

DEVELOPMENT OF A LABORATORY SCALE  
MODEL FOOD EXTRUDER

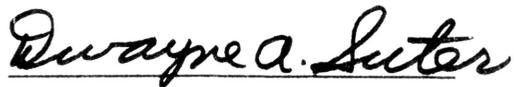
by

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ABSTRACT

## DEVELOPMENT OF A LABORATORY SCALE

## MODEL FOOD EXTRUDER

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Extrusion processing has many useful applications in the food industry. The process yields low-cost texturized proteins which has great potential for growth on a world market. Most of the research in the area of texturization of vegetable proteins has focused on solving problems related to process control. These studies indicate that product development is more of an art than a science. The process becomes very unstable under the conditions necessary to texture protein ingredients. Very little definitive information is known about the rheological, thermal, and chemical interactions occurring in the extrusion process of various vegetable raw materials.

An understanding of the effect of various interactions on the resulting extrudate will permit more precise control of product quality while minimizing energy inputs. Over-processing is expensive and usually produces inferior products. Research data should aid in maximizing extruder operating efficiency in the production of texturized vegetable protein foods with specific desirable characteristics from various raw materials.

A high protein soy flour was subjected to controlled temperature, pressure, and shear rate in a viscometer similar in design to the Instron Capillary Rheometer. Initially soy flour was utilized, but the process can be applied to other oilseed isolates such as cottonseed meal.

Physical and rheological properties of the extrudate were measured and correlated. These properties included extrudate hydration, thermodynamic activation energy, extruding viscosity, and extrudate stress-strain behavior. Results indicate a need for improved extruder designs for a wide variety of products from soy and cottonseed materials.

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J. E. M.

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## INTRODUCTION

The extrusion texturization process has potential application to the production of a wide range of food products. Recent developments in this area give indication of easy adaptability to the different traditions of societies in the world today. Textural studies involving the extrusion process have contributed to the understanding of the properties of fabricated vegetable protein products.

Texturized products have been received well by the consumers since the raw material is restructured in such a way that the final product has a fibrous structure and integrity similar to that of muscle tissue. The high cost of animal protein has produced an increased interest in the use of vegetable proteins for mankind.

Past research has been primarily concentrated on solving processing problems and maintaining quality control. Very little information is available on the rheological and physical interactions which take place during the extrusion process.

The main objectives of this research was to start to develop basic scientific knowledge necessary to facilitate texturization of a wide range of vegetable protein materials. More specifically, the following objectives were used as guidelines-

- 1.) To determine the effect of temperature, pressure, and shear rate in the formation of texturized foods.
- 2.) To evaluate the use of a viscometer similar in design to the Instron Capillary Rheometer as a research tool to establish operational parameters to texturize various vegetable protein materials.
- 3.) To determine extruding viscosity, extrudate size, thermodynamic activation energy, extrudate hydration, and extrudate stress-strain behavior as an index of texture.

## REVIEW OF LITERATURE

New texturized vegetable protein products are being developed each year. Many of the above products are produced by extrusion cooking processes. Extrusion processing first became important to the food industry when it was used to extrude pasta products (Farrell, 1971).

Some of the cooking extruders being used today were originally designed to expel oil from oil seeds, gelatinize starch in animal feeds, or mix additives with animal feeds. Extrusion cooking is now widely used to produce many food products including: breakfast cereals, snacks, breadings, gelatinized starches, nutritional foods, protein concentrates, beverage powders, pet foods, and texturized proteins (Anderson, *et al.*, 1969; Clark, 1969; Conway, 1968; Daniels, 1970; de Muelenaere and Buzzard, 1969; Farrell, 1971; Harmann and Harper, 1972; Hummel, 1966; Kissinger, 1969; Lachman, 1969; Mustakas, *et al.*, 1964; Mustakas, 1970; Sanderude and Ziemba, 1968; Sanderude, 1969; Schaefer, *et al.*, 1969; Smith 1969; Smith, 1971; Thompson and Rosenow, 1972; Ziemba, 1964; Archer Daniels Midland Company, British Patent 1,049,484, 1966 and U. S. Patent 3,488,770, 1970).

Harper and Harmann (1973) effectively documented some of the research needs in extrusion cooking and forming. They cite previous work (Smith, 1971) in stating the following advantages of extrusion cooking: versatility, high productivity, low cost, high product quality, and the ability to modify ingredients. Recent discussions (Harper, 1975) have underlined the fact that current extrusion processing is more of an art than a science. Harper and Harmann (1973) have concluded that to facilitate further applications of the food extruder, there are specific research needs in the following areas where special attention should be given: (a) extruder modeling, (b) die design, (c) physical properties, (d) product quality, and (e) process control.

Much of the extrusion theory developed to date has been directly associated with polymer extrusion processes. Molten polymers are compressible, non-Newtonian fluids which upon extrusion can have an effective viscosity much smaller than that measured by certain conventional viscometers (Pezzin, 1962). Therefore, a need exists for special viscometers capable of measuring viscosities in a wide range of shear rates (up to  $10^6 \text{ sec}^{-1}$ ) in order to obtain information relating to the behavior of materials during extrusion processing.

Extrusion-type rheometers have been successfully used to measure viscosities of molten polymers over a wide range of shear rates (Pezzin, 1962; Einhorn and Turetzky, 1963; Smith and Darby, 1976; Zahler and Murfitt, 1963). Pezzin (1962) has used a capillary rheometer to obtain a series of rheological data on polystyrene and other molten polymers. Pezzin (1962) concluded that from viscosity measurements on polymers one may obtain important molecular parameters and information on the elastic behavior of the materials. He also concluded that such rheological data can be correlated with the behavior of polymers in the manufacturing process. A perfect correlation has been obtained between spiral molding data and measurements obtained from a capillary rheometer at a fixed shear rate of  $140 \text{ sec}^{-1}$  and temperatures between 160 and  $220^\circ \text{C}$  (Skinner and Taylor, 1960).

As indicated above, current development in extruder theory from polymer research might be used to correlate rheological data of vegetable raw materials with the design of cooking extruders. A capillary rheometer should provide an adequate means to measure certain rheological properties of vegetable raw materials under operating conditions similar to those encountered in cooking extruders.

Soy materials are currently being used extensively today in the production of texturized protein products by extrusion processing. Similar products made from certain cottonseed materials may offer great potential in the food industry. The primary

objective in extrusion processing of the oilseed products is to restructure the raw materials in such a way that the final product exhibits a fibrous structure and integrity similar to that of muscle tissue.

A cooking extruder has three main sections: (a) feed, (b) transition, and (c) metering, which feed, cook, and meter the food material respectively. The granular raw material (flour or meal) to be extruded and formed is first rehydrated to a predetermined moisture content by the addition of either liquid water or steam.

After thorough mixing to insure proper moisture distribution, the mixture is conveyed into the extruder feed section where a plastic-like dough texture is initiated. In the transition section, the mixture is thoroughly worked into a dough, compressed, partially cooked by heat from external sources and internal viscous shear, and elevated in pressure. Further cooking is done in the metering zone where any remaining starch granules may be broken down due to high shear forces resulting from close tolerances between rotating screw and the barrel. The metering section also serves to maintain a constant pressure of the plastic-like dough against the die.

As the dough passes through the die, high viscous shear forces form the material and aid in producing the fibrous texture of the extrudate. The sudden release of pressure as the extrudate passes through the die permits the sudden external release or flashing off of some of the superheated vapor. The above sudden vapor pressure drop and reduction in normal forces from the die on the dough produces a "puffing" of the extrudate. Sudden contact with a lower temperature environment decreases the temperature and size of the extrudate. Continued cooling of the extrudate produces thermosetting and some drying. Additional drying is usually necessary to extend shelf life of the texturized extrudate.

Rotating knives adjacent to the die exit are used to cut the extrudate in predetermined lengths. Exposure of the exposed cross-section permits escape of superheated vapor through the exposed area.

The porosity of the expanded extrudate depends on several factors. Two of the most important of these are the combination of vapor pressure drop across the die and degree of fibrous development in the extrudate. The geometrical arrangement of the fibrous material produced from thermoplastic extrusion have been described as a pleximellar structure (Gordon, 1969). The cellular-like structure formed as the extrudate leaves the die produces irregular shaped cells or pockets of air (Gordon, 1969). Physical properties of the cellular-like extrudate are frequently referred to as texture.

Although the word texture is used frequently to partially describe the extrudate, an acceptable scientific definition based on experimental data is yet to be developed. Results of textural studies of various foods have been shown that many problems still exist in developing an adequate understanding of how to measure and describe food texture (Suter, 1976; Smith, 1976; Morrow, 1972; Szczesniak, 1972, 1969, 1963; Kramer, 1972; Abbott, 1972; Sherman, 1972). The relationship between the physical, rheological and chemical properties of extrudates produced from extrusion processing of high protein flours (usually of oilseed origin) are not known. Knowledge of the above properties and their relationships will provide a more useful basis to formulate a functional definition of texturized protein products and a means by which degree of texturization can be predicted and measured.

DEVELOPMENT OF THEORY

Development of Capillary Rheometer Governing Equations:

Recall the well known Poiseuille Flow Equation for laminar, steady-state, isothermal, constant property, Newtonian flow:

$$\tau_w (2\pi RL) = \Delta P (\pi R^2) \quad (\text{Force balance on fluid element})$$

then

$$\tau_w = \frac{\Delta P R_c}{2L_c} = \frac{\Delta P D_c}{4L_c} \quad \dots \dots \dots (\text{Equation 1})$$

$\tau_w$  = wall shear stress

Recall,

$$\Delta P = F/A = F/4\pi D_b^2$$

By substituting  $\Delta P = F/\pi D_b^2$  into Equation 1, yields:

$$\tau_w = \frac{F D_c}{\pi L_c D_b^2} \quad \dots \dots \dots (\text{Equation 2})$$

$\tau_w$  = shear stress in  $\frac{\text{dynes}}{\text{cm}^2}$

F = plunger force, dynes

$D_c$  = capillary diameter, cm

$L_c$  = capillary length, cm

$D_b$  = barrel diameter, cm

From solution of the conservation of momentum equation, we obtain for a Newtonian fluid the following relation between shear rate  $\dot{\gamma}$  and the radius r:

$$\dot{\gamma} = 4Qr/\pi R^4 \quad \dots \dots \dots (\text{Equation 3})$$

where

Q = volumetric flow rate,  $\frac{\text{cm}^3}{\text{sec}}$

$r$  = radius from capillary die centerline, cm

$R$  = capillary die radius, cm

Since both the shear rate and shear stress must be evaluated at a common geometrical point, it is only logical that  $r = R$  be chosen since  $\tau$  is known at that point ( $\tau_w$ ). Therefore, the shear rate at the wall for a Newtonian fluid is found to be:

$$\gamma_a = 4Q/\pi R^3 \quad \text{or} \quad \gamma_a = \frac{2}{15} \frac{V_{ch} D_c^2}{D_c^3}$$

where

$$V_{ch} = \text{plunger velocity, } \frac{\text{cm}}{\text{sec}}$$

Assuming no slippage at the wall, Rabinowitch (1929) has shown that every fluid shows a relationship between  $\tau_w$  and  $\gamma_a$  where  $\gamma_a$  gives the capillary wall shear rate for a Newtonian fluid and the quantity:

$$\gamma_w = \frac{3n + 1}{4n} \gamma_a$$

where

$$n = \frac{d \ln \tau_w}{d \ln \gamma_a}$$

represents the wall shear rate for any non-Newtonian fluid.

The average apparent viscosity can be determined from:

$$\eta_{AU} = \frac{\tau_w}{\gamma_a}$$

### Discussion of Errors:

The following consideration and treatment of errors was predominantly based on Ballman and Brown's work.

Plunger friction is one of the major sources of error. There is friction between the barrel wall and the O-rings. The correction for this was done through calibration drag tests in an empty barrel to determine the drag.

The error due to back-flow of fluid along the plunger was negligible. It was assumed the teflon O-rings prevented back-flow.

Errors due to fluid compressibility and viscous heat generation were assumed negligible.

It is assumed in most work that the barrel pressure drop is negligible compared to capillary pressure drop. The pressure drop equation for Newtonian materials is

$$\frac{\Delta P_b}{\Delta P_c} = \frac{L_b}{L_c} \left( \frac{D_c}{D_b} \right)^4$$

In this study, the value was 0.03 for the dimensions used and could be neglected.

Zahler and Murfit indicated that for polystyrene tested under conditions similar to those of this study that an  $\frac{L}{D} \geq 20$  resulted in negligible entrance effects. Findings of this study also indicate that observed values of viscosities from Zahler and Murfit's work were very similar in magnitude to those values obtained in this study. It was therefore hypothesized that entrance effects could be neglected.

## MATERIALS

The studies utilized defatted soy flour as the base raw material. Defatted soy flour is the most widely available and used raw material for the production of texturized proteins. Most previous research reported in the literature indicates the wide use of soy flour in vegetable protein texturization studies. The soy flour used had a final protein concentration of 60% (moisture free basis). It was obtained from the Texas A & M University Oilseed Products Laboratory.

## EXPERIMENTAL EQUIPMENT AND PROCEDURE

The capillary viscometer constructed for this study is shown in Figures 1 and 2. The barrel was 9.525 mm. in diameter and 198.12 mm. in length. The plunger was seated with a Teflon O-ring and spacer to prevent leakage between the barrel wall and plunger during extrusion.

A 3.175 mm. die of 63.5 mm. in length ( $\frac{L}{D} = 20$ ) was used for all standard experimental runs. Two additional 9.525 mm. diameter dies (25.4 mm. and 50.8 mm. in length) were used to calibrate the viscometer dies for entrance loss effects.

The viscometer barrel was heated with ten heating elements positioned along its length as indicated in Figure 2. All heating elements were controlled with variable transformers. Thermocouples were used to record temperature of the upper, middle, and lower portions of the barrel. The shear rate was controlled using a Tinus Olsen Load Machine. The applied loads were recorded using a calibrated load cell and Tinus Olsen Strip-chart Recorder.

Physical properties of the extrudate were measured and recorded on an Instron Testing Machine equipped with an Ottawa Testing Cell (six-wire grid). Moisture contents were determined by oven drying methods.

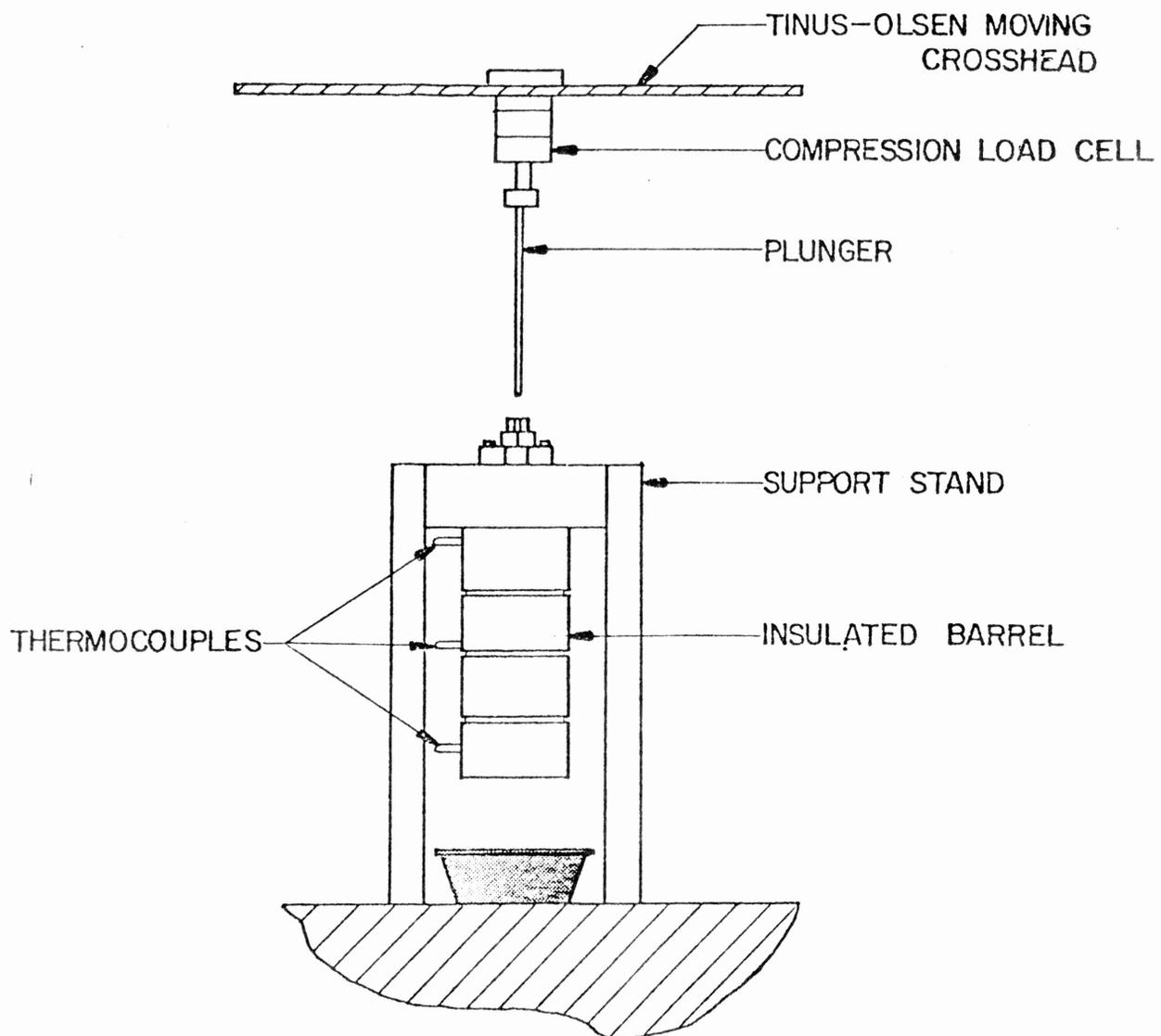


Figure 1. Schematic of Experimental Extruder.

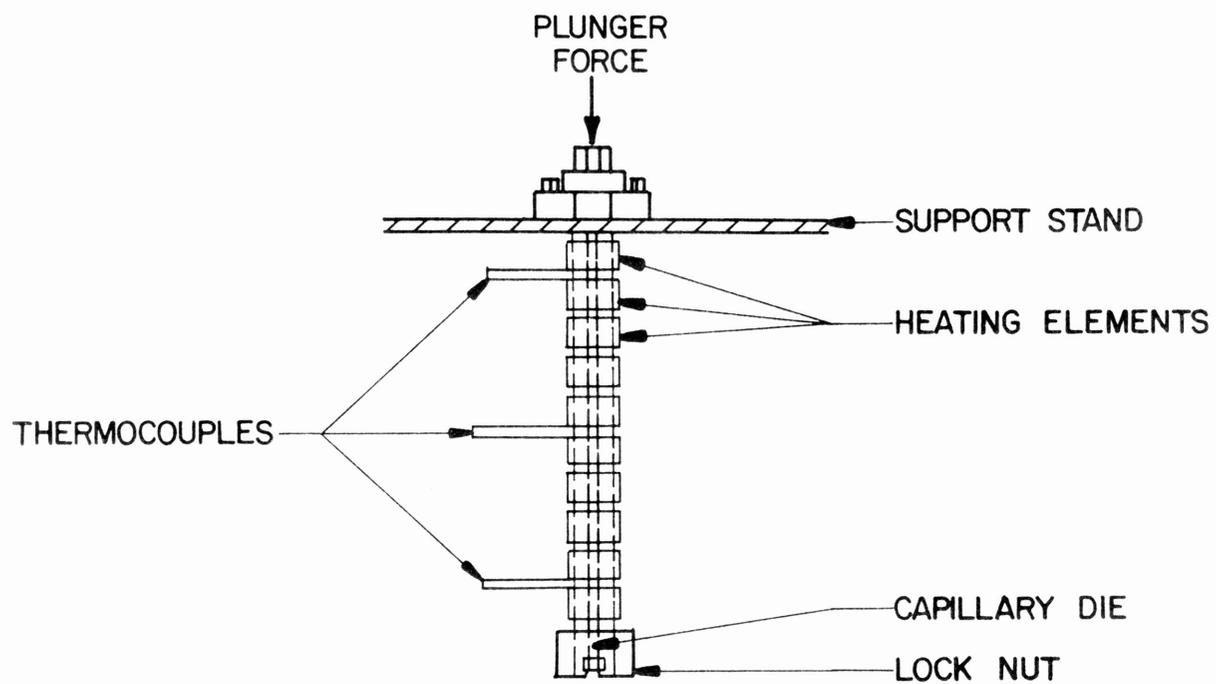


Figure 2. Capillary Rheometer Barrel and Heating Elements.

Viscometer Measurements:

The experimental design parameters selected for this study are shown in Table 1. Three replications for each combination of variables were performed. The tests were blocked because of instrumental limits. In other words three replications of the three shear rates were randomly tested for each blocked temperature-moisture content combination.

TABLE 1.  
EXPERIMENTAL DESIGN PARAMETERS

TREATMENT	LEVEL
Temperature ( $^{\circ}\text{C}$ )	162.78, 176.67, 190.56
Moisture Content (% w. b.) <sup>*</sup>	35, 40
Shear Rate ( $\text{sec}^{-1}$ )	79.5, 127.1, 196.8

(\*All moisture contents reported in this study are on a % wet basis.)

Raw material for each test was hydrated to the design moisture content using a variable speed blender. The variation in moisture content did not exceed  $\pm 1.0\%$  from the design moisture content. After mixing, the hydrated material was placed in air tight containers and stored at  $-6^{\circ}\text{C}$  until testing time. Each batch was stored for at least twenty-four hours before testing to allow it to reach an equilibrium moisture content. Approximately four hours prior to testing each batch was removed from the frozen storage chamber and allowed to reach ambient temperature. The actual moisture content was then determined from random samples of each batch.

After the material was allowed to thaw, 15 gram samples were weighed and rolled into cylinders approximately 9.000 mm. in diameter. This was necessary to facilitate rapid loading of the viscometer.

A typical test run consisted of preheating the barrel to the desired temperature. Then a 15 gram cylindrical sample was quickly

lowered into the viscometer barrel. Immediately after loading the plunger was used to compress the sample to a predetermined density ( $1.25 \frac{\text{grams}}{\text{cm}^3}$ ). The sample was allowed to cook for a given time that would result in a combined average cooking and extruding time of 50 seconds. These predetermined cooking times are given in Table 2 for each experimental shear rate.

TABLE 2.  
PREDETERMINED COOKING TIMES

SHEAR RATE	PRE-COOKING TIME	EXTRUSION TIME	AVERAGE COOKING & EXTRUDING
79.5	27 sec.	47.7 sec.	50.5 sec.
127.1	35 sec.	29.5 sec.	49.7 sec.
196.8	40 sec.	19.0 sec.	49.5 sec.

All samples were packed in air-tight containers immediately upon extrusion from the capillary die. After cooling to room temperature, the samples were re-stored at  $-6^{\circ}\text{C}$  until their use for texture and hydration measurements.

#### Texture Measurements:

Texture measurements were conducted on the samples after they were rehydrated. The samples were removed from the frozen storage chamber and allowed to reach ambient temperature. They were chopped up to a size which would allow them to pass through a No. 4 standard sieve and remain on a No. 10 standard sieve.

The samples were weighed and then placed in water and allowed to rehydrate for five minutes. The rehydrated samples were also weighed. A rehydrated sample (10 grams) was placed in the six-wire cell and placed on the Instron Testing Machine. The OTMS tests were conducted with a load rate of  $100 \frac{\text{mm.}}{\text{min.}}$  and the plunger was stopped 1.5 mm. from the bottom of the cell.

## RESULTS AND DISCUSSION

Preliminary study of plots of  $\tau_w$  versus  $\gamma_a$  indicated sample variations and experimental error that resulted in inaccurate estimation of  $\gamma_w$ . Therefore, in the following analysis,  $\gamma_a$  was used in calculating  $\eta_A$  and, therefore, all results and conclusions are subjected to the error incorporated in assuming  $\gamma_w \approx \gamma_a$ . However, comparisons made of the parameters listed in the objectives should still remain relative even though the absolute value may have considerable error due to the above assumption.

The replication means of calculated average viscosity are plotted for the design shear rates, moisture content, and temperatures in Figures 3 to 5. Figure 3 indicates for 163 degrees Centigrade, the flow index behavior coefficient,  $\underline{n}$ , for 40% and the 35% moisture content are very similar in magnitude. It should be noted here that it was assumed throughout this analysis that the extrudate during extrusion could be represented by the following power law fluid

$$\eta_{AU} = m\dot{\gamma}^{n-1}$$

where

$$m = \text{consistency coefficient, } \frac{\text{dynes} \cdot \text{sec}^n}{\text{cm}^2}$$

$n = \text{flow index behavior}$

Figure 4 indicates that at 177 degrees Centigrade, the flow index behavior appears to increase as moisture content increases from 35 to 40% m. c. Figure 5 indicates similar results at 191 degrees Centigrade with a smaller increase in  $\underline{n}$  as moisture content increased from 35 to 40%. Flow index behavior ( $n$ ) increased with an

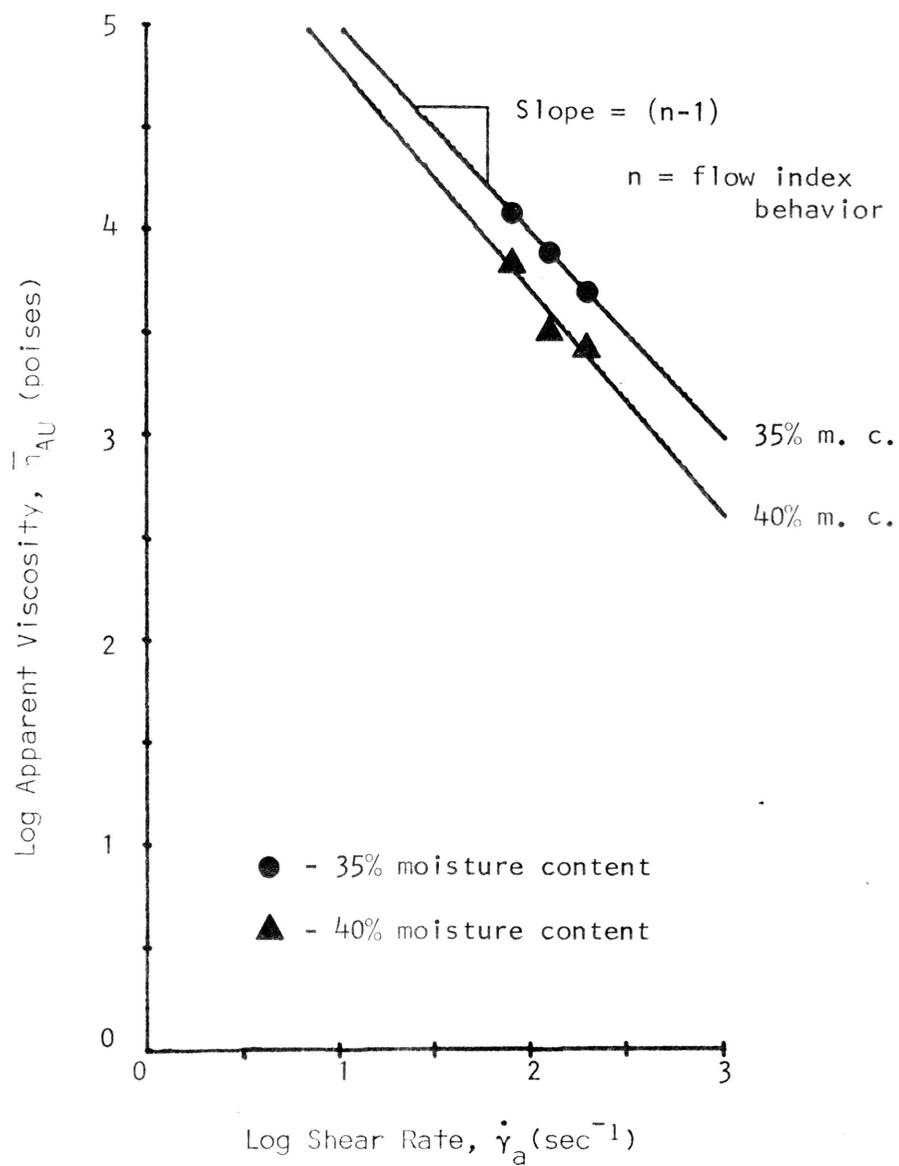


Figure 3. Relationship between apparent shear rate and apparent viscosity.

Temperature =  $163^{\circ}\text{C}$

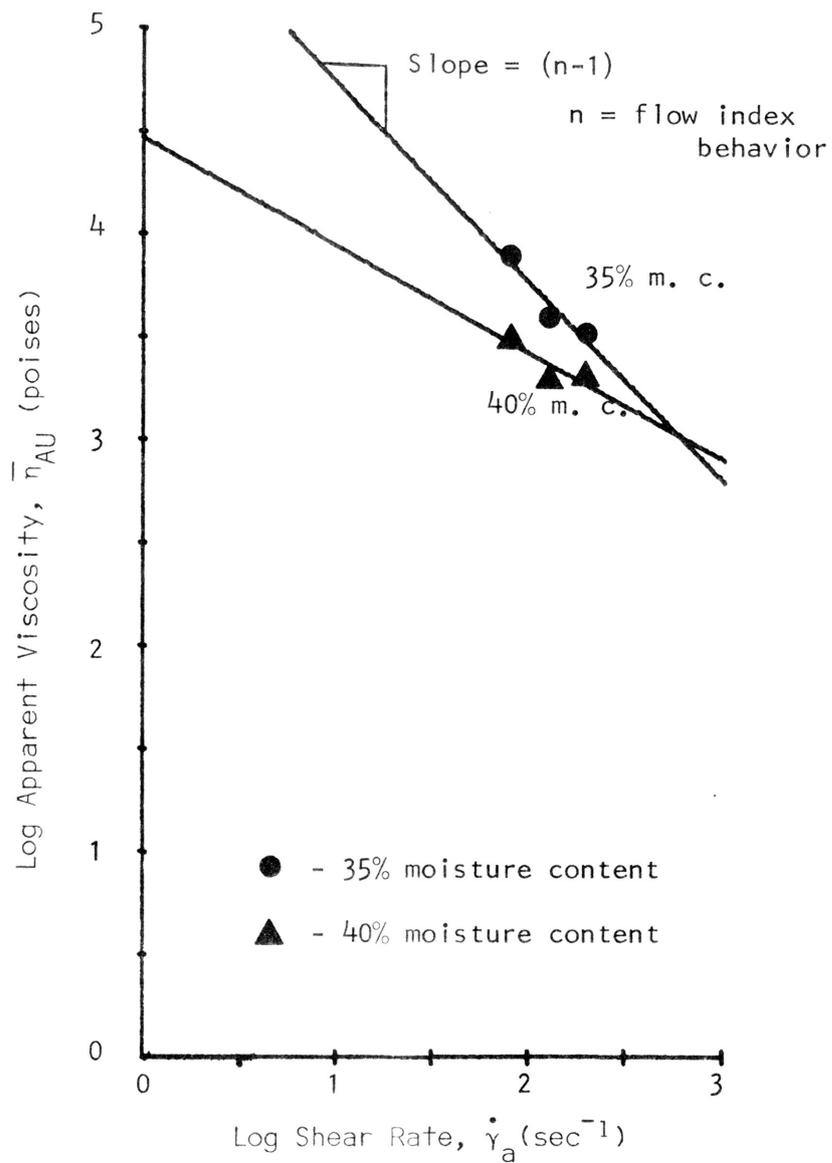


Figure 4. Relationship between apparent shear rate and apparent viscosity.

Temperature = 177° C

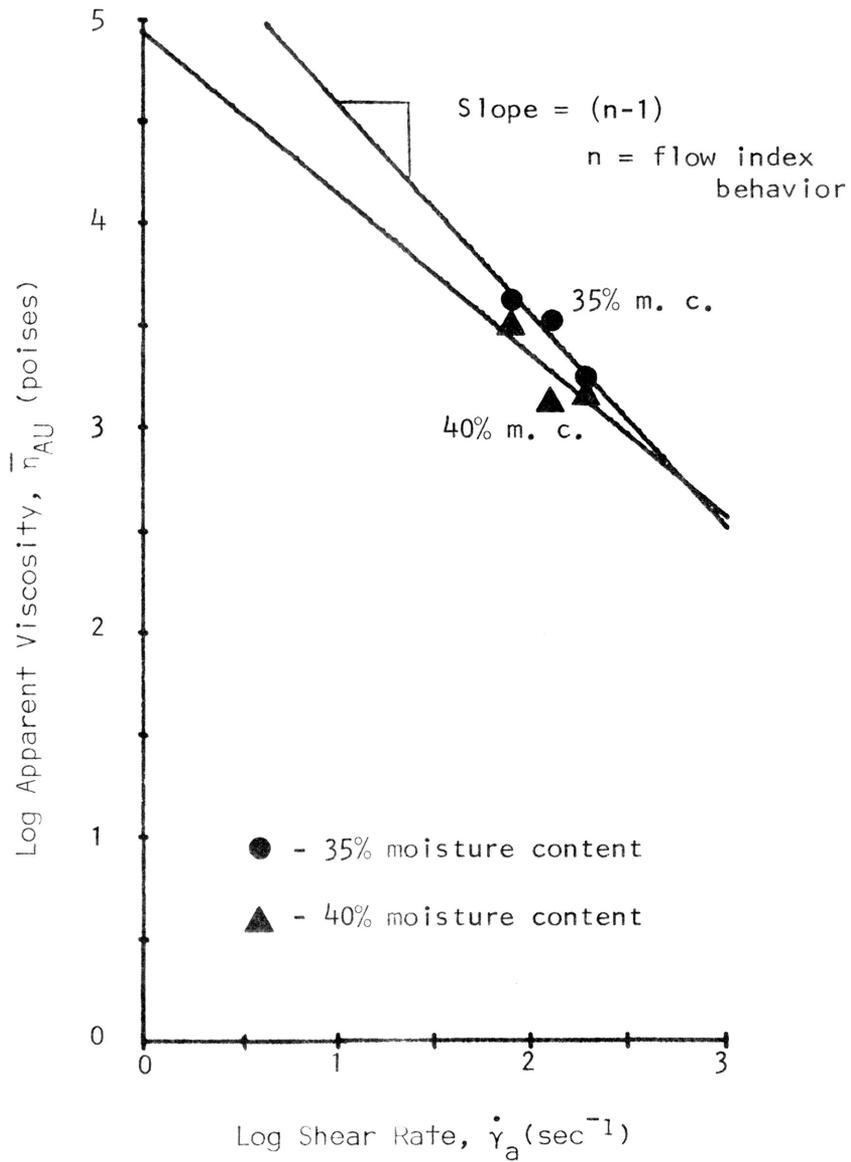


Figure 5. Relationship between apparent shear rate and apparent viscosity.

Temperature = 191° C

increase in moisture content for temperatures greater than or equal to 177 degrees Centigrade.

The well known Arrhenius equation was used to relate the activation energy,  $E_a$ , to apparent viscosity ( $\eta_{AU}$ ) by the following equation:

$$\eta_{AU} = A e^{\frac{E_a}{R} \frac{1}{T_A}}$$

where

$A$  = constant

$E_a$  = activation energy,  $\frac{\text{Kcal}}{\text{kg-mole}}$

$R$  = universal gas constant,  $1.986 \frac{\text{Kcal}}{\text{kg-mole-K}}$

$T_A$  = absolute temperature, degrees Kelvin

Figure 6 shows a plot of apparent viscosity versus  $\frac{1}{T_A}$  for both experimental moisture contents. Preliminary graphical analysis indicated that  $E_a$  was approximately the same for all shear rates in a given moisture content. Therefore, the data points in Figure 6 are averages of replications and all shear rates at that moisture content. Results of Figure 6 indicate the following activation energies:

$$E_a = 14,820 \frac{\text{Kcal}}{\text{kg-mole}} \text{ at } 35\%$$

$$E_a = 11,255 \frac{\text{Kcal}}{\text{kg-mole}} \text{ at } 40\%$$

These results indicate, as would be expected, less energy is required at higher moisture contents to result in a temperature induced viscosity change. This is probably due to the fact that the higher moisture content results in larger available amounts of

free water that undergoes a phase change to superheated vapor. Increasing moisture content from 35 to 40% reduced the apparent viscosity by 50% for temperatures ranging from 163 degrees Centigrade to 177 degrees Centigrade. At 191 degrees Centigrade, increasing the moisture content from 35 to 40% decreased the apparent viscosity by approximately 33%. As temperature increased, the effects of moisture content on viscosity appeared to decrease. Activation energy for 35% flour was 25% higher than that for 40% flour.

Results from texture measurements from the OTMS are graphically depicted in Figures 7 to 9. In this study, it was assumed that maximum force required to push a 10 gram sample through the OTMS cell was used as an index of texture. It was necessary to correct these values for rehydration amounts measured where rehydrating the samples for texture measurements. Rehydration values were calculated as the amount of water regained per unit of dry matter. The product of maximum force ( $F_m$ ) times the rehydration ratio ( $H_r$ ) is plotted against temperature in Figures 7 to 9 for both moisture contents at each shear rate. Observation indicates there are no large differences in  $F_m \cdot H_r$  due to moisture content and/or shear rate differences. This is subject to the fact that there are large experimental differences between data points in each replication. Therefore, it may not be statistically possible to establish any significance in texture due to moisture content and shear rate.

Figures 7 to 9 indicate that increasing extrusion temperature from 168 to 177 degrees Centigrade increases ( $F_m \cdot H_r$ ) by about 33%.

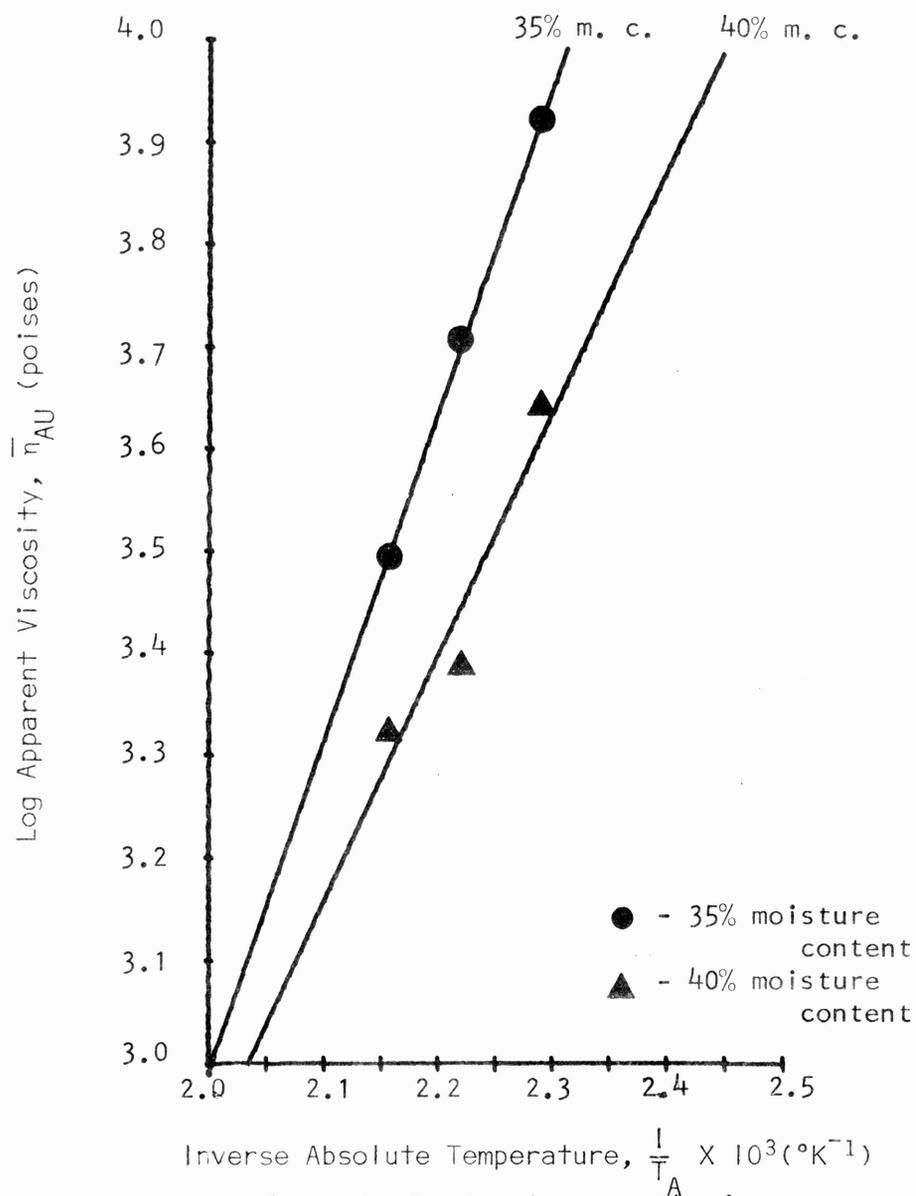


Figure 6. Relationship between the inverse of the absolute temperature and apparent viscosity.

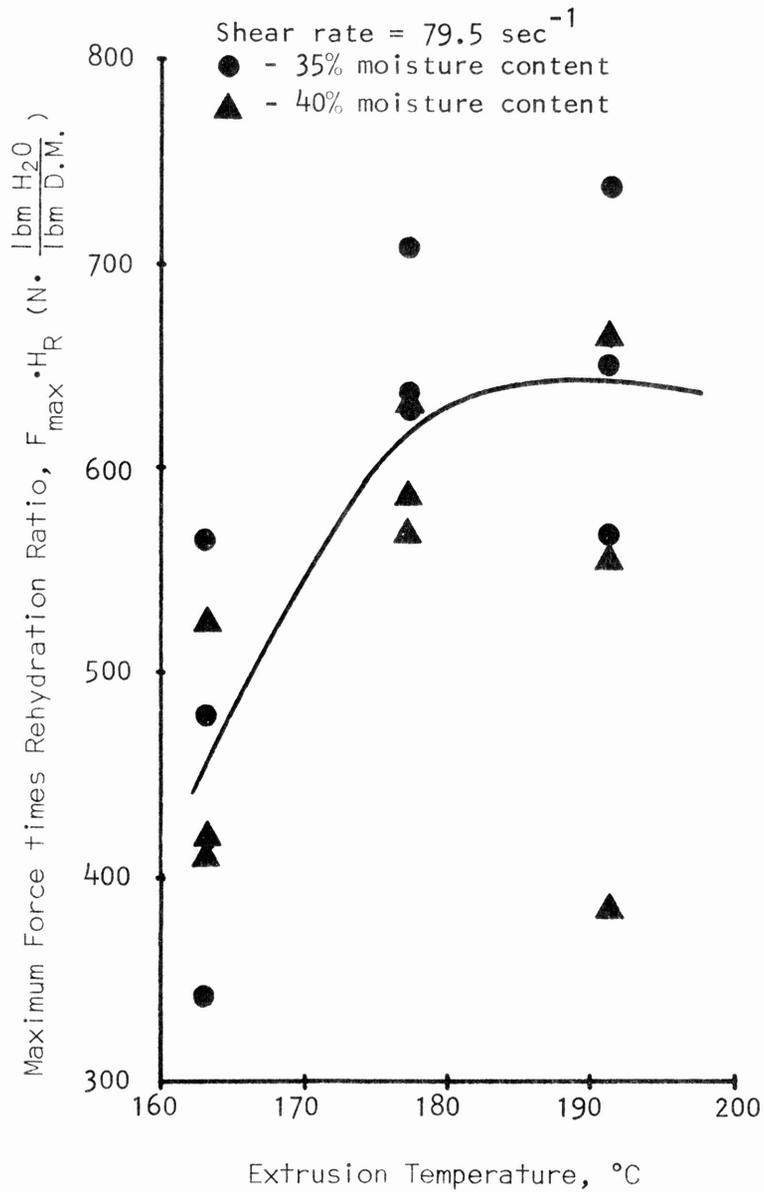


Figure 7. Relationship between the extrusion temperature and product of maximum force and hydration rate.

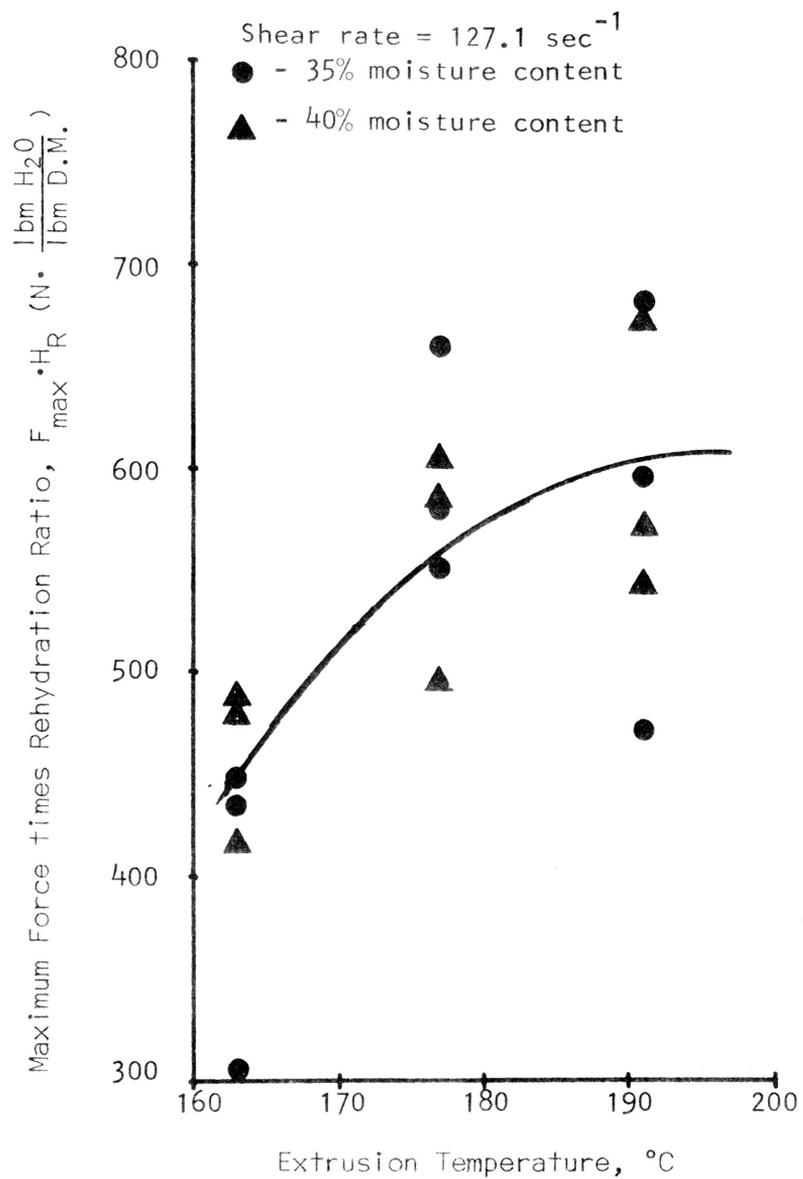


Figure 8. Relationship between the extrusion temperature and product of maximum force and hydration.

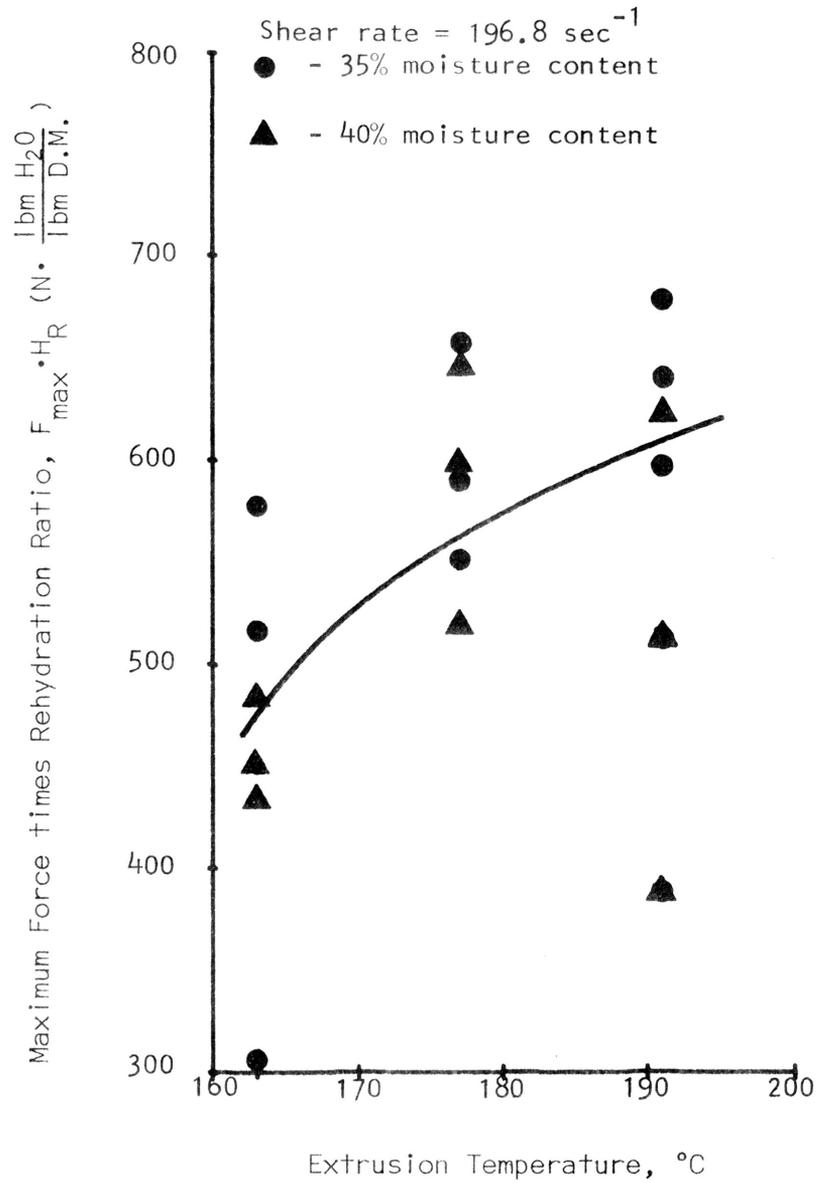


Figure 9. Relationship between the extrusion temperature and product of maximum force and hydration rate.

However, there appears to be no significant increase in texture when the extrusion temperature is increased from 177 to 191 degrees Centigrade. This corresponds with the visual appearance of extrudate at the three experimental temperatures. It was observed at 163 degrees Centigrade that extrudate appeared to be under-cooked which yielded lower texture measurements. Also, it was noted that cooking at 191 degrees Centigrade, the extrudate was over-cooked, which probably caused a denaturization in protein. It would seem from graphical data in Figures 7 to 9 and visual appearance of the samples that a temperature of 177 degrees Centigrade is approaching an optimum temperature.

#### CONCLUSIONS

It should be noted that these conclusions were based on the preceding data analysis and assumptions mentioned earlier and are, therefore, subject to the associated errors of each. Also, extreme caution should be exercised in extrapolation of data beyond the scope of this study.

Effects of moisture content on viscosity appeared to decrease with an increase in temperature. The activation energy decreased 25% with a 5% point increase in moisture content. Texture analysis and visual observation both revealed that a temperature of approximately 177 degrees Centigrade was near optimum for this extruder. Maximum force values observed in texture measurements were comparable with those observed earlier of screw extruded cottonseed meal extrudate. Viscosities observed were of relative magnitude with referenced literature for elastic polymers.

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