Effects of Frost and Immaturity on the Quality of a Canadian Hard Red Spring Wheat[1]

K. R. PRESTON, R. H. KILBORN, B. C. MORGAN, and J. C. BABB

Cereal Chem. 68(2):133–138

ABSTRACT

A Canadian hard red spring wheat, variety Neepawa, was subjected to controlled freezing in the field during maturation for two years. The overall quality of untreated (control) seed showed significant improvement during maturation until seed moisture reached approximately 45%, after which changes were much less evident. Kernel hardness, kernel weight, test weight, wheat ash, milling quality parameters (yield, flour ash, and color), and physical dough properties showed large changes (improvements) during maturation, whereas protein and remix baking quality parameters showed much smaller changes. The response of quality characteristics to frost was dependent on both temperature and maturity. At early maturity, temperatures below −3°C resulted in decreased kernel weight and protein content but increased kernel hardness. Effects were less evident at later maturity (seed moisture below approximately 45%). Low-temperature treatment had little effect on dough strength properties. However, treatment at all but the most mature stages resulted in large, significant increases in starch damage and farinograph absorption. Milling-related parameters (test weight, wheat ash, flour ash, flour color, and yield) were all adversely affected by low-temperature treatment except at the most mature stages. Remix baking quality (loaf volume, baking strength index, and crumb and crust characteristics) was also adversely affected during the early maturation phase.

Canada uses a wheat grading system based primarily on visual characteristics. The major purpose of this system is to ensure that wheat with reduced quality due to adverse environmental conditions is assigned to lower grades. This has been accomplished by setting rigid specifications for a wide variety of degrading factors in the top grades of each wheat class.

Two of the major degrading factors for the Canada Western Red Spring (CWRS) wheat class (which accounts for approximately 80% of total Canadian wheat production) are frost and immaturity. Almost every year a certain proportion of this crop is frozen before reaching maturity. Immaturity also may be due to secondary growth, which often follows a drought early in the growing season.

Previous studies of commercial samples of CWRS wheat (Geddes et al 1932, Malloch et al 1937) showed a negative relationship between flour yield and the percentage of immature and heavily frosted kernels. Baking quality appeared to be related to these factors in the former study but not in the latter one. In a more recent study (Dexter et al 1985), the effects of frost damage on the milling and baking quality of hard red spring (HRS) wheat were examined in cargoes of wheat graded as Canada Feed. As the visual degree of frost damage increased, flour yield, ash, and color increased, while loaf volume decreased, and crumb and crust characteristics became progressively poorer. In addition, physical dough properties weakened, flour starch damage increased, and farinograph absorption increased.

Field studies involving the cutting of wheat at various stages of maturity have been used to study the effects of immaturity on the quality characteristics and chemical properties of wheat and flour. Mangels and Stoa (1928) harvested Marquis HRS wheat at five stages of maturity. Their results indicated that the stage of maturity had little effect on protein content or baking quality, whereas flour ash and diastase activity showed elevated levels at the earliest (dough and hard dough) stages. Hoseney et al (1966) showed that the overall quality of hard red winter wheats (test weight, flour yield, and loaf volume) improved during maturation until approximately two weeks before ripeness. Baking absorption decreased during maturation. These changes were accompanied by a decrease in water and salt-extractable flour proteins and a gradual increase in the average molecular weight and complexity of the proteins being synthesized. Tipples (1980) found that the patterns of change in the quality characteristics of Canadian HRS wheat were more closely related to moisture content at cutting than to the number of days after anthesis. Grade, test weight, flour yield, ash, and color improved as the moisture content decreased to approximately 45%. Further reductions in moisture content had much smaller effects on these quality characteristics. Maturation was also associated with increasing dough strength properties, decreasing flour starch damage, and decreasing farinograph and baking absorption values. Loaf volume was adversely affected only at the most immature stages. Crumb color improved with maturity.

Few published field studies concern the effects on wheat quality of freezing wheat at various stages of maturity. McCalla and Newton (1935) and Newton and McCalla (1935) suggested that quality is affected by both the degree of frost and the maturity of the plant at the time of frost. These studies showed that frost at early stages of maturity reduced flour yield and baking quality compared with nonfrosted samples harvested at the same maturity. Frost also increased flour water absorption and maltose value but had minimal effect on wheat ash, test weight, and kernel weight. At more mature stages, where samples were harvested at moisture contents of less than 45%, frost showed little effect on quality characteristics.

In the present study, controlled field experiments were used to further investigate the effect of frost at various stages of maturity on the quality characteristics of a Canadian HRS wheat. The results are intended to confirm and extend previous research and to provide information to assist in the setting of grade tolerances for Canadian wheats.

MATERIALS AND METHODS

Certified seed of the Canadian HRS wheat variety Neepawa was obtained from a seed grower. The seed was planted on a 40 × 40-m plot using a seed drill (row spacing 13 cm, seeding rate 84 kg/ha) at the Agriculture Canada farm at Glenlea, Manitoba. Soil analysis showed that fertilization of the plot was not required.

Description of Freezer Units

Each freezer unit was constructed by welding a frame of angle iron (7.0 ft long, 4.0 ft wide, and 5.5 ft high) (2.75 × 1.20 × 1.65 m) and insulating the sides and top with sheets of 4-in. thick (102 mm) styrofoam insulation. A ½-HP (120 volts AC) condenser, placed on top of the frame, was used to operate the refrigeration coil and cool the interior of the unit. A fan was placed inside the unit to circulate the air. Large wheels (13-in. trailer tires) were mounted to a retractable rod attached to one end of the frame for moving the units. The retractable rod was used to raise the wheels after placement, allowing the frame to touch the ground. A removable panel and handle were placed

[1]Contribution 654 of the Canadian Grain Commission, Grain Research Laboratory, 1404-303 Main Street, Winnipeg, MB R3C 3G8, Canada.

at the other end of each unit, allowing them to be easily moved (like a wheelbarrow) over the grain and into position. Temperature and time of treatment were controlled with an RD-type thermocouple attached to a data logger (DL-2020 Digital Data Logger, Cole-Parmer Co., Chicago, IL). Set points of 0.1°C below and above the desired setting were used for temperature control. A circuit designed in our laboratory provided a minimum 3-min delay between the times when the compressor turned off after reaching the low-temperature set point and turned on again. Its effect on temperature control was minimal, and it prevented rapid on-off cycling of the compressor, which could reduce life-time and increase ice buildup on the compressor coils.

Experimental Design

Freezing of wheat in the field was initiated when the grain moisture content was approximately 70%. A path 5 m wide was cut across the field to provide access to the freezer unit. The wheat adjacent to the path was then separated into blocks of sufficient size to accommodate the three freezer units used in the 1983 study or the two freezer units used in the 1984 study. Additional space was left in each block for controls. The location of freezers and controls within blocks was randomized. Blocks were harvested sequentially along the cut path during maturation. When all wheat (except a perimeter row) was harvested on both sides of the path, the next inside rows were used. Areas of the field where maturity did not appear to be uniform were not used.

For each experiment, the freezer units were placed over the wheat in the selected block. Sandbags were placed along the bottom edges of the units to prevent excessive air leakage and improve insulation. Each freezer unit, at ambient temperature, was set to the desired temperature, which then ran at that setting for 4 hr. Minimum temperature was normally attained after 30–60 min. Two experiments were conducted each day (morning and late afternoon). Plants from each freezer plot and a control were cut the next day, stooked in the field to dry (three to five days) and then thrashed in a Hage Thrasher (Hage Equipment Inc, Colwich, KS). The seed was allowed to dry on a laboratory bench to 8–10% moisture content and was stored at 4°C until further use.

Preliminary experiments showed that the period of freezing (2–6 hr) and the time of freezing (morning, afternoon, or evening) had no significant effect ($P < 0.05$) on quality parameters. No significant difference was noted between results obtained at −5°C and those obtained at lower temperatures (−7 and −10°C). Therefore, −5°C was chosen as the lowest temperature for testing.

In 1983, daily freezing of wheat in the field was done at −1, −2, −3, −4, and −5°C for 26 days. Samples from each freezer were tested in duplicate for moisture, kernel weight, wheat hardness (particle size index), and protein content.

In 1984, daily freezing of wheat in the field was done at −5°C for 28 days to ensure the maximum effect on quality characteristics. Individual grain samples (frozen and corresponding control samples) were analyzed for moisture, kernel weight, wheat hardness, and protein content, as in the 1983 study. Composite samples representing six maturity stages were prepared from individual samples from each freezer to provide sufficient material to perform replicate milling, baking, physical dough, and other test procedures. Each composite sample was collected over four days, except for the most immature samples, which required eight days to obtain sufficient material for testing.

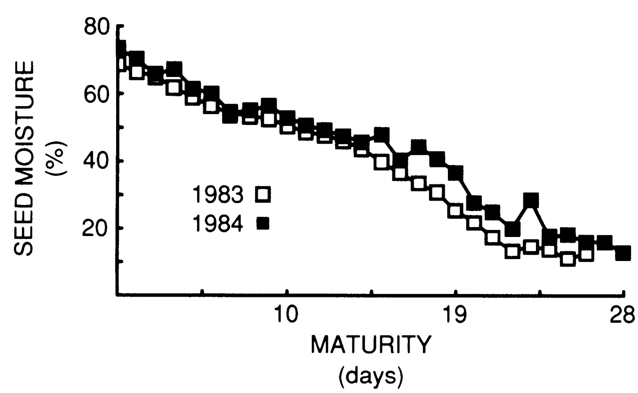

Fig. 1. Relationship of seed moisture and seed maturity during maturation of Canadian hard red spring wheat, variety Neepawa, grown in 1983 and 1984.

Testing of Wheat and Flour Samples

The methods for determining quality used in the present study have been described in a previous publication and references cited therein (Preston et al 1988). A KT 3303 grinder (Falling Number, Huddinge, Sweden) was used to measure particle size index (PSI) in the 1983 study; a Udy Cyclone grinder (Udy Corporation, Fort Collins, CO) was used in the 1984 study.

All wheat and flour data were corrected to a 13.5 and 14.0% moisture basis, respectively. Data were analyzed by *t*-test methods using Stat-Packets version 1.0 (Walonic Associates, Minneapolis, MN) with Lotus 1-2-3 files (Lotus Development Corporation, Orem, UT) on an IBM-AT computer.

RESULTS

The HRS wheat variety Neepawa was chosen for this study due to its predominance in western Canada over the last 15 years. During this period (1973–1987), Neepawa accounted for over 50% of farmer deliveries that graded into the CWRS wheat class (Canadian Grain Commission figures).

The maturity of the grain was determined by measuring the time of treatment and the moisture content. The relationship between these parameters (Fig. 1) followed a similar trend for both years.

Results of 1983 Study

In 1983, experiments were conducted to determine the effect of freezing temperature (control or −1 to −5°C) on a restricted number of wheat quality characteristics during maturation. Kernel weight and wheat hardness (as assessed by PSI) were chosen because of their known sensitivity to maturity and frost (Hoseney et al 1966, Tipples 1980, Dexter et al 1985). Wheat protein content was also measured.

Data obtained from daily trials were grouped into different stages of maturity, including early (the first 10 days), intermediate (the next eight days), and late (the last eight days) for statistical analysis. Results are shown in Table I. During the early stage

TABLE I
Effects of Freezing Temperature (°C) on 1,000-Kernel Weight, Protein Content, and Particle Size Index of Neepawa Hard Red Spring Wheat at Three Stages of Maturity[a]

		Freezing Temperature				
Maturity[b]	Control	−1°C	−2°C	−3°C	−4°C	−5°C
1,000-Kernel weight (g)						
Early	22.8	···	22.3	22.3[c]	19.7[c]	20.2[d]
Intermediate	29.7	30.2	29.5	29.3	29.2	29.6
Late	30.3	30.4	30.4	30.1	30.0	30.5
Protein content (%)						
Early	15.8	···	16.0	15.6	15.2[c]	15.0[c]
Intermediate	16.3	16.3	16.3	16.2	16.1	15.9[c]
Late	16.5	16.5	16.4	16.4	16.5	16.6
Particle size index (units)						
Early	11.0	···	10.9	9.8	8.3[d]	7.8[d]
Intermediate	15.5	15.0	15.3	14.5	13.5	12.6[c]
Late	15.0	15.4	15.3	15.3	15.4	14.8

[a] All values are averages of at least eight samples obtained during each maturity stage at equally spaced time intervals in 1983.
[b] Early, intermediate, and late maturity refer to samples harvested over the first 10 days, the next eight days, and the last 10 days, respectively. See text for moisture ranges.
[c] Significantly different from control at the 5% level. See text for significant differences between maturity stages for each treatment.
[d] Significantly different from control at the 1% level.

of maturity, lowering the temperature to less than −3°C had a significant effect on all three quality test results compared with the control. Kernel weight and protein content showed reduced values, while wheat hardness increased (had a lower PSI) with the lower temperatures. Only kernel weight was significantly affected at −3°C. At the intermediate stage of maturity, the effect of temperature was much less pronounced. During the late stage of maturity, no significant effects due to temperature were evident.

Quality differences between maturity stages were also analyzed for selected treatments (control, −3°C, and −5°C). Average values for kernel weight, PSI, and protein content (Table I) obtained at the early maturity stage were significantly ($P < 0.01$) lower than those obtained at the intermediate and late stages of maturity for all treatments. No significant ($P > 0.05$) quality differences were noted between the intermediate and late maturity stages for the control and −3°C treatments. However, the −5°C treatment resulted in significant differences in protein content ($P < 0.01$) and wheat hardness ($P < 0.05$).

Results of 1984 Study

Table II gives the average values of individual daily samples grouped by six maturity stages for kernel weight, protein content, and wheat hardness (PSI). The average moisture content for each period is also shown. Daily moisture averages are given in Figure 1. The differences in PSI values between the two years can be attributed to the use of different grinders. The KT 3303 grinder used in 1983 produces a coarser meal and thus a lower PSI value than the Udy Cyclone grinder used in 1984.

Average values obtained for these quality parameters showed a similar trend when compared with results obtained from the 1983 experiments. Kernel weight, protein content, and PSI values during the most immature stage (1–8 days) were significantly ($P < 0.01$) lower when treated at −5°C than when not treated (control). After the most immature stage, the effect of freezing on kernel weight was not significant. In contrast, freezing had significant effects on protein content during the second stage and on PSI values from the second to the fourth stages.

Significant ($P < 0.05$) increases in kernel weight were evident during the first three maturation stages for both the control and −5°C treatments. Increases in PSI values ($P < 0.05$) were most evident during the intermediate maturity stages. Overall, changes in these parameters were more pronounced with the −5°C treatment than with the control. Changes in protein content with maturation for the control and −5°C treatments showed a parallel trend, but no pattern in these changes was evident.

The composites representing the early maturity stages (up to 16 days) were graded as Canada Feed by the Inspection Division of the Canadian Grain Commission. The major degrading factors included shrunken, immature, and green kernels. Frosted kernels were also a major degrading factor in composites from the −5°C treatment. All later control composites were graded No. 1 CWRS. The 17–20 day −5°C composite was graded as Canada Feed (due to severely frosted kernels) and the 21–24 day composite as No. 3 CWRS (due to heavy frost), while the most mature −5°C composite (25–28 days) was graded No. 1 CWRS.

Quality data for the composite samples (control and −5°C) obtained for each maturity stage are shown in Tables III–VII. The effect of frost on protein-related parameters (Table III) was most evident during the earliest maturity stages. Wheat protein, flour protein, and wet gluten content were significantly ($P < 0.05$) lower in the frosted wheat. At later stages of maturity, differences between the control and −5°C treated composites were not evident. The ratio of wet gluten to flour protein was similar for both treatments except at the most immature stage.

Significant differences ($P < 0.05$) were evident in milling quality parameters between the control and −5°C treated composites during the first four maturity stages (Table IV). Flour yield was lower, and flour ash and color values were higher in the frosted composites. Test weight was also lower in the −5°C composites during the first four maturity stages. For the two most mature stages, frost did not have a major impact on milling quality. However, frost significantly increased wheat ash at all stages of maturity except the most immature. During the early stages, this effect was probably due to a higher proportion of bran to endosperm in frosted compared with control composites. However, the higher wheat ash levels in frosted composites at the later

TABLE II
Effects of Freezing Temperature on 1,000-Kernel Weight, Protein Content, and Particle Size Index of Neepawa Hard Red Spring Wheat at Six Stages of Maturity[a]

Maturity[b] (days)	Average Moisture (%)	1,000-Kernel Weight (g)		Protein Content (%)		Particle Size Index (units)	
		Control	−5°C	Control	−5°C	Control	−5°C
1–8	63.5	19.5	16.0[c]	14.8	13.4[c]	33.9	28.7[c]
9–12	52.4	28.4	28.2	12.9	12.3[c]	34.6	28.3[c]
13–16	45.3	32.7	31.0	13.7	13.6	37.8	27.8[c]
17–20	37.4	33.7	33.3	14.7	15.1	39.3	36.5[c]
21–24	22.8	33.4	33.3	14.7	14.6	49.1	49.4
25–28	15.7	33.4	33.3	13.9	13.9	50.6	51.2

[a] All values are averages of at least eight samples obtained during each maturity stage at equally spaced time intervals in 1984.
[b] See Figure 1 for moisture range of composites.
[c] Significantly different from control at the 1% level.

TABLE III
Protein-Related Quality Data for Control and −5°C Treated Wheat Composites at Six Stages of Maturity[a]

Composite[b] (days)	Wheat Protein (%)		Flour Protein (%)		Wet Gluten (%)		Ratio of Wet Gluten to Protein (%)	
	Control	−5°C	Control	−5°C	Control	−5°C	Control	−5°C
1–8	14.8	12.9[c]	14.1	11.9[c]	33.1	18.0[c]	2.4	1.5[c]
9–12	12.9	12.5[c]	12.3	11.7[c]	33.3	29.0[c]	2.7	2.5
13–16	13.4	13.4	13.2	12.8[c]	36.5	33.2[c]	2.8	2.6
17–20	14.2	14.8[c]	14.3	14.4	38.2	37.9	2.7	2.6
21–24	14.2	14.4	14.3	14.0	45.6	41.8[c]	3.2	3.0
25–28	13.9	14.0	13.2	13.4	35.9	35.1	2.7	2.6

[a] All values are averages of replicate samples (each was analyzed in duplicate in 1984).
[b] See Figure 1 for moisture range of composites.
[c] Significantly different from control at the 5% level. See text for significant differences between maturity stages for each treatment.

stages of maturity are difficult to explain, considering the fact that milling quality was not adversely affected.

The control showed significant ($P < 0.05$) improvement in milling quality (flour yield, ash, and color) and test weight during the first three maturity stages, while significant improvements in these parameters were evident during the first four maturity stages for the composites treated at −5°C. Flour ash and color values obtained for the mature wheat composites were higher than normally expected for Canadian HRS wheat (Preston et al 1988). Wheat ash values showed significant decreases over the first three maturity stages for the control. Changes were less evident for the frosted composites during maturation.

Physical dough properties of the composites, including farinograph dough development time and stability, were not significantly different ($P > 0.05$) for the control and −5°C treatments at corresponding maturity stages, with the exception of one period for each parameter (Table V). However, farinograph absorption values were significantly higher ($P < 0.05$) in frosted composites than in controls during the first four stages of maturity. These higher values were probably due to the higher levels of starch damage in the frosted composites (Table VII). Previous studies showed that the level of starch damage was closely related to dough water absorption potential (Farrand 1969, Preston et al 1987). Sodium dodecyl sulfate (SDS) sedimentation values for the −5°C composites were much lower ($P < 0.05$) than for the controls during the three most immature stages and significantly lower during the next two stages. Although the SDS sedimentation test is normally used to estimate flour strength, the large differences in sedimentation volume between treatments, compared with the small corresponding changes in farinograph properties, indicate that factors other than flour strength were responsible for these results.

Farinograph dough development time and stability values showed large increases after the second and/or third maturity period for the control and −5°C composites. After the fourth period, no further significant changes were evident. Farinograph absorption decreased during maturation, most likely in response to decreasing starch damage values (Table VII). Increases in SDS sedimentation volumes for the control were evident only after the first maturity stage, while significant increases occurred in volume throughout maturation for the frosted composites.

Baking quality (Table VI) was adversely affected by the −5°C treatment compared with the control during the three earliest maturity periods as assessed by the remix-to-peak baking

TABLE IV
Milling-Related Quality Data for Control and −5°C Treated Wheat Composites at Six Stages of Maturity[a]

Composite[b] (days)	Test Weight (kg/hl)		Wheat Ash (%)		Flour Yield (%)		Flour Ash (%)		Flour Color (KJ units)	
	Control	−5°C	Control	−5°C	Control	−5°C	Control	−5°C	Control	−5°C
1–8	69.7	67.7[c]	2.02	2.00	71.1	65.3[c]	0.79	0.96[c]	4.1	11.8[c]
9–12	79.8	67.7[c]	1.74	1.92[c]	74.9	71.1[c]	0.60	0.82[c]	1.1	6.1[c]
13–16	81.7	78.0[c]	1.64	1.82[c]	76.2	72.8[c]	0.58	0.75[c]	1.2	5.1[c]
17–20	81.6	79.0[c]	1.60	1.84[c]	76.5	75.1[c]	0.56	0.62[c]	1.2	2.0[c]
21–24	80.4	79.8	1.63	1.86[c]	76.5	76.6	0.58	0.62[c]	0.9	1.4
25–28	79.3	79.4	1.71	1.84[c]	76.9	76.8	0.59	0.58	0.8	0.9

[a] All values are averages of replicate samples, each analyzed in duplicate in 1984.
[b] See Figure 1 for moisture range of composites.
[c] Significantly different from control at the 5% level. See text for significant differences between maturity stages for each treatment.

TABLE V
Physical Dough and Related Properties of Control and −5°C Treated Wheat Composites at Six Stages of Maturity[a]

Composite[b] (days)	Sodium Dodecyl Sulfate Sedimentation (cm)		Farinograph Absorption (%)		Farinograph Dough Development Time (min)		Farinograph Stability (min)	
	Control	−5°C	Control	−5°C	Control	−5°C	Control	−5°C
1–8	59	37[c]	69.3	76.8[c]	2.0	2.0	4.5	3.5
9–12	69	40[c]	67.5	74.3[c]	2.1	2.0	4.3	2.0[c]
13–16	72	47[c]	66.0	71.4[c]	4.0	2.6[c]	7.5	6.8
17–20	73	63[c]	65.6	67.0[c]	4.9	4.8	8.5	8.3
21–24	75	67[c]	65.1	65.2	4.6	4.5	7.8	8;0
25–28	70	71	64.6	64.2	4.3	4.1	7.0	7.0

[a] All values are averages of replicate samples, each analyzed in duplicate in 1984.
[b] See Figure 1 for moisture range of composites.
[c] Significantly different from control at the 5% level. See text for significant differences between maturity stages for each treatment.

TABLE VI
Remix Baking Properties of Control and −5°C Treated Wheat Composites at Six Stages of Maturity[a]

Composite[b] (days)	Loaf Volume (cc)		Baking Strength Index (%)		Appearance (units)		Crumb Color (units)		Crumb Structure (units)		Absorption (%)	
	Control	−5°C	Control	−5°C	Control	−5°C	Control	−5°C	Control	−5°C	Control	−5°C
1–8	825	250[c]	89.5	32.6[c]	6.5	1.0[c]	3.2	0.1[c]	6.8	0.1[c]	65	70[c]
9–12	800	470[c]	99.6	62.3[c]	7.8	4.5[c]	6.5	1.5[c]	6.5	4.2[c]	64	66
13–16	880	580[c]	101.6	69.2[c]	8.0	5.0[c]	7.5	3.5[c]	6.5	4.2[c]	66	66
17–20	900	885	97.4	93.8	8.2	8.0	7.5	6.5[c]	6.5	6.8	66	65
21–24	935	930	101.2	100.9	8.0	8.2	7.5	8.0	6.0	6.0	65	66
25–28	880	800	102.4	90.9[c]	8.2	7.5[c]	7.5	6.5[c]	6.8	6.8	65	63

[a] All values are averages of replicate samples, each analyzed in duplicate in 1984.
[b] See Figure 1 for moisture range of composites.
[c] Significantly different from control at the 5% level. See text for significant differences between maturity stages for each treatment.

procedure (Kilborn and Tipples 1981). The frosted composites showed much lower loaf volumes and baking strength index values (a measure of the loaf volume as a percentage of that normally expected for CWRS wheat at the same protein level). They also had much poorer loaf appearance, crumb color, and crumb structure scores than did the corresponding controls. Significant ($P < 0.05$) but much less pronounced differences were evident between treatments at the most mature stage. Reasons for this are not evident. Baking absorption, in contrast to farinograph absorption, was affected by frost only at the most immature stage. This difference in response can probably be attributed to the relative contribution of starch damage and protein to the two water absorption test methods. Previous studies have shown that farinograph absorption is much more sensitive than baking absorption to changes in starch damage (Tipples 1969).

After the most immature stage, the baking quality of the control composites did not show significant ($P < 0.05$) changes in any of the baking quality parameters except loaf volume. However, changes in loaf volume were probably due to changes in protein content, since the baking strength index showed minimal change. In contrast, baking quality of the frosted composites showed large significant increases during the first three maturity stages for all parameters except absorption. Remix absorption showed little change during maturation for both treatments.

The effect of frost and immaturity on a selected number of other quality tests are shown in Table VII. Frost and maturity did not have large effects on wheat falling number values. This can be attributed to the dry conditions that prevailed during these studies, which promoted the development of sound kernel characteristics. Flour starch damage was much higher ($P < 0.05$) for the $-5°C$ composites than for the corresponding controls during the first three maturity periods. Differences were not evident for the more mature stages. Maltose value, which is closely related to starch damage, showed the same trend.

During maturation, the control composites showed decreases in starch damage and maltose values. However, decreases in these parameters were much more pronounced in the frosted composites. These changes occurred during the first three maturity periods, with no significant change during the later periods.

DISCUSSION

As in previous studies (Whitcomb and Sharp 1926; Newton and McCalla 1934, 1935; McCalla and Newton 1935; Tipples 1980), changes in the quality characteristics of maturing wheat (in the absence of frost) were most evident during the early maturity stages. In general, quality improved as seed moisture decreased to a value of approximately 45%, after which further improvement was much less evident. This finding is in general agreement with the studies cited above. However, individual quality parameters showed differential response to maturity. In the 1984 study (Tables II–VII), kernel weight increased until seed moisture was reduced to approximately 45%, whereas test weight showed no improvement below 52% seed moisture. These values are higher than those previously reported by Tipples (1980) for HRS wheat. Maturation had significant effects on kernel hardness as measured by PSI, even at later stages of maturity. In contrast, flour starch damage, which showed very high values at early maturity stages, showed little change below 37% seed moisture. The lack of continuity in these results may be due to the inability of the PSI test to accurately measure hardness in immature wheat because of high bran and other nonendosperm material, compared with mature wheat. It was noted during our studies that the grinding and sieving efficiency of immature wheat was impaired by the presence of this tissue. The very high farinograph absorption values obtained at the early maturity stages are consistent with the high levels of starch damage (Farrand 1969).

Milling quality parameters (flour yield, ash, and color) showed improvement until seed moisture reached 45% but little change thereafter. This is in general agreement with previous studies by Hoseney et al (1966) and Tipples (1980). Changes in wheat ash seemed to parallel those of flour ash.

Physical dough strength (farinograph dough development time and stability) increased during maturation until seed moisture reached 45%. Increases in the SDS sedimentation value, which is used to predict wheat strength and baking quality (Blackman and Gill 1980), also increased during the same period.

Detrimental effects on baking quality, measured by the remix procedure (Kilborn and Tipples 1981), were evident only at the most immature stages. Crumb color showed the most prolonged response to maturation. In contrast to farinograph absorption, baking absorption showed little response to maturation in spite of large changes in starch damage. Tipples (1969) showed that baking absorption (especially with longer fermentation processes) was much less sensitive to starch damage and more dependent on protein content than farinograph absorption.

In general agreement with previous studies (Whitcomb and Sharp 1926; Newton and McCalla, 1934, 1935; McCalla and Newton, 1935), the effect of frost on quality test results was much more evident during the early maturity stages. In all cases where response was evident, frost had a negative effect on the quality parameter compared with the control. Our 1983 studies also suggest that a temperature below approximately $-3°C$ is required to bring out this response and that maximum response is attained over a narrow temperature range. This temperature and the steep response to temperature below approximately $-3°C$ are similar to results reported by Marcellos and Single (1984) for frost injury in immature wheat as measured by ear fertility. These workers found that temperatures below this threshold temperature resulted in ice nucleation in the seed and vegetative parts of the plant.

Frost caused a large significant decrease in wheat protein content at the two most immature stages (Table I) and no effect thereafter. A similar result was reported by Whitcomb and Sharp (1926). Kernel weight was also strongly affected by frost at the most immature stage. These responses to frost are probably related to physiological changes occurring in the seed during drying in the stook (after cutting). Frost could disrupt these processes and alter changes occurring in seed size and protein content. Marcellos and Single (1984) and Single (1985) showed that ice nucleation occurring at below $-4°C$ caused disruption of immature seed cell membranes and tracheary elements of the rachis and rachilla, where translocation of nutrients from vegetative tissue to the growing seed would occur. At later stages of maturity, frost did not produce these lethal effects (Single 1985).

Milling quality was adversely affected by frost at all but the most mature stage (Table IV). However, as shown in previous studies (Whitcomb and Sharp 1926, Newton and McCalla 1935), the most pronounced effect of frost occurred at the most immature stages (seed moisture >37%). This finding is consistent with the study of Malloch et al (1937), who found a close relationship between milling quality and the percentage of immature and heavily frosted kernels in commercial HRS wheat samples. The adverse effect of frost on milling quality has been mainly attributed to poor mill balance associated with very hard kernel character-

TABLE VII
Miscellaneous Quality Properties of Control and $-5°C$ Treated Wheat Composites at Six Stages of Maturity[a]

Composite[b] (days)	Wheat Falling Number (sec)		Starch Damage (Farrand units)		Maltose Value (g/100 g)	
	Control	$-5°C$	Control	$-5°C$	Control	$-5°C$
1–8	420	340	45	80[c]	2.9	4.7[c]
9–12	460	450	45	71[c]	2.6	4.0[c]
13–16	450	350	39	60[c]	2.4	3.8[c]
17–20	515	505	33	36	2.0	2.2
21–24	510	500	31	34	2.0	2.1
25–28	515	485	34	33	2.1	2.0

[a] All values are averages of replicate samples, each analyzed in duplicate in 1984.
[b] See Figure 1 for moisture range of composites.
[c] Significantly different from control at the 5% level. See text for significant differences between maturity stages for each treatment.

istics and to the heavy yield of shorts due to the difficulty in reducing middling stocks (Geddes et al 1932, Dexter et al 1985). The latter may be closely associated with the disruption of cell structure by ice nucleation induced by low temperature, as discussed above. Electron micrographs of heavily frosted HRS wheat kernels revealed marked structural differences from undamaged kernels, including less ordered aleurone and subaleurone cell structure and a more amorphous endosperm structure (Dexter et al 1985).

Whitcomb and Sharp (1926) and McCalla and Newton (1935) showed that the baking quality of immature wheat above 45% seed moisture content is adversely affected by frost. Geddes et al (1932) and Dexter et al (1985) reported similar effects for commercial wheat samples containing immature and frosted wheat kernels. In contrast, Malloch et al (1937) did not find a close correlation between baking quality and the presence of these degrading factors. Our results are generally consistent with the above studies, showing that baking quality parameters (including loaf volume, baking strength index, and crumb and crust characteristics) show a marked deterioration in frozen immature wheat above approximately 45% seed moisture content compared with controls of the same maturity (Table VI).

These differences may, in part, be related to the higher starch damage in flours obtained from the frosted wheat. High levels of starch damage have been shown to decrease loaf volume and cause a coarsening of the crumb structure (Tipples 1969). Lower baking quality (particularly crumb color) of the frosted immature samples, compared with the corresponding controls, may also be associated with the higher flour ash and color values of the former. The general similarity of dough strength properties and the ratio of wet gluten to protein of the $-5°C$ treated and control immature samples seems to suggest that protein quality does not play a major role in the differences in baking quality. However, recent studies by Dexter et al (1985) indicate the opposite. Reduction of starch damage in frost-damaged Canadian commercial wheat samples (by altering milling conditions) to levels comparable to those of undamaged samples resulted in flours still exhibiting very short mixing times and inferior baking quality, suggesting frost-related effects on protein properties. Recent studies in our laboratory (*unpublished data*) also indicate differences in the distribution of protein fractions from frosted and control samples of immature wheat flour.

ACKNOWLEDGMENTS

The technical assistance of E. Mydlo, L. Morris, L. Minty, C. Taplin, G. Kawamoto, I. Phillips, L. Dushnicky, R. Desjardins, J. Lachance, E. Lysenko, L. Oneschuk, C. Panting, and G. Paulley and the assistance of B. Soloman and staff of the Glenlea experimental farm of Agriculture Canada is gratefully acknowledged.

LITERATURE CITED

BLACKMAN, J. A., and GILL, A. A. 1980. A comparison of some small scale tests for bread-making quality used in wheat breeding. J. Agric. Sci. 95:29.

DEXTER, J. E., MARTIN, D. G., PRESTON, K. R., TIPPLES, K. H., and MacGREGOR. 1985. The effect of frost damage on the milling and baking quality of red spring wheat. Cereal Chem. 62:75.

FARRAND, E. A. 1969. Starch damage and alpha-amylase as bases for mathematical models relating to flour water absorption. Cereal Chem. 46:103.

GEDDES, W. F., MALLOCH, J. G., and LARMOUR, R. K. 1932. The milling and baking quality of frosted wheat of the 1928 crop. Can. J. Res. 6:119.

HOSENEY, R. C., FINNEY, K. F., and POMERANZ, Y. 1966. Changes in urea-dispersibility of proteins during maturation. J. Sci. Food Agric. 17:273.

KILBORN, R. H., and TIPPLES, K. H. 1981. Canadian test baking procedures. I. Grain Research Laboratory remix method and variations. Cereal Foods World 26:624.

MALLOCH, J. G., GEDDES, W. F., LARMOUR, R. K., and McCALLA, A. G. 1937. The quality and grading of frosted wheat. Annual surveys of the 1930 to 1935 western Canadian crops. Can. J. Res. Sect. C 15:567.

MANGELS, C. E., and STOA, T. E. 1928. Effect of stage of maturity on composition and baking quality of Marquis wheat. Cereal Chem. 5:385.

MARCELLOS, H., and SINGLE, W. V. 1984. Frost injury in wheat ears after ear emergence. Aust. J. Plant Physiol. 11:7

McCALLA, A. G., and NEWTON, R. 1935. Effect of frost on wheat at progressive stages of maturity. II. Composition and biochemical properties of grain and flour. Can. J. Res. Sect. C 13:1.

NEWTON, R., and McCALLA, A. G. 1934. Effect of frost on wheat at progressive stages of maturity. I. Physical characteristics of the kernels. Can J. Res. 10:414.

NEWTON, R., and McCALLA, A. G. 1935. Effect of frost on wheat at progressive stages of maturity. III. Milling and baking quality. Can. J. Res. Sect. C 13:263.

PRESTON, K. R., KILBORN, R. H., and DEXTER, J. E. 1987. Effects of starch damage and water absorption on the alveograph properties of Canadian hard red spring wheat. Can. Inst. Food Sci. Technol. J. 20:75.

PRESTON K. R., MORGAN, B. C., and TIPPLES, K. H. 1988. A review and analysis of export cargo quality data for Canada Western Red Spring wheat: 1973-1986. Can. Inst. Food Sci. Technol. J. 21:520.

SINGLE, W. V. 1985. Frost injury and the physiology of the wheat plant. J Aust. Inst. Agric. Sci. 51:128.

TIPPLES, K. H. 1969. The relation of starch damage to the baking performance of flour. Baker's Dig. 43(6):28.

TIPPLES, K. H. 1980. Effect of immaturity on the milling and baking quality of red spring wheat. Can. J. Plant Sci. 60:357.

WHITCOMB, W. O., and SHARP, P. F. 1926. Wheat and flour studies. VII. Milling and baking tests of frozen and nonfrozen wheat harvested at various stages of maturity. Cereal Chem. 3:301.

[Received April 6, 1990. Accepted August 21, 1990.]