

Genetic and Environmental Effects on Dough Mixing Characteristics and Agronomic Performance of Diverse Hard Red Winter Wheat Genotypes¹

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ABSTRACT

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Wheat (*Triticum aestivum* L.) genotypes with short mixing times usually have low mixing tolerance values, which make them more sensitive to overmixing in commercial bread production. In this study, we evaluated the genotypic and environmental effects on agronomic performance and end-use quality of 27 experimental genotypes (hereafter referred to as mixing tolerant genotypes) which were identified in an initial screen as having short mixing times and good mixing tolerances to 1) determine whether genotypes identified in a preliminary end-use quality screen as lines with usually long tolerances but short mixing times were due to their genotype (G), the environment (E), or G × E; and as these results were unusual, 2) determine whether or not our initial screen predicts end-use quality, and 3) determine the stability of both agronomic and end-use quality traits. The 27 genotypes and five check cultivars were grown in a randomized complete block design with two replicates in nine environments in 1997 and 1998. All plots were harvested for grain yield. The harvested grain from the first replicate and random genotypes from the second replicate were micromilled to

produce flour samples for evaluation of flour yield, protein content, and mixograph mixing time and mixing tolerance values. Seed diameter, thousand kernel weight, and kernel hardness were also measured in three environments. Environment, G, and G × E interaction effects (mainly changes in magnitude) were significant for most agronomic and end-use quality parameters. Our initial screen, which had identified 27 genotypes, was partially effective in identifying genotypes that have shorter mixing time values compared with their mixing tolerance values. We identified four genotypes (15%) from the mixing tolerant genotypes that had a good mixing tolerance value and relatively shorter mixing time, as did the released cultivars 'Agate' and 'Scout 66'. However, mixing characteristics values of all genotypes fell within the acceptable limits, indicating our screen effectively identified genotypes with acceptable quality. Mixing tolerant genotypes, which had been identified as having short mixing time scores and long mixing tolerance scores, were considered stable across environments.

Dough mixing properties are very important in breadmaking, and flours milled from different wheat (*Triticum aestivum* L.) cultivars can vary widely in the work and energy input required for optimum dough development. The fundamental reasons for these differences are not fully understood, however it is believed that protein content and interactions are involved in the differences between cultivars (Bushuk 1998). Bread doughs should be mixed to the point of optimum gluten development to produce good bread. More or less mixing causes improper dough development, which produces an inferior quality bread (Doerry 1995). An important factor affecting dough quality is the dough mixing time. Dough mixing time refers to the amount of time required to mix the ingredients to form dough, which determines the energy consumed by dough mixers. To reduce energy costs, bakers would like short mixing flours. However, flours with short mixing time often have low mixing tolerance values, which means they can be readily overmixed. Overmixing occurs when the ingredients are added or doughs are mixed beyond the optimal mixing time. Overmixing first results in dough breakdown and products made from overmixed doughs are inferior (Bushuk 1998), even when the best flour is used (Paredes-Lopez and Bushuk 1983). The practical advantage of a wheat cultivar that is milled to make a flour with a shorter dough mixing peak time (an indication of optimum dough development and stability) but with good mixing tolerance (an indicator of the resistance of a dough to overmixing) is that less labor, time, and energy are needed in the bakery to develop the optimum dough, and that the resultant dough is tolerant of overmixing, thus improving consistency of the final product.

In a preliminary screening of wheat germplasm within the Nebraska breeding program in 1996, a number of genotypes were identified that had shorter mixing times relative to mixing toler-

ance values. Mixing time is scored as time (min) to peak dough development. Mixing tolerance is scored on a 0–7 scale (Nebraska Wheat Quality Lab, Lincoln, NE), taking into account both curve width after peak development and the angle of departure (Baenziger et al 2001). While mixing time and mixing tolerance are measured in different units, the numerical values (not units) for mixing time in winter wheat tend to correlate with those of mixing tolerance, and it is very rare that the numerical value for mixing tolerance is greater than the numerical value for mixing time. Historically, winter wheat cultivars with good mixing tolerance values have very strong, long mixing time characteristics (Baenziger et al 2001). As this was a preliminary screen from one environment, the short mixing time characteristic coupled with the good mixing tolerance value could have been due to the environment (E) as well as the genotypes (G). Though impossible to measure in one environment, it is known that end-use quality characteristics are influenced by genotypic and environmental factors and their interactions (G × E) (Peterson et al 1992). For many quality characteristics, environmental variances were generally larger than those due to genetics (Graybosch et al 1996).

The objectives of this study were to 1) determine whether genotypes identified in a preliminary end-use quality screen as having mixing time values smaller than mixing tolerance values were due to G, E, or G × E; and as these results were unusual 2) determine whether or not our initial screen predicts end-use quality; and 3) determine the stability of both agronomic and end-use quality traits.

MATERIALS AND METHODS

Plant Materials

Thirty-two hard red winter wheat genotypes including 27 F3-derived F5 genotypes from diverse crosses that had mixing tolerance values greater than the mixing time values in preliminary testing of grain that were harvested in 1996 at Lincoln, NE, and five check cultivars ('Agate', 'Arapahoe', 'Centura', 'Scout 66', and 'Siouxland') were used in this study. The genotypes were grown at the following Nebraska locations: Lincoln (1997), Clay Center (1997), North Platte (1997 and 1998), Alliance (1997), Sidney (1997 and 1998), and Mead (1997 and 1998). These locations are

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representative of diverse Nebraska wheat production areas (Peterson 1992). The genotypes were planted in a randomized complete block design with two replicates using recommended cultural practices. Each genotype was planted in a four-row plot that was 2.4 m long with 30 cm between rows.

Agronomic Performance Measurements

Grain yield was measured by harvesting the middle two rows at Lincoln and Mead, and harvesting all four rows at Clay Center, North Platte, Alliance, and Sidney of both replicates. Grain volume weight was measured on a 200-mL sample with a volumetric scale (Seedburo Equipment Co., Chicago, IL) at Lincoln (1997), Clay Center (1997), North Platte (1997), Alliance (1997), Sidney (1997), and Mead (1997 and 1998) using first replicate, and a few random lines from the second replicate. Thousand-kernel weight and seed diameter were measured using the Single Kernel Characterization System (SKCS 4100, Perten Instruments, Springfield, IL). SKCS analysis was performed on three samples of 100 seeds each at North Platte (1998), Mead (1998), and Sidney (1998).

End-Use Quality Analysis

Grain samples (35 g) from each plot were tempered to a moisture basis of 15.2% and milled on a Brabender Quadraplex experimental mill (South Hackensack, NJ). Flour was separated from bran using a shaker (Strand, Minneapolis, MN) at 225 rpm for 90 sec with a U.S. Standard Sieve No. 70 and weighed to estimate flour yield. Flour mixing characteristics were evaluated using a 10-g mixograph (National Mfg. Co., Lincoln, NE) according to Approved Method 54-40 (AACC 2000) with absorption of 0.6 mL of H₂O/g of flour. Mixing time was measured as the minutes required to reach full-peak development. Mixing tolerance was rated subjectively on a 0–7 scale (Nebraska Wheat Quality Lab, Lincoln, NE), taking into account both curve width after peak dough development and angle of departure, ranging from very low (0) to very high tolerance (7) of the dough to mixing. Wheat lines with a mixing time of >3 min (preferably higher), and mixing tolerance scores of >3 (preferably higher) are considered as having acceptable end-use quality (Baenziger et al 2001).

Flour protein concentration was determined on a 14% flour moisture basis using the Udy dye-binding method (Approved Method 46-14A) and periodically verified with 14% flour moisture basis using a Leco N analysis (Approved Method 46-30) by the Soil Analytical Laboratory, Department of Agronomy and Horticulture, University of Nebraska, Lincoln. Kernel hardness was analyzed by SKCS 4100 on the same samples used to measure 1,000 kernel weight and seed diameter.

Statistical Analysis

Analyses of variance were calculated considering each location-year as a separate environment using PROC GLM (SAS Institute, Cary, NC). Homogeneity of variance test was conducted to determine whether error variances were homogenous across environments and, if so, data from individual environments (E) were pooled to evaluate G × E interactions from a combined ANOVA across environments. Environments were considered as random effects in the combined analysis, whereas genotypes were treated as a fixed effect. Data for each trait were analyzed for normality using PROC UNIVARIATE (SAS). For agronomic traits, all of the plot data were used. For the end-use quality traits, flour from every genotype from the first replicate was used, and flour of 15–20 randomly selected genotypes from the second replicate was used to estimate variation. Historically, the coefficient of variation for most microquality analyses from a random subsample of genotypes in the second replicate was representative of the variation from the complete replicate (Baenziger et al 2001). Single degree of freedom (df) contrasts were performed for check cultivars versus mixing tolerant genotypes. Flour protein content was used as a covariate to help explain mixing time and mixing tolerance because wheat flour protein content is correlated to mixing time and mixing tolerance (Graybosch et al 1996).

To evaluate our initial screen, we looked at genotypes identified with mixing time values smaller than mixing tolerance values to see whether these values were within the acceptable limits in other environments. Acceptability was established for genotypes by choosing absolute limits for each of the five quality traits to reflect the needs and perspective of the milling and baking industry. A genotype was considered acceptable for an individual trait if the value for that trait fell within these established bounds. Values chosen for upper and lower limits were flour protein 12.5–19.0%, mixing time 3.5–8.0 min, mixing tolerance 2.5–7.0 (on a 0–7 scale), flour yield 500–650 g/kg, kernel hardness 25–65 SKCS unit. A line's chance of falling within acceptable limits was calculated using univariate (Eskridge and Mumm 1992) and multivariate (Eskridge et al 1994) probabilities. Probabilities were calculated as a proportion of locations that met acceptability limits for each trait separately and all traits similarly. In practice, our selected genotypes are expected to have consistent mixing times of >3 min and mixing tolerance scores of >3.

Stability parameters (Eberhart and Russell 1966) were estimated by regressing genotype means on an environmental index. The environmental index was estimated as the mean of all genotypes at a specific environment minus the grand mean. The *b*-values were tested for the differences from *b* = 1.0 by a *t*-test. A line was considered stable if *b*₁ = 1.0. The deviations from the

TABLE I
Mean Square (MS) Values for Combined Analysis of Variance Across Nine Environments in the 1997-1998 Crop Seasons in Nebraska

Source ^b	Grain Yield (kg/ha)		Grain Vol. Wt. (kg/hL)		TKW ^a (g)		Seed Dia. ^a (mm)		Hardnes s ^a (unit)		Flour Yield (g/kg)		Flour Protein (%)		Mix. Time (min)		Mix. Tol. (0–7)	
	df	MS	df	MS	df	MS	MS	MS	df	MS	df	MS	MS	MS	MS	MS		
Environment (E)	8	45657943**c	6	971.88**	2	164.66**	0.21**	295.40**	8	93879.9**	8	87.58**	37.10**	6.18**				
Genotype (G)	31	436800	31	12.61**	31	18.36**	0.04**	239.10**	31	1472.3**	31	1.44*	2.65**	2.79**				
Check cultivars (C)	4	566415	4	4.99	4	40.45**	0.06**	42.03**	4	441.68	4	1.01	2.31**	1.18				
Mixing tolerant lines (L)	26	406696*	26	12.48**	26	15.33**	0.04**	318.45**	26	1736.94**	26	1.76**	3.73**	3.43**				
C vs. L	1	701077	26	1220.74**	1	85.49**	0.21**	0.03	1	4446.04**	1	4.59**	8.81**	1.75				
E × G	248	309614	168	3.16	58	4.91**	0.02**	21.04**	243	271.0	248	0.92**	0.75**	0.88**				
E × C	32	163863	15	3.56	8	3.14**	0.01*	12.65**	28	339.99	32	0.80*	0.55	0.81*				
E × L	208	287993	148	3.13	48	5.11**	0.02**	17.55**	208	253.96	208	0.91**	0.76**	0.85**				
E × (C vs. L)	8	1454768**	5	2.32	2	6.48**	0.04**	35.45**	7	502.01	8	2.00**	1.48**	1.79**				
Pooled error	279	256016	35	4.12	59	1.08	0.005	3.59	124	366.2	93	0.47	0.39	0.51				
CV %		17.88		2.74		3.37	3.05	3.86		3.42		5.46	14.96	18.84				
Genotype means		2845		75.1		30.6	2.3	49		558.0		12.6	4.2	3.8				

^a 1,000 kernel weight (TKW), seed diameter, and kernel hardness from SKCS 4100 analysis.

^b Block (E) was considered in the ANOVA model but not reported in this table.

^c *, ** Significant at *P* = 0.05 and *P* = 0.01, respectively.

regression were tested for significance by an *F*-test. Regression coefficients for genotypes were compared among the lines by a two-tailed *t*-test.

RESULTS AND DISCUSSION

Agronomic Performance Traits

Significant differences among all of the genotypes were observed for all traits except grain yield. The *G* × *E* interaction was also significant for most agronomic traits except grain yield and grain volume weight (Table I). From the partitioned analysis of variance, check cultivars differed for 1,000 kernel weight and seed diameter; however they did not differ for grain yield and grain volume weight. Mixing tolerant lines differed for all agronomic traits. Hence, genetic variation for agronomic traits existed among the mixing tolerant lines. The single degree of freedom contrasts of check cultivars versus mixing tolerant genotypes indicated the check cultivars and mixing tolerant genotypes were similar for grain yield, but check cultivars had lower grain volume weight and greater 1,000 kernel weight and seed diameter. The interactions of environment with check cultivars and environment with mixing tolerant lines were significant for 1,000 kernel weight and seed diameter but not for grain yield and grain volume weight. These results indicated that genetic differences among check cultivars and mixing tolerant lines were similar across environments for grain yield and grain volume weight. However,

their respective environmental responses were not similar for 1,000 kernel weight and seed diameter. The environment × (check cultivars vs. mixing tolerant lines) interaction was significant for grain yield, 1,000 kernel weight, and seed diameter but not for grain volume weight. The significant interactions were mainly due to changes in magnitude, not reversals in order; hence, we will discuss the genotypic means averaged over environments.

The mixing tolerant genotypes had similar grain yield (2,845 kg/ha) as check cultivars (2,749 kg/ha). Mean grain yields of mixing tolerant genotypes across environment ranged from 2,608 to 3,186 kg/ha whereas grain yields of check cultivars ranged from 2,455 to 2,928 kg/ha. NE96539 (3,010 kg/ha), NE96545 (3,010 kg/ha), NE96408 (3,032 kg/ha), NE96440 (3,003 kg/ha), NE96456 (3,068 kg/ha), and NE96587 (3,186 kg/ha) were the best-yielding genotypes among the mixing tolerant genotypes. NE96587 was superior to all check cultivars except Siouxland (Table II). Mean grain volume weights of mixing tolerant genotypes ranged from 72.0 to 78.2 kg/hL. However, mean grain volume weights of check cultivars were low compared with mixing tolerant lines and ranged from 65.3 to 68.2 kg/hL. NE96539 (78.2 kg/hL), NE96545 (77.2 kg/hL), and NE96587 (74.7 kg/hL) were superior to check cultivars for grain volume weight. Mean 1,000 kernel weight of mixing tolerant genotypes ranged from 27.1 to 32.4 g. Means of check cultivars ranged from 29.3 to 35.7 g. NE96545 (32.3 g) and NE96683 (32.9 g) were the highest in performance and superior to Siouxland, Centura, and Arapahoe for

TABLE II
Genotype Mean Values for Agronomic Performance and Quality Characteristics of 32 Hard Red Winter Wheats Grown Across Nine Environments in 1997 and 1998 Crop Seasons in Nebraska

Genotype	Grain Yield (kg/ha)	Grain Volume Wt (kg/hL)	1,000 Kernel Wt (g)	Seed Diameter (mm)	Kernel Hardness (SKCS unit)	Flour Yield (g/kg)	Flour Protein (%)	Mixing Time (min)	Mixing Tolerance (0–7 scale)
Check cultivars									
Agate	2776	68.2	35.7	2.5	46	571	12.8	3.5	3.8
Arapahoe	2837	67.0	29.3	2.3	51	572	12.8	4.2	3.6
Centura	2456	65.3	30.8	2.3	52	565	13.1	4.3	4.0
Scout 66	2751	67.9	35.5	2.5	46	582	13.2	3.2	3.7
Siouxland	2926	66.9	32.1	2.4	50	572	12.4	3.9	3.2
Mean values	2749	67.1	32.7	2.4	49	572	12.9	3.8	3.7
Mixing tolerant lines									
NE96401	2616	74.6	27.1	2.1	54	556	12.3	4.8	3.5
NE96406	2608	76.0	31.3	2.3	16	518	13.2	5.5	5.1
NE96408	3032	74.7	31.3	2.3	47	557	11.8	4.0	3.4
NE96411	2826	76.6	30.8	2.3	47	568	12.6	4.0	3.5
NE96412	2668	73.9	32.4	2.3	51	550	12.6	3.9	3.7
NE96440	3003	75.1	30.1	2.2	47	561	12.8	4.5	4.4
NE96446	2978	75.4	30.3	2.3	53	555	12.7	3.5	3.4
NE96456	3068	74.4	29.3	2.3	52	555	12.3	4.3	3.9
NE96457	2848	73.7	27.7	2.1	54	559	12.1	4.2	4.3
NE96459	2645	75.0	29.6	2.2	54	543	12.9	4.1	4.3
NE96469	2925	74.9	29.9	2.3	53	573	12.3	3.9	3.7
NE96500	2867	76.8	32.3	2.4	41	560	12.8	3.7	3.6
NE96507	2690	73.9	31.5	2.3	50	564	12.5	4.6	4.3
NE96539	3010	78.2	29.5	2.3	59	566	12.3	3.4	3.1
NE96540	2869	75.9	32.1	2.3	51	565	12.5	4.1	3.9
NE96542	2742	74.9	29.8	2.3	38	540	12.5	4.6	4.2
NE96545	3010	77.2	32.3	2.4	49	552	12.8	4.4	4.3
NE96564	2731	74.5	28.5	2.2	55	564	12.7	4.3	3.9
NE96572	2755	73.7	33.0	2.4	47	570	12.5	4.5	3.7
NE96583	2882	75.9	32.4	2.4	49	558	13.2	4.5	5.3
NE96587	3186	74.7	28.2	2.2	51	563	12.0	5.0	3.8
NE96588	2952	73.4	28.6	2.2	51	572	11.8	5.6	3.3
NE96610	2769	74.6	31.7	2.3	55	553	12.4	3.7	3.2
NE96626	2771	74.4	31.9	2.4	58	552	12.2	4.2	3.3
NE96653	2715	75.6	28.5	2.2	48	566	12.3	3.9	3.6
NE96667	2782	75.6	33.2	2.4	43	568	13.0	3.6	3.5
NE96683	2872	72.0	32.9	2.4	53	548	13.0	3.5	3.6
Mean values	2845	75.1	30.6	2.3	49	558	12.6	4.2	3.8
LSD (0.05) ^a	332.0	2.1	1.4	0.1	2.5	15.0	0.6	0.50	0.6

^a Least significant differences (*P* = 0.05).

1,000 kernel weight. The mixing tolerant genotypes had seed diameters (2.3 mm) similar to that of the check cultivars (2.4 mm). Seed diameters of Agate and Scout 66 (2.5 mm) had the highest value compared with other genotypes tested in this study. However, NE96583, NE96683, NE96667, NE96626, NE96572, NE96545, and NE96500 seed diameters (2.4 mm) were superior to those of Arapahoe and Centura and equal to Siouxland. These results indicate that the potential exists for improving grain yield and other agronomic traits of mixing tolerant genotypes. These genotypes can also be used as parents in breeding programs for deriving genotypes with higher performance compared with check cultivars.

End-Use Quality Traits

The effects of environments and genotypes were significant for all end-use quality traits. The G × E interaction was also significant for most traits except flour yield (Table I). From the partitions of the genotypes, nonsignificant differences were found among check cultivars for each trait except mixing time and kernel hardness. End-use quality uniformity is considered very desirable by flour millers who source wheat grain from different cultivar distribution. Mixing tolerant genotypes showed highly significant variation for all end-use quality traits. The single degree of freedom contrasts of check cultivars versus mixing tolerant genotypes indicated the check cultivars and mixing tolerant genotypes were similar for hardness and mixing tolerance but significantly different for the other end-use quality traits. The check cultivars had significantly higher flour protein concentrations and flour yield, but shorter mixing times than the mixing tolerant cultivars.

The environment is a critical variable in the expression of the quality traits (Peterson et al 1992; Fenn et al 1994; Graybosch et

al 1996). In our study, the interaction of the check cultivars with environment was significant for kernel hardness, flour protein content, and mixing tolerance but was not significant for flour yield, and mixing time. Differences in environmental response of these genotypes to mixing tolerance, flour protein content, and kernel hardness were due mainly to changes in magnitude and small reversals in order. These results indicated that genetic differences among check cultivars were relatively similar across environments for flour yield and mixing time. However, response to the environment was different for kernel hardness, flour protein content, and mixing tolerance. The results for flour protein content in this study agree with results reported earlier by Moreno-Sevilla et al (1995). However, they found similar response to environment for mixing time and mixing tolerance, which may be due to population structure (IBL/IRS genotypes). Our results also confirm results of Peterson et al (1992), who reported that environments had remarkable effects on variation in kernel hardness, flour protein, and mixing characteristics.

The G × E interaction of mixing tolerant lines was significant for all traits except flour yield, indicating that they responded similarly to environment for flour yield but were different for the other end-use quality traits. The E × C vs. L interaction was also significant for all end-use quality traits except for flour yield. Hence, the check cultivars and mean of mixing tolerant lines responded similarly to the environment for flour yield characteristics. The G × E interaction was due to changes in magnitude not reversals in order.

Flour protein concentrations of NE96406 (13.2%) and NE96583 (13.3%), genotypes that had shorter mixing time scores and mixing tolerance values, were higher than all check cultivars except Scout 66 (13.2%) which is one of the best performing genotypes for both flour protein and flour yield. Mixing time and

TABLE III
Univariate Probabilities for Quality Characteristics Values Falling Within Acceptable Limits^a

Genotype	Flour Protein	Mixing Time	Mixing Tolerance	Flour Yield	Kernel Hardness	All Traits ^b
Agate	0.67	0.44	0.89	0.89	0.33	0.11
Arapahoe	0.56	0.56	1.00	0.89	0.33	0.00
Centura	0.67	0.78	1.00	0.78	0.33	0.11
Scout66	0.78	0.33	1.00	0.89	0.33	0.11
Siouxland	0.67	0.67	0.67	0.89	0.33	0.11
NE96401	0.44	0.56	1.00	0.89	0.33	0.00
NE96406	0.67	1.00	1.00	0.67	0.00	0.00
NE96408	0.11	0.44	1.00	0.89	0.33	0.00
NE96411	0.56	0.67	0.89	1.00	0.33	0.11
NE96412	0.44	0.78	1.00	0.89	0.33	0.00
NE96440	0.67	0.78	0.89	1.00	0.33	0.11
NE96446	0.56	0.44	1.00	0.78	0.33	0.00
NE96456	0.56	0.78	1.00	0.78	0.33	0.00
NE96457	0.33	0.89	1.00	0.78	0.33	0.11
NE96459	0.78	0.67	1.00	0.67	0.33	0.00
NE96469	0.44	0.67	1.00	0.89	0.33	0.00
NE96500	0.56	0.56	0.89	0.89	0.33	0.11
NE96507	0.56	0.78	1.00	1.00	0.33	0.11
NE96539	0.33	0.44	0.78	1.00	0.33	0.00
NE96540	0.44	0.56	1.00	1.00	0.33	0.11
NE96542	0.56	1.00	1.00	0.78	0.33	0.11
NE96545	0.67	0.78	1.00	0.78	0.33	0.11
NE96564	0.67	0.67	1.00	1.00	0.33	0.11
NE96572	0.44	0.67	1.00	1.00	0.33	0.11
NE96583	0.67	0.78	1.00	1.00	0.33	0.11
NE96587	0.22	1.00	1.00	0.78	0.33	0.00
NE96588	0.22	0.89	1.00	1.00	0.33	0.00
NE96610	0.33	0.56	0.78	0.78	0.33	0.00
NE96626	0.44	0.67	0.89	0.78	0.22	0.00
NE96653	0.56	0.67	0.89	0.89	0.22	0.00
NE96667	0.67	0.44	0.89	1.00	0.22	0.11
NE96683	0.56	0.33	0.89	0.78	0.22	0.00

^a Values chosen for upper and lower limits were flour protein 12.5–19.0%, mixing time 3.5–8.0 min, mixing tolerance 2.5–7.0 (on a 0–7 scale), flour yield 500–650 g/kg, kernel hardness 25–65 SKCS units.

^b Multivariate probabilities of all traits for 32 genotypes grown in nine environments.

mixing tolerance values of Agate were 3.5 and 3.8 min, respectively. Mixing time values of NE96457 (4.2 min), NE96459 (4.1 min), NE96583 (4.5 min), and NE96683 (3.5 min) genotypes were shorter than mixing tolerance values (4.3, 4.3, 5.3, and 3.6, respectively) across all environments. However, mixing time values of the remaining genotypes in this study were higher than mixing tolerance values (Table II), as was commonly found in previous research (Baenziger et al 2001). Hence, our preliminary screen, which identified 27 genotypes with mixing tolerance values that were larger than the mixing time values, was only partially effective (4/27 = 15% were correctly identified, 85% were incorrectly identified) in identifying genotypes with these characteristics. Evidently, the environment affects these traits and the relative magnitudes.

An important question is whether flour protein content could explain the mixing characteristics. To answer this question, flour protein content was treated as a covariate of mixing time and mixing tolerance in analyses of covariance. The effect of the flour protein content covariate was significant ($P < 0.05$) for mixing time; however, it was nonsignificant for mixing tolerance. These results indicated that mixing time was affected by flour protein content, whereas, mixing tolerance was not.

Univariate and multivariate approaches were conducted to determine the value of our initial screen using sample proportion of environment where values of a cultivar trait fell within a specified limits (Eskridge and Mumm 1992; Eskridge et al 1994). Univariate probability values were 0.11–1.0 and reflected the probability of traits falling within the established absolute acceptability limits (Table III). NE 96457 and NE96459, which had shorter mixing time than mixing tolerance, showed the highest probability of meeting absolute acceptability standards for mixing tolerance. NE96583, which is also identified as having shorter mixing time values, had higher probability for mixing time and mixing tolerance ($P = 0.78$ and $P = 1.0$, respectively). These values indicated that the probability of identifying acceptable end-use quality in an initial screen when grown at a single location is similar to results from multiple environments for dough mixing characteristics. Univariate probabilities for mixing tolerant lines, which were originally selected on the basis of shorter mixing time values, also had a probability of equaling or exceeding mixing time of the check cultivars. These values reflected the high probability of achieving acceptable quality for individual traits and all traits when the lines are grown in a single environment that is representative of future testing environments (Eskridge et al 1994). Overall, we identified 12 mixing tolerant lines (NE96411, NE96440, NE96457, NE96500, NE96507, NE96540, NE96542, NE96545, NE96564, NE96572, NE96583, and NE96667), which had multivariate probabilities of equaling or exceeding the check cultivars for all end-use quality traits. In addition, every mixing tolerant line had mixing time and tolerance values >3 and would be considered as acceptable. Hence, our preliminary screen successfully selected the genotypes with acceptable mixing time and tolerance values.

Stability of Traits and Environmental Interactions

Partitioning $G \times E$ interactions (linear) into mixing tolerant lines (linear), and check cultivars (linear) showed nonsignificant differences in slope for all traits except among the mixing tolerant lines (linear) for grain volume weight (Table IV). Hence, genotypes within the mixing tolerant group and within the check cultivars performed similarly from low to high environmental indices for grain yield, flour yield, flour protein, mixing time, and mixing tolerance. However, the check cultivars Scout 66 and Siouland performed dissimilarly from one another under different environmental conditions for dough mixing characteristics (mixing time and mixing tolerance) and grain volume weight. Scout 66 and Siouland (both had shorter mixing time values vs. mixing tolerant values) were more responsive to environments versus other check cultivars for mixing characteristics. This suggested that genotypes with shorter mixing times were generally less stable across environments. These results are contrary to findings of Peterson et al (1992), who reported that genotypes with higher mixing time and increased mixing tolerance, such as Karl and Redland, were generally more responsive to environments.

There were few significant deviations from regression, indicating that agronomic and end-use quality traits generally illustrated a linear trend across environments. Nonsignificant deviations from regression also indicated most genotypes were stable for all traits tested. Regressing genotype means on an environmental index indicated that check cultivars were not environmentally sensitive, except Scout 66, which was highly sensitive to environments for mixing time. The mixing tolerant genotypes differed significantly in their linear regression coefficients for grain volume weight. As was expected, some mixing tolerant genotypes showed more sensitivity to different environmental conditions compared with check cultivars, as indicated by differences in slope between the two sets of genotypes for grain volume weight and mixing time (Table IV). NE96683, NE96586, NE96459, and NE96457, which had been identified with mixing time scores shorter than mixing tolerance scores, had nonsignificant regression coefficients and would be considered stable for all traits tested. Crossover interactions for the effects of genotypes for all traits tested were not significant, again indicating the significant $G \times E$ was due to changes in magnitude, rather than reversals in order.

CONCLUSIONS

In conclusion, we found that previously released Agate (3.5 min and 3.8) and Scout 66 (3.2 min and 3.6) and four mixing tolerant lines, NE96457, NE96459, NE96583, and NE96683 had mixing tolerance values that were slightly greater than their mixing time values. Our preliminary screen, which had identified 27 genotypes, was only slightly effective in identifying genotypes (15%) that have shorter mixing time values compared with mixing tolerance values. Our initial screen predicted acceptable end-use quality traits very well, but the environment caused significant variation

TABLE IV
Linear and Nonlinear Portioning of Genotype \times Environment Interactions^a

Source	df	Grain Yield	Grain Volume Wt	Flour Yield	Flour Protein	Mixing Time	Mixing Tolerance
Genotypes (G)	31	223851	27.7**b	1325.0**	1.2*	2.2**	2.3**
Environment (E) (linear)	1	184231336**b	1318.9**	484181**	609.9**	182.1**	26.2**
$G \times E$ (linear)	31	89926	101.2**	142.1	0.8	0.6	0.8
Check cultivars (C) \times E	4	65039	4.2	174.6	0.5	0.6	0.8
Mixing tolerant lines (L) \times E	26	84786	25.9**	138.6	0.8	0.5	0.7
(C vs. L) \times E (linear)	1	323114	514.0**	174.4	0.2	3.2*	1.8
Pooled deviations	224	161033	13.3 ^c	217.7	0.8	0.6	0.8

^a Mean square values for grain yield, grain volume weight, flour yield, flour protein, mixing time, and mixing tolerance across nine environments in the 1997-98 crop seasons in Nebraska.

^b *, ** Significant at $P = 0.05$ and $P = 0.01$, respectively.

^c Degrees of freedom for grain volume weight (pooled deviations) is 209.

for both mixing time and mixing tolerance. Hence, to accurately estimate end-use quality traits of a genotype, multiple-environments testing is needed. This is routinely done with multiyear testing (Baenziger et al 2001). Environmentally sensitive genotypes determined by partitioning the $G \times E$ interaction were detected for grain volume weight and mixing time and was caused by changes in magnitude and not reversals in order. Because there was significant variation among the genotypes in response of quality traits to environments, we evaluated consistency of performance regarding upper limits of industry acceptability. Univariate and multivariate approach showed that end-use quality values of mixing tolerant lines fell within acceptable end-use quality limits. Stability of agronomic and end-use quality characteristics across environments is important to breeders and the milling and baking industry to enhance product consistency. With the probability approach, NE96583 and NE96457, which had mixing tolerance scores higher than mixing time scores showed a high probability of maintaining acceptable quality standards across environments and a high level of consistency when measured in relation to industry quality needs.

LITERATURE CITED

American Association of Cereal Chemists. 2000. Approved Methods of the AACC, 10th ed. The Association: St. Paul, MN.
 Baenziger, P. S., Shelton, D. R., Shipman, M. J., and Graybosch, R. A.

2001. Breeding for end-use quality: Reflections on the Nebraska experience. *Euphytica* 119:95-100.
 Bushuk, W. 1998. Interactions: The keys to cereal quality. *Am. Assoc. Cereal Chem.*: St. Paul, MN.
 Doerry, W. 1995. *Baking Technology*. Vol. 1. Am Inst. Baking: Manhattan, KS.
 Eberhart, S. A., and Russell, W. A. 1966. Stability parameters for comparing varieties. *Crop Sci.* 6:36-40.
 Eskridge, K. M., and Mumm, R. F. 1992. Choosing plant cultivars based on the probability of outperforming a check. *Theor. Appl. Genet.* 84:494-500.
 Eskridge, K. M., Peterson, C. J., and Grombacher, A. W. 1994. Probability of the wheat quality traits falling within acceptable limits. *Crop Sci.* 34:866-869.
 Graybosch, R. A., Peterson, C. J., Shelton, D. R., and Baenziger, P. S. 1996. Genotypic and environmental modification of wheat flour protein composition in relation to end-use quality. *Crop Sci.* 36:296-300.
 Paredes-Lopez, O., and Bushuk, W. 1983. Development and undevelopment of wheat dough by mixing: Physicochemical studies. *Cereal Chem.* 60:19-23.
 Peterson, C. J. 1992. Similarities among test sites based cultivar performance in the hard red winter wheat region. *Crop Sci.* 32:907-912.
 Peterson, C. J., Graybosch, R. A., Baenziger, P. S., and Grombacher A. W. 1992. Genotype and environment effects on quality characteristics of hard red winter wheat. *Crop Sci.* 32:98-103.

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