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RHEOLOGICAL PROPERTIES AND ADHESION OF
FLOUR-BASED BATTER TO CHICKEN NUGGETS

presented by

Hsien-Yu Hsia

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M.S. degree in 1989

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Major professor

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RHEOLOGICAL PROPERTIES AND ADHESION OF
FLOUR-BASED BATTER TO CHICKEN NUGGETS

By

Hsien-Yu Hsia

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Food Science and Human Nutrition

1989

6036028

ABSTRACT

RHEOLOGICAL PROPERTIES AND ADHESION OF FLOUR-BASED BATTER TO CHICKEN NUGGETS

By

Hsien-Yu Hsia

Rheological characteristics of chicken batters, containing three hydrocolloids (guar, xanthan, and carboxymethylcellulose (CMC)) at three concentrations (0.25, 0.5, 1.0%) and two solids contents (30%, 40%), were determined using mixer viscometry techniques. Time-dependence, apparent viscosity, shear-thinning behavior and batter recovery were determined. Most batters exhibited thixotropy. Apparent viscosity of the 30% solids batters decreased with hydrocolloid type: xanthan, guar, CMC, and the control, respectively. Apparent viscosity of the 40% solids batters was slightly different and decreased in the order: guar, xanthan, CMC, and the control, respectively. Apparent viscosity and adhesion increased with an increase in hydrocolloid concentration and batter solids content in the batter. Apparent viscosity was highly correlated to batter adhesion characteristics such as percent coating pickup, percent overall yield, and percent cooking yield. Mixer viscometry techniques can be used to follow changes in batter rheological properties caused by mixing speed and time and to predict the adhesion of batter to chicken nuggets.

I sincerely dedicate this thesis to my parents
Mr. Si-Long Hsia and Mrs. Chang-Hui Chen Hsia
for their invigoration and love

ACKNOWLEDGMENTS

I express my deepest appreciation to my major professor, Dr. D. Smith, for her earnest instruction and support in finishing this research project.

I also appreciate the assistance of the committee members guiding this study, Dr. J. F. Steffe, Dr. P. Markakis, and Dr. C. J. Flegal for their advice and inspiration.

Thanks are expressed to Dr. C. M. Stine, Dr. J. F. Price, Dr. M. A. Uebersax, and T. T. Forton for their supplying some of the experimental instruments, materials, and space.

Special acknowledge is extended to F. A. Osorio, M. E. Castell-Perez, M. S. Yeh, T. C. Wang, S. M. Lai, and T. J. Herald for their expertise and assistance.

Appreciation is also extended to Newly Weds Foods Incorporated, Miles Laboratories Incorporated, and TIC Gums Incorporated for supplying some of the experimental materials.

Finally, I present my most cordial thanks to my parents for their financial support and invigoration during my master study. I sincerely dedicate this thesis to them.

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NOMENCLATURE

A	intercept of torque vs time, N m
B	slope of torque vs time
C	coefficient, N m s ⁿ
CMC	sodium carboxymethylcellulose
k'	mixer viscometer constant, 1/rad
K	consistency coefficient, dimensionless
K _x	consistency coefficient of tested fluid, Pa s ⁿ
M	torque, N m
MDB	mechanically deboned chicken
n	flow behavior index, dimensionless
t	time, min
TPP	tripolyphosphate
x	test fluid
y	standard fluid
$\dot{\gamma}$	shear rate, 1/s
$\dot{\gamma}_a$	average shear rate, 1/s
σ	shear stress, Pa
μ_a	apparent viscosity, Pa s
Ω	angular velocity, rad/s

INTRODUCTION

The market for poultry products has increased rapidly in the United States. The use of fresh and processed poultry meat has increased in franchise stores, fastfood and other foodservice establishments, and in the home. The market for fresh and processed poultry has increased in the past 10 years and this increase is expected to continue (USDA,1987) (Table 1). Moreover, the sales of further-processed poultry are increasing as a percentage of the total market (Table 2).

The total poundage of frozen products using breading increased from 400 million in 1962 to 1960 million in 1980. The total poundage of batter and breading used on frozen products increased from 120 million in 1962 to 580 million in 1980 (Quick Frozen Foods, Nov. 1981). Therefore, the manufacture of batter and breading is a billion-dollar a year industry in the United States.

The benefits of batter and breading to poultry products include providing processors with their greatest value-added assessment by increasing yield to reduce the cost, improving sensory and texture characteristics of the food and improving product color for consumer acceptability.

Consumers and food processors want batters and breadings that adhere well. Breading losses which result from less than ideal adhesion are a common problem. Adhesion is the chemical and physical binding of a

coating with itself and the food product it coats. There are many factors affecting the adhesion of batters and breadings. The addition of various hydrocolloids continues to be an area of investigation. New chicken batters are expected to be developed due to the better adhesive properties of hydrocolloid containing batters.

The ideal batter mix should have minimizing time-dependency, since the batter was expected to have stable properties over the time of mixing. For engineering, batter with appropriate recovery was also expected. Recovery was related to the increase of apparent viscosity of batter over the time of mixing, energy cost to restart the machine, and batter texture maintenance.

The advantages of using mixer viscometry techniques for measuring batter rheological properties can be categorized as:

1. Minimizing loading shear degradation of the material.
2. Eliminating errors due to wall slip effects.
3. Preventing settling of particles in batter suspensions.
4. Minimizing the effect of particles in suspensions, to reduce the experiment error caused by the suspended particles

The overall objective of this research was to determine and compare the relationship between adhesion characteristics of batters to chicken nuggets and rheologically measured properties of batters of different solids content containing various hydrocolloid types and concentrations. Therefore, the specific objectives of this research were :

- (1) To evaluate the effect of hydrocolloid type, hydrocolloid concentration and batter solids content on the rheological properties of a batter mix.
- (2) To evaluate the effect of hydrocolloid type, hydrocolloid

concentration and batter solids content on the adhesion of batter mix to chicken nuggets.

- (3) To determine the relationship between rheological properties and adhesion characteristics of batter mixes.

Table 1 The market for fresh and processed poultry in the United States for selected years (in millions of dollars)

	Fresh poultry	Processed poultry
1973	—	491.5
1977	11,741.6	—
1980	—	1,125.8
1986	—	2,766.3
1987*	21,073.2	2,996.7
1996**	—	8,718.8

* Estimate

** Projection; percentage increased based on

Source : U. S. Department of Commerce; Business Trade Analysts

Table 2 Fresh and processed poultry expressed as a percentage of
manufacturers' sales

Year	Unprepared poultry	Further-processed poultry
1972	89.6 %	10.4 %
1980	87.0	13.0
1986	77.5	22.5
1987*	77.1	22.9
1996**	72.4	28.6

* Estimate

** Projection

Source : U. S. Department of Commerce; Business Trade Analysts

LITERATURE REVIEW

A. BATTER COMPOSITION

Batter may be prepared with a wide variety of ingredients. A dry batter mix is primarily composed of starch and flour (Donahoo, 1970). Seasonings, salt, and monosodium glutamate (MSG) are also common ingredients. Batter formulas for food products are mentioned by Hale and Goodwin (1968), Funk et al. (1971), Heath et al. (1971), Strommer and Valentas (1976), Schnell (1976), and Kaufman (1977). Ingredients used in batter formulations were categorized into two groups: (1) those such as flour, eggs, and milk, which are widely used and make up the bulk of most formulas, and (2) those such as gums, spices, leavening, salt, and sugar added in relatively small amounts for specific effects (Davis, 1983).

Batters are applied to food products for the following functions: appearance (Elston, 1975), taste characteristics, crispy texture (Zwiercan, 1974; Elston, 1975), color (Libby, 1963; Elston, 1975), nutritional value (Elston, 1975), moisture holding (Dawson et al., 1962; Libby, 1963; Sison, 1972; Love and Doodwin, 1974), and tenderization (Baker et al., 1972).

B. HYDROCOLLOID COMPOSITION

Food hydrocolloids have been developed as stabilizers, emulsifiers, thickeners, suspending agents, bodying agents, or foam enhancers in foods.

Guar gum is derived from the seed of the guar plant, Cyamopsis tetragonolobus. It is structurally composed of a straight backbone chain of D-mannopyranose units with a side-branching unit of D-galactopyranose on every other unit. The molecular weight is in the range of 200,000-300,000. Guar gum is stable over a wide pH range and is compatible with salts over a wide range of electrolyte concentrations, that is, it maintains its viscosity over a wide range of salt concentrations (Goldstein et al., 1973).

Xanthan gum is a biosynthetic heteropolysaccharide produced by bacterial fermentation using Xanthomonas species. The polymer contains D-glucose, D-mannose, and D-glucuronic acid in 3 : 3 : 1 ratio. It also contains about 4.7 % D-acetyl groups and 3.0-3.5 % pyruvic acid. The molecular weight is about 24,000,000. Xanthan gum is stable at pH's between 6 and 9. It is also compatible with many salts (Goldstein et al., 1973).

Carboxymethylcellulose (CMC) is manufactured by reacting sodium monochloroacetate with alkalicellulose. Solutions of CMC maintain viscosity over a wide pH range. CMC is compatible with most water-soluble gums over a wide range of concentrations. Viscosities of CMC solutions decrease with increasing temperature (Batdorf et al., 1973).

C. RHEOLOGICAL MEASUREMENTS AND TECHNIQUES

1. RHEOLOGICAL CHARACTERISTICS OF FLUID FOODS

Fluid foods exhibit a wide range of rheological behavior due to variations in composition and structure. A Newtonian fluid is a liquid for which a graph of shear stress against shear rate is linear . However, many fluid foods follow non-Newtonian models for which no linear relationship between shear stress and shear rate is found when the rheological properties are characterized. Non-Newtonian fluids may be classified into three groups :

- (1) Time-independent fluids — the shear rate of the fluid was a function of the shear stress only.
- (2) Time-dependent fluids — the shear rate was a function of both the magnitude and the duration of the shear stress.
- (3) Viscoelastic fluids — an elastic recovery was observed when the shear stress was removed from the material.

Time-independent fluids are classified into two groups :

- (1) Pseudoplastic (shear-thinning) fluids — shear stress (σ) decreased with increasing shear rate ($\dot{\gamma}$) in a power law model :

$$\sigma = K \dot{\gamma}^n \quad [1]$$

where, σ = shear stress, Pa s

$\dot{\gamma}$ = shear rate, 1/s

K = consistency index, Pa sⁿ

n = flow behavior index, dimensionless

Equation [1] may be expressed as:

$$\log \tau = \log K + n \log (\dot{\gamma}) \quad [2]$$

where, $0 < n < 1$ for shear-thinning fluids.

- (2) Dilatant (shear-thickening) fluids — shear stress (τ) increased with increasing shear rate ($\dot{\gamma}$) in a power law model $\tau = K \dot{\gamma}^n$. If

for a logarithm power law model $\log r = \log K + n \log (\dot{\gamma})$, the slope $1 < n < \infty$.

Time-dependent fluids were classified as :

- (1) Thixotropic fluids — shear stress (τ) decreased as time increased at a fixed shear rate.
- (2) Rheopectic fluids — shear stress (τ) increased as time increased at a fixed shear rate.

The percent recovery reflects the time-dependent behavior of the samples. When percent recovery equals 100, there is no time-dependency or complete recovery in the sample. While percent recovery does not equal 100, the sample has irreversible structural breakdown.

Yield stress (σ_0) is another important rheological property of some foods. σ_0 means fluid requires a minimum force to cause flow. A food exhibiting a yield stress retains its shape under gravity. If subjected to a force greater than gravity, the food will flow almost like a liquid. When the force is removed the food retains its shape and ceases to flow.

Dynamic measurement refers to an experiment in which either the stress or the strain (and usually both) vary harmonically with time. It is assumed that a shear stress,

$$\sigma = \sigma_0 \cos \omega t \quad [3]$$

produced a strain,

$$\gamma = \gamma_0 \cos (\omega t - \delta) \quad [4]$$

The phase lag δ and the amplitude ratio γ_0/σ_0 depend on the material and, under linear conditions, can be regarded as material properties. However, both δ and γ_0/σ_0 will vary with frequency ω . Rheological properties measured dynamically are often expressed by the storage modulus,

$$G' = (\sigma_0 \cos \delta) / \gamma_0 \quad [5]$$

and the loss modulus,

$$G'' = (\sigma_0 \sin \delta) / \gamma_0 \quad [6]$$

(Whorlow, 1979).

2. RHEOLOGICAL BEHAVIOR OF FOODSTUFFS

Several researchers have studied the rheological properties of foodstuffs. Foods exhibiting Newtonian behavior include tea, coffee, beer, wine, soda pop, milk, sucrose, corn syrup, honey, and molasses (Matz, 1962, Rao, 1977).

Most foods express non-Newtonian behavior, such as pseudoplasticity and thixotropy. Pseudoplasticity has been observed for mayonnaise (Tiu and Boger, 1974), soups and sauces (Wood, 1968), tomato puree (Harper, 1961; Charm, 1962, 1963), and xanthan gum (Rao and Kenny, 1975). Dilatancy has been reported for honey from Eucalyptus ficifolia, Eucalyptus eugenioides, Eucalyptus orymbosa, and Opuatia eugelmanii (Pryce-Jones, 1953). Thixotropy has been observed for egg white (Tung et al., 1970), mayonnaise (Tiu and Boger, 1974), and sweetened condensed milk (Higgs and Norrington, 1971). Rheopexy has not been reported in foods.

Viscoelastic foods include ice cream (Sherman, 1975), cream (Prentice, 1968, 1972), butter, canned frosting, ketchup, and whipped cream cheese (Bistany and Kokini, 1983). Foods exhibiting a yield stress include chocolate products (Chevalley, 1975; Rostagno, 1974) and hydrocolloids (Balmaceda et al., 1973).

3. MODELS FOR TIME-INDEPENDENT PSEUDOPLASTIC (SHEAR-THINNING) FLUIDS

The power law model is widely used for describing time-independent characteristics of pseudoplastic food products (Holdsworth, 1971). It is often extended to include a yield stress term (σ_0) and expressed as a Herschel Bulkley model, as :

$$\sigma = K\dot{\gamma}^n + \sigma_0 \quad [7]$$

Apparent viscosity is defined by :

$$\mu_a = \tau / \dot{\gamma} \quad [8]$$

Therefore, the apparent viscosity (μ_a) of a pseudoplastic material, derived from Equation [3], is :

$$\mu_a = K\dot{\gamma}^{n-1} \quad [9]$$

Since the power law does not always fit the experimental data with great accuracy, a few workers have used alternative models, including the Herschel-Bulkley Model (Herschel and Bulkley, 1926), Sisko Model (Sisko, 1958), Casson Model (Casson, 1959), Charm Model (Charm, 1963), Generalized Model (Bird, 1965), Molecular Model (Bird, 1965), Spriggs Truncated Power Law (Bird, 1965), and Sutterby Model (Bird, 1965), and Ofoli model (Ofoli et al., 1987).

The Ofoli model, proposed by Ofoli, Morgan, and Steffe (1987), incorporated many of the above models:

$$\tau^{n_1} = \tau_0^{n_1} + \mu_\infty \dot{\gamma}^{n_2} \quad [10]$$

and,

$$\eta = [(\tau_0 / \dot{\gamma})^{n_1} + \mu_\infty \dot{\gamma}^{n_2-n_1}]^{1/n_1} \quad [11]$$

The advantage of this model is its ability to predict flow behavior over many decades of shear. This is used in those processes where wide shear rate ranges are encountered.

4. MODELS FOR TIME-DEPENDENT, THIXOTROPIC FLUIDS

Time-dependent thixotropy is common in rheological behavior of many foodstuffs. There are several factors affecting the application of time-dependent models, such as temperature, molecular structure changes, time, product formulation, and shear rate.

Temperature has important effects on the rheological expression of materials. The Arrhenius equation suggested an equation for correcting the change in viscosity with temperature, as:

$$\mu = C e^{E_a/RT} \quad [12]$$

where, C = constant, Pa s

E_a = activation energy, Kcal/mol

R = ideal gas constant, Kcal.mol/ $^{\circ}$ K

T = absolute temperature, $^{\circ}$ K

The molecular characteristics of materials change under high shear rates. The Herschel-Bulkley model erroneously predicts a viscosity decrease to zero at high shear rates if $n < 1$. Dekee et al. (1980) suggested an exponential model in which containing parameters may be related to the molecular structure of time-dependent materials.

A structural theory originated by Cheng and Evans (1965) and extended by Petrellis and Fulmerfelt (1973) described the time-dependent behavior of shear degradable crude oils. Tiu and Boger (1974) designed a kinetic and rheological model for mayonnaise which included a structural parameter accounting for time-dependent effects.

Figoni et al. (1981) reviewed the characteristics of structure breakdown of foods based on changes in flow properties. Time-dependence was discussed in terms of viscoelasticity and structural changes. The

stress decay varied with product formulation and experimental conditions, such as temperature and shear rate.

Steffe and Ford (1985) quantified irreversible thixotropy in starch-thickened, strained apricots. A linear regression analysis was employed to determine the slope and intercept of the torque-time equation. Speers and Tung (1986) studied the effect of temperature on the flow behavior of xanthan gum dispersions. The Arrhenius equation was used to examine the effect of temperature on the variation of apparent viscosity.

5. RHEOLOGICAL CHARACTERISTICS OF BATTER MIXES

Cunningham and Tiede (1981) studied the influence of batter viscosity on breading of chicken products. They reported that as batter viscosity increased, the amount of breading pickup increased, the cooking loss decreased, and the adhesion of the breading improved. Our experiment expanded Cunningham and Tiede's work. We try to determine the time factor on the influence of batter apparent viscosity, whether adhesion characteristics were correlated to batter apparent viscosity, and the effect of hydrocolloid to the rheological properties and adhesion characteristics of the batter mix. Lane and Abdel-Ghany (1986) examined the relationship between viscosity and pickup (percent coating weight) of a fish and chip batter. They indicated that a statistically significant correlation existed between viscosity, wheat flour protein content, percent pickup, and batter temperature.

6. RHEOLOGICAL CHARACTERISTICS OF HYDROCOLLOIDS

(1) Guar Gum

Guar gum forms a viscous colloidal dispersion when hydrated in cold water and exhibits a pseudoplastic rheological system. Aqueous systems containing guar gum at very low concentrations have very high viscosities. Maximum viscosity is achieved at temperatures of 25-40°C (Goldstein et al., 1973).

There are numerous studies describing the rheological characteristics of guar gum. Schutz (1970) used the Cross model to characterize different concentrations of guar gum in solutions, as:

$$\mu = \mu_{\infty} + \left(\frac{\mu_0 - \mu_{\infty}}{1 + \alpha \dot{\gamma}^{2/3}} \right) \quad [13]$$

where, μ = apparent viscosity, Pa s

μ_0 : viscosity at $\dot{\gamma} = 0$, Pa s

μ_{∞} : viscosity at $\dot{\gamma} = \infty$, Pa s

α : constant

$\dot{\gamma}$: shear rate, rad/s

Balmaceda et al. (1973) found that at low shear rate, the Herschel Bulkley model was satisfactory with guar gum solutions. They also reported that at 21 °C, a 0.7 % guar gum solution exhibited dilatancy, but a 1.0 % solution exhibited pseudoplasticity. Doublier and Launay (1974) used the Cross Model to describe guar gum solutions over a wide range of shear rates, concentrations, and temperatures. The power law model was satisfactory only for a 0.19 % guar gum solution. Krumel and Sarkar (1975) reported apparent viscosities as a function of shear rate in guar gum solutions. Rao and Kenny (1975) found that the power law

model was satisfactory at all concentrations of guar gum below 2 %. Rao et al. (1981) reported that prolonged heat treatment of 1 % guar gum solutions resulted in a permanent loss of viscosity.

(2) Xanthan Gum

Xanthan gum dissolves in hot or cold water to form viscous, pseudoplastic solutions (Goldstein et al., 1973). Collins and Dincer (1973) reported that 50 % xanthan gum resulted in thickening of syrups. Rao and Kenny (1975) used the power law model to describe xanthan gum solutions. Whitecomb and Macosko (1978) found that at sufficient dilution and low shear rates, xanthan solutions showed Newtonian viscosity, but more concentrated solutions appeared to have a yield stress. Zatz and Knapp (1984) investigated the effect of salts on xanthan gum solutions. They found that at low shear rates, all exhibited pseudoplasticity. Speers and Tung (1986) studied the effects of temperature and concentration on xanthan gum solutions. All showed pseudoplasticity and were described by a power law model.

(3) Sodium Carboxymethylcellulose (CMC)

CMC has typical non-Newtonian, pseudoplastic properties in solution (Batdorf et al., 1973). Balmaceda et al. (1973) found that at low shear rate, the Herschel Bulkley model described CMC solutions. Krumel and Sarker (1975) reported apparent viscosities as a function of shear rate for solutions of CMC. Rao et al. (1981) found that prolonged heat treatment of 1 % CMC solutions resulted in a permanent loss of

viscosity.

7. VISCOMETRIC TECHNIQUES FOR FOODSTUFFS

Rao (1977) reviewed the use of viscometers for studying the rheological behavior of foods. For Newtonian foods, instruments operating at a single shear rate are suitable. Examples include a glass capillary viscometer operated under the force of gravity and a rolling ball viscometer, such as the Hoesppler viscometer (Van Wazer et al., 1963). For non-Newtonian fluids, Brookfield, capillary, couette, tube, concentric cylinder, cone and plate, and mixer viscometers have been widely used.

8. MIXER VISCOMETER TECHNIQUE FOR FOODSTUFFS RHEOLOGICAL MEASUREMENTS

Many foods are suspensions with large particles and may change from a liquid to a semi-solid during processing. Therefore, Voisey and deMan (1970) and Tanaka et al. (1973) employed the mixer viscometer to study the rheological behavior of foods. The major reason to use mixer viscometer technique to mix suspension foods is to avoid the problem of particle settling. Other viscometer, like Brookfield, if it has proper impeller, also could be used to mix suspension foods.

Rao (1975) used a mixer viscometer to study the flow properties of selected food suspensions. Using the method developed by Rieger and Novak (1973), a mixer viscometer for power law fluids when an average shear rate is used to estimate viscosity had the relationship of parameters below:

$$\log (P / K \Omega^{n+1} d^3) = \log A - (\log k') (1-n) \quad [14]$$

where, P = power, N m/s

K = consistency index of fluid, dimensionless

Ω = rotational speed, rad/s

n = flow behavior index, dimensionless

d = diameter of the impeller, m

A = constant depending on system geometry, dimensionless

k' = mixer viscometer constant, 1/rad

For a power law model $\tau \propto M$, and $\dot{\gamma} \propto \Omega$, where M is torque and Ω is angular velocity; therefore,

$$M = CK \Omega^n \quad [15]$$

$$\text{and, } \log M = \log (CK) + n \log \Omega \quad [16]$$

where, n is the slope of log M vs log Ω .

By considering the power law model for the test substance, x, and a fluid of known flow properties, y, the shear stress (τ) and the shear rate ($\dot{\gamma}$) are directly proportional to the torque (M) and the rotational speed (N), respectively and the only unknown, K_x , can be determined :

$$\frac{M_x}{M_y} = \frac{\tau_x}{\tau_y} = \frac{K_x N_x^n k_x^n}{K_y N_y^n k_y^n} \quad [17]$$

Steffe and Ford (1985) evaluated the shelf-stability of starch-thickened, strained apricots with mixer viscometry techniques. The rheological properties were in compliance with the investigation by Rao (1975) and his efforts based on the earlier work of Metzmer and Otto (1957). Ford and Steffe (1986) used mixer viscometry techniques to quantify thixotropy in starch-thickened, strained apricots. The rate of breakdown and equilibrium structure of the product was determined.

D. ADHESION MEASUREMENTS AND TECHNIQUES

1. THEORY FOR THE ADHESION OF BATTER TO POULTRY SKIN

The structure of poultry skin is important in coating of batters and breadings. Lucas and Stettenheim (1972) described the structure of poultry skin. Skin consists of two layers, the epidermis and the dermis (Figure 1).

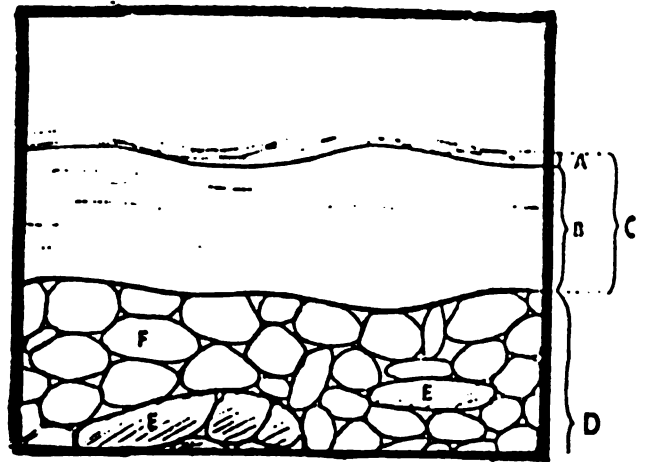


Figure 1 Transverse section of poultry skin showing the (A) Stratum corneum, (B) Stratum germinativum, (C) epidermis, (D) dermis, (E) muscle fibers, and (F) adipose cells.
From Suderman and Cunningham (1980)

The cohesion forces between the cuticle (stratum corneum) and the cuticle-stratum germinativum interface and between cells within the epidermis and dermis play important roles in batter and breading adhesion. The cohesive forces within the epidermis may be a combination of physical, chemical, and electrostatic interactions (Montagna and Lobitz, 1964). The cohesive forces at the epidermal-dermal interface may be physical in nature due to projections of papillae from the dermis into the epidermis (Pinkus and Mehregan, 1969).

Poultry skin without the cuticle may have a greater potential for improved batter and breading adhesion, as coating particles may lodge between skin protrusions extending up from the rough surface of stratum germinativum. If the cuticle were interlocked into this surface, the coating would only adhere to the smooth cuticle surface (Suderman and Cunningham, 1980). In addition, the cuticle-stratum germinativum bond is the weakest bond interface within the skin (Montagna and Lobitz, 1964). This could indicate greater potential for coating removal if a stronger bond developed between the coating and cuticle. Secondary binding forces, such as physical, chemical, and electrostatic, also contribute to the total adhesion of coatings to skin (Suderman and Cunningham, 1980).

2. METHODS TO MEASURE THE ADHESION OF COATING

A method to measure the adhesion of a coating to a food product was first reported by May et al. (1969). Breaded and cooked products were weighed, placed in a container with water, agitated with compressed air for about 15 min to remove breadings, then blotted 2 min to remove

excess moisture and reweighed to determine the percentage breadding.

Suderman and Cunningham (1979) developed a quick and accurate method to measure percent breadding loss using a standard wire sieve in a portable sieve shaker. This method has been widely used by researchers to study the coating of food products (Suderman and Cunningham, 1981; Proctor and Cunningham, 1983; Corey et al., 1987).

3. EFFECT OF POULTRY PROCESSING ON ADHESION OF COATING

The age of the bird may affect the skin surface, especially the cuticle. Suderman and Cunningham (1980) found that age did not affect poultry ultrastructure noticeably, although there was some decline in the observable cuticle as the birds got older. The influence of skin thickness, which increases with age, was not shown in their research.

Proctor and Cunningham (1983) investigated the effect of drumstick weight on the adhesion of coating to poultry products. There was no significant correlation between % coating pickup and original drumstick weight. There were significant relationships between % cooking loss, % crumb loss, % overall yield and drumstick weight.

Hale and Mayfield (1976) studied the effects of chilling processed fowl. Suderman and Cunningham (1980) also studied the effects of chilling on poultry skin ultrastructure. They showed that ice slush chilling gave no noticeable differences in coating adhesion to nonchilling.

Graf and Stewart (1953) studied the effect of temperature on removal of the epidermis of poultry skin. The birds had a glossy appearance and were slightly sticky after the epidermis was removed by

the subscald. Similar research was also reported by Zeigler and Stadelman (1955). Suderman and Cunningham (1980) used scanning electron micrographs to show that less cuticle remained in poultry skin as scald water temperature was increased from 54.4° to 65.5°C.

The effect of freezing poultry parts before applying batter and breading has been examined by Suderman and Cunningham (1981). They concluded that freezing poultry parts before breading application may slightly improve coating adhesion. Corey et al. (1987) reported that freeze-thaw cycles resulted in moisture loss from the breading, but did not influence coating loss.

Proctor and Cunningham (1984) found that broiler drumsticks without skin had significantly increased coating pickup and decreased crumb loss over those with the skin intact. Cooking losses were significantly lower for drumsticks coated with the skin on, but the % overall yields were not significantly different.

4. EFFECT OF PREDIPS, COATING COMPOSITION, AND COATING PREPARATION

METHODS ON ADHESION OF COATING

Suderman and Cunningham (1981) evaluated the effect of predips on batter adhesion. The results showed that the type of predip significantly affected the amount of breading adhering to drumsticks. Seeley (1981) compared various chemical predips and their effects on batter adhesion. The results indicated that Cruafor^R tripolyphosphate, sodium tripolyphosphate and sodium hexametaphosphate blend, and Kena^R all showed significantly less crumb loss as the concentrations of these additives in the solution increased. Citric acid did not significantly

affect crumb loss.

Hanson and Fletcher (1965) studied the influence of thickening agents, egg content, and solid-water ratio on batter adhesion. They found that increasing the proportion of thickening agent to water increased thickness of the coating. Egg content of the batter had little effect on adhesion or appearance of the coating. Increasing amounts of fat in the batter caused greater uptake of the frying fat. Baker et al. (1972) evaluated the effect of predust materials on adhesion of coating to poultry products. High protein materials produced crusts with better adhesion than starches, and hydrocolloids. Toloday (1975) reported that adhesion of batter and breading to shrimp increased when a vegetable gum premix was substituted for guar gum. Suderman et al. (1981) determined the effects of protein and gum type and amount on the adhesion of breadings to poultry skin. Among the proteins, gelatin and egg albumen most effectively improved adhesion. Only CMC was significantly better at improving adhesion than guar, tragacanth, and xanthan gum. Increased levels of gums and proteins in the breading did not significantly affect adhesion. The results from our experiment showed that either guar or xanthan gum had better adhesion than CMC. The major reason seemed because they added hydrocolloids to breading, but we added them to batter.

Effect of coating preparation methods on yields of chicken coating were studied. Yang and Chen (1979) found that fried chicken prepared with a flour predust-batter-flour method had higher yields than that prepared with the batter-breading method. Nakai and Chen (1986) found the final product yields prepared using the flour predust-batter-flour or batter-breading methods, were higher than those using the breading method or the noncoated controls.

5. EFFECT OF COATING TEMPERATURE ON ADHESION OF COATING

The effect of poultry part temperature prior to batter and breading on adhesion has been studied by Hale and Goodwin (1968). They reported that cooling poultry parts to 2°C before coating improved the texture of the coating, but did not affect yield. Proctor and Cunningham (1984) found that % coating pickup decreased with temperature in the following order : 23°C > 4°C > 110°C or -15.5°C. Poultry parts coated at -15.5°C had the highest cooking loss. Parts coated at 110°C had the lowest % crumb loss. The % overall yield of drumsticks coated at 23°C and 4°C was higher than at the other temperature.

6. EFFECT OF FRYING MEDIUM, FRYER TEMPERATURE AND HOLDING ON ADHESION OF COATING

Yang and Chen (1979) reported that a slightly higher yield was observed for broiler parts fried in solid shortening than for those fried in liquid shortening.

Yang and Chen (1979) found that the cooking yields of fried chicken decreased with an increase in frying temperature. Lane et al. (1982) found that less moisture loss occurred when breaded chicken thighs were fried at 163°C than at two higher frying temperatures of 177 and 191°C. However, percent yield of breaded chicken thighs did not vary with frying temperature.

Yang and Chen (1979) reported that under the same holding temperature, the weight loss of fried chicken parts held under heat

lamps, was greater than those held in an electric oven. Seeley (1981) observed that coating adhesion improved and less crumb loss was found as the temperature of drumsticks decreased.

7. EFFECT OF COOKING METHOD ON ADHESION OF COATING

Mickelberry and Stadelman (1962) listed 5 cooking procedures for poultry products : (1) microwave, (2) deep-fat fryer, (3) deep-fat fryer and microwave, (4) rotary-reel oven, and (5) steam and deep-fat fryer.

Baker et al. (1972) evaluated eight cooking methods. These methods included precooking by : steaming, simmering, boiling, all followed by breading, battering and breading then frying to brown; and breading, battering and breading followed by deep fat frying to doneness. Also included were four methods involving steaming after breading and/or battering and breading. They found that simmering was slightly the best of the precooked method. The most desirable product was made by breading, battering, and breading, frying 20 seconds, steaming until done, than refrying 20 seconds.

Seeley (1981) tested 5 methods of cooking : (1) microwave oven, (2) microwave plus browning element, (3) low pressure deep-fat fry, (4) oven-broil, (5) oven bake. Proctor and Cunningham (1983) reported that cooking methods affected cooking losses of chicken products as follows : baked < broiled < microwave heated < panfried < pressurized deepfat fried. Baker et al. (1986) also studied 4 cooking methods for phosphate dipped broiler breasts, thighs, drums, and wings which were dusted, battered, and breaded, then cooked. Treatments included: (1) full frying (FF), (2) short, deep fat frying, steaming followed by short, deep fat

frying (FSF), (3) short, deep fat frying followed by oven-cooking (FOC), and (4) the parts were cooked in water followed by dusting, battering, breading, and short, deep fat frying (WC). Final average yield (final weight / raw weight) for combined parts was highest for pieces cooked by FSF, followed by FOC.

MATERIALS AND METHODS

A. BATTER PREPARATION

The control batter formulation was composed of three equal amounts of modified starch (Fri-BindTM 411, A. E. Staley Manufacturing Company, Decatur, IL), wheat flour (North Dakota Mill, Grand Fords, ND), and yellow corn flour (Lauhoff Grain Company, Danvill, IN). The formula used in this study was similar to commercial products.

Control batter was prepared using three different hydrocolloids (guar gum, xanthan gum, and sodium carboxymethylcellulose (CMC)) at three different concentrations (0.25 %, 0.5 %, and 1.0 %). Guar gum was provided by TIC gums Incorporated, New York. Xanthan gum was manufactured by Jungbunzlauer Xanthan Gesellschaft M. B. H., Austria, and was distributed by Miles Laboratories Incorporated, Elkhart, IN. CMC was produced by Walocel and was distributed by Miles Laboratories Incorporated, Elkhart, In.

Batters containing 30 % and 40 % solids were prepared. Thirty percent solids batters were prepared using all ten batter treatments. Batters containing 40 % solids included the control batter and 1.0 % hydrocolloid treatments.

Batter/water mixture was placed into a mixer (Model K5-4, Kitchenaid division, Hobart Corporation, Troy, Ohio) and mixed with the

paddle attachment at the temperature and speed controlled for the time needed. For rheological measurements, batter mixes with a 30% or 40% solid concentration were mixed at speed 2 for 5 min. Batter/water mixes were put in an ice bath to rapidly lower the temperature. For adhesion measurements, batter were mixed for 3 min at speed 1 to reach the same torque condition as in the Haake at 70 rpm after 60 min rotation. During mixing, the batter temperature was kept under 10°C by putting ice on the bottom of the bowl.

Moisture was determined in quadruplicate by drying samples in a 130°C forced air oven for 1 hr (AOAC, 1984).

B. PREPARATION OF CHICKEN NUGGETS

Stewing fowls and mechanically deboned chicken (MDB) packed by Nottwa Gardens Corporation (Athens, MI) were purchased from MSU Food Store. White and dark meat were separated from the bone. Salt was from GarGill Incorporated, Minneapolis, MN. Sodium tripolyphosphate (TPP) was produced by Stauffer Chemical Company, Westport, CT (CURAFOS Formula 11-2).

The weight ratio of white meat : dark meat : MDB : salt : water : sodium tripolyphosphate was 45 : 30 : 19 : 0.5 : 5 : 0.5. Both white meat and dark meat were ground through an 0.635 cm plate of a meat grinder (Model K5-A, Kitchenaid Division, Hobart Corporation, Troy, Ohio). Sodium tripolyphosphate was thoroughly mixed with water prior to the addition of salt to the same solution. Ground meat, MDB, salt-TPP-water solution was put into a mixing bowl (Model H-600, Kitchenaid Division, Hobart Corporation, Troy, Ohio) and mixed at speed 1 for 4 min

with the paddle attachment. The raw mixture was stuffed into 8.9 cm fibrous casings (Union Carbide Corporation, Chicago, IL) and frozen at -24°C for 4 hr. The frozen patties were sliced on a meat slicer (Model 512, Hobart Corporation, Troy, Ohio) to prepare nuggets 1.5 cm thick. Before use, chicken nuggets were tempered at 4°C in a refrigerator.

C. RHEOLOGICAL MEASUREMENT AND CALCULATION

1. RHEOLOGICAL MEASUREMENT

A Haake RV-12 (calibrated by dead weight testing) viscometer with a Haake PG 142 rotational speed controller interfaced to a Hewlett-Packard 85 computer (Hewlett-Packard Company, Corvallis, OR) was used to measure the rheological properties of the batter. The reason to use mixer viscometry primary is to avoid the settling problem. A Haake F-3C water circulator was used to keep samples at a constant temperature (10°C). Ethylene glycol and water (ratio 1 : 1) were used in the water circulator to help control the temperature. Samples were loaded into an MV cup (0.021 m radius) to reach the lower mark on the cup and allowed to stand for several minutes until the thermocouple indicated a constant temperature. The cup was attached to an MV paddle sensor (Fig. 2) which was connected to the viscometer drive head. In 30 % solids batter measurement, an M-150 head was used, whereas, in 40 % solids batter measurement, an M-500 head was used for higher driving power. Torque (N m) versus time (min) data were collected to characterize the rheological properties of batters under conditions of controlled rotational speed at 10°C .

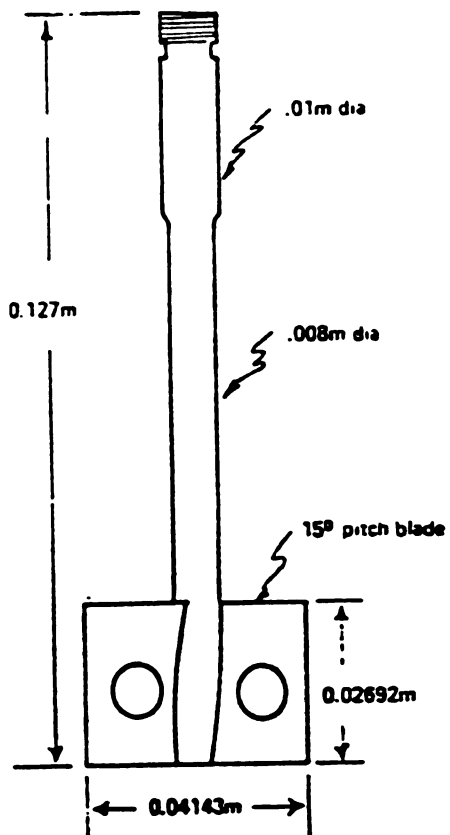


Figure 2 MV paddle sensor (Steffe and Ford, 1985)

A 70 rpm (revolution per minute) rotational speed was applied for 60 min to measure the time-dependency of the batters since 70 rpm was commonly used in commercial mixer.. Next, the rotational speed was adjusted stepwise to 10 rpm, 30 rpm, 50 rpm, 70 rpm, and 90 rpm for 2.5 min individually to measure the apparent viscosity of the batters. After this, 70 rpm was applied for 5 min to equilibrate the batter. The batters were then allowed to rest for 30 min. After that, torque versus time data was collected at 70 rpm for 10 min. The recovery of batters was evaluated by comparing the initial torque and the torque after the rest period. All of the batters were tested in triplicate. The testing procedure is briefly illustrated in Figure 3.

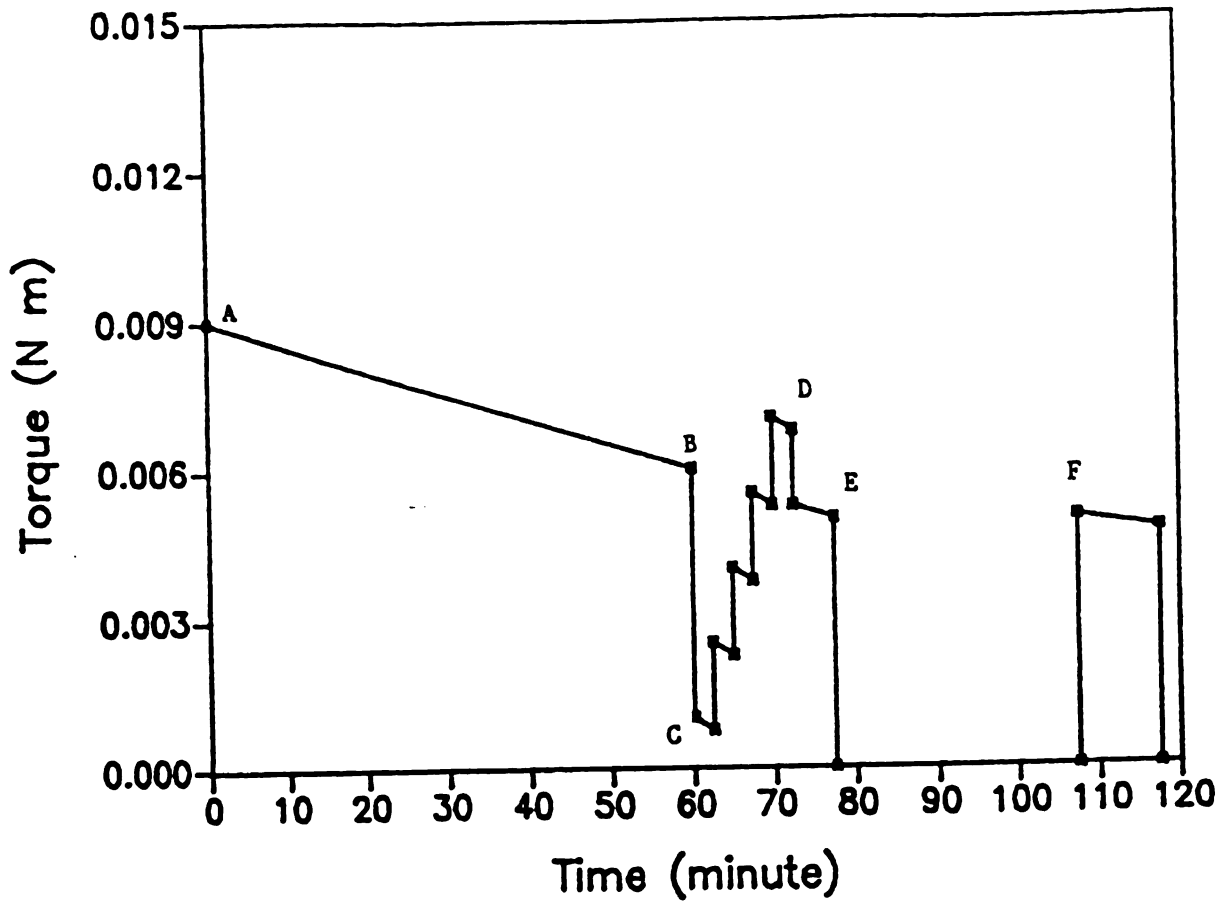


Figure 3 Representative plot of torque vs. time data collected using Haake RV-12 viscometer

A-B : Data for evaluating time-dependent thixotropy

B-C : Changing rotational speed

C-D : Data for evaluating power law parameter and time-independent apparent viscosity

D-E : Equilibration at 70 rpm prior to rest period

E-F : Rest period

A,F : Data to evaluate recovery

2. RHEOLOGICAL CALCULATIONS

(1) Time Dependency

The batter was mixed for 60 min at 70 rpm (A-B, Fig.3) to evaluate the time-dependency of the materials. After averaging the triplicate torque data, linear regression analysis of torque versus time was calculated as :

$$M = A - B \ln (t) \quad [18]$$

where, M = torque, N m

A = intercept, N m

B = slope, N m

t = time, min

(2) Apparent Viscosity and Shear Thinning Behavior

It was assumed that the time dependency factor was removed by mechanical agitation at 70 rpm for 60 min. Time independency and apparent viscosity were determined from data collected at 10 rpm, 30 rpm, 50 rpm, 70 rpm and 90 rpm for 2.5 min (C-D, Fig.3). Torque at each speed was averaged across the 2.5 min analysis time.

In apparent viscosity calculations, power law parameters were determined from a linear regression analysis of the torque versus angular velocity data (Equation [16]) as described by Steffe and Ford (1985).

The consistency coefficient was determined from Equation [17]:

$$K_x = \frac{M_x (k' \Omega_x)^{n_y}}{M_y (k' \Omega_x)^{n_x}} K_y \quad [19]$$

Where, x and y were subscripted referring to the batter and a standard solution, respectively. Guar gum (1.5 %) (Table 3) was used as the standard in the calculations and the mixer viscometer constant (k') was 4.46 (Steffe and Ford, 1985). All consistency coefficient values were recalculated using 60 rpm data for the guar gum.

Table 3. Data of 1.5 % guar gum standard used to evaluate batter consistency coefficients from the MV paddle data

	K_y (Pa s ⁿ)	n_y	M_y (N m) (at 60 rpm)
	30.98	0.158	0.0052
	31.65	0.159	0.0054
	27.39	0.169	0.0050
Average	30.01	0.162	0.0052

The constants were applied in our experiment to calculate the batter consistency coefficients (K_x) under variable rotational speeds. Therefore, referring to each Ω_x , we had an M_x , and there was a K_x for each sample.

Using the power law, the apparent viscosity was expressed as :

$$\mu_a = K (\dot{\gamma})^{n-1} \quad [20]$$

where, μ_a = apparent viscosity, Pa s

K = consistency coefficient, Pa sⁿ

$\dot{\gamma}$ = shear rate, 1/s

n = flow behavior index, dimensionless

However, for mixer viscometry techniques, the equation was expressed as :

$$\mu_a = K_x (k' \Omega_x)^{n_x-1} \quad [22]$$

where, μ_a = apparent viscosity of test fluid, Pa s

$k' \Omega_x = \dot{\gamma}_a$ = average shear rate, 1/s

Rotational speeds (rpm) were converted to angular velocity (Ω_x). Therefore, referring to each Ω_x , a μ_a for each sample was calculated. Triplicate tests of each treatment were averaged to determine apparent viscosity under variable angular velocities.

(3) Determination of Recovery

The torque after the 30 min rest period divided by the initial torque was defined as the % recovery of the batter. Referring to Fig. 3, the calculation of recovery was expressed as :

$$\% \text{ recovery} = \frac{F}{A} \times 100 \quad [23]$$

where, A = initial torque

F = torque after 30 minutes rest, N m

Results were the average of triplicate tests.

D. ADHESION MEASUREMENT AND CALCULATION METHODS

Each batter treatment was tested in triplicate. Six chicken nuggets (8.9 cm diameter, 1.5 cm thickness) were used in each replicate.

Nuggets tempered to 4°C were weighed, then individually immersed in batter for 15 sec, drained for 15 sec, and immersed in a container with commercial breading mix (No. 5042, Newly Weds Foods, Inc., Chicago, IL) for 15 sec. The breading mix contained bleached wheat flour, salt, corn flour, natural flavor, spices, monosodium glutamate, dextrose, and oleoresin paprika. After breading, the nuggets were weighed again to determine the coated weight. The nuggets were fried for 90 sec in 193°C oil in a Hotpoint fryer (Model HK3, General Electric, Chicago, IL) until an internal temperature of 76°C was reached. The frying oil was liquid frying shortening produced by Kraft, Inc., Glenview, IL. The ingredients in the oil included partially hydrogenated soybean oil, TBHQ, and methylsilicone. After cooling for 20 min, the nuggets were reweighed to determine the cooked weight, and shaken for 1 min (30 sec on each side) on a sieve shaker (No. 15421, RO-TAP Testing Sieve Shaker, The W. S. Tyler Company, Cleveland, Ohio) on a 1/4 inch grid sieve (Fidher Scientific Company), then weighed again to determine the shaken weight.

Results were calculated as :

$$\% \text{ crumb loss} = \frac{\text{cooked wt. of breaded nugget} - \text{shaken wt. of cooked nugget}}{\text{initial wt. of raw unbreaded nugget}} \times 100 \quad [23]$$

$$\% \text{ cooking loss} = \frac{\text{coated wt. of raw breaded nugget} - \text{cooked wt. of breaded nugget}}{\text{initial wt. of raw unbreaded nugget}} \times 100 \quad [24]$$

$$\% \text{ coating pickup} = \frac{\text{coated wt. of raw breaded nugget} - \text{initial wt. of raw unbreaded nugget}}{\text{initial wt. of raw unbreaded nugget}} \times 100 \quad [25]$$

$$\% \text{ overall yield} = \frac{\text{shaken wt. of cooked nugget}}{\text{initial wt. of raw unbreaded nugget}} \times 100 \quad [26]$$

$$\% \text{ cooking yield} = \frac{\text{cooked wt. of breaded nugget}}{\text{initial wt. of raw unbreaded nugget}} \times 100 \quad [27]$$

E. STATISTICAL ANALYSIS

PLOTIT was used for linear regression analysis on the experimental variables. Variables were natural logarithm of time and torque during the calculation of time dependence, and angular velocity and torque during the calculation of apparent viscosity.

The complete randomized design using 2 factor factorial (adhesion characteristics and apparent viscosity) for each treatment was used to determine the correlation between the factors in the experiment. Tukey's test was used to evaluate the significant difference between the means at the 0.01 level of probability.

RESULTS AND DISCUSSION

This research showed that a relationship existed between apparent viscosity and the adhesion characteristics of batter samples. Gum containing batters had higher apparent viscosity and greater adhesion than those of non-gum containing batters. The adhesion of coatings to chicken nuggets can be predicted based on batter rheological properties.

A. TIME-DEPENDENT EVALUATION OF CHICKEN BATTERS

Table 16 and 17 list the data of torque (M_x) vs time of 30% and 40% solids batters, respectively.

Figure 4 illustrates the torque vs time of the 30% solids control batter and batter containing 0.25, 0.5, and 1.0% guar gum. The control batter had the lowest torque curve. The effect of mixing time on the torque of 30% solids batter containing 0.25, 0.5, and 1% xanthan gum is shown in Figure 5. One percent xanthan gum batter had the highest torque curve, followed in decreasing order by 0.5%, 0.25% xanthan batters and the control batter. Torque vs time curves of CMC containing batter and control batter are illustrated in Figure 6. The torque curve increased with increasing hydrocolloid concentration. Very little difference was observed between 0.25% CMC batter and the control batter. CMC containing batters also showed the lowest torque curves compared to the other two

hydrocolloid containing batters on an equal hydrocolloid concentration basis.

Torque curves of all 40% solids batter treatments are illustrated in Figure 7. Guar gum batter had the highest torque curve, followed by xanthan gum batter. Torque curves of the 40% solids CMC containing batter and control batter were similar. However, control batter still showed the lowest curve. The 40% solids batter exhibited higher torque curves than 30% solids batters at the same hydrocolloid concentration (Figure 8).

In 30% solids batters, initial torque (M_0) increased with increasing hydrocolloid concentration (Table 4). M_0 of batters decreased in the following order: xanthan > guar > CMC > control batter at the same hydrocolloid concentration. The highest M_0 was observed in the 1.0% xanthan batter and the lowest was the control batter. Batter with increasing hydrocolloid concentration had increasing final torque (M_{60}). M_{60} of batters decreased with 0.5 & 1.0% hydrocolloid concentration in the following order: xanthan > guar > CMC > control. The highest M_{60} was exhibited in the 1.0% xanthan batter and the lowest was in the 0.25% CMC batter. The change of initial apparent viscosity μ_0 and intercept (A) was the same as M_0 . The change of final apparent viscosity μ_{60} was the same as M_{60} .

The slope increased as hydrocolloid concentration in the batter was increased (Table 4). The slope decreased in the following order: guar > xanthan > CMC > control batter at 0.25% and 1% hydrocolloid concentration, but xanthan > guar > CMC > control batter at 0.5% hydrocolloid concentration.

In 40% solids batters containing 1.0% hydrocolloid (Table 5), M_0 decreased in the order of guar > xanthan > CMC > control batter. The

change in order of M_{60} , μ_0 , μ_{60} , and A was the same as M_0 . The order of B was xanthan > guar > CMC > control batter.

The 30% solids control batter exhibited increasing torque with time compared to the 40% solids control. All hydrocolloid containing batters showed decreasing torque with time of mixing. The 30% control batter and 30% batter containing 0.25% CMC had slopes (Table 4) close to zero which is characteristic of Newtonian fluids. The batters were stable over the time of mixing. All other batters had positive slopes (Table 4 & Table 5), indicating thixotropic properties, which meant shear stress decreased as time increased at a fixed rotational speed. Therefore, batters were unstable (with decreased apparent viscosity) over the time of mixing. Higher absolute slope meant higher degree of time-dependency, and less stable properties over time of mixing. One percent guar gum batter containing 30% solids and 1% xanthan gum batter containing 40% solids had the largest absolute slopes, which indicated the largest degree of time-dependency and the least stable properties among the 30% and 40% solids batters, respectively. Batters containing 0.25% CMC and control batters had the least degree of time-dependency and the most stable properties among the 30% and 40% solids basis batters, respectively, as indicated by their lowest absolute B.

Comparing the slope of chicken batter in 30% and 40% solids content at the same hydrocolloid concentration, we found that control and 1.0% xanthan batters had an increased slope, but 1.0% guar and 1.0% CMC batters had a decreased slope when the batter solids content increased from 30% to 40%. It meant that control and 1.0% xanthan batter had a higher degree of time-dependency and less stable properties, but 1.0% guar and 1.0% CMC batters had a lower degree of time-dependency and more stable

properties when the batter solids content increased.

Therefore, hydrocolloids, especially guar or xanthan gum, contributed to a higher torque, apparent viscosity, and degree of time-dependency but less stable properties than control and CMC in chicken batter. Increasing the hydrocolloid concentration increased the torque, apparent viscosity and degree of time-dependency, but decreased the stable properties of chicken batter. As batter solids content increased, guar and CMC had increased apparent viscosity and more stable properties than control and xanthan. At low concentrations of CMC, the difference between the CMC containing batter and control batter was not evident. In this experiment, we did not find a hydrocolloid which give the batter both higher apparent viscosity and more stable properties. Therefore, future work should be directed toward finding a hydrocolloid, independent of concentration or batter solids content, which produces a high apparent viscosity and more stable properties in the batter.

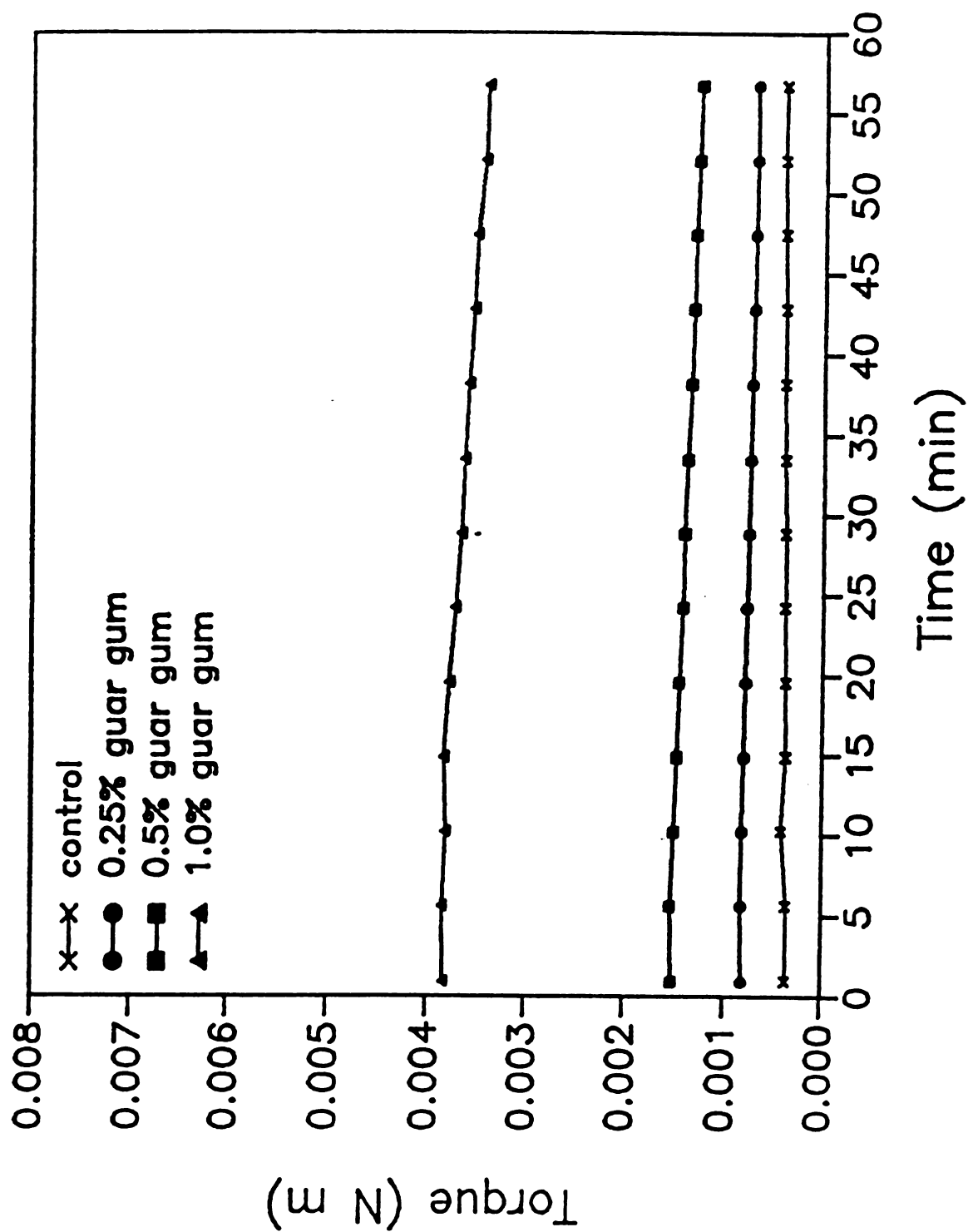


Figure 4. Torque of 30% solids batters with and without guar gum measured at 70 rpm, 10°C

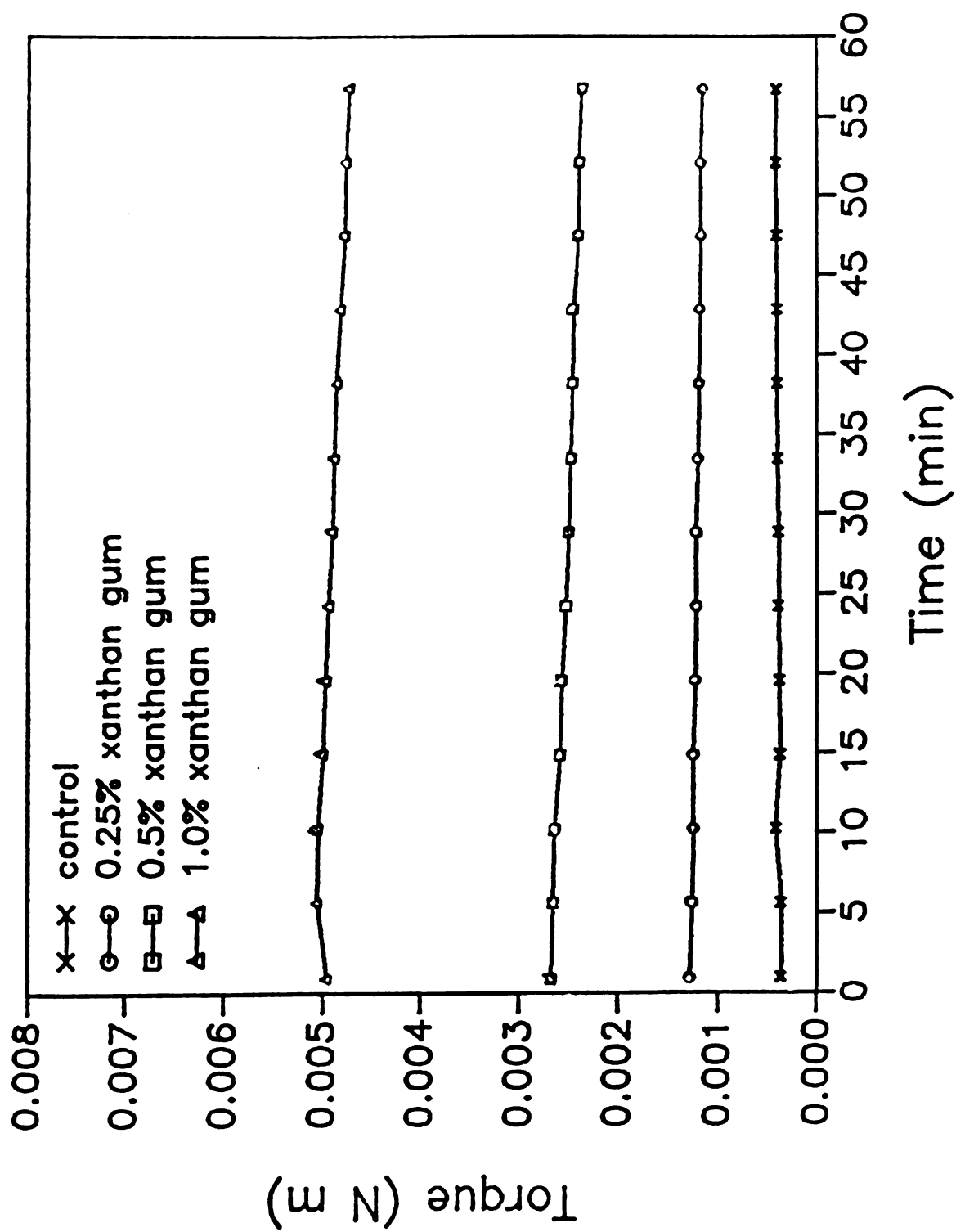


Figure 5 Torque of 30% solids batters with and without xanthan gum measured at 70 rpm, 10°C

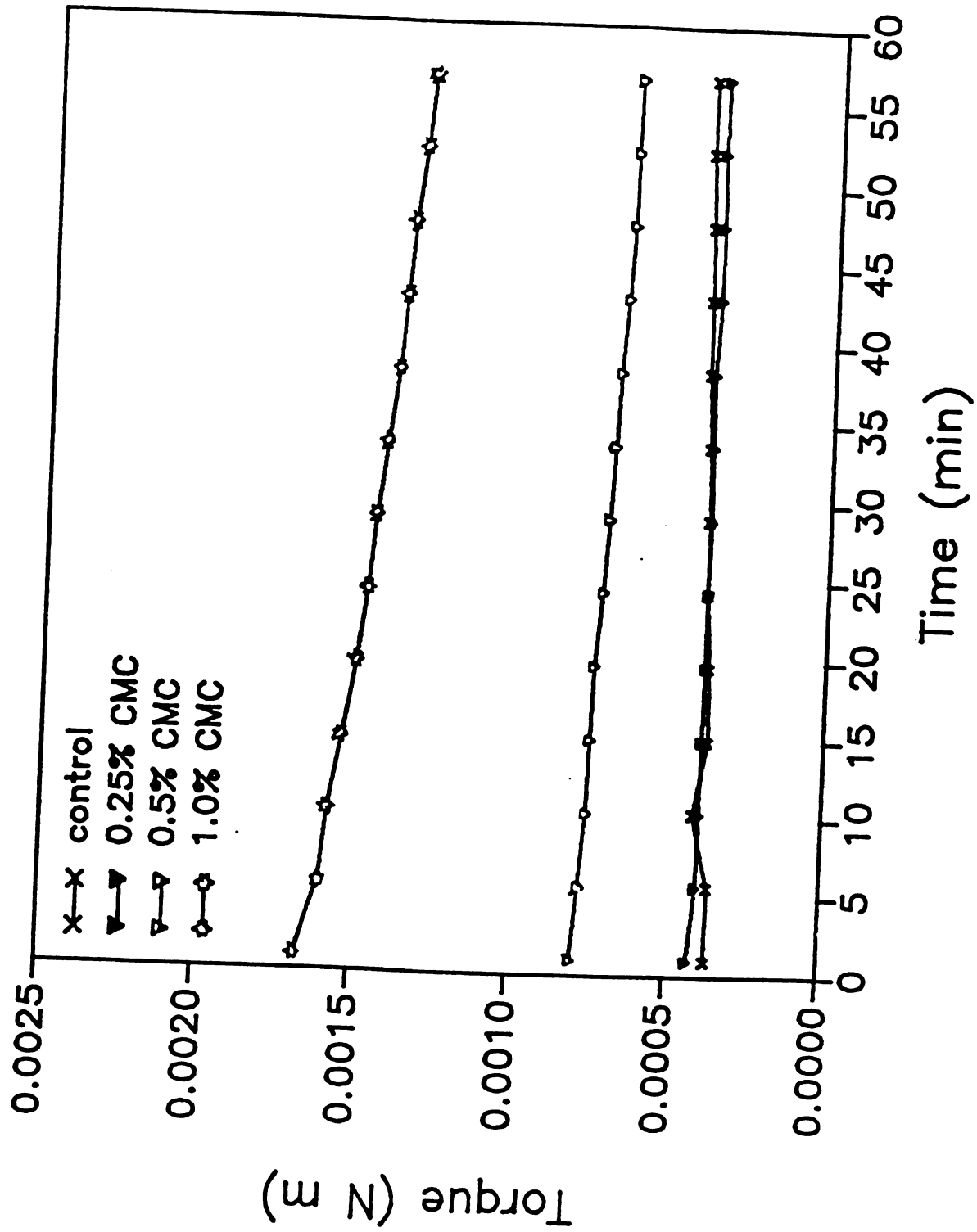


Figure 6 Torque of 30% solids batters with and without sodium carboxymethylcellulose (CMC) measured at 70 rpm, 10°C

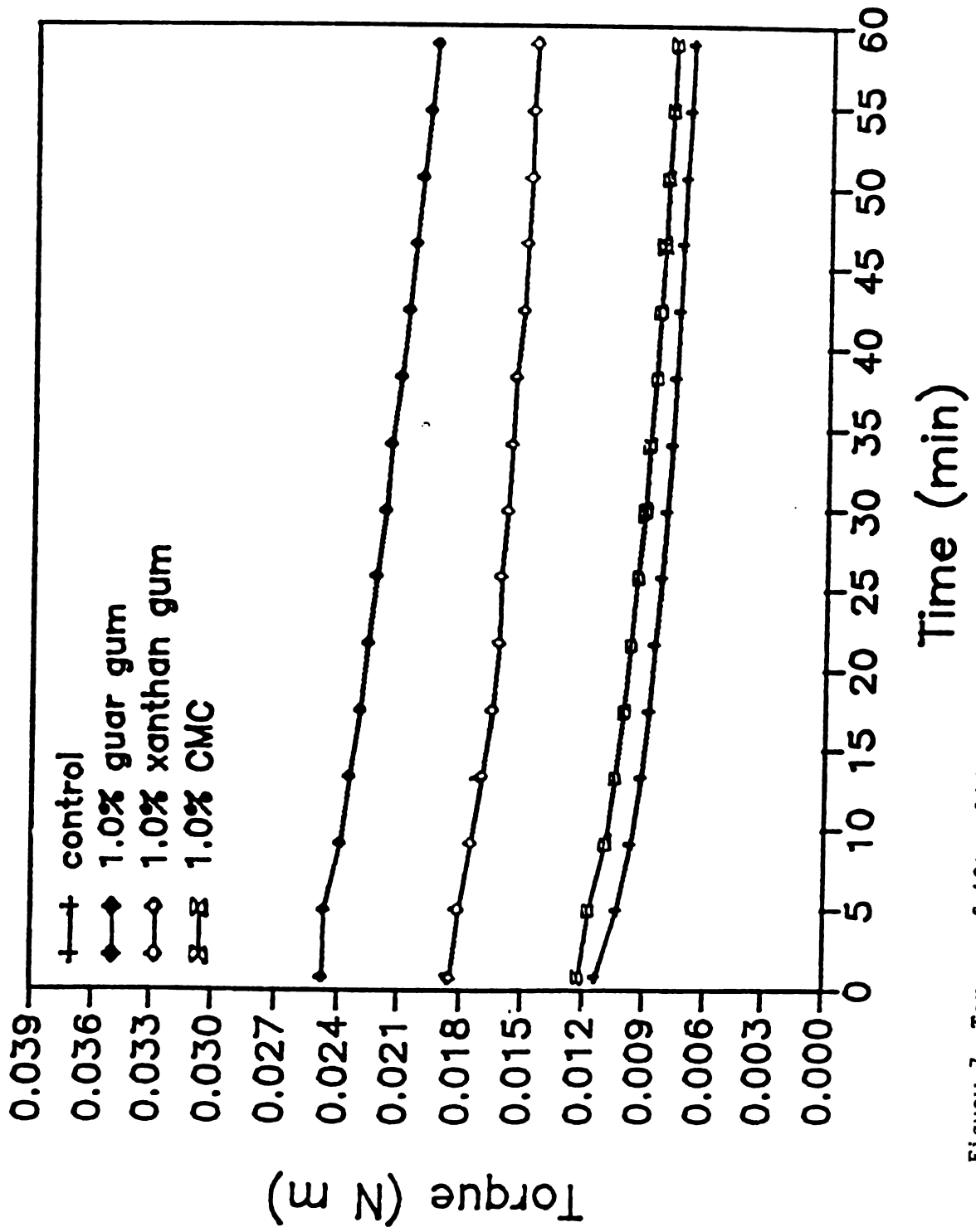


Figure 7 Torque of 40% solids batters with and without 1% hydrocolloids (guar gum, xanthan gum, sodium carboxymethylcellulose (CMC)) measured at 70 rpm, 10°C

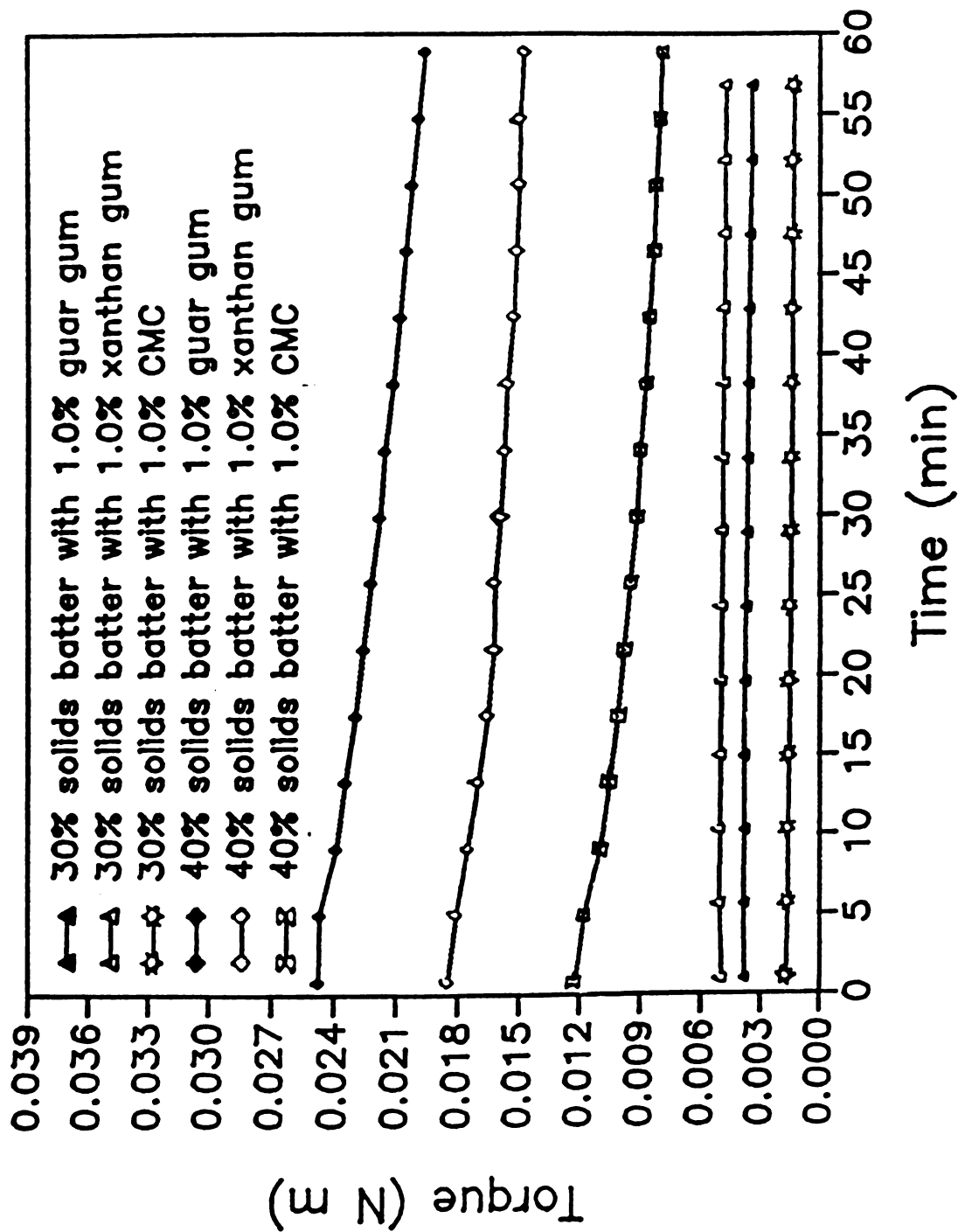


Figure 8 Torque of 30% and 40% solids batters with 1% hydrocolloids (guar gum, xanthan gum, sodium carboxymethylcellulose (CMC)) measured at 70 rpm, 10°C

Table 4 Time dependency data of 30% solids batters containing various hydrocolloids

Treatment	Torque ₃ (N m) x10 ³		Apparent viscosity (Pa s)		intercept ₃ A (N m)x10 ³	slope ₄ B x10 ⁴
	0 min (M ₀)	60 min (M ₆₀)	0 min (μ ₀)	60 min (μ ₆₀)		
control	0.37	0.42	0.11	0.13	0.35	-0.14
0.25% guar	0.82	0.69	0.25	0.22	0.91	0.51
0.5% guar	1.51	1.25	0.47	0.39	1.67	0.99
1.0% guar	3.83	3.37	1.19	1.05	4.14	1.82
0.25% xanthan	1.29	1.15	0.39	0.36	1.35	0.48
0.5% xanthan	2.68	2.34	0.83	0.73	2.84	1.16
1.0% xanthan	4.96	4.83	1.54	1.50	5.22	1.25
0.25% CMC	0.42	0.37	1.13	0.12	0.43	0.13
0.5% CMC	0.80	0.64	0.25	0.20	0.86	0.51
1.0% CMC	1.67	1.28	0.52	0.40	1.80	1.22

Table 5 Time dependency data of 40% solids batters containing various hydrocolloids

Treatment	Torque (N m) $\times 10^2$		Apparent viscosity (Pa s)		intercept, A (N m) $\times 10^2$	slope, B $\times 10^3$
	0 min	60 min	0 min	60 min		
	(M_0)	(M_{60})	(μ_0)	(μ_{60})		
control	1.14	0.70	3.53	2.17	1.18	1.10
1.0% guar	2.44	1.76	7.57	5.47	2.61	1.35
1.0% xanthan	1.85	1.47	5.74	4.56	2.04	1.42
1.0% CMC	1.22	0.78	3.80	2.42	1.30	1.14

B. TIME-INDEPENDENT APPARENT VISCOSITY OF BATTERS AT EQUILIBRIUM

1. TORQUE (M_x) VS ANGULAR VELOCITY (Ω_x) OF BATTERS

We assumed that time-dependency was removed by 60 min mixing at 70 rpm. Time-independent apparent viscosities (μ_a) of the samples were determined by increasing the rotational speed (N_x) of the viscometer from 10 to 90 rpm in intervals of 20 rpm. Table 6 shows the torque vs angular velocity of 30% solids batters and Table 7 illustrates those of 40% solids batters.

Batters containing the same hydrocolloid showed an increase in torque as hydrocolloid concentration increased at each rotational speed. Torque decreased in batters containing the same hydrocolloid concentration, at each rotational speed, except 10 rpm, in the following order: xanthan guar > CMC > control. At 10 rpm and 0.25% hydrocolloid concentration, torque decreased in the following order: xanthan > CMC > control > guar. Torque increased when rotational speed of the viscometer increased at the same hydrocolloid concentration.

Torque vs angular velocities of 40% batter solids content are shown in Table 7. Only control batter and 1.0% hydrocolloid concentration batters were measured. Guar batter had the highest torque, followed by xanthan, CMC and control batter at each rotational speed except at 10 rpm, where xanthan batter had the highest torque. Torque increased with increased rotational speed at the same hydrocolloid concentration.

Table 6 Angular velocity (Ω_x) vs torque (M_x) of 30% solids batters

N_x (rpm)	Ω_x (1/s)	Torque (N m)x10 ³			
		Hydrocolloid Concentration(%)			
		control	0.25	0.5	1.0
		Guar			
10	1.047	0.15	0.13	0.31	0.97
30	3.142	0.25	0.32	0.66	1.95
50	5.236	0.35	0.50	0.96	2.65
70	7.330	4.42	0.66	1.24	3.30
90	9.425	5.36	0.82	1.50	3.72
Xanthan					
10	1.047	0.15	0.34	0.99	2.41
30	3.142	0.25	0.64	1.58	3.47
50	5.236	0.35	0.88	2.02	4.13
70	7.330	4.42	1.12	2.41	4.68
90	9.425	5.36	1.34	2.75	5.18
CMC					
10	1.047	0.15	0.18	0.19	0.33
30	3.142	0.25	0.28	0.41	0.78
50	5.236	0.35	0.37	0.52	1.16
70	7.330	4.42	0.48	0.74	1.52
90	9.425	5.36	0.58	0.88	1.84

Table 7 Angular velocity (Ω_x) vs torque (M_x) of 40% solids batters containing 1% hydrocolloid

N_x (rpm)	Ω_x (1/s)	Torque (N m) $\times 10^2$			
		control	1.0% guar	1.0% xanthan	1.0% CMC
10	1.047	0.10	0.66	0.66	0.16
30	3.142	0.29	1.19	0.96	0.37
50	5.236	0.48	1.57	1.19	0.56
70	7.330	0.68	1.88	1.40	0.74
90	9.425	0.86	2.13	1.58	0.91

2. FLOW BEHAVIOR INDEX (n_x) OF BATTERS

The flow behavior index (calculated from Eq. [16]) varied among the different hydrocolloid containing batters and control batter. However, the flow behavior index decreased with increasing hydrocolloid concentration in guar and xanthan batters, but increased with increasing concentrations of CMC (Table 8). Xanthan containing batter had the lowest and control batter had the highest flow behavior index in 40% solids batters (Table 9).

All batters had a flow behavior index less than 1, indicating that the batters were shear-thinning or pseudoplastic materials under time-independent measurement. The batters became thinner when the rotational speed increased. The use of higher speeds to mix the batters will require less energy, since materials have less resistance. Other authors also have reported that hydrocolloids exhibit pseudoplastic properties (Goldstein et al., 1973; Batdorf et al., 1973).

Table 8 Power law model parameters of 30% solids control batter and batters containing different concentration of three hydrocolloids

Treatment	Flow behavior index, n_x (dimensionless)	Correlation coefficient
control	0.587	0.995
0.25% guar	0.829	1.000
0.5% guar	0.710	1.000
1.0% guar	0.619	1.000
0.25% xanthan	0.615	0.998
0.5% xanthan	0.462	0.999
1.0% xanthan	0.345	0.999
0.25% CMC	0.528	0.990
0.5% CMC	0.697	0.996
1.0% CMC	0.786	1.000

Table 9 Power law model parameters of 40% solids control batter and batters containing 1% of three hydrocolloids

Treatment	Flow behavior index, n_x (dimensionless)	Correlation coefficient
control	0.977	1.000
1.0% guar	0.535	1.000
1.0% xanthan	0.349	0.997
1.0% CMC	0.789	1.000

3. CONSISTENCY COEFFICIENT (K_x) OF BATTERS:

Consistency coefficients under different average shear rates ($k'\Omega_x$) and the average of consistency coefficients under different average shear rates were measured on 30% solids (Table 10) and 40% solids batters (Table 11).

K_x increased when hydrocolloid concentration in 30% solids batter was increased under the same average shear rate, except in CMC containing batter. The K_x of the CMC batter containing 0.5% hydrocolloid was lower than that of the batters containing 0.25% CMC. K_x increased in 0.5% and 1.0% hydrocolloid containing batters in the following order: xanthan > guar > CMC > control. However, in 0.25% hydrocolloid batters, the order was xanthan > CMC > control > guar under each average shear rate. The K_x always increased when the average shear rate increased at the same hydrocolloid concentration. The average K_x increased in 0.5% and 1.0% hydrocolloid containing batters was also in the order of xanthan > guar > CMC > control. In 0.25% hydrocolloid batters, the order of average K_x was also xanthan > CMC > control > guar.

K_x and the average K_x of 40% solids batters were always xanthan > guar > CMC > control. Also, K_x increased as the average shear rate increased at the same hydrocolloid concentration.

As hydrocolloid concentration increased, average K_x increase. Thirty percent basis control and 0.25% CMC batters had the least average K_x compared to the others. Forty percent batters had higher average K_x than 30% batters at the same hydrocolloid concentration. Xanthan and guar batter had higher average K_x than CMC and control batters on both a 30% and 40% solids basis containing 1% hydrocolloid concentration.

Table 10 Consistency coefficients of 30% solids batters

			Consistency Coefficient, K_x (Pa s ⁿ)			
Rotational Speed (rpm)	Average Shear Rate, $k'\Omega_x$ (1/s)	Hydrocolloid Concentration (%)				
		control	0.25	0.5	1.0	
		Guar				
10	4.67	0.44	0.27	0.78	2.76	
30	14.01	0.47	0.32	0.90	3.37	
50	23.35	0.53	0.35	0.99	3.83	
70	32.69	0.58	0.37	1.06	3.87	
90	42.04	0.63	0.39	1.11	3.89	
Average	50	23.35	0.53	0.34	0.97	3.54
			Xanthan			
10	4.67	0.44	0.99	3.62	10.50	
30	14.01	0.47	1.11	4.12	12.35	
50	23.35	0.53	1.22	4.54	13.38	
70	32.69	0.58	1.33	4.89	14.27	
90	42.04	0.63	1.42	5.18	15.08	
Average	50	23.35	0.53	1.21	4.47	13.12
			CMC			
10	4.67	0.44	0.59	0.47	0.72	
30	14.01	0.47	0.61	0.58	0.87	
50	23.35	0.53	0.68	0.56	0.94	
70	32.69	0.58	0.77	0.67	0.99	
90	42.04	0.63	0.85	0.69	1.03	
Average	50	23.35	0.53	0.70	0.59	0.91

Table 11 Consistency coefficient of 40% solids batters

Rotational Speed (rpm)	Average Shear Rate, $k'\Omega_x$ (1/s)	Consistency Coefficient, K_x (Pa s ⁿ)			
		control	1.0%guar	1.0%xanthan	1.0%CMC
10	4.67	1.67	21.45	26.72	3.53
30	14.01	1.93	25.71	29.99	4.13
50	23.35	2.15	28.01	33.19	4.53
70	32.69	2.29	29.54	36.04	4.79
90	42.04	2.37	30.50	38.27	5.07
Average 50	23.35	2.08	27.04	32.84	4.41

4. APPARENT VISCOSITY (μ_a) OF BATTERS

Batter apparent viscosity results are tabulated in Table 18 for the 30% solids batters, and Table 19 for the 40% solids batters.

The effect of shear rate on apparent viscosity of 30% solids batters containing guar, xanthan and CMC are illustrated in Figures 9, 10 and 11, respectively. When batter contained the same percentage hydrocolloid, xanthan batter always showed the highest apparent viscosity, followed by guar batter, CMC batter, and control batter at each rotational speed. The average apparent viscosity was in the same decreased order. At 10 rpm and 0.25% hydrocolloid content, the apparent viscosity decreased with hydrocolloid type in the following order: xanthan > CMC > control > guar. Generally, increasing the rotational speed decreased the apparent viscosity in each hydrocolloid batter, except in 0.25% guar batter and 1.0% CMC batter, where the apparent viscosity varied irregularly with increasing rotational speed. The degradation of apparent viscosity with increasing rotational speed was probably due to the destruction of the binding forces in the batter, for example, between hydrogen bonds of the carbohydrates.

Apparent viscosity under each rotational speed and the average apparent viscosity of 40% solids batters were decreased in the order of 1.0% guar > 1.0% xanthan > 1.0% CMC > control, except at 10 rpm, the order was 1.0% xanthan > 1.0% guar > 1.0% CMC > control (Figure 12). The batters exhibited decreased apparent viscosity when the rotational speed increased, except the control batter which had increased apparent viscosity with increased rotational speed.

The apparent viscosity vs average shear rate of 1.0% gum containing

batters of 30% and 40% solids content is illustrated in Figure 13. Forty percent solids batter had higher apparent viscosities than thirty percent solids batters.

Therefore, results indicated that control and 0.25% CMC batters had the lowest average apparent viscosity. Xanthan and guar batters had higher apparent viscosity than CMC batter at the same hydrocolloid concentration. When hydrocolloid concentration or batter solids content increased, the average apparent viscosity increased.

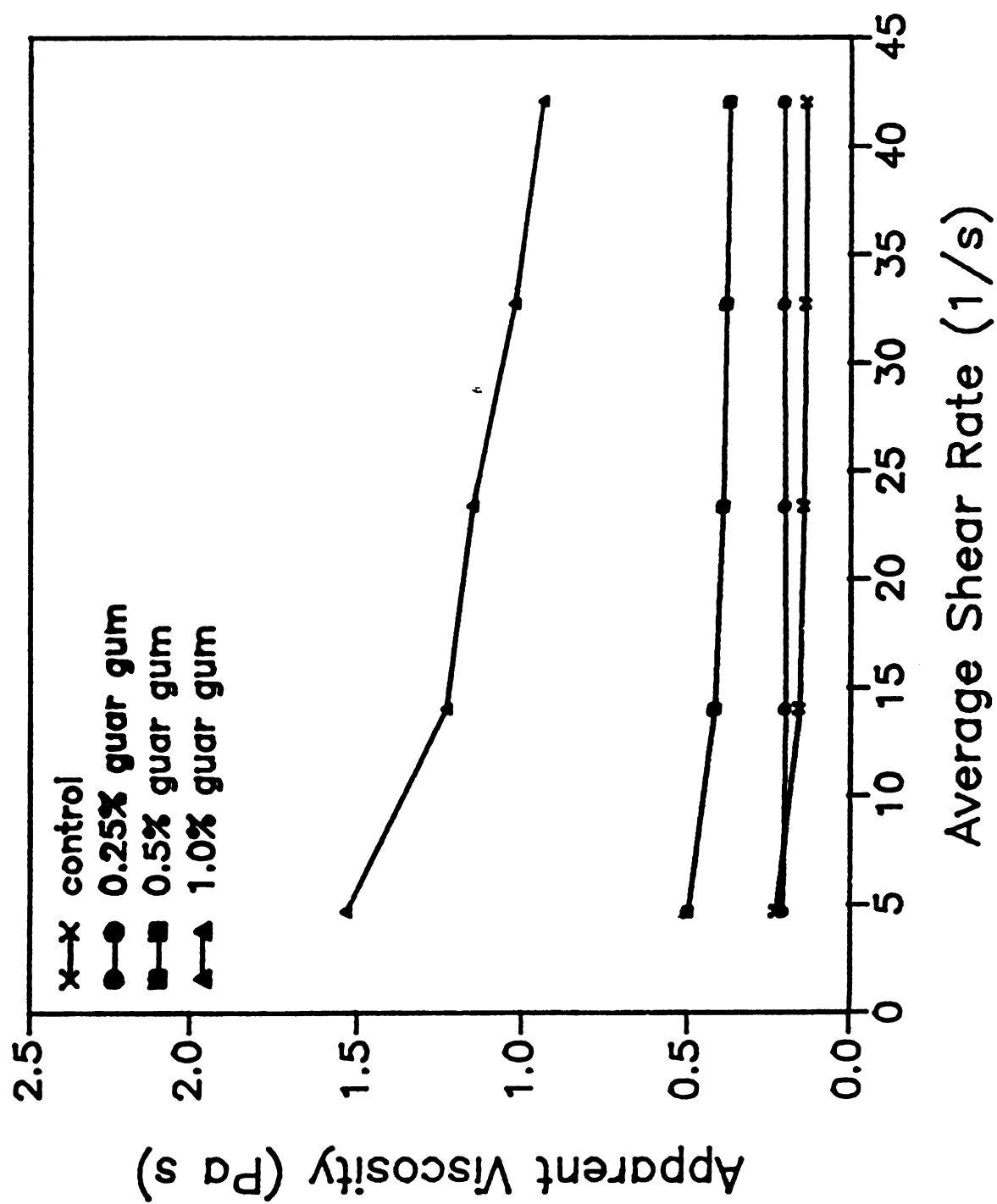


Figure 9 Apparent viscosity vs average shear rate of 30% solids batter containing guar gum

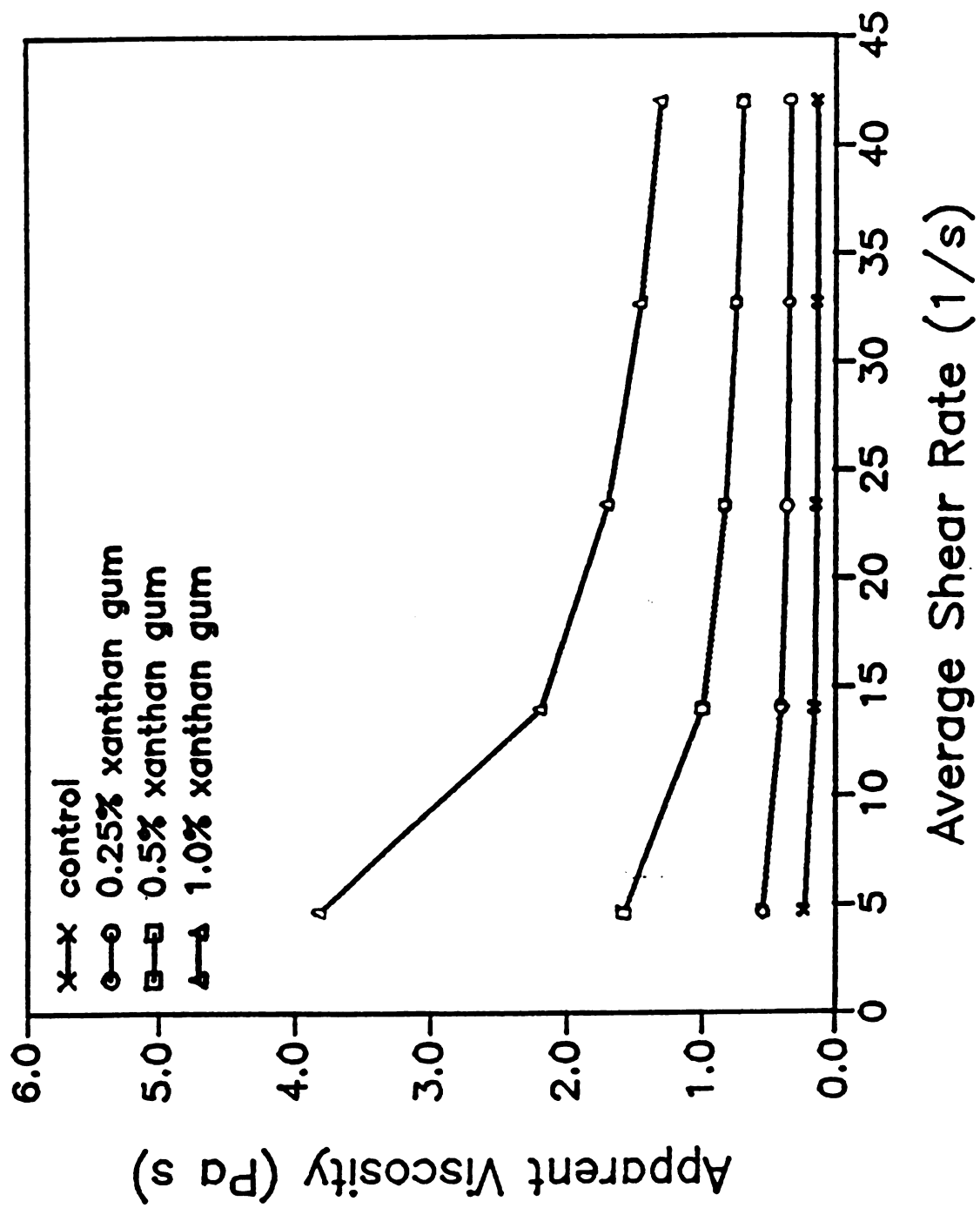


Figure 10 Apparent viscosity vs average shear rate of 30% solids batter containing xanthan gum

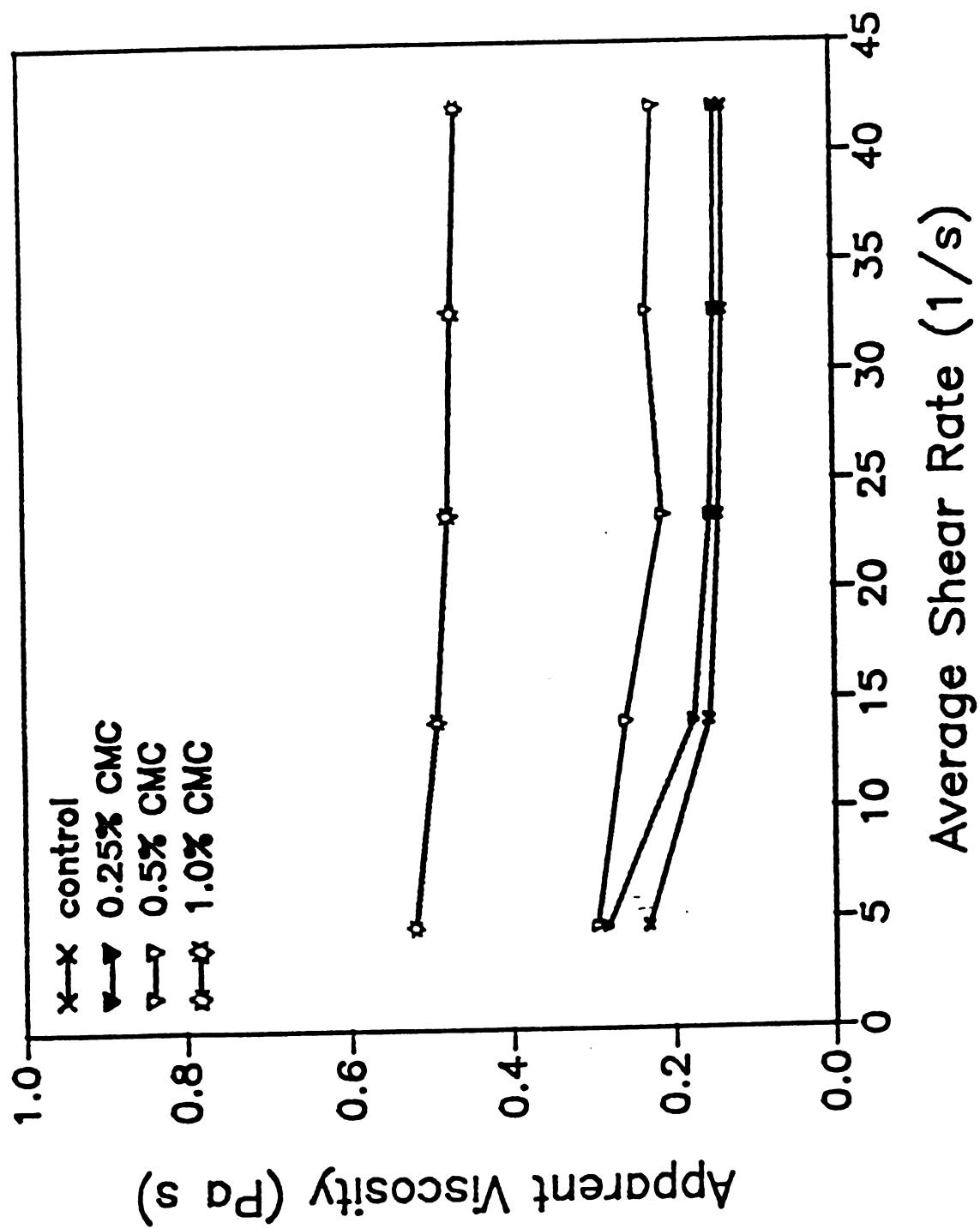


Figure 11 Apparent viscosity vs average shear rate of 30% solids batter containing sodium carboxymethylcellulose (CMC)

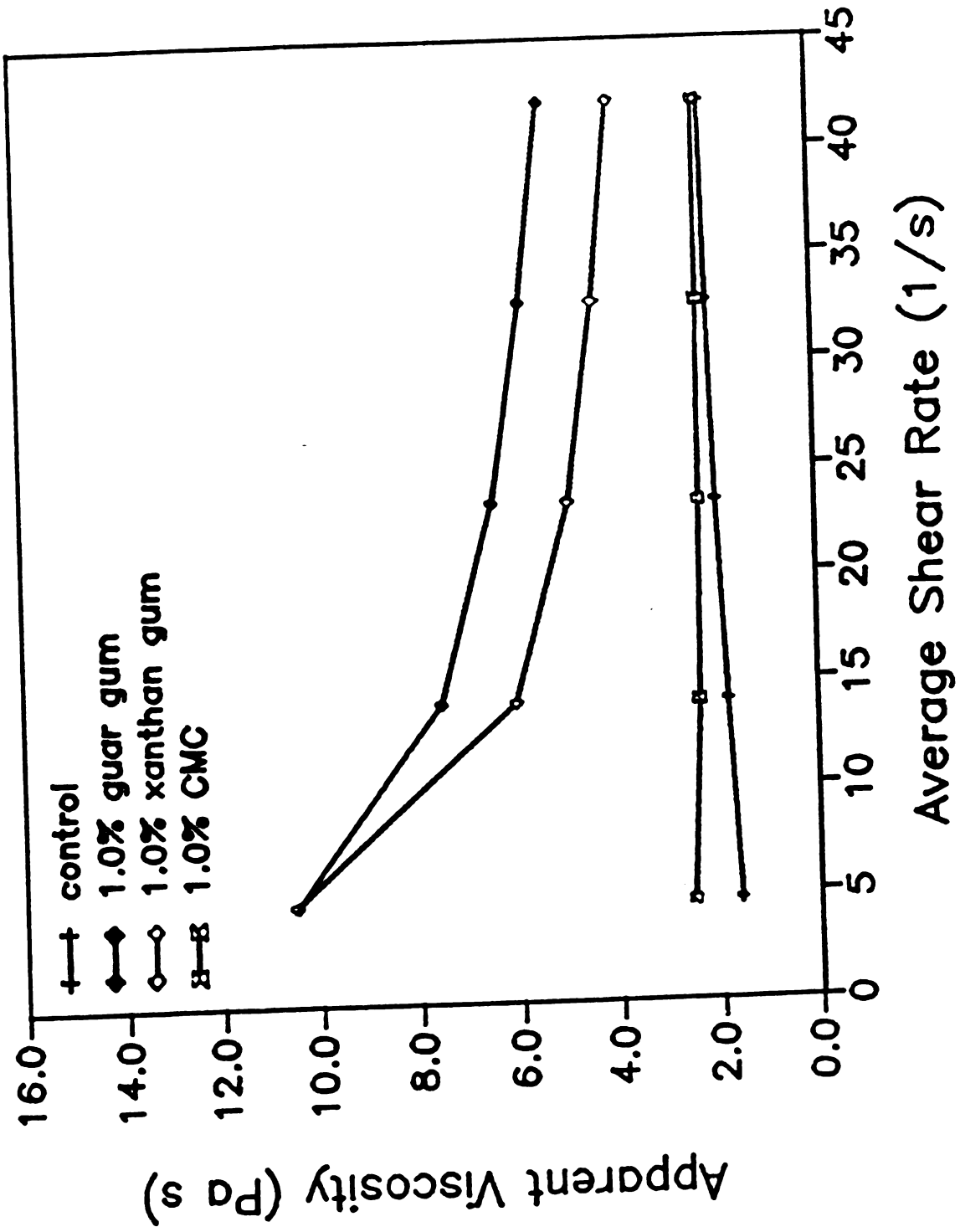


Figure 12 Apparent viscosity vs average shear rate of 40% solids batter containing 1% hydrocolloid (guar gum, xanthan gum, sodium carboxymethylcellulose (CMC))

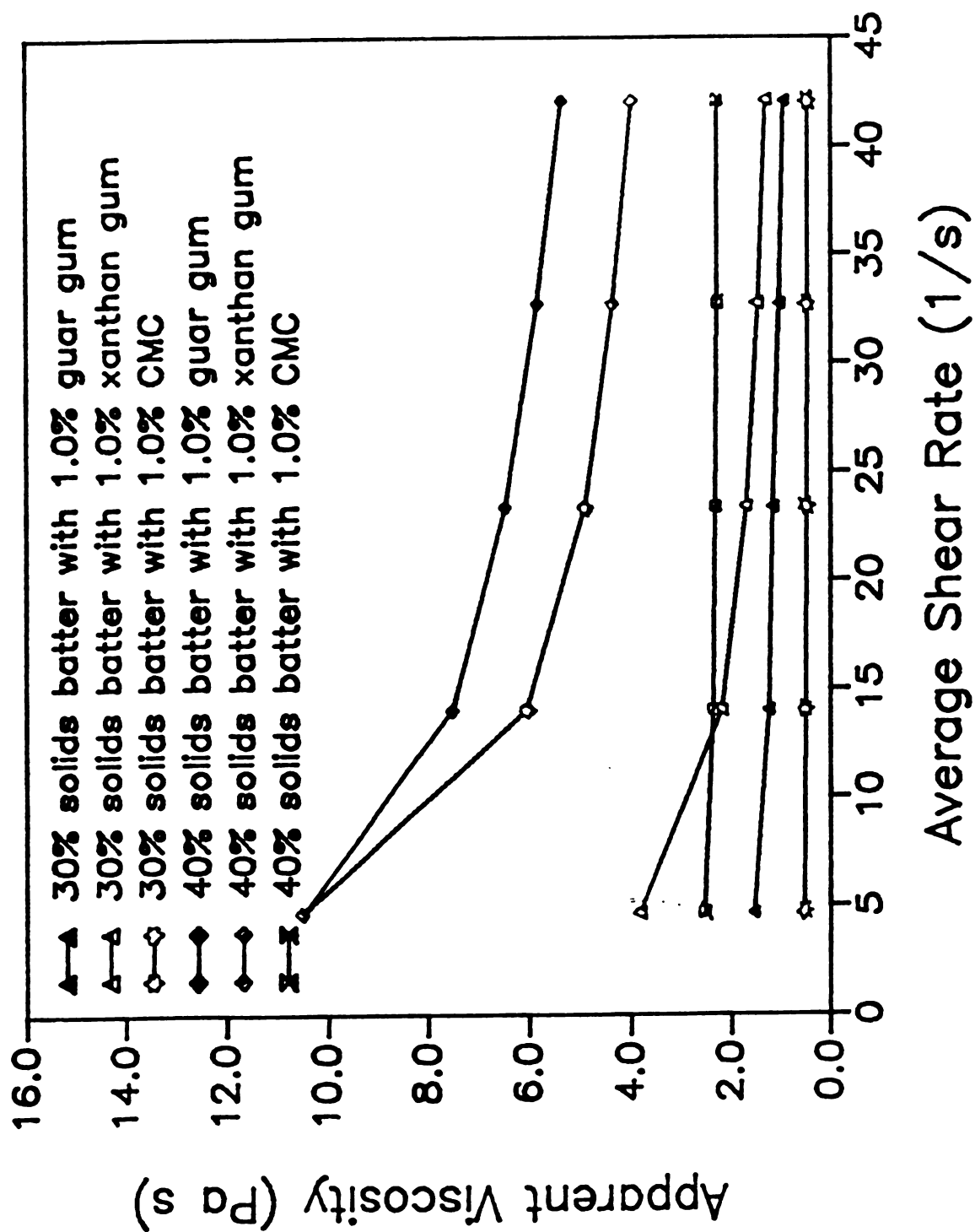


Figure 13 Apparent viscosity vs average shear rate of 30% and 40% solids batter containing 1% hydrocolloid (guar gum, xanthan gum, sodium carboxymethylcellulose (CMC))

5. RECOVERY OF CHICKEN BATTERS:

All batters had recoveries less than 100%, except 30% control batter (Table 12 and Table 13). Thirty percent control batter had 127% recovery. The hydration of starch granules caused the increase of apparent viscosity and over 100% recovery. The other batters had hydrocolloid surrounding the starch granules which prevented the hydration of starch granules. Therefore, they had recoveries less than 100% and decreased apparent viscosity over time of mixing. When batter solids content increased, there were more starch granules in the batter and less starch hydration. Therefore, the recoveries of 40% solids batters were less than those of 30% solids batters at the same hydrocolloid concentration.

The percent recovery reflects the properties of time-dependent behavior of the samples, while time-dependency reflects the change of batter viscosity with time. When percent recovery equals 100, there is no time-dependent behavior or complete recovery in the sample. If recovery does not equal to 100, there is irreversible structural breakdown in the sample. The far the percent recovery from 100, the stronger the time-dependency properties. If the percent recovery is over 100, more energy will be needed to mix the sample. Similarly, less energy is needed when percent recovery is less than 100. The quality is also different in these two situations.

Recovery can be used as an index to indicate how much energy is needed to restart the machine and how much batter quality is changed on standing.

Table 12 Recovery of 30% solids control batter and batters containing different hydrocolloids

Treatment	Recovery (%)
control	127 ^a
0.25% guar	73 ^{c, d}
0.5% guar	71 ^{c, d}
1.0% guar	77 ^c
0.25% xanthan	81 ^{b, c}
0.5% xanthan	86 ^{b, c}
1.0% xanthan	92 ^b
0.25% CMC	98 ^b
0.5% CMC	66 ^d
1.0% CMC	86 ^{b, c}

Any two means with the same letter(s) were not significantly different from each other by Tukey's Test at $\alpha = 0.01$.

Table 13 Recovery of 40% solids control batter and batters containing different hydrocolloids

Treatments	Recovery (%)
control	60 ^c
1.0% guar	69 ^{b,c}
1.0% xanthan	81 ^a
1.0% CMC	56 ^c

Any two means with the same letter(s) were not significantly different from each other by Tukey's Test at $\alpha = 0.01$.

C. ADHESION CHARACTERISTICS OF BATTERS

1. ADHESION CHARACTERISTICS OF 30% SOLIDS CHICKEN BATTERS

Adhesion characteristics of batter to chicken nuggets were evaluated by determining percent crumb loss, percent cooking loss, percent coating pickup, percent overall yield, and percent cooking yield. Results are tabulated in Table 20.

No significant difference was observed in percent crumb loss (Figure 14) or percent cooking loss (Figure 15) of the ten 30% solids batter treatments. Type and concentration of hydrocolloid did not influence the percent crumb loss or percent cooking loss of batters. The standard deviation and experimental error may have been caused by manipulation error, fryer temperature control error or frying time error.

Batter composition had a large influence on the amount of coating picked up by the chicken nuggets (Figure 16). Percent coating pickup increased as hydrocolloid concentration increased in the batter. Percent coating pickup of the batters increased significantly by 140% compared to the control at guar gum concentration of 1.0%. The largest increase in coating pickup with hydrocolloid concentration was observed in the xanthan gum containing batters. A 135% and 296% increase in coating pickup was observed over the control when 0.5 and 1.0% xanthan gum was added to the batters. At the same hydrocolloid concentration, xanthan gum containing batters exhibited the highest coating pickup followed by guar gum containing batters. Coating pickup in CMC containing batters did not differ significantly from the control.

Overall yield of the chicken nuggets was significantly influenced

by the type and concentration of hydrocolloid in the batter mix. At the same hydrocolloid concentration, the percent overall yield decreased in the following order: xanthan > guar > CMC > control (Figure 17). Compared to the control, a 16% increase of overall yield was observed at 1% guar gum. For the xanthan gum batter, an increase of 37% over the control was observed at 1.0% xanthan concentration in the batter. The % overall yield of CMC containing batters did not differ significantly from the control.

The concentration of xanthan gum also significantly influenced the % cooking yield of the batters (Figure 18). The percent cooking yield had the same decreased order as the percent overall yield had when the same hydrocolloid concentration was in the batter. The highest cooking yield was observed in xanthan gum containing batter. At xanthan concentrations of 0.5 and 1.0%, cooking yield increased significantly by 16% and 38% compared to the control. Guar gum and CMC in the batters did not increase cooking yield compared to the control.

Therefore, we found that 1% xanthan batter had the significantly highest coating pickup, overall yield, and cooking yield among the samples. However, control and 0.25% CMC batters had the significant lowest coating pickup, overall yield, and cooking yield among the samples. As hydrocolloid concentration increased, coating pickup, overall yield, and cooking yield also increased.

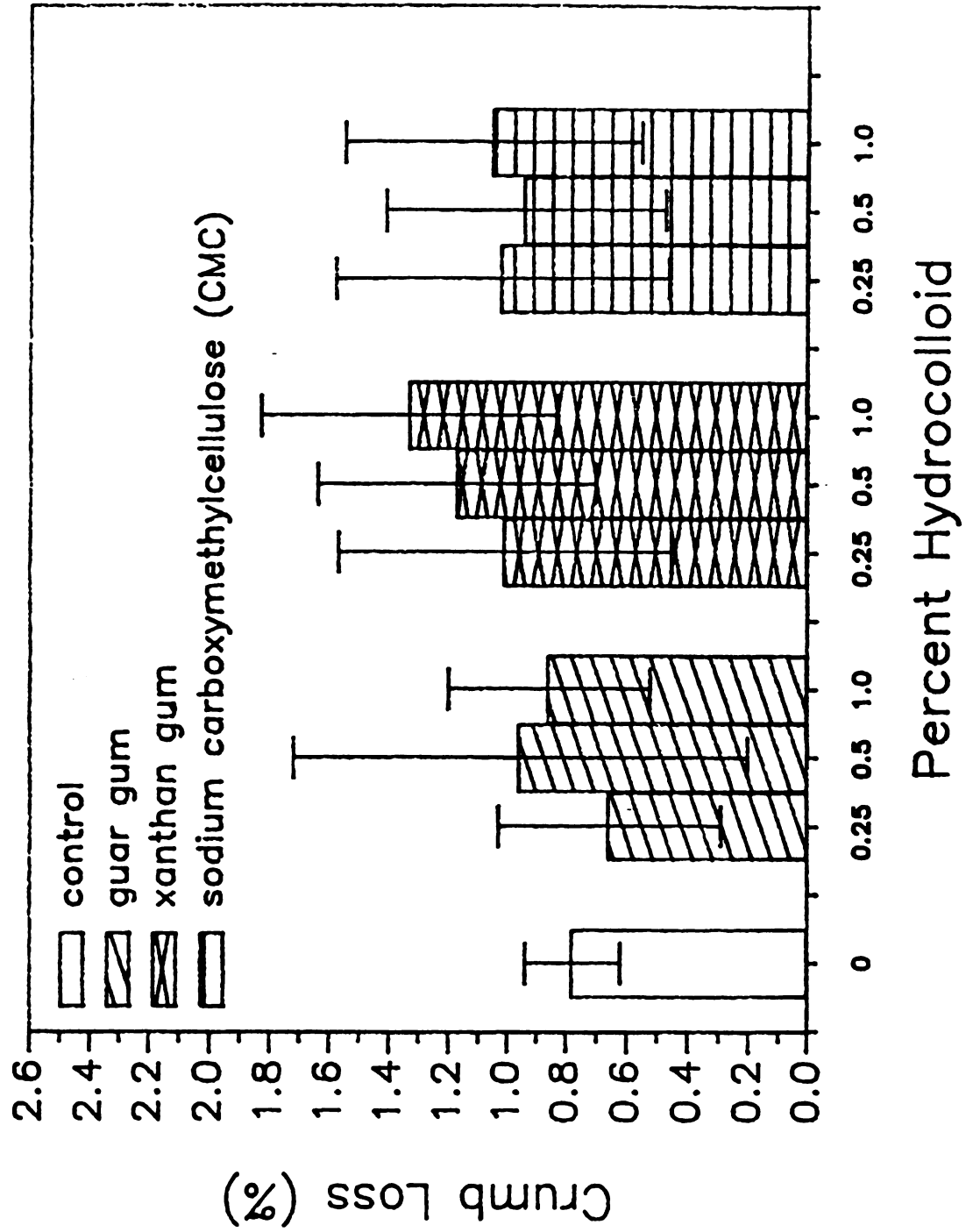


Figure 14 Percent crumb loss of chicken nuggets prepared with 30% solids batters containing different hydrocolloids (error bars are standard deviation)

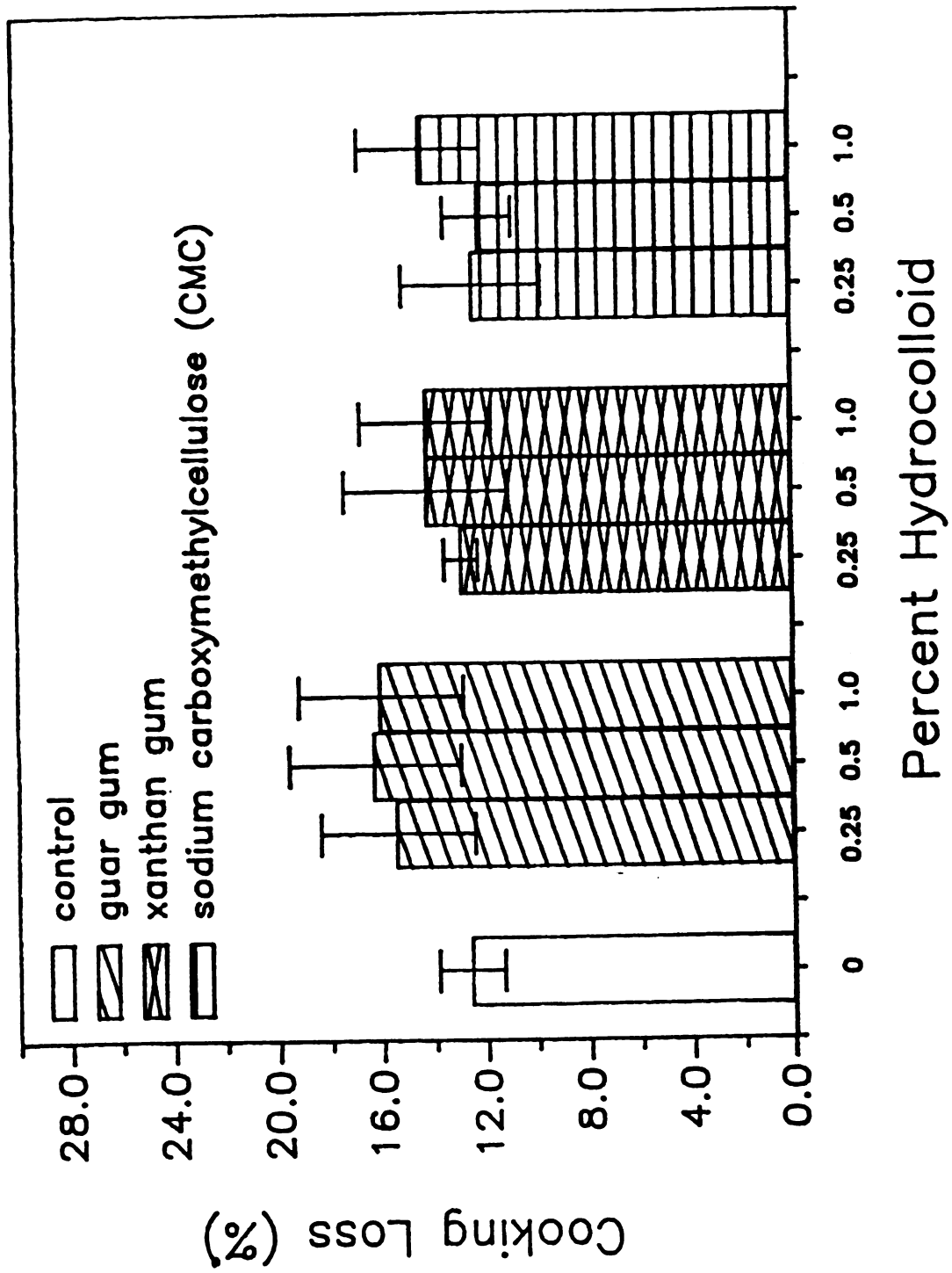


Figure 15 Percent cooking loss of chicken nuggets prepared with 30% solids batters containing different hydrocolloids (error bars are standard deviation)

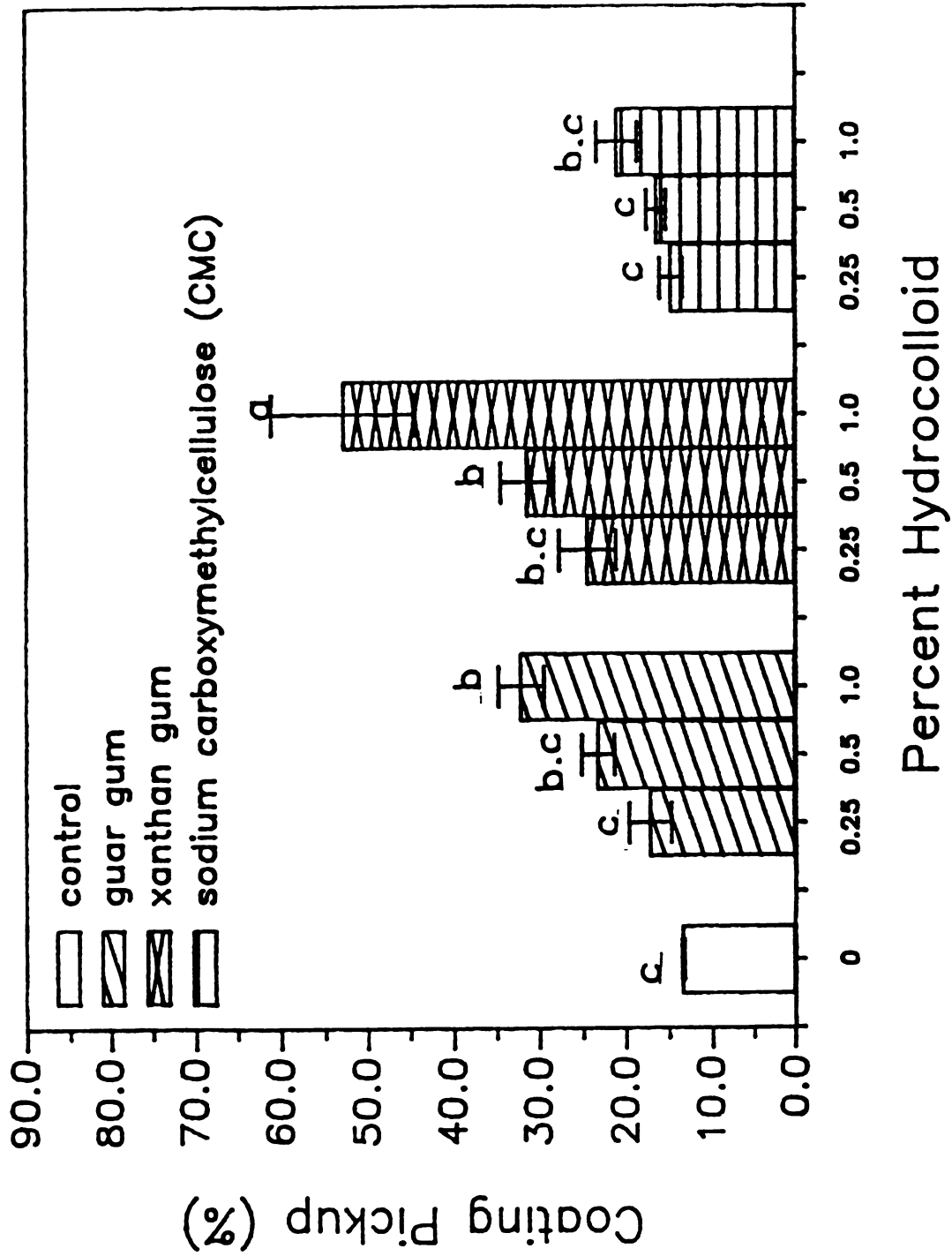


Figure 16 Percent coating pickup of chicken nuggets prepared with 30% solids batters containing different hydrocolloids (error bars were standard deviation) (any two means with the same letter(s) were not significantly different from each other by Tukey's test at $\alpha = 0.01$)

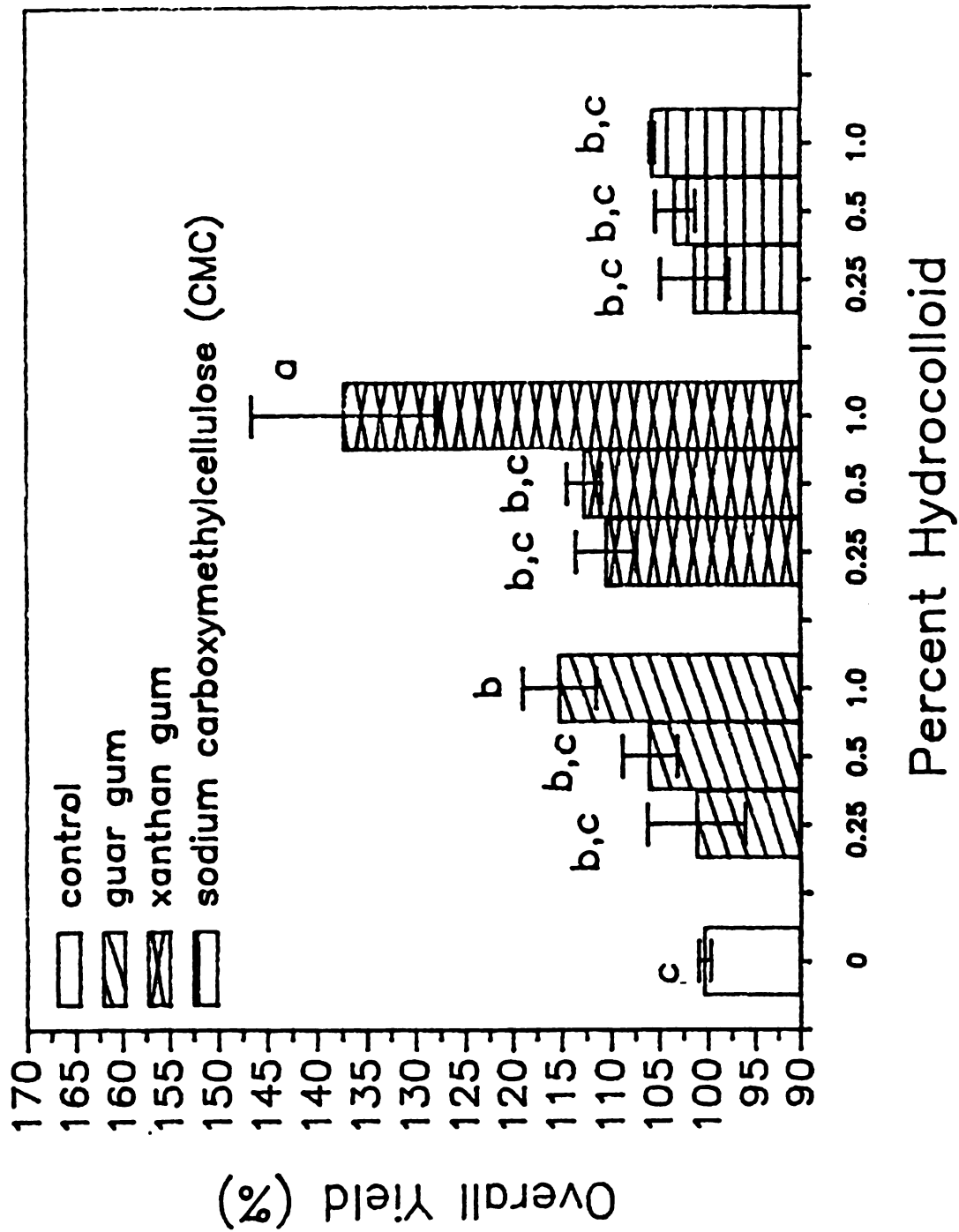


Figure 17 Percent overall yield of chicken nuggets prepared with 30% solids batters containing different hydrocolloids (error bars were standard deviation) (any two means with the same letter(s) were not significantly different from each other by Tukey's test at $\alpha = 0.01$)

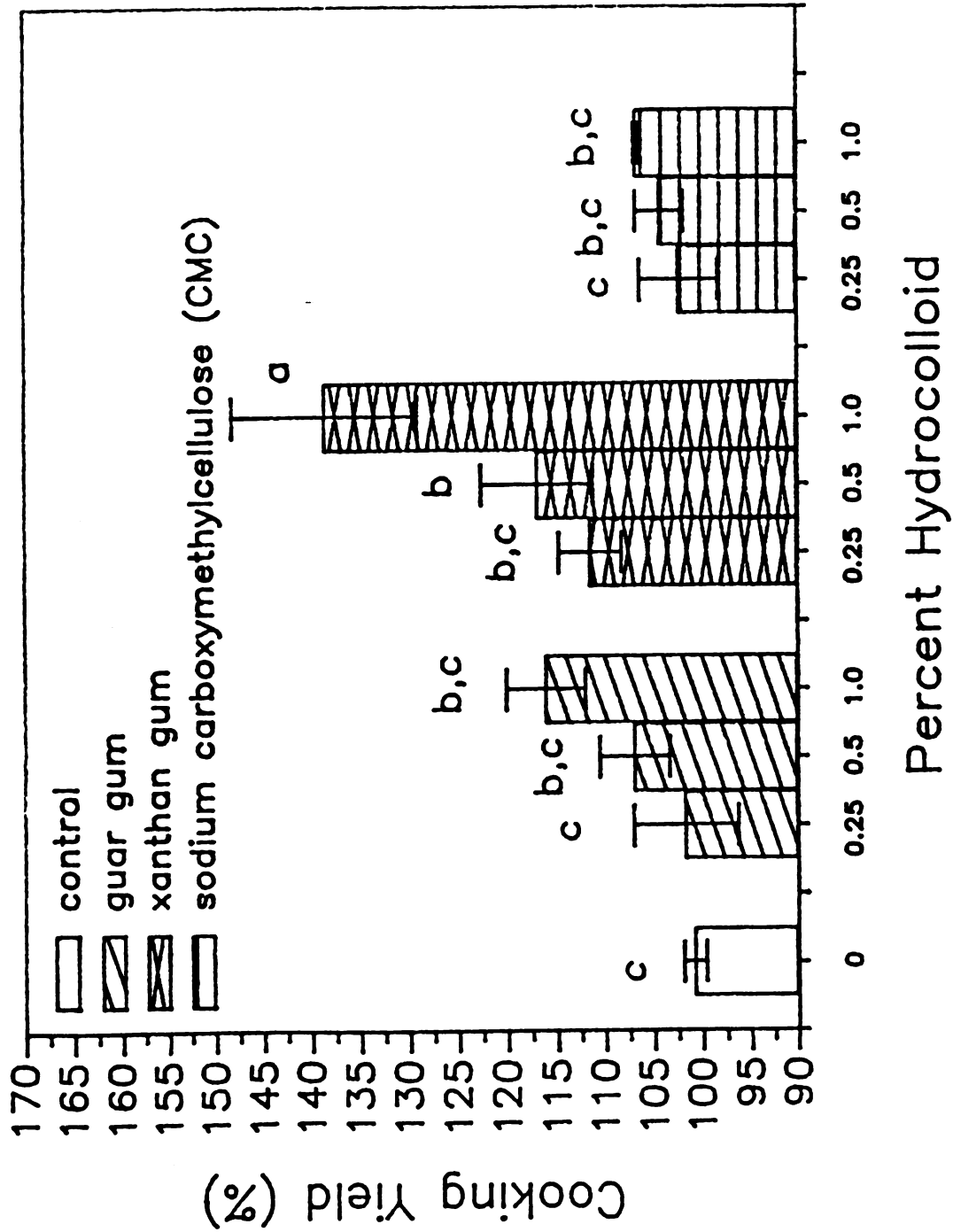


Figure 18 Percent cooking yield of chicken nuggets prepared with 30% solids batters containing different hydrocolloids. (error bars were standard deviation) (any two means with the same letter(s) were not significantly different from each other by Tukey's test at $\alpha = 0.01$)

2. ADHESION CHARACTERISTICS OF 40% SOLIDS CHICKEN BATTERS

There were statistically significant differences among the treatments in all of the measured adhesion characteristics. Table 21 shows the results of adhesion characteristics of 40% solids chicken batters.

Gum containing batters had higher percent crumb loss than non-gum containing batters (Figure 19). One percent xanthan gum gave the batter the highest loss of crumb among the others. Crumb loss of the batters increased by 167% and 100% at 1% xanthan and 1% CMC as compared to the control. Crumb loss of 1% guar containing batter did not differ significantly from the control. The higher crumb-loss batter had higher standard deviation than the lower crumb-loss batter. The reason seemed the same as the previous description, such as the manipulation error, fryer temperature control error or frying time error.

Guar gum containing batter had the highest and the control batter had the lowest cooking loss among the samples (Figure 20). Percent cooking loss decreased in the order of guar > CMC > xanthan > control. An increase of 50% of cooking loss as 1% guar was added to the control. The percent cooking loss of xanthan and CMC containing batter did not differ significantly from the control.

Guar gum batter had the highest coating pickup among the samples containing 1% hydrocolloid, followed by xanthan gum. Guar and xanthan gum (1%) increased coating pickup by of 121% and 98% over the control, respectively (Figure 21). CMC in batters did not increase coating pickup significantly compared to the control. The lowest value was given by the control.

Xanthan and guar batters had almost the same high overall yield (Figure 22). The control exhibited the lowest overall yield. Overall yield of the batters increased by 20% when 1% xanthan or 1% guar was added to the batter. CMC in the batters did not increase overall yield significantly compared to the control.

Percent cooking yield of the samples was similar to those of the percent overall yield (Figure 23). An increase of approximately 20% in cooking yield was observed when 1% xanthan and 1% guar were added to the batter. The percent cooking yield of 1% CMC containing batter did not differ significantly from the control.

Therefore, we found that coating pickup, overall yield, and cooking yield were high in xanthan and guar batters, but low in control and CMC batters. Results also indicated that batters with higher crumb loss also had higher coating pickup, overall yield, and cooking yield. Cunningham and Tiede's (1981) also found that, as the viscosity of the batters increased, the amount of breading pickup and crumb-loss increased.

In general, gum containing batters had higher adhesion than non-gum containing batters. It was concluded that gums were helpful in increasing the yield of battered and breaded products. Our conclusion agreed with a similar report by Suderman et al. (1981), that gum source significantly affected adhesion of breading to poultry drum-sticks. However, they found that there was no effect of gum level or level-source interaction. In their report, CMC was significantly better than guar, and guar was significantly better than xanthan in crumb loss. In our research, we could not find significant differences in crumb loss among our different batter treatments. Also, coating pickup, overall yield, and cooking yield of treatments were significantly different. Xanthan gum

gave the best coating pickup, overall yield, and cooking yield among the tested hydrocolloids. CMC contributed the least to adhesion of batter to chicken batters. The difference in results between our experiment and Suderman et al. (1981) may be caused by formulation differences. We added hydrocolloids to the batter mix while Suderman added the gum to the breading. In Suderman's research, hydrocolloids interfaced to breading and chicken drumsticks. While in our research, hydrocolloid interfaced to water, batter, chicken nuggets, and breading. Xanthan gum exhibited the highest crumb loss in both studies, but also gave the highest coating pickup, overall yield, and cooking yield in our study. CMC gave the lowest crumb loss in both studies, but also gave the lowest coating pickup, overall yield, and cooking yield in our study.

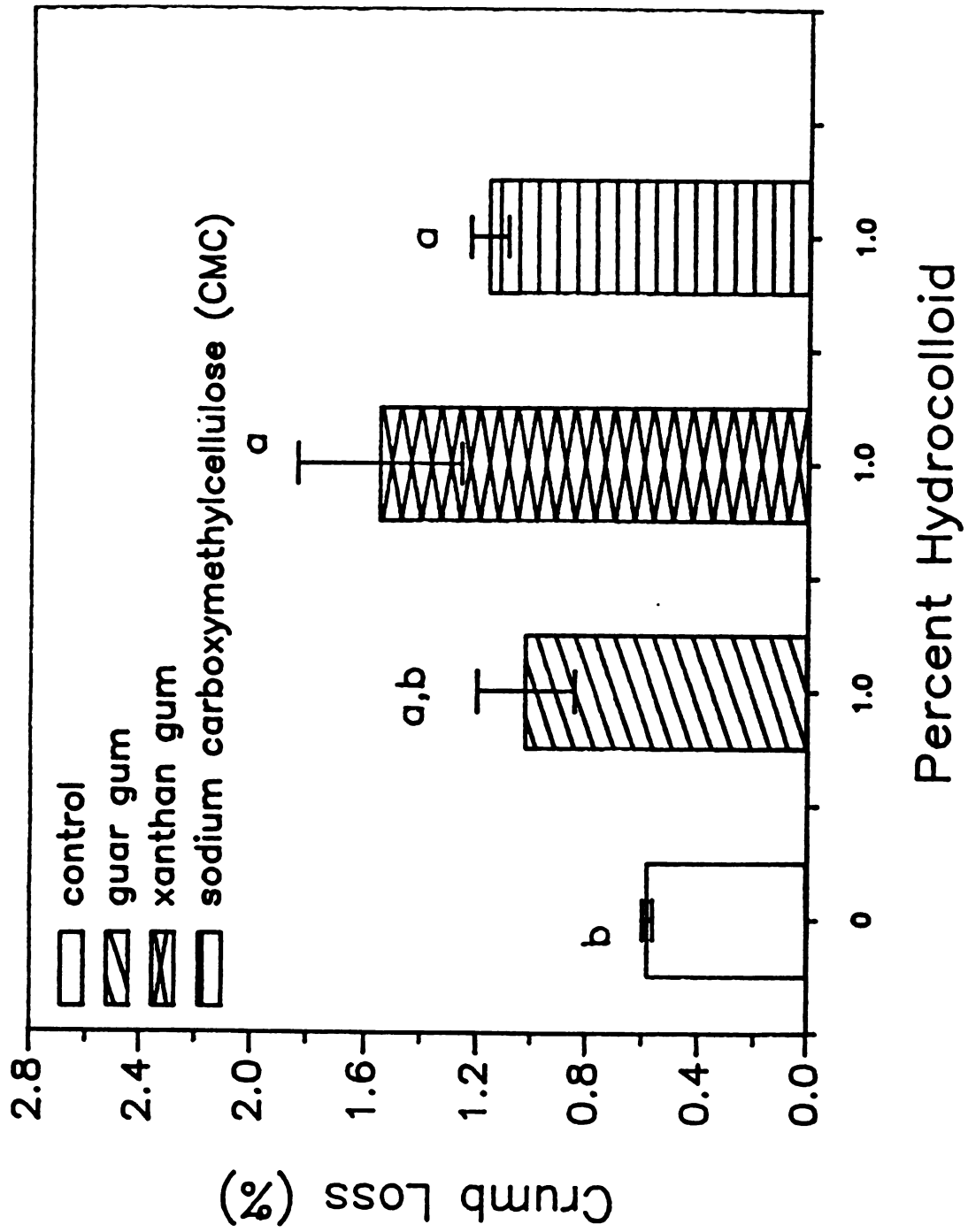


Figure 19 Percent crumb loss of chicken nuggets prepared with 40% solids batters containing different hydrocolloids (error bars were standard deviation) (any two means with the same letter(s) were not significantly different from each other by Tukey's test at $\alpha = 0.01$)

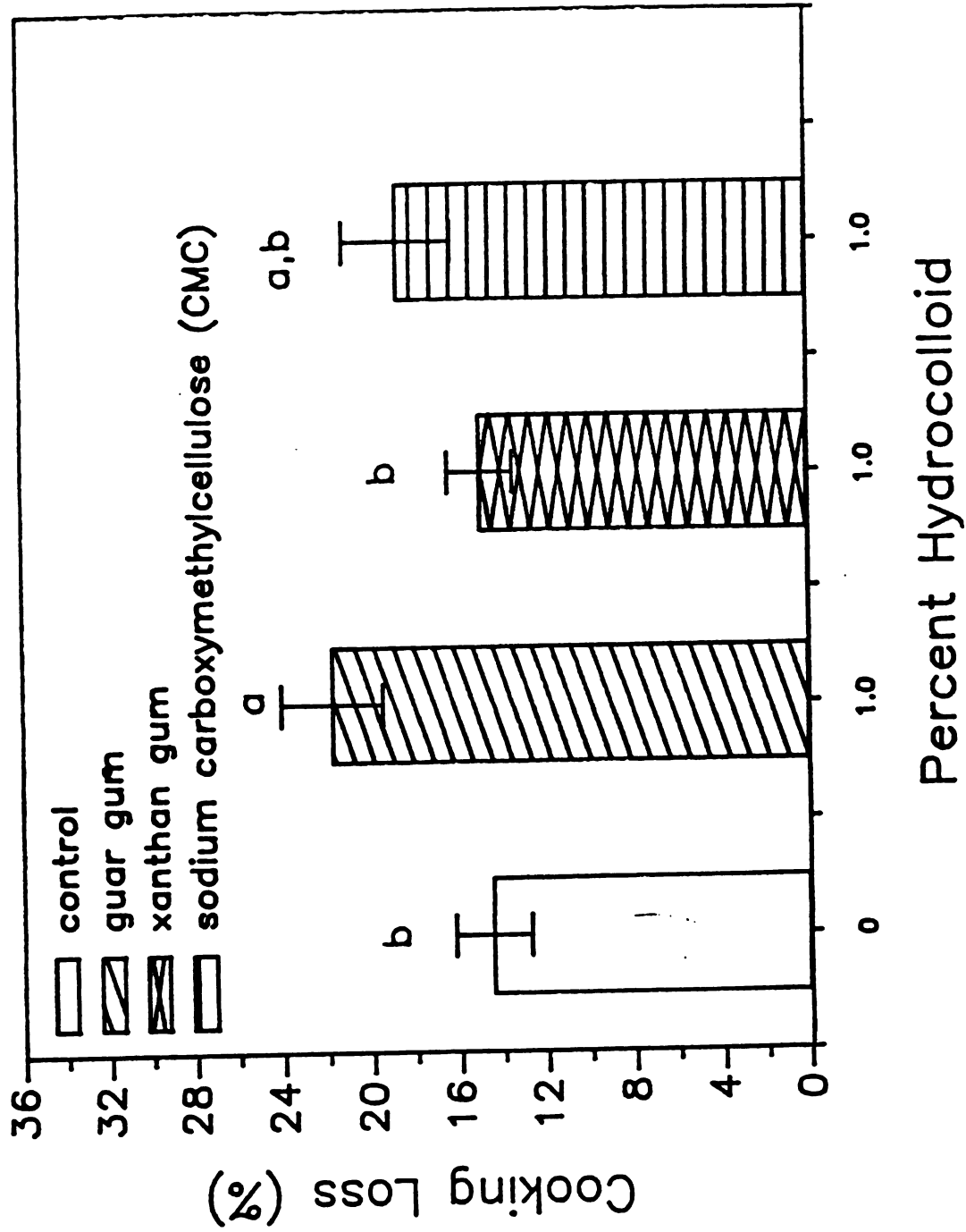


Figure 20 Percent cooking loss of chicken nuggets prepared with 40% solids batters containing different hydrocolloids (error bars were standard deviation) (any two means with the same letter(s) were not significantly different from each other by Tukey's test at $\alpha = 0.01$)

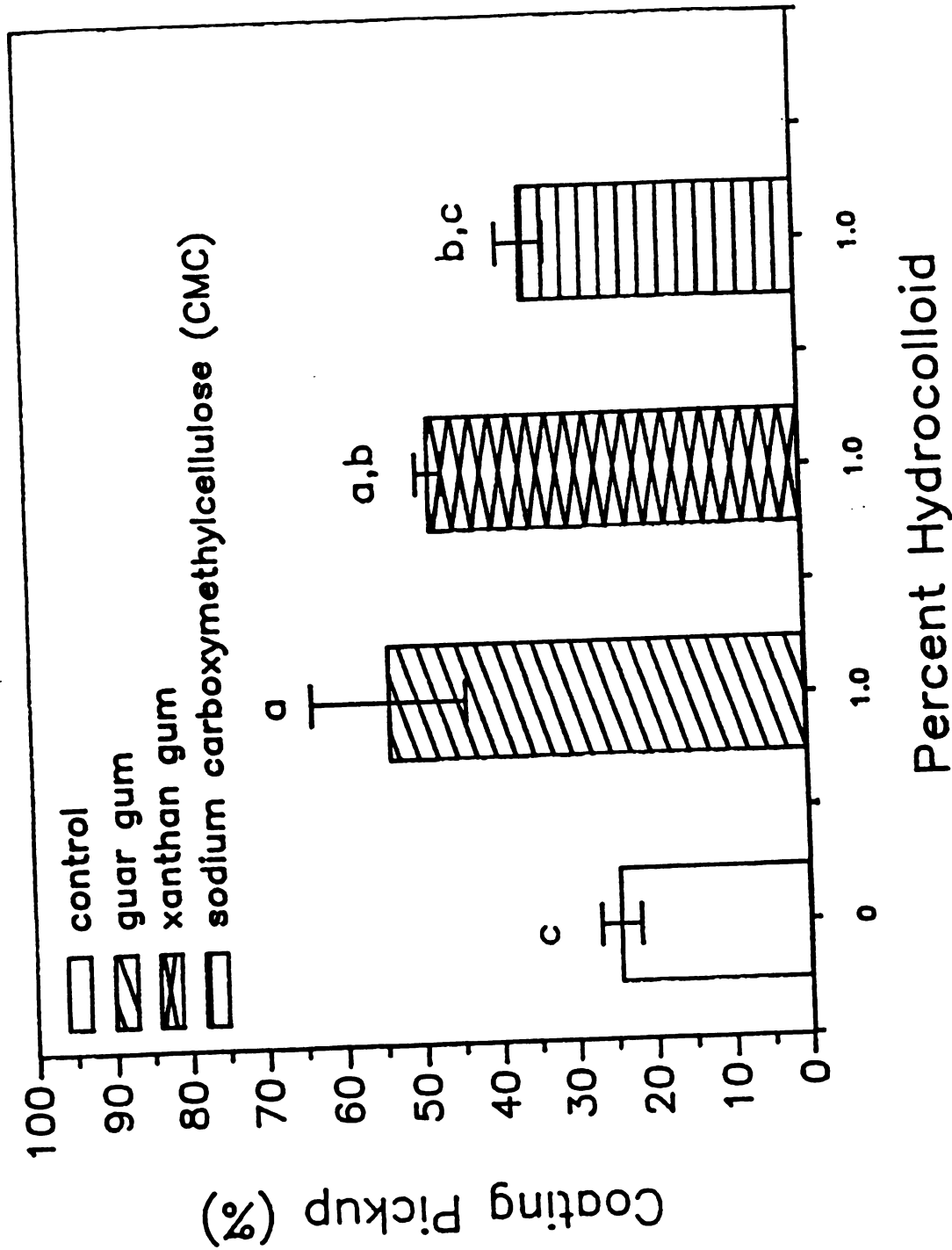


Figure 21 Percent coating pickup of chicken nuggets prepared with 40% solids batters containing different hydrocolloids (error bars were standard deviation) (any two means with the same letter(s) were not significantly different from each other by Tukey's test at $\alpha = 0.01$)

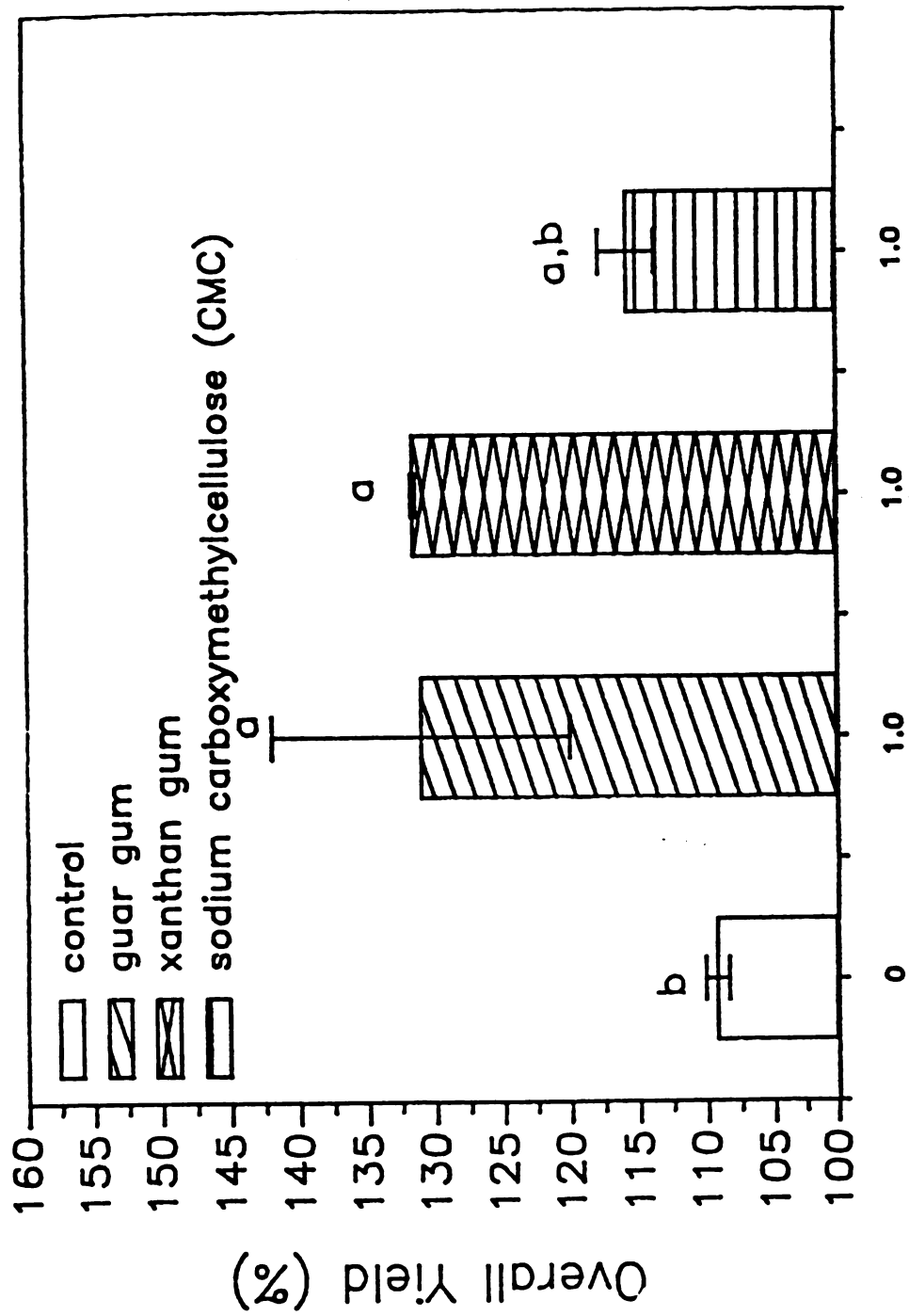


Figure 22 Percent overall yield of chicken nuggets prepared with 40% solids batters containing different hydrocolloids (error bars were standard deviation) (any two means with the same letter(s) were not significantly different from each other by Tukey's test at $\alpha = 0.01$)

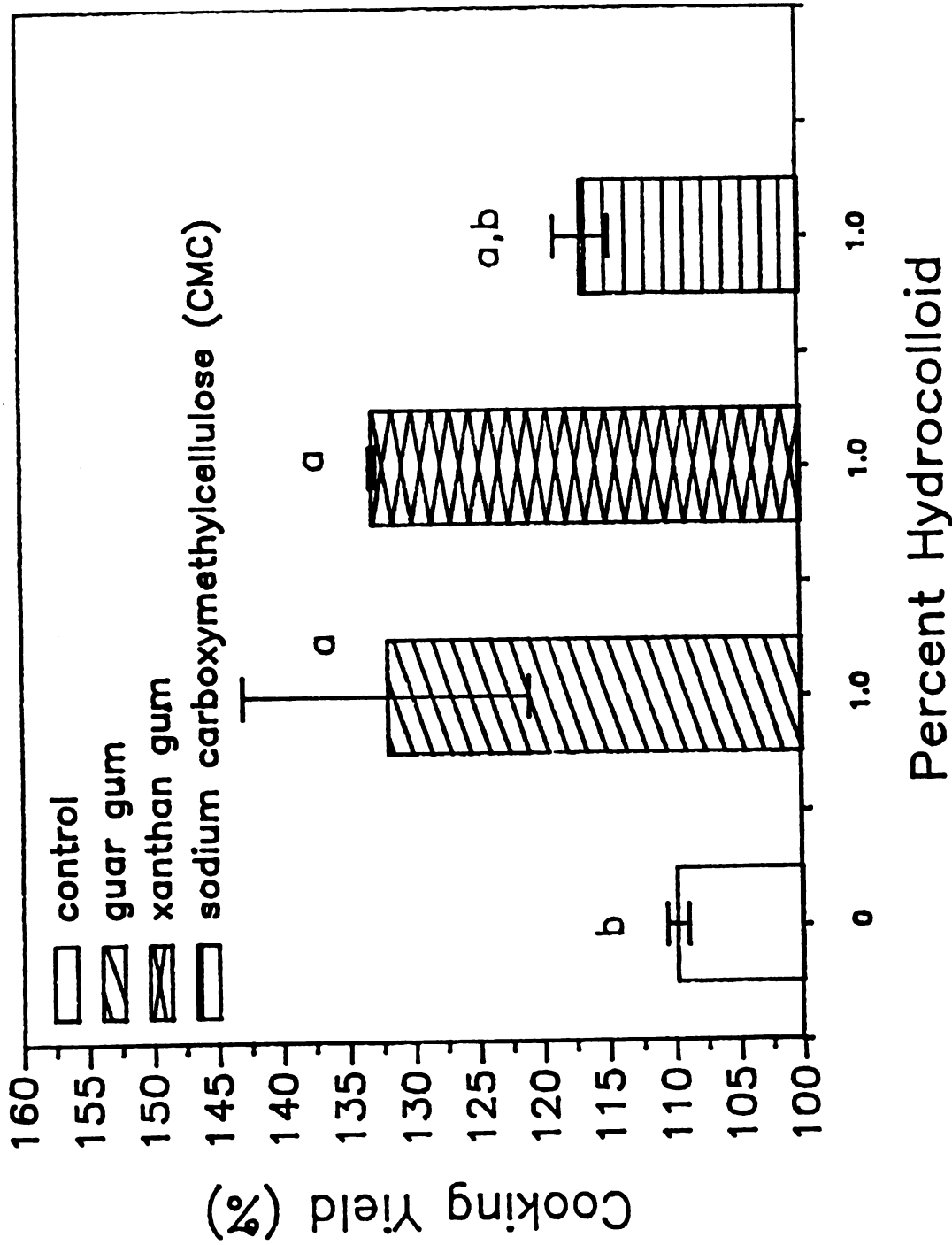


Figure 23 Percent cooking yield of chicken nuggets prepared with 40% solids batters containing different hydrocolloids (error bars were standard deviation) (any two means with the same letter(s) were not significantly different from each other by Tukey's test at $\alpha = 0.01$)

3. COMPARISON OF ADHESION CHARACTERISTICS OF 30% AND 40% SOLIDS BATTERS

We compared the adhesion characteristics of batters containing 1% hydrocolloid and found that, except control batter, percent crumb loss of 40% solids batters was higher than that of 30% solids batters. Thirty percent solids control batter had higher percent crumb loss than that of 40% solids control batter. Percent cooking loss of 40% solids batters were higher than those of 30% solids batters. Forty percent solids batters had higher percent coating pickup, percent overall yield, and percent cooking yield than those of 30% solids batters, with the exception of xanthan containing batter. Thirty percent xanthan containing batter had higher percent coating pickup, percent overall yield, and percent cooking yield than those of 40% xanthan containing batter.

D. RELATIONSHIP BETWEEN RHEOLOGICAL PROPERTIES AND ADHESION CHARACTERISTICS OF CHICKEN BATTERS

Average apparent viscosity (C-D, Figure 3) was correlated to the adhesion characteristics of chicken batters. A high correlation coefficient meant a high relationship between rheological properties and adhesion characteristics of the chicken batters.

High correlation coefficients were observed between apparent viscosity and percent coating pickup, percent overall yield, and percent cooking yield of 30% solids batters (Table 14). The correlation coefficients were up to 0.98. Low correlation coefficients were observed between apparent viscosity and percent crumb loss and percent cooking loss.

Apparent viscosity of batters cannot be used to predict the percent crumb loss or percent cooking loss of the nuggets. A high correlation coefficient of 0.98 was observed between apparent viscosity and percent coating pickup. When the apparent viscosity of the sample increased, the percent coating pickup increased also. Correlation of apparent viscosity and percent overall yield had a coefficient of 0.98. The correlation of apparent viscosity with percent cooking yield exhibited a high coefficient of 0.98, also.

Table 15 showed the correlation coefficient of apparent viscosity vs adhesion characteristics of the 40% solids batters. Percent coating pickup, percent overall yield, and percent cooking yield showed a high correlation coefficient with apparent viscosity. Due to the low correlation coefficient, apparent viscosity could not be used to predict the percent crumb loss or percent cooking loss of the batter on chicken nuggets.

The results indicated a relationship between batter apparent viscosity and adhesion characteristics such as coating pickup, overall yield and cooking yield. However, we did not find a relationship between apparent viscosity and crumb loss or cooking loss due to the low correlation. Coating pickup, overall yield and cooking yield will be the parameters to measure if food processors hope to compare the influence of hydrocolloid source and concentration for improving adhesion characteristics.

When comparing the relationship between adhesion and time-dependency of the samples, control and 0.25% CMC have the lowest adhesion and lowest degree of time-dependency, but the highest stable properties among the samples. Xanthan and guar gum batters have higher adhesion and degree of time-dependency but lower stability than CMC did. When hydrocolloid concentration or batter solids content increase, the adhesion and degree

of time-dependency increase, but the stability of the sample decreases.

The 30% solids control had the lowest adhesion but over 100% recovery, which showed the batter had increased apparent viscosity over time of mixing. When batter contained hydrocolloid or increased solids content, batters have increased adhesion but less than 100% recovery and indicating the batters have decreased apparent viscosity over the time of mixing.

In our experiment, we did not find a hydrocolloid that contributed all of the following characteristics to the batter: higher adhesion and apparent viscosity, higher time-dependency or more stable properties over the time of mixing, and reasonable recovery for quality maintenance over the time of mixing.

Table 14 Correlation coefficient of apparent viscosity vs adhesion characteristics of 30% solids chicken batters

Comparison	Correlation coefficient
Apparent Viscosity vs % Crumb Loss	0.69
Apparent Viscosity vs % Cooking Loss	0.32
Apparent Viscosity vs % Coating Pickup	0.98
Apparent Viscosity vs % Overall Yield	0.98
Apparent Viscosity vs % Cooking Yield	0.98

Table 15 Correlation coefficient of apparent viscosity vs adhesion characteristics of 40% solids chicken batters

Comparison	Correlation coefficient
Apparent Viscosity vs % Crumb Loss	0.51
Apparent Viscosity vs % Cooking Loss	0.51
Apparent Viscosity vs % Coating Pickup	0.96
Apparent Viscosity vs % Overall Yield	0.96
Apparent Viscosity vs % Cooking Yield	0.95

E. PRACTICAL APPLICATIONS OF THE RESEARCH

The results of this research can be applied as follows:

1. Hydrocolloids can be applied to the batter industry to increase the adhesion and apparent viscosity of batter mixes.
2. Since time factors, hydrocolloid type and concentration, and batter solids content influenced the stability of batters during mixing, it is desirable to find a batter with the lowest time-dependency and the most stable properties. This kind of batter also needs to have high adhesion and apparent viscosity.
3. Strain history which is calculated by the multiplication of time and shear rate can be used to quantify the influence of time-dependency during the mixing and pumping of batters. We could design equipment to maintain optimum batter properties and adhesion.

SUMMARY AND CONCLUSION

The objectives of this research were accomplished by the study. The effect of hydrocolloid type and concentration, and batter solids content on the rheological and adhesion characteristics of a batter mix to chicken nuggets was determined. A relationship was found between the rheological properties and adhesion characteristics of batter mixes.

Batter rheological properties changed with time of mixing. The 30% solids control and 0.25% CMC batters showed Newtonian behavior and had more stable properties during the time of mixing. All other batters exhibited thixotropy. All batter treatments displayed pseudoplasticity (shear-thinning). Generally, increasing rotational speed decreased apparent viscosity. Higher hydrocolloid concentration and higher batter solids content caused a higher apparent viscosity and degree of time-dependency but less stability. Thirty percent solids control and 0.25% CMC batters had the lowest degree of time-dependency and apparent viscosity but the most stable properties among the treatments. Xanthan and guar gums exhibited greater time-dependency and apparent viscosity but less stable properties than CMC at the same concentration. Batters with greater time-dependency or less recovery need less energy during mixing.

Hydrocolloid composition of the batter had a large influence on adhesion to chicken nuggets. Higher hydrocolloid concentration and higher batter solids content gave higher adhesion, as measured by coating pickup,

overall yield, and cooking yield. In 40% solids batters, increased coating pickup led to increased crumb loss. However, there was no evidence for the same correlation in 30% solids batters. Xanthan and guar gums showed better adhesion than CMC at the same concentration. Control batter had lower adhesion than hydrocolloid batters.

A positive correlation was made between apparent viscosity and adhesion characteristics, such as percent coating pickup, percent overall yield, and percent cooking yield. No predictability could be made between apparent viscosity and percent crumb loss or percent cooking loss. Batters with higher apparent viscosity usually have higher adhesion properties.

FUTURE RESEARCH

Several ideas for further research and quality improvement are suggested as follows:

1. The effect of other type, concentration, or the combinations of hydrocolloids on the rheological and adhesion properties of the batter.
2. The effect of batter mix composition on the rheological and adhesion properties of the batter.
3. Studies of stirring time in the mixer to achieve better adhesion and higher apparent viscosity of the batter.
4. Investigation of the oil absorption ability of hydrocolloid containing batters during frying to determine influence of oil absorption on adhesion.
5. Studies of other viscometers (e.g. Brookfield with proper impellers) for measuring the apparent viscosity of batter mixes.
6. Evaluation of sensory acceptance of hydrocolloid containing batters.

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APPENDIX

Table 16 Torque vs time¹ of 30 % solids batters measured at 70 rpm,
10°C

Torque (N m) x 10 ³				
Time(min)	control	0.25% guar	0.5% guar	1.0% guar
0.9482	0.37	0.82	1.52	3.83
5.5990	0.36	0.83	1.53	3.84
10.250	0.42	0.83	1.50	3.81
14.890	0.38	0.82	1.48	3.83
19.540	0.38	0.80	1.46	3.78
24.190	0.39	0.79	1.43	3.72
28.840	0.39	0.78	1.39	3.64
33.480	0.40	0.77	1.39	3.64
38.130	0.41	0.75	1.36	3.60
42.780	0.41	0.73	1.34	3.55
47.420	0.41	0.72	1.32	3.52
52.070	0.42	0.72	1.29	3.44
56.710	0.41	0.71	1.27	3.41

¹ Data were averaged by triplicated tests.

² BB was basic batter.

Table 16 (cont'd)

Time(min)	Torque (N m) x 10 ³		
	0.25% xanthan	0.5% xanthan	1.0% xanthan
0.9482	1.29	2.68	4.96
5.5990	1.26	2.66	5.06
10.250	1.25	2.64	5.05
14.890	1.25	2.59	5.01
19.540	1.23	2.57	4.97
24.190	1.22	2.53	4.94
28.840	1.22	2.50	4.90
33.480	1.20	2.48	4.88
38.130	1.19	2.46	4.85
42.780	1.18	2.45	4.81
47.420	1.17	2.40	4.76
52.070	1.17	2.39	4.75
56.710	1.15	2.36	4.71

Table 16 (cont'd)

Time(min)	Torque (N m) $\times 10^3$		
	0.25% CMC	0.5% CMC	1.0% CMC
0.9482	0.42	0.80	1.67
5.5990	0.40	0.78	1.16
10.250	0.40	0.76	1.58
14.890	0.40	0.76	1.54
19.540	0.39	0.75	1.50
24.190	0.39	0.73	1.47
28.840	0.39	0.71	1.45
33.480	0.39	0.70	1.42
38.130	0.39	0.69	1.39
42.780	0.38	0.68	1.37
47.420	0.38	0.66	1.35
52.070	0.38	0.66	1.32
56.710	0.38	0.65	1.30

Table 17 Torque vs time¹ of 40 % solids batters measured at 70 rpm,
10°C

Time(min)	Torque (N m) x 10 ²			
	control	1.0% guar	1.0% xanthan	1.0% CMC
0.8460	1.14	2.44	1.85	1.22
4.9900	1.04	2.47	1.81	1.18
9.1340	0.97	2.39	1.75	1.10
13.280	0.92	2.35	1.70	1.05
17.420	0.89	2.30	1.65	1.01
21.560	0.86	2.26	1.62	0.98
25.700	0.83	2.22	1.62	0.95
29.840	0.81	2.18	1.59	0.92
33.980	0.79	2.15	1.57	0.90
38.130	0.77	2.11	1.55	0.87
42.270	0.76	2.08	1.52	0.86
46.410	0.74	2.05	1.50	0.83
50.550	0.73	2.02	1.49	0.82
54.690	0.71	1.98	1.49	0.80
58.830	0.70	1.95	1.47	0.79

^{1,2} The same definition as Appendix A.

Table 18 Apparent viscosity, μ_a , of 30% solids chicken batters

				Apparent Viscosity (Pa s)			
N_x	Ω_x	γ_a	Hydrocolloid Concentration (%)				
			control	0.25	0.5	1.0	
			Guar				
10	1.047	4.67	0.23	0.21	0.50	1.53	
30	3.142	14.01	0.16	0.20	0.42	1.23	
50	5.236	23.35	0.14	0.20	0.40	1.15	
70	7.330	32.69	0.14	0.21	0.39	1.02	
90	9.425	42.04	0.13	0.21	0.38	0.94	
Average	50	5.236	23.35	0.16	0.21	0.42	1.17
				Xanthan			
10	1.047	4.67	0.23	0.54	1.58	3.83	
30	3.142	14.01	0.16	0.40	1.00	2.19	
50	5.236	23.35	0.14	0.36	0.83	1.70	
70	7.330	32.69	0.14	0.35	0.75	1.45	
90	9.425	42.04	0.13	0.34	0.69	1.30	
Average	50	5.236	23.35	0.16	0.40	0.97	2.09
				CMC			
10	1.047	4.67	0.23	0.28	0.30	0.52	
30	3.142	14.01	0.16	0.18	0.26	0.49	
50	5.236	23.35	0.14	0.15	0.21	0.48	
70	7.330	32.69	0.14	0.15	0.23	0.47	
90	9.425	42.04	0.13	0.15	0.22	0.46	
Average	50	5.236	23.35	0.16	0.18	0.24	0.48

Table 19 Apparent Viscosity, μ_a , of 40% solids chicken batters

			Apparent Viscosity (Pa s)				
N_x	Ω_x	$\dot{\gamma}_a$	control	1.0% guar	1.0% xanthan	1.0% CMC	
10	1.047	4.67	1.61	10.47	10.50	2.55	
30	3.142	14.01	1.82	7.53	6.06	2.36	
50	5.236	23.35	1.99	6.47	4.92	2.33	
70	7.330	32.69	2.11	5.83	4.35	2.29	
90	9.425	42.04	2.17	5.36	3.97	2.30	
Average	50	5.236	23.35	1.94	7.13	5.96	2.37

Table 20 Percent crumb loss, percent cooking loss, percent coating pickup, percent overall yield, and percent cooking yield of 30% solids chicken batters

Batter	Adhesion Characteristics				
	%crumb loss	%cooking loss	%coating pickup	%overall yield	%cooking yield
control	0.78	12.61	13.35 ^c	100.30 ^c	100.74 ^c
0.25% guar	0.66	15.42	17.14 ^c	101.06 ^{b, c}	101.68 ^c
0.5% guar	0.96	16.29	23.19 ^{b, c}	105.93 ^{b, c}	106.90 ^{b, c}
1.0% guar	0.86	16.04	32.10 ^b	115.20 ^b	116.03 ^{b, c}
0.25% xanthan	1.01	12.92	24.38 ^{b, c}	110.40 ^{b, c}	111.46 ^{b, c}
0.5% xanthan	1.17	14.20	31.34 ^b	112.65 ^{b, c}	116.87 ^b
1.0% xanthan	1.33	14.21	52.82 ^a	137.27 ^a	138.60 ^a
0.25% CMC	1.02	12.39	14.65 ^c	101.25 ^{b, c}	102.25 ^c
0.5% CMC	0.94	12.14	16.36 ^c	103.28 ^{b, c}	104.22 ^{b, c}
1.0% CMC	1.05	14.36	20.92 ^{b, c}	105.60 ^{b, c}	106.65 ^{b, c}

Any two means in the same column with the same letter(s) were not significantly different from each other by Tukey's Test at $\alpha = 0.01$.

Table 21 Percent crumb loss, percent cooking loss, percent coating pickup, percent overall yield, and percent cooking yield of 40% solids chicken batters

Batter	Adhesion Characteristics				
	%crumb loss	%cooking loss	%coating pickup	%overall yield	%cooking yield
control	0.58 ^b	14.46 ^b	24.30 ^c	109.24 ^b	109.83 ^b
1.0% guar	1.02 ^{a,b}	21.73 ^a	53.76 ^a	130.99 ^a	132.01 ^a
1.0% xanthan	1.55 ^a	14.92 ^b	48.03 ^{a,b}	131.57 ^a	133.11 ^a
1.0% CMC	1.16 ^a	18.62 ^{a,b}	35.44 ^{b,c}	115.69 ^{a,b}	116.82 ^{a,b}

Any two means in the same column with the same letter(s) were not significantly different from each other by Tukey's Test at $\alpha = 0.01$.

