

Swelling Index of Glutenin Test. II. Application in Prediction of Dough Properties and End-Use Quality¹

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ABSTRACT

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Small-scale tests, including SDS and Zeleny sedimentation, gel protein, insoluble glutenin content, and a newly developed method, the swelling index of glutenin (SIG), were compared with dough and gluten rheological parameters and end-use quality parameters for 20 wheat cultivars or breeders lines. The SIG test is equal to or slightly better than the other small-scale tests in prediction of dough strength. Quality parameters were divided into two groups according to associations with insoluble glutenin content and glutenin quality. The glutenin quality is defined as the glutenin swelling properties with short swelling time (≤ 5 min) that are contributed by soluble and insoluble glutenin content and their swelling properties. Parameters in the first group were mainly dependent on insoluble glutenin content and appeared to reflect gluten strength.

The impact of protein content and protein quality on bread-making quality of wheat flours was shown by Finney and Barmore (1948) and was well documented by MacRitchie (1992). Most evidence suggests physical dough properties, especially those associated with dough strength, and baking properties, are determined mainly by qualitative and quantitative properties of glutenins. The relationships between glutenin content and dough properties and baking quality have been established by reconstitution studies, solvent fractionation studies, and molecular weight distribution obtained by gel filtration and size-exclusion HPLC (Weegels et al 1996). Protein quality, therefore, was defined by insoluble glutenin content (Orth and Bushuk 1972). Glutenin quality is more complex than protein quality, and it is a vague concept that is easier to realize than to define. The definition of glutenin quality in the 1980s was enhanced by obtaining the high molecular weight glutenin subunit composition (Payne et al 1987). Cereal chemists now believe that the amount and composition of high and low molecular weight glutenin subunits determine glutenin quality. In addition, the molecular weight distribution of glutenin, another important concept for glutenin quality, is certain to be a key factor in the variations of dough strength (Huebner and Wall 1976; Ewart 1987; Huang and Khan 1997; Southan and MacRitchie 1999). However, techniques for determining glutenin molecular weight distribution are not readily available, and the concept of glutenin quality is mainly based on the content of insoluble glutenin or the ratio of peak area for higher molecular weight glutenin to the peak area for lower molecular weight glutenin from chromatographic methods (Southan and MacRitchie 1999). The glutenin swelling curves, based on the swelling index of glutenin test (SIG) with different swelling times, reflect the glutenin swelling properties (Wang and Kovacs 2002). At a short swelling time, the soluble glutenin is in a state between swelling and dissolving, while insoluble glutenin is in a state between semiswelling and completely swelling. Therefore, similar to SDS and Zeleny sedimentation volumes and gel protein content, the SIG value, determined with short swelling time, is contributed by soluble and insoluble glutenin content and swelling properties, and is a parameter

reflecting glutenin quality. As the swelling time increased, soluble glutenin is dissolved in the solvent and SIG value is based mainly on the insoluble glutenin content (Wang and Kovacs 2002). Parameters in the second group were dependent not only on glutenin content, but also on glutenin quality. Small-scale tests are best to predict quality parameters within the same group, but not those in the other group. The glutenin swelling curve, obtained with different swelling times, was correlated with mixograph or farinograph data. Dough development time in farinograph and mixing time in mixograph were strongly related to the swelling time of peak SIG value in the swelling curve ($r = 0.92$, $r = 0.86$, respectively, $P < 0.001$). Farinograph stability was significantly related to the time of swollen stage in swelling curves ($r = 0.62$, $P < 0.01$). Similar to mixograph or farinograph data, the glutenin swelling curves can be used to differentiate some strong cultivars that can not be differentiated by sedimentation, gel protein, and insoluble glutenin values.

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The development of fast prediction methods for end-use quality continues to be a major focus of wheat breeding programs. Ideally, as discussed above, screening test methods should differentiate protein quality of wheat cultivars for end-use and should also lend themselves to rapid routine tests. Several small-scale tests for measuring glutenin content quantitatively and semiquantitatively have been developed as predictors of wheat quality in breeding programs (Weegels et al 1996). Zeleny and SDS sedimentation tests are fast and simple and are still widely used to estimate glutenin to predict baking quality (Weegels et al 1996). Based on a mechanism similar to sedimentation tests, the gel protein content is strongly related to the SDS sedimentation volume (SDSV) and loaf volume (Moonen et al 1982). Usually, the small-scale tests correlate well with dough properties and breadmaking quality (Weegels et al 1996), but they do not always differentiate effectively between wheats of different quality, especially between some extra strong or some weak cultivars (Pritchard 1993; Khartker et al 1996; Wang and Kovacs 2002).

Previously, we reported that the SIG test, determined with different swelling time, had strong correlations with sedimentation volumes, gel protein content, and insoluble glutenin content (Wang and Kovacs 2002). The present work further compares the new test with other small-scale tests for prediction of dough properties and end-use quality.

MATERIALS AND METHODS

Wheat Samples

A set of 20 cultivars or breeding lines with a wide range of quality was used in this study (Wang and Kovacs 2002). Table I gives means, standard deviations, coefficients of variation, and ranges of quality tests for the samples.

Small-Scale Tests

Flour protein ($N \times 5.7$) was determined by Approved Method 46-13 (AACC 2000). The SDS sedimentation test was conducted according to Kovacs (1985). The Zeleny sedimentation test was conducted as specified by AACC Approved Method 56-60. The insoluble glutenin content, the gel protein content, and the swelling index of glutenin in SDS and lactic acid (SDSLA) were determined according to Wang and Kovacs (2002). Flour samples (30–40 mg) were hydrated with 0.6 mL of deionized water in a 1.5-mL centrifuge tube for 20 min and then were swollen for different times after

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adding 0.6 mL of 3.0% SDSLA (identical to the solvent used in SDS sedimentation test in AACC Approved Method 56-70). The tubes and the residues were centrifuged at $300 \times g$ for 5 min. The residue was weighed after removing the supernatant. The SIG value is calculated as the weight of the residue divided by the original sample weight. The standard SIG test is 20 min of swelling time and is represented as SIG in the text. The SIG with short swelling time indicates the swelling time ≤ 5 min and the SIG with long swelling time represents the swelling time >20 min.

Quality Tests

Dough rheological properties were measured using mixograph, farinograph, and alveograph techniques. Mixing time (MDT) and total energy (TEG) in mixogram were obtained according to Pon et al (1989) using a computerized 10-g mixograph. Farinograph dough arrival time (ART), dough development time (DDT), stability (STA), and mixing tolerance index (MTI) were determined according to AACC Approved Method 54-21. Extensigraph maximum resistance (R_{max}) and extensibility (EXT) were obtained by AACC Approved Method 54-10. Alveograph P , G , and W indices were obtained using AACC Approved Method 54-30A. Wet gluten content and gluten index (GI) were determined by AACC Approved Method 38-12. Cooked gluten viscoelasticity (CGVS) was obtained using the procedure of Kovacs et al (1994). The breadmaking procedure was the optimized straight-dough with long fermentation (180 min) baking test of Approved Method 10-10B.

Fresh noodles and dry noodles (Chinese style white noodles) were made according to the procedures described by Kovacs et al (1997a). For fresh noodle preparation (3 mm \times 1 mm), 10 g of flour was mixed with 3.2 mL of deionized water containing 0.2 g of sodium chloride for 10 min using a 10-g mixograph. The crumbly dough was sheeted seven times using a bench-top noodle machine (K&S Tool and Die, Winnipeg, MB, Canada). After the first pass

(roll gap = 4 mm) the dough was folded once and passed through the same gap. The dough was rested for 20 min and then reduced six times to a thickness of 1 mm. The dough sheet length (DSL) was measured. Dry noodles (3 \times 0.7 mm cross-section) were made using flour (1 kg), and deionized water containing 20 g of sodium chloride to give 32% water absorption. This was mixed for 20 min at 100 rpm using a Hobart mixer. The crumbly dough was sheeted seven times using pilot-type sheeting rolls (Othake, Japan). With similar reduction used in the fresh noodle preparation, the noodles were dried at low temperature (25–35–25°C) in a humidity controlled (50–90–50% rh) drier. Fresh noodle was cooked with constant time (5 min) and dry noodle was cooked with optimum cooking time (inner white core disappeared). Firmness of the cooked fresh and dry noodles were determined by measuring the cutting force (Kovacs et al 1997a). The viscoelasticity of cooked dry and fresh noodles was determined according to Kovacs et al (1994) with load weights of 1.0 kg.

Statistical Analysis

All measurements are means of two determinations. Correlations between small-scale tests and quality parameters of dough and end-products were calculated by using the data analysis tools of Microsoft Excel 97.

RESULTS AND DISCUSSION

Associations Between Small-Scale Tests and Dough Strength

The correlation coefficients of small-scale tests with dough strength parameters are given in Table II. Dough strength parameters MDT, DDT, STA, MTI, R_{max} , and W were significantly related to Zeleny and SDS sedimentation volumes (Zeleny and SDSV, respectively) and weight of gel protein consistent with previous reports (Axford 1979; Preston et al 1982; Campbell et al 1987). As expected, SIG

TABLE I
Means, Standard Deviation (SD), Coefficients of Variation (CV), and Ranges for Flour Quality of 20 Wheat Samples

Attribute	Mean	SD	CV	Range
Protein, %	11.63	1.14	9.81	10.17–14.27
Small-scale tests				
Swelling index of glutenin (SIG)	5	0.87	17.46	3.00–6.81
SDS sedimentation (SDSV), mL	69	11.1	16.12	43–86
Zeleny volume, mL	47	5.51	11.85	33.8–53.6
Gel protein	2.91	0.44	14.91	1.93–3.70
Insoluble glutenin protein (IG/P), %	25.5	3.1	12.16	17.31–31.52
Insoluble glutenin flour (IG/F), %	2.98	0.54	18.26	1.76–4.00
Farinograph				
Arrival time (ART), min	2.72	0.612	22.46	1.20–3.67
Dough developing time (DDT), min	5.94	2.63	44.28	2.07–15.60
Stability, min	12.75	4.36	34.17	3.20–17.70
Mixing tolerance index (MTI), BU	44	28.14	64.02	0–142
Mixograph				
Mixing time (MT), min	2.31	0.96	41.66	0.80–5.6
Total energy (TEG)	45.71	7.7	16.85	31.30–68.90
Extensigraph				
Maximum resistance (R_{max}), BU	327	122.73	37.53	100–610
Extensibility (Ext), cm	19.05	2.13	11.19	14–22
Alveograph Index				
P , mm	67.55	15.33	22.69	3.38–103.40
G , mL	26.185	2.55	9.73	21.6–30.2
W , 10^{-4} J	254	77.51	30.51	83.56–428.6
Gluten quality				
Cooked gluten viscoelasticity (CGVS), %	35.79	8.53	23.85	16–53.9
Gluten index (GI), %	76.75	12.91	16.82	50–99
Baking				
Loaf volume (LV), mL	849	76.9	9.06	700–1,005
Noodle quality				
Dry noodle cooking time (DNCT), min	11.1	1.03	9.28	8.5–12.5
Dry noodle cutting force (DCF)	0.92	0.073	7.91	0.82–1.12
Dry noodle viscoelasticity (DNV), %	21.3	8.99	42.22	2.52–33.92
Fresh noodle cutting force (FCF)	3.97	0.49	12.23	2.89–5.07
Fresh noodle viscoelasticity (FNV), %	31.5	5.5	17.45	20.36–39.66
Dough sheet length (DSL), mm	223.7	20.03	8.95	179–283

exhibited correlations to these dough strength parameters that were equal to or slightly stronger than for SDSV and gel protein content because the SIG test with the standard procedure is strongly related to insoluble glutenin content (Wang and Kovacs 2002). It is widely accepted that dough strength is mainly determined by the amount of unextractable protein (mainly insoluble glutenin) that is largely independent of different solvents (propanol, acetic acid, or SDS) and extraction procedures (Orth and Bushuk 1972; Dachkevitch and Autran 1989; Bean et al 1998).

Generally, the insoluble glutenin content is expressed by two compositional variables: relative glutenin content (insoluble glutenin in the total protein [%IG/P]) and absolute glutenin content (insoluble glutenin in the flour [%IG/F]). From the correlation coefficients between the dough strength parameters and these two variables (Table II), it is evident that the IG/P correlated equally or better than other tests to all dough quality parameters except ART and TEG. This does not agree with the results from Gupta et al (1992), who reported that the relative polymeric protein content correlated best with MDT and the absolute polymeric protein content best with DDT. This different result may be due to the different techniques used in the determination of polymeric protein or different sets of samples.

Alveograph *P* value is also used as an index of dough elasticity. This study showed that alveograph *P* was significantly related ($P < 0.05$) to gel protein and SIG, but not ($P > 0.05$) to the sedimentation tests (Table II). The dough sheet length (DSL) was inversely related to SIG and IG/F (Table II). Strong dough contracts significantly after sheeting. Therefore, the DSL could be useful for the evaluation of dough elasticity.

Correlation coefficients of SIG values determined with different swelling times with TEG, MDT, MTI, DDT, STA, R_{max} , *P*, *W*

value, and DSL increased as swelling time increased (Table III). This suggests that dough strength is governed primarily by insoluble glutenin content because as swelling time increased the soluble glutenin dissolves, and only insoluble glutenin contributes to the swelling capacity of glutenin (Wang and Kovacs 2002). This supports the assumption of Southan and MacRitchie (1999) who suggested that not all of the glutenin (only a fraction above a certain molecular size) contributes to dough strength (the critical molecular size for effective entanglements). It is believed that insoluble glutenin contains distinctly higher proportion of large-sized polymers than in the soluble glutenin fraction (Gupta et al 1993; Bean and Lookhart 2001). The present results showed that the amount of larger molecular weight glutenin (the remaining swelling state after a long swelling time to remove low molecular weight glutenin) determines dough strength and tolerance to dough mixing.

The farinograph arrival time (ART) is significantly correlated with the small scale tests, while gel protein content and IG/P had the highest and lowest coefficients, respectively (Table II). Correlation coefficients between ART and SIG were smaller when SIG was determined at longer swelling times (Table III). The highest coefficient occurred at 2 min of swelling time, which was similar to the correlation coefficient of gel protein with ART (Table II). This indicated that ART is influenced by glutenin content and quality.

Associations Between Small-Scale Tests and Dough Extensibility

Alveograph *G* index and extensigraph extensibility (EXT) are used to evaluate the extensibility of dough. EXT and *G* had no significant correlation with SIG and insoluble glutenin content (Table II). Interestingly, *G* index was significantly related to sedimentation and gel protein tests, whereas Zeleny had the highest correlation coefficient

TABLE II
Correlation Coefficients Between Small-Scale Tests and Dough Quality Parameters for 20 Wheat Flour Samples^{a,b}

	Mixograph		Farinograph				Extensigraph		Alveograph			
	MDT	TEG	ART	DDT	STA	MTI	R_{max}	EXT	<i>P</i>	<i>G</i>	<i>W</i>	DSL
Protein	0.23	0.56**	0.61**	0.38	0.23	-0.56**	0.43	0.41	0.3	0.36	0.58**	-0.64**
SIG	0.62**	0.75**	0.66**	0.73***	0.73***	-0.83***	0.87***	0.22	0.57**	0.43	0.93***	-0.87***
SDSV	0.49*	0.61**	0.63**	0.63**	0.75***	-0.68***	0.75***	0.48*	0.34	0.61**	0.74***	-0.59**
Zeleny	0.45*	0.45*	0.69***	0.50*	0.74***	-0.71***	0.70***	0.34	0.21	0.72***	0.67**	-0.60**
Gel	0.45*	0.72***	0.71***	0.61**	0.68***	-0.77***	0.68***	0.54*	0.44*	0.62**	0.83***	-0.77***
IG/P	0.81***	0.72***	0.53**	0.83***	0.84***	-0.83***	0.91***	0.11	0.62**	0.24	0.92***	-0.85***
IG/F	0.66**	0.76***	0.64**	0.76***	0.66**	-0.81***	0.77***	0.2	0.58**	0.3	0.90***	-0.89***

^a SIG = swelling index of glutenin with 20 min of swelling time; SDSV = SDS sedimentation volume, IG/P = % insoluble glutenin in total flour protein; IG/F = % insoluble glutenin in flour; MDT = dough mixing time; TEG = total energy; ART = arrival time; DDT = dough development time; STA = stability; MTI = mixing tolerance index; R_{max} = maximum resistance; EXT = extensibility; alveograph *P*, *G*, and *W* index; DSL = dough sheet length.

^b *, **, *** = significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

TABLE III
Correlation Coefficients of Dough Quality Parameters with Swelling Index of Glutenin (SIG) Tests from Different Swelling Times for 20 Wheat Flour Samples^{a-c}

ST(min)	Mixograph		Farinograph				Extensigraph		Alveograph			
	MDT	TEG	ART	DDT	STA	MTI	R_{max}	EXT	<i>P</i>	<i>G</i>	<i>W</i>	DSL
0	0.47*	0.66**	0.67**	0.61**	0.68***	-0.69***	0.72***	0.54*	0.34	0.68***	0.79***	-0.68***
2	0.50*	0.70***	0.73***	0.63**	0.70***	-0.80***	0.73***	0.42	0.47*	0.58**	0.88***	-0.80***
5	0.50*	0.71***	0.69***	0.63**	0.74***	-0.82***	0.76***	0.34	0.50*	0.54*	0.89***	-0.82***
7	0.58**	0.75***	0.68***	0.69***	0.74***	-0.83***	0.78***	0.34	0.53*	0.49*	0.92***	-0.85***
10	0.59**	0.73***	0.68***	0.68***	0.76***	-0.85***	0.78***	0.29	0.50*	0.52*	0.90***	-0.86***
15	0.62**	0.75***	0.65**	0.72***	0.76***	-0.83***	0.81***	0.28	0.58**	0.43	0.93***	-0.86***
20	0.62**	0.75***	0.66**	0.73***	0.73***	-0.83***	0.87***	0.22	0.57**	0.43	0.93***	-0.87***
30	0.70***	0.75***	0.60**	0.77***	0.77***	-0.83***	0.86***	0.22	0.56**	0.4	0.94***	-0.87***
40	0.73***	0.74***	0.58**	0.80***	0.77***	-0.82***	0.87***	0.18	0.59**	0.33	0.94***	-0.86***
50	0.76***	0.77***	0.54*	0.82***	0.79***	-0.82***	0.90***	0.19	0.57**	0.37	0.94***	-0.86***
60	0.76***	0.74***	0.53*	0.82***	0.76***	-0.80***	0.90***	0.19	0.57**	0.35	0.94***	-0.84***
70	0.78***	0.73***	0.51*	0.82***	0.77***	-0.79***	0.92***	0.15	0.57**	0.32	0.93***	-0.84***

^a ST = swelling time; MDT = dough mixing time; TEG = total energy; ART = arrival time; DDT = dough development time; STA = stability; MTI = mixing tolerance index; R_{max} = maximum resistance; EXT = extensibility; alveograph *P*, *G*, and *W* index; DSL = dough sheet length.

^b *, **, *** = significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

^c Vortexing for 5 sec at beginning and ending of swelling period, and vortexing for 5 sec at 10-min intervals.

cient with *G* index. In addition, EXT was significantly correlated to SDS sedimentation volume and gel protein but not to Zeleny.

As swelling time increased, the correlation coefficients of SIG with EXT and *G* decreased (Table III). The highest values of coefficients occurred at 0 min (a brief vortex after addition of SDSLA solution). After 0 min of swelling time, the coefficients dropped dramatically and there was no significant correlation for EXT at 2 min and for *G* at 15 min of swelling time. Based on the effects of soluble glutenin on SIG values (Wang and Kovacs 2002), it is evident that glutenin quality plays a role in dough extensibility. Other studies have shown that most of the variation in dough extensibility could be explained by the differences in flour polymeric protein content (including soluble and insoluble glutenin) assessed by SE-HPLC of SDS sonicated-enhanced extracts of flour (Gupta et al 1992; Bangur et al 1997). More recently, using two pairs of wheat lines grown in different locations, the differences of extensibility of dough were explained with total polymeric protein content and unextractable polymeric protein content (Larroque et al 1999). They found that at a similar level of insoluble glutenin content, the higher extensibility of dough corresponded to higher polymeric protein content and also to lower insoluble glutenin content at a similar level of polymeric protein content. It must be remembered, however, that the high correlation of extensibility with SIG at short swelling time is based on soluble and insoluble glutenin content and swelling properties (Wang and Kovacs 2002). At short swelling time, the quantitative contributions to SIG value by soluble glutenin, insoluble glutenin, and glutenin quality are unknown. Therefore, it is difficult to correlate them with conclusions from other studies that were based on polymeric protein content. SIG values with short swelling time presumably reflect a kind of balance between soluble and insoluble glutenin content and quality, which may be a reason for its significant correlation with extensibility of dough.

Relationships Between Swelling Curves and Dough Mixing Graphs

A curve of SIG values versus swelling time was divided into three distinct stages in which swelling properties of glutenin depended on cultivars (Wang and Kovacs 2002). Mixograms or farinograms also have three stages when flour is mixed with water to form dough (dough development, peak, and breakdown). To explore the relationship between the two kinds of graphs (swelling curve and dough mixing graphs), several parameters were arbitrarily obtained from swelling curves such as swelling time to peak SIG value (STP), swollen time (ST) calculated by the range of STP \pm 10% SIG peak value around peak time, and area under the curve (Fig. 1). STP is strongly correlated to DDT in farinograph and to MDT in mixograph ($r = 0.92$, $r = 0.86$, respectively, $P < 0.001$), while it has no significant correlation with farinograph ART. A significant

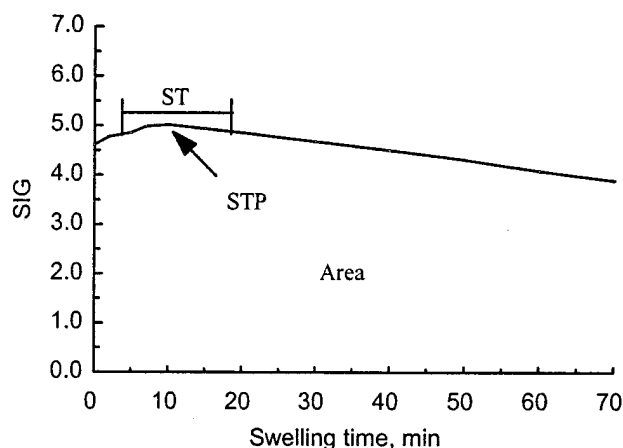


Fig. 1. Representative swelling curve showing measured indices of swelling time to peak (STP), swollen time (ST), and area under the curve.

correlation between ST and farinograph stability is also observed ($r = 0.62$, $P < 0.01$). The area under the swelling curve is significantly related to mixograph TEG ($r = 0.75$, $P < 0.001$). Therefore, glutenin swelling curves, similar to mixograms and farinograms, could be used to differentiate some strong cultivars or weak cultivars that could not be identified with sedimentation, gel protein, insoluble glutenin, and single SIG test (Pritchard 1993; Kharter et al 1996; Wang and Kovacs 2002). Although our results revealed a strong relationship between glutenin swelling curves and dough mixing graphs, the two processes are based on different mechanisms. During dough mixing, gluten protein (gliadin and glutenin) hydrates and forms a gluten network (MacRitchie 1980). In contrast, the swelling process is determined only by glutenin (Echert et al 1993) and it is assumed that glutenin molecules tend to dissociate to swell and partially dissolve in SDS solvent. The nature of the relationship between these two processes is currently unknown.

Correlation of Small-Scale Tests with Gluten Properties

The statistical relationships between small-scale tests and gluten quality parameters are shown in Table IV. Wet gluten content mainly depends on protein content. Gluten index (GI) is significantly correlated to the small-scale tests but not to protein content. GI had the strongest correlation with relative insoluble glutenin content (IG/P). Cooked gluten viscoelasticity (CGVS), developed and applied in our laboratory for evaluating gluten quality (Kovacs et al 1994, 1997a,b), was significantly related to small-scale tests. The highest correlation coefficient was obtained between CGVS and gel protein.

As swelling time increased, the correlation coefficients of wet gluten content with SIG slightly decreased (Table V). Insoluble glutenin content contributed to GI because the correlation coeffi-

TABLE IV
Correlation Coefficients of Small-Scale Tests with Gluten Quality Parameters for 20 Wheat Flour Samples^{a,b}

	WG	GI	CGVS
Protein	0.93***	-0.01	0.44*
SIG	0.64**	0.53*	0.78***
SDSV	0.26	0.64**	0.78***
Zeleny	0.26	0.54*	0.67**
Gel Protein	0.65**	0.44*	0.82***
IG/P	0.09	0.75***	0.70***
IG/F	0.51*	0.49*	0.70***

^a SIG = swelling index of glutenin with 20 min of swelling time; SDSV = SDS sedimentation volume; IG/P = % insoluble glutenin in total flour protein; IG/F = % insoluble glutenin in flour; WG = wet gluten content; GI = gluten index; CGVS = cooked gluten viscoelasticity.

^b *, **, *** = significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

TABLE V
Correlation Coefficients of Gluten Quality Parameters with Swelling Index of Glutenin (SIG) Tests from Different Swelling Times for 20 Wheat Flour Samples^{a-c}

ST (min)	WG	GI	CGVS
0	0.53*	0.52*	0.81***
2	0.64**	0.46*	0.80***
5	0.63**	0.50*	0.78***
7	0.64**	0.51*	0.80***
10	0.61**	0.52*	0.75***
15	0.61**	0.55**	0.79***
20	0.64**	0.53*	0.78***
30	0.55**	0.62**	0.76***
40	0.52*	0.64**	0.76***
50	0.46*	0.69***	0.77***
60	0.47*	0.68***	0.77***
70	0.44*	0.69***	0.76***

^a ST = swelling time; WG = wet gluten content; GI = gluten index; CGVS = cooked gluten viscoelasticity.

^b *, **, *** = significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

^c Vortexing for 5 sec at beginning and ending of swelling period, and vortexing for 5 sec at 10-min intervals.

cients between SIG and GI increased as swelling time increased. The correlation coefficients of SIG with CGVS decreased with the increase of swelling time, indicating that viscoelasticity of gluten is also affected by glutenin content and quality.

Correlation of Small-Scale Tests with Breadmaking Quality

SIG, sedimentation, and gel protein tests showed strong correlation with loaf volume (LV) (Table VI). Zeleny sedimentation volume, however, had a higher correlation coefficient than SDSV, and this is not consistent with the results of Axford et al (1979). They found the SDS sedimentation test superior to the Zeleny sedimentation test in predicting LV of bread produced both by mechanical development and long fermentation procedures. Similar to the Zeleny sedimentation test, gel protein was strongly correlated with loaf volume. Strong positive relationships between insoluble glutenin content and loaf volume have been found by many others (Orth and Bushuk 1972; Gupta et al 1993; Preston et al 1992; Bean et al 1998). However, we found in this study that insoluble glutenin contents, expressed as IG/F or IG/P, had no significant correlation with LV. This different result may be due to the different set of samples or different baking procedures. The set of flour samples used in this study possessed a wide range of dough strength (Table I). Some cultivars like Glenlea (very high insoluble glutenin content but very low LV) are probably too strong under the present baking test to get its potential LV (Tipples 1979). The correlation coefficient of LV with IG/F and SIG increased to $r = 0.68$, $P < 0.01$, and $r = 0.70$, $P < 0.001$, respectively, when Glenlea was omitted (19 cultivars considered). Because the correlation coefficients of LV with gel protein and Zeleny sedimentation tests were higher than that with insoluble glutenin content or SIG, baking quality (LV) corresponds to glutenin content and its quality.

Correlation coefficients of loaf volume with SIG declined as swelling time increased (Table VII). Similarly, Khan et al (1989)

showed that the correlation coefficient of loaf volume with residue protein after 70% ethanol extraction ($r = 0.49$, $P < 0.01$) was higher than that with residue protein after 1.5% SDS extraction ($r = 0.32$, $P < 0.05$). This is most likely due to SDS solvent extracting more soluble glutenin than aqueous ethanol. These results strongly indicate that baking quality is mainly determined by glutenin contributed by both soluble and insoluble glutenins.

Correlation of Small-Scale Tests with Quality of Chinese Salted White Noodle

Protein content significantly affects all textural parameters of Chinese salted white noodle (CSWN) except the firmness (cutting force) of dry noodles (DCF) (Table VI). The firmness of cooked noodles was significantly related to small-scale tests. SIG and IG/F had stronger correlations with firmness than gel protein and sedimentation tests. The optimum cooking time for dry noodles (DNCT) was also strongly related to SIG and insoluble glutenin content. The firmness and DNCT are governed by dough strength or insoluble glutenin content. This is probably due to protein content and quality which play important roles in the texture of cooked CSWN (Huang and Morrison 1988; Lin et al 1996). On the other hand, cooked noodle viscoelasticity for both fresh and dry noodles was significantly related to small-scale tests, while gel protein had the highest correlation coefficient. Viscoelasticity was not only correlated with glutenin content, but also with glutenin quality. Correlation coefficients of textural parameters of cooked fresh noodles and small-scale tests were higher than those from dry noodles. Processing of noodles, such as drying, influences the texture of cooked noodles.

The correlation coefficients of cooked noodle texture with SIG from different swelling times indicate that the firmness of cooked noodles and DNCT are closely related to insoluble glutenin content, and viscoelasticity of cooked noodles is related to glutenin content and quality (Table VII).

TABLE VI
Correlation Coefficients of Small-Scale Tests with Baking and Noodle-Making Quality for 20 Wheat Flour Samples^{a,b}

	LV	DNCT	DCF	DNV	FCF	FNV
Protein	0.53**	0.56**	0.42	0.77***	0.67**	0.79***
SIG	0.54**	0.66**	0.73***	0.74***	0.89***	0.85***
SDSV	0.54**	0.45*	0.61**	0.57**	0.59**	0.72***
Zeleny	0.68***	0.46*	0.49*	0.67**	0.59**	0.76***
Gel protein	0.68***	0.57**	0.62**	0.80***	0.79***	0.86***
IG/P	0.31	0.68***	0.79***	0.52*	0.82***	0.66**
IG/F	0.43	0.74***	0.75***	0.73***	0.89***	0.84***

^a SIG = swelling index of glutenin with 20 min of swelling time; SDSV = SDS sedimentation volume; IG/P = % insoluble glutenin in total flour protein; IG/F = % insoluble glutenin in flour; LV = loaf volume; DNCT = dry noodle cooking time; DCF = dry noodle cutting force; DNV = viscoelasticity for cooked dry noodles; FCF = fresh noodle cutting force; FNV = viscoelasticity for cooked dry noodles.

^b *, **, *** = significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

TABLE VII
Correlation Coefficients of Baking and Noodle-Making Quality with Swelling Index of Glutenin (SIG) Tests from Different Swelling Times for 20 Wheat Flour Samples^{a,b}

ST (min)	LV	DNCT	DCF	DNV	FCF	FNV
0	0.63**	0.54*	0.64**	0.74***	0.72***	0.86***
2	0.68***	0.63**	0.64**	0.82***	0.82***	0.89***
5	0.65**	0.65**	0.65**	0.77***	0.84***	0.87***
7	0.60**	0.68***	0.69***	0.77***	0.86***	0.87***
10	0.62**	0.68***	0.67**	0.76***	0.87***	0.86***
15	0.55*	0.65**	0.72***	0.73***	0.88***	0.84***
20	0.54*	0.66**	0.73***	0.74***	0.89***	0.85***
30	0.48*	0.68***	0.76***	0.68***	0.88***	0.81***
40	0.42	0.67**	0.76***	0.63**	0.88***	0.78***
50	0.41	0.66**	0.79***	0.62**	0.87***	0.77***
60	0.39	0.65**	0.78***	0.61**	0.87***	0.75***
70	0.36	0.64**	0.80***	0.58**	0.86***	0.73***

^a ST = swelling time; LV = loaf volume; DNCT = dry noodle cooking time; DCF = dry noodle cutting force; DNV = viscoelasticity for cooked dry noodles; FCF = fresh noodle cutting force; FNV = viscoelasticity for cooked dry noodles.

^b *, **, *** = significant at $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively.

^c Vortexing for 5 sec at beginning and ending of swelling period, and vortexing for 5 sec at 10-min intervals.

Classification of Quality Parameters

Quality parameters in this study can be divided into two groups according to their relationships with insoluble glutenin content or glutenin quality. The first group included parameters such as SIG, MDT, TEG, DDT, STAB, MTI, R_{max} , W , P , DSL, GI, and firmness of cooked noodles. The parameters were directly related to insoluble glutenin content, and correlation coefficients of the parameters with SIG increased as swelling time increased. The second group included parameters such as SDSV, Zeleny, gel protein content, SIG with short swelling time, EXT, G , ART, LV, and viscoelasticity of cooked gluten and noodles. Unlike the first group, the parameters in the second group cannot be explained simply by protein composition. The parameters were based on glutenin content and quality, including both soluble and insoluble glutenin. Because this classification is based on the relationships between quality parameters and soluble and insoluble glutenin content and quality, the functionality of soluble and insoluble glutenin is important for the explanation of both groups of quality parameters. Soluble and insoluble glutenins are presumed to consist of low molecular weight and high molecular weight glutenin, respectively (Gupta et al 1993; Bean and Lookhart 2001). It is believed that small and large size glutenins have different functionality in dough. The low molecular weight glutenin fraction showed viscous-like behavior, and the high molecular weight glutenin fraction showed gel-like behavior (Tsiami et al 1996a,b). Quality parameters in the first group, which are based on large-size glutenin fractions, may reflect the gel-like properties of large-size glutenin. These parameters reflect the strength of the gluten network. On the other hand, the second group based on both small and large size glutenin reflects both the viscosity and elasticity of the gluten network. Because each group of parameters arises from similar physical processes, the correlations of the parameters in the same group were generally significant as we found in the current study. Conversely, correlation coefficients of the parameters from different groups were not significant except for a few (results not shown) because these two groups of parameters arise from different physical processes.

CONCLUSIONS

Quality evaluation of wheat lines at early stages of their breeding is constrained by the small size of the samples and the large number of lines to be tested. The SIG test satisfies nearly all the requirements for the breeding program. It is rapid, simple, and needs only a small sample size in the standard SIG test procedure. In the standard procedure, SIG values predict quality parameters based on the insoluble glutenin content, such as strength of the gluten. Similar to sedimentation volumes and gel protein contents, SIG values obtained with short swelling time are correlated with quality parameters determined by glutenin content and quality, such as dough extensibility. Furthermore, similar to dough mixing graphs in mixograph and farinograph, the glutenin swelling curves have the potential to differentiate extra strong cultivars or weak cultivars that failed to be identified with sedimentation, gel protein, and insoluble glutenin content tests.

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