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Eva Agrawal

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James F. Steffe
Major professor

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EVALUATION OF FLUID FOODS USING A HELICAL RIBBON VISCOMETER

By

Eva Agrawal

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ABSTRACT

EVALUATION OF FLUID FOODS USING A HELICAL RIBBON VISCOMETER

By

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A helical ribbon impeller was calibrated and evaluated for use in the rheological testing of food products. Constants that characterize the helical ribbon were evaluated: k'' (mixer coefficient) equaled 1632 rev/m^3; and k' (mixer viscometer constant) ranged from 3 – 11 1/rev. Higher values of k' corresponded to lower flow behavior indices, and lower angular velocities. The helical ribbon was found to be very effective in testing rheological properties of highly viscous, non – homogenous, yield stress fluids such as mustard, ketchup, and salad dressing. The change in textural properties of Mayonnaise and Miracle Whip (at 5°C, 21°C, and 37°C) were studied by observing changes in the apparent viscosity with the addition of water at the shear rates corresponding to those found in the mouth. The addition of water in the sample was scaled up to match the bolus, saliva volume, and flow rate. Rheological data showed clear differences in the change in apparent viscosity at different temperatures and fat levels.

DEDICATION

To my wonderful family

for their love, support and encouragement.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

A	system constant, 1/rev
d	impeller diameter, m
h	height of the impeller or bob, m
k'	mixer viscometer constant, 1/rev
k''	mixer coefficient, rev/m^3
K	consistency coefficient, Pa s^n
m	mass, g
M	torque, N m
n	flow behavior, dimensionless
N	angular velocity, rev/s
N_{Po}	power number, dimensionless
$N_{Re,I}$	impeller Reynolds number, dimensionless
P	power, N m/s
R_b	radius of bob or impeller, m
R_c	radius of cup, m
V	volume, ml
Vm	maximum volume of water added to the food sample, ml
Vw	the volume of water added to the particular food sample, ml
α	constant, R_c/R_b
σ	stress, Pa
Ω	angular velocity, rad/sec

η apparent viscosity, Pa s

ρ density, kg / m^3

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

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

μ Newtonian viscosity, Pa s

CHAPTER 1

INTRODUCTION

Rheology deals with the response of any material to the applied stress or strain; hence, it is the study of deformation and flow of material. It has wide applications in varied fields including geology and mining, concrete technology, soil mechanics, plastics, and many other areas. In the food industry, it is particularly helpful in quality control, product development (to evaluate ingredient functionality), shelf life determination, sensory evaluation, and process engineering calculations.

Viscosity is an important variable that determines the texture of fluid food, contributes to the overall mouth – feel, and influences the intensity of flavor (Houska et al, 1998). It is represented by the ratio of shear stress and shear rate, which gives the basic Newtonian model that describes the flow behavior of simple fluids:

$$\sigma = \mu\dot{\gamma} \qquad [1.1]$$

Fluids including water, honey, corn syrup, and vegetable oil in which the viscosity remains constant with changing shear rate exhibit Newtonian behavior. The power law model is often used to model the flow behavior of fluids in which the apparent viscosity varies with the shear rate:

$$\eta = K\dot{\gamma}^{n-1} \qquad [1.2]$$

Fluids like apple sauce, banana puree, orange juice concentrate that depict decrease in apparent viscosity (n < 1) with increase in shear rate are termed as pseudoplastic (shear – thinning) fluids, and fluids like corn starch solutions that depict increase in apparent viscosity (n > 1) with shear rate are termed dilatent (shear – thickening) fluids.

Power law fluids have been extensively tested using mixer viscometers for quality control and engineering designing applications. Mixer viscometry has been helpful in assessing fluids exhibiting slip, time – dependent behavior, having large sized particles, and particle – settling problems. Traditional viscometers including concentric cylinder system, plate and cone system, and parallel plate system have been used in the past for rheological studies but encountered errors with emulsion type, yield stress possessing semi – solid foods due to wall slip and in non – homogenous foods due to its particulate nature leading to settlement of particles or clogging of particles in the clearance.

The helical ribbon is an under – utilized mixer impeller designed for the study of non – homogenous, yield stress fluids. This system reduces the wall slip, keeps particles suspended, provides a suitable clearance for larger particles, and provides good agitation during the testing. Thus, this system, once calibrated, can be used for the studies of textural properties of emulsions and other yield – stress – possessing fluids that can be utilized in product improvement and development keeping consumer acceptance in view.

In mixer viscometry, properties of fluids are evaluated on the basis of a shear rate estimation which involves the determination of impeller calibration constants based on the matching viscosity concept. The basis of the matching viscosity method lies in the comparison of the power curves for Newtonian fluids and the non – Newtonian fluids, and leads to the concept that the viscosity of Newtonian fluids is equivalent to the apparent viscosity of the non – Newtonian fluids at equivalent shear rates. This concept was used in the current study.

Ingested food undergoes various physical changes in the oral cavity that correlate to mouth feel. The instrumental evaluation of textural changes in mouth can be further related to sensory analysis and this information can be utilized in developing products with desired texture. For instrumental emulation of mastication, saliva or saliva replacement needs to be uniformly incorporated into the sample. Traditional viscometers encounter problems like wall slip and improper mixing of sample and water, so a new impeller was required to overcome these limitations. Hence, a helical ribbon has been designed that can effectively mix the water into the sample while avoiding wall slip and settling of the particles.

Objectives

The overall goal of this project was to develop a helical ribbon mixer viscometer for viscous fluid foods with the potential to emulate mastication. There were three specific objectives:

1. To calibrate a helical ribbon impeller for fluid foods by determining the mixer coefficient (k'') and the mixer viscometer constant (k').
2. To evaluate the efficacy of the helical ribbon impeller with typical food products.
3. To observe the effect of water addition on the rheological properties of Mayonnaise and Miracle Whip determined with the helical ribbon system.

CHAPTER 2

LITERATURE REVIEW

2.1 Oral Factors

Any edible material when placed in the mouth is subjected to physical and chemical changes due to the various factors related to oral cavity including incorporation of saliva, application of force by the teeth, tongue, cheeks, palate and floor of the mouth. In this study, this aspect of ingestion where major textural modifications are incurred was evaluated instrumentally. These results can be related to the sensory analysis data to develop new products with more desirable texture and mouth feel. The study concentrated on two different emulsion type products: mayonnaise and miracle whip.

2.1.1 Saliva

Saliva is the most important aqueous portion of the oral milieu and contains secretions of the major and minor salivary glands along with bacteria, food debris and fluid from the gingival crevice. The secretion of the major and the minor salivary glands mainly determines the composition of the saliva. It is a vital fluid involved in digestion, antibacterial activity, buffering, lubrication, water balance and excretion (Roth and Calmes, 1981).

Saliva secretion occurs through three major glands present in the mouth – submandibular, parotid and sublingual. Numerous minor salivary glands present in the palate, tongue, lower lip, cheeks and pharynx also contribute to the total volume of saliva. Also, the gingival crevice is reported to secrete liquid from the epithelium of gums (Brill, 1962). The submandibular gland is the major contributor of saliva providing 60 - 65 % of the total saliva secreted. Parotid (22 - 30%), sublingual (2 - 4%) and minor salivary glands (<10%) follow the submandibular system (Roth and Calmes, 1981). Secretion of saliva through the three different glands is complicated since the composition and contribution of each gland varies with the stimulus and conditions prevailing in the mouth. Also, the rate of secretion and the composition of saliva vary in different individuals, and in the same individual under different circumstances (Jenkins, 1966).

Saliva is mainly composed of water (99.5%) (Best and Taylor, 1961). Besides water, saliva contains protein (0.3%), inorganic constituents including calcium, phosphorus, sodium, potassium, fluoride, chlorine, magnesium, phosphate, and bicarbonate; and dissolved gases including nitrogen, oxygen and carbon dioxide (Jenkins, 1966; Roth and Calmes, 1981). The protein content of human saliva consists of mucoides, enzymes, amino acids, albumin, globulin, urea and ammonia (Jenkins, 1966). Saliva composition is affected by many factors: rate of saliva secretion, age and sex, time of the day, nature of stimulus, composition of diet, hormones, fatigue and race (Jenkins, 1966; Roth and Calmes, 1981).

Unstimulated saliva has a pH of 6.75 (5.6 – 7.6) (Jenkins, 1966; Spector, 1956) and a specific gravity that varies from 1.002 to 1.008 (Best and Taylor, 1961). Kerr (1961) stated that specific gravity increases with increase in rate of flow. The relative viscosities at the stimulated state, reported as Newtonian fluids, for the three major secretions at the room temperature are as follows: parotid 1.5 cp, submandibular 3.4 cp, and sublingual 13.4 cp (Jenkins, 1966). The viscosity of the mixed saliva tends to fall if left to stand for an hour, which has been attributed to the depolymerization of mucoids by the bacterial proteolytic enzymes present in the saliva. However, during the time when there is a fall in viscosity, very little change in protein concentration has been observed (Jenkins, 1966).

Grant et al. (1979) reported that the flow rate under stimulated conditions from the parotid gland is 0.7 ml/min and from submandibular gland is 0.6 ml/min. The rate of saliva secretion under the basal conditions is 0.5 ml/min and under the sour taste conditions ranges from 5.0 to 8.0 ml/min with the total volume of saliva secreted in a 24-hour period ranging from 800 to 1500 ml (Moore, 1980). The maximum secretion from a gland is also dependent on the weight of the gland with an average rate of 1 ml / mg weight of the gland in one minute (Johnson, 1998; Berne and Levy, 1983).

Mixing of saliva and food in the mouth initiates the digestion process and saliva plays a major role in bringing about desirable changes in the food after ingestion. The major enzyme in saliva is the salivary amylase (called ptyalin), which leads to the breakdown of starch into maltose in the mouth. It might play an active role when mixed with food products but is inactivated once the food bolus reaches the stomach because of the acidic conditions (pH <4) found there. Other enzymes present in saliva include lipase, aldolase, lysozyme, esterase and peroxidase (Jenkins, 1966). Lipase might be an enzyme of concern in high fat foods such as mayonnaise. Salivary lipase has low activity since the conditions prevailing in mouth are not favorable for the salivary lipase to be active. Jenkins (1966) stated that salivary amylase is the only enzyme that is sufficiently active in the mouth to play a significant part in breakdown of the food constituents in mouth.

2.1.2 Oral Cavity

Oral cavity, or the mouth, is bounded by lips, cheeks, palate and the floor of the mouth, all of which participate in modifying the food ingested. In addition, gingivae, teeth and tongue all contribute to changes in the bolus. Kuroda et al. (1996) found the size of oral cavity to be 61.15 cubic cm and the surface area of the palate to be 30.22 square cm. Davenport (1966) reported the amount of bolus swallowed at a time as 5 – 15 cubic cm, while Logemann reported the bolus size as 7 – 10 cubic cm (information received through personal communication with Dr. Sonies). Logemann reported that along with the bolus, 1 – 2 ml saliva is also swallowed (Manual for the Videofluorographic Study of Swallowing, 2nd edition).

Logemann found that the tongue depth is normally 5 – 6 cm, and when at rest, it fills the whole oral cavity (information obtained through personal communication with Dr. Sonies) and while swallowing, it squeezes the food into the pharynx. Pressure exerted by tongue depends on the viscosity of food material, and an increase in bolus consistency significantly increases the amplitude of lingual pressure (Shaker et al., 1988; Smith et al., 1997). Pressure applied by lips varies from 0 to 90 mm Hg as stated by (Shaker et al., 1988). They also found that pressure amplitude is related to the consistency of food but is not correlated with the volume of food. Miller and Watkin (1996) reported that the volume of the bolus does not significantly influence the force amplitude.

When the food is ingested, teeth break the solid materials down to small particles of few cubic millimeters that can be easily swallowed and digested (Johnson, 1998; Davenport, 1966). During mastication, the food is comminuted and lubricated with saliva simultaneously. Each chewing cycle lasts for 0.5 – 1.2 sec (Roth and Calmes, 1981). Hiiemae (1999) confirmed that the average time for which the bolus resides in the mouth is 7.5 sec. While in the mouth, food is subjected to the squeezing forces of the tongue, palate and cheeks, and crushing forces of teeth. The biting forces developed on a tooth as reported by Roth and Calmes (1981), may range from 20 – 200 kg and the force generated on molar teeth can be 5 – 10 kg. Ruch and Patton reported biting forces of 11 – 25 kg due to the incisor teeth. Liquids with viscosities typical of soups and sauces experience shear rates of approximately 50 sec^{-1} (Wood et al., 1973).

2.2 Mayonnaise and Miracle Whip

Mayonnaise is used as a spread in conjunction with the salads, breads and other foods. It is an oil – in – water emulsion in which oil (dispersed phase) is dispersed in water (continuous phase) and forms a space – filling structure that gives consistency to the fluids. For any emulsion, the lower the fat content, the higher would be the aqueous phase. The size of droplets ranges from 1 μm to 5 μm (Rosenthal, 1999) and determine the amount of oil that can be dispersed in the continuous phase (water). A wider range of droplet size distribution gives a higher amount of oil dispersed in the water. The droplets of dispersed phase determine the properties of mayonnaise. Certain undesirable processes, like creaming, flocculating and coalescence lead to changes in the physical condition resulting in changes in the rheological behavior. To avoid these physical changes, an emulsifier like egg yolk or gum is added to reduce the interfacial tension to only a few mPa m instead of 30 mPa m (Rosenthal, 1999) between oil and water thus stabilizing the emulsion. Emulsifiers are also used to increase viscosity in light mayonnaise.

Regular mayonnaise, unlike low fat mayonnaise, has an oil concentration of about 70 – 80% (Rao, 1999). It is a stable emulsion with complex viscoelastic rheological behavior. The emulsion undergoes structural rearrangements to impart properties like yield stress, pseudoplasticity and time – dependent behavior to the mayonnaise (Peressini et al. 1998, Plucinski et al. 1998); hence, it is a non – Newtonian fluid whose shear viscosity decreases with increase in shear rate. Its viscous nature is determined by the volume fraction (quantity of fat drops present) of the dispersed drops. At a low volume fraction, viscosity of the emulsion increases with the amount of dispersed phase; at an intermediate volume fraction, a nonlinear relationship exists between viscosity and the amount of dispersed phase; and at a high volume fraction, the emulsions exhibit plastic behavior rather than viscous behavior.

The viscoelastic nature of mayonnaise is attributed to the deformability of the fat drops present in the emulsion (amount of fat drops present in any emulsion is represented by the volume fraction). As long as the applied stresses are below the stresses produced during the homogenization process, deformation of fat drops is negligible. Therefore, emulsions at intermediate volume fraction behave as viscous fluids during handling and eating. In emulsions with high volume fraction (high amount of fat in the emulsion), individual fat drop is surrounded by other fat drops and so the motion of fat drops is possible only when the neighboring drops deform sufficiently to make space for the fat droplet to move. Hence, flow occurs at stress high enough to deform the fat drops. Thus the emulsions with high concentrations of fat have significant yield stresses.

The yield stress of traditional full – fat mayonnaise has been reported to be 50 Pa (Rosenthal, 1999) and the yield stress decreases with the decrease in oil content (Peressini et al., 1998). The structure of mayonnaise comprises a close network of lipids and proteins with the oil droplets entangled within the network. Peressini et al., 1998 asserted that this compact packing of oil drops in the lipoproteic network is responsible for the deformation resistance and resilient properties of the emulsion. The network formed defies the effect of force applied and hence, provides the elastic characteristic to the mayonnaise.

Researchers have reported presence of wall slip while collecting measurements using the rotational viscometers, thus rendering some conventional viscometers ineffective for rheological measurements of mayonnaise even at very low shear rates (10^{-3} sec^{-1}) (Plucinski et al., 1998).

In a product such as Miracle Whip, which has a high amount of starch or carbohydrates, action of salivary amylase might be a probable factor in product breakdown. Also, it can be assumed that there are no significant chemical changes in the fat or oil present in the food ingested. Since a product such as mayonnaise is an oil in water emulsion, there are no major changes in the chemical composition; however, there are significant changes in the physical composition of the mayonnaise (and also in Miracle Whip) due to the incorporation of large amount of water from saliva.

2.3 Mixer Viscometer Constant (k')

The mixer viscometer constant is an entity that converts the angular velocity into shear rate. It is a unique value that differs depending on the impeller being used and is determined from experimental data. It is a factor that depends on the geometry of the impeller and has been shown to be influenced by the flow behavior index (n) and angular velocity (N) (Castell – Perez and Steffe, 1990 and Mackey et al., 1987). Similar studies have been conducted in the past with different impellers to find the value of k'. For a flag impeller the value of k' was found to be 20.1 rev^{-1} in a Brookfield small sample adaptor by Briggs and Steffe, 1996; for a star impeller, k' was reported to be 19.7 rev^{-1} by Rao and Cooley (1984); for a pitched paddle impeller, the corresponding value was found to be 28 rev^{-1} in a Haake MV1 cup (Ford and Steffe, 1986).

CHAPTER 3

THEORETICAL DEVELOPMENT

An impeller must be calibrated prior to being used for conducting experiments, so that the instrumental data obtained can be utilized to gain information about the food material being tested. To standardize an impeller, two constants, mixer coefficient (k'') and the mixer viscometer constant (k'), must be calculated. The calculation of these constants involves various assumptions and mathematical relationships as described in the subsequent sections.

3.1 Flow Regime During Mixing and k''

The flow regime can be characterized by the impeller Reynolds number ($N_{Re,I}$), which corresponds to the ratio of the inertial force to the opposing viscous force in a Newtonian fluid during mixing. The numerical value of $N_{Re,I}$ indicates if the flow is laminar, transitional or the turbulent during mixing. At $N_{Re,I}$ values less than 10, laminar flow exists in the system and at values above 10,000, a turbulent flow is present when the angular velocity is expressed in units of rev/sec. At a value between 10 and 10,000, transitional flow is present. If the value for angular velocity is expressed as rad/sec, the corresponding values for $N_{Re,I}$ are 63 and 63,000, respectively. The impeller Reynolds number is defined as

$$N_{\mathrm{Re},I} = \frac{\rho N d^2}{\mu} \tag{3.1}$$

Under the laminar flow regime, the mixing power number (N_{Po}) and impeller Reynolds number ($N_{Re,I}$) involved in mixing of Newtonian fluids are related by the following equation (Metzner and Otto, 1957):

$$N_{Po} = \frac{A}{N_{\mathrm{Re},I}} \tag{3.2}$$

where A is a constant, which depends on the system geometry and the flow regime. Substitution of $N_{Po} = \frac{P}{\rho N^3 d^5}$ and $N_{\mathrm{Re},I} = \frac{\rho N d^2}{\mu}$ in Eq. [3.2] yields,

$$\frac{P}{\rho N^3 d^5} = \frac{A\mu}{\rho N d^2} \tag{3.3}$$

Eq. [3.3] was rewritten by Mackey et al. (1987) as

$$M = \frac{N\mu}{k''} \tag{3.4}$$

or

$$k'' = \frac{N\mu}{M} \tag{3.5}$$

where $k'' = 1/(Ad^3)$ rev/m^3. The value of the parameters can be determined from experimental data as the inverse of the slope of the plot between torque and the product of angular velocity and viscosity as also indicated by Eq [3.5]. k'' is a constant that depends only on the dimensions of the impeller and cup; hence, it is a unique value for every system.

3.2 Mixer Viscometer Constant, k'

k' is the mixer viscometer constant expressed in units of 1/rad or 1/rev. It has a unique value for a particular mixing system that depends on the geometry of the system and the flow regime. The constant is required to convert angular velocity into average shear rate. It can be determined by two methods: slope method and matching viscosity method. In this study, the matching viscosity method was utilized to evaluate k'.

Using the "matching viscosity" assumption, which states that when the viscosity of Newtonian fluid is equivalent to the apparent viscosity of the non – Newtonian fluid, the average shear rate of a non – Newtonian fluid is equal to the average shear rate of the Newtonian fluid (Steffe, 1996).

Based on this assumption, Newtonian viscosity or apparent viscosity (in case of non–Newtonian fluids) is related to the average shear rate as,

$$\mu = \eta = K\left(\dot{\gamma}_a\right)^{n-1} \qquad [3.6]$$

Equating the Newtonian viscosity, defined for the case of laminar mixing, by Eq. [3.4], Eq. [3.6] may be written as,

$$k''\frac{M}{N} = K\left(\dot{\gamma}_a\right)^{n-1} \qquad [3.7]$$

According to Metzner and Otto (1957), the average shear rate is linearly proportional to the impeller rotational speed when the mixing regime is laminar. The proportionality constant is called mixer viscometer constant (k'). Thus, the relation between average shear rate and angular velocity is depicted as

$$\dot{\gamma}_a = k'N \qquad [3.8]$$

Substitution of Eq. [3.8] into Eq. [3.7] gives the mathematical relationship between k' and k'',

$$k' = \left(\frac{1}{N}\right)\left(\frac{Mk''}{KN}\right)^{\frac{1}{n-1}} \qquad [3.9]$$

CHAPTER 4

MATERIALS AND METHODS

4.1 Experimental Equipment

Experiments were conducted using Haake VT 550 rotational viscometer (Haake USA, Paramus, NJ) that has a maximum torque capacity of 3 N cm (Fig. 4.1). Two systems were used for testing: 1) The MV1 concentric cylinder (Fig. 4.2) with 4.0 cm and 4.2 cm as internal and external diameters, respectively, and 2) The helical ribbon and MV1 cup (Fig. 4.3) with 3.3 cm and 4.2 cm internal and external diameters, respectively, and 3.40 cm impeller height. Fig. 4.4 illustrates the complete dimensions of the helical ribbon that was manufactured from 304 stainless steel. The helical ribbon was attached to the Haake VT 550 using a Haake flag adapter. The viscometer was interfaced with Haake RheoWin Job Manager software for control and data acquisition. Data were analyzed using Microsoft Excel.

During testing, sample temperatures were maintained at 5° C (refrigeration temperature) or 21° C (room temperature), or 37° C (body temperature), with a variation of ± 0.5° C. The temperatures were

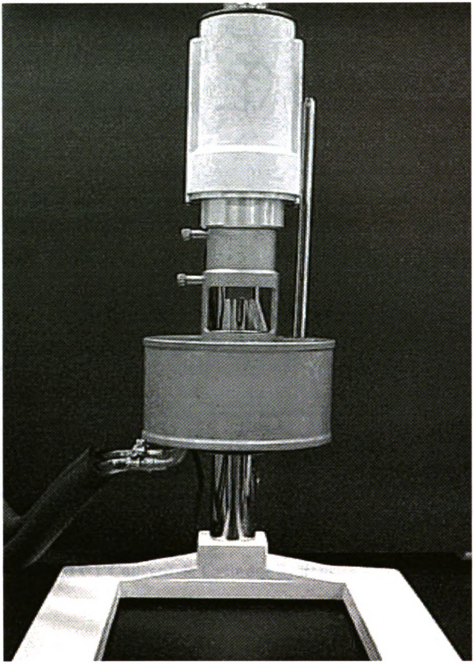


Fig. 4.1 Haake VT 550 Rotational Viscometer

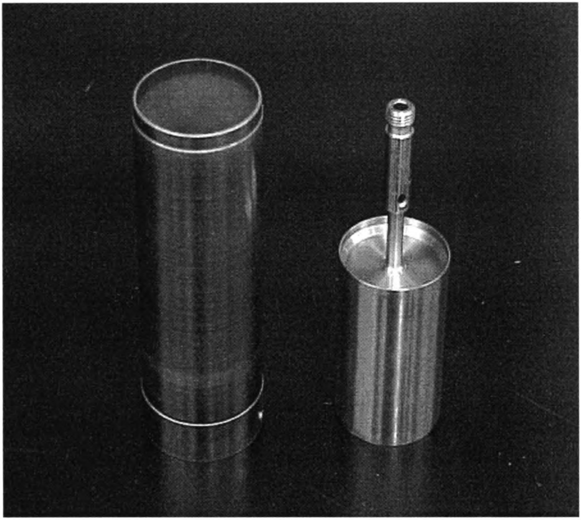


Fig 4.2 MV 1 Concentric Cylinder System

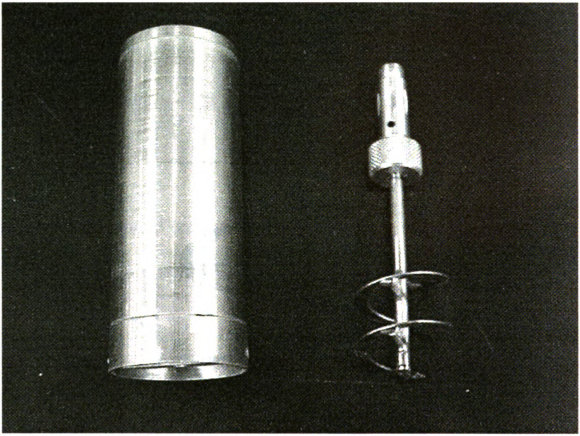
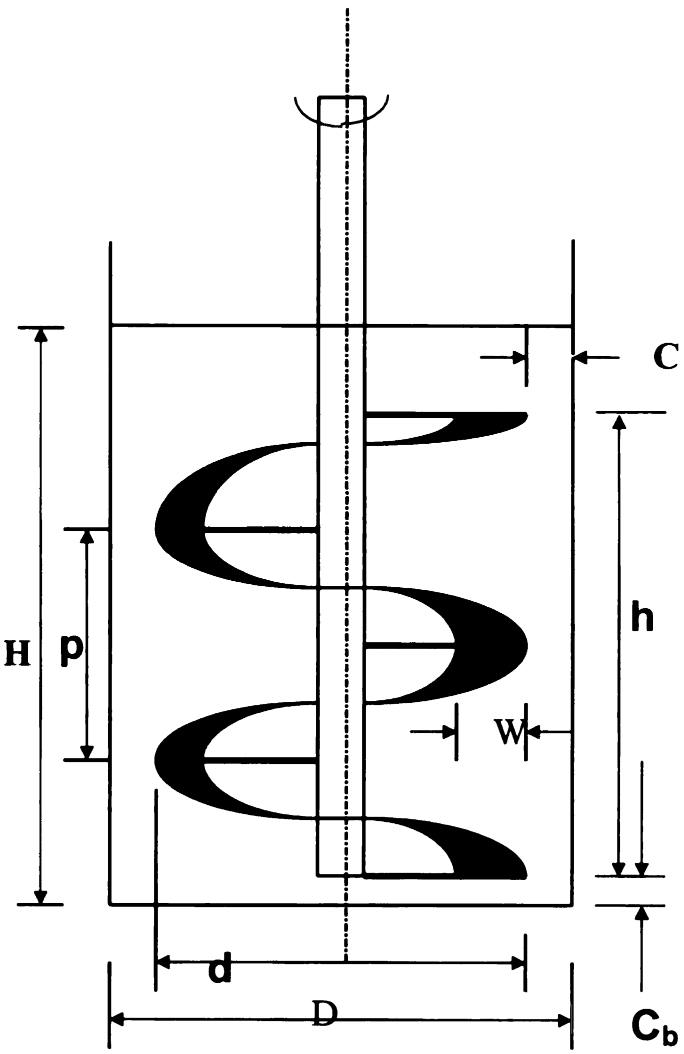


Fig 4.3 Helical Ribbon and Cylinder System



where: C = clearance between impeller and cup (0.30 cm)

C_b= clearance between bottom and impeller (0.8 cm)

D = cup diameter (4.20 cm)

d = impeller diameter (3.30 cm)

h = impeller height (3.40 cm)

H = height of sample in cup (4.2 cm)

p = pitch (1.70 cm)

W = blade width of ribbon (0.50 cm)

Fig 4.4. Complete dimensions for helical ribbon and sample cup

maintained using a Haake F6 / C25 water bath. When required, Cole – Parmer® 74900 – Series Multi-channel Syringe Pump (Cole – Parmer Instrument Company, IL) (Fig. 4.5) was used to add de – ionized water into the sample.

4.2 Characterization of Helical Ribbon

The helical ribbon was characterized by determining the values of the mixer coefficient (k'') and mixer viscometer constant (k'), which are unique for the system used in this study. The value for each constant was found from experimental data.

4.2.1 Determination of k''

Glycerin (Columbus Chemical Industries, Inc., Columbus, WI) and silicon oil (Brookfield Engineering, Stoughton, MA), with varying viscosities (Table 4.1), were used for the determination of k''. These materials are standard Newtonian fluids that have a linear relationship between shear stress and shear rate.

The value of k'' was determined using the Torque Curve Method (Mackey et al, 1987). All the experiments were conducted in laminar

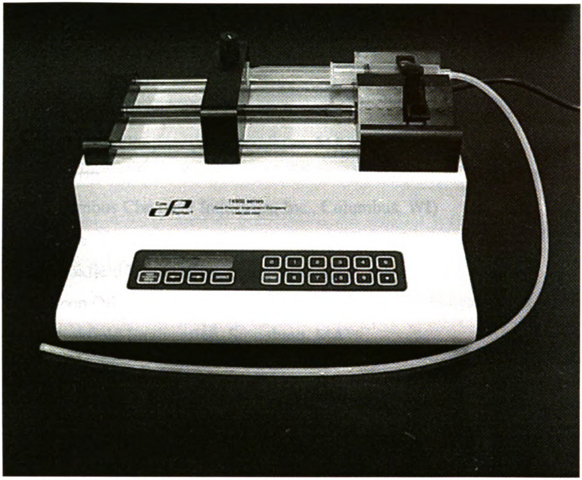


Fig 4.5 Multi – Channel Syringe pump

Table 4.1: Newtonian fluids used with the helical ribbon impeller to evaluate k′

Fluid	Viscosity (Pa s)
Silicon Oil (Brookfield Engineering, Stoughton, MA)	0.490
Glycerin (Columbus Chemical Industries, Inc., Columbus, WI)	0.740
Silicon Oil (Brookfield Engineering, Stoughton, MA)	5.20
Silicon Oil (Brookfield Engineering, Stoughton, MA)	5.28

flow region defined by the magnitude of the impeller Reynolds number Eq. [3.1]: ($N_{Re,I}$) < 10, when angular velocity is expressed in units of rev/s. The respective ranges of angular velocities calculated and used during the experiments are listed in Table 4.2

The fluid density used in determining the angular velocity range was calculated as:

$$\rho = \frac{m}{V} \qquad [4.1]$$

Prior to running experiments, the fluid was loaded in the cylinder and allowed to sit undisturbed for 30 min to equilibrate to the desired temperature. The experiments were conducted using the helical ribbon at an angular velocity range to ensure the laminar flow. Raw data between torque (M), angular velocity (N) and viscosity (μ) were obtained. Employing linear regression, the slope of the linear curve (defined by Eq. 3.4) was obtained and the inverse of this slope yielded the value of k''.

Table 4.2. Range of angular velocity (rpm) for Newtonian Fluids with different viscosities as calculated using the Reynolds number

Viscosity (Pa s)	Angular velocity range (rpm)
0.49	10 – 40
0.74	5 – 50
5.20	50 – 450
5.28	50 – 450

4.2.2 Determination of k'

Non-Newtonian fluids including guar gum (Sigma Chemical Company) and hydroxypropyl methyl – cellulose (HPMC) (A4M PREM) (The Dow Chemical Company) were employed at different concentrations to obtain the value of k'. Guar gum and HPMC were available in the powdered form and 1.00%, 1.50%, 2.00%, 2.25% and 2.50% (weight basis) solutions of both were made by dissolving them in warm, deionized water. While mixing the powders in the water, care was taken to avoid incorporation of air bubbles into the solution. The powder was added evenly and in small quantities at a time, and mixing was carried out slowly and carefully. Solutions were allowed to sit overnight to allow the complete hydration of the powder.

The experiments to determine k' were then conducted on the above solutions at room temperature (21°C ± 0.5 °C) using both the helical ribbon and cylinder systems. Solutions were loaded and allowed to sit for approximately 30 minutes to attain the equilibrium temperature. Using a similar angular velocity range as used during the determination of k'', the raw data with angular velocity (Ω) and torque (M) were obtained.

Employing the raw data for the concentric cylinder system, shear stress and shear rate were calculated using the following equations:

$$\sigma = \frac{M}{2\pi h R_b^2} \qquad [4.3]$$

$$\dot{\gamma} = 2\Omega\left(\frac{\alpha^2}{\alpha^2 - 1}\right) \qquad [4.4]$$

A curve was obtained between shear rate and stress for each solution. Employing regression analysis, the values for consistency coefficient (K) and flow behavior index (n) were obtained for each non – Newtonian solution (Table 4.3) based on the power law model:

$$\sigma = K\dot{\gamma}^n \qquad [4.5]$$

Using these values of K and n, the values of k' were calculated with the helical ribbon data from Eq. [3.9]:

$$k' = \left(\frac{1}{N}\right)\left(\frac{Mk''}{KN}\right)^{\left(\frac{1}{n-1}\right)}$$

With these calculated values of k', curves were obtained between k' values and the respective angular velocities for each solution. From the curves, a single and constant value was obtained to represent each fluid.

Table 4.3: Non – Newtonian fluids used with the helical ribbon impeller to evaluate the value of k'

Product	K (Pa s^n)	n (-)
2.50% Guar Gum	122	0.14
2.25% Guar Gum	72.0	0.24
2.00% Guar Gum	76.9	0.19
1.50% Guar Gum	28.0	0.27
1.00% Guar Gum	6.66	0.39
2.50% Methyl Cellulose	11.4	0.64
2.25% Methyl Cellulose	6.76	0.62
2.00% Methyl Cellulose	5.95	0.73
1.50% Methyl Cellulose	1.22	0.79
1.00% Methyl Cellulose	0.33	0.85

Using these individual constant values of k'(obtained at high speeds) for all the solutions, a curve was plotted between the k' values and flow behavior indices. Linear regression established a relationship between k' and n. The resulting equation was used to calculate the values of k' for different food products having different flow behavior indices when being tested for rheological properties using the helical ribbon.

4.3 Evaluation of Helical Ribbon

The helical ribbon system was assessed and its performance was compared to a traditional concentric cylinder viscometer. Food products used to evaluate the helical ribbon were Heinz tomato ketchup (H. J. Heinz Co.), French's mustard (Reckitt & Colman Inc.) and Henri's classic Southwest ranch dressing (Henri's Food Products Co.). Ketchup and mustard are homogenous products but Henri's ranch dressing is a non-homogenous product and was found to contain particles up to 4mm length.

Experiments were conducted at the room temperature (21°C ± 0.5 °C) with the Haake MV1 concentric cylinder system at shear rate range of 1 – 50 1/sec for 60 sec. The raw data obtained contained values for shear rate, stress and apparent viscosity. A curve was plotted between shear rate and stress and a power law regression model (Eq. [4.6]) was evaluated to obtain the value of flow behavior index (n) for all the foods tested. Using the respective values of n and the relationship between k' and flow behavior index (n) (Sec 4.2.2), the values of k' were calculated for the respective food products. With the calculated values of k', as obtained above, the range of angular velocity (N) at shear rate range of 1 – 50 1/sec for each food product was calculated using the Eq. [4.7]:

$$N = \frac{\dot{\gamma}}{k'} \qquad [4.7]$$

Using the appropriate range of angular velocities, experiments were conducted at the room temperature (21°C ± 0.5 °C) on the fresh food products using the helical ribbon system. Raw data were torque (M) and angular velocity (N). Using this information, the shear rate ($\dot{\gamma}$) and apparent viscosity (η) values were calculated using Eq. [4.7] and [4.8], respectively,

$$\eta = k'' \frac{M}{N} \qquad [4.8]$$

After conducting similar experiments on the fresh food product samples with the shear rate range input of 1 – 50 1/sec using the concentric cylinder system, resulting rheograms were compared to those obtained with the helical ribbon data. Each food product was evaluated three times and the average of the three data sets for individual food products was taken to compile the result.

4.4 Evaluation of Physical Changes in Food Emulsions with Addition of Water

Kraft Fat – Free Mayonnaise, Kraft Light Mayonnaise, Kraft Real Mayonnaise, Kraft Miracle Whip and Hellmann's Real Mayonnaise were used to evaluate the effect of water addition on the flow behavior of emulsions. These materials were taken from the 32 – oz jars of the same lot for all the replications. Table 4.4 lists the major ingredients in these products. De-ionized water was used in all experiments. The experimental set up was scaled – up seventeen times to emulate the conditions existing in the mouth (Table 4.5), which included the volume of sample and water, water flow rate, running time of experiment, and shear rate that matched the volume of bolus and saliva, saliva flow rate, residence time, and shear rate in the oral cavity, based on the published literature. These variations gave the proportional increase to instrumentally meet the conditions of the oral cavity. The

Table 4.4 Major ingredients present in the five food products

Food Product	Major Ingredients
Kraft Fat Free Mayonnaise	Water, modified food starch, high fructose corn syrup
Kraft Light Mayonnaise	Water, modified food starch, egg yolks, soybean oil
Kraft Real Mayonnaise	Water, egg yolks, soybean oil
Kraft Miracle Whip	Water, starch, egg yolks, soybean oil
Hellmann's Real Mayonnaise	Water, egg yolks, whole eggs, soybean oil

Table 4.5 Scaled – up numerical values used during the experiments to meet the conditions existing in the oral cavity

Conditions	**Oral Cavity***	**Sample**	**Scale**
Volume (ml)	3.0	51.2	1 : 17
Residence time (s)	7.5	127.5	1 :17
Water Flow Rate (ml/min)	4.0	4.0	1 : 1
Water Volume (ml)	0.5	8.5	1 : 17

* The values for the oral cavity were based on the published literature

impeller was completely immersed and was in level with the sample.

Water addition was carried out using two methods: without manual mixing (using a syringe pump) and with manual mixing (mixing by hand). When not mixed manually, the product's rheological behavior can be studied before, during and after the incorporation of water. Occasionally, undesirable results were encountered with this mixing method, which led to the introduction of the manual mixing method.

In the manual mixing method, the changes occurring during incorporation of water could not be studied as water was added prior to experimentation. Rheological properties before and after mixing of water were determined.

4.4.1 With Automatic Water Injection

The whole data set consisted of a set of three tests as described below. In all the tests, the sample was loaded and kept for about half an hour before running the test so that the sample attained the equilibrium temperature of 21°C ± 0.5°C.

Test 1: A pre – shear test was conducted on each sample with the concentric cylinder system at the shear rate of 25 1/sec for 60 sec. Following this, another test was carried out on the same sample with the same system over the shear rate range of 1 – 50 1/sec in 60 sec period. With the raw data, a rheogram was plotted between shear rate and stress. By employing the power law regression model, the values for the flow behavior index (n) and consistency coefficient (K) were obtained. Using the linear relationship between flow behavior index (n) and k' (Sec. 4.2.2), the value for k' was found for the respective food product. Using this value of k', the value of angular velocity (N) was derived using Eq. [4.7] at shear rates 1.25 1/sec and 2.5 1/sec.

Test 2: To observe the changes brought about in the food product during the mixing of water, a test was conducted on a fresh food product sample of 52-ml. The helical ribbon system was employed and the test was carried out at the angular velocity calculated in Test 1 and de – ionized water was injected into the system through a multi-channel syringe pump at a rate of 4 ml/min and the total volume of water added was 8.5 ml. Total running time for each experiment conducted was

127.5 sec. Data obtained were saved for further analysis and the sample was further used to conduct Test 3 as described below.

Test 3: The sample obtained above was used to run another experiment with concentric cylinder system at the shear rate range of 1 – 50 1/sec for 60 sec (similar to Test 1). Using the raw data, a rheogram was obtained between shear rate and stress. With the use of power law, the values for flow behavior index (n) and consistency coefficient (K) were evaluated. Comparison of these values to that of the corresponding values obtained prior to addition of water (Test 1) indicates the changes brought about from the addition of water.

Tests 1, 2 and 3 indicate the rheological properties of the food product before, during and after addition of water, respectively. The same data sets were collected at three temperatures: refrigeration temperature (5°C), room temperature (21°C), and body temperature (37°C). Four replications of the above tests were conducted in a similar manner at each temperature with each food product.

4.4.2 With Manual Mixing

One complete data set under this method of water addition consisted of four tests as elaborated below. All the tests were conducted at 21°C ± 0.5°C. Required range of angular velocities (N) was obtained by using the Eq. [4.7]. The value of k' to be used in this equation was obtained by taking an average of the k' values obtained while conducting Test 1, Sec 4.4.1, for all the products at all temperatures.

Test 1: A test was conducted using the helical ribbon on a fresh 52 – ml food sample within the range of angular velocity at average shear rates of 1 to 50 1/sec (as calculated using the Eq. [4.7]) for 60 sec. During the test, both ramp up and ramp down variations were conducted to check for thixotropic behavior of the food product. From the raw data of torque (M) and angular velocity (N), the shear rates ($\dot{\gamma}$) and apparent viscosity (η_a) were calculated using the Eq. [4.7] and Eq. [4.8] respectively for all the data points.

Test 2: The next test was similar to Test 1 but prior to running the experiment, 2.125 ml of water was added to the fresh food sample of 52 ml and was manually mixed. This sample was used to conduct an experiment under similar conditions as for Test 1 and was followed by similar calculations.

Test 3: In this test 4.25 ml water was added to a 52 ml fresh food sample and mixed manually prior to carrying out the experiment. The test was conducted in a similar manner as was conducted under Test 1, and shear rate and apparent viscosity were calculated.

Test 4: A fresh sample of 52 ml was taken and 8.5 ml water was added and mixed manually. Then the experiment was carried out as in Test 1 followed by calculation of shear rate and apparent viscosity.

With the data obtained in Tests 1, 2, 3, and 4, a graph was plotted between average shear rate and apparent viscosity for the food samples with different amounts of water incorporated. Employing the power law (Eq. [4.6]), a relationship was obtained between apparent viscosity and shear rate for each sample. With the equations obtained, the apparent viscosities were calculated at shear rates 1, 25 and 50 1/sec and a graph was plotted with apparent viscosity and the ratio of water incorporated in the sample to maximum water incorporated (i.e., 8.5 ml) in the sample at all the three shear rates. Thus, three curves were obtained on the same graph for one food product that would correspond to the three shear rates.

Using the manual mixing method, three temperatures were considered for the tests, refrigeration temperature (5°C), room temperature (21°C), and body temperature (37°C) to observe the effect of temperature on the product at different level of water incorporation. Each food product was evaluated at three temperatures in a similar manner to obtain four replicates.

4.5 Evaluation of Kraft Miracle Whip with Different Textural Properties

Five types of Kraft Miracle Whip (obtained directly from Kraft), varying slightly in their textural properties, were evaluated with the helical ribbon to measure structural differences instrumentally. Five samples (labeled 219, 221, 234, 240 – 1, and 240 – 2) were tested at room temperature (21°C) applying the "with manual mixing" analogy as described under Section 4.4.2. The following textural specifications for the samples were provided by Kraft: 219 was soft, gel type of body that would give a creamy mouth feel after the application of shear in the mouth; 221 was reported to be lumpy that would undergo fast breakdown; 234 sample was a light textured miracle whip with slightly lumpy body; samples 240 – 1 and 240 2 were similar with thick body, and good cling to the mouth, sample 240 – 2 was also reported to have a good body.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Characterization of the Helical Ribbon

The helical ribbon impeller was characterized by determining various constants that can be utilized to evaluate the rheological properties of different food products. The viscometer coefficient (k'') and the mixer viscometer constant (k') are the major parameters involved in the analysis of the data obtained by conducting experiments with helical ribbon.

5.1.1 Evaluation of k''

Viscometer coefficient (k'') is the constant that is solely dependent on the geometry of the impeller and thus is a unique value for a particular impeller. Figure 5.1 depicts the plot obtained for the determination of k''. The experiments were conducted at room temperature (21° C ± 0.5 °C) using the Newtonian fluids (silicon oil and glycerin). The data obtained for the standards at different viscosities were pooled together to obtain a curve between torque and the product of angular velocity and viscosity. By inserting the linear trend line, the slope of the curve

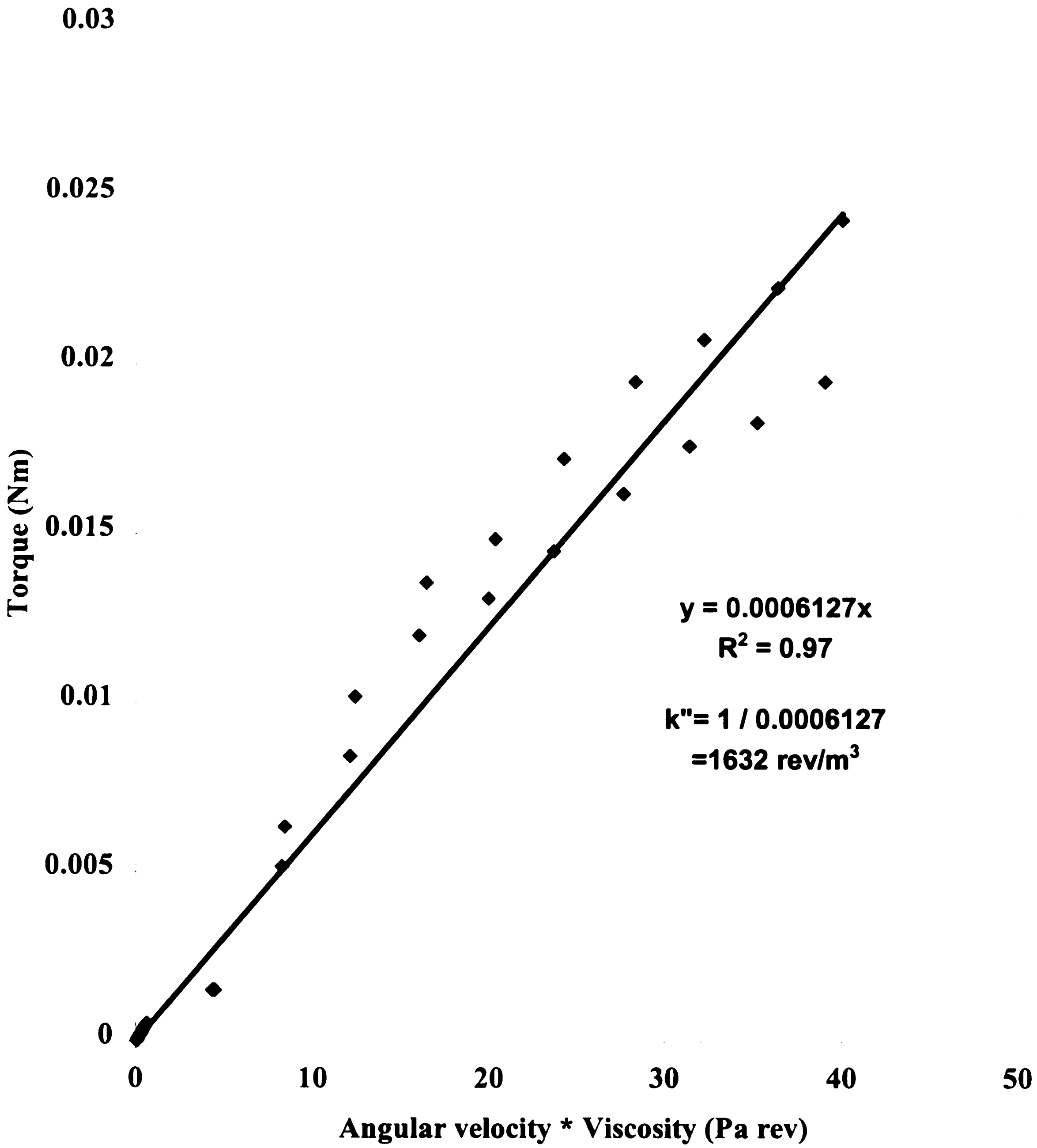


Figure 5.1 Plot obtained for the determination of k" using Newtonian fluids

(defined by Eq. 3.4) was found to be 0.0006127, the inverse of which yielded the value of k'' as 1632 rev/m^3.

Since the Newtonian fluids used during the evaluation of k'' had different viscosities (Table 4.1), the ranges of angular velocities used while conducting the experiment were different (Table 4.2). This range was based on the Reynolds number and was calculated using the Eq. 3.1 to ensure a laminar flow in the sample. The angular velocity range was found to be lower for the standards with lower viscosity, which in turn gave the data sets in the different regions of the graph. Thus, the data were pooled to obtain one value of k'' representing the helical ribbon for all the food materials irrespective of their viscosities.

5.1.2 Evaluation of k'

In addition to the value of k'', the value of K and n are also required to determine the value of k' at different angular velocities using the Eq. 3.9. To find K and n, plots (Fig. 5.2 and 5.3) were obtained for stress (Pa) and shear rate (1/sec) for non – Newtonian fluids, guar gum

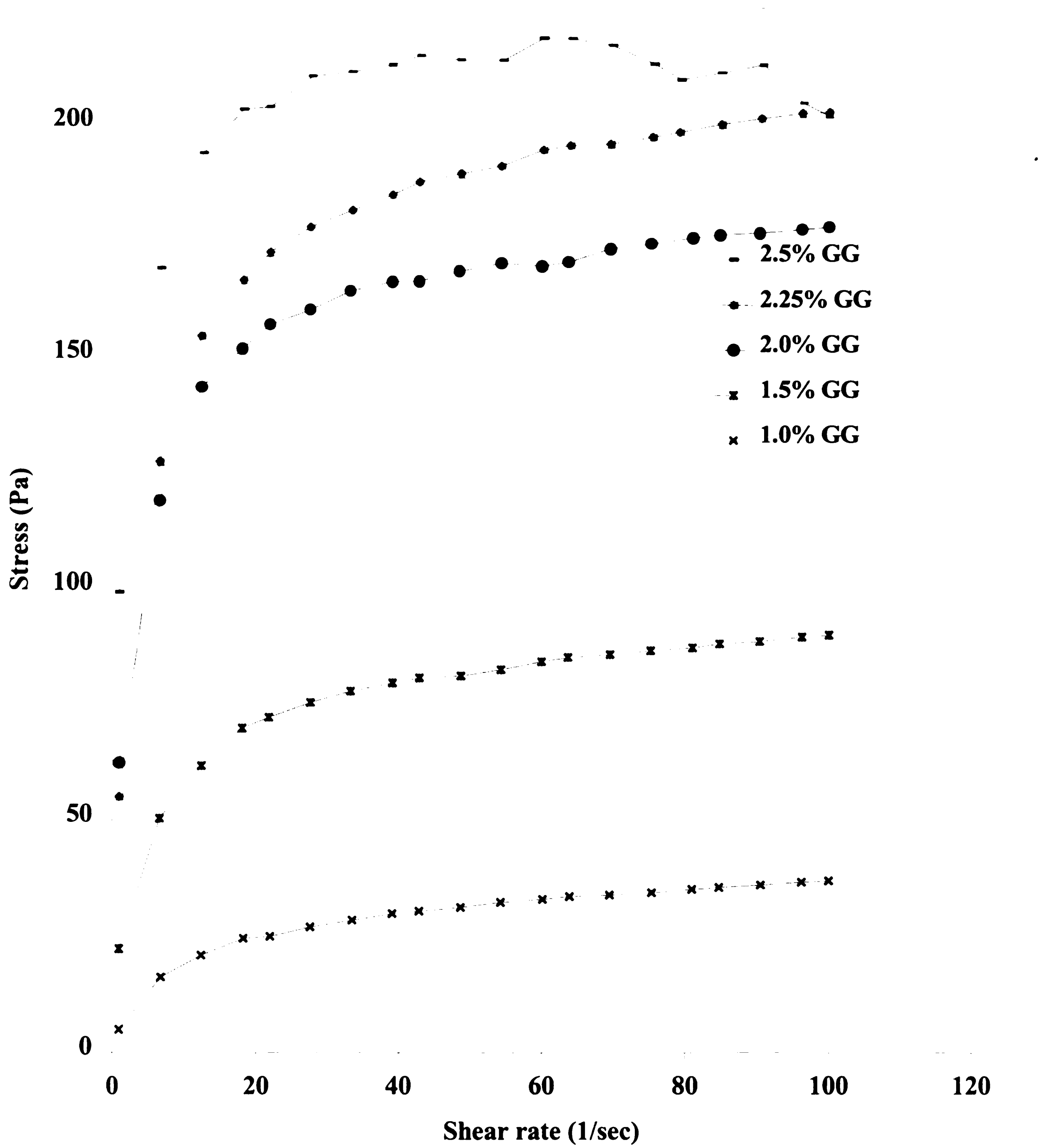


Figure 5.2 K and n values for guar gum at different concentrations

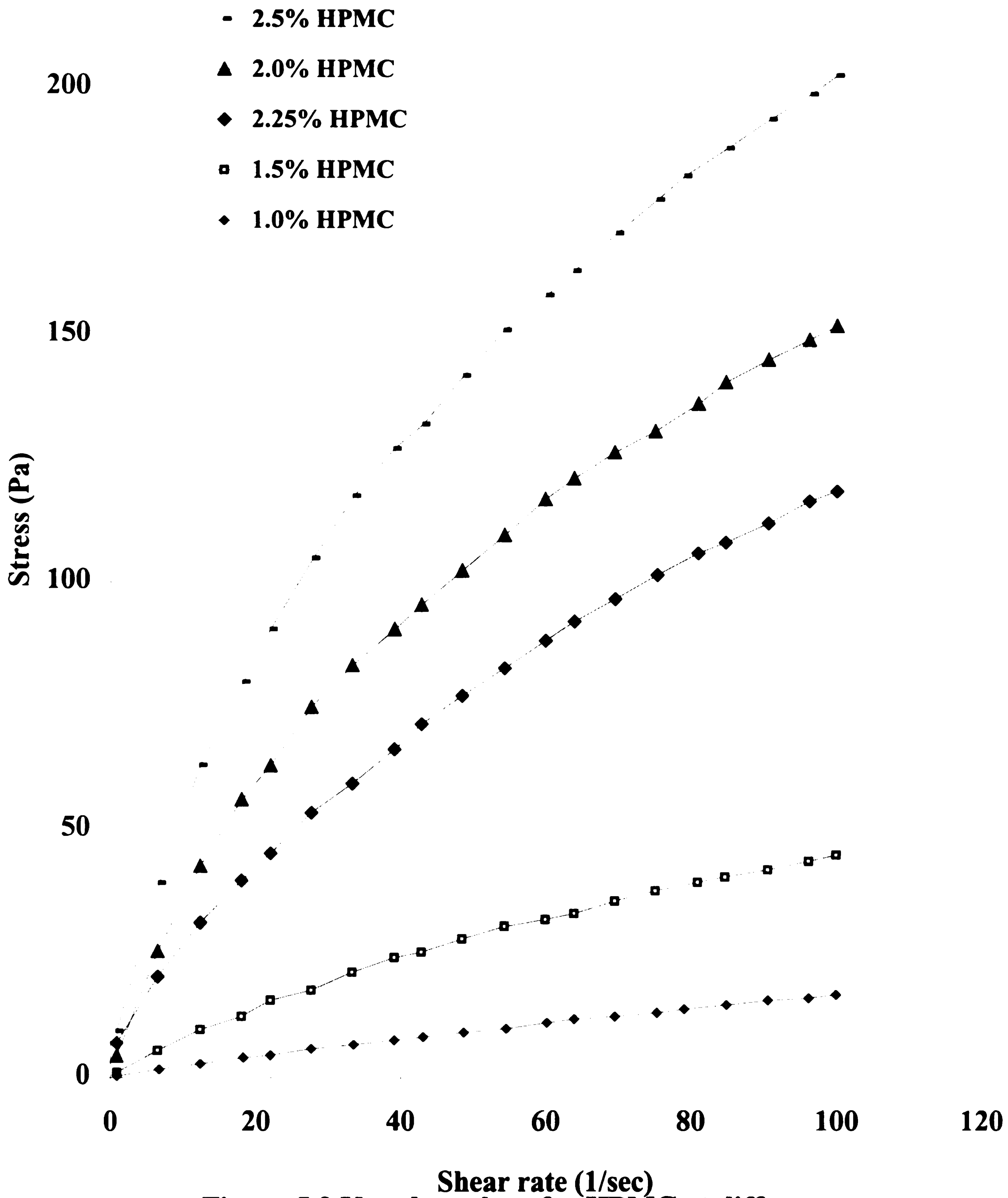


Figure 5.3 K and n values for HPMC at different concentrations

and HPMC at different concentrations. By using the power law regression model, the values of K and n were obtained for each fluid (Table 4.2). It can be observed from the table that the value of K increases with the increase in the concentration of the solution indicating the increasing thickness of the fluid. The values of n, on the other hand, show the opposite trend, which decreases with the increase in the concentration of the solution, with the exception of 2.25% guar gum and 2.5 % HPMC.

With the known values of k'', K and n, the values of k' were calculated and were plotted against angular velocity (Fig 5.4 and 5.5). From these curves it can be seen that the values of k' are a function of angular velocity and were found to decrease sharply as the angular velocity increased from 0 to 0.1 rev/sec for both the guar gum and HPMC solutions. The guar gum solutions acquired a constant value for k' at the angular velocity of 0.2 rev/sec at all the concentrations except for the 1.0 % guar gum solution, which attained a constant value at the angular velocity of 0.1 rev/sec. From the curves obtained, a constant and an average value of k' was obtained for each non – Newtonian solution and thus a range of k' values was obtained after

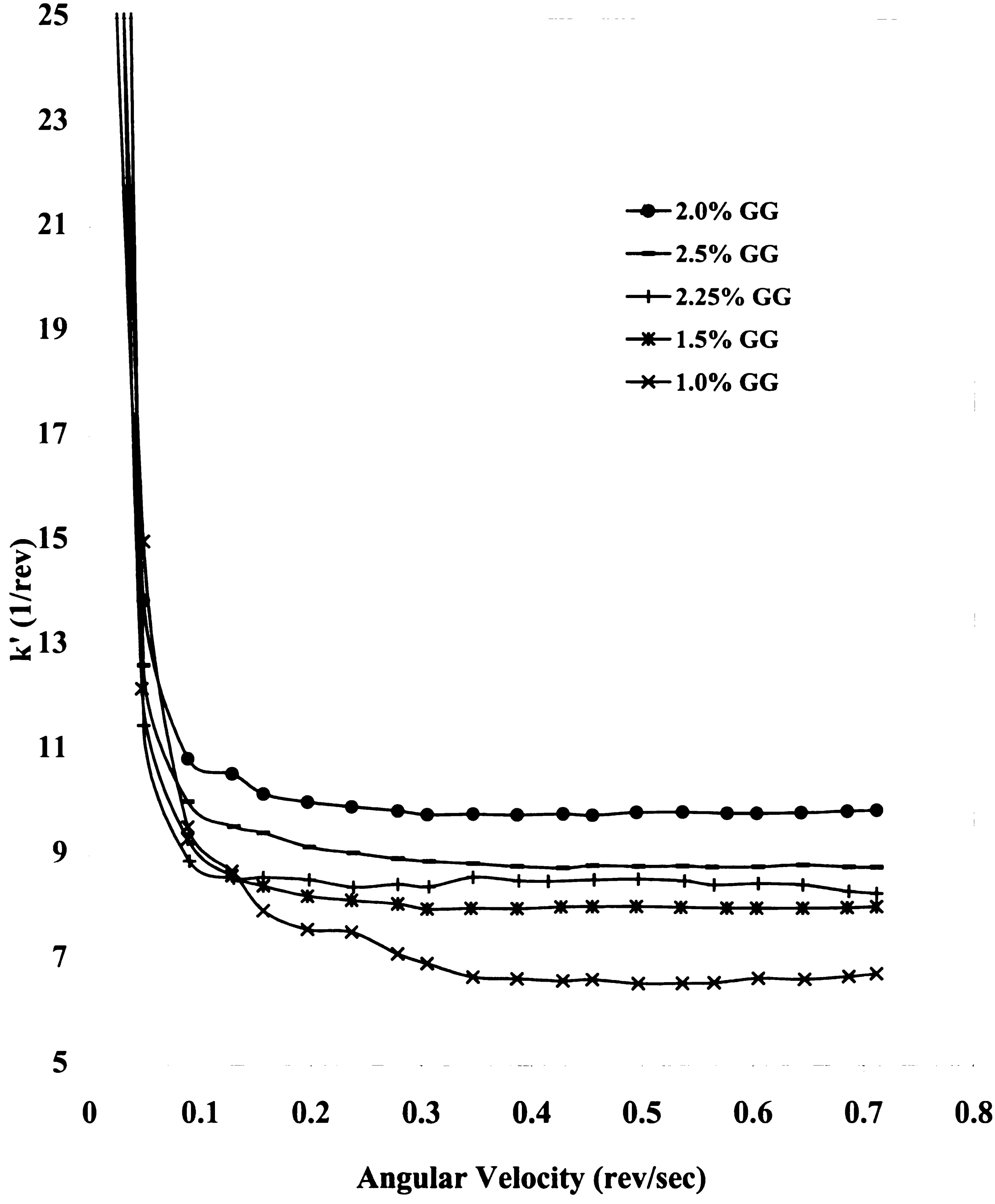


Figure 5.4 k' at different angular velocities for Guar Gum at different concentrations

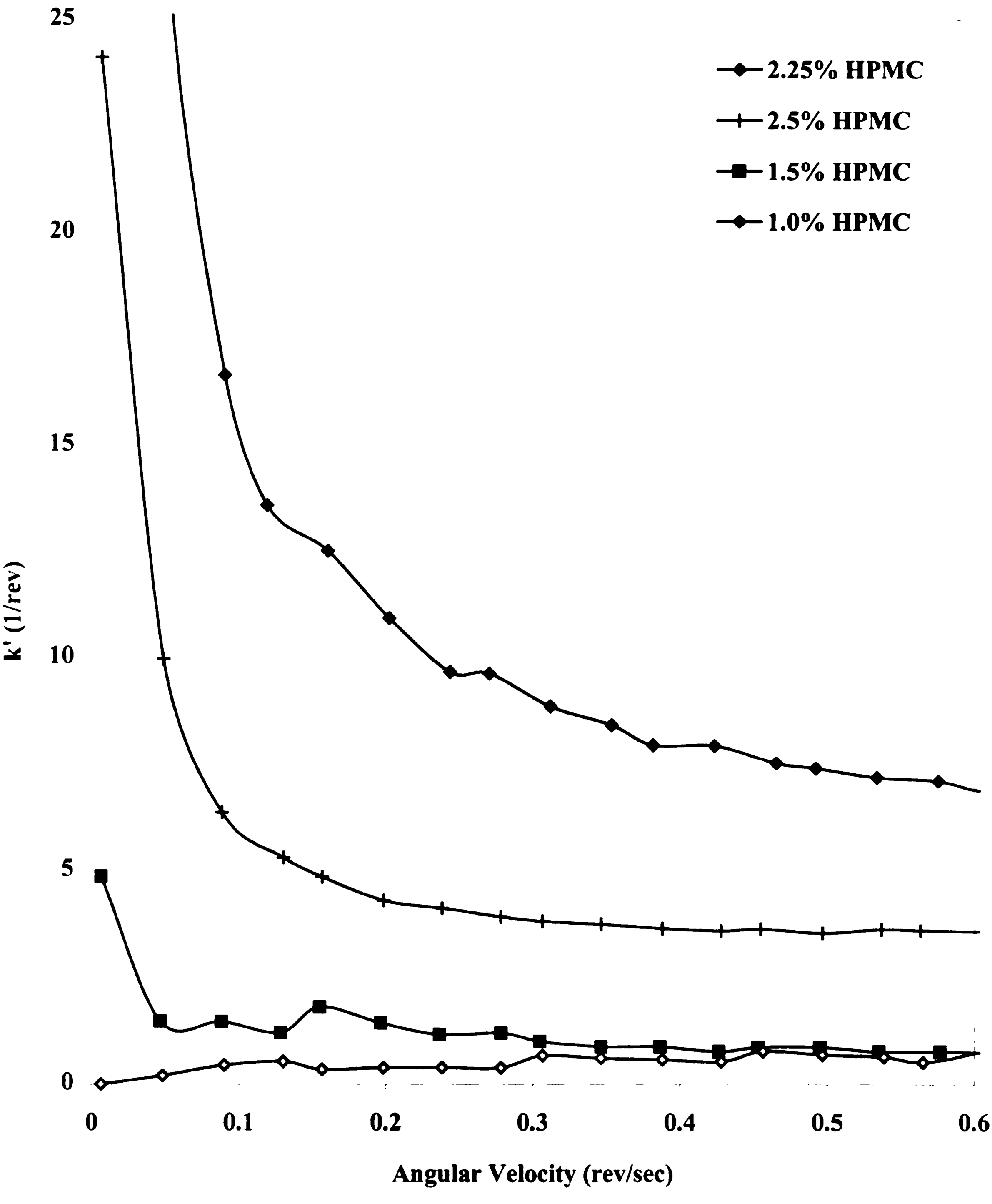


Figure 5.5 k' at different angular velocities for HPMC at different concentrations

pooling all the constant values attained for all the solutions (thus, 10 constant values for k') as 3 – 11 1/rev. Value of the constant for any solution would be within this range. Also, it can be seen that the values of k' decreased with the decrease in the concentration in each fluid. Hence the constant was found to be a variable entity depending on the experimental set up.

Besides changing with the angular velocity, the value of k' was also found to vary with the flow behavior index (n). It decreases with the increase in n meaning that as the concentration and the viscosity of the fluid decrease, the value of k' also decreases. However, this trend was not seen in the 2.0% GG and 2.50% HPMC solution. The relationship between k' and the n is depicted in the Fig. 5.6 with the actual values given in Table 5.1. From this curve, it is evident that k' and n are linearly related to each other and hence, on application of the linear regression, an equation can be obtained relating the two entities. Using this equation, the value of k' was calculated using the value of n for the food products tested using the helical ribbon. The equation obtained was

$$k' = -11.486\, n + 11.521$$

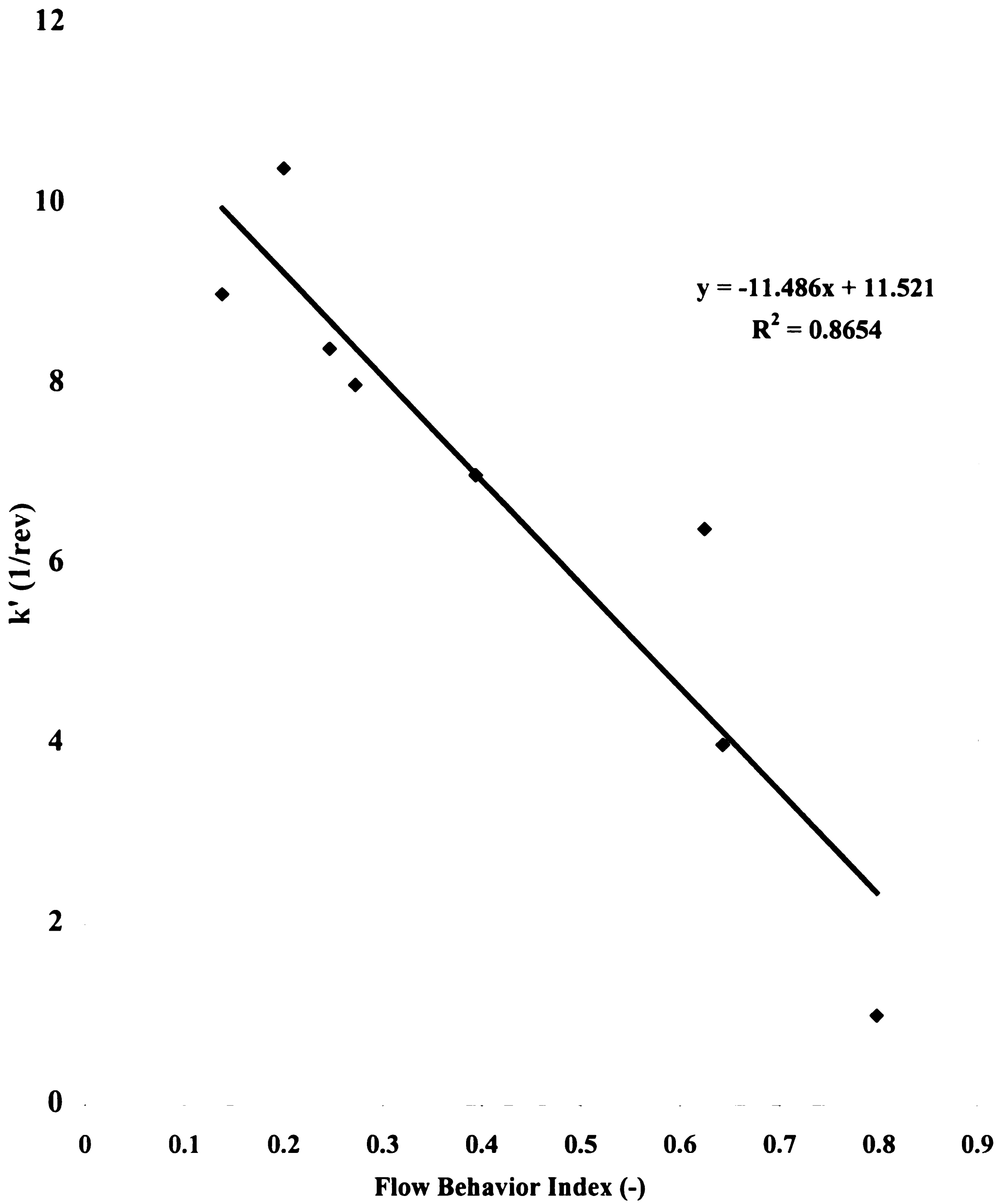


Figure 5.6 Mixer viscometer constant (k') and flow behavior index (n) for guar gum and HPMC at different concentraitons

Table 5.1 Values of flow behavior index (n) and mixer viscometer constant (k′) for guar gum (GG) and HPMC at different concentrations

Non – Newtonian fluid	n	k′ (1/rev)
2.50 % GG	0.136	9.0
2.25 % GG	0.244	8.4
2.00 % GG	0.198	10.4
1.50 % GG	0.271	8.0
1.00 % GG	0.392	7.0
2.50 % HPMC	0.642	4.0
2.25 % HPMC	0.623	6.4
2.00 % HPMC	0.727	3.2
1.50 % HPMC	0.797	1.0
1.00 % HPMC	0.849	1.8

5.2 Evaluation of the Helical Ribbon

The performance of the helical ribbon was evaluated and compared to the performance of a traditional concentric cylinder viscometer. The comparison of rheograms (Fig. 5.7) indicates that curves acquired by both the systems show similar trends. The curves obtained for the ketchup and mustard by the two systems are very close to each other, which indicates that the helical ribbon reveals similar results as the concentric cylinder. However, some differences are seen in the curves of Henri's Ranch dressing and this trend is also observed by comparing the values of consistency coefficient and flow behavior index (Table 5.2).

The rheograms for the three food products can be compared by considering the values of consistency coefficient (K) and flow behavior index (n) for the respective curves (Table 5.2). The values for K and n are very close for ketchup and mustard and the greatest variation is revealed for the Henri's Ranch dressing. Ketchup and mustard are homogenous food materials while the Henri's Ranch dressing is a non – homogenous food material. The variation in the values of Henri's Ranch dressing might be attributed to the presence of large (size $\leq$ 4

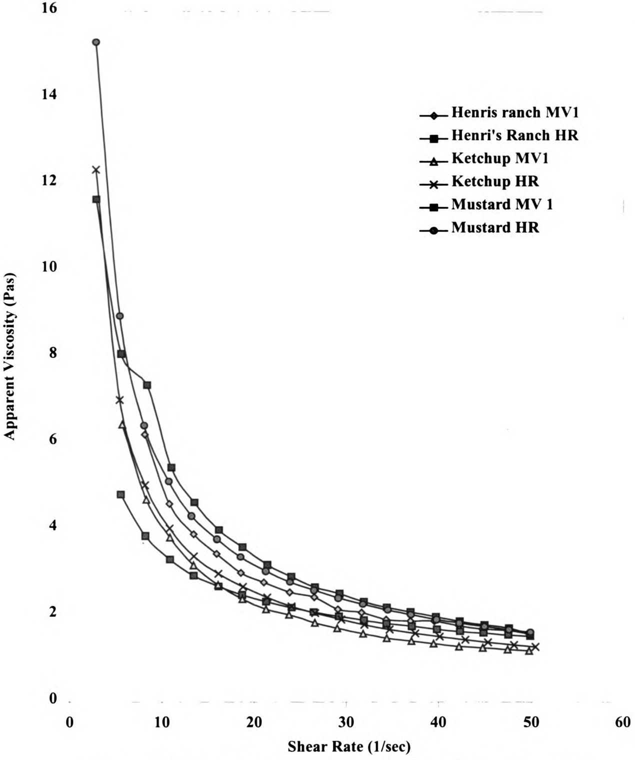


Figure 5.7 Rheograms of different food products comparing results from Haake Concentric Cylinder (MV1) and Helical Ribbon (HR) systems

Table 5.2 Comparison of consistency coefficient (K) and shear – thinning indices (n) for typical food products as obtained with helical ribbon and concentric cylinder systems

Food Product	Helical Ribbon		Haake VT 550	
	K (Pa s^n)	n (-)	K (Pa s^n)	n (-)
Henri's Ranch Henri's Food Products Co., Inc. Milwaukee, WI	1.312	0.482	24.90	0.285
Ketchup H. J. Heinz Co. Pittsburgh, PA	25.97	0.226	24.38	0.212
Mustard Reckitt & Colman Inc., Wyne, NJ	28.91	0.253	24.12	0.306

mm) particles in the dressing, which might lead to variable results with the concentric cylinder. Since the particle size is large as compared to the clearance between the concentric cylinder and the bob, the torque response during the experiment might be erroneous. In experiments with the helical ribbon, on the other hand, particles have enough space to move around the sensor, which also helps keep the particles in suspension. Hence, the helical ribbon is more reliable than traditional sensors and can be effective sensor measuring the rheological properties of the non – homogenous food products with a significant yield stress or large particles.

5.3 Evaluation of Physical Changes in Food Products with Addition of Water During Mixing

Food products behaved differently under the two analogies (automatic vs. manual addition of water) and demonstrated various structural changes with water that were visually apparent with automatic water addition. In this case, Kraft Fat Free Mayonnaise showed an even mixing of water but the sample had a rough texture, very loose body and small pieces of mayonnaise separating from the bulk. In the Kraft Light Mayonnaise sample, water was fully incorporated in the sample but it became lumpy, and structural disintegration into small clumps was observed. Upon completion of the experiment, the sample had a coarse texture. Kraft Real Mayonnaise incorporated a significant amount of water into the structure initially, but did not easily incorporate water to a large extent and by the end of the experiment; a thin water layer could be seen on top of the sample, which looked smooth after the addition of the water. In the case of Kraft Miracle Whip, even mixing of water was observed and a creamy mixture with smooth texture and slightly cloudy liquid at the periphery was obtained. Hellmann's Real Mayonnaise behaved in a similar manner. Initially with the addition of water, a uniform, smooth mixture without the separated and distinguished layer of liquid water, and solid mayonnaise was obtained. As the experiment proceeded, a smooth solid mixture and slight cloudy liquid at the periphery was produced, and ultimately, a uniform liquid mixture was obtained.

In context, manual mixing of water into the sample produced a uniform material in every case. Final samples were smooth and creamy and differences in the body were not observed. The mixing was more uniform.

5.3.1 Automatic Water Injection

Satisfactory mixing with the helical ribbon was only obtained for some products at some temperatures. Kraft Light Mayonnaise at 37 °C, Kraft Real Mayonnaise at 21°C and 37 °C, and Hellmann's Real Mayonnaise at 37 °C did not give satisfactory results with this method. Mixing was not homogenous which led to separate water and mayonnaise layers. Mayonnaise tended to stick to the central shaft of the helical ribbon, which prevented the water from being incorporated in the sample. Alternative impellers are needed to overcome this problem.

Figures 5.8 through 5.12 compare the behavior of Kraft Fat Free, Kraft Light Mayonnaise, Kraft Real Mayonnaise, Kraft Miracle Whip, and Hellmann's Real Mayonnaise, respectively, at three temperatures, 5°C, 21°C, and 37°C with 8.5 ml water added at the rate of 4.0 ml/min. The data were compiled by running four replications for each experiment and the average of the four runs was considered for the analysis. Using the raw data for angular velocity, shear rate was calculated using Eq. 3.8, which was plotted against apparent viscosity as strain history (shear rate * time). From all the curves a general trend can be observed in the behavior of the food products: the apparent viscosity decreases with

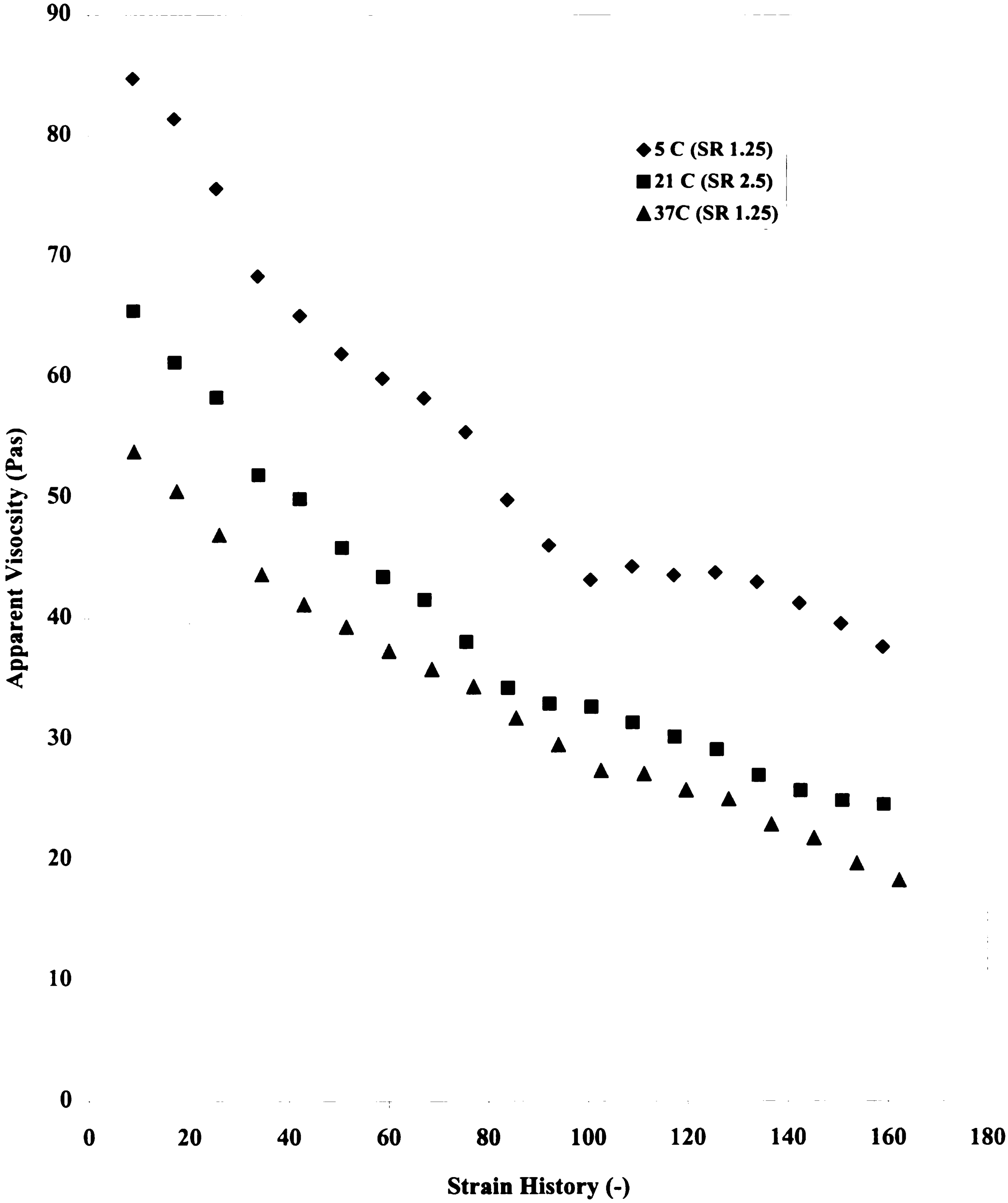


Fig 5.8 Kraft Fat Free at different temperatures during the addition of 8.5 ml water at the rate of 4.0 ml/min (with automatic addition of water)

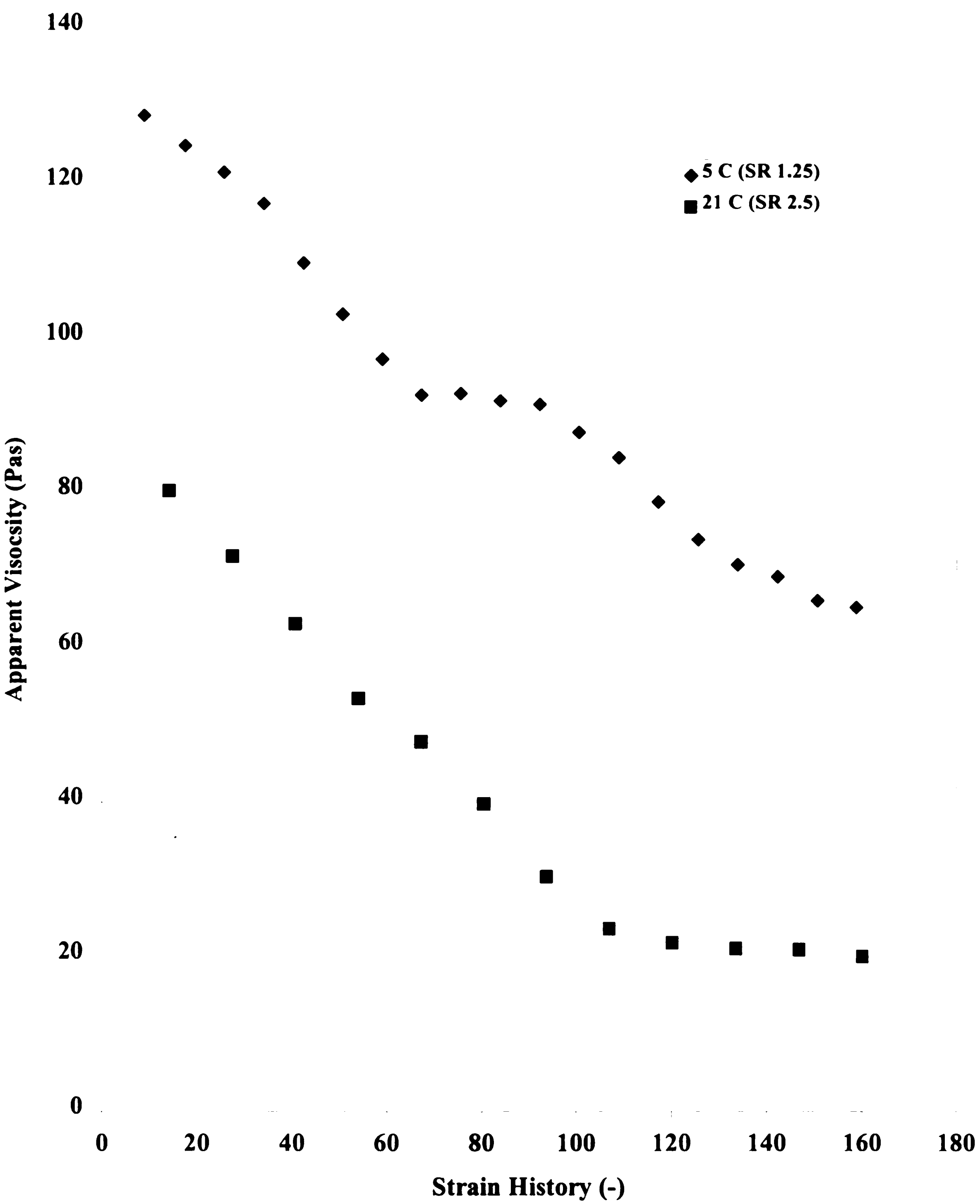


Fig 5.9 Kraft Light Mayonnaise at different temperatures during the addition of 8.5 ml water at the rate of 4.0 ml/min (with automatic addition of water)

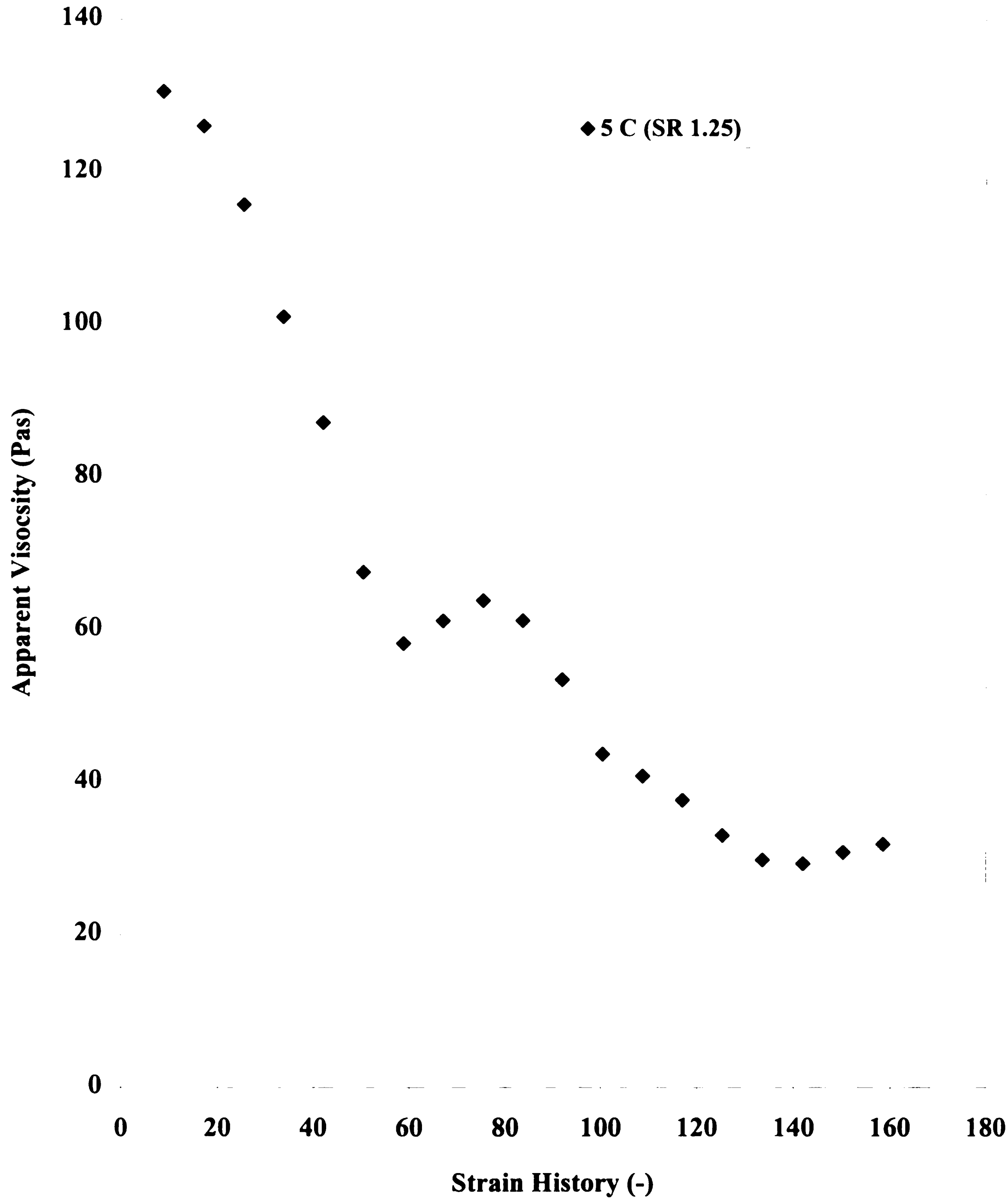


Fig 5.10 Kraft Real Mayonnaise at 5 C during the addition of 8.5 ml water at the rate of 4.0 ml/min (without manual mixing)

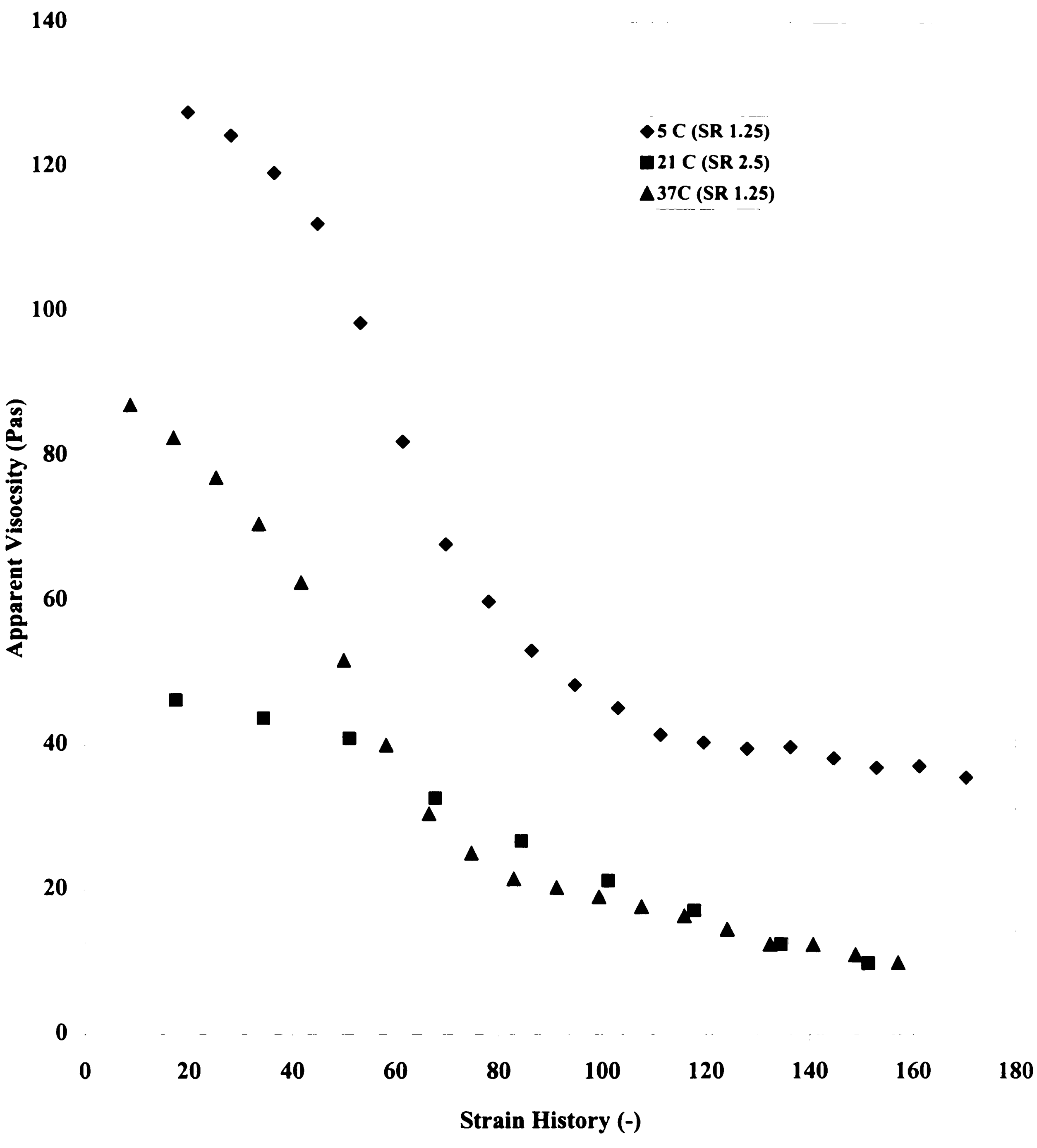


Fig 5.11 Kraft Miracle Whip at different temperatures uring the addition of 8.5 ml water at the rate of 4.0 ml/min (with automatic addition of water)

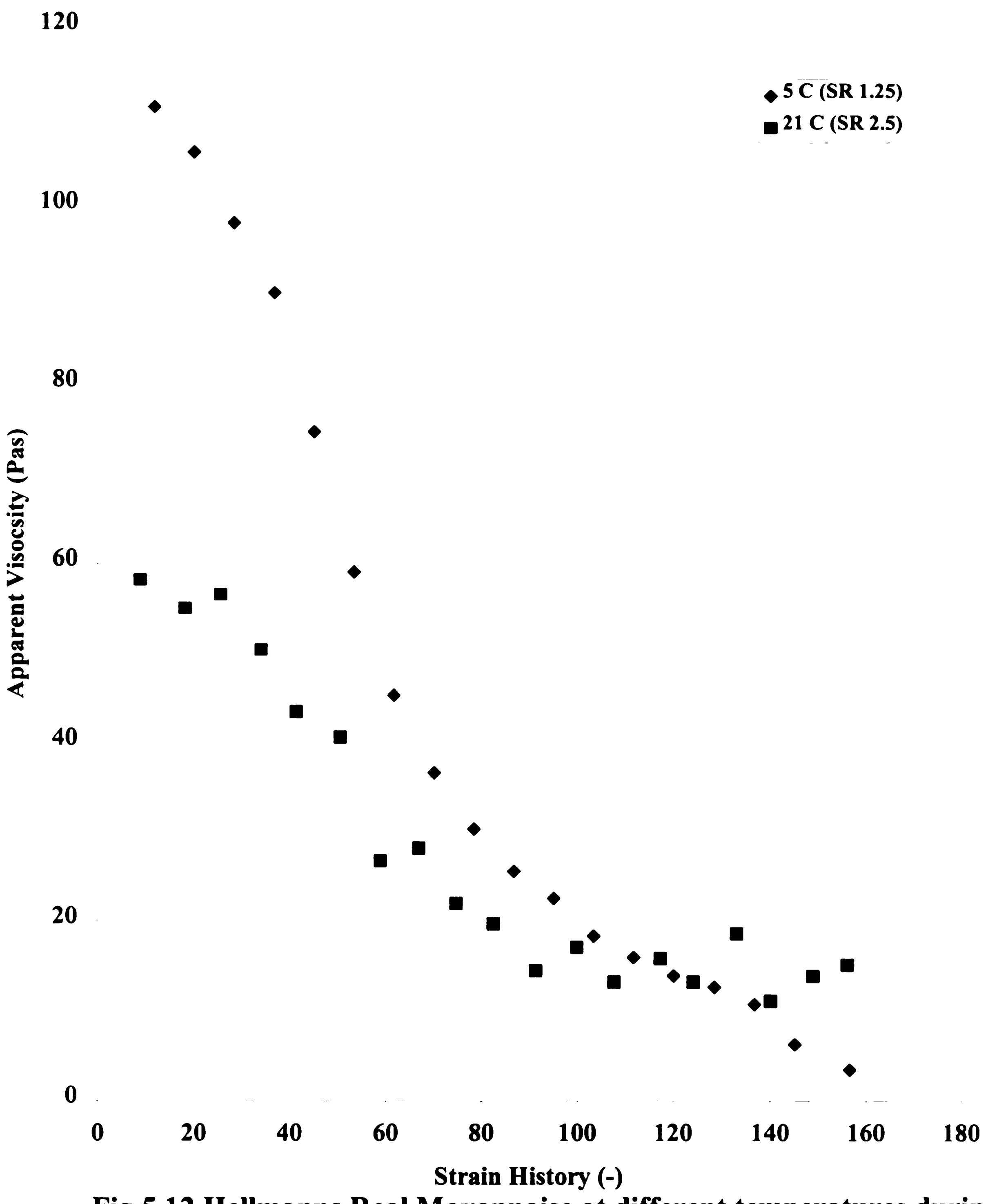


Fig 5.12 Hellmanns Real Mayonnaise at different temperatures during the addition of 8.5 ml water at the rate of 4.0 ml/min (with automatic addition of water)

increase in the strain history during water addition.

The experiments at 5°C were conducted at 1.25 1/sec shear rate for all the food samples. However, the experiments for the samples at 21°C did not give the appropriate mixing; hence, they were conducted at 2.5 1/sec shear rate except for the Kraft Fat Free Mayonnaise, which performed well at the lower shear rate. At body temperature, experiments were conducted satisfactorily at the lower shear rate. This variation of shear rates resulted from the inadequate mixing of water in the sample at the lower shear rate for some food products.

Comparison of behavior of the Kraft Fat Free Mayonnaise at three different temperatures (Fig 5.8) indicates that the sample was thickest at the refrigeration temperature (5°C) and thinnest at the body temperature (37°C) throughout the experiment. The difference in apparent viscosities at the three temperatures for Kraft Fat Free Mayonnaise was significantly lower than the difference observed for other food samples.

Fig 5.9 illustrates the behavior of Kraft Light Mayonnaise at different temperatures. At 5°C, the sample was found to be significantly thicker as compared to the sample at 21°C. Experiments for Kraft Real Mayonnaise sample could be conducted only at 5°C, since it did not incorporate water properly at 21°C and 37°C at any shear rate considered (1.25 and 2.5 1/sec. Fig 5.11 depicts the behavior of Kraft Miracle Whip, which shows an initial fall in the apparent viscosity at 5°C, conducted at 1.25 1/sec shear rate, that later attains an almost constant value. The samples at 21°C and 37°C were found to attain a similar apparent viscosity at the completion of the experiment although the sample at 37°C started at a higher apparent viscosity value. In case of Hellmann's Real Mayonnaise (Fig 5.12) the sample at 5°C had the higher apparent viscosity at the beginning of the experiment but had the lower apparent viscosity at the end when compared to the sample at 21°C. The experiments could not be evaluated at 37°C at any shear rate because of inadequate mixing.

Figures 5.13 through 5.15 compare rheological properties of the five food products at three temperatures. At 5°C, Kraft Light Mayonnaise showed the thickest texture (Fig 5.13) throughout the experiment and had a very

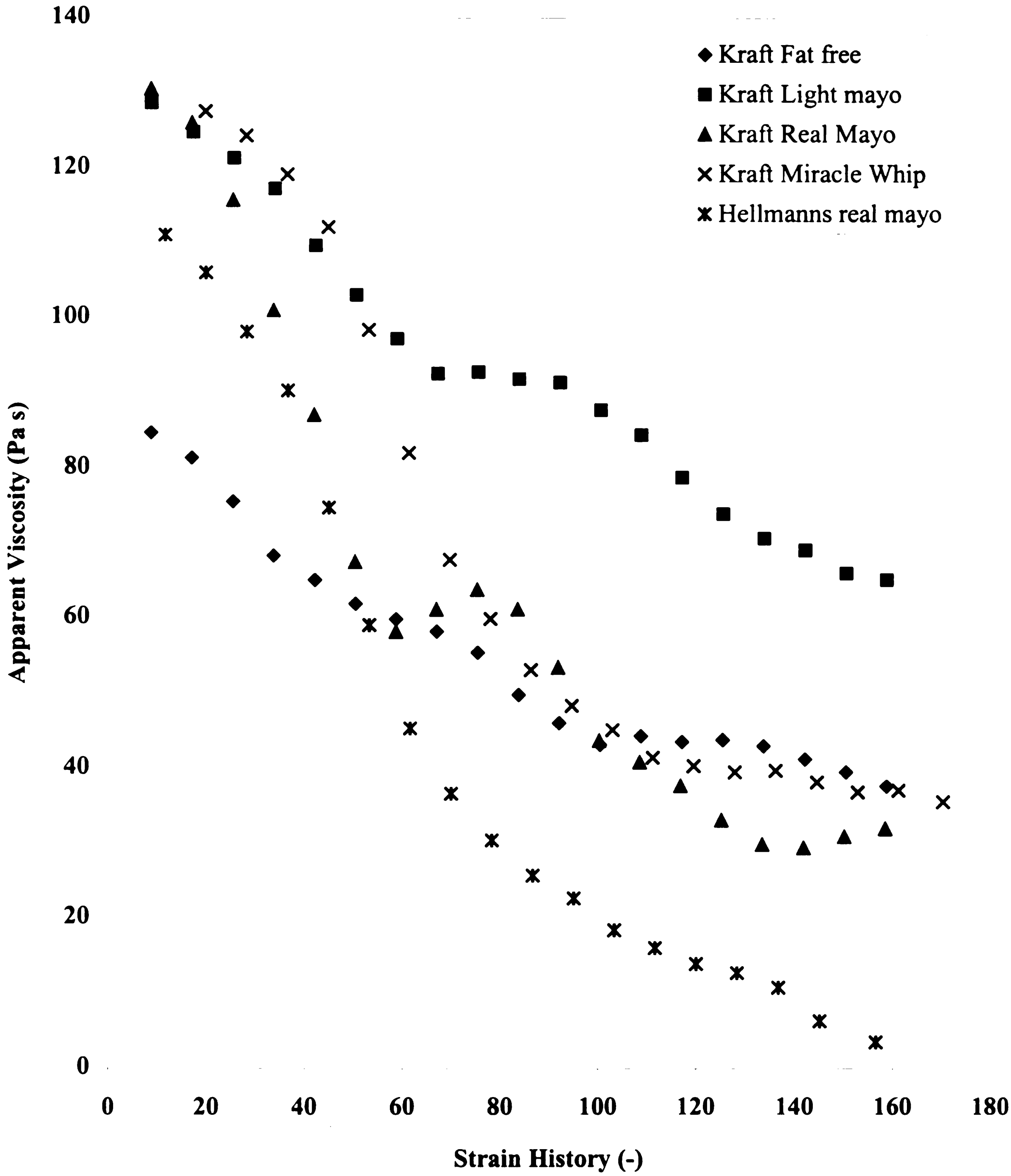


Fig 5.13 Food products at 5 C at 1.25 1/sec shear rate during the addition of 8.5 ml water at 4 ml/min (with automatic addition of water)

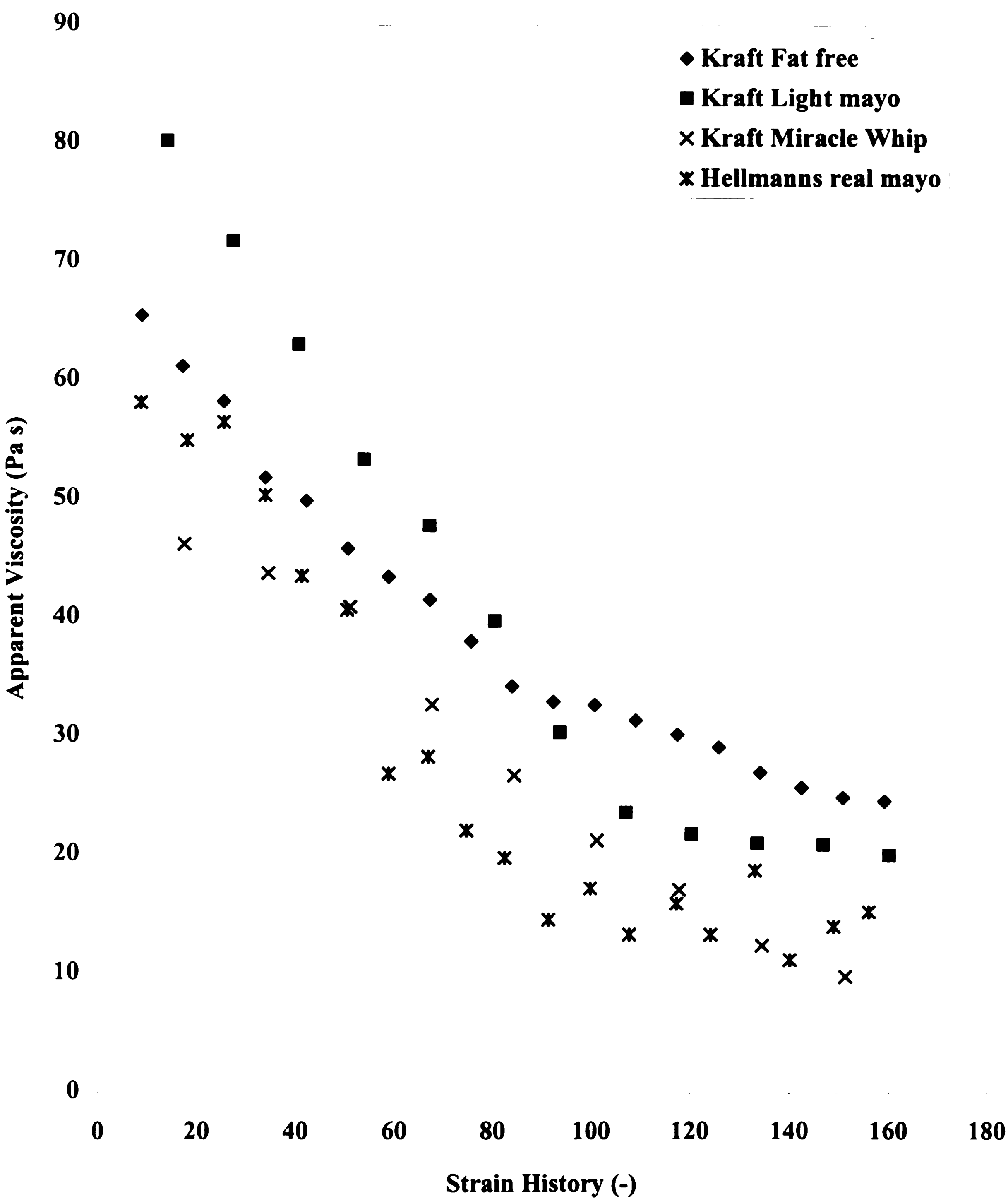


Fig 5.14 Food products at 21 C at 2.5 1/sec shear rateduring the addition of 8.5 ml water at 4.0 ml/min (with automatic addition of water)

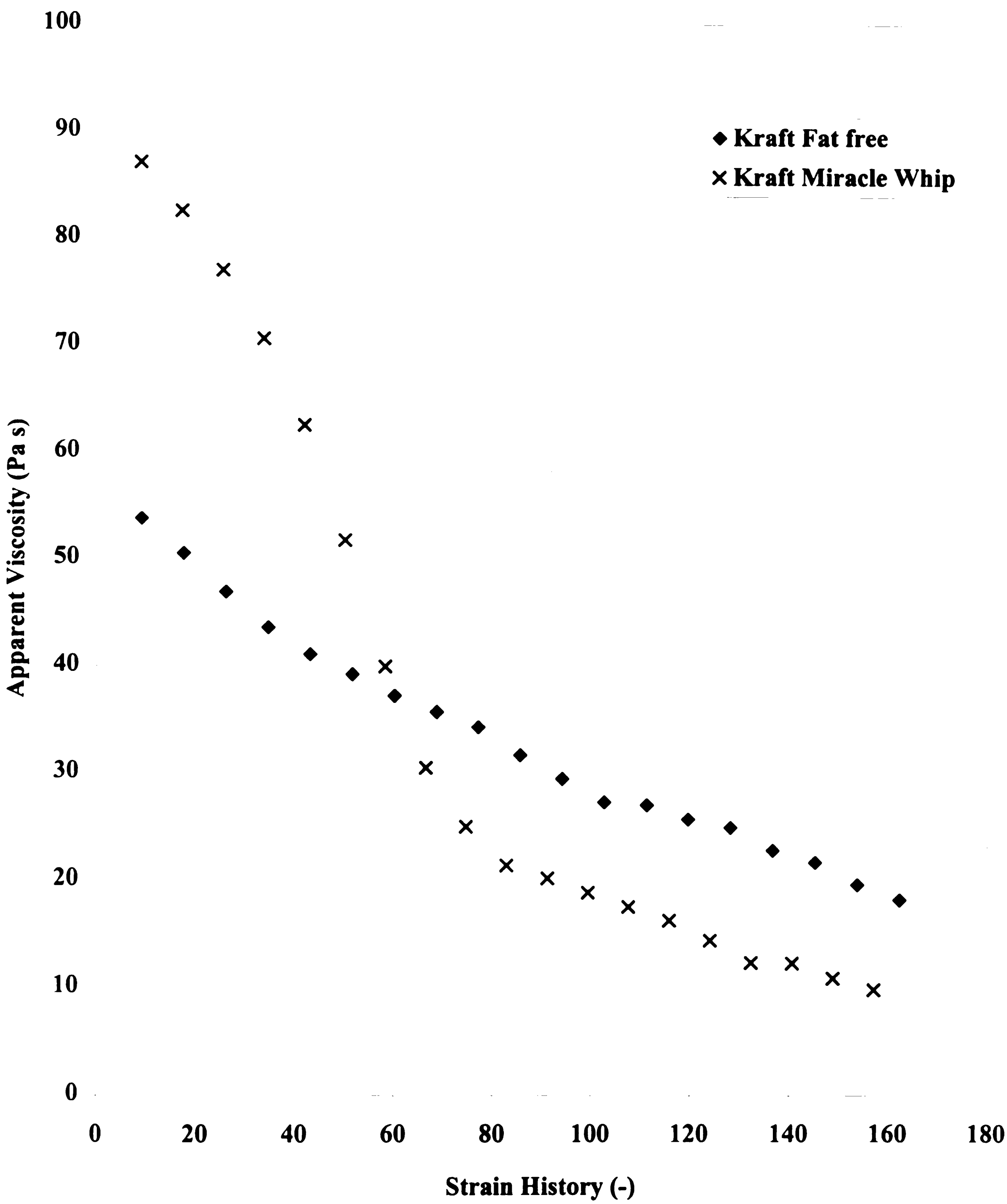


Fig 5.15 Food products at 37 C at 1.25 1/sec shear rate during the addition of 8.5 ml water at 4.0 ml/min (with automatic addition of water)

low rate of viscosity change. Kraft Fat Free Mayonnaise had the lowest apparent viscosity before the experiment but Hellmann's Real Mayonnaise showed the lowest viscosity at the end of the experiments, which was also seen to thin out the maximum amount during the experiment going from 110 Pas to 2 Pa s with the highest rate of viscosity change. Kraft Real Mayonnaise showed a high rate of viscosity change and thinned out significantly during the experiment. Before testing, it had the highest viscosity along with Kraft Light Mayonnaise. Kraft Fat Free Mayonnaise shows the least effect of water addition on its consistency, and has the minimum rate of change in its apparent viscosity. Kraft Miracle Whip also showed significant textural changes with a moderate rate of viscosity change. At this temperature water mixed into all the samples satisfactorily.

At 21°C (Fig 5.14), Kraft Light Mayonnaise showed the highest apparent viscosity at the beginning of the experiment, but Kraft Fat Free Mayonnaise had a higher viscosity at the end. Kraft Fat Free Mayonnaise showed the minimum effect of the water addition on the apparent viscosity. Data for Kraft Real Mayonnaise could not be collected because of the inappropriate mixing. A general trend of decreasing apparent viscosity with increasing strain history was observed in all the food products though the apparent viscosity tended to attain a constant value. Kraft Fat Free Mayonnaise, Kraft Miracle whip, and Hellmann's Real Mayonnaise showed similar amount of change in the viscosity and showed approximately the same rate of viscosity change. Kraft Light Mayonnaise had the highest rate of change of viscosity at 21°C.

Fig 5.15 depicts the behavior of food products at the body temperature (37°C). Kraft Miracle Whip had the higher apparent viscosity initially, but after testing it had the lower apparent viscosity; it showed the maximum change in the textural properties due to the addition of water. Kraft Fat Free Mayonnaise showed an almost constant drop in the viscosity throughout the experiment; however Kraft Miracle Whip showed a drastic change in the viscosity at the beginning but the rate of change of viscosity decreased later. The results obtained at this temperature for Kraft Light Mayonnaise, Kraft Real Mayonnaise and Hellmann's Real Mayonnaise were not reliable as the samples were found to be sticking to the helical ribbon that inhibited proper mixing of water in the sample. The experiments for these products were conducted using the concentric cylinder analogy instead of the helical ribbon calculations to determine shear rate.

5.3.2 Manual Mixing of Water

This analogy to human mastication involved manual incorporation of water into the sample before conducting the experiments; therefore, it did allow evaluation of changes occurring in the sample during mixing of the water. Using manual mixing method, the structural composition of the food samples was studied after different volumes of water were added to the sample. Comparisons were made by studying the change of apparent viscosity with respect to the ratio of volume of water added to the sample (Vw = 0, 1.25, 2.5, and 8.5 ml) divided by the maximum volume of water added (Vm = 8.5 ml). The mixing speed was calculated using a constant value of k' equal to 8.64 1/rev.

In general, it was seen that as the ratio of Vw / Vm approached 1, the apparent viscosity decreased. The apparent viscosities at a shear rate of 1 1/sec were significantly higher than the viscosities at shear rates of 25 and 50 1/sec for all the food samples at all the temperatures. There was a significant drop in viscosity at the beginning of each experiment. Little change in the viscosity was observed between 25 and 50 1/sec shear rate at all temperatures for all food products. The highest viscosities were found at the refrigeration temperature at all the shear rates, followed (as expected) by the viscosities at room temperature and body temperature.

Figures 5.16 through 5.20 compare the changes in the apparent viscosity with respect to Vw / Vm for the food products individually, at three temperatures, at 1 1/sec shear rate for different levels of water added to the sample. Fig 5.16 depicts the plot for Kraft Fat Free Mayonnaise, which indicates maximum overall change in the apparent viscosity at the refrigeration temperature. The result obtained at 5°C at 0 level water for the Kraft Fat Free Mayonnaise is not reliable because the sample was seen sticking to the helical ribbon. Unexpectedly, the apparent viscosity at 37°C at the maximum water level (Fig 5.16) was recorded to be highest. Not much difference was observed at 37°C at the 2.125 and 4.25 ml water levels. The sample showed significant change in the structure at 5°C and 21°C, though not much variation was observed at the body temperature. Kraft Light Mayonnaise (Fig 5.17) behaved as expected. The highest viscosities were recorded at 5°C, followed by 21°C and 37°C. The data point at 5°C with 0 ml water was unreliable since the

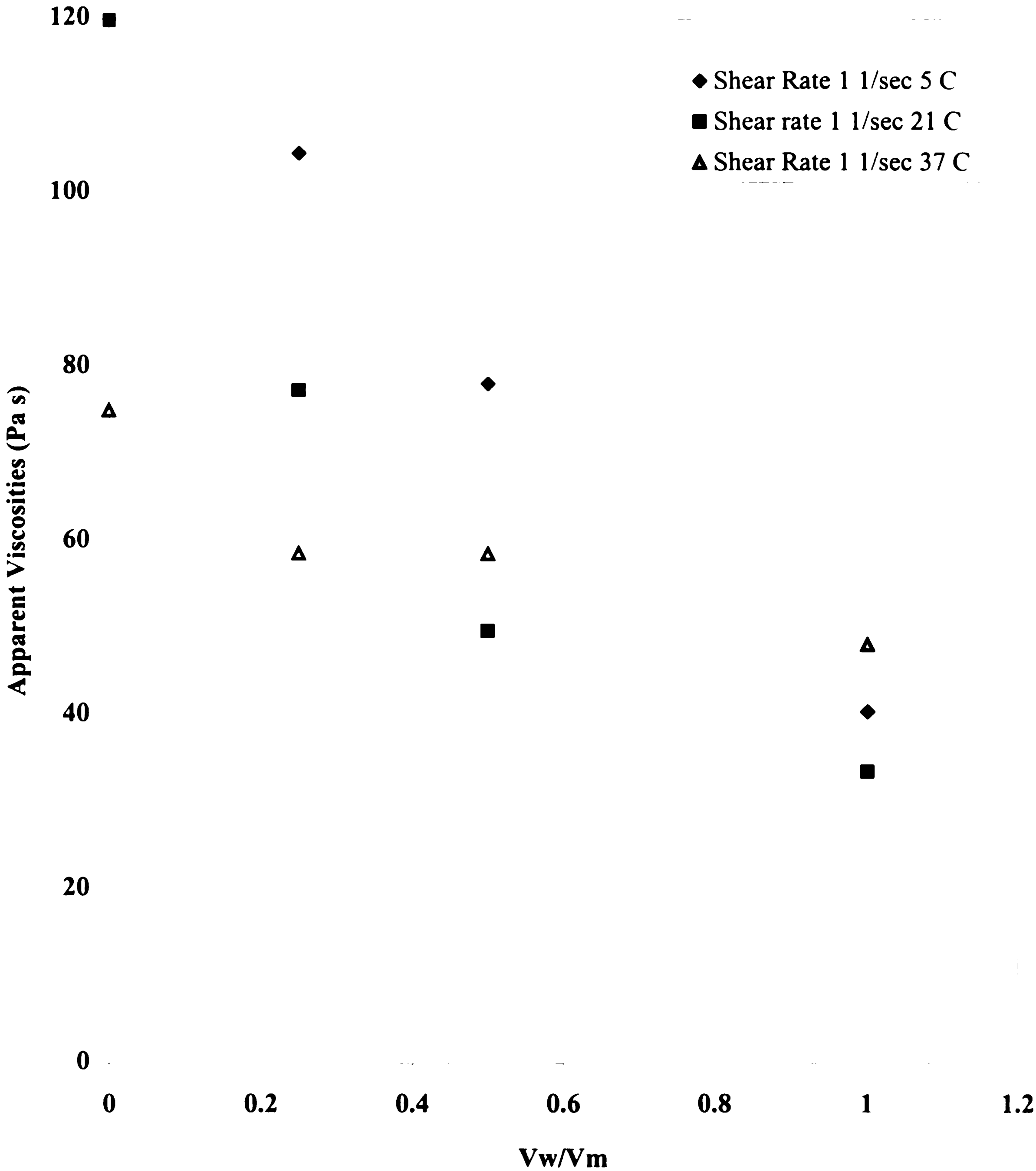


Fig 5.16 Kraft Fat Free Mayonnaise at three temperatures at 1 1/sec shear rate (manual mixing)

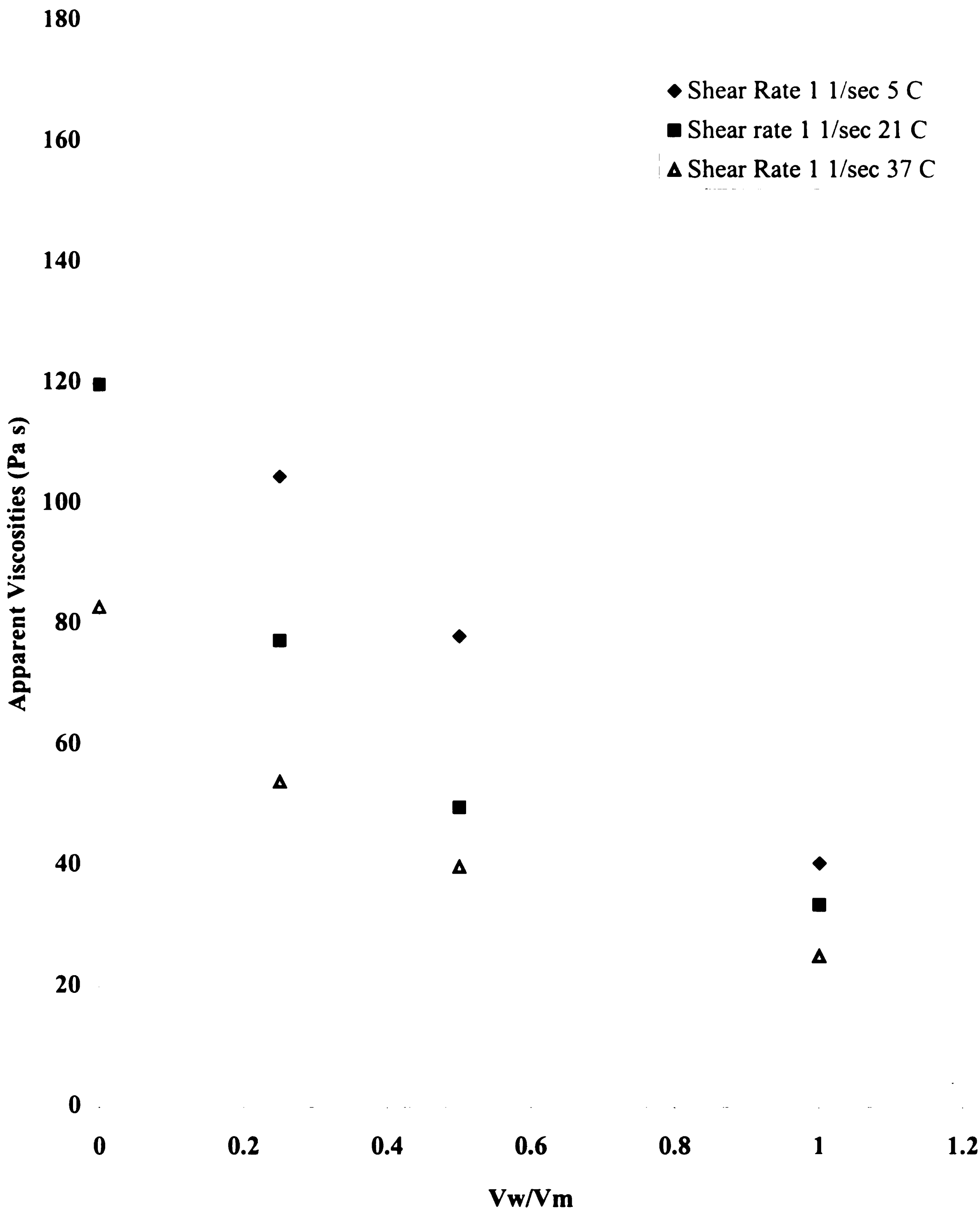


Fig 5.17 Kraft Light Mayonnaise at three temperatures at 1 1/sec shear rate (manual mixing)

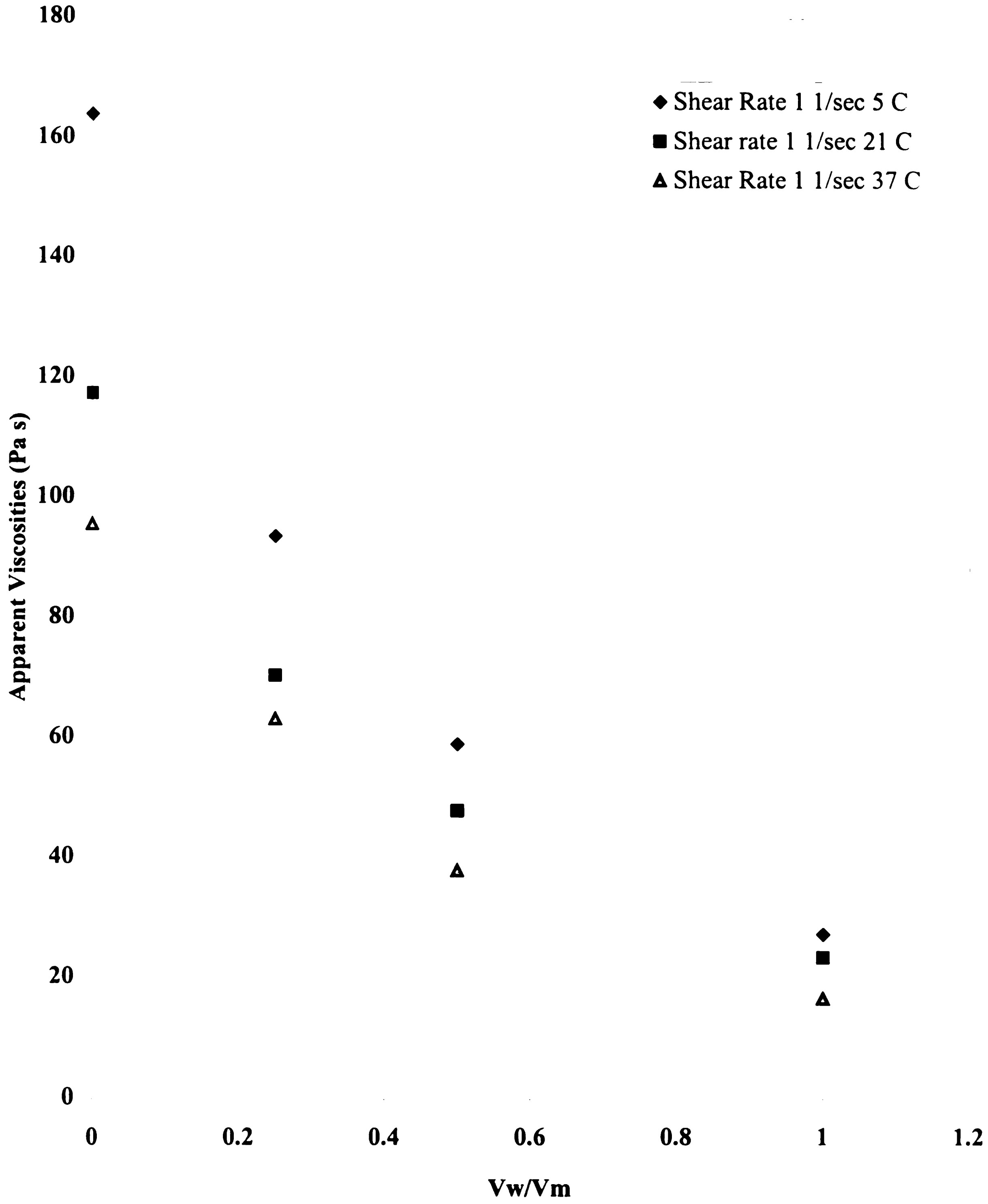


Fig 5.18 Kraft Real Mayonnaise at three temperatures at 1 1/sec shear rate (manual mixing)

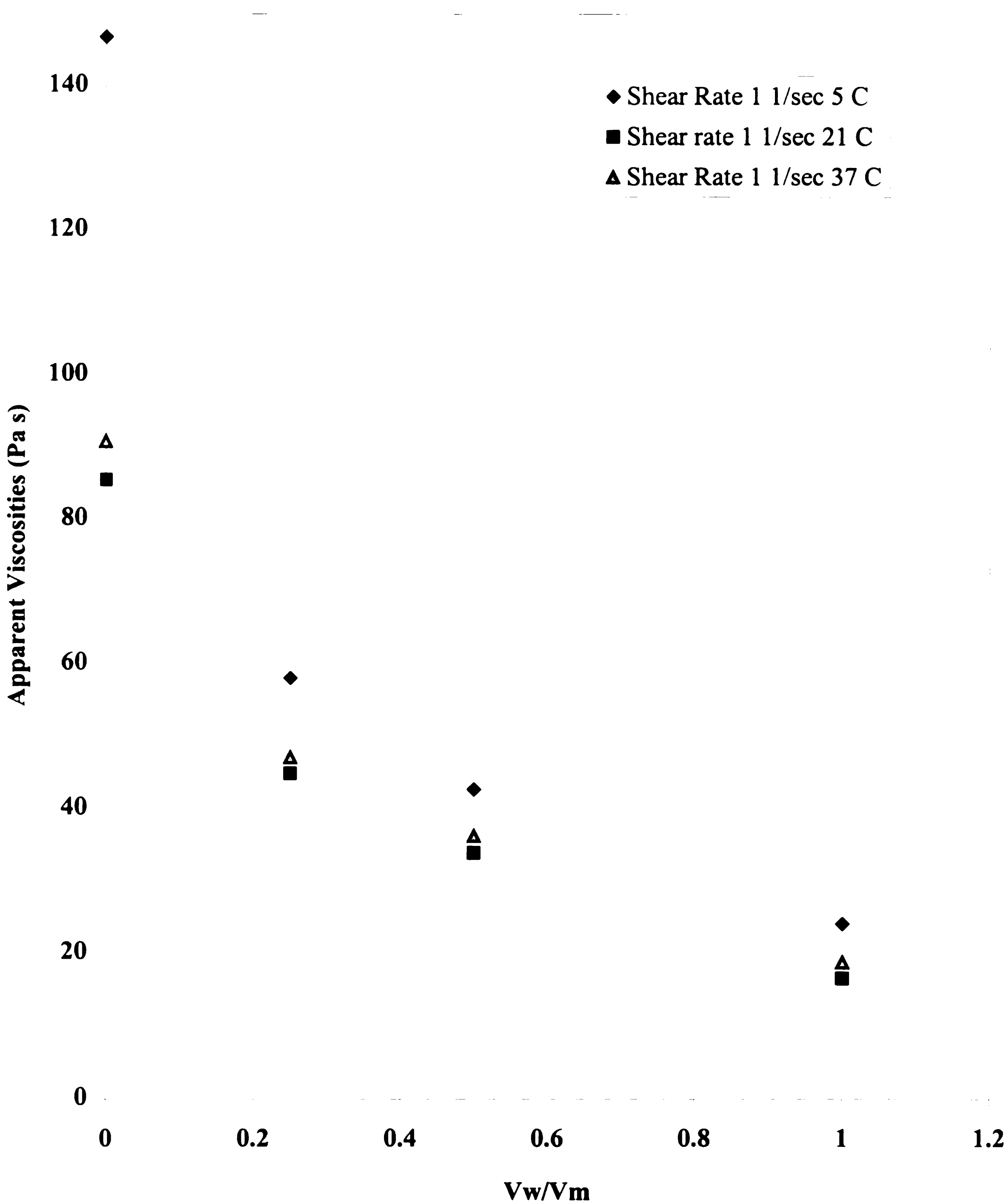


Fig 5.19 Kraft Miracle Whip at three temperatures at three Shear rates (manual mixing)

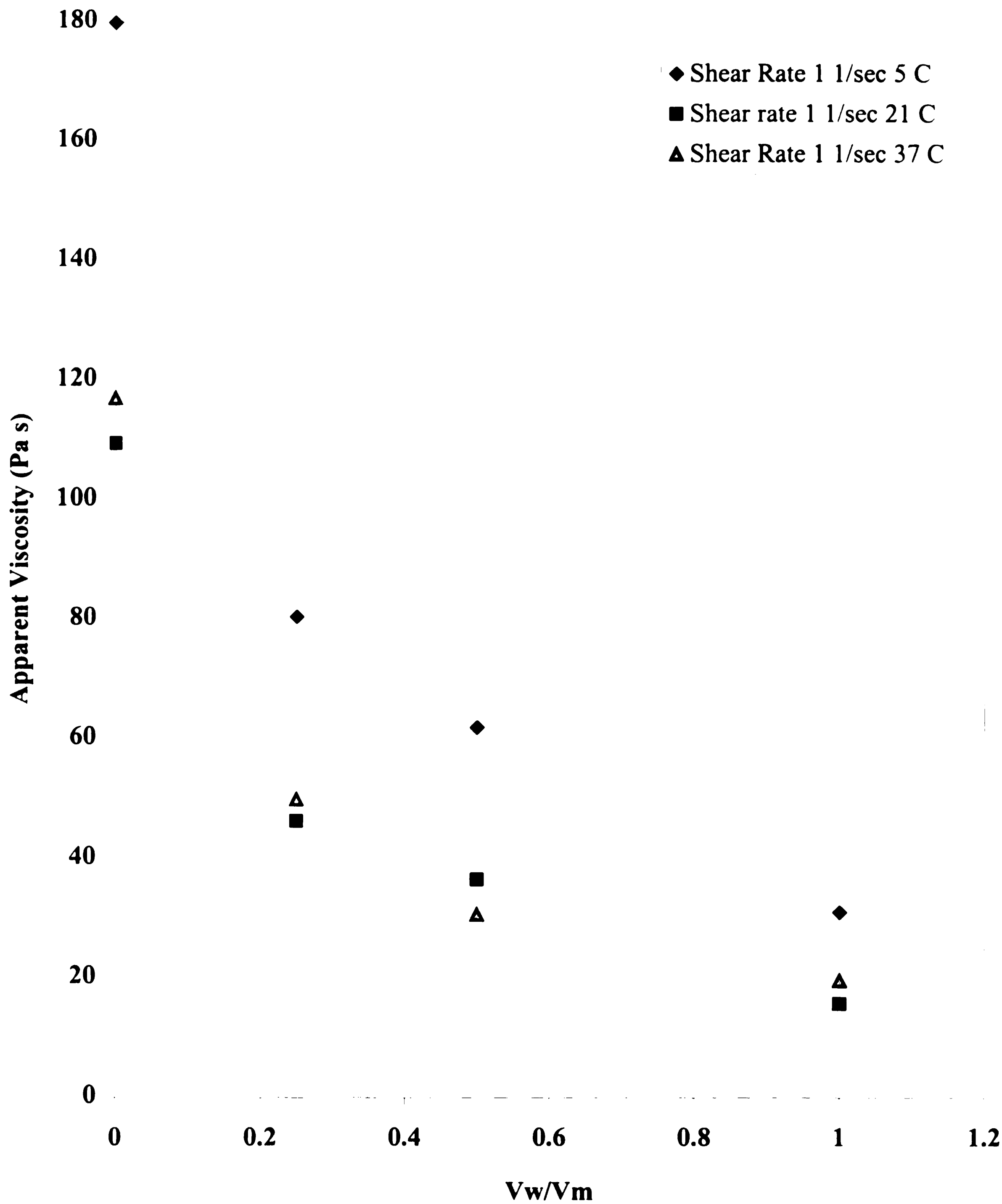


Fig 5.20 Hellmanns Real Mayonnaise at three temperatures at 1 1/sec shear rate (manual mixing)

sample stuck to the impeller leading to a flawed result. The maximum change in the consistency was observed at refrigeration temperature and minimum at body temperature. Kraft Real Mayonnaise (Fig 5.18) showed the expected trend at all temperatures and water levels, with maximum changes occurring at the refrigeration temperature and minimum at the body temperature.

Fig 5.19 illustrates the plot obtained for the Kraft Miracle Whip, which showed a similar trend to the Kraft Real Mayonnaise. Little difference was observed between the viscosities at room temperature and body temperature at all the water levels. The viscosities for all samples with 8.5 ml water were found to be similar.

Hellmann's Real Mayonnaise (Fig 5.20) showed a higher viscosity at 37°C than at 21°C except at 4.25 ml water level where the sample at 21°C had a higher viscosity, but the viscosities were close at all water levels at room temperature and body temperature. As with other materials, the maximum overall change in apparent viscosity was observed at refrigeration temperature.

Figures 5.21 through 5.25 display the plots obtained for all the food products at a shear rate of 25 1/sec. Apparent viscosities recorded at 25 1/sec were significantly lower than those at 1 1/sec for all the products at all the temperatures. Kraft Fat Free (Fig 5.21) shows tremendous change in the viscosity at 5°C and 21°C, but not much change was observed at 37°C. Viscosity was highest at refrigeration temperature as expected. The data at 5°C with 0 level water was not reliable due to the inadequate mixing. Kraft Light Mayonnaise (Fig. 5.22) behaved in a similar way as the Kraft Fat Free did at 25 1/sec but there was a significant change in the apparent viscosity at 37°C. A similar trend was shown by the Kraft Real Mayonnaise samples (Fig. 5.23) with significant changes in the apparent viscosity at all temperatures. Kraft Miracle Whip (Fig 5.24) and Hellmann's Real Mayonnaise (Fig 5.25) followed the pattern but showed little difference in the apparent viscosities at room temperature and body temperature.

Related plots for food products at 50 1/sec are shown in the Figures 5.26 through 5.30. All products followed the expected trend with higher viscosities at the refrigeration temperature and lower viscosities at body temperature. The data points for Kraft Fat Free Mayonnaise (Fig 5.26)

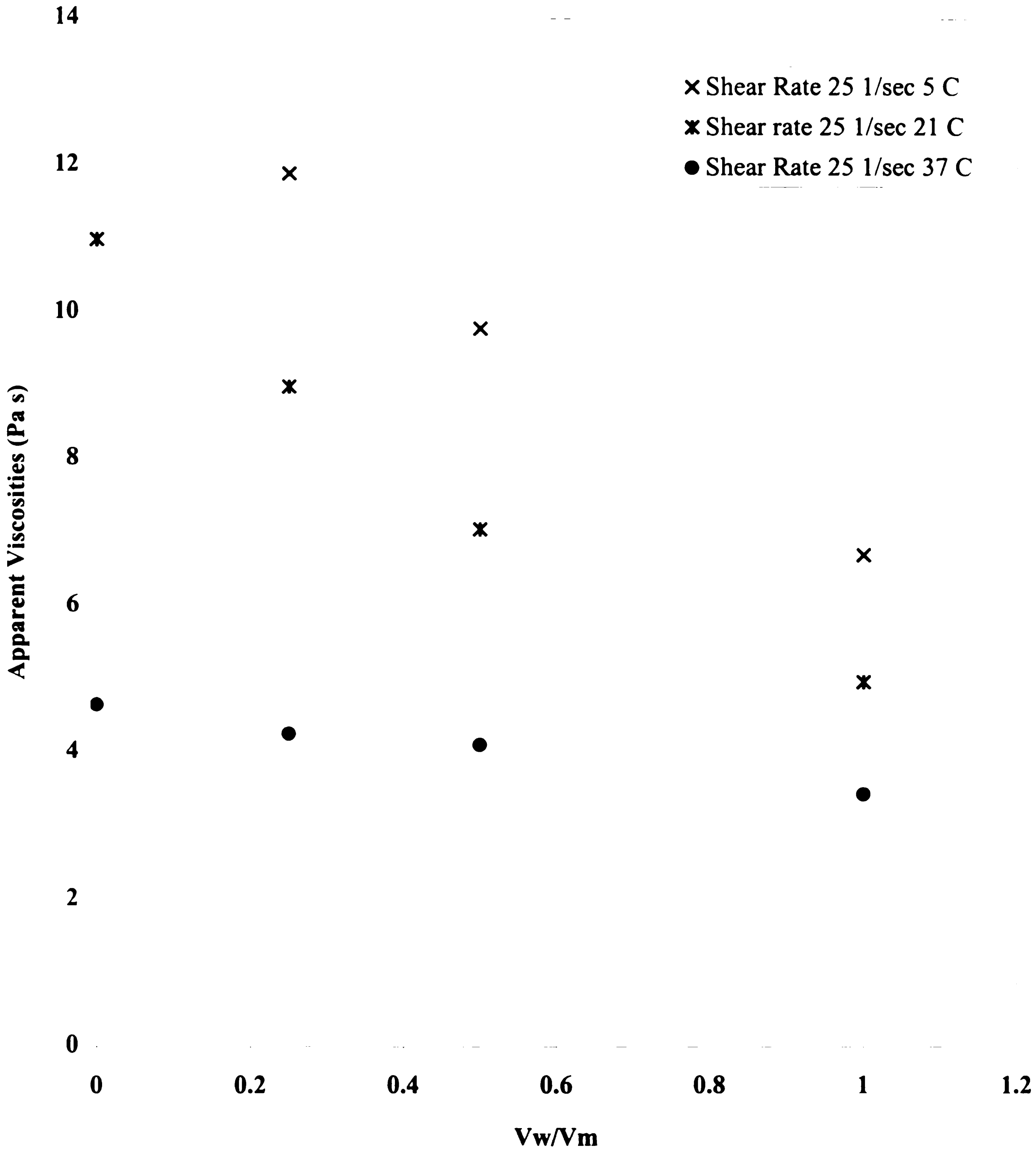


Fig 5.21 Kraft Fat Free Mayonnaise at three temperatures at 25 1/sec shear rate (manual mixing)

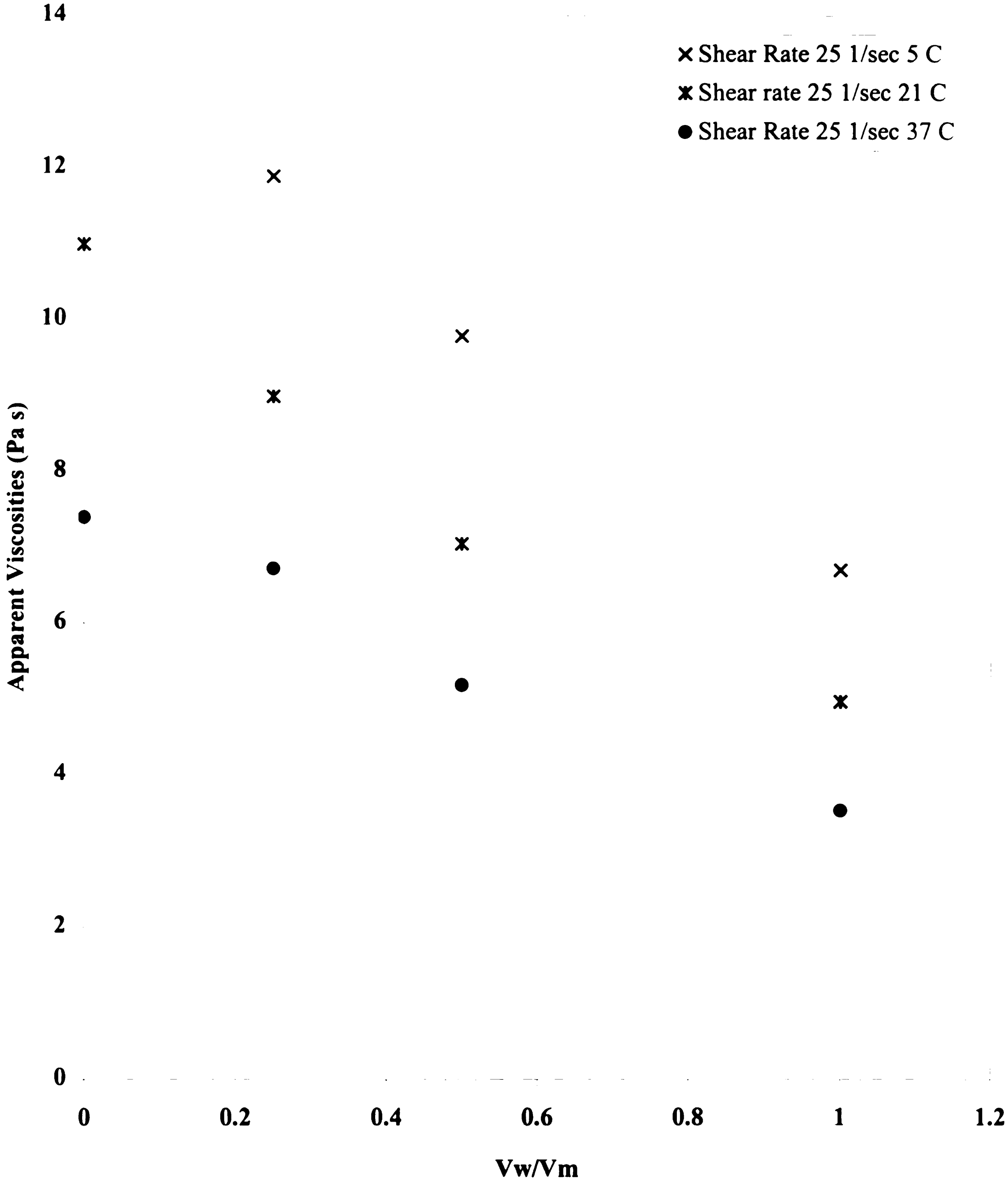


Fig 5.22 Kraft Light Mayonnaise at three temperatures at 25 1/sec shear rate (manual mixing)

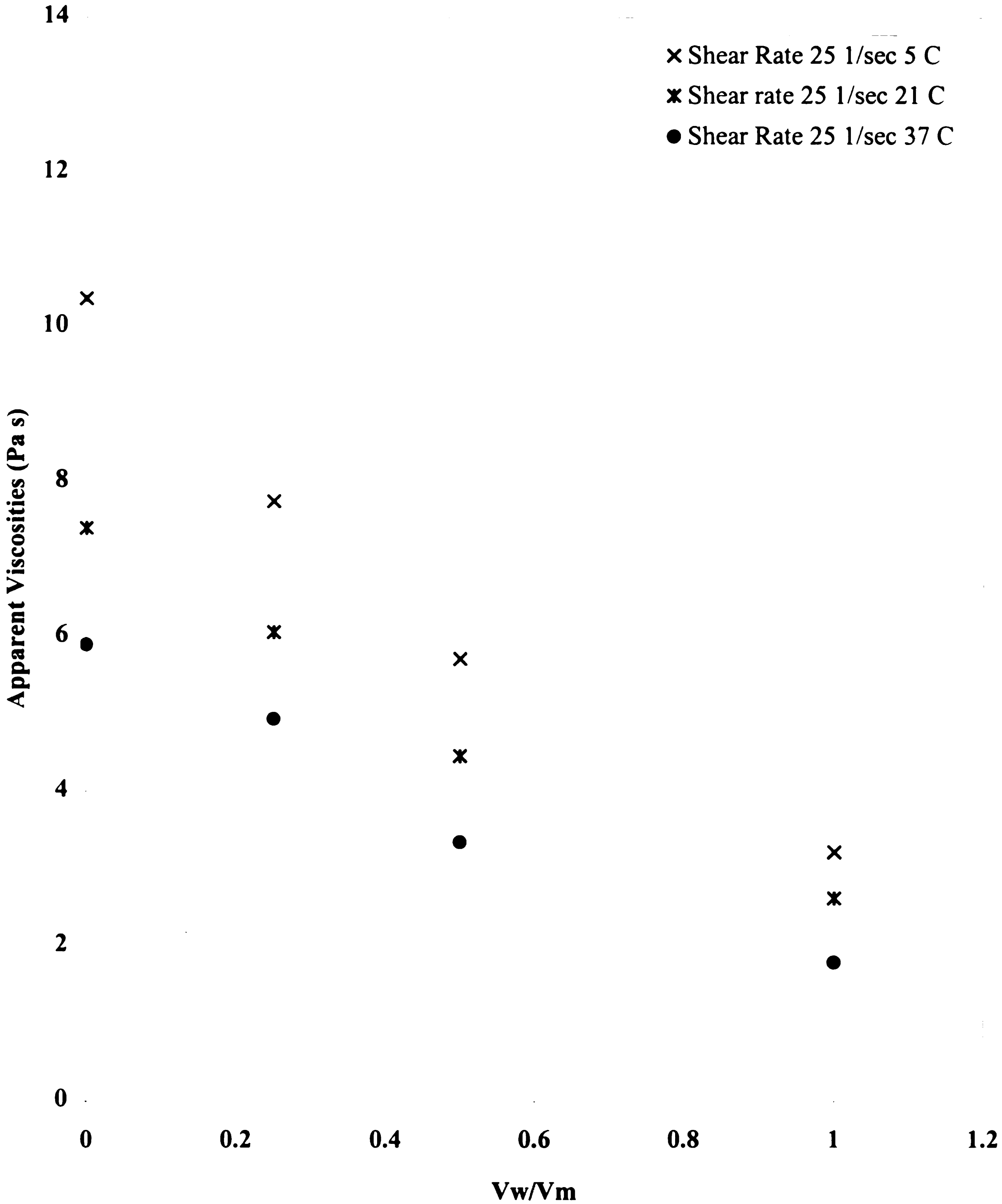


Fig 5.23 Kraft Real Mayo at three temperatures at 25 1/sec shear rate (manual mixing)

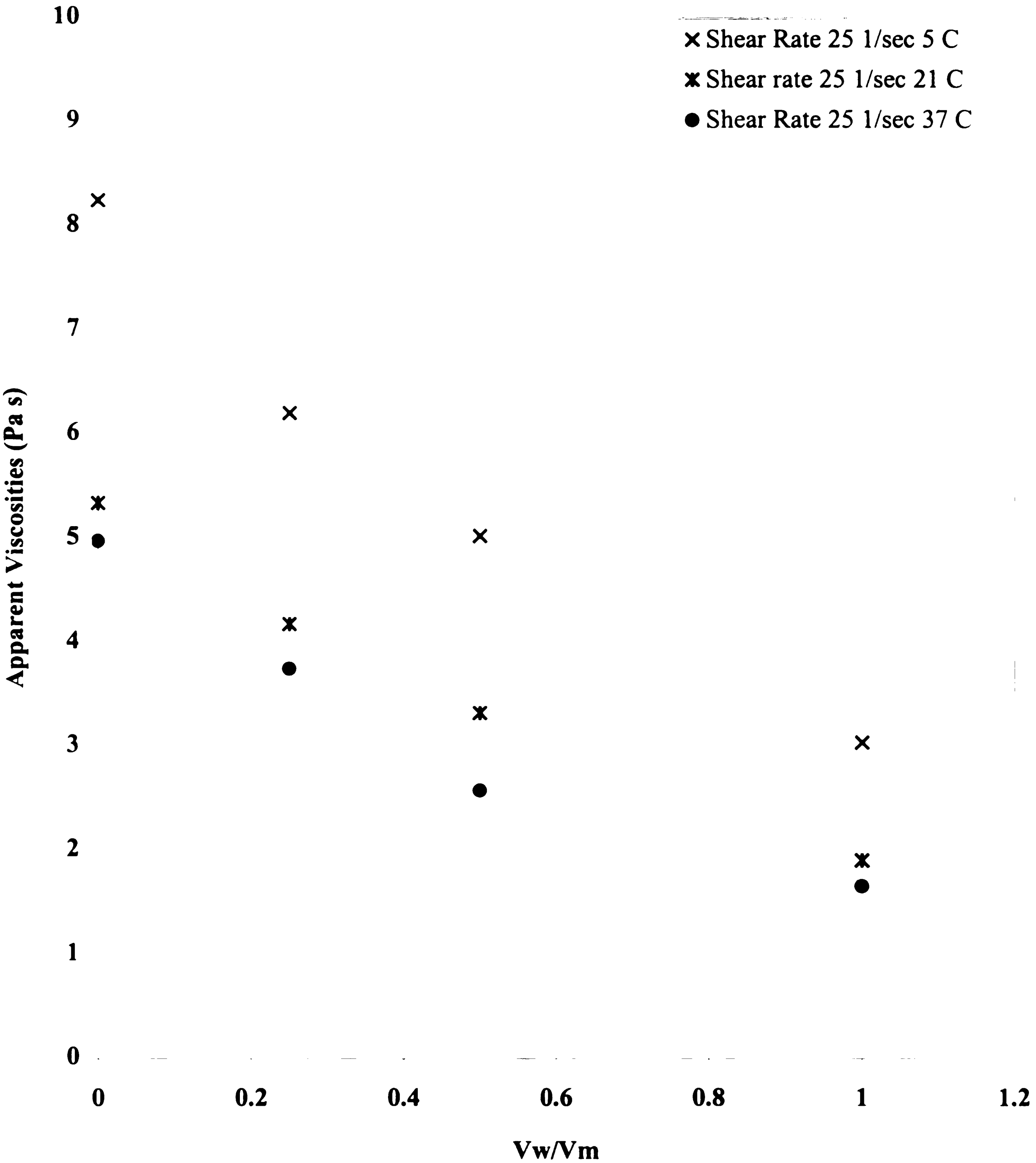


Fig 5.25 Hellmann's Real Mayonnaise at three temperatures at 25 1/sec shear rate (manual mixing)

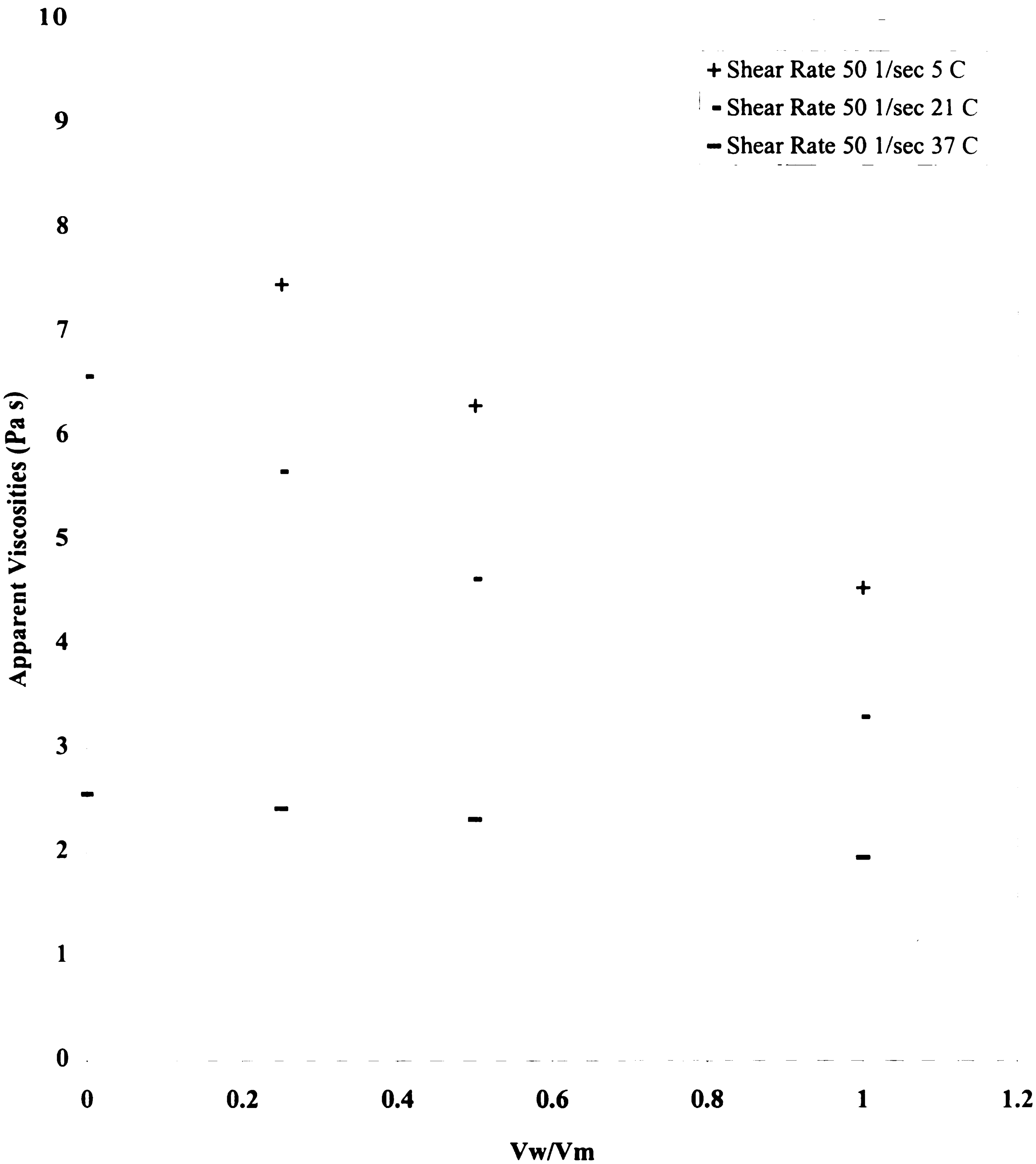


Fig 5.26 Kraft Fat Free Mayonnaise at three temperatures at 50 1/sec shear rate (manual mixing)

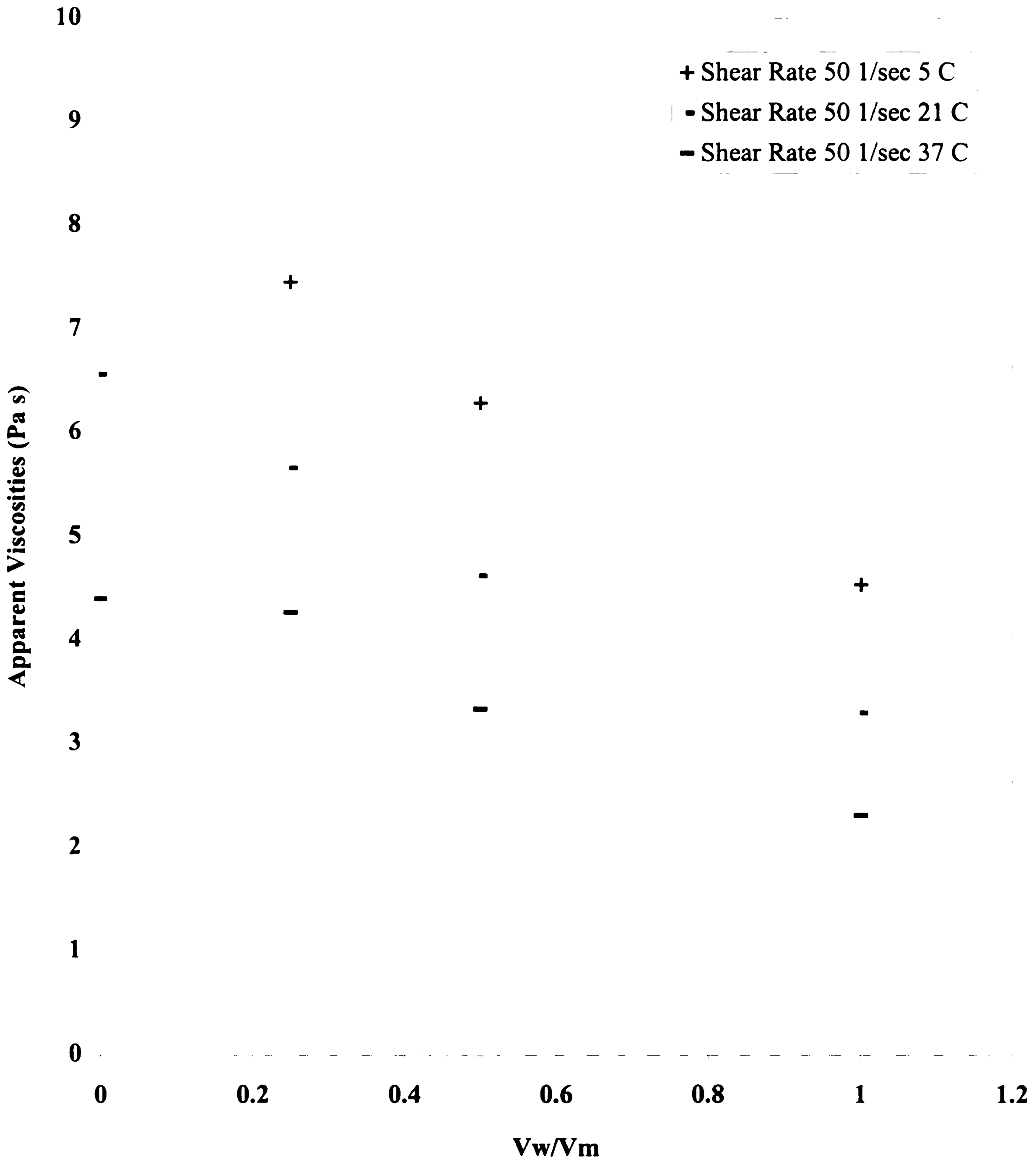


Fig 5.27 Kraft Light Mayonnaise at three temperatures at 50 1/sec shear rate (manual mixing)

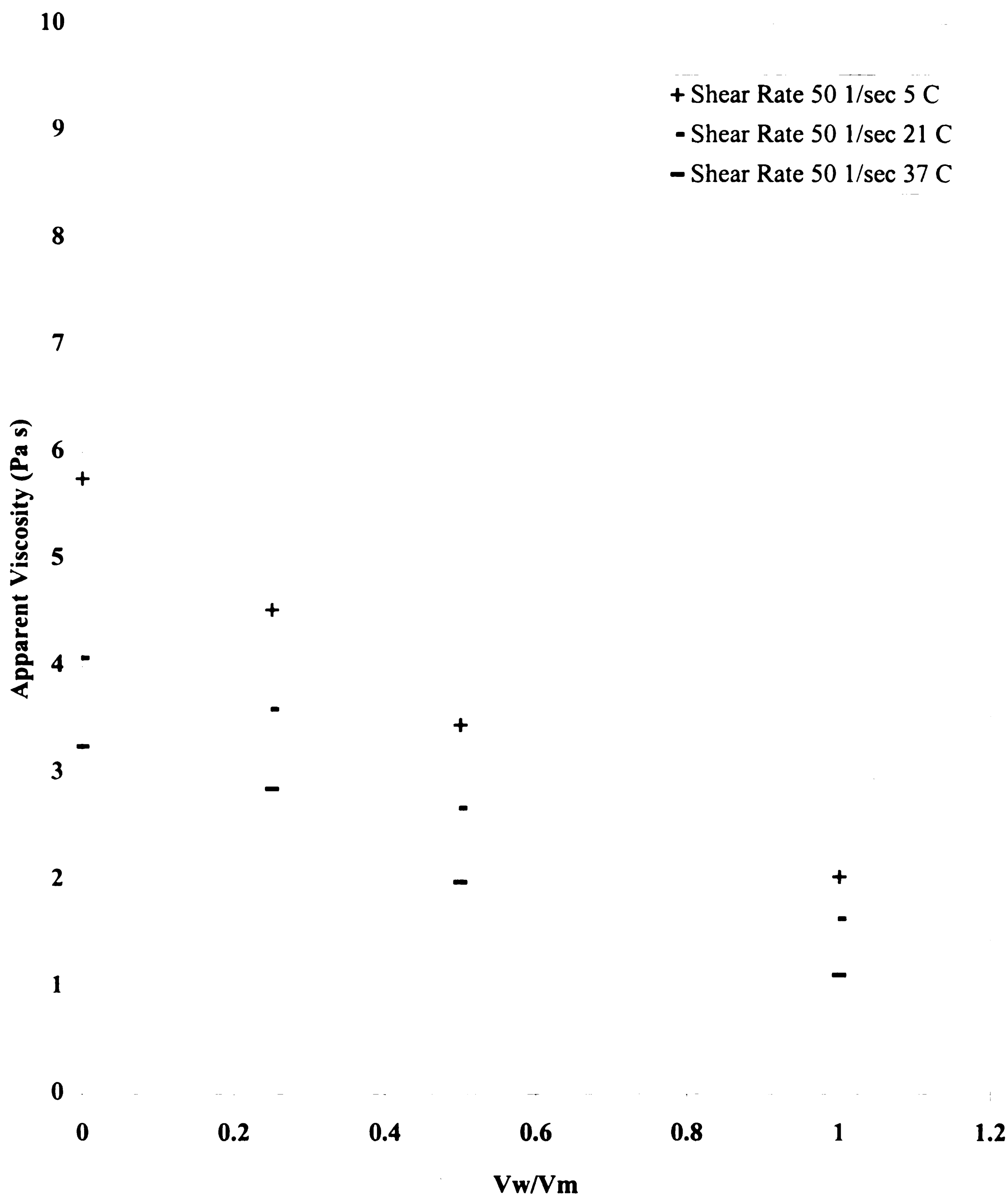


Fig 5.28 Kraft Real Mayonnaise at three temperatures at 50 1/sec shear rate (manual mixing)

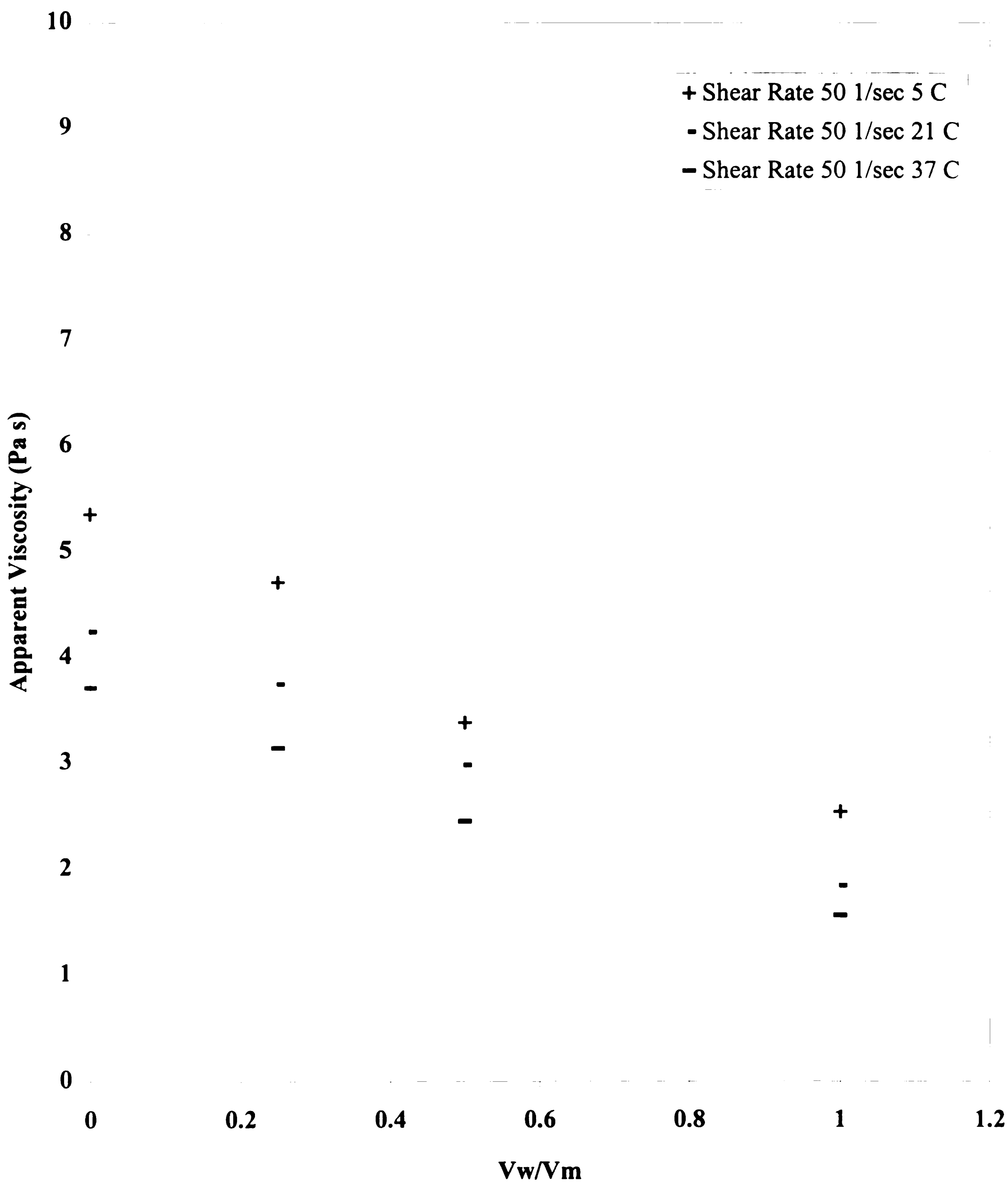


Fig 5.29 Kraft Miracle Whip at three temperatures at 50 1/sec shear rate (manual mixing)

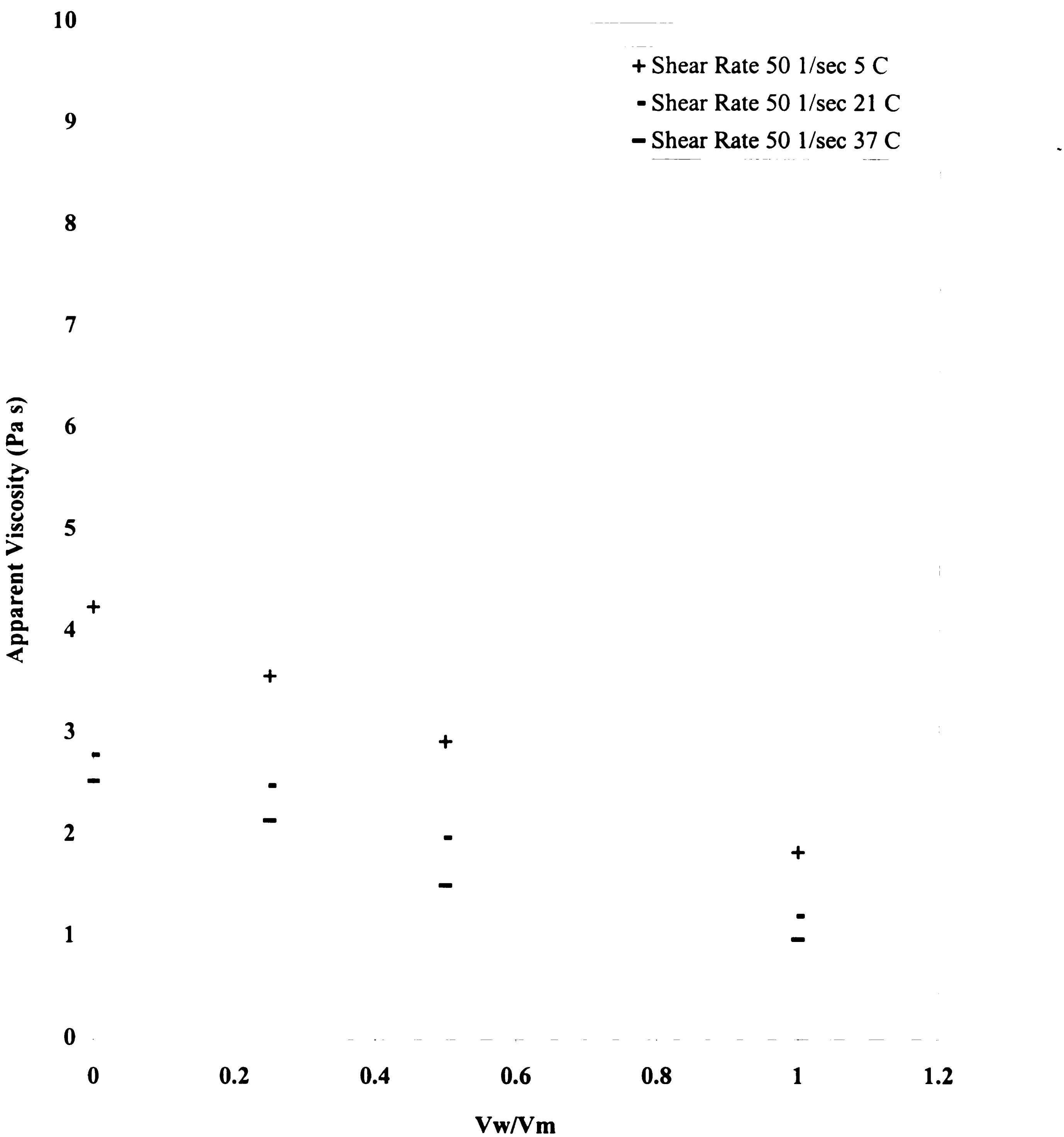


Fig 5.30 Hellmanns Real Mayonnaise at three temperatures at 50 1/sec shear rate (manual mixing)

and Kraft Light Mayonnaise (Fig. 5.27) at 5°C at 0 ml water in the sample could not be collected because the sample stuck to the ribbon which prevented proper mixing. Not much variation was shown by Kraft Fat Free Mayonnaise (Fig. 5.26) at 37°C with the increased water, though there was a significant difference between the apparent viscosities at different temperatures. Kraft Light Mayonnaise showed similar behavior, as the Kraft Fat Free Mayonnaise. Both samples underwent significant textural changes with different water levels at 50 1/sec. Kraft Light Mayonnaise had significant change at 37°C, unlike Kraft Fat Free Mayonnaise, though not much change was observed between the sample with 0 ml water and the sample with 2.125 ml water, but with further addition of water, the viscosity changed significantly. The patterns for Kraft Real Mayonnaise (Fig. 5.28), Kraft Miracle Whip (Fig. 5.29), and Hellmann's Real Mayonnaise (Fig. 5.30) followed Kraft Light Mayonnaise. The change in the viscosities at all the temperatures was not as much as that observed with Kraft Light Mayonnaise. Plots for Hellmann's Real Mayonnaise at 21°C and 37°C were very close indicating very minor difference in the texture at the two temperatures.

On comparing the plots obtained at different shear rates for a product, it can be observed that the Kraft Fat Free Mayonnaise and Kraft Light Mayonnaise had lower viscosities at 25 1/sec at 37°C than the viscosities of the samples at 50 1/sec at 5°C and 21°C. The data points obtained for Kraft Real Mayonnaise at 50 1/sec at 5°C and 25 1/sec at 37°C were found to be similar. For Hellmann's Real Mayonnaise it was observed that initially during the experiment, the viscosities at 25 1/sec at 37°C were higher than the viscosities at 50 1/sec at 5°C, but at the end of the experiment, the viscosities at body temperature were found to be lower than the viscosities at refrigeration temperature.

Figures 5.31 through 5.33 are the plots obtained for all the food products at three temperatures at 25 1/sec. Kraft Light Mayonnaise was found to have the highest consistency at all temperatures and underwent the maximum change in the apparent viscosity. At 5°C (Fig. 5.31), Kraft Fat Free Mayonnaise did not show a big difference with added water, and the change in viscosity was minor between the sample without water and the sample with 8.5 ml water. A rise in apparent viscosity was observed in the sample with 1.25 ml water compared to the sample without water, which might be attributed to the presence of starch in the mayonnaise.

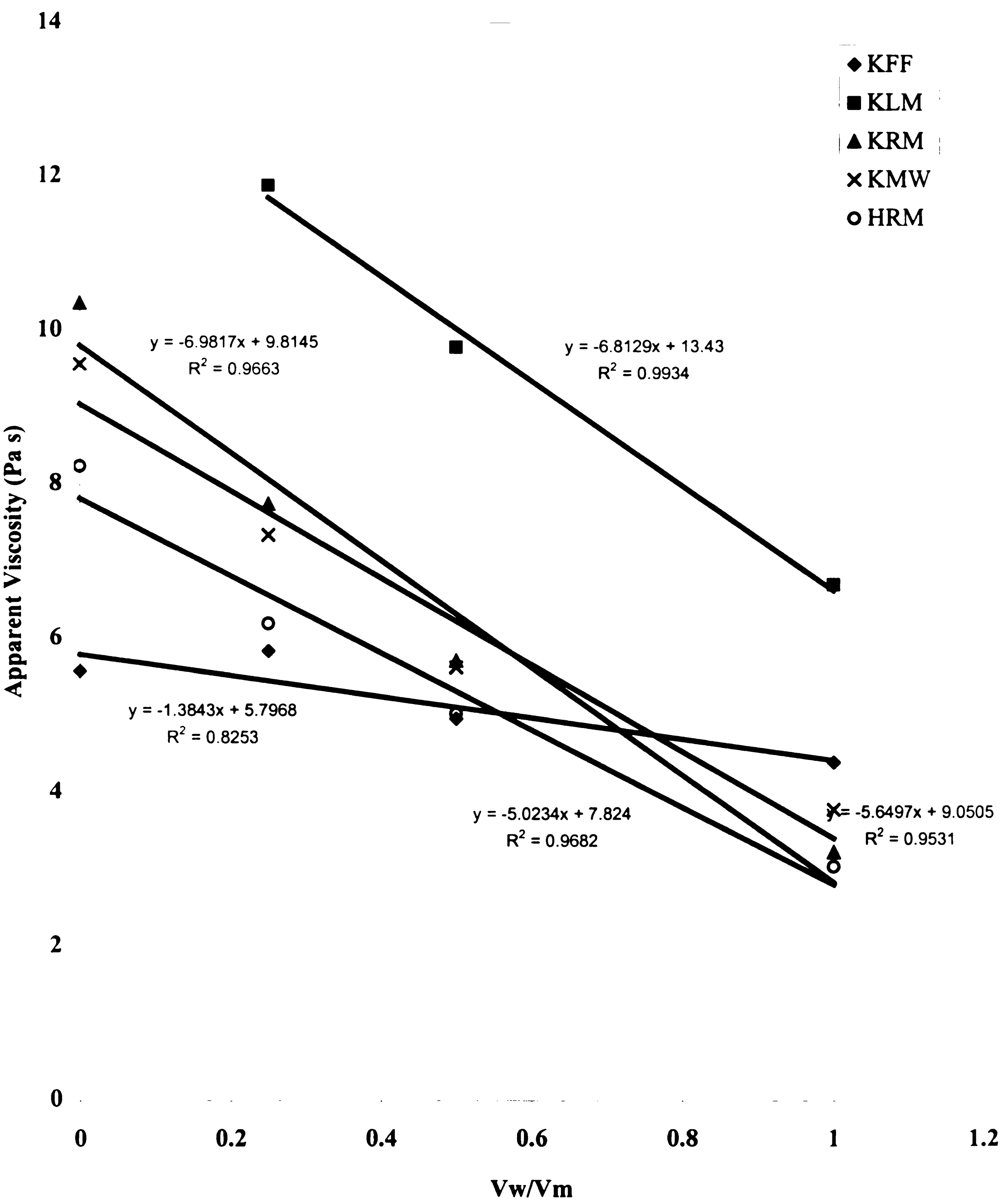


Fig 5.31 All food products at 5 C at shear rate 25 1/sec (manual mixing)

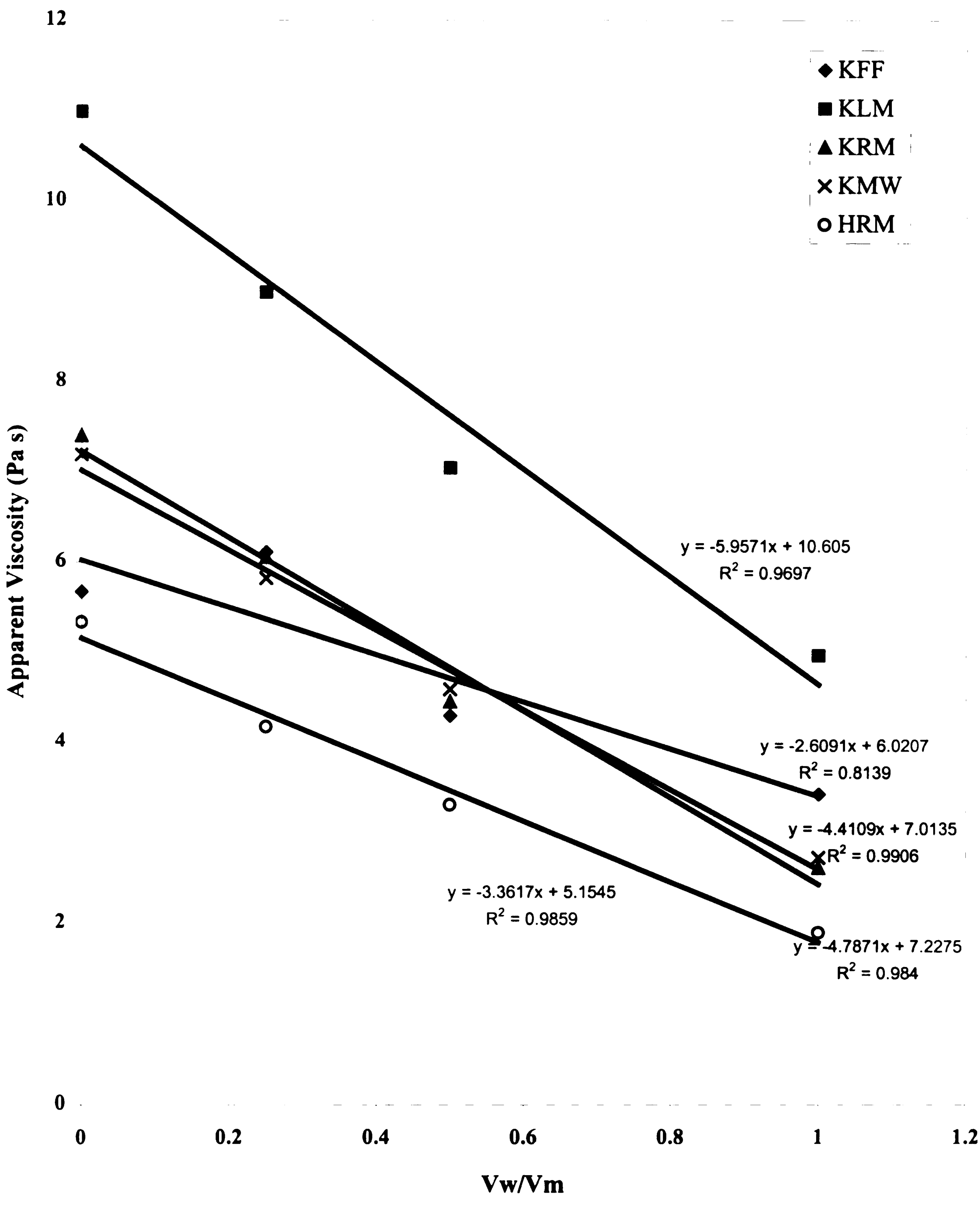


Fig 5.32 All food products at 21 C at shear rate 25 1/sec (manual mixing)

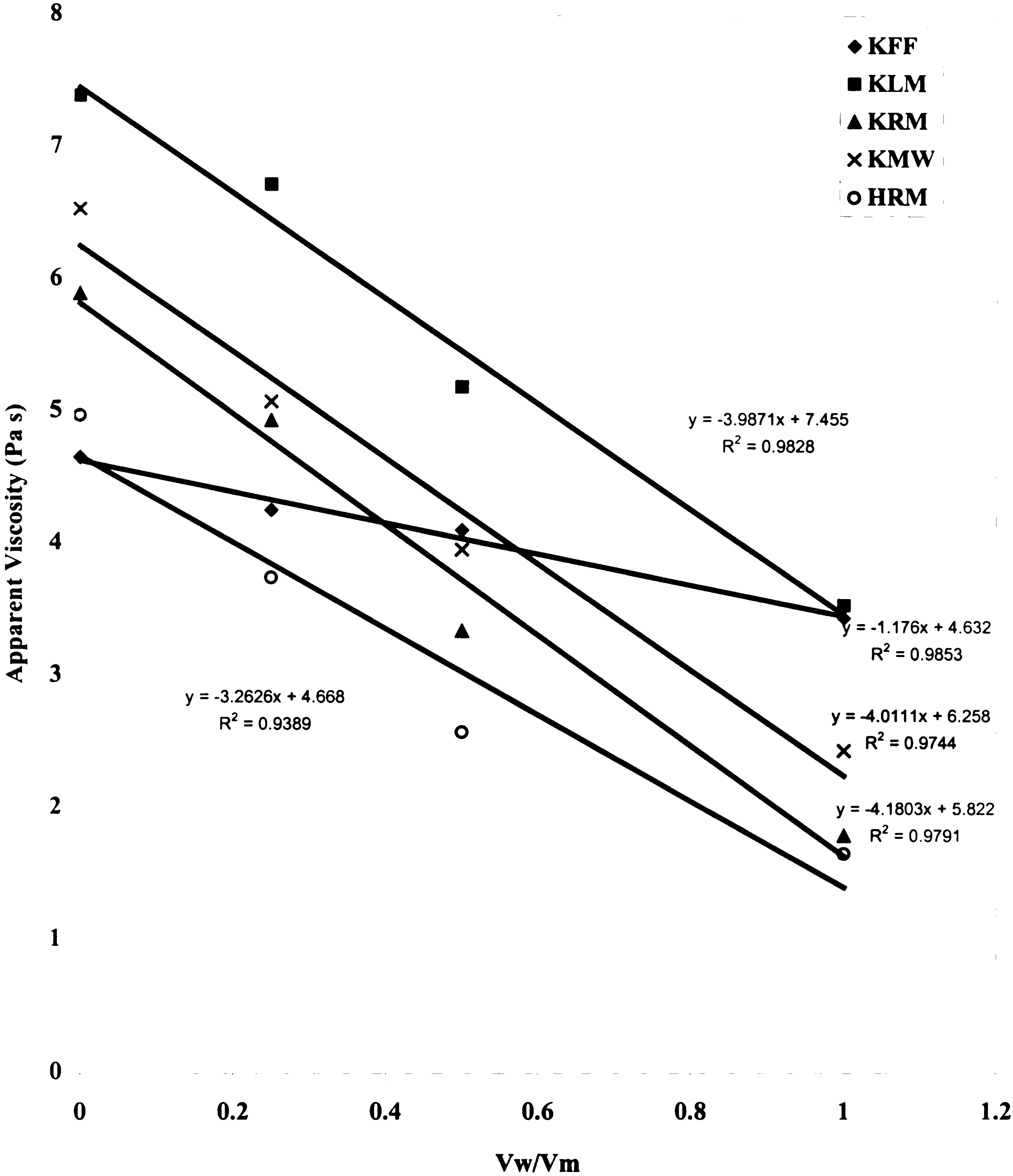


Fig 5.33 All food products at 37 C at shear rate 25 1/sec (manual mixing)

Starch absorbs water and swells leading to an increase in apparent viscosity. Kraft Light Mayonnaise showed the highest apparent viscosity at all water levels. Kraft Real Mayonnaise had a thicker consistency in the beginning but in the sample with 8.5 ml water, they had similar viscosities. Kraft Miracle Whip showed lower decrease in apparent viscosity than the Kraft Real Mayonnaise, and was found to be thicker than Kraft Real Mayonnaise at the end of the experiment.

At 21°C (Fig. 5.32), Hellmann's Real Mayonnaise had the lowest apparent viscosity in all tests. Kraft Fat Free, Kraft Real Mayonnaise, and Kraft Miracle Whip had similar viscosities at 1.25 and 2.5 ml water level while at 0 and 8.5 ml, the viscosity for Kraft Fat Free was slightly different from the rest of the two samples. Kraft Light Mayonnaise, at this temperature behaved normally and the experiment could also be conducted satisfactorily without addition of water. The sample had the thickest consistency at all the water levels.

At 37°C (Fig. 5.33), Hellmann's Real Mayonnaise showed the thinnest texture at all water levels except for the pure sample where the Kraft Fat Free had the lowest apparent viscosity. Kraft Fat Free Mayonnaise changed little in texture during experimentation; however, Kraft Real Mayonnaise and Kraft Miracle Whip underwent significant changes in texture.

Tables 5.3 through 5.5 show the linear slopes obtained for different food products at three temperatures. Through these tables, the change in viscosity can be studied and correlated to the behavior of the product. Some products were seen to break down faster than the others. At all the temperatures, Kraft Fat Free Mayonnaise had the minimum slope and underwent minimum change in the apparent viscosity with addition of water. It absorbs water and maintains consistency throughout the experiment. Kraft Real Mayonnaise shows the maximum slope except at 21°C at which Kraft Light Mayonnaise had the maximum change in apparent viscosity. At other temperatures, Kraft Light Mayonnaise closely followed Kraft Real Mayonnaise. At 5°C (Table 5.3), Kraft Miracle whip and Hellmann's Real Mayonnaise followed Kraft Real Mayonnaise and Kraft Light Mayonnaise. At 21°C (Table 5.4), Kraft Light Mayonnaise underwent maximum change in consistency that was followed by Kraft Miracle Whip, Kraft Real Mayonnaise, and Hellmann's Real Mayonnaise. At 37°C (Table 5.5), Kraft Real

Table 5.3 Slopes obtained for all food products at 5 °C at 25 1/sec

Products	Slope (Pa s)	R^2
KFF	-1.38	0.82
KLM	-6.81	0.99
KRM	-6.98	0.97
KMW	-5.65	0.95
HRM	-5.02	0.97

Table 5.4 Slopes obtained for all food products at 21 °C at 25 1/sec

Products	Slope (Pa s)	R^2
KFF	-2.60	0.81
KLM	-5.97	0.97
KRM	-4.41	0.99
KMW	-4.79	0.98
HRM	-3.36	0.98

Table 5.5 Slopes obtained for all food products at 37 °C at 25 1/sec

Products	Slope (Pa s)	R^2
KFF	-1.17	0.98
KLM	-3.98	0.98
KRM	-4.18	0.97
KMW	-4.01	0.97
HRM	-3.26	0.94

Mayonnaise was followed by Kraft Miracle Whip, Kraft Light Mayonnaise, and Hellmann's Real Mayonnaise.

The manual mixing analogy worked satisfactorily with all products and gave important insight into the textural properties after mixing water in the sample. The analogy has been proven to work satisfactorily with emulsions and would be helpful for other semi fluid, yield stress possessing food products on which conducting experiments has been difficult. The mastication analogy, involving the automatic addition of water produced some unsatisfactory results. Manual mixing generated superior results and seems to be a method with excellent potential for evaluating the mastication of fluid foods.

5.4 Analysis of Kraft Miracle Whip with different textural characteristics

The helical ribbon was used to study the textural differences instrumentally in different Kraft Miracle Whip samples subjected to partial sensory evaluation. Manual mixing analogy to mastication was employed since it was proven to be effective for studying the minor

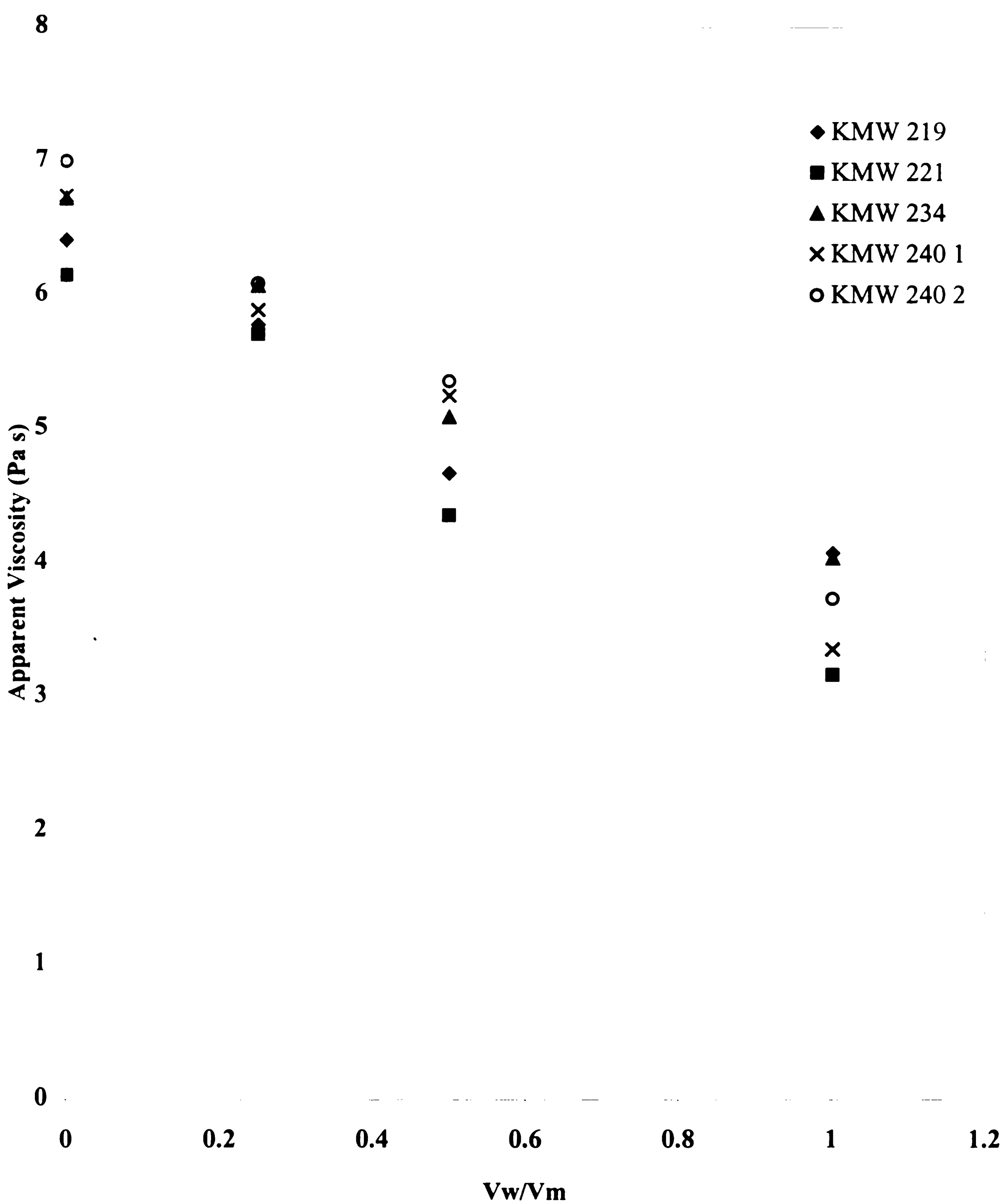


Fig 5.34 All Miracle Whip samples at 21 C at shear rate 25 1/sec (manual mixing)

differences in the products. Fig 5.34 shows the plot obtained for the five types of Miracle Whip tested. All the samples show a similar trend with minor differences in the rate of change in apparent viscosity with water. Sample numbered 219 was reported by Kraft to have a soft texture, which would give a creamy texture in the mouth after the shear application. Sample 221 was lumpy and underwent fast breakdown with the addition of water. Sample 234 had a slightly lumpy appearance with light texture. The sample numbered 240 – 1 was relatively thick, firm, not in the gelled form, and was stated to have good cling in the mouth. Sample 240 – 2 was similar to 240 – 1 and had a good body. From the plot, it can be seen that sample 221 maintained the lowest apparent viscosity and had the softest texture among all the samples. Samples numbered 240 (1 and 2) had a similar rate of change of viscosity but 240 – 1 had a softer texture. These samples exhibited the highest rate of viscosity change. Sample numbered 219 had the minimum change in the viscosity and showed the minimum rate of change in viscosity.

CHAPTER 6

CONCLUSIONS AND SUMMARY

The helical ribbon impeller was characterized by determining the value of the mixer coefficient (k'') as 1632 rev/m^3, and the range of the mixer viscometer constant (k') as 3 – 11 1/rev. The impeller was seen to be an effective tool in studying the rheological properties of food products when results obtained were compared to those found through conventional viscometry.

The change in the viscosities in emulsions like mayonnaise (with varying amount of fat present) and Miracle Whip were studied using automatic incorporation or manual mixing of water. Manual mixing proved to be superior in differentiating products and can be strongly recommended for further studies. Results obtained may be utilized to study the effect of fat replacers on the mouth feel of emulsions. The helical ribbon viscometer has a potential as a mastication emulator.

Water addition had a significant effect on the consistency of the emulsions with the apparent viscosity falling considerably with the addition of water.

The extent of decreasing viscosity and overall emulsion behavior were influenced by the presence of the fat replacer. Kraft Fat Free Mayonnaise proved to be the most stable product showing minimal change in the consistency with added water. The influence of temperature was also evident on all the products as the data obtained for the viscosities at higher temperature were lower than the viscosities obtained at lower temperature. With all factors considered, Kraft Light Mayonnaise was found to have the thickest consistency. Thus the impeller can be satisfactorily utilized in studying the effects of varying ingredients on product flow behavior.

CHAPTER 7

RECOMMENDATIONS FOR FUTURE STUDIES

In the light of current work on the helical ribbon impeller, the following topics are suggested for further research:

1. Utilizing the impeller to study other food products that have large sized particles or a significant yield stress.

2. Studying the effect of new fat replacers and other ingredients on the textural properties of the Mayonnaises and Miracle whips with the helical ribbon.

3. Correlate the results obtained by instrumental evaluation to the sensory panel analysis to identify the desirable texture for a product.

4. Utilizing the manual addition of water to other food products to study structural modifications occurring simultaneously with the increase in water level and change in temperature.

APPENDIX

Table A.1. Data for silicon oil with viscosity 0.490 cp used during the determination of *k″*:

Silicone oil (Viscosity = 0.490 cp)			
M (Nm)	N (rpm)	N (rps)	N*η (Pa Rev)
0.00007	9.903	0.1650	0.0808
0.00008	13.20	0.2200	0.1078
0.00010	16.60	0.2766	0.1355
0.00013	20.00	0.3333	0.1633
0.00014	23.30	0.3883	0.1902
0.00017	26.60	0.4433	0.2172
0.00019	29.90	0.4983	0.2441
0.00021	33.20	0.5533	0.2711
0.00023	36.60	0.6100	0.2989
0.00025	39.90	0.6650	0.3258

Table A.2. Data for glycerin with viscosity 0.740 cp used during the determination of *k″*:

Glycerin (Viscosity = 0.740 cp)			
M (Nm)	N (rpm)	N (rps)	N*η (Pa rev)
0.00002	4.899	0.0816	0.0604
0.00010	9.998	0.1666	0.1233
0.00016	15.00	0.2500	0.1850
0.00022	20.00	0.3333	0.2466
0.00026	25.00	0.4166	0.3083
0.00031	30.10	0.5016	0.3712
0.00037	35.00	0.5833	0.4316
0.00042	40.10	0.6683	0.4945
0.00048	45.20	0.7533	0.5574
0.00053	49.70	0.8283	0.6129

Table A.3. Data for silicon oil with viscosity 5.20 cp used during the determination of *k″*:

Silicone oil (Viscosity = 5.20 cp)			
M (Nm)	N (rpm)	N (rps)	N*η (Pa rev)
0.0015	49.90	0.831	4.324
0.0051	94.90	1.581	8.224
0.0084	139.5	2.325	12.09
0.0120	184.7	3.078	16.00
0.0131	230.1	3.835	19.94
0.0145	272.9	4.548	23.65
0.0162	318.3	5.305	27.58
0.0176	361.3	6.021	31.31
0.0183	405.4	6.756	35.13
0.0195	449.6	7.493	38.96

Table A.4. Data for silicon oil with viscosity 5.30 cp used during the determination of *k″*:

Silicon Oil (Viscosity = 5.28)			
M (Nm)	N (rpm)	N (rps)	N*V (Pa rev)
0.0015	49.90	0.831	4.441
0.0063	94.10	1.568	8.374
0.0101	138.9	2.315	12.36
0.0135	184.4	3.073	16.41
0.0148	228.4	3.806	20.32
0.0172	272.1	4.535	24.21
0.0195	317.5	5.291	28.25
0.0207	361.1	6.018	32.13
0.0222	407.8	6.796	36.29
0.0242	448.8	7.480	39.94

Table A.5 Data for the determination of k'' using the Newtonian fluids:

Angular Velocity * Viscosity (Pa s)	Torque (Nm)
0.060	0.0001
0.123	0.0001
0.185	0.0001
0.246	0.0002
0.308	0.0002
0.371	0.0003
0.431	0.0003
0.494	0.0004
0.557	0.0004
0.612	0.0005
4.324	0.0015
8.224	0.0051
12.09	0.0084
16.00	0.0120
19.94	0.0131
23.65	0.0145
27.58	0.0162
31.31	0.0176
35.13	0.0183
38.96	0.0195
0.080	0.0001
0.107	0.0001
0.135	0.0001
0.163	0.0001
0.190	0.0001
0.217	0.0002
0.244	0.0001
0.271	0.0002
0.298	0.0002
0.325	0.0002
4.441	0.0015
8.374	0.0063
12.36	0.0101
16.41	0.0135
20.32	0.0148
24.21	0.0172
28.25	0.0195
32.13	0.0207
36.29	0.0222
39.94	0.0242

Table A.6 Data sets for K and *n* values for guar gum at different concentrations

1.0% GG		1.5% GG	
Stress (Pa)	**Shear rate (1/sec)**	**Stress (Pa)**	**Shear rate (1/sec)**
4.928	0.939	22.21	0.939
16.10	6.794	50.26	6.549
20.83	12.40	61.63	12.40
24.37	18.26	69.71	18.01
24.83	21.99	72.07	21.77
26.87	27.62	75.29	27.62
28.38	33.46	77.72	33.23
29.76	39.09	79.5	39.09
30.22	42.82	80.55	42.82
31.14	48.68	81.01	48.68
32.19	54.29	82.39	54.29
32.78	60.14	84.10	59.92
33.44	63.90	85.08	63.65
33.84	69.51	85.74	69.51
34.3	75.36	86.59	75.14
35.02	80.97	87.18	80.97
35.48	84.73	88.04	84.73
36.00	90.58	88.56	90.34
36.66	96.19	89.55	96.19
36.99	99.95	90.01	99.95

2.0% GG		2.25% GG	
Stress (Pa)	**Shear rate (1/sec)**	**Stress (Pa)**	**Shear rate (1/sec)**
62.22	0.939	54.99	0.939
118.8	6.549	127.3	6.549
143.3	12.4	154.3	12.4
151.6	18.01	166.4	18.26
156.8	21.99	172.4	21.99
160	27.62	177.8	27.62
164	33.23	181.4	33.46
166.1	39.09	184.7	39.09
166.2	42.82	187.5	42.82
168.3	48.45	189.3	48.68
170	54.29	190.9	54.29
169.4	59.92	194.4	60.14

170.2	63.65	195.4	63.9
173.1	69.51	195.7	69.51
174.2	75.14	197.2	75.36
175.4	80.97	198.2	79.12
176.1	84.73	200	84.95
176.5	90.34	201.2	90.58
177.3	96.19	202.4	96.19
177.8	99.95	202.6	99.95

2.5% GG

Stress (Pa)	Shear rate (1/sec)
99.08	0.939
168.9	6.794
193.7	12.63
203.2	18.26
203.7	21.99
210.3	27.85
211.2	33.46
212.9	39.09
214.8	43.07
213.8	48.68
213.7	54.53
218.5	60.14
218.4	64.12
216.9	69.75
213.1	75.59
209.7	79.34
211	84.95
212.9	90.81
204.5	96.42
201.8	99.95

Table A.7 Data sets for K and *n* values for HPMC at different concentrations:

1.0% HPMC		1.5% HPMC	
Stress(Pa)	Shear rate (1/sec)	Stress (Pa)	Shear Rate (1/sec)
0.329	0.939	1.051	0.939
1.643	6.794	5.453	6.549
2.759	12.40	9.724	12.40
4.008	18.26	12.35	18.01
4.468	21.99	15.57	21.99
5.782	27.62	17.61	27.62
6.636	33.46	21.29	33.23
7.490	39.09	24.18	39.09
8.212	43.07	25.29	42.82
9.132	48.68	27.99	48.45
9.921	54.53	30.48	54.29
11.10	60.14	31.86	59.92
11.83	63.90	33.05	63.90
12.35	69.51	35.61	69.51
13.07	75.36	37.71	75.14
13.80	79.12	39.42	80.97
14.65	84.95	40.47	84.73
15.57	90.58	41.92	90.58
16.03	96.19	43.62	96.19
16.69	99.95	44.94	99.95

2.0% HPMC		2.25% HPMC	
Stress (Pa)	Shear rate (1/sec)	Stress (Pa)	Shear rate (1/sec)
4.402	0.939	6.964	0.939
25.49	6.549	20.43	6.549
42.57	12.40	31.21	12.40
55.98	18.01	39.68	18.01
62.87	21.99	45.14	21.99
74.77	27.62	53.35	27.62
83.18	33.23	59.26	33.23
90.40	39.09	66.23	39.09
95.33	42.82	71.35	42.82
102.3	48.45	77.07	48.45
109.5	54.29	82.65	54.29
116.8	59.92	88.17	59.92

121.0	63.90	92.11	63.90
126.3	69.51	96.58	69.51
130.5	75.14	101.5	75.36
136.1	80.97	105.9	80.97
140.4	84.73	108.1	84.73
145.0	90.58	112.0	90.58
149.1	96.19	116.5	96.19
151.9	99.95	118.5	99.95

2.5% HPMC	
Stress (Pa)	**Shear rate (1/sec)**
9.461	0.939
39.29	6.794
63.01	12.40
79.89	18.26
90.47	21.99
104.8	27.85
117.5	33.46
127.1	39.09
132.0	43.07
141.8	48.68
151.0	54.29
158.1	60.14
163.1	63.90
170.7	69.75
177.5	75.36
182.3	79.12
187.8	84.95
193.7	90.81
198.8	96.42
202.6	99.95

Table A.8 Data for determination of k' at different angular velocities for guar gum at different concentrations:

1.0% GG		1.5% GG		2.0% GG	
N (rev/sec)	k'	N (rev/sec)	k'	N (rev/sec)	k'
0.006	40.85	0.006	48.74	0.006	34.14
0.048	14.99	0.046	12.17	0.048	13.86
0.088	9.540	0.088	9.309	0.088	10.84
0.128	8.694	0.128	8.608	0.128	10.55
0.156	7.939	0.156	8.415	0.156	10.17
0.196	7.577	0.196	8.222	0.196	10.01
0.236	7.532	0.236	8.143	0.236	9.932
0.278	7.119	0.278	8.073	0.278	9.854
0.305	6.933	0.305	7.978	0.305	9.786
0.346	6.676	0.345	7.990	0.346	9.793
0.386	6.643	0.386	7.986	0.386	9.782
0.428	6.602	0.426	8.019	0.428	9.798
0.455	6.628	0.455	8.028	0.455	9.773
0.496	6.554	0.495	8.029	0.495	9.827
0.536	6.560	0.535	8.016	0.536	9.838
0.565	6.569	0.576	8.000	0.576	9.812
0.605	6.654	0.603	8.001	0.603	9.813
0.646	6.635	0.645	8.001	0.643	9.826
0.686	6.694	0.685	8.017	0.685	9.855
0.711	6.750	0.711	8.034	0.711	9.878

2.25% GG		2.5% GG	
N (rev/sec)	k'	N (rev/sec)	k'
0.006	72.47	0.006	69.09
0.048	11.47	0.048	12.62
0.089	8.889	0.088	10.02
0.130	8.566	0.130	9.552
0.156	8.579	0.156	9.432
0.198	8.538	0.198	9.156
0.238	8.394	0.238	9.048
0.278	8.448	0.278	8.945
0.306	8.405	0.306	8.888
0.346	8.590	0.346	8.850
0.388	8.523	0.386	8.798
0.415	8.513	0.428	8.769
0.456	8.540	0.455	8.814
0.496	8.555	0.496	8.798
0.538	8.519	0.536	8.808
0.565	8.445	0.563	8.789
0.605	8.473	0.605	8.792
0.645	8.448	0.645	8.834
0.686	8.327	0.686	8.799

Table A.9 Data for determination of *k'* at different angular velocities for HPMC at different concentrations:

1.0% HPMC		1.5% HPMC	
N (rev/sec)	k'	N (rev/sec)	k'
0.006	0.001	0.006	4.867
0.048	0.201	0.046	1.470
0.090	0.453	0.088	1.460
0.130	0.533	0.128	1.205
0.156	0.347	0.155	1.807
0.198	0.391	0.196	1.436
0.238	0.396	0.236	1.159
0.278	0.391	0.278	1.198
0.306	0.675	0.305	1.001
0.346	0.617	0.346	0.876
0.388	0.581	0.386	0.876
0.428	0.536	0.426	0.767
0.456	0.769	0.453	0.863
0.496	0.693	0.495	0.861
0.538	0.642	0.535	0.760
0.565	0.515	0.576	0.757
0.605	0.758	0.603	0.748
0.645	1.087	0.643	0.734
0.686	1.546	0.685	0.791
0.711	1.197	0.711	0.716

2.25% HPMC		2.5% HPMC	
N (rev/sec)	k'	N (rev/sec)	D*F = k'
0.006	56.32	0.006	24.11
0.048	27.49	0.048	9.975
0.089	16.64	0.088	6.378
0.118	13.53	0.130	5.313
0.159	12.52	0.156	4.860
0.201	10.94	0.198	4.309
0.243	9.681	0.238	4.126
0.270	9.645	0.278	3.922
0.311	8.879	0.306	3.822
0.353	8.439	0.346	3.756
0.381	7.968	0.388	3.657
0.423	7.957	0.428	3.601
0.465	7.557	0.455	3.645
0.491	7.436	0.496	3.552
0.533	7.216	0.536	3.636
0.575	7.132	0.563	3.615
0.603	6.909	0.605	3.595
0.645	6.814	0.645	3.609
0.686	6.601	0.686	3.658

Table A.10 Rheograms obtained for different food products comparing the results obtained from MV1 and Helical Ribbon systems:

Mustard (MV1)		Mustard (HR)	
Shear Rate (1/sec)	Apparent Viscosity(Pas)	Shear Rate (1/sec)	Apparent Viscosity (Pas)
2.890	11.63	2.849	15.28
5.540	8.057	5.426	8.925
8.350	7.330	8.054	6.387
11.00	5.420	10.72	5.097
13.49	4.610	13.17	4.307
16.15	3.973	15.94	3.761
18.73	3.573	18.51	3.348
21.45	3.167	21.26	3.027
24.04	2.893	23.91	2.768
26.61	2.650	26.50	2.580
29.26	2.500	29.14	2.405
31.91	2.317	31.82	2.255
34.40	2.183	34.51	2.121
36.98	2.077	37.02	2.017
39.71	1.967	39.76	1.911
42.28	1.863	42.25	1.824
44.94	1.780	44.93	1.744
47.59	1.703	47.57	1.673
49.86	1.555	49.91	1.614

Ketchup MV1		Ketchup (HR)	
Shear Rate (1/sec)	Apparent Viscosity(Pas)	Shear Rate (1/sec)	Apparent Viscosity(Pas)
5.692	6.410	5.397	6.986
8.276	4.676	8.163	5.009
10.84	3.800	10.81	4.005
13.41	3.153	13.45	3.364
16.07	2.700	16.13	2.961
18.73	2.373	18.79	2.656
21.29	2.140	21.44	2.411
23.79	2.010	24.06	2.205
26.60	1.827	26.62	2.051
29.03	1.697	29.47	1.902
31.83	1.577	31.99	1.779
34.40	1.467	34.73	1.672
37.06	1.400	37.50	1.577

39.47	1.340	40.12	1.504
42.20	1.280	42.88	1.430
44.78	1.243	45.32	1.375
47.43	1.207	48.14	1.316
49.78	1.183	50.47	1.271

Henri's Ranch (MV 1)			
Shear Rate (1/sec)	**Apparent Viscosity(Pas)**	**Shear Rate (1/sec)**	**Apparent Viscosity(Pas)**
8.120	6.183	8.183	3.834
10.77	4.577	10.86	3.286
13.41	3.877	13.42	2.915
15.92	3.423	16.14	2.663
18.56	2.980	18.69	2.469
21.05	2.763	21.28	2.318
23.87	2.533	24.08	2.174
26.52	2.417	26.45	2.069
29.10	2.140	29.20	1.975
31.67	2.067	31.91	1.887
34.33	1.903	34.38	1.813
36.98	1.867	37.12	1.748
39.55	1.867	39.80	1.677
42.20	1.760	42.32	1.627
44.71	1.687	44.85	1.586
47.42	1.657	47.51	1.546
49.78	1.573	49.87	1.510

Table A.11 Data for Kraft Fat Free Mayonnaise at different temperatures with automatic addition of 8.5 ml water at 4.0 ml/min:

Temp 5C		Temp 21		Temp 37 C	
Strain History	Apparent Viscosity	Strain History	Apparent Viscosity	Strain History	Apparent Viscosity
8.750	84.76	8.880	65.49	9.001	53.76
17.03	81.42	17.10	61.21	17.48	50.49
25.39	75.59	25.44	58.29	25.98	46.88
33.69	68.36	33.86	51.86	34.50	43.60
42.13	65.10	42.16	49.90	42.97	41.10
50.47	61.93	50.60	45.86	51.47	39.25
58.71	59.88	58.84	43.46	60.04	37.25
67.05	58.24	67.20	41.54	68.63	35.75
75.43	55.42	75.56	38.06	77.03	34.33
83.78	49.82	83.91	34.26	85.55	31.73
92.11	46.06	92.28	32.95	94.06	29.52
100.4	43.20	100.6	32.70	102.5	27.35
108.8	44.32	108.9	31.38	111.2	27.10
117.5	43.58	117.3	30.19	119.5	25.75
125.4	43.80	125.7	29.15	128.1	24.99
133.7	43.02	134.7	27.01	136.6	22.88
142.2	41.26	142.1	25.73	145.1	21.76
150.4	39.56	150.7	24.89	153.6	19.68
158.7	37.63	159.1	24.60	162.2	18.28

Table A.12 Data for Kraft Light Mayonnaise at two temperatures with automatic addition of 8.5 ml water at 4.0 ml/min:

Temp 5C		Temp 21	
Strain History	**Apparent Viscosity**	**Strain History**	**Apparent Viscosity**
8.870	128.6	14.02	80.25
17.36	124.8	27.31	71.81
25.62	121.3	40.61	63.06
33.93	117.2	53.88	53.41
42.29	109.6	67.18	47.79
50.58	103.0	80.40	39.76
58.92	97.23	93.67	30.38
67.25	92.61	107.0	23.63
75.54	92.83	120.2	21.82
83.88	91.90	133.5	21.04
92.25	91.43	146.8	20.93
100.5	87.77	160.1	20.03
108.8	84.44	173.4	17.55
117.1	78.78	186.7	13.18
125.5	73.93	200.0	11.36
133.8	70.67	213.2	11.63
142.2	69.11	226.4	10.61
150.5	66.02	239.8	11.36
158.7	65.14	253.0	10.36

Table A.13 Data for Kraft Real Mayonnaise at 5C temperature with automatic addition of 8.5 ml water at 4.0 ml/min:

Temp 5C	
Strain History	**Apparent Viscosity**
8.756	130.2
17.09	126.0
25.42	115.7
33.67	101.0
41.95	87.11
50.32	67.52
58.74	58.19
66.97	61.14
75.33	63.79
83.61	61.20
91.88	53.41
100.2	43.70
108.5	40.83
116.8	37.67
125.2	33.07
133.4	29.85
141.8	29.37
150.2	30.87
158.5	31.96

Table A.14 Data for Kraft Miracle Whip at different temperatures with automatic addition of 8.5 ml water at 4.0 ml/min:

Temp 5C		Temp 21		37 C	
Strain History	**Apparent Viscosity**	**Strain History**	**Apparent Viscosity**	**Strain History**	**Apparent Viscosity**
19.80	127.5	17.50	46.22	8.720	87.05
28.14	124.3	34.40	43.76	17.01	82.50
36.46	119.9	51.10	40.93	25.25	76.97
44.82	112.1	67.70	32.69	33.46	70.56
53.13	98.41	84.40	26.74	41.71	62.50
61.36	82.03	101.2	21.26	49.95	51.73
69.72	67.83	117.8	17.10	58.18	39.98
78.03	59.91	134.5	12.42	66.48	30.50
86.32	53.10	151.3	9.780	74.65	25.01
94.68	48.34	168.0	9.990	82.90	21.42
103.0	45.13	184.8	8.850	91.21	20.25
111.2	41.44	201.4	6.760	99.40	18.93
119.5	40.35	218.4	6.600	107.6	17.59
127.9	39.50	234.8	6.680	115.8	16.31
136.2	39.70	251.6	6.130	124.1	14.44
144.6	38.16	268.4	5.400	132.3	12.37
152.8	36.85	285.0	4.420	140.6	12.31
161.1	37.07	301.7	3.890	148.8	10.92
170.3	35.55	318.5	4.050	157.1	9.850

Table A.15 Data for Hellmann's Real Mayonnaise at two temperatures with automatic addition of 8.5 ml water at 4.0 ml/min:

Temp 5C		Temp 21	
Strain History	**Apparent Viscosity**	**Strain History**	**Apparent Viscosity**
11.62	111.1	8.730	58.17
19.92	106.0	18.07	54.96
28.25	98.15	25.47	56.51
36.63	90.37	33.84	50.35
44.99	74.77	41.25	43.53
53.27	59.08	50.41	40.68
61.65	45.32	58.86	26.88
70.04	36.64	66.91	28.30
78.36	30.40	74.69	22.08
86.74	25.68	82.48	19.77
95.11	22.64	91.36	14.55
103.4	18.42	99.85	17.19
111.7	16.05	107.7	13.31
120.1	13.95	117.2	15.91
128.4	12.72	124.1	13.31
136.8	10.79	133.1	18.73
145.7	6.320	148.9	13.99
156.6	3.490	156.0	15.23

Table A.16 Data for all the food products at 5°C at 1.25 1/sec shear rate with automatic addition of 8.5 ml water at the rate of 4.0 ml/min:

Kraft Fat Free		Kraft Light Mayo		Kraft Real mayo	
Strain History	Apparent Viscosity	Strain History	Apparent Viscosity	Strain History	Apparent Viscosity
8.750	84.76	8.870	128.6	8.750	130.5
17.03	81.42	17.36	124.8	17.09	126.0
25.39	75.59	25.62	121.6	25.42	115.7
33.69	68.36	33.93	117.2	33.67	101.0
42.13	65.10	42.29	109.6	41.95	87.11
50.47	61.93	50.58	103.0	50.32	67.52
58.71	59.88	58.92	97.23	58.74	58.19
67.05	58.24	67.25	92.61	66.97	61.14
75.43	55.42	75.54	92.83	75.33	63.79
83.78	49.82	83.88	91.90	83.61	61.20
92.11	46.06	92.25	91.43	91.88	53.41
100.4	43.20	100.5	87.77	100.2	43.70
108.7	44.32	108.8	84.44	108.5	40.83
117.1	43.58	117.1	78.78	116.8	37.67
125.4	43.80	125.5	73.93	125.2	33.07
133.7	43.02	133.8	70.67	133.4	29.85
142.1	41.26	142.2	69.11	141.8	29.37
150.7	39.56	150.5	66.02	150.9	30.87
158.7	37.63	158.7	65.14	158.4	31.96

Cont.

Kraft Miracle Whip		Hellmanns Real Mayo	
Strain History	**Apparent Viscosity**	**Strain History**	**Apparent Viscosity**
19.80	127.5	11.62	111.1
28.14	124.3	19.92	106.0
36.46	119.1	28.25	98.15
44.82	112.1	36.63	90.37
53.13	98.41	44.99	74.77
61.36	82.03	53.27	59.08
69.72	67.83	61.65	45.32
78.03	59.91	70.04	36.64
86.32	53.10	78.36	30.40
94.68	48.34	86.74	25.68
103.0	45.13	95.11	22.64
111.2	41.44	103.4	18.42
119.5	40.35	111.7	16.05
127.9	39.50	120.1	13.95
136.2	39.70	128.4	12.72
144.6	38.16	136.8	10.79
152.8	36.85	145.1	6.320
161.1	37.07	156.6	3.490
170.3	35.55		

Table A.17 Data for all the food products at 21°C at 1.25 1/sec shear rate with automatic addition of 8.5 ml water at the rate of 4.0 ml/min:

Kraft Fat Free Mayonnaise		Kraft Light Mayonnaise		Kraft Miracle Whip		Hellmanns Real Mayonnaise	
Strain History	Apparent Viscosity	Strain History	Apparent Viscosity	Strain History	Apparent Viscosity	Strain History	Apparent Viscosity
8.880	65.49	14.02	80.25	17.50	46.22	8.734	58.17
17.10	61.21	27.31	71.81	34.42	43.75	18.06	54.96
25.44	58.29	40.61	63.06	51.05	40.95	25.46	56.51
33.86	51.86	53.88	53.41	67.70	32.68	33.83	50.35
42.16	49.90	67.18	47.79	84.39	26.73	41.25	43.53
50.60	45.86	80.40	39.76	101.1	21.25	50.40	40.68
58.84	43.46	93.67	30.38	117.7	17.09	58.86	26.88
67.20	41.54	107.0	23.63	134.5	12.41	66.91	28.30
75.56	38.06	120.2	21.82	151.3	9.782	74.69	22.08
83.91	34.26	133.5	21.04	168.0	9.991	82.48	19.77
92.28	32.95	146.8	20.93	184.8	8.853	91.34	14.55
100.6	32.70	160.1	20.03	201.4	6.762	99.85	17.19
108.6	31.38	173.4	17.55	218.3	6.602	107.7	13.31
117.3	30.19	186.7	13.18	234.8	6.677	117.2	15.91
125.7	29.15	200.0	11.36	251.5	6.135	124.1	13.31
134.0	27.01	213.2	11.63	268.4	5.399	133.1	18.73
142.4	25.73	226.4	10.61	284.9	4.425	140.1	11.19
150.7	24.89	239.8	11.36	301.7	3.887	148.9	13.99
159.0	24.60	253.1	10.36	318.5	4.055	156.0	15.23

Table A.18 Data for all the food products at 37°C at 1.25 1/sec shear rate with automatic addition of 8.5 ml water at the rate of 4.0 ml/min:

Kraft Fat Free		Kraft Miracle whip	
Strain History	Apparent Viscosity	Strain History	Apparent viscosity
9.000	53.76	8.720	87.05
17.48	50.49	17.01	82.50
25.98	46.88	25.25	76.97
34.50	43.60	33.46	70.56
42.97	41.10	41.71	62.50
51.47	39.25	49.95	51.73
60.04	37.25	58.18	39.98
68.63	35.75	66.48	30.50
77.03	34.33	74.65	25.01
85.55	31.73	82.90	21.42
94.06	29.52	91.21	20.25
102.5	27.35	99.40	18.93
111.2	27.10	107.6	17.59
119.5	25.75	115.8	16.31
128.1	24.99	124.1	14.44
136.6	22.88	132.3	12.37
145.1	21.76	140.6	12.31
153.6	19.68	148.8	10.92
162.2	18.28	157.1	9.850

Table A.19 Data for Kraft Fat Free Mayonnaise at three temperatures at 1 1/sec shear rate with manual mixing:

Vw/Vm	Temp 5 C	Temp 21C	Temp 37C
0.00	19.32	119.8	75.05
0.25	104.6	77.34	58.68
0.50	78.08	49.70	58.60
1.00	40.46	33.60	48.13

Table A.20 Data for Kraft Light Mayonnaise at three temperatures at 1 1/sec shear rate with manual mixing:

Vw/Vm	Temp 5 C	Temp 21C	Temp 37 C
0.00	19.31	119.8	82.94
0.25	104.6	77.34	53.96
0.50	78.08	49.70	39.89
1.00	40.46	33.60	25.10

Table A.21 Data for Kraft Real Mayonnaise at three temperatures at 1 1/sec shear rate with manual mixing:

Vw/Vm	Temp 5 C	Temp 21 C	Temp 37 C
0.00	164.0	117.4	95.65
0.25	93.66	70.47	63.24
0.50	59.04	47.90	38.00
1.00	27.41	23.55	16.64

Table A.22 Data for Kraft Miracle Whip at three temperatures at 1 1/sec shear rate with manual mixing:

Vw/Vm	Temp 5 c	Temp 21 C	Temp 37 C
0.00	146.7	85.53	90.83
0.25	58.11	44.88	47.11
0.50	42.72	33.94	36.30
1.00	24.21	16.66	18.90

Table A.23 Data for Hellmann's Real Mayonnaise at three temperatures at 1 1/sec shear rate with manual mixing:

Vw/Vm	Temp 5 C	Temp 21 C	Temp 37 C
0.00	179.8	109.4	116.9
0.25	80.46	46.30	49.87
0.50	61.94	36.50	30.63
1.00	31.05	15.74	19.62

Table A.24 Data for Kraft Fat Free Mayonnaise at three temperatures at 25 1/sec shear rate with manual mixing:

Vw/Vm	Temp 5 C	Temp 21 C	Temp 37 C
0.00	1.230	10.99	4.657
0.25	11.88	8.990	4.260
0.50	9.782	7.045	4.110
1.00	6.697	4.970	3.442

Table A.25 Data for Kraft Light Mayonnaise at three temperatures at 25 1/sec shear rate with manual mixing:

Vw/Vm	Temp 5 C	Temp 21 C	Temp 37 C
0.00	1.230	10.99	7.392
0.25	11.88	8.990	6.722
0.50	9.782	7.045	5.190
1.00	6.697	4.970	3.537

Table A.26 Data for Kraft Real Mayonnaise at three temperatures at 25 1/sec shear rate with manual mixing:

Vw/Vm	Temp 5 C	Temp 21 C	Temp 37 C
0.00	10.36	7.397	5.895
0.25	7.747	6.055	4.937
0.50	5.710	4.457	3.345
1.00	3.220	2.622	1.795

Table A.27 Data for Kraft Miracle Whip at three temperatures at 25 1/sec shear rate with manual mixing:

Vw/Vm	Temp 5 C	Temp 21 C	Temp 37 C
0.00	9.570	7.187	6.537
0.25	7.347	5.822	5.077
0.50	5.622	4.592	3.960
1.00	3.775	2.732	2.437

Table A.28 Data for Hellmann's Real Mayonnaise at three temperatures at 25 1/sec shear rate with manual mixing:

Vw/Vm	Temp 5 C	Temp 21 C	Temp 37 C
0.00	8.245	5.335	4.975
0.25	6.200	4.177	3.747
0.50	5.022	3.317	2.580
1.00	3.037	1.905	1.660

Table A.29 Data for Kraft Fat Free Mayonnaise at three temperatures at 50 1/sec shear rate with manual mixing:

Vw/Vm	Temp 5 C	Temp 21 C	Temp 37 C
0.00	3.061	3.150	2.560
0.25	3.300	3.333	2.422
0.50	2.843	2.443	2.320
1.00	2.542	1.996	1.952

Table A.30 Data for Kraft Light Mayonnaise at three temperatures at 50 1/sec shear rate with manual mixing:

Vw/Vm	Temp 5 C	Temp 21 C	Temp 37 C
0.00	0.690	6.570	4.407
0.25	7.460	5.662	4.275
0.50	6.292	4.627	3.337
1.00	4.542	3.302	2.317

Table A.31 Data for Kraft Real Mayonnaise at three temperatures at 50 1/sec shear rate with manual mixing:

Vw/Vm	Temp 5 C	Temp 21 C	Temp 37 C
0.00	5.752	4.077	3.250
0.25	4.530	3.597	2.855
0.50	3.450	2.675	1.980
1.00	2.032	1.637	1.112

Table A.32 Data for Kraft Miracle Whip at three temperatures at 50 1/sec shear rate with manual mixing:

Vw/Vm	Temp 5 C	Temp 21 C	Temp 37 C
0.00	5.357	4.247	3.715
0.25	4.712	3.752	3.145
0.50	3.387	2.986	2.455
1.00	2.545	1.850	1.567

Table A.33 Data for Hellmann's Real Mayonnaise at three temperatures at 50 1/sec shear rate with manual mixing:

Vw/Vm	Temp 5 C	Temp 21 C	Temp 37 C
0.00	4.247	2.792	2.535
0.25	3.567	2.490	2.147
0.50	2.925	1.980	1.510
1.00	1.840	1.210	0.980

Table A.34 Data for all products at 5°C at 25 1/sec shear rate with manual mixing:

Vw/Vm	KFF	KLM	KRM	KMW	HRM
0.00	5.579	1.230	10.36	9.570	8.245
0.25	5.840	11.88	7.747	7.347	6.200
0.50	4.955	9.782	5.710	5.622	5.022
1.00	4.390	6.697	3.220	3.775	3.037

Table A.35 Data for all products at 21°C at 25 1/sec shear rate with manual mixing:

Vw/Vm	KFF	KLM	KRM	KMW	HRM
0.00	5.670	10.99	7.397	7.187	5.335
0.25	6.113	8.990	6.055	5.822	4.177
0.50	4.300	7.045	4.457	4.592	3.317
1.00	3.433	4.970	2.622	2.732	1.905

Table A.36 Data for all products at 37°C at 25 1/sec shear rate with manual mixing:

Vw/Vm	KFF	KLM	KRM	KMW	HRM
0.00	4.657	7.392	5.895	6.537	4.975
0.25	4.260	6.722	4.937	5.077	3.747
0.50	4.110	5.190	3.345	3.960	2.580
1.00	3.442	3.537	1.795	2.437	1.660

Table A.37 Data for all Kraft Miracle Whip samples at 21°C at 25 1/sec shear rate with manual mixing:

Vw/Vm	219	221	234	240-1	240-2
0.00	6.41	6.15	6.72	6.74	7.00
0.25	5.78	5.71	6.07	5.89	6.09
0.50	4.67	4.36	5.09	5.25	5.36
1.00	4.08	3.17	4.04	3.36	3.74

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