Effect of Partial Sodium Chloride Replacement by Other Salts on Wheat Dough Rheology and Breadmaking

H. SALOVAARA, Department of Food Chemistry and Technology, University of Helsinki, Viikki, SF-00710 Helsinki 71, Finland

ABSTRACT

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The rheological properties of wheat dough were studied when 20, 40, or 100% of sodium chloride (2.0%, flour weight basis) was replaced with an equivalent amount of potassium chloride, magnesium chloride, calcium chloride, magnesium acetate, magnesium sulfate, or sodium sulfate. Farinograph, extensigraph, and rotation viscometer measurements and test baking were applied to doughs containing various salts. At replacement levels of 20 and 40%, magnesium chloride and calcium chloride weakened the physical properties of dough, whereas magnesium and sodium sulfate strengthened them. Replacement with potassium chloride or magnesium acetate had no significant effect on dough rheology. The peak time and stability value of the farinograms and the extension and extension resistance values of the extensigrams could be arranged in order of the lyotropic series of the corresponding ions. Viscometer flow curves revealed marked differences between chloride, acetate, and sulfate at 100% replacement. When optimum mixing times were used in the baking test, no difficulties in baking performance due to 40% replacement with potassium or calcium chloride or magnesium salts were detected. The flavor of these breads was poor.

In recent years, recommendations based on nutritional and medical observations have been made to restrict the amount of sodium in diets. The present average dietary sodium intake (10–12 g per day) is harmful to those with a tendency for hypertension (Select Committee on GRAS Substances 1979). The balance of various minerals in the body is essential for proper physiological functions. Potassium has a protective effect against the toxicity of sodium, although the mechanism by which potassium alters blood pressure responses to excess sodium intake is unknown (Meneely and Battarbee 1976, Parfrey et al 1981). Magnesium may have an important role in balancing mineral levels, especially in diets with a high calcium content (Seelig and Heggtveit 1974, Varo 1980). Replacing at least a part of the sodium chloride with potassium or magnesium salts should, therefore, be nutritionally beneficial.

Sodium chloride is an important ingredient in bread because it enhances the flavor. It also affects the dough rheology by strengthening the gluten, thus enhancing the machinability of dough and regulating fermentation.

The effect of electrolytes on rheological dough properties is based on gluten protein aggregation. Ions may theoretically enhance either protein association or dissociation. When sodium chloride is present, association is dominant because sodium chloride strengthens the dough and reduces water absorption (Bennett and Ewart 1965, Galal et al 1978). Ionic, hydrophobic, and hydrogen bonds are involved in these reactions as described by the above authors and by others (Bernardin 1978, Wehrli and Pomeranz 1969).

The partial replacement of sodium chloride with another electrolyte instead of the mere reduction of sodium chloride in the formula offers the opportunity to maintain the electrolyte concentration. The specific character of a given electrolyte also plays a role in protein-protein and protein-water interactions (Eagland 1975). The ions of neutral salts can be arranged in the lyotropic series with respect to their effects on biological macromolecules. Guy et al (1967) showed that some ions will tend to arrange themselves in lyotropic order with respect to dough-water absorption capacity and to the mixing properties of wheat dough as measured with the farinograph. Therefore, the effect of partial replacement of sodium chloride in dough with some other salt probably can be predicted on the basis of the general lyotropic properties of the corresponding ions.

This article reports the rheological dough properties and baking performance obtained when sodium chloride was partly replaced with some other salts (ie, potassium chloride, calcium chloride, sodium sulfate, and magnesium salts).

MATERIALS AND METHODS

Wheat Flour

Lots of commercial wheat flours (A and B) were used. Flour A was milled from a wheat mixture containing 40% U.S. northern spring, 40% U.S. hard winter and 20% domestic Finnish spring wheat. Two grams of ascorbic acid per 100 kg of wheat was added to both flours during the milling. Flour B was milled from a wheat mixture containing 65% U.S. wheat (hard winter and northern spring, 1:1) and 35% domestic spring wheat. The flours contained

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14.0±0.1 and 14.5±0.1% moisture, 13.1±0.1 and 13.5±0.1% protein (5.7 × N), and 0.68 and 0.70% ash, respectively. Protein and ash contents were expressed on a dry basis. The wet gluten contents for flours A and B, respectively, were 30.0 and 28.5%, and falling numbers were 384 and 322.

Flour A was used in flow curve determinations, and flour B was used in farinograph and extensigraph measurements and in test bakings.

Sodium Chloride Replacement

The salts used were sodium chloride, potassium chloride, calcium chloride dihydrate, magnesium chloride hexahydrate, magnesium acetate tetrahydrate, magnesium sulfate heptahydrate, and sodium sulfate. All salts were analytical reagent grade compounds.

The reference dough contained 2.0% of sodium chloride (flour weight basis). In the doughs subjected to farinograph and extensigraph tests, 20 or 40% of the sodium ions (equivalents) were replaced with potassium, magnesium, or calcium equivalents. The concentration of the sulfate ion in sodium sulfate was equivalent to that in magnesium sulfate doughs. For determination of flow curves, the replacement levels were 20, 40, and 100%.

Physical Dough Tests

The physical dough properties were determined in a farinograph, an extensigraph, and a rotation viscometer. In the farinograph determinations, the AACC (1962) constant flour weight (300 g) procedure was applied. The salts were diluted in 135 ml of water, and this solution was poured on the flour during the first few seconds of mixing. The rest of the water was added from a buret. Extensigrams were obtained by the AACC procedure (1962).

Farinograph and extensigraph determinations were replicated four times for the reference dough, and twice for othe the other samples. The standard error of the mean of the curve characteristics was calculated for each reference dough.

Analysis of variance followed by Tukey's method (Steel and Torrie 1960) was applied in estimating significant differences at $P = 0.05$ in extensigraph resistance and extension values.

The method of flow curve determination was that described by Weipert (1976, 1977). The same basic instrument, a Haake Rotovisco RV 3 (Karlsruhe, West Germany), equipped with the SV II rotator and a cup, was used. The doughs were prepared from 50 g of flour A, the salt combination, and water. Constant absorption (63.4%) corresponding to the farinograph absorption of the reference dough with 2.0% sodium chloride was used. The salts were diluted in water and the solution poured onto the flour. The dough was mixed for 12 sec in a Waring Blendor. Mixing (speed 1) was interrupted after 5 and 10 sec, and the dough adhering to the inner walls of the bowl was added to the rest of the dough. An 8.0-g sample of the dough was immediately weighed and shaped by hand into a cylinder, which was then carefully placed into the sample cup of the instrument and allowed to rest for 2 min. The temperature of the rotator and cup had been adjusted to 30.0° C. The temperature of the dough sample was 28.5±0.5° C. Rotator speed was raised from zero at a rate of 2.5 rpm. The torque was registered on recording paper. Each measurement was replicated three times using fresh dough samples. The means of the maximum shear stress values were calculated.

Baking Test and Bread Quality Evaluation

The standardized mixing and fermentation procedure for experimental baking test suggested by El-Dash (1978) was applied with minor modifications. The formula used was as follows: 100% flour (14% mb), 2% sodium chloride, 5% sucrose, 3% fresh compressed yeast, and 3% hydrogenated shortening.

The doughs were mixed in a farinograph until a drop of 10 farinograph units (FU) after reaching maximum consistency (500 FU) was observed. The doughs were fermented at 30° C in the fermentation chamber of a fermentograph (S.J.A. Fermentograph, Nässjö, Sweden) until a gas volume of 650 cm^3 had evolved in two 150-g dough pieces. The breads were baked for 20 min at 170° C in an oven with agitated air flow (Bauknecht Thermidor, Zurich, Switzerland), corresponding to approximately 220° C in a conventional oven.

Bread volume was determined by seed displacement within 1–2 hr after baking. The specific volume was calculated and multiplied by 3.33 to obtain a maximum of 20 points for bread with a specific volume of 6. The remaining bread quality characteristics were evaluated independently by two baking technologists following the criteria suggested by El-Dash (1978).

Crust color (10 points), break and shred (five points), and symmetry (five points) were also regarded as external characteristics of the bread loaf (maximum total = 20 points). The internal characteristics (35 points) included the internal character of the crust (five points), crumb color (10 points), and grain and texture of the crumb (10 points each). Aroma (10 points) and taste (15 points) were included to bring the maximum total score to 100 points.

Analytical Methods

Moisture of the flours was determined after drying the samples (5-g) for 60 min at 130±2° C. Protein was determined by the Kjeldahl procedure (AOAC 1975) using the 5.7 conversion factor for nitrogen. The AOAC (1975) magnesium acetate method was used for ash determination. The falling number and the wet gluten content were determined by the ICC (1978) methods. The pH of doughs was measured by punching the electrodes into the dough. All determinations were made in duplicate.

RESULTS

Farinograph Studies

The results obtained with the farinograph on the effects of sodium chloride and of its partial substitution on water binding capacity and dough rheology are presented in Table I. Sodium chloride reduced the water absorption capacity of the dough by 1.8% units. The differences in water absorption were insignificant,

TABLE I
Farinograph Data[a] for Doughs with Various Sodium Chloride Substitutions

Farinograph Measure	Control	Reference NaCl (2.0%[b])	Substitution Level[c]	Substitution of NaCl by					
				KC1	$CaCl_2$	$MgCl_2$	$Mg(OAc)_2$	$MgSO_4$	Na_2SO_4
Absorption (%)	59.3	57.5 ± 0.1	20	57.5	57.2	57.5	58.0	58.0	58.0
			40	57.3	57.1	57.2	57.6	57.5	57.5
Arrival Time (min)	1.1	1.2 ± 0.1	20	1.0	1.2	1.3	1.3	2.1	3.5
			40	1.3	1.3	1.7	1.7	5.5	5.0
Peak Time (min)	2.5	19.1 ± 0.5	20	19.0	10.5	17.0	19.5	20.5	22.5
			40	18.0	6.5	12.5	18.0	20.0	24.0
Stability (min)	16.5	32.0 ± 0.8	20	29.0	28.0	31.0	33.5	36.0	38.0
			40	34.0	19.0	24.0	28.0	38.0	45.0

[a] Average and standard errors of four replications for the reference dough and average of two replications for other samples.
[b] Based on flour weight (14% mb).
[c] Percentage of sodium equivalents substituted compared to the reference dough.

TABLE II

Extensigraph Data[a] for Doughs with Various Sodium Chloride Substitutions

Extensigraph Measure	Reference NaCl (20%[b])	Substitution Level[c]	Substitution of NaCl by KCl	$CaCl_2$	$MgCl_2$	$Mg(OAc)_2$	$MgSO_4$	Na_2SO_4
45 min								
Resistance (BU)[d]	410 ± 17	20	415	390	340	420	380	530
		40	370	380	340	360	405	680
Extension (mm)	187 ± 3	20	188	182	189	191	157	135
		40	190	178	191	170	166	135
Ratio	2.2	20	2.2	2.1	1.8	2.2	2.4	3.9
		40	1.9	2.1	1.8	2.1	2.4	5.0
90 min								
Resistance (BU)	551 ± 11	20	532	440	510	593	553	770
		40	475	430	400	500	575	813
Extension (mm)	164 ± 5	20	168	172	162	157	144	134
		40	161	173	173	159	140	134
Ratio	3.4	20	3.2	2.6	3.1	3.8	3.8	5.7
		40	3.0	2.5	2.3	3.1	4.1	6.1
135 min								
Resistance (BU)	594 ± 29	20	587	430	495	650	700	790
		40	452	350	415	588	682	960
Extension (mm)	158 ± 3	20	158	169	171	150	154	137
		40	165	175	178	158	130	125
Ratio	3.8	20	3.7	2.5	2.9	4.3	4.5	5.8
		40	2.7	2.0	2.3	3.7	5.2	7.7

[a] Average and standard error of eight replications for the reference dough and average of four replications for other samples.

[b] Based on flour weight (14% mb).

[c] Percentage of sodium equivalents substituted compared to the reference dough.

[d] BU = Brabender units.

TABLE III

Tukey Test for Significant Differences Between Extensigram Values in Various Salted Doughs

Substitution Level[b]	Extensigram Values[a] at 135 Min						
	Resistance to Extension (BU)[c]						
20%	$CaCl_2$ 430 a	$MgCl_2$ 495 a	KCl 587 b	NaCl 594 b	$Mg(OAc)_2$ 650 bc	$MgSO_4$ 700 cd	$NaSO_4$ 790 d
40%	$CaCl_2$ 350 a	$MgCl_2$ 415 a	KCl 452 ab	$Mg(OAc)_2$ 588 b	NaCl 594 b	$MgSO_4$ 682 b	Na_4SO_4 960 c
	Extension (mm)						
20%	$MgCl_2$ 171 a	$CaCl_2$ 169 a	KCl 158 ab	NaCl 158 ab	$MgSO_4$ 154 ab	$Mg(OAc)_2$ 150 ab	Na_2SO_4 137 b
40%	$CaCl_2$ 178 a	$MgCl_2$ 175 ab	KCl 165 ab	$Mg(OAc)_2$ 158 b	NaCl 158 b	$MgSO_4$ 130 c	Na_2SO_4 125 c

[a] Means followed by the same letter in rows showed no significant difference at $P = 0.05$.

[b] Percentage of sodium equivalents substituted with the salt mentioned. The NaCl dough acts as a reference.

[c] BU = Brabender units.

regardless of the sodium chloride replacement used. The rheological behavior of the dough was totally altered by the addition of 2.0% sodium chloride as compared to the unsalted control. The type and concentration of the salt used for sodium chloride substitution also affected the dough rheological characteristics, such as arrival time, peak time, and stability.

The peak time, or dough development time, is a measure of the time required for a dough to reach maximum consistency. The peak time in the present study ranged from 6.5 to 24.0 min in variously salted doughs. Addition of calcium chloride and magnesium chloride produced doughs with peak times significantly shorter than that of the reference. Substitution with potassium chloride had no significant effect on the peak time, whereas magnesium and sodium sulfates increased it slightly.

The stability of a dough is an indication of the dough's tolerance to mixing. The stability values measured in variously salted doughs in this study ranged from 19 to 45 min. Calcium chloride and magnesium chloride reduced the stability, whereas magnesium sulfates increased it. Of all the salts studied for sodium chloride replacement, potassium chloride and magnesium acetate had the smallest effect on farinogram characteristics.

Extensigraph Studies

The results of the extensigraph tests are presented in Table II. The resistance of a dough to extension is a measure of the energy required to stretch the dough. Values of resistance to extension ranged from 350 to 960 Brabender units (BU) in the final measurement (135 min). The Tukey test of significance of the 5% level showed that variously salted doughs differed significantly in resistance to extension and in extension (Table III). When calcium or magnesium chloride were used, the values of resistance to extension were significantly below that of the reference. The effects of potassium chloride and magnesium acetate were insignificant, whereas sodium sulfate gave very high values of resistance to extension. Magnesium sulfate was considerably less effective than sodium sulfate.

The extensibility of a dough is a measure of the distance that a dough piece can be stretched before it breaks. The extension values measured (135 min) ranged between 125 and 178 mm according to the sodium chloride substitution (Table II). The lowest extension values were associated with sodium and magnesium sulfates and the highest with calcium and magnesium chlorides. The values obtained for potassium chloride and magnesium acetate did not differ significantly from the reference values (Table III).

Flow Curve Studies with Rotation Viscometer

Some typical flow curves of the 20, 40, and 100% sodium chloride replacement levels are presented in Fig. 1. The most notable difference between the variously salted doughs was seen in the maximum values of shear stress (T_m), or peak height. All the salts studied reduced the dough peak height as compared to unsalted dough (control). Two distinct groups of maximum shear stress values became evident in the flow curves at 100% substitution: chlorides and other salts (Fig. 1). The sharp peak of the curve disappeared when magnesium acetate or the sulfates of sodium or magnesium were used. This phenomenon was not seen at 20% replacement.

The flow curves seem to indicate significant differences in the peak heights of variously salted doughs. However, because the range of variation in replicated measurements was comparatively wide, the differences in peak heights at the 20% replacement level were not statistically significant. At the 40 and 100% replacement levels, all salts except magnesium chloride caused significant differences ($P < 0.05$) in peak height as compared to the reference. The Tukey test is a rather conservative statistical calculation that demonstrates only severe differences and ignores subtle ones that might be considered significant by other means of calculation.

Baking Study

Table IV shows the effects of 40% sodium chloride substitution on dough mixing time, pH, and fermentation time on bread quality. The mixing time needed for optimal dough development was reduced significantly by calcium and magnesium chlorides and increased by magnesium and sodium sulfates; potassium chloride or magnesium acetate had no effect. Dough pH was not significantly affected by the various replacements.

Changes in the fermentation time needed for a constant gas volume were not significant. This also holds true for loaf volume and other external bread characteristics in general, with the exception of breads baked with sodium sulfate, which had a greater volume but poorer characteristics in symmetry and grain. The most important differences in quality of the variously salted breads were aroma and taste. Cations other than sodium (ie, potassium, calcium, and magnesium) gave a bitter and highly undesirable off-flavor at the 40% substitution level of sodium chloride.

DISCUSSION

When the salts used were arranged according to their effect on farinograph peak time and stability as well as on extensigraph resistance and extension values, the following general order was obtained: $CaCl_2$, $MgCl_2$, KCl, NaCl (reference), $Mg(OAc)_2$, $MgSO_4$, Na_2SO_4. This series greatly resembles the lyotropic series of the corresponding ions. Guy et al (1967) also reported a lyotropic order of ions with respect to the farinograph characteristics they produced in wheat dough at 100% replacement with sodium chloride.

Of the salts studied, potassium chloride and magnesium acetate had the least effects when used as partial sodium chloride replacements. In the lyotropic series of ions, potassium and sodium are seldom separated from each other; this is readily understandable, considering the physical and chemical similarity of these ions. The nearly identical behavior of these ions in dough is therefore not surprising. Lorenz et al (1971) reported no difficulties in baking performance even when sodium chloride was totally replaced with potassium chloride. The results of the present study substantiate their observation.

In contrast to potassium chloride, the chlorides of the divalent cations studied (ie, calcium and magnesium) had a pronounced reducing effect on farinograph dough development time (peak time) and on mixing stability. The weakening effect of these ions was also revealed by the extensigraph and the optimal mixing time in the baking test. In the lyotropic series, calcium and magnesium are distinctly separated from sodium but close to each other at the end of the series where the stabilizing effects of the cations on protein configuration are weakest (von Hippel and Wong 1964).

The stabilizing effect of sulfate on a native configuration of proteins as compared to that of chloride is a well known phenomenon that is also evident from the position of this ion in the lyotropic series (Eagland 1975, von Hippel and Wong 1964). This effect was also detected when only a part of the sodium chloride in dough was replaced with sodium sulfate. The strengthening effect of sodium sulfate on wheat dough as compared to sodium chloride was also reported by Guy et al (1967). In certain cases, the

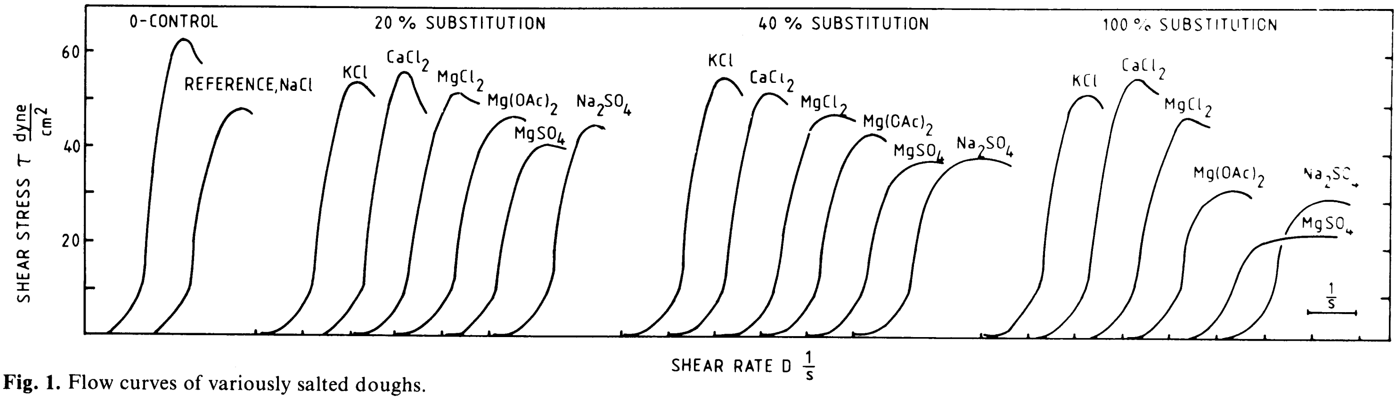

Fig. 1. Flow curves of variously salted doughs.

TABLE IV
Effect of 40% Sodium Chloride Substitution on Mixing Time, Dough pH, Fermentation Time, and Bread Quality

	Reference	Substitution of NaCl by					
NaCl (2.0%)[b]	**NaCl (2.0% on flour basis)**	**KCl**	**$CaCl_2$**	**$MgCl_2$**	**$Mg(OAc)_2$**	**$MgSO_4$**	**Na_2SO_4**
Mixing time (min)[a]	23.0	23.0	14.5	15.5	23.0	25.0	28.0
Dough pH	5.6	5.6	5.5	5.5	5.7	5.6	5.6
Fermentation time (min)[b]	73	74	76	72	74	72	72
Bread quality[c]							
Volume (sp vol × 3.33)	12.5	12.8	12.9	12.9	12.6	12.6	13.4
Other external characteristics	17	17	16	17	17	16	14
Internal characteristics	31	31	31	29	31	31	27
Aroma and taste	25	15	10	10	15	10	22
Total bread quality score	85.5	75.8	69.9	68.9	75.6	69.6	76.4

[a] Time required to mix until at 10 Brabender unit drop was observed after reaching maximum development.

[b] Time required to produce 650 ml of gas in two 150-g dough pieces in the fermentograph (30° C).

[c] Maximum scores: volume (sp vol × 3.33) 20, other external characteristics 20 (crust color, 10; break and shred, 5; symmetry, 5), internal characteristics 35 (character of crust, 5; crumb color, 10; grain, 10; texture, 10), aroma and taste 25 (aroma, 10; taste, 15).

strengthening effect of the sulfate ion was partly masked by the opposite effect of the magnesium ion. This is probably also valid for magnesium acetate. The weakening effect of the magnesium ion and the strengthening effect of the acetate ion may have resulted in rheological dough characteristics very similar to those of the reference dough. The acetate ion lies somewhere between the sulfate and chloride ions in the lyotropic series (von Hippel and Wong 1964). This is indeed the order of these three anions in this study.

The results obtained with the rotation viscometer indicated a greater difference between the anions studied than between cations. The flow curves of the doughs at 100% replacement showed an effect of acetate and sulfate ions very dissimilar from that of the chloride. The loss in the maximum shear stress value (peak height) and the disappearance of a distinct peak were the most essential differences. Weipert (1976, 1977) showed fairly similarly shaped flow curves of unsalted wheat doughs baked using wheat of poor baking quality, producing adhesive doughs (nonbaking wheat). None of the doughs prepared in this study were exceptionally sticky. The fall in shear stress following the peak probably is due to increasing slippage at the metal-dough contact when the rotator accelerates, and to the rupture mechanisms at the level of the hydrated macromolecules and/or protein aggregates essential to the dough rheological behavior (Launay and Burê 1973).

The differences in the rheological behavior of variously salted doughs were not, however, critical when considering baking performance. This is surprising but is possibly explained by the optimized mixing time in the baking procedure applied. The flavor of the breads with 40% sodium equivalents replaced by potassium, magnesium, or calcium was poor (Salovaara 1982).

No essential technological problems are likely to be met when as much as 40% of sodium normally present in bread is replaced with equivalent amounts of potassium chloride or certain magnesium salts.

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