± 2.4 cd	46.3 ± 8.6 ab	39.0 ± 4.1 bcd	70.7 ± 7.7 ab
DT 369	12.0 ± 1.6 bc	11.6 ± 2.2 defg	12.7 ± 1.0 fg	37.8 ± 6.2 cd	28.4 ± 4.2 e	53.2 ± 7.4 de
Ofanto	10.6 ± 2.0 cd	15.4 ± 1.5 bc	19.9 ± 4.3 c	38.3 ± 6.6 cd	59.1 ± 6.7 a	64.9 ± 8.4 bc
Grazia	8.2 ± 0.5 e	11.5 ± 2.3 defg	13.6 ± 0.6 f	32.3 ± 4.8 de	34.5 ± 5.1 cde	55.3 ± 3.5 de
Simeto	10.3 ± 0.7 cde	13.2 ± 0.9 cd	13.7 ± 1.2 ef	32.9 ± 5.9 de	40.0 ± 7.6 bc	53.7 ± 4.5 de
Creso	8.8 ± 1.1 de	12.1 ± 3.6 def	14.0 ± 0.8 ef	37.0 ± 2.9 cde	33.3 ± 5.4 cde	61.1 ± 8.7 cd
Arcangelo	14.8 ± 2.4 a	17.6 ± 4.7 a	25.6 ± 5.4 b	49.9 ± 6.7 a	56.3 ± 8.0 a	69.8 ± 15.2 ab
AC Barrie	10.0 ± 2.0 cde	10.0 ± 2.1 fg	31.5 ± 4.2 a	41.8 ± 7.3 bc	35.7 ± 3.4 bcde	76.6 ± 5.1 a
Glenlea	8.7 ± 0.9 de	9.7 ± 1.2 g	14.7 ± 1.7 ef	38.2 ± 3.5 cd	36.1 ± 3.8 bcde	58.2 ± 6.5 cd
Averages	10.9 ^{C}	12.5 ^{B}	17.0 ^{A}	39.8 ^{B}	39.3 ^{B}	58.8 ^{A}
Mean of N.A.[1]	11.7 ± 1.4	12.2 ± 2.1	14.6 ± 3.1	41.2 ± 6.9	36.0 ± 5.5	54.1 ± 10.2
Mean of Itl.[2]	10.5 ± 2.6	13.9 ± 2.5	17.4 ± 5.3	38.1 ± 7.1	44.6 ± 12.3	61.0 ± 6.7
LSD-A[3]	2.1	2.2	2.8	7.3	7.9	8.2
LSD-F[3]	0.68			2.1		
CV	18.0	19.8	34.5	15.8	23.0	16.8

[1]North American Durums.
[2] Italian Durums.
[3]Least Significant Difference; A is among genotypes and F is among fermentation times
Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within fermentation times 15, 90 or 165 min and upper case letters are different among averages of fermentation times 15, 90 and 165 min. n=6±SD.

Table 36. Comparison of resilience (%) of durum and common wheat samples for G at fermentation times 15, 90 and 165 min.

	Resilience – Day 1			Resilience – Day 5		
Genotypes	**15 min**	**90 min**	**165 min**	**15 min**	**90 min**	**165 min**
AC Melita	44.0 ± 4.1ef	46.5 ± 0.8 de	46.4 ± 0.9 ab	42.5 ± 2.8 bcd	42.9 ± 1.6 abc	40.7 ± 2.6 abcd
AC Morse	44.6 ± 1.0 def	48.0 ± 1.7 cd	45.5 ± 2.1 abc	40.4 ± 1.5 def	44.0 ± 2.8 abc	40.0 ± 2.9 bcd
Kyle	45.6 ± 1.3 cde	47.2 ± 1.4 cde	43.7 ± 2.2 de	43.2 ± 3.2 bcd	45.1 ± 5.6 ab	41.0 ± 2.9 abc
Durex	49.9 ± 1.4 a	50.6 ± 1.4 a	46.7 ± 2.4 ab	47.2 ± 4.5 a	44.4 ± 2.0 abc	43.4 ± 3.9 a
DT 674	46.6 ± 3.2 bcd	49.9 ± 1.2 ab	47.1 ± 1.8 a	43.5 ± 1.4 bc	43.5 ± 3.6 abc	38.0 ± 2.1 de
DT 369	42.3 ± 0.9 f	46.1 ± 1.3 e	44.2 ± 1.1 cde	41.7 ± 2.0 cde	43.0 ± 3.6 abc	40.2 ± 1.6 bcd
Ofanto	47.1 ± 1.9 bc	44.1 ± 2.3 f	46.0 ± 1.3 abc	43.2 ± 3.1 bcd	39.0 ± 3.6 d	39.8 ± 2.9 bcd
Grazia	47.7 ± 2.1 abc	50.1 ± 1.6 a	46.4 ± 0.7 ab	46.7 ± 4.7 a	46.1 ± 1.0 a	42.1 ± 2.5 ab
Simeto	47.7 ± 1.5 abc	48.3 ± 1.1 bc	45.3 ± 0.9 bcde	45.5 ± 1.9 ab	45.6 ± 4.8 a	38.9 ± 1.4 cde
Creso	48.1 ± 0.9 ab	46.5 ± 1.4 de	45.3 ± 1.7 abcd	43.6 ± 1.5 bc	41.5 ± 3.1 bcd	38.7 ± 1.1 cde
Arcangelo	46.2 ± 3.6 bcde	43.6 ± 1.7 f	43.5 ± 2.4 e	39.1 ± 2.1 ef	38.8 ± 3.0 d	36.4 ± 3.2 ef
AC Barrie	43.3 ± 1.1 g	44.2 ± 1.2 f	46.5 ± 0.8 ab	42.7 ± 2.1 bcd	41.4 ± 3.2 cd	42.1 ± 1.6 ab
Glenlea	39.9 ± 1.5 f	39.0 ± 0.9 g	39.1 ± 0.4 f	38.6 ± 2.2 f	38.2 ± 2.9 d	34.3 ± 1.5 f
Averages	45.6 ^{B}	46.5 ^{A}	45.1 ^{C}	42.9 ^{A}	42.6 ^{A}	39.7 ^{B}
Mean of N.A.[1]	45.5 ± 2.6	48.0 ± 1.8	45.6 ± 1.4	43.1 ± 2.3	43.8 ± 0.9	40.5 ± 1.8
Mean of Itl.[2]	47.4 ± 0.7	46.5 ± 2.8	45.3 ± 1.1	43.6 ± 2.9	42.2 ± 3.5	39.2 ± 2.0
LSD-A[3]	2.3	1.6	1.8	3.0	3.6	2.7
LSD-F[3]	0.54			0.89		
CV	6.0	6.9	4.7	6.0	6.2	6.2

[1]North American Durums.
[2] Italian Durums.
[3]Least Significant Difference; A is among genotypes and F is among fermentation times
Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within fermentation times 15, 90 or 165 min and upper case letters are different among averages of fermentation times 15, 90 and 165 min. n=6±SD.

Table 37. Comparison of percent increase in peak force (g) and gradient (g*s) and decrease in resilience (%) from day 1 to day 5 of durum and common wheat samples for G at fermentation times 15, 90 and 165 min.

	% Increase in Peak Force			% Increase in Gradient			% Decrease in Resilience		
Genotypes	**15 min**	**90 min**	**165 min**	**15 min**	**90 min**	**165 min**	**15 min**	**90 min**	**165 min**
AC Melita	278.6 ab	213.9 abcde	268.7 abcde	307.1 abc	238.6 abcd	297.7 abc	2.9 bcd	7.7 abc	12.4 bcd
AC Morse	245.4 abcd	238.0 abc	235.8 cde	266.5 bcd	261.2 abc	253.2 cd	9.4 ab	8.4 abc	12.0 bcde
Kyle	180.1 e	161.9 cde	243.0 abcde	198.8 d	178.8 cd	260.7 cd	5.2 bcd	4.5 bc	6.2 e
Durex	266.3 abc	258.1 ab	228.6 de	293.8 abc	281.8 ab	247.5 cd	5.4 bcd	12.1 a	6.9 de
DT 674	245.9 abcd	146.6 de	258.0 abcde	266.6 bcd	158.0 d	273.9 bcd	6.4 bcd	13.0 a	19.5 a
DT 369	201.7 cde	140.0 e	297.4 ab	219.9 d	154.5 d	324.6 ab	1.2 d	6.5 abc	9.1 cde
Ofanto	238.0 bcde	267.4 a	218.5 ef	264.0 bcd	288.3 a	231.7 de	8.1 bcd	11.6 ab	13.4 abc
Grazia	260.1abcd	195.0 abcde	284.9 abc	296.8 abc	217.5 abcd	306.8 abc	2.3 cd	7.9 abc	9.4 cde
Simeto	198.2 de	185.6 bcde	272.2 abcde	219.4 d	200.3 bcd	294.2 abc	4.6 bcd	5.6 abc	14.0 abc
Creso	283.8 ab	187.2 bcde	312.9 a	321.8 ab	207.8 abcd	337.4 a	9.2 abc	10.7 ab	14.7 abc
Arcangelo	224.6 bcde	220.1 abcd	170.9 fg	242.3 cd	235.2 abcd	178.3 ef	15.2 a	11.0 ab	16.1 ab
AC Barrie	288.8 ab	241.0 ab	141.8 g	323.7 ab	267.5 ab	146.8 f	1.4 d	6.4 abc	9.4 cde
Glenlea	304.2 a	248.7 ab	278.0 abcd	342.8 a	278.9 ab	301.8 abc	3.1 bcd	2.0 c	12.3 bcde
Averages	247.4	208.0	247.0	274.1	228.3	266	5.7	8.3	12.0

Means with the same letter are not significantly different at $p < 0.05$ level; lower case letters are different among genotypes within fermentation times 15, 90 and 165 min.
n= 6±SD

5. GENERAL DISCUSSION

The purpose of this study was to develop a better understanding of the physico-chemical properties of durum wheat semolina and dough in relation to its baking potential. The potential of durum wheat for breadmaking has been reported in a number of studies (Quick and Crawford, 1983; Boggini and Pogna, 1989; Pena et al. 1994; Dexter et al. 1994; Boyacioglu and D'Appolonia 1994a; Ammar et al. 2000; Palumbo et al. 2002). The consensus conclusion is that durum bread has LV substantially than that of common wheat bread.

The wheat samples used in this study were a combination of both North American and Italian genotypes of diverse strength. As the samples were grown in one location, the samples were all affected similarly by climatic conditions. The wheat used in this study was within a narrow range of protein contents for all durum genotypes. Semolina reduction was carried out by gentle action on corrugated rolls, limiting excessive starch damage. The three mill products obtained G (granular semolina), 2R (twice reduced semolina) and 6R (six-times reduced semolina) with increasing reduction, resulted in a substantial decrease in the proportion of large ($\leq$ 250 μm) particles and increase of small ($\geq$ 150 μm) particles. Protein quality was effectively measured on the basis of fractionation by solubility in 50%- 1- propanol without and with the reducing agent DTT, giving a precise separation of monomeric proteins from HMW glutenin polymeric proteins. Dough sheet length (DSL) using a full baking formula at varying fermentation times (15, 90 and 165 min) provided a practical gauge of durum dough extensibility properties. Crumb texture was instrumentally evaluated to address anecdotal views in the literature with regard to the superior keeping quality of durum wheat breads. Crumb

structure was assessed quantitatively by DIA and a strong correlation was established with the long standing subjective GRL bread score method presently in use.

The level of starch damage and gassing power of mill products G, 2R and 6R were all significantly different. The gassing power of mill product G was limited by its low starch damage. Contrary to earlier results of Ammar et al. (2000), the present study showed no strong correlation between protein content and LV (r = - 0.07). This lack of a strong relationship, accommodated a clear analysis and understanding of the effects of protein quality.

Dough mixing properties were found to be influenced by starch damage and particle size distribution of mill products G, 2R and 6R. The correlation between Mixograph WIP and IG content of semolina and IG/SP were, r = 0.82 ans r = 0.83, respectively. Similarly LV was correlated to IG and IG/SP with correlations of r = 0.48 and r = 0.66, respectively. MT and WIP were very good predictors of LV, particularly for 6R material (r = 0.82 and r = 0.89, respectively). FDDT and MT were highly correlated for both mill products G and 6R (r = 0.87). This relationship indicates that MT at constant absorption was a good predictor of dough strength. Farinograph absorption increased and FDDT decreased with increasing starch damage. There was no strong relationship between FDDT and protein content; such a relationship would have been more prominent with a wider range of protein contents.

Alveograph measurements on mill product G, showed no strong relationship to LV for all genotypes. But durum wheat Alveograph W values were strongly related (r = 0.84) to LV. Quaglia (1988) reported that Alveograph W values of about 200 were required to produce good leavened bread. Quaglia (1988) also noted that P/L values

> 1.5 would improve LV. All P/L values of durum genotypes were less than 1.5 and not related to increased LV. This could imply that P/L ratios > 1.5 might have contributed to higher LV than were found in this thesis research. However, it should be noted that at constant absorption, P/L values are influenced greatly by the extent of damaged starch. Extensibility as measured by Alveograph L was not correlated to LV, as observed by Marchylo et al. (2001), but not by Ammar et al. (2000), who found a strong positive correlation (r = 0.80). DSL measured at optimum baking absorption was negatively related to LV for both mill products (G, r = - 0.55, 6R, r = - 0.69), at long fermentation (165 min). The same negative relationship was observed for mill product G at short fermentation times; 15 min (r = - 0.80) and 90 min (r = - 0.73). At shorter fermentation times lower extensibility corresponded with increased LV; 15 min, r = -0.80, 90 min, r = -0.73.

Quick and Crawford (1983) found strong gluten durums were more elastic than those from weak gluten durums. The strong gluten durums produced greater LV than the weak gluten cultivars and approached breadmaking quality of bread wheats. Feillet (1988) reported that durum doughs had a higher gliadin to glutenin ratio yielding an extensible but inelastic dough. Further, it has been postulated that a higher glutenin to gliadin ratio results in stronger doughs (MacRitchie and Lafiandra 1997) and in turn results in increased LV. In this study, this relationship was confirmed as the ratio of IG/SP was positively correlated with LV (r = 0.66) for all genotypes.

Some studies have identified variations at the *Glu-B1* (HMW-GS) locus as determinants of breadmaking quality of durum wheat (Boggini and Pogna 1989; Pena et al, 1994). On the other hand, Ammar et al. (2000) found that HMW-GS were not good

indicators of breadmaking quality. In this study, no correlative relationship was established between HMW-GS and increased LV. Genotype Grazia with subunit 20, produced a significantly higher LV for both G and 6R (665 cc) mill products, compared to Ofanto (G , 603 cc and 6R, 600 cc) which had the same HMW-GS composition. The difference in LV between the two genotypes could not be explained on the basis of their quantitative protein fractions. This absence of a clear association continues to be a challenge in understanding the influence of protein quality on the baking performance of durum wheat.

Examining the effect of particle size on LV has shed new light on the influence of particle size distribution on LV; LV was not significantly different between mill product G and 6R for durum genotypes despite the large differences in particle size, and concomitant differences in starch damage and gassing power. Measure of oven rise (OR) of the two mill products was not significantly different between G and 6R, although gassing power was significantly higher for 6R at long fermentation (165 min). Baking absorption on average was similar for 6R (61.2%) and G (60.8%). There was no LV benefit to the increased starch damage. Accordingly, the influence of particle size distribution might very likely be a contributing factor to the better than expected baking performance of granular semolina (G).

In keeping with the context of the objective of this study, the results of varying fermentation times on baking properties were interesting. Averaged over all samples, LV for mill product G was significantly higher at 15 min compared to 165 min. This improved performance at short fermentation, has shown that durum genotypes have a reduced tolerance to long fermentation times. This reduced fermentation tolerance may

be a result of the lower concentration of high molecular weight polymeric glutenin proteins in durum doughs (compared to e.g. Glenlea). However, Glenlea despite its very high content of IG and high ratio of IG/SP also showed lack of fermentation tolerance. It seems clear therefore that the lower baking performance (LV) of durum wheats and the specific issue of fermentation intolerance likely have different mechanisms. Curioni et al. (2000) reported that the high level of intermolecular bonding of the LMW-GS results in a lack of elasticity and increased tenacity of durum doughs limiting the baking potential of durum wheats.

Crumb grain properties assessed subjectively established no difference in crumb structure (CS) and crumb color (brightness) between mill products G and 6R. Total bread score was also not different. This was expected, as LV was not significantly different between the two mill products. Differences in crumb grain for mill product G between short (15 min) and long (165 min) fermentation times was not significant for all traits. LA was significantly higher at short fermentation time; this was influenced by the improved LV at the shorter fermentation time. CS (cell wall thickness) and crumb color was not different between short and long fermentation times. The overall total bread score (loaf appearance, crumb structure and crumb color) was higher at 15 min fermentation, concomitant with high LV.

Correlative studies indicated that objective analysis of crumb grain characteristics by DIA were highly related to subjective analysis for total bread score ($R^2 = 0.87$). The best two-variable model incorporated, number of cells in a slice and the total area of cells greater than 25 mm^2. As LV highly influences the total bread score an analysis was carried out between subjective and objective bread score, excluding LV. The best two-

variable model in this case was, number of cells smaller in area than 7.0 mm^2 and the ratio of the cell area divided by area of the slice ($R^2 = 0.82$). These results clearly show that DIA can be used effectively to score bread.

The keeping quality of durum breads at ambient temperature was comparable to common wheat breads at long fermentation. Increased crumb firmness and reduced resilience was found for mill product G compared to 6R at the long fermentation time. The crumb firmness was lower and resilience was higher at 15 min and 90 min compared to 165 min. This was consistent with the higher LV at 15 min. Boyacioglu and D'Appolonia (1994a) found bread made with durum flour was significantly less firm on day one and day four after baking compared to bread made with semolina. LV was significantly lower for semolina bread. In this thesis project, the LV was not different between mill products G and 6R for durum wheat genotypes. Mill product G had higher baking absorption (67%) at 15 min compared to longer fermentation times.

6. SUMMARY

For the purpose of studying the interrelationships between dough strength, effect of particle size and baking potential, eleven durum and two common wheat genotypes were milled into three mill products; G, 2R and 6R. Minimal differences in milling yield and particle size distribution were found among durum genotypes for each mill product. Protein content was within (1.6%) a narrow range for all durum genotypes. Starch damage was lowest for G and highest for 6R. Gassing power increased with increasing starch damage for all genotypes.

For detailed characterization of protein quality, semolina was fractionated into propanol soluble protein, insoluble glutenin and residue protein. Differences in protein quality among genotypes was strongly reflected by differences in IG content. Durum wheat genotypes contained a higher proportion of soluble protein to insoluble glutenin compared to common wheats. Compared to durum wheats, common wheats had a higher proportion of insoluble glutenin.

Further analysis of dough strength by physical rheological tests established a significant influence of particle size and concomitant starch damage on relative mixing time. Higher starch damage translated to higher Farinograph absorption values. Farinograph dough development time (FDDT), stability time and mixing tolerance index (MTI) were not different between 2R and 6R mill products. Due to reduced particle size and/or increased starch damage FDDT, MT and Stability time decreased. Softening index (MTI) was higher with increased starch damage.

Extensibility (measured by Alveograph L) was correlated to protein content but Alveograph W was highly correlated to IG content. An alternate measure of extensibility by dough sheet length was longer at long fermentation and was strongly negatively correlated to IG content.

LV of durum genotypes was not affected by reduced particle size distribution. LV was significantly higher at short (15 min) fermentation times. Oven rise was not different for all genotypes between mill products G and 6R at long fermentation and was significantly lower at short fermentation for mill product G.

Loaf appearance, crumb structure, crumb color and total bread score were not different between G and 6R mill products. At short (15 min) fermentation time all bread scores were superior to longer fermentation time for mill product G.

Bread slices were firmer, less fragile and more resilient for mill product G on day one at long fermentation time. On day five, the slices were much firmer and less resilient. Shorter fermentation times (15 min) produced bread that was significantly less firm on day one. On day five there was no difference between 15 and 90 min fermentation times for all crumb texture parameters. The slices at shorter fermentation time were less firm, more fragile and highly resilient compared to long (165 min) fermentation time on day five.

7. CONCLUSION

The present work has shown that

- There is no breadmaking advantage to reducing G mill product particle size for durum genotypes.
- On the other hand, common wheats AC Barrie and Glenlea were negatively affected by low starch damage at long fermentation time.
- Durum wheats lack fermentation tolerance; durum breadmaking quality improves at short fermentation times (15 min).
- Common wheat, G mill product showed a similar deficiency from tolerance.
- Dough extensibility as measured by dough sheet length was negatively correlated to breadmaking quality.
- Insoluble glutenin content was a very good predictor of dough strength and baking potential of durum genotypes in particular.
- Crumb grain of durum wheats was not negatively affected by milling treatments and was superior at short fermentation time.
- Digital imaging was effective for evaluating the crumb grain objectively.
- Keeping quality of durum wheats was comparable to common wheats.
- Keeping quality of 15 min fermentation time loaves were better than at 90 or 165 min.
- North American durums that are best for breadmaking are AC Melita, DT 369 and Durex.
- Durum genotypes with poor baking performance are Arcangelo, Ofanto and DT 674.

Further understanding is needed of the nature of biochemical changes during fermentation, especially the lack of fermentation tolerance of durum wheat granulars, the biochemical nature of genotypic differences, especially related to glutenin subunit composition and the sensory qualities of durum bread at short fermentation for taste and flavor.

8. LITERATURE CITED

American Association of Cereal Chemists (AACC), 2000. Approved Methods of the AACC, 10th ed. Method 44-15A, Method 08-01, Method 76-31, Method 54-21, Method 22-11, Method 74-10A. The Association: St. Paul, MN.

Amarjeet, K., Bhupendar, S. and Sidhu, J.S. 1993. Studies on bread and durum wheat blends. Chem. Mikrobiol. Technol. Lebensm. 15:35-40.

Ammar, K., Kronstad, W.E. and Morris, C.F. 2000. Breadmaking quality of selected durum wheat genotypes and its relationship with high molecular weight glutenin subunits allelic variation and gluten protein polymeric compostition. Cereal Chem. 77: 230-236.

Bakhshi, A.K. and Bains, G.S. 1987. Study of the physico-chemical, rheological, baking and noodle quality of improved durum and bread wheat cultivars. Journal Food Sci. Technol. India 24:217-221.

Bloksma, A.H. 1990. Rheology of the breadmaking process. Cereal Foods World. 35: 228-236.

Bloksma, A.H. and Bushuk, W. 1988. Rheology and chemistry of dough. Pages 131-217. In:Wheat: Chemistry and Technology, 3rd edition, Vol 2. Y. Pomeranz, ed. Am. Assoc. Cereal Chem., St. Paul, MN.

Boggini, G. and Pogna, N.E. 1989. The breadmaking quality and storage protein composition of Italian durum durum wheat. J. Cereal Sci. 9:131- 138.

Boggini, G., Tusa, P. and Pogna, N.E. 1995. Bread making quality of durum wheat genotypes with some novel glutenin subunit compositions. J. Cereal Sci. 22:105-113.

Boyacioglu, M.H. and D'Appolonia, B.L. 1994a. Characterization and utilization of durum wheat for breadmaking. I. Comparison of chemical, rheological, and baking properties between bread wheat flours and durum wheat flours. Cereal Chem. 71:21-28.

Boyacioglu, M.H. and D'Appolonia, B.L. 1994b. Characterization and utilization of durum wheat for breadmaking. II. Study of flour blends and various addittives. Cereal Chem. 71:28-34.

Boyacioglu, M.H. and D'Appolonia, B.L. 1994c. Characterization and utilization of durum wheat for breadmaking. III. Staling properties of bread baked from bread wheat flours and durum wheat flours. Cereal Chem. 71:34-41.

Branlard, G., Autran, J.C. and Monneveux, P. 1989. High molecular weight glutenin subunit in durum wheat (*T. durum*). Theor. Appl. Genet. 78:353-358.

Branlard, G., Pierre, J. and Rousset, M. 1992. Selection indices for quality evaluation in wheat breeding. Theor. Appl. Genet. 84:57-64.

Buonocore, F., Caporale, C. and Lafiandra, D. 1996. Purification and characterisation of high M_r glutenin subunit 20 and its linked y-type subunit from durum wheat. J. Cereal Sci. 23:195-201.

Calucci, F. 2003. Personal communication. Visiting Researcher. Grain Research Laboratory.

Carrillo, J.M., Vasquez, M. and Orellana, T. 1990. Relationship between gluten strength and glutenin proteins in durum wheat cultivars. Plant Breeding 104:325-333.

Ciaffi, M., Lafiandra, D., Turchetta, T., Ravaglia, S., Bariana, H., Gupta, R. and MacRitchie, F. 1995. Breadbaking potential of durum wheat lines expressing both x- and y-type subunits at the *Glu-A1* locus. Cereal Chem. 72:465-469.

Curioni, A., D'Incecco, N., Pogna, N.E., Pasini, G., Simonato, B. and Peruffo, A.D.B. 2000. Durum wheat glutenin polymers: A study based on extractability and SDS-PAGE. Pages 154-157. In: Wheat Gluten. P.R. Shewry and Tatham, A.S., eds. Royal Society of Chemistry, Cornwall, UK.

Cubbada, R. 1988. Evaluation of durumwheat, semolina, and pasta in Europe. In:Durum Wheat: Chemistry and Technology, 1st edition G. Fabriani and C. Lintas, eds. Am. Assoc. Cereal Chem., St. Paul, MN.

Damidaux, R., Autran, J.C. and Feillet, P. 1980. Gliadin electrophoregrams and measurements of gluten viscoelasticity in durum wheats. Cereal Foods World. 25:754-756.

Dexter, J.E. and Matsuo, R.R. 1980. Relationship between durum wheat protein properties and pasta dough rheology and spaghetti cooking quality. J. Agric. Food Chem. 28:899-902.

Dexter, J.E., Matsuo, R.R., Preston, K.R. and Kilborn, R.H. 1981. Comparison of gluten strength, mixing properties, baking quality and spaghetti quality of some Canadian durum and common wheats. Can. Inst. Food Sci. Technol. J. 14:108-111.

Dexter, J.E., Williams, P.C., Edwards, N.M. and Martin D.G. 1988. The relationships between durum wheat vitreousness, kernel hardness and processing quality. J. Cereal Sci. 7:169-181.

Dexter, J.E., Matsuo, R.R. and Kruger, J.E. 1990. The spaghetti-making quality of commercial durum wheat samples with variable α-amylase activity. Cereal Chem. 67:405-412.

Dexter, J.E., Preston, K.R., Martin, D.G. and Gander, E.J. 1994. The effects of protein content and starch damage on the physical dough properties and bread-making quality of Canadian durum wheat. J. Cereal Sci. 20:139-151.

D'Ovidio, R., Simeone, M., Masci, S., Porceddu, E. and Kasarda, D.D. 1995. Nucleotide sequence of a γ-gliadin type gene from a durum wheat: correlation with γ-type glutenin subunit from biotype. Cereal Chem. 72:443-449.

D'Ovidio, R., Marchitelli, C., Cardelli, L.E. and Porceddu, E. 1999. Sequence similarity between allelic *Glu-B3* genes related to quality properties of durum wheat. Theor. Appl. Genet. 98:455-461.

Du Cros, D.L. 1987. Glutenin proteins and gluten strength in durum wheat. J. Cereal Sci. 5:3-12.

Dubois, D. 1984. What is fermentation ? It's essentail to bread quality. Bakers Digest (January)11-14.

Edwards, N.M., Peressini, D., Dexter, J.E. and Mulvaney, S.J. 2001. Viscoelastic properties of durum wheat and common wheat dough of different strengths. Rheo. Acta. 40:142-153.

Edwards, N.M. 2002. Gluten and the starch-gluten interface in relation to the viscoelastic properties of durum dough. Ph.D. Thesis, University of Manitoba, Winnipeg, MB. 119pp.

Faridi, H. and Rasper, V.F. 1987. The Alveograph handbook. AACC., St. Paul, MN.

Feillet, P. 1988. Protein and enzyme composition of durum wheat. Pages 93-119 In:Durum Wheat: Chemistry and Technology, 1st edition G. Fabriani and C. Lintas, eds. Am. Assoc. Cereal Chem., St. Paul, MN.

Feillet, P., Ait-Mouh, O., Kobrehel, K. and Autran, J. C. 1989. The role of low molecular weight glutenin proteins in the determination of cooking quality of pasta products: An overview. Cereal Chem. 66:26-30.

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

Fu, B. and Sapirstein, H. 1996. Procedure for isolating monomeric proteins and polymeric glutenin of wheat flour. Cereal Chem. 73:143-152.

Gras, P.W., Carpenter, H.C. and Anderssen, R.S. 2000. Modelling the development rheology of wheat-flour dough using extension tests. J. Cereal Sci. 31:1-13.

Gupta, R.B., Popineau, Y., Lefebvre, Y., Cornect, M., Lawrence, G.J. and MacRitchie, F. 1995. Biochemical basis of flour properties in bread wheats. II. Changes in polymeric protein formation and dough/gluten properties associated with the loss of low M_r or high M_r glutenin subunits. J. Cereal Sci. 21:103-116.

Hayman, D., Hoseney, R.C. and Faubion, J.M. 1998. Bread crumb grain development during baking. Cereal Chem. 75:577-580.

Hareland, G.A. 1994. Evaluation of flour particle size distribution by laser diffraction, sieve analysis and near-infrared reflectance spectroscopy. J. Cereal Sci. 21:183-190.

Hareland, G.A. and Puhr, D.P. 1998. Baking performance of durum and soft wheat flour in a sponge-dough breadmaking procedure. Cereal Chem. 75:830-835.

Hug-Iten, S., Escher, F. and Conde-Petit, B. 2001. Structural properties of starch in bread and bread model systems: influence of an antistaling α-amylase. 78:421-428.

International Association for Cereal Science and Technology, Standard Methods of the ICC, Standard no. 121. ICC, Vienna, Austria (1980).

Jackson, E.A., Holt, L.M. and Payne, P.I. 1983. Characterisation of the high-molecular-weight gliadin and low-molecular weight glutenin subunits of wheat endosperm by two-dimensional electrophoresis and the chromosomal location of their controlling genes. Theor. Appl. Genet. 66:29-37.

Joppa, L.R. and Williams, N.D. 1988. Genetics and breeding of durum wheat in the United States. . In:Durum Wheat: Chemistry and Technology, 1st edition G. Fabriani and C. Lintas, eds. Am. Assoc. Cereal Chem., St. Paul, MN.

Kasarda, D.D. 1989. Pages 277-302. Glutenin structure in relation to wheat quality. In: Wheat is Unique. Y. Pomeranz, ed. Am. Assoc. Cereal Chem., St. Paul.

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

Kilborn, R.H. and Irvine, G.N. 1963. Baking laboratory layout and procedures. Cereal Sci. Today 6:253.

Kilborn, R.H. and Tipples, K.H. 1981. Canadian test baking procedures. I. GRL remix method and variations. Cereal Foods World 26:624-628.

Kim, S.K. and D'Appolonia, B.L. 1977. Bread staling studies:II. Effect of protein content and storage temperature on the role of starch. Cereal Chem. 54:216-224.

Kosmolak, F.G., Dexter, J.E., Matsuo, R.R., Leisle, D. and Marchylo, B.A. 1980. A relationship between durum wheat quality and gliadin electrophoregrams. 60:427-432.

Kurimoto, Y. and Shelton, D.R. 1988. The effect of flour particle size on baking quality and other flour attributes. Cereal Foods World. 33:429-433.

Lafiandra, D., Kasarda, D.D. and Morris, R. 1984. Chromosomal assignment of gene coding for the wheat gliadin protein components of the cultivar Cheyenne and Chinese Spring by two dimensional electrophoresis. Theor. Appl. Genet. 68:531-539.

Lafiandra, D., Masci, S., Blumenthal, C. and Wrigley, C.W. 1999. Cereal Foods World. 44:572-575.

Lafiandra, D., Masci, S., D'Ovidio, R. and Margiotta, B. 2000. The genetics of wheat gluten proteins: An overview. Pages 3-10 In: Wheat Gluten. P.R. Shewry and Tatham, A.S., eds. Royal Society of Chemistry, Cornwall, UK.

Liu, C.Y., Shepherd, K.W. and Rathjen, A.J. 1996. Improvement of durum wheat pastamaking and breadmaking qualities. Cereal Chem. 73:155-166.

Lukie, C.A. 2001. Effects of genotype and environment on the breadmaking quality of Canada Western Extra Strong red spring wheat cultivars. M.Sc. Thesis, University of Manitoba, Winnipeg, MB. 101pp.

Luraschi, A. 1955. Trattato della moderna panificazione. Hoepli, Milan. As cited by Quaglia, 1988 In:Durum Wheat: Chemistry and Technology.

MacRitchie, F. 1984. Baking quality of wheat flours. Adv. Food Nutr. Res. 29:201-277.

MacRitchie, F. 1992. Physicochemical properties of wheat proteins in relation to functionality. Adv. Food Nutr. Res. 36:1-87.

MacRitchie, F. and Lafiandra, D. 1997. Structure-function relationships of wheat proteins. Pages 293-323 In: Food Proteins and Their Applications. S. Damodaran and A. Paraf, eds. Marcel Dekker: New York.

Mailhot, W.C. and Patton, J.C. Pages 69-90. In:Wheat: Chemistry and Technology, 3rd edition, Vol 2. Y. Pomeranz, ed. Am. Assoc. Cereal Chem., St. Paul, MN.

Margiotta, B., Pfluger, L., Roth, M.R., MacRitchie, F. and Lafiandra, D. 2000. Isogenic bread wheat lines differing in number and type of high M_r glutenin subunits. Pages 29-33 In: Wheat Gluten. P.R. Shewry and Tatham, A.S., eds. Royal Society of Chemistry, Cornwall, UK.

Marchylo, B.A., Dexter, J.E., Clarke, F.R., Clarke, J.M. and Preston, K.R. 2001. Relationship among breadmaking quality, gluten strength, physical dough properties, and

pasta cooking quality for some Canadian durum wheat genotypes. Can. J. Plant Sci. 81:611-620.

Masci, S.M., Porceddu, E., Colaprico, G. and Lafiandra, D. 1991. Comparison of the B and D subunnits of glutenin encoded at the Glu-D3 locus in two biotypes of the common wheat cultivar Newton with different technological characteristics. J. Cereal Sci. 14:35-46.

Masci, S., Egorov, T.A., Ronchi, C., Zuzmicky, D.D., Kasarda, D.D. and Lafiandra, D. 1999. Evidence for the presence of only one cysteine residue in the D-type low molecular weight subunits of wheat glutenin. J. Cereal Sci. 29:17-25.

Masci, S., D'Ovidio, R., Lafiandra, D. and Kasarda, D.D. 2000. A 1B-coded low-molecular-weight glutenin subunit associated with quality in durum wheats shows strong similarity to a subunit present in some bread wheat cultivars. Theor. Appl. Genet. 100: 396-400.

Matsuo, R.R. and Dexter, J.E. 1980a. Relationship between some durum wheat physical characteristics and semolina milling properties. Can. J. Plant Sci. 60:49-53.

Matsuo, R.R. and Dexter, J.E. 1980b. Comparison of experimentally milled durum wheat semolina to semolina produced by some Canadian commercial mills. Cereal Chem. 57:117-122.

Mattern, P.J. 1961. Some factors affecting fermentation requirements. Bakers Digest (April) 60-63.

Nieto-Taladriz, M.T., Ruiz, M., Martinez, M.C., Vazquez, J.F. and Carrillo, J.M. 1997. Variation and classification of B low molecular weight glutenin subunit alleles in durum wheat. Theor. Appl. Genet. 95:1155-1160.

Orth, R.A. and Bushuk, W. 1972. A comparative study of the proteins of wheats of diverse baking qualities. Cereal Chem. 49:268-275.

Orth, R.A. and Bushuk, W. 1973. Studies of glutenin. III. Identification of subunits coded by the D-genome and their relation to breadmaking quality. Cereal Chem. 50: 680-687.

Orth, R.A, Dronzek, B.L. and Bushuk, W. 1973. Studies of glutenin. IV. Microscopic structure and its relations to breadmaking quality. Cereal Chem. 50: 688-696.

Osborne, T. 1907. The proteins of the wheat kernel. Carnegie Inst. Washington, DC, USA. Publ. No. 84.

Palumbo, M., Spina, A. and Boggini, G. 2002. Bread-making quality of Italian durum wheat (*Triticum durum* desf.) cultivars. Ital. J. Food Sci. 12:123-133.

Pasqui, L.A., Paoletti, F., Caproni, E. and Volpi, M. 1991. Functional properties of durum wheat in relation to its employment in the breadmaking. (In Italian). Tec. Molitoria 42:1-7.

Pasqui, L.A., Carcea, M. and Paoletti, F. 1994. Characterization of durum wheat for breadmaking: influence of cultivar and protein content. (In Italian). Tec. Molitoria 45:223-228.

Pasqui, L.A., Carcea, M. and Paoletti, F. 1995. Relationship between protein content and bread volume in Italian durum wheat cultivars. (In Italian). Tec. Molitoria 46:587-592.

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

Payne, P.I. and Corfield, K.G. 1979. Subunit composition of wheat glutenin proteins, isolated by gel filteration in a dissociating medium. Planta 145:83-88.

Payne, P.I. Jackson, E.A. and Holt, L.M. 1984. The association between γ-gliadin 45 and gluten strength in durum wheat varieties: a direct casual effect or the result of genetic linkage ? J. Cereal Sci. 2:73-81.

Pena, R.J., Zarco-Hernandez, J., Amaya-Celis, A. and Mujeeb-Kazi, A. 1994. Relationship between chromosome 1B-encoded glutenin subunit compositions and bread-making quality characteristics of some durum wheat (Triticum turgidum) cultivars. J. Cereal Sci. 19: 243-249.

Pogna, N.E., Lafiandra, D., Feillet, P. and Autran J.C. 1988. Evidence for a direct causal effect of low molecular weight subunits of glutenins on gluten viscoelasticity in durum wheats. J. Cereal Sci. 7:211-214.

Pogna, N.E., Autran, J.C., Mellini, F., Lafiandra, D. and Feillet, P. 1990. Chromosome 1B-encoded gliadins and glutenin subunits in durum wheat : genetics and relationship to gluten strength. J. Cereal Sci. 11:15-34.

Pogna, N.E., Mazza, M., Redaelli, R., Ng, P.K.W. 1996. Gluten quality and storage protein composition of durum wheat lines containing the *Gli-D1/Glu-D3* loci. Pages 18-20 In: Proc. 6th Int. Gluten Workshop. C.W. Wrigley ed. Royal Society of Chemistry, Cambridge, UK.

Pomeranz, Y. 1988. Composition and functionality of wheat flour components. Pages 219-370. In:Wheat: Chemistry and Technology, 3rd edition, Vol 2. Y. Pomeranz, ed. Am. Assoc. Cereal Chem., St. Paul, MN.

Quaglia, G.B. 1988. Other durum wheat products. Pages 263-282. In:Durum Wheat: Chemistry and Technology, 1st edition G. Fabriani and C. Lintas, eds. Am. Assoc. Cereal Chem., St. Paul, MN.

Quick, J.S. and Crawford, R.D. 1983. Bread baking potential of new durum wheat cultivars. Pages 851-856 In: Proc. 6th Int. Wheat Genet. Symp. Sakamoto, ed. Plant Germplasm Institute, Kyoto University, Kyoto, Japan.

Rao, V.K., Mulvaney, S.J., Dexter, J.E., Edwards, N.M. and Peressini, D. 2001. Stress-relaxation properties of Mixograph semolina-water doughs from durum wheat cultivars of variable strength in relation to mixing characteristics, bread- and pasta-making performance. J. Cereal Sci. 34:215-232.

Ruiz, M. and Carrillo, J.M. 1993. Linkage relationships between prolamin genes on chromosomes 1A and 1B in durum wheat. Theor. Appl. Genet. 87:353-360.

Ruiz, M. and Carrillo, J.M. 1995. Separate effects on gluten strength of Gli-1 and Glu-3 prolamin genes on chromosomes 1A and 1B in durum wheat. J. Cereal Sci. 21: 137-144.

Sapirstein, H.D. 1999. The imaging and measurement of bubbles in bread. Pages 233-243 In:Bubbles in Food, 1st edition G. M. Campbell, C. Webb, S. S. Pandiella and K. Niranjan, eds. Am. Assoc. Cereal Chem., St. Paul, MN.

Sapirstein, H.D. and Bushuk, W. 1985. Computer-aided analysis of gliadin electrophoregrams. I. Improvement of precision of relative mobility determination by using a three reference band standardization. Cereal Chem. 62:372-377.

Sapirstein, H. and Fu, B. 1998. Intercultivar variation in the quantity of monomeric proteins, soluble and insoluble glutenin, and residue protein in wheat flour and relationships to breamaking quality. Cereal Chem. 74:500-507.

Sapirstein, H. and Johnson, W. 2000. A rapid spectrophotometric method for measuring insoluble glutenin content of flour and semolina for wheat quality screening. Pages:307-312 in: Wheat Gluten, Proceedings of the 7th International Gluten Workshop. P.R. Shewry and A.S. Tatham, eds. Royal Society of Chemistry, Cambridege, UK.

Sapirstein, H., Roller, R. and Bushuk, W. 1994. Instrumental measurement of bread crumb grain by digital image analysis. Cereal chem. 74:383-391.

Shewry, P., Tatham, A., Forde, J., Kreis, M. and Miflin, B. 1986. The classification and nomenclature of wheat gluten proteins: A reassessment. J. Cereal Sci. 4:97-106.

Shewry, P.R., Halford, N.G. and Tatham, A.S. 1992. High molecular weight subunits of wheat glutenin. J. Cereal Sci. 15:105-120.

Shewry, P.R., Tatham, A.S. and Lazzeri, P. 1997. Biotechnology of wheat quality. J. Sci. Food Agric. 73:397-406.

Shogren, M. 1990. A short history of the Mixograph. Cereal Foods World 35(5):480-482.

Sidhu, J.S., Al-Saqer, J. and Al-Zenki, S. 1997. Comparison of methods for the assessment of the extent of staling in bread. Food Chem. 58:161-167.

Spina, A., Palumbo, M., Petralia, S. and Boggini, G. 1998. Utilization of durum wheat flour in industrial bread production. (In Italian). Tec. Molitoria 49:569-577.

Sweeney, R.A. and Rexroad, P.R. 1987. Comparison of LECO FP-228 "Nitrogen Determinator" with AOAC copper catalysed Kjeldahl method for crude protein. J. Assoc. Off. Anal. Chem. 70:1028-1030.

Tipples, K.H. 1969. The relation of starch damage to the baking performance of flour. Bakers Digest 43:28-32, 44.

Tipples, K.H., Preston, K.R. and Kilborn, R.H. 1982. Implications of the term "strength" as related to wheat and flour quality. Bakers Digest 56:16-18, 20.

Troccoli, A., Borrelli, G.M., De Vita, P., Fares, C. and Di Fonzo, N. 2000. Durum wheat quality: A multidisciplinary concept. J. Cereal Sci. 32:99-113.

Vensel, W.H., Adalsteins, A.E. and Kasarda, D.D. 1997. Purification and characterization of the glutenin subunits of Triticum tauschii, progenitor of the D genome in hexaploid bread wheat. Cereal Chem.74: 108-114.

Vogel, H. and Bailey, C.H. 1927. A Study of durum wheats. Cereal Chem. March:136-148.

Welsh, J.R. and Hehn, E.R. 1964. Effect of chromosome 1D on hexaploid wheat flour quality. Crop Sci. 4:320-323.

Zeleznak, K.J. and Hoseney, R.C. 1986. The role of water in the retrogradation of wheat starch gels and bread crumb. Cereal Chem. 63:407-411.

Appendix I. Correlation matrix of chemical, milling and protein compositional parameters for mill product G of all samples.

	PC	*Ash*	*≥250PSD*	*180PSD*	*≤150PSD*	*SD*	*GP-300*	*SP*	*IG*	*RP*	*IG/SP*	*SP-PC*	*IG-PC*	*RP-PC*
PC	1.00													
Ash	-0.63	1.00												
≥250PSD	-0.78	0.89	1.00											
180PSD	-0.50	0.56	0.61	1.00										
≤150PSD	0.78	-0.88	-0.99	-0.70	1.00									
SD-G	-0.68	0.94	0.91	0.67	-0.91	1.00								
GP-300	-0.61	0.66	0.75	0.73	-0.79	0.69	1.00							
SP	0.90	-0.54	-0.75	-0.46	0.76	-0.56	-0.65	1.00						
IG	0.51	-0.57	-0.50	-0.57	0.51	-0.69	-0.33	0.17	1.00					
RP	-0.31	0.49	0.55	0.67	-0.59	0.64	0.57	-0.42	-0.43	1.00				
IG/SP	-0.06	-0.20	-0.01	-0.24	0.01	-0.30	0.09	-0.44	0.81	-0.14	1.00			
SP-PC	0.49	-0.22	-0.45	-0.22	0.47	-0.23	-0.48	0.82	-0.34	-0.41	-0.80	1.00		
IG-PC	0.12	-0.34	-0.19	-0.40	0.20	-0.47	-0.08	-0.24	0.91	-0.33	0.97	-0.64	1.00	
RP-PC	-0.73	0.66	0.77	0.71	-0.80	0.80	0.68	-0.75	-0.58	0.87	-0.09	-0.52	-0.32	1.00

Appendix II. Correlation matrix of chemical, milling, rheological and baking parameters for mill product G of all samples.

	PC	*Ash*	*≥250PSD*	*180PSD*	*≤150PSD*	*SD*	*GP-300*	*SP*	*IG*	*RP*	*IG/SP*	*SP-PC*	*IG-PC*	*RP-PC*
MT	-0.09	-0.24	-0.01	0.05	-0.04	-0.25	0.32	-0.47	0.67	0.10	0.88	-0.81	0.82	0.09
WIP	0.25	-0.39	-0.23	-0.16	0.20	-0.38	0.09	-0.15	0.82	0.01	0.83	-0.63	0.82	-0.14
PDR	0.77	-0.69	-0.72	-0.59	0.73	-0.71	-0.57	0.68	0.68	-0.66	0.21	0.35	0.41	-0.88
BW	0.36	-0.41	-0.31	-0.44	0.32	-0.48	-0.34	0.18	0.74	-0.59	0.56	-0.10	0.68	-0.63
BR	0.51	-0.35	-0.56	-0.34	0.58	-0.33	-0.58	0.76	-0.13	-0.46	-0.55	0.82	-0.40	-0.57
FDDT	0.17	-0.57	-0.35	-0.20	0.31	-0.61	0.06	-0.13	0.79	-0.30	0.79	-0.48	0.82	-0.32
Stab	0.23	-0.23	-0.11	-0.39	0.13	-0.35	-0.07	-0.16	0.84	-0.11	0.85	-0.61	0.87	-0.21
MTI	-0.19	-0.01	-0.12	0.01	0.15	0.11	-0.30	0.20	-0.72	-0.09	-0.78	0.62	-0.76	0.08
Fabs	0.24	0.34	0.12	0.03	-0.09	0.40	-0.07	0.26	-0.21	0.31	-0.34	0.21	-0.34	0.11
P	-0.01	-0.23	-0.07	-0.23	0.07	-0.22	0.10	-0.34	0.72	-0.12	0.85	-0.67	0.83	-0.10
L	0.62	-0.35	-0.50	-0.44	0.53	-0.46	-0.62	0.76	0.09	-0.53	-0.37	0.73	-0.18	-0.70
P/L	-0.23	-0.06	0.12	0.05	-0.14	0.03	0.32	-0.54	0.47	0.21	0.74	-0.79	0.64	0.27
W	0.33	-0.53	-0.41	-0.54	0.42	-0.61	-0.26	0.04	0.93	-0.51	0.82	-0.37	0.91	-0.55
DSL	-0.39	0.42	0.33	0.43	-0.33	0.48	0.32	-0.05	-0.90	0.32	-0.80	0.41	-0.87	0.45
RTPT	-0.17	-0.17	0.10	-0.05	-0.11	-0.16	0.22	-0.55	0.65	0.10	0.92	-0.87	0.83	0.15
LV	-0.07	0.21	0.39	0.20	-0.41	0.11	0.36	-0.37	0.48	0.09	0.66	-0.60	0.62	0.05
SV	-0.11	0.25	0.43	0.24	-0.45	0.15	0.40	-0.38	0.42	0.10	0.61	-0.57	0.57	0.08
OR	0.67	-0.68	-0.61	-0.49	0.59	-0.79	-0.47	0.40	0.90	-0.52	0.59	-0.06	0.73	-0.74
Babs	0.25	-0.13	-0.07	-0.23	0.07	-0.19	-0.08	-0.13	0.76	0.01	0.76	-0.58	0.77	-0.14

Appendix III. Correlation matrix of rheological and baking parameters for mill product G of all samples.

	MT	*WIP*	*PDR*	*BW*	*BR*	*FDDT*	*Stab*	*MTI*	*Fabs*	*P*	*L*	*P/L*	*W*	*DSL*	*RTPT*	*LV*	*SV*	*OR*	*Babs*
MT	1.00																		
WIP	0.90	1.00																	
PDR	0.09	0.42	1.00																
BW	0.38	0.57	0.79	1.00															
BR	-0.63	-0.42	0.41	-0.10	1.00														
FDDT	0.87	0.82	0.42	0.52	-0.31	1.00													
Stab	0.72	0.82	0.37	0.64	-0.53	0.64	1.00												
MTI	-0.75	-0.77	-0.25	-0.52	0.54	-0.63	-0.79	1.00											
Fabs	-0.38	-0.08	0.08	-0.05	0.25	-0.59	-0.08	0.07	1.00										
P	0.79	0.87	0.37	0.61	-0.43	0.71	0.79	-0.62	-0.05	1.00									
L	-0.49	-0.33	0.51	0.30	0.52	-0.19	-0.16	0.15	0.08	-0.45	1.00								
P/L	0.80	0.80	0.05	0.27	-0.50	0.58	0.61	-0.49	0.01	0.91	-0.75	1.00							
W	0.67	0.81	0.70	0.85	-0.19	0.79	0.82	-0.63	-0.19	0.86	0.02	0.59	1.00						
DSL	-0.59	-0.78	-0.66	-0.82	0.17	-0.62	-0.80	0.69	0.01	-0.78	0.00	-0.55	-0.90	1.00					
RTPT	0.93	0.86	0.05	0.39	-0.58	0.75	0.75	-0.70	-0.25	0.83	-0.55	0.84	0.68	-0.65	1.00				
LV	0.62	0.57	0.09	0.52	-0.60	0.46	0.67	-0.87	-0.08	0.50	-0.14	0.39	0.48	-0.55	0.63	1.00			
SV	0.59	0.52	0.05	0.48	-0.59	0.43	0.61	-0.84	-0.09	0.46	-0.14	0.35	0.43	-0.48	0.60	1.00	1.00		
OR	0.48	0.66	0.80	0.78	0.06	0.71	0.68	-0.60	-0.22	0.49	0.37	0.19	0.82	-0.82	0.44	0.47	0.43	1.00	
Babs	0.62	0.80	0.40	0.65	-0.43	0.46	0.86	-0.75	0.18	0.75	-0.22	0.63	0.72	-0.88	0.68	0.61	0.55	0.59	1.00

Appendix IV. Correlation matrix of milling, rheological and baking parameters for mill product 6R of all samples.

	≥250PSD	180PSD	≤150PSD	SD	GP	MT	WIP	PDR	BW	BR
≥250PSD	1.00									
180PSD	0.59	1.00								
≤150PSD	-0.61	-1.00	1.00							
SD	0.40	0.82	-0.81	1.00						
GP	0.39	0.56	-0.56	0.78	1.00					
MT	-0.24	-0.45	0.44	-0.37	0.11	1.00				
WIP	-0.34	-0.60	0.59	-0.51	-0.11	0.95	1.00			
PDR	-0.46	-0.62	0.62	-0.64	-0.62	0.27	0.55	1.00		
BW	-0.46	-0.41	0.41	-0.39	-0.34	0.54	0.73	0.85	1.00	
BR	0.46	0.34	-0.35	0.17	0.05	-0.72	-0.77	-0.42	-0.72	1.00
FDDT	-0.50	-0.68	0.68	-0.66	-0.23	0.87	0.92	0.57	0.68	-0.67
Stab	-0.43	-0.51	0.51	-0.54	-0.13	0.90	0.93	0.49	0.68	-0.68
MTI	0.54	0.71	-0.71	0.53	0.27	-0.67	-0.76	-0.41	-0.47	0.67
Fabs	0.31	0.60	-0.59	0.82	0.44	-0.64	-0.63	-0.31	-0.30	0.32
DSL	0.18	0.26	-0.26	0.23	0.35	-0.44	-0.60	-0.66	-0.79	0.77
RTPT	0.21	0.00	-0.01	0.07	0.26	0.70	0.64	0.03	0.37	-0.55
LV	-0.52	-0.47	0.47	-0.42	-0.18	0.82	0.89	0.55	0.79	-0.89
SV	-0.50	-0.42	0.42	- 0.37	-0.12	0.82	0.88	0.51	0.77	-0.90
OR	-0.59	-0.70	0.70	-0.76	-0.65	0.60	0.77	0.79	0.80	-0.68
Babs	-0.33	-0.48	0.47	-0.45	-0.38	0.60	0.70	0.53	0.70	-0.59

Appendix V. Correlation matrix of rheological and baking parameters for mill product 6R of all samples.

	FDDT	*Stab*	*MTI*	*Fabs*	*DSL*	*RTPT*	*LV*	*SV*	*OR*	*Babs*
FDDT	1.00									
Stab	0.94	1.00								
MTI	-0.72	-0.75	1.00							
Fabs	-0.74	-0.67	0.46	1.00						
DSL	-0.46	-0.45	0.39	0.17	1.00					
RTPT	0.45	0.57	-0.47	-0.12	-0.51	1.00				
LV	0.82	0.89	-0.79	-0.53	-0.69	0.57	1.00			
SV	0.80	0.87	-0.77	-0.51	-0.68	0.57	0.99	1.00		
OR	0.80	0.78	-0.75	-0.65	-0.70	0.32	0.85	0.81	1.00	
Babs	0.64	0.72	-0.66	-0.40	-0.63	0.57	0.75	0.69	0.78	1.00

Appendix VI. Correlation matrix of breadscore and loaf volume for mill product G and 6R of all samples.

	LA	*CS*	*CC*	*BS*	*LV*	*LA-6R*	*CS-6R*	*CC-6R*	*BS-6R*	*LV-6R*
LA	1.00									
CS	0.57	1.00								
CC	0.69	0.14	1.00							
BS	0.93	0.76	0.65	1.00						
LV	0.80	0.83	0.57	0.95	1.00					
LA-6R						1.00				
CS-6R						0.70	1.00			
CC-6R						0.83	0.31	1.00		
BS-6R						0.96	0.63	0.85	1.00	
LV-6R						0.91	0.66	0.70	0.94	1.00

Appendix VII. Correlation matrix of breadscore and loaf volume for mill product G at varying fermentation times for all samples.

	LA	*CS*	*CC*	*BS*	*LV*	*LA-15*	*CS-15*	*CC-15*	*BS-15*	*LV-15*	*LA-90*	*CS-90*	*CC-90*	*BS-90*	*LV-90*
LA	1.00														
CS	0.57	1.00													
CC	0.69	0.14	1.00												
BS	0.93	0.76	0.65	1.00											
LV	0.80	0.83	0.57	0.95	1.00										
LA-15						1.00									
CS-15						0.70	1.00								
CC-15						0.62	0.41	1.00							
BS-15						0.90	0.73	0.84	1.00						
LV-15						0.88	0.67	0.78	0.93	1.00					
LA-90											1.00				
CS-90											0.70	1.00			
CC-90											0.74	0.50	1.00		
BS-90											0.89	0.75	0.92	1.00	
LV-90											0.87	0.63	0.81	0.92	1.00

Appendix VIII. Correlation matrix of milling, chemical and baking parameters for mill product G of all samples at varying fermentation times.

	≥250PSD	180PSD	≤150PSD	SD	GP-300	SP	IG	RP	IG/SP	SP-PC	IG-PC	RP-PC
DSL-15	0.30	0.48	-0.31	0.53	0.36	0.03	-0.87	0.49	-0.81	0.39	-0.89	0.50
DSL-90	0.28	0.48	-0.29	0.48	0.28	0.02	-0.91	0.36	-0.84	0.46	-0.90	0.43
DSL	0.29	0.43	-0.30	0.47	0.29	-0.02	-0.91	0.31	-0.82	0.44	-0.88	0.43
RTPT-15	-0.23	-0.06	0.18	-0.48	0.17	-0.28	0.67	-0.25	0.78	-0.54	0.78	-0.19
RTPT-90	-0.18	-0.12	0.15	-0.47	0.12	-0.34	0.74	-0.12	0.88	-0.68	0.85	-0.11
RTPT	0.06	-0.04	-0.09	-0.19	0.22	-0.53	0.66	0.12	0.91	-0.87	0.83	0.14
LV-15	-0.46	-0.30	0.43	-0.67	-0.21	0.26	0.87	-0.42	0.65	-0.18	0.76	-0.62
LV-90	-0.59	-0.51	0.58	-0.76	-0.48	0.40	0.86	-0.56	0.55	-0.02	0.70	-0.74
LV	0.36	0.20	-0.39	0.08	0.39	-0.39	0.51	0.06	0.70	-0.62	0.65	0.04
SV-15	-0.48	-0.35	0.45	-0.70	-0.25	0.26	0.88	-0.46	0.65	-0.17	0.77	-0.64
SV-90	-0.59	-0.51	0.59	-0.77	-0.45	0.39	0.87	-0.59	0.56	-0.03	0.71	-0.76
SV	0.40	0.24	-0.43	0.11	0.43	-0.41	0.46	0.07	0.66	-0.61	0.61	0.07
OR-15	-0.43	-0.18	0.41	-0.44	-0.01	0.26	0.18	-0.39	-0.02	0.25	0.08	-0.40
OR-90	-0.64	-0.51	0.65	-0.65	-0.36	0.52	0.32	-0.54	-0.04	0.41	0.11	-0.63
OR	-0.63	-0.45	0.64	-0.64	-0.34	0.47	0.28	-0.59	-0.05	0.41	0.10	-0.62
Babs-15	-0.01	-0.05	-0.01	-0.11	-0.04	-0.20	0.62	-0.12	0.68	-0.50	0.68	-0.14
Babs-90	-0.04	-0.20	0.04	-0.19	-0.28	-0.27	0.49	-0.17	0.60	-0.46	0.61	-0.10
Babs	-0.07	-0.23	0.07	-0.19	-0.08	-0.13	0.76	0.01	0.76	-0.58	0.77	-0.14

Appendix IX. Correlation matrix of rheological and baking parameters for mill product G of all samples at varying fermentation times.

	MT	*WIP*	*PDR*	*BW*	*BR*	*FDDT*	*Stab*	*MTI*	*Fabs*	*P*	*L*	*P/L*	*W*	*DSL-15*	*DSL-90*	*DSL*
DSL-15	-0.57	-0.66	-0.59	-0.87	0.26	-0.63	-0.80	0.63	0.20	-0.71	-0.15	-0.41	-0.91	1.00		
DSL-90	-0.63	-0.79	-0.63	-0.85	0.27	-0.66	-0.85	0.70	0.09	-0.80	0.02	-0.56	-0.92	0.93	1.00	
DSL	-0.62	-0.80	-0.65	-0.82	0.18	-0.65	-0.81	0.72	0.02	-0.79	0.01	-0.57	-0.91	0.91	0.98	1.00
RTPT-15	0.87	0.75	0.30	0.47	-0.39	0.97	0.56	-0.55	-0.66	0.71	-0.33	0.63	0.73	-0.59	-0.61	-0.58
RTPT-90	0.94	0.85	0.26	0.49	-0.49	0.95	0.69	-0.65	-0.56	0.77	-0.36	0.70	0.76	-0.65	-0.70	-0.68
RTPT	0.95	0.87	0.05	0.38	-0.58	0.76	0.75	-0.71	-0.26	0.81	-0.55	0.84	0.67	-0.60	-0.69	-0.69
LV-15	0.60	0.71	0.72	0.77	-0.12	0.80	0.69	-0.71	-0.31	0.57	0.24	0.29	0.83	-0.80	-0.77	-0.79
LV-90	0.42	0.58	0.77	0.77	0.03	0.65	0.70	-0.54	-0.21	0.50	0.39	0.17	0.82	-0.82	-0.73	-0.75
LV	0.68	0.62	0.11	0.54	-0.61	0.53	0.68	-0.88	-0.12	0.55	-0.18	0.44	0.53	-0.59	-0.58	-0.59
SV-15	0.59	0.69	0.72	0.78	-0.12	0.80	0.70	-0.70	-0.34	0.55	0.29	0.25	0.84	-0.81	-0.77	-0.78
SV-90	0.43	0.58	0.78	0.77	0.04	0.68	0.69	-0.55	-0.25	0.50	0.38	0.17	0.83	-0.82	-0.74	-0.75
SV	0.66	0.57	0.07	0.50	-0.61	0.50	0.63	-0.85	-0.14	0.52	-0.19	0.42	0.48	-0.55	-0.53	-0.54
OR-15	0.14	0.14	0.35	0.24	-0.08	0.39	0.13	0.06	-0.40	0.11	0.19	-0.05	0.26	-0.09	-0.03	0.09
OR-90	-0.03	0.06	0.50	0.28	0.14	0.32	0.20	0.09	-0.36	0.02	0.42	-0.22	0.31	-0.18	-0.11	-0.01
OR	-0.01	0.05	0.49	0.29	0.16	0.33	0.15	0.16	-0.36	0.04	0.39	-0.18	0.32	-0.18	-0.08	0.02
Babs-15	0.56	0.70	0.44	0.70	-0.30	0.45	0.70	-0.56	0.14	0.81	-0.33	0.70	0.71	-0.72	-0.79	-0.81
Babs-90	0.44	0.48	0.21	0.61	-0.40	0.29	0.66	-0.35	0.06	0.59	-0.03	0.45	0.60	-0.77	-0.64	-0.62
Babs	0.62	0.80	0.40	0.65	-0.43	0.46	0.86	-0.75	0.18	0.75	-0.22	0.63	0.72	-0.76	-0.88	-0.87

Appendix X. Correlation matrix of baking parameters for mill product G of all samples at varying fermentation times.

	RTPT-15	*RTPT-90*	*RTPT*	*LV-15*	*LV-90*	*LV*	*SV-15*	*SV-90*	*SV*	*OR-15*	*OR-90*	*OR*	*Babs-15*	*Babs-90*	*Babs*
RTPT-15	1.00														
RTPT-90	0.95	1.00													
RTPT	0.75	0.89	1.00												
LV-15	0.71	0.70	0.48	1.00											
LV-90	0.53	0.54	0.35	0.93	1.00										
LV	0.50	0.58	0.66	0.61	0.47	1.00									
SV-15	0.70	0.70	0.48	1.00	0.94	0.60	1.00								
SV-90	0.56	0.56	0.36	0.94	1.00	0.47	0.95	1.00							
SV	0.48	0.56	0.63	0.58	0.43	1.00	0.57	0.43	1.00						
OR-15	0.39	0.22	-0.12	0.33	0.33	-0.11	0.33	0.34	-0.11	1.00					
OR-90	0.25	0.12	-0.22	0.39	0.49	-0.23	0.41	0.50	-0.24	0.90	1.00				
OR	0.28	0.13	-0.21	0.36	0.48	-0.23	0.39	0.49	-0.24	0.93	0.98	1.00			
Babs-15	0.47	0.52	0.62	0.57	0.54	0.62	0.53	0.53	0.58	-0.07	-0.13	-0.10	1.00		
Babs-90	0.28	0.40	0.53	0.39	0.53	0.50	0.41	0.48	0.47	-0.07	-0.08	0.00	0.71	1.00	
Babs	0.41	0.55	0.69	0.58	0.54	0.62	0.57	0.52	0.56	-0.10	-0.07	-0.12	0.84	0.65	1.00

Appendix XI. Correlation matrix of textural properties for mill product G of all samples.

	PF1-D1	*GR-D1*	*RS-D1*	*PF1-D5*	*GR-D5*	*RS-D5*	*%PF*	*%GR*	*%RS*	*Babs*	*LV*
PF1-D1	1.00										
GR-D1	1.00	1.00									
RS-D1	-0.09	-0.09	1.00								
PF1-D5	0.96	0.96	-0.09	1.00							
GR-D5	0.96	0.96	-0.09	1.00	1.00						
RS-D5	0.01	0.01	0.80	-0.09	-0.09	1.00					
%PF	-0.23	-0.24	0.05	0.04	0.04	-0.33	1.00				
%GR	-0.28	-0.29	0.07	-0.01	-0.01	-0.31	1.00	1.00			
%RS	-0.08	-0.08	-0.43	0.07	0.07	-0.88	0.53	0.52	1.00		
Babs	-0.07	-0.07	-0.27	-0.14	-0.14	0.03	-0.27	-0.27	-0.26	1.00	
LV	-0.88	-0.88	0.09	-0.80	-0.80	-0.08	0.38	0.42	0.19	0.26	1.00

Appendix XII. Correlation matrix of textural properties for mill product 6R of all samples.

	PF1-D1	*GR-D1*	*RS-D1*	*PF1-D5*	*GR-D5*	*RS-D5*	*Babs*	*LV*	*%PF*	*%GR*	*%RS*
PF1-D1	1.00										
GR-D1	1.00	1.00									
RS-D1	-0.69	-0.69	1.00								
PF1-D5	0.97	0.97	-0.73	1.00							
GR-D5	0.97	0.97	-0.73	1.00	1.00						
RS-D5	-0.27	-0.27	0.79	-0.39	-0.39	1.00					
Babs	-0.36	-0.36	0.31	-0.50	-0.50	0.36	1.00				
LV	-0.83	-0.83	0.47	-0.88	-0.88	0.19	0.73	1.00			
%PF	-0.50	-0.50	0.13	-0.29	-0.29	-0.31	-0.24	0.20	1.00		
%GR	-0.58	-0.58	0.18	-0.37	-0.37	-0.27	-0.16	0.29	1.00	1.00	
%RS	-0.48	-0.47	0.01	-0.33	-0.33	-0.60	-0.20	0.31	0.67	0.68	1.00

Appendix XIV. Comparison of Ovenrise (cm) of durum and common wheat samples for G at fermentation times 15, 90 and 165 min.

Genotypes	Ovenrise		
	15 min	**90 min**	**165 min**
AC Melita	23.8 ± 2.1	25.3 ± 1.3	29 ± 0.58
AC Morse	20.8 ± 0.5	23.5 ± 1.0	25 ± 0.96
Kyle	19.0 ± 1.4	20.8 ± 1.3	22 ± 2.94
Durex	19.3 ± 1.0	21.3 ± 1.5	26 ± 0.58
DT 674	11.8 ± 1.9	15.0 ± 1.2	13 ± 1.41
DT 369	21.3 ± 1.9	24.0 ± 1.6	25 ± 2.22
Ofanto	12.3 ± 2.1	15.0 ± 2.4	13 ± 1.15
Grazia	18.5 ± 1.3	20.0 ± 1.6	21 ± 1.50
Simeto	13.3 ± 1.5	14.3 ± 1.9	17 ± 0.50
Creso	15.8 ± 2.6	17.5 ± 1.3	16 ± 3.92
Arcangelo	6.3 ± 0.5	7.5 ± 1.7	5 ± 2.06
AC Barrie	21.0 ± 1.2	28.8 ± 3.0	33 ± 0.82
Glenlea	27.8 ± 1.7	29.0 ± 0.8	33 ± 5.44
Averages	17.7 [A]	20.1 [B]	21.2 [C]
Mean of N.A.[1]	19.3 ± 4.1	21.6 ± 3.7	23.1 ± 5.4
Mean of Itl.[2]	13.2 ± 4.6	14.9 ± 4.7	14.3 ± 6.0
LSD-F[3]	0.73		
CV(%)	30.4	30.8	39.1

[1]North American Durums.
[2] Italian Durums.
[3]Least Significant Difference; F is among fermentation times.
Means with the same letter are not significantly different at $p < 0.05$ level; upper case letters are different among averages of fermentation times 15, 90 and 165 min.
n=4±SD.