Effects of salt and fat reduction on the rheological and gelation properties of turkey meat batters

S. BARBUT[1] and G. S. MITTAL[2]

[1]*Department of Animal and Poutry Science and* [2]*School of Engineering, University of Guelph, Guelph, ON, Canada N1G 2W1.*

Received 1 August 1988, accepted 26 January 1989.

Barbut, S. and Mittal, G. S. 1989. **Effects of salt and fat reduction on the rheological and gelation properties of turkey meat batters.** Can. Agric. Eng. **31**: 271-277. The gelation and rheological properties of turkey meat batters prepared with two fat levels (16 and 23%) and three salt levels (2.5% NaCl, 1.75% NaCl, 1.75% NaCl + 0.4% hexametaphosphate (HMP)) were studied. The relationship between shear rate and shear stress for the different raw meat batters was found to be nonlinear and followed the Bingham pseudoplastic behavior. The yield stress for the high-fat batter containing 2.5% NaCl was significantly lower than all the other treatments. The highest rigidity modulus (G) values obtained during cooking were observed in the low-fat batter with 1.75% NaCl followed by the 2.5% NaCl batters with high- and low-fat content and the high-fat batter with 1.75% NaCl. The batters containing HMP showed the lowest G values, regardless of fat content, exhibiting the strong effect of HMP on rigidity development.

INTRODUCTION

Lowering the salt and fat levels in processed meat products to reduce dietary sodium and caloric intake currently receives increased consumer attention. However, both components play an important role in the production of a high-quality meat product. To avoid product failures, when both salt and fat levels are reduced, the processor will require a better understanding of the factors affecting the formation of an acceptable texture.

Sodium reduction in the Western diet has been recommended as a means of decreasing hypertension and subsequent cardiovascular diseases, stroke, and renal failure. However, sodium chloride (NaCl) is an essential ingredient in processed meat products, where it serves three major functions: solubilize proteins to create the desired texture, provide flavor, and control microbial growth. Maximum water-holding capacity (WHC) can be accomplished with 4.5 - 5.8% NaCl, but 2.3 - 3.5% NaCl is generally sufficient for good functionality (Whiting 1988). Emulsion-type meat products (i.e., frankfurters, bologna) on the market typically contain 2.5% NaCl (Whiting 1988). Reducing the NaCl content below 2.5% does require various modifications in the formation and/or handling of the product. One of the most popular approaches to reduce NaCl levels is partial substitution with polyphosphates. Various polyphosphates have been shown to act synergistically with low levels of NaCl and enhance WHC, texture and flavor (Sofos 1986; Barbut et al. 1988).

The fat present in food products contributes to their texture (firmness, juiciness and overall mouth-feel) as well as to their flavor. Reducing the fat level in meat products may therefore alter the textural and organoleptic properties of the product. In frankfurters, reducing the fat content from 27 to 12% increased the toughness of the product (Sofos and Allen 1977) or the force required to fracture the product (Foegeding and Ramsey 1986). In the latter study, fat reduction (27 - 12%) did not affect the overall acceptability.

Knowledge of the rheological behavior of comminuted meat batters is necessary not only for the design of machines, processes and operations but also for control of end-point characteristics and consumer acceptability (Rizvi 1981). Garbatov and Garbatov (1974) presented various equations and correlations for the flow behavior of Russian-sausage meat batters under various conditions of stress. Correlation equations were presented for predicting pressures required to force the batters through pipes or nozzles.

The development of an acceptable texture in a meat system involves the coagulation of various proteins to form an elastic gel which is responsible for the unique characteristics of each product. Recently, continuous rigidity scanning was reported to be a more sensitive method for detecting sol-gel transformation transitions in protein systems than batch techniques. Rheological monitoring has the potential to be an extremely valuable and widely used instrumental method for evaluating and understanding the physical properties of heat-set gel formation in the presence of different additives (Hamann 1987).

The objectives of this study were to determine the effect of salt and fat reduction in conjunction with phosphate addition on the rheological and gelation properties of poultry meat batters.

MATERIALS AND METHODS

Ingredients and product manufacture

Six different poultry meat emulsions were prepared with two fat levels (16 and 23%) and three salt levels [2.5% NaCl, 1.75% NaCl, 1.75% NaCl + 0.5% hexametophosphate (HMP)] as outlined in Table I. Hexametophosphate was used since it has the lowest effect on the meat batter pH (Barbut et al. 1988). Fresh mechanically deboned turkey meat (MDTM) and turkey abdominal fat were obtained from a local processing plant. The MDTM and fat were repackaged in 1.5-kg portions and kept frozen up to a month at −20°C prior to use. Proximate analysis of the raw meat, carried out according to the Association of Official Analytical Chemists (1980), was: 66.2% moisture, 16.2% fat, 13.9% protein and 1.0% ash. The turkey abdominal fat composition was: 52.5% fat, 45.6% moisture, 0.9% protein and 0.1% ash.

A nonvacuum bowl cutter (Hobart, model 84142, Troy, OH) was used to chop the batters (1.5 kg each). For the high-fat batter (23% fat), 80% MDTM and 20% turkey abdominal fat were

Table I. Herschel-Bulkley equation constants for the rheology of turkey meat batter containing various fat and salt levels†

Treatment	Yield Stress T_o (Pa)	Consistancy coefficient *b* ($Pa.s^n$)	Flow behavior index *n*
Low fat (16%) batter			
2.5% NaCl	374.0*b*	199.0*b*	0.45*b*
1.75% NaCl	453.5*b*	126.3*b*	0.52*b*
1.75% NaCl + 0.5% HMP	278.4*b*	310.5*a*	0.37*b*
High fat (23%) batter			
2.5% NaCl	225.5*c*	291.2*b*	0.37*b*
1.75% NaCl	294.0*b*	264.8*b*	0.39*b*
1.75% NaCl + 0.5% HMP	506.6*a*	82.6*c*	0.60*a*

†Results are the mean of two replicate measurements.

a-c Means of parameters in the same column followed by the same letter are not significantly different at the 95% level.

Statistics: Coefficient of determination (R^2) > 0.996; degree of freedom for error > 27; and mean sum of squares of error was between 2217 and 5949.

used. For the reduced-fat batter (16% fat), which represents one-third fat reduction, 100% MDTM was used. Batters were chopped for 3.5 min; the final chopping temperature did not exceed 7°C in any of the cases. The batters were vacuum tumbled using a table-top tumbler (Lyco, WI) for 30 s at 15.2 kPa presure to remove small air bubbles. The pH of the raw emulsions was determined in duplicate (Chemcadet J-598, Cole Parmer, Chicago, IL).

Rheology

The rheological parameters were determined in duplicate using a Haake-type rotary viscometer (model RV3, Haake, Federal Republic of Berlin, W. Germany), and the SV-II measuring system, at a temperature of 10°C. The gap between the cup and the rotor was very small (0.3 mm). The viscous drag of a rotating body, immersed in the emulsion, was converted to shear rate (s^{-1}) by multiplying it by a factor of 0.89 provided by the manufacturer. Similarly scale readings were converted to shear stress (Pa) by multiplying the values obtained by a factor of 34.94.

Modulus of rigidity

Continuous evaluation of the modulus of rigidity (G) during thermal processing of the meat emulsion was performed by using a modified thermal scanning rigidity monitor (TSRM) based on the model described by Montejano et al. (1984). The TSRM consisted of a cylindrical jacketed chamber with a hollow cylinder held in the center by upper and lower removable guides. The rate of heating was manually controlled at 0.5°C/min from 20 to 75°C using a variable auto transformer (Varian V20; General Radio Co., Cambridge, MA) connected to a heating coil immersed in the water bath, as described by Barbut and Mittal (1988). The TSRM was mounted on an Instron Universal Testing machine (model TM, Instron Engineering Corp., Canton, MA) and at 2-min intervals a cyclic force (from the upward - downward cyclic motion of the crosshead at 0.5 mm/min) was applied to the samples producing a small variable cyclic deformation. Prior to the beginning of the test, the guides were removed. No flow due to gravity occurred due to the large enough yield strength of the emulsion. The peak-to-peak force was calculated from the data recorded on a chart. The shear modulus or modulus of rigidity (G) was calculated as the ratio of maximum shear stress to maximum shear strain. Mathematically it was calculated by:

$$G = F\,[\ln (R_2/R_1)]\;/\;(2\pi LD) \qquad (1)$$

where:

G is the shear rigidity modulus in Pa;

F is the force amplitude in N;

R_2 is the inside radius of the outer cylinder, 2.2975 cm;

R_1 is the outside radius of the inner cylinder, 1.503 cm;

D is the displacement amplitude, 0.0005 m; and

L is the average length of the annular volume occupied by the meat batter (Barbut and Mittal 1988).

Statistical analyses were performed using the Statistical Analysis System (SAS 1982). The General Linear Model and Nonlinear procedures for regression analyses, ANOVA procedure for analysis of variance and Duncan's multiple range test for ranking were used.

RESULTS AND DISCUSSION

Raw emulsion viscosity

The relationship between shear rate and shear stress for the different treatments is illustrated in Fig. 1. The relationship is nonlinear, and looks like Bingham pseudoplastic behavior. On a molecular level, Bingham materials are envisioned as consisting of a three-dimensional network when at rest. Applied forces are resisted up to the point at which the network breaks down and the flow becomes essentially pseudoplastic. Shearing rate tended to increase faster than the shearing stress. The particles of the emulsion which were initially randomly oriented became increasingly more aligned as shear was applied. Particle interactions and the contributions of these interactions to the apparent viscosity of fluid (Metzner 1961) decreased when the shearing stress was increased. All the batters required the application of a definite shearing force before any noticeable flow took place.

The general power law (Herschel-Bulkley) model with yield stress, was used to fit the data.

$$\tau = T_0 + b\dot{\gamma}^n \qquad (2)$$

In this model τ is the shear stress in Pa; $\dot{\gamma}$ is the shear rate in

s^{-1}; T_0 is the yield stress in Pa; b is the consistency coefficient in Pa.s^n and n is the flow behavior index. Table I summarizes these rheological parameters for the different treatments. This equation was found to be an adequate model ($R^2 > 0.99$, Table I) for describing the flow behavior of meat batters in the range of the experimental conditions used.

The confidence interval at the 95% level for T_0 was 241 - 470 Pa, for b it was 115 - 310 Pa.s^n, and for n it was 0.353 - 0.548 (Table I). These values indicate that the T_0 and n were unaffected by NaCl and HMP at the 16% fat level. However, the value of T_0 decreased with the increase in fat level (to 23%) in the 2.5% NaCl treatment, but the values of T_0 and n increased in the HMP added treatment. On the other hand, HMP increased the b value at lower fat level, but decreased it at the higher fat level. Thus, HMP effect on meat batter rheology was very pronounced and was influenced by the total amount of fat in the product.

Toledo et al. (1977), using a tube viscometer, determined the constants for sausage meat batters of varying composition containing 2.25% NaCl. They reported values of T_0 ranging from 0 to 28 Pa, values of b between 14 and 858 Pa.s^n, and n values between 0.104 and 0.722. The yield values obtained here are much larger, but the values of b and n are within the ranges reported by Toledo et al. (1977). The difference may be due to the use of the rotational viscometer in our study. According to Garbatov and Garbatov (1974) more stable formulations tend to have higher b values, lower n values, and larger T_0 values. Payne and Rizvi (1988) reported flow behavior index of 0.2 - 0.4 for beef and pork meat batters by using a capillary extrusion viscometer (at shear rates of 50 - 250 s^{-1}). Some of our values for n are higher than their values, probably due to lower shear rate and differences in the batter composition.

The rheological parameters were also determined using the Casson equation:

$$\sqrt{\tau} = K_0 + K_1\sqrt{\dot{\gamma}} \qquad (3)$$

where:

K_0 is the Casson flow limit, and K_1 is the Casson viscosity. These constants are given in Table II. HMP increased the value of K_0 at low-fat level and decreased the value of K_1 at high fat level. This again signifies the importance of HMP in changing the meat batter rheology. Feher et al. (1981), also using a Haake-type rotary viscometer and the SV measuring system, reported the following constants for meat emulsions:

$K_0 = 13.1$ to $14.1\sqrt{\text{Pa}}$, and $K_1 = 0.88$ to $1.13\sqrt{\text{Pa}\cdot\text{s}}$. Their emulsions were prepared with 1.6% NaCl, and shear rates were from 1.5 to 44 s^{-1}. In our study shear rates of 1.8 to 57 s^{-1} were used. Thus the difference in rheological parameters may be due to the higher NaCl content and the type of meat used. Feher et al. (1981) concluded that a higher value of K_0 was associated with an extremely uniform structure with an ordered distribution. In this study, we determined the parameters for the Herschel-Bulkley and the Casson equations. However, Herschel-Bulkley equation parameters are more commonly used in the design of pipes and sizing of pumps.

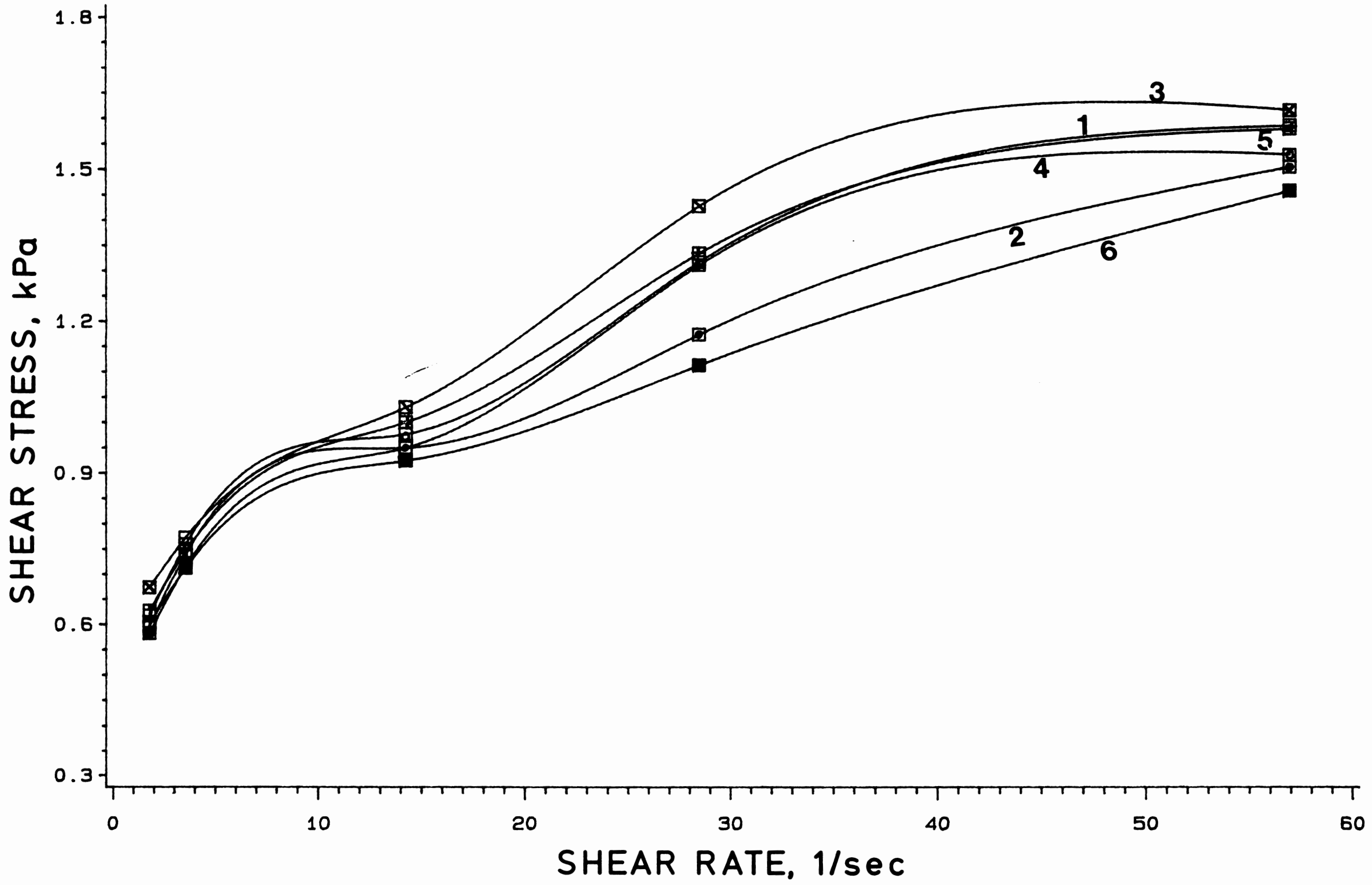

Figure 1. Relationship between shear stress and shear rate for comminuted meat batters with various fat and salt levels, measured with a Haake rotational viscometer. "1" or "□" = 2.5% NaCl + 16% fat; "2" or "◘" = 1.75% NaCl + 16% fat; "3" or "☒" = 1.75% NaCl + 0.5% HMP + 16% fat; "4" or "▣" = 2.5% NaCl + 23% fat; "5" or "⊞" = 1.75% NaCl + 23% fat; and "6" or "■" = 1.75% NaCl + 0.5% HMP + 23% fat.

Table II. Casson equation constants for the rheology of meat batters containing various fat and salt levels†

Treatment	Casson flow limit K_0 $\sqrt{Pa}$	Casson apparent viscosity K_1 $\sqrt{Pa.s}$
Low fat (16%) batters		
2.5% NaCl	22.45*b*	2.39*a*
1.75% NaCl	22.28*b*	2.21*a*
1.75% NaCl + 0.5% HMP	23.30*a*	2.38*a*
High fat (23%) batters		
2.5% NaCl	21.75*c*	2.42*a*
1.75% NaCl	22.44*b*	2.40*a*
1.75% NaCl + 0.5% HMP	22.20*b*	2.10*b*

†Results are the mean of two replicate mesurements.

a-c Means of parameters in the same column followed by the same letter are not significantly different at the 95% level.

Statistics: Coefficient of determination (R^2)>0.953; degree of freedom for error >28; and mean sum of squares of error <1.56.

Burge and Acton (1984) used a capillary extrusion viscometer to determine the rheological parameters of meat batters containing various levels of fat (11, 18 and 23%). The batter exhibited pseudoplastic behavior with the apparent viscosity increasing as the fat level decreased. The batter's fat level did not significantly affect the coefficient of shear rate when the fat level was increased from 11 to 18%, but significantly affected the yield stress which decreased from 587 to 239 Pa for the same fat level increase. However, no significant decrease in yield stress was reported when the fat level increased to 26% (239 to 148 Pa, respectively). They reported that T_0 values changed from 148 Pa to 587 Pa; *b* values from 245 to 442 Pa.s^n, and *n* values from 0.37 to 0.42 when the fat level was decreased from 26 to 11%, respectively. Our values for T_0 were within their range, and only a few *b* and *n* values were out of their reported ranges. Differences may have been due to the measuring system and type of meat used.

In an emulsified meat batter the dispersed particles are bound to one another by coagulation forces resulting from the excess of their surface energy (Feher et al. 1981). If the bonds within the aggregates are extremely strong, the system may display a yield value. At low shear rates, the aggregates may be deformed but remain essentially intact. As the shear rate increases, the aggregates may be broken down into individual particles, decreasing the friction and therefore the viscosity.

Apparent viscosity, Uapp, was calculated by:

$$U_{\text{app}} = T_0 / \dot{\gamma} + b\,\dot{\gamma}^{n-1} \quad (4)$$

The equation was derived from Newton's law of viscosity. Figure 2 illustrates the relationship between U_{app} and shear stress. Apparent viscosity decreased with the increase in shear rate and shear stress. A significant change was observed due to the use of HMP. No significant differences in apparent viscosity were noticed due to fat reduction by one third. Payne and Rizvi (1988) reported an increase in apparent viscosity of beef and pork meat batter (at 10°C) with an increase in the fat level from 5 to 30%. The difference between the results might be due to their definition of apparent viscosity which did not include the effects of T_0, *b* and *n*. In addition, they reported the data for higher shear rates (50 – 250 s^{-1}) whereas in our study shear rates were from 2 to 57 s^{-1}. The small pH differences among the treatments (6.41 ± 0.05) are not believed to be the main cause for the differences observed in the emulsion viscosities; it is rather the type and concentration of the ions present (NaCl, HMP) which seem to play the major role in the differences observed.

Gelation – modulus of rigidity

Plots of rigidity modulus (*G*) versus internal temperature of the meat emulsions are shown in Fig. 3. The low fat emulsion with 1.75% NaCl exhibited the highest rigidity modulus (51.4 kPa) followed by the high fat emulsion with 2.5% NaCl (33.4 kPa), low fat emulsion with 2.5% NaCl (21.8 kPa) and high fat emulsion with 1.75% NaCl (15.4 kPa). The addition of HMP resulted in the lowest rigidity values. Thus, HMP decreased the rigidity modulus of the emulsion irrespectively of the fat content. The high-fat emulsion with 1.75% NaCl + 0.5% HMP had the lowest *G* peak value (11.2 kPa) followed by the low-fat emulsion (14.5 kPa). That would suggest that if fat is going to be reduced in meat emulsions currently containing HMP, no alterations in the product's formulation are necessary. Barbut et al. (1988) indicated that reduced salt (2.0 or 1.5%) meat emulsions (frankfurters) containing HMP were as acceptable as a 2.5% salt product.

During heating, all the emulsions showed a small but continual increase in rigidity up to a certain temperature (43 – 55°C), followed by a rapid increase up to their peak values. This indicates the formation of stable, stiff, matrix structures typical of heat-induced protein gels. With further increase in temperature, there was no increase in *G* values; however, a decrease was noted in one case. In most of the curves two transition temperatures were observed. The general pattern observed for the denaturation of turkey muscle proteins is similar to the pattern reported for a low fat turkey paste containing 2.5% NaCl (Montejano et al. 1984), and for poultry meat emulsions containing various phosphate treatments (Barbut and Mittal 1988). The reduced fat meat emulsion (16% fat) with 2.5% NaCl showed the first transition at 45°C and the second at 61°C. There was a slower increase in *G* values between 45 and 61°C, but a rapid increase above 61°C. The transition occurring between 54 and 58°C has been attributed to myosin denaturation and the transition between 65 and 69°C was assigned to collagen and the sarcoplasmic proteins (Wright et al. 1977). Decreasing the NaCl level (1.75% NaCl with 16% fat) significantly increased the rigidity of the gel. The first transition occurred at 60°C and the second at 76°C. With the addition of HMP (16% fat with 1.75% NaCl + 0.5% HMP), the gel rigidity significantly decreased. The first transition was observed at 67°C and the second at 76°C. The transitions observed at around 34-38°C are believed to be associated with fat melting (Montejano et al. 1984). In the other treatments, since no appreciable change was observed between 30 and 40°C, fat melting might have been gradual.

Increasing the fat level to 23% resulted in significantly lower rigidity values, except in the case of 2.5% NaCl, where the opposite effect was observed. It seems that when enough salt—soluble proteins (mainly actin and myosin) were extracted by the high salt level (2.5% NaCl) the fat globules could be firmly held by the extracted proteins, thus decreasing the effect of higher fat level on the rigidity observed. In the case of HMP addition, which is believed to increase protein solubility, the higher fat treatment resulted in lower final *G* values as was observed in the low-salt treatment. However, the magnitude of the difference within the HMP treatments was not as large as in the low-salt treatments, probably due to the additional amount of protein extracted by HMP. Foegeding and Ramsey (1987), also using the TSRM, reported similar rigidity modulus patterns when fat content was increased from 13 to 25.5% (with 2.35% NaCl) in beef meat emulsions; the high fat showed consistently higher rigidity values during the entire heating process. Their values were also in the same range as the values reported here. When salt was reduced there was not enough actin and myosin to coat and entrap all the fat globules properly resulting in lower rigidity values. Phosphate addition to the low salt treatment (1.75% NaCl) was not sufficient to increase the product rigidity. However, in the presence of HMP the magnitude of difference between the high and low fat emulsions was much smaller than the 1.75% NaCl treatments.

The high fat meat batter with 2.5% NaCl showed the first thermal transition at 43°C and the second at 63°C. There was no change in rigidity above 63°C. In the case of the high fat batter with 1.75% NaCl, the first transition was observed at 52°C and the second at 62°C. This indicates that higher salt level had more effect on suppressing the transition temperature of the myosin as was recently reported by Kijowski and Mast (1988). The high fat emulsion with 1.75% NaCl + 0.5% HMP showed first transition at 50°C and the second at 60°C.

Wu et al. (1985), who studied transitions occurring during the gelation of meat emulsions, also by using TSRM, observed three transition temperatures at 38, 46 and 60°C. Rigidity increase beyond 46°C was related to the formulation of a stable network and a strong gel structure. According to Patana-anake and Foegeding (1985), shear modulus decreased from 20 to 35°C due to the melting of pork fat, and then remained relatively constant over the 40-50°C range. They observed a major rigidity transition at 54-57°C which continued to increase for the remainder of the heating period. Schweid and Toledo (1981), using volumetric expansion on heating, reported transitions points in meat batter to occur at 33-35°C and at 57-67°C. They

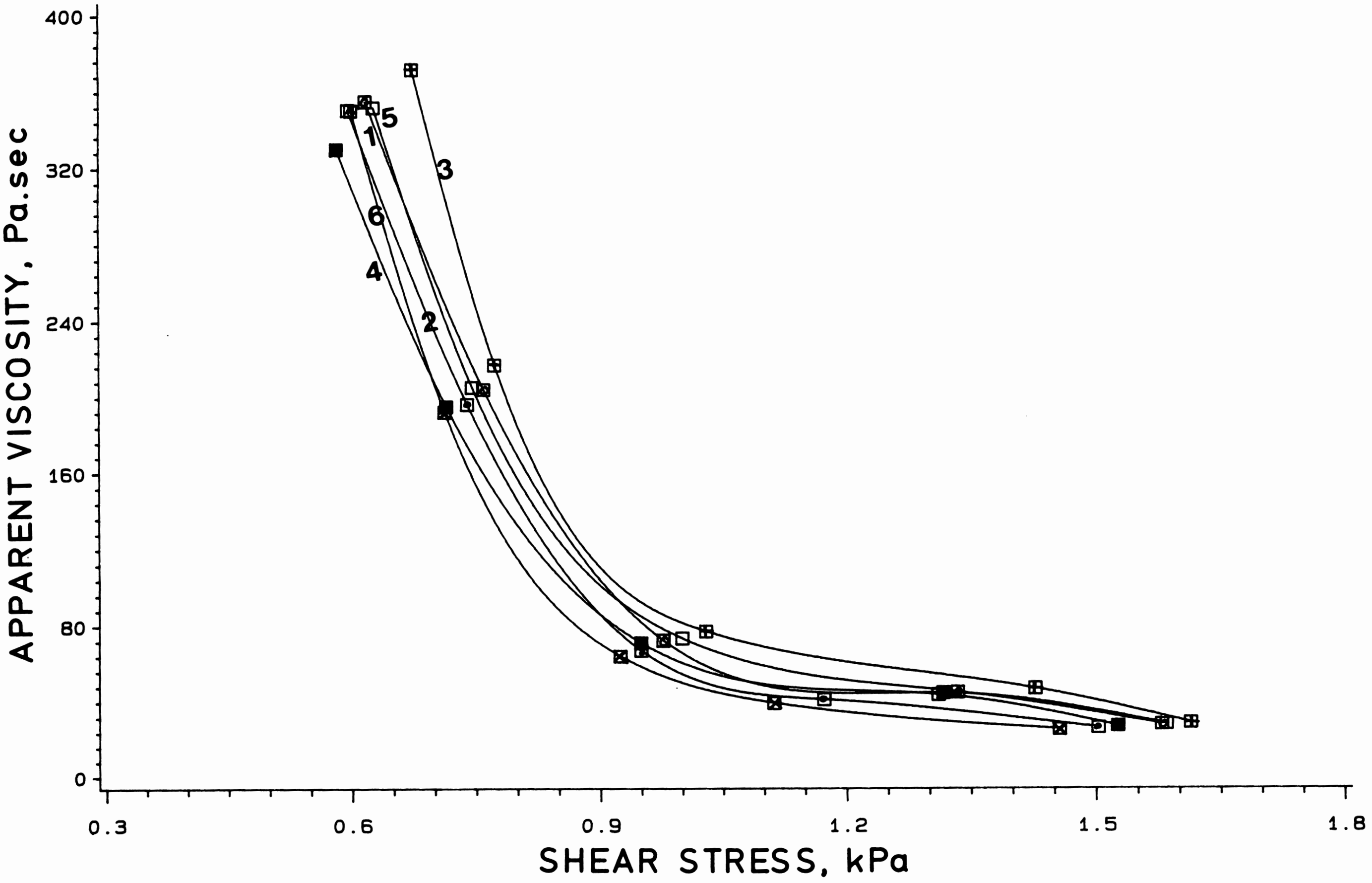

Figure 2. Relationship between the apparent viscosity and shear stress of meat batters containing various levels of fat and salt, measured with a Haake rotational viscometer. "1" or "⊡" = 2.5% NaCl + 16% fat; "2" or "▣" = 1.75% NaCl + 16% fat; "3" or "⊞" = 1.75% NaCl + 0.5% HMP + 16% fat; "4" or "■" = 2.5% NaCl + 23% fat; "5" or "□" = 1.75% NaCl + 23% fat; and "6" or "⊠" = 1.75% NaCl + 0.5% HMP + 23% fat.

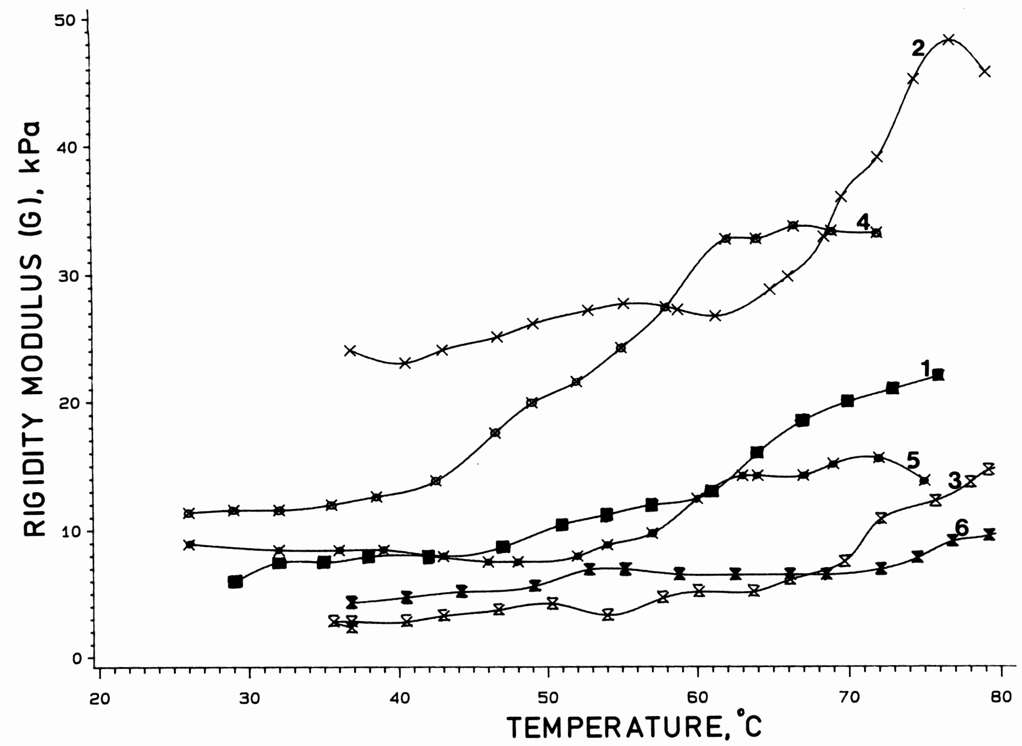

Figure 3. Profile of rigidity modulus versus temperature of meat batters containing various levels of fat and salt during cooking. "1" = 2.5% NaCl + 16% fat; "2" = 1.75% NaCl + 16% fat; "3" = 1.75% NaCl + 0.5% HMP + 16% fat; "4" = 2.5% NaCl + 23% fat; "5" = 1.75% NaCl + 23% fat; and "6" = 1.75% NaCl + 0.5% HMP + 23% fat.

suggested that these temperatures represent the points where muscle proteins insolubilized and solubilized, respectively.

The shear modulus values were highly correlated ($P \leq 0.0003$) with temperature for all the treatments. Generally, *G* increased with the increase in temperature. The average values of *G* in decreasing order for the various emulsions were: 16% fat with 1.75% NaCl, 23% fat with 2.5% NaCl, 16% fat with 2.5% NaCl, 23% fat with 1.75% NaCl, 16% fat with HMP, and 23% with HMP. A similar trend was observed when peak values of *G* were considered. The correlation of *G* with temperature for all the treatments was 0.343, and the correlation of *G* with treatment (treating them as indicator variable by assigning them values from 1 to 6 as shown in Fig. 3) was −0.37.

Rigidity modulus is an indication of rigidity and stiffness of the material and not its degree of elasticity. It has been suggested that the toughening reaction of muscle proteins during heating could be due to tightening of the network of protein structure during denaturation (Hamm and Deatherage 1960). Harris (1976) indicated that by the time the meat temperature reached 60°C, the majority of the sarcoplasmic and myofibrillar proteins were already denatured. The denaturation was observed to be accompanied by a large decrease in WHC and an increase in sample rigidity. Cooking to temperatures above 60°C increased the rigidity of the myofibrillar structure and caused meat fibers to contract along their longitudinal axis. The contraction started at 55-60°C, with the largest rate of contraction observed at 70-75°C.

The processes taking place during the cooking of a meat batter are complex. However, both the changes taking place during the transition of a gel meat system to a solid system and the rate of those changes can be measured. The kinetics of gelation and its effect on the physical properties of the finished product can then be studied. In this experiment, the two fat levels and three salt levels tested were found to affect the gelation and rheological properties of the poultry meat batters differently. Those changes should be taken into account when attempts to reduce the fat and/or salt levels in a batter type meat product are made.

ACKNOWLEDGMENTS

We thank Ms. N. Kemp for her technical support. This research was supported by the University of Guelph, the Ontario Ministry of Agriculture and Food, and the Natural Sciences and Engineering Research Council of Canada.

REFERENCES

ASSOCIATION OF OFFICIAL ANALYTICAL CHEMISTS. 1980. Official methods of analysis. 13th ed. AOAC, Washington, DC.

BARBUT, S. B. and G. S. MITTAL. 1988. Rheological and gelation properties of batters prepared with three chloride salts. J. Food Sci. 53:1296–1299.

BARBUT, S., A. J. MAURER, and R. C. LINDSAY. 1988. Effects of sodium chloride and added phosphates on physical and sensory properties of turkey frankfurters. J. Food Sci. 53:62–66.

BURGE, D. L. and J. C. ACTON. 1984. Rheological properties of comminuted-meat batters and the relationship to constituent interactions. J. Food Technol. 19:719–724.

FEHER, L., K. KABOK, and T. HUSZKA. 1981. Correlation between the rheological parameters and microstructure of Bolugnese-type sausages. Proc. European Meat Workers Conf. pp. 280–284.

FOEGEDING, E. A. and R. S. RAMSEY. 1987. Rheological and water-holding properties of gelled meat batters containing iota carrageenan, kappa carrageenan or xanthan gum. J. Food Sci. 52:549–553.

FOEGEDING, E. A. and S. R. RAMSEY. 1986. Effect of gums on low fat meat batters. J. Food Sci. 51:33–36.

GARBATOV, A. V. and V. M. GARBATOV. 1974. Advances in sausage meat rheology. J. Text. Studies. 4:406–437.

HAMANN, D. D. 1987. Methods for mesurement of rheological changes during thermally induced gelation of proteins. Food Technol. *41(3):100–108*.

HAMM, R. and F. E. DEATHERAGE. 1960. Changes in hydration, solubility and protein changes of muscle protein during heating of meat. Food Res. 25(3):587–610.

HARRIS, P. V. 1976. Structural and other aspects of meat tenderness. J. Text. Studies 7:41–63.

KIJOWSKI, J. M. and M. G. MAST. 1988. Effect of sodium chloride and phosphates on the thermal properties of chicken proteins. J. Food Sci. 53:367–370.

METZNER, A. B. 1961. Non-Newtonian technology. *In* T. B. Drew and J. W. Hooper, eds. Advances in chemical engineering. Vol. I. Academic Press, Inc., New York, NY.

MONTEJANO, J. G., D. D. HAMANN, and T. C. LANIER. 1984. Thermally induced gelation of selected comminuted muscle systems-Rheological changing during processing; Final strengths and microstructre. J. Foods Sci. 49:1496–1505.

PATANA-ANAKE, C. and E. A. FOEGEDING. 1985. Rheological and stability transitions in meat batters containing soy protein concentrate and vital wheat gluten. J. Food Sci. 50:160–164.

PAYNE, N. N. and S. S. H. RIZVI. 1988. Rheological behavior of comminuted meat batters. J. Food Sci. 53:70–73.

RIZVI, S. S. H. 1981. Rheological properties of comminuted meat systems. Food Technol. 35(5):238–243.

Statistical Analysis System Institute, Inc. 1982. SAS user's guide. 1982 Edition. SAS Institute, Cary, NC.

SCHWEID, J. M. and R. T. TOLEDO. 1981. Changes in physical properties of meat batters during heating. J. Food Sci. 46: 850–855.

SOFOS, J. N. 1986. Use of phosphates in low sodium meat products. Food Technol. 40(9):52–69.

SOFOS, J. N. and C. E. ALLEN. 1977. Effects of lean meat source and levels of fat and soy protein on the properties of wiener type products. J. Food Sci. 42:875–878.

TOLEDO, R., J. CABOT, andd D. BROWN. 1977. Relationship between composition, stability and rheological properties of raw comminuted meat batters. J. Food Sci. 42:725–727.

WHITING, R. C. 1988. Ingredients and processing factors that control muscle protein functionality. Food Technol. 42(4):104–114.

WRIGHT, D. J., I. B. LEACH, and P. WILDING. 1977. Differential scanning calorimeter studies of muscle and its constituent proteins. J. Sci. Food Agric. 28:557–564.

WU, M. C., T. C. LANIER, and D. D. HAMANN. 1985. Rigidity and viscosity changes of croaker actomyosin during thermal gelation. J. Food Sci. 50:14–19.