

DEVELOPMENT AND PERFORMANCE EVALUATION OF A SINGLE- SCREW
STARCH EXTRUDER

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DEDICATION

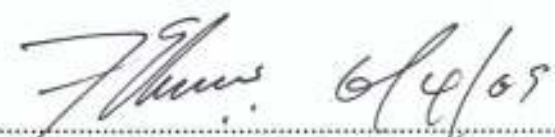
This work is dedicated to God who gives inspiration and directs the course of man's life.

CERTIFICATION

- (a) This work has not been presented elsewhere for the award of a degree, or any other purpose.

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ABSTRACT

Graveyards of unserviceable and broken down machines litter the landscape of many developing countries including Nigeria because of poor adaptation. Also, in Nigeria and other tropical countries, significant amount of locally produced agricultural materials including starch producing crops, are lost both in quality and quantity during the peak seasons due to inadequate storage and processing technology. In this study, a single screw starch extruder was designed, fabricated and tested using locally available materials as a means of arresting post harvest losses of starch based crops in Nigeria. The extruder is the dry type. It consists of a hopper, feeding screw with agitator, extruder screw rotating in a closely fitting barrel with surrounding jacket of variable flow rate for cooling, and variable die all made of stainless steel. The extruder has a capacity of 1.06 t/h, a compression ratio of approximately 4.5: 1 and is powered by a 4 kW electric motor. A unit of the machine costs ₦ 470, 390.00.00 as at April 2007. It is self cleaning and requires little maintenance.

The extruder was used to investigate the process for screw extrusion of the flour and starch of maize and cassava which are grown in Nigeria in large quantity. These were compared with wheat flour which is commonly used for the production of alimentary pastes. Response Surface Methodology, stepwise regression, correlation and Analysis of Variance were employed to a factorial experiment in completely randomized design. The effect of extrusion variables: feed moisture (25, 30, 40%), extruder temperature (40, 70, 100 °C) built up by varying the duration of sampling and screw speed (100, 150, 200 rpm) on system parameters including product temperature, mean residence time (MRT), torque, specific mechanical energy input (SME) and product quality attributes, that is water absorption index (WAI) and water solubility index (WSI), product moisture, transverse expansion, melt viscosity, cold and hot paste viscosity and strength properties of extrudates were studied. A maximum temperature of 150 °C/30 minutes was attained through viscous dissipation and up to a moisture loss of 55% w.b.

An increase in temperature and screw speed increased transverse expansion and WAI up to a critical value of 6.46 g/g above which it decreased. The melt viscosity reduced with an increase in moisture content and temperature. The extrudates' moisture loss is directly proportional with expansion. Increasing feed moisture content caused a decrease in transverse

expansion and increase in extrudate moisture content. A high temperature process produced extrudates with low moisture content.

Cold paste viscosity decreased when moisture decreased and temperature increased. An increase in moisture content of maize starch decreased the transverse expansion and the WSI, but increased the WAI and hot paste viscosity. Also, an increase in moisture content decreased the gelatinization of cassava starch and maize flour than that of wheat flour. SME decreased with increasing moisture content and a lower product temperature.

The equations relating the various dependent and independent variables were established to predict the performance of the machine and the quality of the products. Generally, the response surface study revealed the range of the extrusion variables for optimum performance. Quadratic coefficients (0.61- 0.86) fitted the extrusion data very well, better than linear models.

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INTRODUCTION

1.1 GENERAL INTRODUCTION

The problem of widespread food insecurity is one of the most serious challenges that face the world with about 840 million under - nourished people (Adetunji, 2004). A number of policies and strategies are being initiated to effectively tackle the problem. Current thought in developing economies is that economic growth and food security can be accelerated if attention is focused on issues of integrated rural development, regarding farm production, agro- industries, facilitating services and marketing of inputs and outputs (Afonja, 1998). In view of this and in a bid to ensure food security for the populace, the rural agricultural sector has received considerable attention from the Nigeria Government in recent times. As a result, the production of tropical crops such as cocoa, cassava, soybeans, corn, oil palm, and cowpea has increased tremendously (Balogun, 2000).

Cassava (Manihot esculenta, Crantz) and maize (Zea mays) are important starch-rich crops that contribute to economic development and food security, most especially in low income food deficient countries because of their inherent characteristics. Cassava tolerates environmental stresses such as short periods of drought, strong and dry winds and low soil fertility (Balogun, 2000). Its cultivation does not involve complicated technology, high labour or other inputs. Cassava is particularly suited to small farm production systems due to it's extremely undemanding nature and its tolerance of a variety of climatic and soil conditions on the farm. Maize, another popular staple food plays an important role in the diet of millions of people because of dry matter per hectare, its ease of cultivation, versatile food uses and storage characteristics (Asiedu, 1990). Nigeria is rated to be one of the largest producers of cassava and maize, producing more than 34 million and 7019 metric tonnes of cassava and maize annually respectively (Adetunji, 2004; CBN, 2003).

In recent times, the Nigerian government at the Federal, State and Local levels gave considerable attention to the mass production of cassava amongst other crops. Improved varieties of cassava, when grown with modern technology could yield about 40-60 tonnes per hectare on most southern part of Nigeria (Atser, 2004). However, a high percentage of the crop is lost because developments in food processing or post- harvest activities could

not keep pace with the rate of increase in food production (Adetunji, 2004; Adelaja, 2004). Also, we are living in the world of wheat. There is wheat bread, wheat ogi, and wheat amala. In fact many processed snack foods and confectionary are made from wheat. Wheat is a useful staple food but its production in Nigeria is very expensive and low. Although starches have a multitude of applications, the experience in Nigeria has proved that starchy crops are only readily accepted for food (RAIDS, 2000).

1.2 ECONOMIC IMPORTANCE OF STARCH

Starch is a carbohydrate, a certain amount of which is necessary in the diet since it provides energy and has a protein sparing function. Table 1.1 lists some functions of starches and application in food.

Table 1. 1: Functions of starches and applications in human food.

Functions	Application
Adhesion	Breaded products
Binding	Formed meats, extruded foods
Clouding	Cream filling, drinks
Dusting	Bread, gum
Flowing aid	10X sugar, baking powder
Foam strengthening	Marshmallows, drinks
Anti-staling	Bakery products
Gelling	Gum drops, pudding
Glazing	Nuts
Moisture retention	Breading
Moulding	Gum drops
Shaping	Meat products, pet foods
Stabilizing	Beverages, salad dressing
Thickening	Gravies, pie fillings, soups

Source: Ihekoronye and Ngoddy (1985)

In the textile industry, starches are employed for sizing yarns preparatory to weaving, for finishing cloth and for printing fabrics with printing pastes made from starch and dye. In paper manufacture, starch has several important functions. When added to pulp in the beaters they assist in the hydration of the fibres. In the paper forming operation, they cause

the fibres to adhere more closely, producing a paper with finer texture and smoother surface. White dextrins, a product of starch finds application as binders in pharmaceutical industries for tableting due to their inertness and stability.

Cassava, maize and wheat are some of the starch producing crops that have high utilization potentials. The starch contained in these crops have multitude of application and market potential in food, paper, textiles, adhesives, pharmaceutical, rubber, wood, brewery, tanning and tobacco industries. In Nigeria and West Africa, starches from cereals, roots and tubers are used as a staple food in the diet of the people. Even those who can afford any food they wish, in practice depend largely upon foods rich in carbohydrate for the supply of their energy. Syrup made from corn starch is used for the most part in confectionary and in table syrup.

1.3. NEED FOR ALTERNATIVE PROCESSING TECHNOLOGY OF CROPS.

Processing is a major area of concern in post harvest technology. There is the need for proper processing to improve the economic value of agricultural produce after harvest and storage, promote the shelf life of the products and also attract both domestic and international market. With proper processing of produce, more income will accrue to farmers thereby resulting in making agriculture a viable economic venture. Also, there will be reduction in the wastage of food crops after harvesting and checking of seasonal fluctuation in food prices. Consequently, food price will be stabilized for both consumer and farmer, thus serving as booster to the farmer towards increased production for better income and improved living standard. Also there will be availability of raw material to manufacturing industries at the time they are required. Moreover, starchy crops need some transformation for human consumption and to satisfy their crave for new and different foods. One of the means to arrest post harvest losses is the expansion of the processing technology. Commercial food processing that utilizes the agro-raw material of the common staples needs to be advanced to a significant degree. Food processing technology, which would maximize the use and economic values of local agricultural product, are available and could be adopted. Food process consists of several steps. The raw materials are received, inspected, cleaned, graded, separated, cut-up or ground, mixed with other food ingredients and additives/preservatives, formed with the desired shapes and size and packaged. Depending on the source of starch and its desired product, a number of methods may be employed. Among these are peeling, cleaning and washing, soaking/steeping,

grating, preconditioning, devolatilisation, drying, milling, fermentation, boiling, roasting, frying, baking and most recently extrusion. A schematic diagram of the unit operations in food processing is shown in Figure 1.1 (Ihekoronye, 1998).

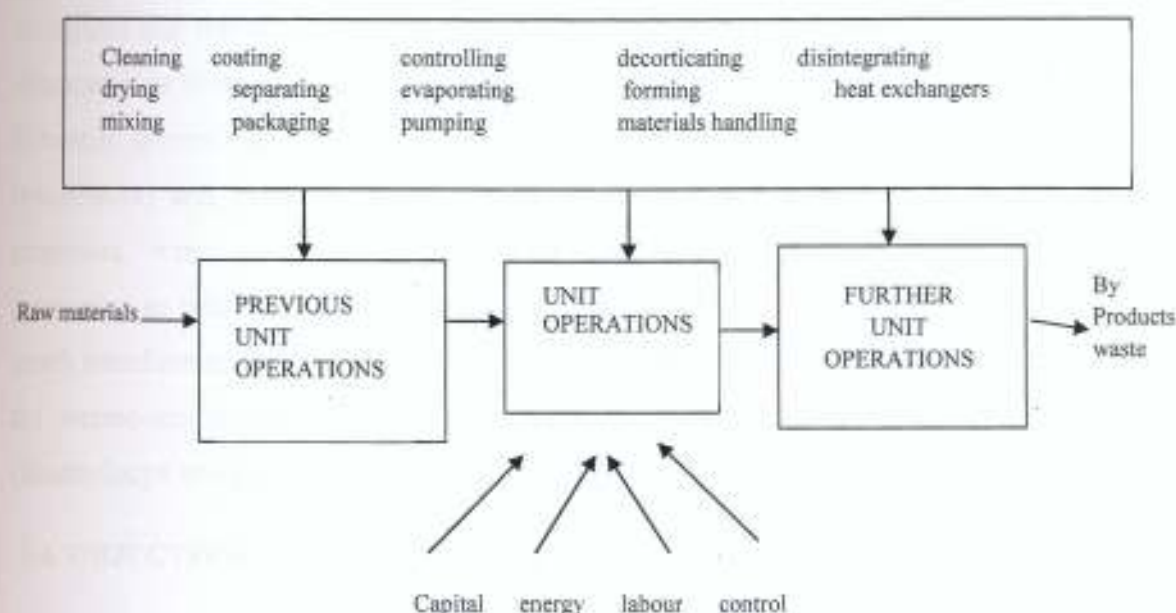


Figure 1.1: Unit operations in food processing (Ihekoronye, 1998).

Extrusion is a food processing operation that can increase the usefulness of starchy crops by producing a range of products with different shapes, nutrients, texture, colours, sizes, flavour etc, thereby increasing the varieties of food products in the diet. Also, with this expansion of the alternative processing options for cassava, sustainable production would be ensured and post harvest losses minimized. Cassava and maize have high potentials for producing extruded foods. Also, it is obvious that the majority of processed foods being consumed presently in Nigeria are made from wheat using imported machines, yet, efficient and increased processing could be achieved by developing an indigenous extruder (Ademosun, 1997). Wheat flour has been widely used in the extrusion industry and the effects of process variables on wheat extrudate properties have been reported (Frame, 1994). Meanwhile, it is obvious that cassava as a crop is not popular for the production of extruded foods. Maize is one of the most common types of starch used for extrusion on which a lot of research work has been done but not in the developing nations where it is grown in large quantity.

When processed by extrusion, any raw material (e.g flour) is transformed into a continuous phase by the application of heat and shear (Ding *et al.*, 2006). Also, starch has reaction behaviour under the influence of a set of extrusion conditions with different machines. Food products are required to have specific properties e.g. crispness, strength brittleness, stringiness and fracturability (Van Den Einde *et al.*, 2003). In order to obtain the required characteristics in an extrudate, a range of values of extrusion parameters must be attained. Extrusion system variables (torque, specific mechanical energy, die pressure and product temperature) and extrudate characteristics (degree of expansion, shear strength, pasting properties, water absorption index, water solubility index, and color) are important parameters as well as indicators of extrusion processes (Hsieh *et al.*, 1997). Understanding starch transformation as a function of process parameters bear potential for optimization of the thermo-mechanical processes and this can lead to the desired product properties (Bhattacharya and Hanna 1987; Lo *et al.*, 1998a).

1.4. OBJECTIVES OF THE PROJECT

1.4.1 The Aim of the Research

The aim of the research is to design, fabricate and evaluate the performance of an equipment for screw extrusion of starch from cassava, maize and wheat.

1.4.2. Specific Objectives of the Research

The specific objectives are to:

- i. design and fabricate a single screw extruder as a test rig for evaluation of starch from maize, cassava and wheat;
- ii. evaluate the performance of the extruder from system parameters and efficiency.
- iii. characterize the product quality attributes of extrudates of the selected crops from the extruder
- iv. establish relationships between product quality attributes and extrusion performance characteristics of the three extrudates.

1.5. JUSTIFICATION OF THE STUDY

Research in starch extrusion is highly relevant to the developing countries because starches from cereals, roots and tubers are used as a staple food in the diet of the people. (Ihekoronye and Ngoddy, 1985). Therefore a research into food extrusion is justified because

- The starch diet will be improved upon by fortifying it with essential components of a balanced diet.
- There will be improved quality and lower cost of production due to more efficient use of energy and greater process control, with great production capacities (Harper, 1979).
- The high production values of starchy crops in Nigeria justify the need for the expansion of their alternative processing options, among which food extrusion is one.
- Through this project, there will be nutritionally improved diet and expansion of the alternative processing options for Cassava and Corn and aversion of their post harvest losses. Subsequently, market will be created and increased earned income of farmers will serve as incentive for sustained production. Also, there will be job creation thereby alleviating poverty of the end-users i.e the local farmers, processors and equipment fabricators.
- Although extrusion comes in a variety of sizes, shapes and methods of operation yet, getting the type that suits the local condition in terms of technological know-how and availability of spare parts for easy maintenance required detailed study and design to suit local conditions, thus preventing high initial costs and poor adaptation of imported machines.
- Need for improvement of local diets from locally available nutritional food materials (Osundahunsi et al, 2002), more so because of the recent ban on importation of goods by the Federal Government of Nigeria. Many highly demanded extrusion fabricated foods such as noodles, spaghetti etc. are produced from wheat, which is very expensive to cultivate in Nigeria. Substituting cassava for wheat (more so, as a government's policy) will reduce cost.

- The constantly changing raw materials (improved varieties of starchy crops) make for continual modification of extrusion condition environment and require continual modification of extrusion conditions to maintain desired product qualities.
- Moreover, the data generated from the study may be used on the design, selection of extruder and promote further research on extrusion technology locally, since it is very obvious that only a few literature are available locally on food extrusion technology.

1.6. EXPECTED CONTRIBUTION OF THE RESEARCH TO KNOWLEDGE

The research is expected to:

- i. provide a test rig which will be useful in further research and training;
- ii. facilitate the development of an indigenous starch extruder adaptable to local conditions;
- iii. provide database on extrusion of selected foodstuffs which may be of benefit in food science technology; and
- iv. establish statistical models for predicting the effect of extrusion process on different system parameters and product quality attributes of the crops.

LITERATURE REVIEW

2.1 SOURCE AND CHEMISTRY OF STARCH

Starch is a polysaccharide that occurs in the organs of plants. Indeed it is the second most abundant compound synthesized by plants (cellulose being the first) and is found in a granular form during dormancy, growth or germination (Birch *et al.*, 1997; Woods and Swinton, 1990). The size and shape of starch granules vary according to the source of the starch. Commercial sources of starch are usually the storage organs of plants such as the seeds of pulses and cereals grains (rice, corn, wheat, sorghum, and millet), roots (cassava), tubers (potatoes, yams), stems (sago palm). Unripe fruits contain appreciable amount of starch which is converted to glucose as the fruit ripens.

The preliminary refining of starch involves physical processes in which the starch is obtained in suspension free from other matters such as fibres, proteins and sugars and usually has purity in the region of 99%. Most starches contain two types of glucose polymer joined together to form spiral chains: (1) a mainly linear molecule consisting of glucose residues linked α -1, 4 called amylose and; (2) a branched polymer which in addition, contains α -1, 6 branch-points, called amylopectin. These two functions occur in different proportion in starches from different sources and contribute to their different physical and chemical properties. In general, amylose is the smaller proportion, constituting 15 – 20% of most common starch although, in the case of the specially bred waxy starches in amylose is present. At the other extreme, amylo-maize starch contains from 50 – 80% amylose according to the variety (Ihekonroye and Ngoddy, 1985).

Starch is synthesized in plants from sugar formed from water and carbon dioxide during photosynthesis. Starch granules are formed around a central nucleus formed by the deposition of a small amount of insoluble material. As material is added to the nucleus, the shape is first spherical but may then become flattened or elongated. Starch granules are insoluble in water at temperature below 60°C. Above this temperature, the granules start to absorb water and swell thereby attaining a colloidal dispersion. This colloidal dispersion of starch is its most important function. The temperature at which starch granules begin to swell rapidly is called the gelatinization temperature. The gelatinization temperature (range)

is distinctive for different types of starches (Table 2.1). The gelatinization of starch is very important in cooking.

Table 2.1: Gelatinization temperature ranges of various food starches

Source	Gelatinization temperature °C
Corn	62 – 72
Sorghum	68 – 78
Potato	58 – 66
Cassava	52 – 64
Rice	68 – 78
Wheat	59.2 – 64

Source: Ihekoronye and Ngoddy (1985); Van Zulichem and Stolp (1987)

Starch pastes are widely used in the food industry, textile, pharmacology, paper industries just to mention a few. Also, starchy crops can vary greatly due to genetic make-up, growing conditions, storage conditions and other reasons (Whistler *et al.*, 1984).

2.2 GLOBAL PRODUCTION OF CASSAVA, MAIZE AND WHEAT.

2.2.1 Cassava

Cassava (*Manihot esculenta*, Crantz) was introduced into Central Africa from South America in the 16th century by the early Portuguese only to become one of the dominant starchy staples in the diet of the people. The emancipated slaves, returning from South America via the islands of Sao Tome and Fernando Po must have introduced cassava into Southern Nigeria, (Balogun, 2000). Cassava however did not become important in the country until the end of the 19th century when processing techniques were introduced, as many more slaves returned home. As a food crop, cassava has some inherent characteristics which make it attractive especially to, the small holder farmers in Nigeria. First, it is rich in carbohydrates especially starch and consequently has a multiplicity of end-uses. Secondly, it is available all year round, making it preferable to other more seasonal crops such as grains, peas and beans and other crops for food security. Compared to grains, cassava is more tolerant to low soil fertility, and more resistant to drought, pest and diseases. More importantly too, the roots of cassava are storable in the ground for months after they are mature. Cassava tolerates environmental stresses such as, short periods of drought, strong and desiccating winds and low soil fertility (Balogun, 2000). Its cultivation does not

involve complicated technology, high labour or other inputs. Cassava is particularly suited to small farm production systems due to its extremely undemanding nature, its tolerance of a variety of climatic and soil conditions on the farm.

In the early years of Nigeria's independence, agriculture accounted for nearly 60 percent of Gross Domestic Product (GDP) and 80 percent of export earnings (Shaib *et al.*, 1997). Today agriculture accounts for a third of GDP and less than one percent of export earnings, oil accounting for the rest. Although room exists for Nigeria to prosper, the country continues to face a number of challenges. Policies to date are yet to diversify the productive base away from the continued reliance on a single industry, petroleum. There is underutilization of industrial capacity, high unemployment and political anxiety. A desirable outcome for the Nigerian current government is a strong diversified economy which is able to generate employment and sustain incomes for its citizens. Increasing the productivity of agriculture, increasing the utilization of industrial capacity, diversifying export earnings and providing gainful employment for its population are all desirable targets. To achieve this, President Olusegun Obasanjo in 1999, pledged to support the agricultural sector and announced the need for immediate action in five agricultural subsectors: cassava, rice, vegetable oils, livestock and tree crops.

The cassava initiative alone seeks to generate US\$5 billion in export revenue by 2007. Since its launch in July 2002, great excitement has been generated, creating new hopes and even greater expectations. Comparing the output of various crops in Nigeria, cassava production ranks first in yield, followed by yam production at 27 million tonnes in 2002, sorghum at 7 million tonnes, millet at 6 million tonnes and rice at 5 million tonnes (FAO, 2004). Expansion of cassava production has been relatively steady since 1980 with an increase between the years 1988 to 1992 owing to the release of improved IITA varieties.

Nigerian cassava production is by far the largest in the world, producing more than 34 million tonnes of cassava annually (Adetunji, 2004), a third more than production in Brazil and almost double the production of Indonesia and Thailand. Cassava production in other African countries, the Democratic Republic of the Congo, Ghana, Madagascar, Mozambique, Tanzania and Uganda appears small in comparison to Nigeria's substantial output. The cassava revolution in Nigeria is at its infancy. In fact, improved varieties of cassava, when grown with modern technology could produce a yield of about 40-60 tonnes per hectare in most of the Southern part of Nigeria (Atser, 2004). Cassava is a very versatile

commodity with numerous uses and by products. Each component of the plant can be valuable to its cultivator. The leaves may be consumed as a vegetable, or cooked as a soup ingredient or dried and fed to livestock as a protein feed supplement. The stem is used for plant propagation and grafting. The roots are typically processed for human and industrial consumption. Meanwhile, it is obvious that cassava as a crop is not popular for production of extruded foods.

In Nigeria, the consumption pattern varies according to ecological zones. Gari, a roasted granule from cassava, is the dominant product and is widely accepted in both rural and urban areas. It can be consumed without any additives with a variety of additives such as sugar, groundnut, fish, meat and stew. *Fufu* and *Akpu*, a fermented wet paste from cassava is also widely consumed throughout the country especially in the Southern zones. Most processors however complain that the wet paste and ready to eat forms of *fufu*, have a very short shelf life.

Estimates of industrial cassava use, suggest that approximately 16 percent of cassava root production was utilized as an industrial raw material in 2001 in Nigeria. Ten percent of this was used as chips in animal feed, 5 percent was processed into a syrup concentrate for soft drinks and less than one percent was processed into high quality cassava flour used in biscuits and confectionary, dextrin pre-gelled starch for adhesives, starch and hydrolysates for pharmaceuticals, and seasonings (Kormawa and Akoroda, 2003). This estimate leaves 84 percent or 28.9 million tonnes of production for food consumption, a portion of this of course being lost in post harvest activities. A high percentage of the crops is lost because developments in food processing or post harvest activities could not keep pace with the rate of increase in food production (Adetunji, 2004; Adelaja, 2004).

Cassava processing operations in Nigeria can be described at 5 levels of capacity (FAO, 2004). The common terms used to describe these capacity levels are household (or cottage), micro, small, medium and large. One of the means to arrest post harvest losses is the expansion of the alternative processing technology of crops. Cassava being a starch rich crop, has high potentials for production of extruded foods.

2.2.2 Maize

Maize, the American Indian word for corn, means literally "that which sustains life". It is, after wheat and rice, the most important cereal grain in the world, providing nutrients for

humans and animals and serving as a basic raw material for the production of starch, oil and protein, alcoholic beverages, food sweeteners and, more recently, fuel. Maize plays an important role in the diet of millions of people because of the dry matter per hectare its ease of cultivation, versatile food uses and storage characteristics (Asiedu, 1992). Maize in its different processed forms is an important food for a large number of people in the developing world, providing a significant amount of nutrients, in particular calories and protein. Its nutritional quality is particularly important for small children. The green plant, made into silage, has been used with much success in the dairy and beef industries. After harvest of the grain, the dried leaves and upper part, including the flowers, are still used today to provide relatively good forage for ruminant animals owned by many small farmers in developing countries. The erect stalks, which in some varieties are strong, have been used as long-lasting fences and walls.

Botanically, maize (*Zea mays*) belongs to the grass family (*Gramineae*). Special crops grown primarily for food include sweet corn and popcorn, although dent, starchy or floury and flint maize are also widely used as food. Flint maize is also used as feed. Immature ordinary corn on the cob either boiled or roasted is widely consumed. Floury maize is a grain with a soft endosperm much used as food in Mexico, Guatemala and the Andean countries. The dent type of maize has a vitreous horny endosperm at the sides and back of the kernel, while the central core is soft. Flint kernels have a thick, hard and vitreous endosperm surrounding a small, granular, starchy centre.

World maize production is on the increase. The increase resulted from additional land area planted, significant increases in production resulted from genetic improvement and more efficient technological field practices and fertilizer applications, as well as from the introduction of new, more highly reproductive varieties (FAO 1992). Maize is used for three main purposes: as a staple human food, particularly in the tropics; as feed for livestock; and as a raw material for many industrial products. Nigeria produces more than 7019 metric tonnes of maize annually (CBN, 2003). It is widely used in Nigeria and other West African countries as food for man and livestock. Fresh, unripe maize is eaten, roasted or boiled on the cob and it is exceedingly popular in this form (FAO 1992). The ripe, dried grains are cooked in combination with pulses, with oil and condiments added and eaten as "adalu". The dried grains are also milled, made into gruel and hard boiled (wrapped in leaves) as "eko" or boiled at a lower temperature as palp. Maize is processed by several

mechanical methods into a variety of foods and industrial products. For example, about 3% of the annual production is processed by the dry – milling industry into breakfast foods, corn meal and fibre for human food and for making fermented malt liquors. More than 4% is processed by the wet corn milling industry into starch, maize germ, and maize gluten. Starch produced are used as such or converted into various adhesives and sizings, particularly for paper and textiles (FAO 1992). The germ is processed for oil and meal.

Maize is also a popular and widely - used feed for all classes of domestic animals including poultry (Asiedu, 1992). Mixed with the residual cake from groundnuts and/or palm kernel, maize offers one of the most valuable source of carbohydrate feed for animals. The grains of locally - grown maize contains about 10% protein, although the crop varies widely in its protein content, the amount present being influenced by many factors including soil conditions, rainfall, location, varieties and earliness or lateness of maturity.

Significant maize losses have been reported in tropical countries. Losses of up to 10 percent have been found, not including those losses caused by fungi, insects or rodents (Igbeka, 2003). If these were included, losses could go up to 30 percent in tropical humid areas or 10 to 15 percent in temperate areas. Maize has high potentials for production of extruded foods thereby increasing the varieties of food in the diet. Maize is one of the most common types of starch used for extrusion on which a lot of research work has been done but not in the developing nations where it is grown in large quantity. It is the most widespread cereals used for snack products (Frame, 1994). Corn is the primary ingredient for corn collects (both baked and fried), onion rings and many pellet products. It is used because of its low cost and it expands well even from the simplest of extruders.

2.2.3 Wheat

Wheat has been grown throughout temperate regions of the world since prehistoric times (McCammon, 2007). It is a member of the family Poaceae (formerly Gramineae). It makes up the genus *Triticum aestivum*. Although wheat's primary use is as a flour, it is also used in brewing and distilling, as livestock feed, and even as a coffee substitute. The former Soviet Union, China, and the United States lead the world in the production of wheat. It ranks highest of the three major cereals of world production, others being maize and rice (Guy, 2001). Maize and rice flours are generally richer in starch than wheat flour due to the lower protein and fibre levels.

Types of wheat are chosen for their adaptability to altitude, climate, and yield. The common wheats grown in the former Soviet republics, the United States, and Canada are spring and winter wheats, planted either in the spring for summer harvest or in the fall for spring harvest. The color of the grain varies from one type to another; white wheats are mostly winter wheats, red are spring wheats. Closely related to the common wheats are the club wheats, which have especially compact spikes, and spelta (not grown in the United States), in which the glumes (reduced, scale like leaves) tightly enclose the grains. Durum wheat (Latin *durum*, "hard") is so called because of the hardness of the grain. It is grown in north-central regions of the United States. New high-yielding wheat were developed in the 1960s for use in developing countries, and research on them continued in the 1970s. Experimental programs have produced commercial wheat varieties for hardness and disease resistance. Wheat flour has been widely used in the extrusion industry and the effects of process variables on wheat extrudate properties have been studied (Frame, 1994).

The main use of wheat is in the manufacture of flour for bread and pastries. In general, hard varieties are used for bread flour and soft varieties for pastry flour. The hard varieties usually have a strong bond between the starch granules and the protein layers. This forms a hard particle of flour that requires more energy to breakdown and will create more heat in the extruder. The soft variety has their starch granules and protein layer loosely bond together and the endosperm is broken down easily. Hence, they require less mechanical energy to process. Wheat is used also in the production of breakfast foods and to a limited extent in the making of beer, whiskey, and industrial alcohol. Low grades of wheat, and by-products of the flour-milling, brewing, and distilling industries, are used as feed for livestock. A minor amount of wheat is used as a coffee substitute, especially in Europe, and wheat starch is employed as a sizing for textile fabrics.

Wheat is not normally used for expanded products except in small amount. Wheat is more difficult to expand due to gluten and protein. It has used more in the fabricated and pellet types of products. However, it can be used for expanded products with twin-screw extruders. Soft springs wheat, with lower gluten levels, will give a more tender expanded product than with semolina or hard winter wheat's. Products made from wheat have an ivory color and a nutty flavor. According to Ding *et al.* (2006), Wheat flour requires high temperature to achieve a significant expansion and reduced density during extrusion cooking. Although wheat is a useful food staple, its production in Nigeria is very low and expensive (CBN, 2003).

2.3. MODIFICATIONS OF STARCH

2.3.1 Native starches

Starch can be classified into two types: native and modified. Native starches are produced through the separation of naturally occurring starch from either grain or root crops such as cassava, maize, and sweet potato, and can be directly used in producing certain foods such as noodles. The raw starches produced still retain the original structure and are called "native starches". Native starch is the basic starch product that is marketed in the dry powder form under different grades for food, and as pharmaceutical, human, and industrial raw material. Native starch has different functional properties depending on the crop source, and specific types of starch are preferred for certain applications. Native starch can be considered a primary resource that can be processed into a range of starch products.

Native starches have limited usage, mainly in the food industry, because they lack certain desired functional properties. The native starch granules hydrate easily when heated in water, they swell and gelatinize; the viscosity increases to a peak value, followed by a rapid decrease, yielding weak- boiled, stringy, and cohesive pastes of poor stability, with low resistance to shear pressure, as commonly employed in modern food processing. However, food, metallurgic, mining, fermentation, construction, cosmetic, pharmaceutical, paper and cardboard, and textiles industries among others use.

2.3.2 Modified starches

For those characteristics, which are unattainable with native starch, modified starch can be used for other industrial application through a series of techniques, chemical, physical, and enzymatic modification. Thus, modified starch is native starch that has been changed in its physical and /or chemical properties. Modifications may involve altering the form of the granule or changing the shape and composition of the constituent amylose and amylopectin molecules. Modifications are therefore carried out on the native properties needed for specific uses. When a starch is modified chemically or physically, the properties of the native starch is altered. Various modifications give the starch properties that make it useful in the industries such as food, pharmaceutical, textile, petroleum, and paper pulp industries. The more commonly utilized modification of starch for food industry are hydrolysis, oxidation, cross-linking, substitution. These can be utilized individually or in combination to offer the wide

range of functional characteristics required by today's diversified processed foods (International Starch Institute, 2005).

The different ways of modifying native starch consist in altering one or more of the following properties: paste temperature, solids/ viscosity ratio, starch paste resistance, reduction of viscosity by acids, heat and or mechanical agitation (shear), retrogradation tendencies, ionic and hydrophilic nature. Modifying starch is important to provide thickening, gelatinization, adhesiveness and /or film-retention, enhance palatability and to remove or add opacity (Ihekoronye and Ngoddy, 1985).

The reasons why native starch is modified are:

- To modify cooking characteristics (gelatinization).
- To reduce retro gradation
- To reduce paste's tendency to gelatinize
- To increase paste's stability when cooled or frozen.
- To increase transparency of pastes and gels
- To improve adhesiveness between different surfaces, such as in paper applications.

Modification can be as simple as sterilizing products required for the pharmaceutical industry or highly complex chemical processes to confer properties totally different from the native starch. A simple modification process is represented by washing, air classification, centrifugation, and pre- gelatinization.

2.4 DEVELOPMENTS IN STARCH PROCESSING MECHANIZATION

To be transformed as food, starch must be processed and gelatinized (Van Zuilichem *et al.*, 1980). Some of the equipment that are used for starch processing are shown in Figures 2.1 to 2.3. There are many forming equipment made for specific products. Figure shows 2.1 a rotary moulder for forming biscuits. This mould has the required size and shape for any specific product. Biscuits are formed by pressing the dough into shaped cavities in a die forming metal moulding roller. Cutting rollers are often used for cutting shapes from a sheet of dough while soft dough can be extruded through a series of dies in a wire cut machine (Figure 2.2). Also, several types of cutting machine are available. Some cutters consist of rotating or reciprocating blades which cut the food as it passes beneath. In some designs, food is held against the blades by centrifugal forces.

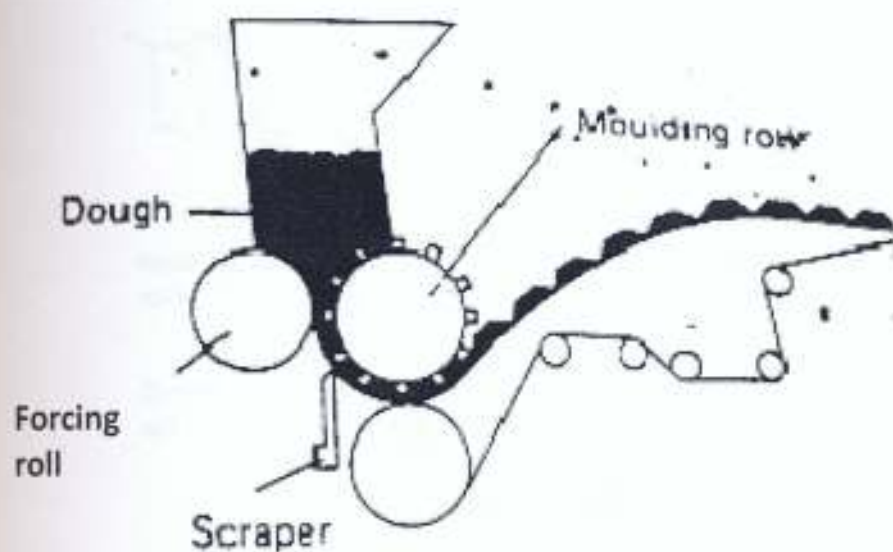


Figure 2.1: A rotary moulder for forming biscuits.

Source: Fellows, (2003)

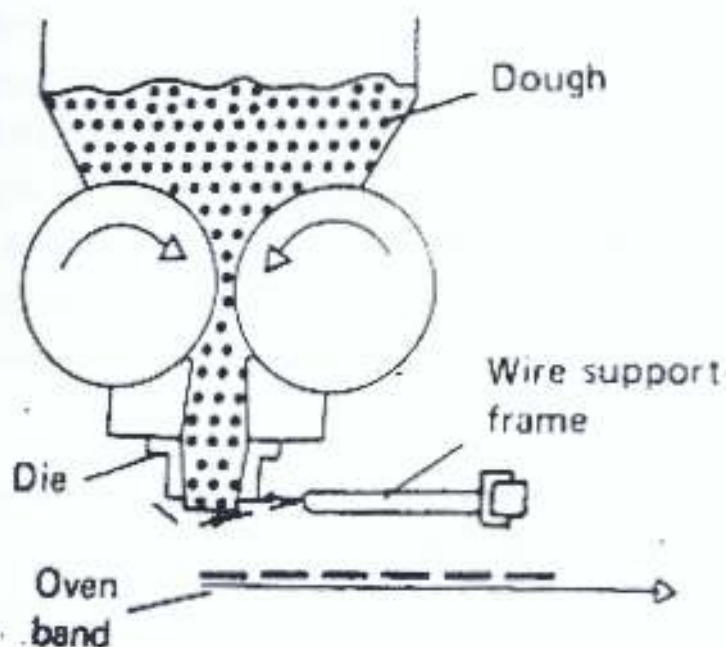


Figure 2.2: Wire cut machine

Source : Fellows (2003)

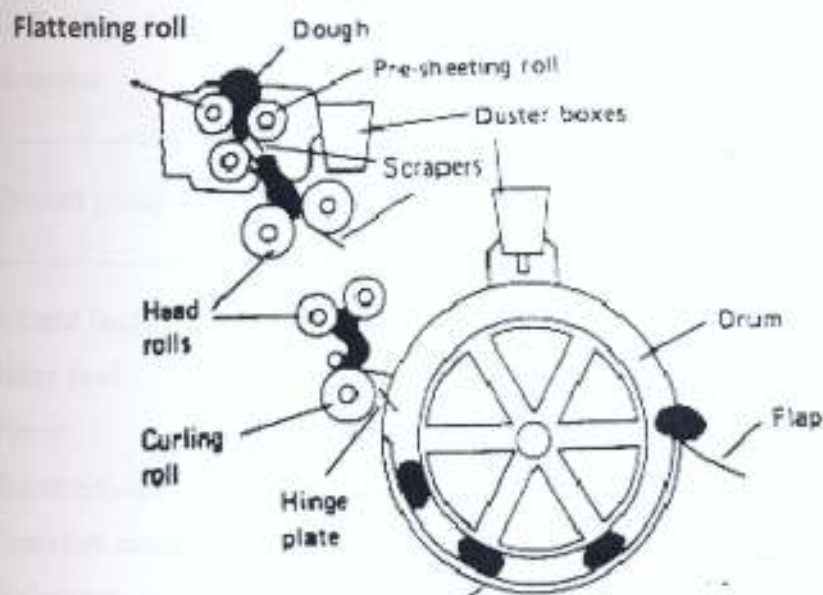


Figure 2.3: A drum moulder for bread doughs.

Source: (Fellow, 2003)

2.5 CONVENTIONAL COOKING PROCESSES IN THE FOOD INDUSTRY BEFORE FOOD EXTRUSION

For obvious reasons, mankind is seeking new and different methods to produce food. Cooking is a necessary step in a food process for the generation of desirable flavour, texture, improvement of nutrient availability and creation of palatable properties. Starchy crops are quite edible in their natural state to birds, insects and other forms of life, but needs some transformation for human consumption. This is perhaps the most important function of cooking. Before the advent of extrusion cooking, a number of processes have been employed in transforming food into the desired product. Table 2.2 shows some food products for which conventional machines and equipment were used in place of an extrusion cooker.

Cooking in the presence of moisture causes these granules to rupture, releasing the starch molecules to create a matrix of gelatinized starch that surrounds and supports other fractions and added constituents. This semi – homogenous material, when at the proper temperature and moisture for each process, flows as directed by the particular process e.g. flaking rolls into the desired shape and responds to thermal stresses induced in other processes e.g. toasting ovens to develop porosity further by evolution of steam from moisture within the product.

Table 2.2: Food products for which conventional machines were used in place of an extrusion cooker.

Product group	Product example	Conventional process
Animal feed	Pet food	Autoclave or oven
Dairy food	Casseinate reaction	Stirred tank reactor
Flavor	Real flavors, caramel, cracknel	Roasting tank
Baked articles	Flat bread, biscuits	Baking oven
Breakfast cereals	Puffed rice, cereal, flakes	Puffing gun, Batch cooker
Farinaceous food	Glass noodles, fish noodles	Cooker
Sweet articles	Liquorice, fruitgums, chocolate	Cooker and mogul conche

Source: Olkku *et al.* (1980)

2.5.1 Principles of Cooking

Cooking raises the temperature of a product above the gelatinization temperature for a sufficient time for the gelatinization reaction to achieve the desired degree of completion. According to Miller (1994), three independent sources of energy are available for generating the heat needed for cooking: direct heating of cooker surfaces for conduction into the product; injection of steam into the product and mechanical energy which is converted to heat by friction within a viscous product when it is sheared or intensively mixed by the machine surfaces. These three energy sources may be used in various combinations but all are transformed to heat in the product.

The Arrhenius law for chemical reactions predicts that reaction rates increase with temperature so that at higher temperature less time is required to achieve any particular degree of completion. Higher temperature processes use shorter cooking times. However, moisture and shear are two other factors important in the speed of gelatinization of starches. In the absence of shear, gelatinization is a hydration process. Although somewhat interchangeable on a thermodynamic basis, shear and moisture affect product properties differently. Variations in moisture and shear also generate products differences on a macroscopic scale. The selection of a cooking process depends very much on the products qualities desired and not just on thermodynamic efficiency.

2.5.2. Overview of Cooking Processes

A range of cooking methods on the continuum of possible starch cooking conditions will be discussed here.

2.5.2.1 Boiling water cookers

With a self-explanatory name, boiling water cookers are perhaps the simplest type (Miller, 1994). Usually they consist of a batch vessel containing grain and sufficient water to permit complete coverage and fluid flow. Boiling water cookers operate at the lowest temperature for the longest time among cooking methods. This is because the cooking pressure (atmosphere) is also the lowest and shear stresses (transmitted by low viscosity water) are essentially zero without significant shear, mechanical energy is not available as a heat source. It produces the least disruption of the grain structure as the starch is gelatinized. The resulting whole grain product is soft without being sticky and, if handled carefully before and after cooking, contains no broken grain fragments. These properties are particularly important in making shredded wheat, and are of interest for any whole grain product.

2.5.2.2 Steam cookers

Whole grains may also be cooked by steam, a common method for flaked products. According to Miller (1994), steam cooking may also be used for granular ingredients (corn frits or coarse floury materials) producing a cooked product with more structural disruption than that boiling water cookers. The steam cooker achieves higher temperature and cook faster than boiling water cooker. Another advantage is that other ingredients such as malt, salt and sugar may be incorporated into the product. Since only a small amount of heat is available from the conversion of mechanical energy (the viscous product is agitated during cooking by rotation of the cooker or with agitator blades in the case of continuous cooking), most of the energy for cooking comes from the steam itself. The steam also adds a significant amount of moisture to the product; this fact must be taken into consideration in formulating the mix entering the cooker, although some newer systems use superheated steam to minimize condensation. Batch processing is the rule with steam cooking. Cooking processes in which all of the heat is supplied by conversion of mechanical energy are called adiabatic or autogenous methods.

2.5.2.3. *Low – shear, low – pressure cookers*

This is a motley group consisting of mixers with heat transfer surfaces (Miller, 1994). It is operated with relatively open discharges to minimize pressure build – up and relatively low screw speeds to minimize shear. Products from these cookers is often granular (non – compressed) and must undergo forming, before further processing.

2.5.2.4 *Continuous steam pre – cooking*

Although steam cooking is normally done in batch cookers, continuous steam cooker are often used in conjunction with extrusion processes to hydrate and partially cook a cereal product before it enters the extrusion step (Miller, 1994). Steam pre – cooking adds several advantage to ordinary extrusion:

- * The longer, gentler overall cook cycle decreases starch damage and improves uniformity hydration, leading to better product quality.

- * Usually less specific energy is required from the extruder, reducing wear.

- * Expensive electrical energy needed to drive the extruder may be to a great extent replaced, often by cheaper forms of energy to generate steam, producing savings in energy costs. These advantages are offset to a degree by the increased capital costs of providing the precooking equipment, boiler and other ancillary equipment.

2.5.2.5 *Flaking*

According to Miller (1994), flaking process consist of flaking rolls which receive parts of cooked products and smash them down into thin flakes which are then toasted to develop crispness (and to dehydrate them for stability). The flaking roll consists of a pair of a parallel counter – rotating horizontal cylinders mounted so that a small gap exists between them. Product pieces, fed from above, are drawn downward into the gap where they are smashed by friction with the rollers surfaces. For proper flaking to occur, the product pieces must possess a degree of fluidity so that they may flow outward within the roller nip without fracturing to form a continuous flake shape (Miller, 1994). The coefficient of friction between the product pieces and the roller surfaces must also be great enough so that the pieces are drawn into the nip; hard, dry product surfaces would cause the pieces to ride above the nip without falling in. Roller surfaces must not be too smooth; they are usually slightly roughened to engage the product pieces properly. After the product pieces are flaked they must be removed from the flaking rolls. Doctor blades are used to remove

flakes that adhere to the roller surfaces.

2.5.2.6 Oven puffing

Expansion is caused by a sudden disequilibrium between the product and the atmosphere which causes rapid steam generation within the product. Rapid heating can cause a similar effect. When a cereal piece is well gelatinized and at the proper moisture (and small enough for heat to penetrate quickly), exposure to very high temperatures will cause it to expand into a cellular structure. This is the process used to produce crisp rice; puffing is done at very high temperatures (up to 343°C) in rotary toasting ovens or more modern fluid bed dryers in which high-velocity air removes the stagnant surface air layer to accelerate heat penetration (Miller, 1994).

2.5.2.6 Gun puffing

Gun puffing is another method of suddenly subjecting a product piece to disequilibrium (Miller, 1994). In this case, the product is heated under pressure in a closed vessel. When the vessel is suddenly opened, a violent decompression causes moisture to flash, inflating the product in much the same way as in direct expansion puffing. One major difference, however, is that the product is not under shear in the gun puffing operation. Thus, the original unpuffed product configuration, although distorted by puffing, is essentially preserved in the puffed piece. Puffed wheat, for example, looks very if much like a wheat berry, only larger. Indeed, in making whole grain gun puffed products, shear is virtually non-existent throughout the process. Since the process does not depend on the fluid properties or dimensions of the product, many unusual materials may be gun puffed, including vegetables. In modernizing the puffing process, automated batch puffing systems have been developed in which a series of puffing guns sequentially discharge in a quasi-continuous stream. True continuous gun puffing in which a stream of product pieces emerges (along with steam) through a small nozzle sized to maintain desired internal pressure has also been introduced on a large scale.

2.6.2.7 Shredded products

Shredded breakfast cereals rely on distinctive forming machinery to create the familiar biscuits and their constituent fine shreds (Miller, 1994). At the heart of the operation are the shredding rolls which consist of a pair of parallel horizontal counter-rotating cylinders smaller than, but superficially similar to, flaking rolls. Rather than being smooth, however,

one of the rollers is embossed with a series of circumferential grooves along its length (and usually a few axial grooves to create cross-members in the shredded web). As the rollers rotate, cooked wheat berries are drawn into the grooves. The crushed mass of wheat then extrudes through the nip and out the other side of the rollers where it falls free as a strand of cooked wheat (with the help of clean out wires riding in the grooves). A cascade of these strands along the roller length is collected on a conveyor which passes under a series of shredding rolls, each contributing a layer to a growing bed of shreds. After the required number of layers is collected (up to 20), a cutting/crimping device separates the bed into individual biscuits with compressed edges holding the biscuit together. The biscuits are then baked to a final moisture of about 4% at 204 -315 °C .Shredding operation requires a non-sticky gelatinized feed material with high moisture. The traditional cooking method is the most gentle - boiling water. It is a long residence time process; exacerbated by a necessary tempering step after cooking for many hours.

2.6. PRINCIPLES AND PURPOSE OF EXTRUSION

2.6.1. Principles of Extrusion

Food extrusion is a process in which food ingredients are forced to flow, under one or several conditions of mixing, heating and shear, through a die that forms and/or puff-dries the ingredients. Extrusion technologies have an important role in the food industry as efficient manufacturing processes. It has been proven to be a very efficient food processing technology that is capable of performing several unit operations simultaneously and is flexible with accommodation of new products. A wide range of products, which cannot be produced easily by any other process, is possible by changing the ingredients, extruder operating conditions and dies while working at lower processing costs and higher productivity with no process effluents. Extrusion Technology is a process that has gained popularity in the developed nations like United States and Europe by producing a range of products with different shapes, textures, colours, flavours from basic ingredients, thereby increasing the variety of food in the diet (Fellows, 2003).

The important elements of a single – screw extruder are shown in Figure 2.4. The food material is fed from a hopper through the feed throat into the channel of the screw. The screw rotates in a barrel which has a hardened liner. A motor drives the screw through a gear reducer, and the backward thrust of the screw is absorbed by a thrust bearing. As the food material is conveyed along the screw channel, it is simultaneously subjected to mixing,

heating and shear. When it is close to the discharge end, i.e. near the die, it has been transformed into a thermoplastic, viscoelastic materials at high pressure. Finally, the material flows through the die. Flow charts for an extrusion system and the sequence of the main extrusion process are shown in Figures 2.5 and 2.6 respectively.

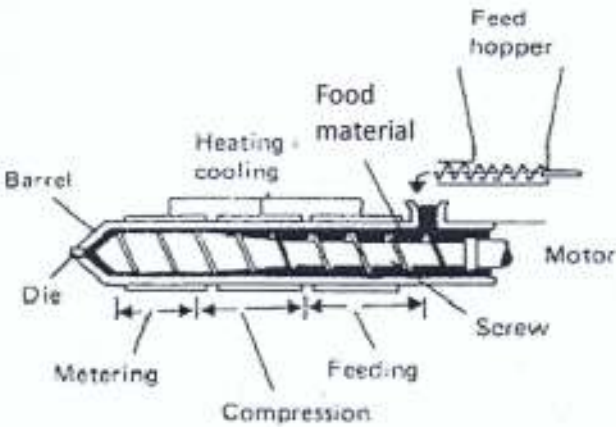


Figure 2.4: The important elements of a single – screw extruder (Frame, 1994)

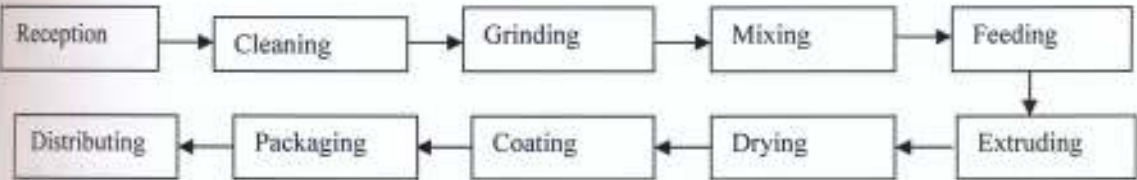


Figure 2.5: Flow chart of a typical extrusion system. (Harper, 1979)

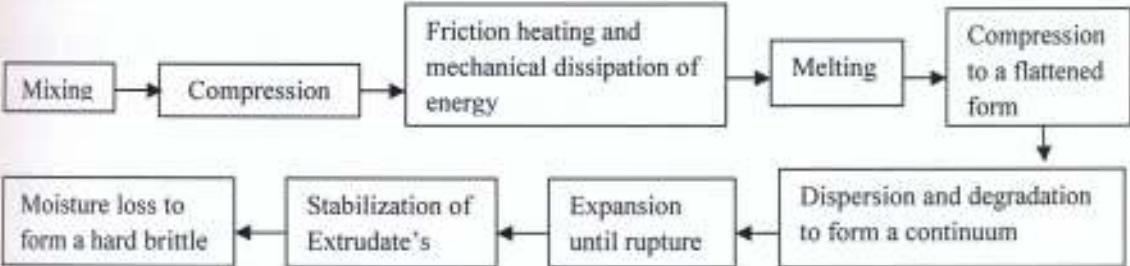


Figure 2.6: Standard sequence of the main extrusion process for a starch rich recipe (Guy, 2001)

For obvious reasons, mankind is seeking new and different methods to produce food. Extrusion technology provides several advantages over traditional methods of food and feed processing feed processing, including the following:

- Options for processing a variety of food products by changing a minor ingredient and/or processing conditions on the machine
- Different shapes, textures, colours, and appearances obtained by minor changes in hardware and processing conditions
- Availability of automation with most new extruders, which can increase productivity
- Improved product quality over other processes because cooking is done in a very short time and less destruction of heat sensitive ingredients occur and
- Easy scale- up of extrusion processes from pilot plant to commercial production.

2.6.2. Uses of Extrusion

Extrusion, a process for creating heat with friction is utilized in several basic ways. Some of the uses are discussed below.

2.6.2.1 Cooking

The use of extrusion methods in cooking is primarily related to inhibitor destruction. With an extremely short processing time and oxygen-free atmosphere, there is very little effect on the protein, energy, or vitamin content of the product (Pet-Pro, 2001). In addition, there is less browning reaction because of the oxygen free atmosphere though there is starch gelatinization, protein denaturation and texturization.

2.6.2.2. Pasteurization and Sterilization

The heat and pressure produced in extruders can be utilized for the destruction of bacterial, mold and yeast. These are natural ingredients that occur on almost all living plant materials and can be very harmful with respect to storage (Riaz, 2002)

2.6.2.3. Expansion

During extrusion process, the continuous pressure, cooking, and sudden release of pressure at the die outlet allow for the gelatinization of starch cells, oil cells rupture and rapid expansion of the product (Frame, 1994).

2.6.2.4. Dehydration

There occurs loss in moisture of extrudate due to rapid fall in temperature at the exit from the die during the extrusion process (Fellows, 2003; Guy, 2001). Within parameter, a 50% loss in moisture can be achieved through the process. This allows for dehydrating many products, which have too high a moisture level for storage.

2.6.2.5. Stabilization

The use of heat and pressure can also be used to inactivate enzymes such as would occur in rice bran or various other ingredients causing rapid destruction of the nutritional properties. In this way, the products are stabilized (Pet-Pro, 2001).

2.6.2.6. Mixing

Mixing (or blending) is a unit operation in which a uniform mixture is obtained from two or more component, by dispersing one within the other(s). Mixing has no preservative effect and is intended solely as a processing aid or to alter the eating quality of foods. It has very wide applications in many food industries where it is used to combine ingredients to achieve different functional properties or sensory characteristics. Extruders serve a mixing function.

2.6.2.7. Forming

Forming is the unit operation in which foods that have a high viscosity or a dough-like texture are moulded into a variety of shapes and sizes, often immediately after a mixing operation. It is used as a processing aid to increase variety and convenience in baked goods, confectionery and snack foods. It has no direct effect on the shelf life or nutritional value of foods. Extrusion incorporates a forming operation. These are examples of size enlargement operations.

2.6.2.8 Other uses

Other uses of extrusion include, degassing and agglomerating ingredients, homogenization, grinding, shearing, enzyme in-activation, product shaping and unitizing (Riaz, 2002).

2.6.3 Applications of Extrusion

According to Riaz (2002), Extrusion cooking has been used to develop a wide range of products, some of which are discussed below.

2.6.3.1 *Snack foods*

Consumers are buying snacks in greater variety and quality than ever and extrusion technology produces almost all of them. Snacks are one of the fastest- growing segments of the food industry, and for years, extrusion has been a mainstay of producing from inexpensive raw materials with minimum processing time.

2.6.3.2 *Functional/ nutraceutical foods*

Nutraceutical and functional foods comprise of foods that are fabricated for specified special purposes and they make up the fastest growing segment of food industry. Extrusion technology can be used to produce functional/ nutraceutical ingredients for foods products.

2.6.3.3. *Cereal – based foods*

Consumers perceive phyto-nutrient- containing cereals as healthy foods. Most cereals can be extruded and cereals-based product, such as breads, cakes, cookies, crackers and ready to eat breakfast cereals can be processed by extrusion.

2.6.3.4 *Baby foods*

One of the major dependencies of developing countries is the sources of food for their young population. Extrusion helps to produce baby foods which are highly soluble fully gelatinized products with various natural sweeteners added to the mix to produce a fully nutritious and fortified product used as baby food supplement.

2.6.3.5 *Pre-gelatinized starches*

When starches, which have been gelatinized and swollen after dissolution in hot water to form slurries, are then dehydrated by passage through either drum driers or spray driers they are referred to as pre-gelatinized starch. Extrusion has become a widely practiced food processing operation used for the production of pre-gelatinized starches, which are being utilized in puddings, gravies and in extruded foods.

2.6.3.6 Confectionery

Extrusion cooking is used to produce a gelatinized chewy product from a mixture of sugar, glucose, and starch. It allows many batch operations to be conducted in the continuous mode. Other benefits include greatly enhanced hygiene, lower energy needs, enhanced control over nutrition, change of state, physical properties, composition and other material changes.

2.6.3.7 Vegetable proteins

Extrusion technology allows producers to engineer meat analogs with true meat texture. Textured vegetable proteins (TVP) are a proven commercial success, and published reports emphasizing the health benefits of soy protein are adding to its popularity. The growing functional foods industry is becoming increasingly interested in adding textured soy protein to its products.

2.6.3.8 Semi-moist foods

Using extrusion to produce human foods products is a new and challenging aspect of extrusion technology. Extrusion's ability to selectively control water activity is crucial to producing soft-moist shelf-stable intermediate-moist foods. It plays an important role in producing nutritionally balanced foods for a variety of markets- breakfast, lunch and snack bars; camping and military field rations; foods for special dietary needs and for feeding during disaster and famine recovery.

2.6.3.9 Animal feed

Most dry and semi moist animal feed, pet and fish foods are produced through extrusion. Process management of raw material formulation, system configuration and processing conditions can profitably manufacture palatable, functional and tailor-made feedstuffs. Extrusion technology can be used to develop profitable and nutritional products using ingredients which were previously under-utilized or poorly accepted, thus increasing the usable portion of the world supply of grain resources to feed an ever growing world population.

2.6.3.10 Biodegradable packaging materials

The recycling of wastes has been a high priority for government of all developed nations. Unfortunately, due to a lack of economic incentives and a feasible technology, there

has been very little success in disposing used plastics products because of their non-degradability (Guan, and Hanna, 2004). Present needs are to produce biodegradable materials made for renewable environmentally friendly materials such as starch, protein and cellulose from sources for packaging. This effort may greatly reduce solid plastic waste and concurrently promote significantly increased use of crops grown. Growing volumes of plastics waste, coupled with limits on available landfill, have placed added emphasis on development of biodegradable and recyclable packaging materials (Moore, 1994). Extrusion is playing an important role in processing biodegradable packaging materials.

2.6.3.11 Multi- purpose, multi- shape products

Packaging materials aren't the only shaped product, which can be produced by extrusion. Other products-plastic toy parts, bowls and plates, toy animals-also can be made through extrusion processes (Riaz, 2002).

2.6.3.12 Fiber for industrial uses

Wheat and rice straws- widely available in many parts of the world – can be combined with other materials and processed by extrusion into raw materials for industrial uses (Riaz, 2002).

2.6.3.13 Protein film

Extrusion can process high-protein oilseed crops into biodegradable plastic packaging films that ensure high quality and long shelf life for foods and other products (Riaz, 2002).

2.6.3.14 Oil seed

Using extrusion technology to process soybeans, bean nuts, cottonseed, sunflower and other specially oil seed crops is a relatively new idea but one that has great promise because it allows you to use all parts of the crops (Riaz, 2002).The seeds themselves can be separated from the oil and used for animal feed, while the oil is used in human foods produces (Maratos, 1999). The process requires no solvents or chemical and generates no significant amount of waste.

2.7 HISTORICAL DEVELOPMENT OF EXTRUSION

The art of extrusion is already old (Janssen, 1978). In England in 1797 Joseph Bramah constructed a hand operated piston press for the manufacture of seamless lead pipe. The machine is generally thought to have been the first extruder. It was not long after that other materials like soap, macaroni and building materials were processed with similar machinery (Van Zulichem *et al.*, 1980). The examination of the main steps of evolution of extruders shows that its field of application has been progressively enlarged. The extruder cookers of the nineteenth century were only used to shape sausage meat and farinaceous products (Wiedman and Strobel, 1987). The meat grinders of the late 1800s have rifling or parallel grooves cut into their barrel for moving the product forward in single-screw extruders. The complete screws and barrels are usually heavy and difficult to transport and set up in lathes or surface machining equipment. Subsequently, segmented screw/barrel extruders evolved.

A design solution to prevent the product from spinning with the screw was borrowed from the Anderson continuous oil screw press, invented at the end of the 1800s by Anderson International Company, Ohio, USA. Instead of the screw segments aligning to form a continuous forward conveying flight, space was intentionally left between the flights, giving rise to the term 'interrupted flights'. Not until 1946 were single screw units used commercially for the extrusion cooking and expansion of corn snacks. In the fifties, baked pet food biscuits were largely replaced by extrusion cooked ones. In the sixties, the use of single screw extruders for pre-cooking starches, texturizing soya proteins and for the direct expansion of breakfast cereals became more popular. In their own account, Rossen and Miller (1973) reported that the single screw extruder was first applied to food processing in 1935 for the continuous extrusion of pasta products. Since 1935, there has been an increasingly greater use of single screw extrusion in the food industry, particularly in those processes which require cooking or gelatinization at some stage, such as in the preparation of snacks, cereals, pasta foods, confectionery products, pet foods, animal feed, sausage products, protein supplements, and meat analogs. Thus, the extrusion function evolved into a more complex, general and wide notion of conditioning (Boulie, 1987).

The call for a screw extruder came from the cable industry. While the intermittency of a ram extruder could be accepted for the earlier application, it was an unacceptable limitation to processes for cable covering. The earliest known concept of single screw extrusion is found in an 1873 drawing owned by Phoenix Gummiwerke A.G. The first known twin

screw extruder was developed in 1869 by Follows and Bates in England for sausage manufacture. The first twin screw extruder for plastics processing was constructed just before the Second World War by Roberto Colombo and Carlo Pasquetti in Italy. Since then the use of these machines has steadily increased. In particular since most of the major mechanical design problems, including the design of thrust bearings, have been solved within the last decade more and more extruders have come into use in the polymer industries. Some of the existing designs are characterized by investment level, design complexity and operation control. The extremes are the so called low cost cookers like the Brady design and the double screw extruders (Harper, 1986).

Since 1980, while the acquired knowledge became richer and some researchers were trying to find modellisation law, it was discovered that the double barrel- screw could also be considered as a very efficient reactor, whereas in some applications the die plate could be left as unuseful. Twin- screw got their popularity in the food industry in the mid- 1980s- mid- 1990s (Guy, 2001).Originally developed for processing plastics, food companies began using twin- screw extruders for products like sticky caramels and candies, that could not be made with single- screw machines. However, the following recent improvements in single screw extruders have made it possible to process several foods formerly made on twin-screw extruders:

- (1) Variable speed drives (VFD) gave single- screw additional flexibility and are approaching twin- screw
- (2) Computer control systems.
- (3) Improved gravimetric feed system and mass flow meters for precise metering of ingredients/ recipe components.

Although double screw extruders permit a better operation control and a wider diversity of product types than single screw extruders, these are still a good alternative for cooking and forming cereal products, because of their lower costs (Harper, 1979). During the last decade the demand for single screw cooking extruders has increased in Argentina.

2.8 GENERAL DESIGN FEATURES OF EXTRUDERS

All extruders consist of a screw(s) which conveys the premixed ingredients through the barrel (Senanayake and Clarke, 1999). Regardless of whether the machine is single- or twin-screw type, general principles apply to all. Screws generally are suspended only from the drive end of the barrel, and rest on the product at the exit end. As a result, the greatest stress and wear on the screw and barrel occur at the exit, and these parts need refurbishing or replacement first. But, complete screws and barrels of even small commercial size extruders are heavy and difficult to transport and set up in lathes or surface machining equipment. Except for very small or old extruders, both the screw and barrel are segmented. The screw typically consists of a shaft that is splined, equipped with a keyway, or hexagonal shape onto which various elements (flight sections, flight 'worms' of different design, and shearlocks/steamlocks) slip before being tightened in place. In twin-screw extruders, each screw consists of modular components too. This design has two major advantages:

- 1) the elements can be arranged in a variety of configurations as needed for specific applications.
- 2) the worn exit segment can be replaced as needed, or moved back on the shaft to a position where its increased clearance with the barrel is less critical.

In addition to segmented barrel sections, which often have liners that can be replaced as wear proceeds, provisions must be made to keep the product from turning with the screw. Screws act as positive displacement pumps in twin-screw design, each screw wipes the other in moving product forward: in the intermeshing counter-rotating design, the screws jointly squeeze the product forward. Other provisions must be made for moving product forward in single-screw extruders. The oldest design solution was introduced in meat grinders in the latter 1800s. Rifting or parallel grooves were cut (more often cast) into the barrel. Both 'wet' and 'dry' single-screw extruders include this feature. Because the barrels and screw flight sections are segmented, a ring-like 'steamlock' or 'shearlock' can be placed between each section, turning the previous section essentially into a pressurized mixing-shearing-reactor cell. Typically, clearances between the 'lock' and the barrel wall decrease as the product are conveyed forward, resulting in zones of increasing pressure.

The second design solution to prevent the product from spinning with the screw was borrowed from the Anderson continuous oil screw press, invented at the end of the 1800s (Guy, 2001). Instead of the screw segments aligning to form a continuous forward conveying flight, space was intentionally left between the flights, giving rise to the term 'interrupted flight'. The barrel inside this type of machine is smooth walled, but 'shearing bolts' protrude through the barrel wall into the space between the flights. As needed, a hollow bolt can replace a solid bolt and convey steam into the product during processing. The die plate at the discharge end of the extruder is the only restriction to product flow and, conceptually, the entire barrel is one reactor cell.

2.9 CLASSIFICATION OF EXTRUDERS

Several types of Extruders have been designed and manufactured to meet various needs of food products. Food extruders can be classified in a number of ways, namely:

2.9.1 Thermodynamic Classification

Food extruders can be thermodynamically classified into the following groups:

Autogenous (Nearly Adiabatic) Extruders generate their own heat by conversion of mechanical energy in the flow process itself. No attempt is made to introduce heat or to cool the unit through the jacket. Puffed snack extruders approach the condition (Starch Extrusion Lecture, 2001)

Isothermal Extruders. Constants temperature is maintained throughout the extruder by cooling to remove heat generated by conversion of mechanical energy (Starch Extrusion Lecture, 2001)

Polytropic Extruders. Operate between the autogenous and isothermal extreme conditions. All food extruders are polytropic, but some tend more toward being autogenous and other more toward being isothermal. This classification becomes necessary only when modeling the behavior of the cooking extruder. Nearly all extruders cooking extruders operate polytrophically (Starch Extrusion Lecture, 2001).

2.9.2 Classification According to how Pressure is developed.

Although extruders may be called upon to serve a variety of functions, they are primarily types of pump, and like pumps, can be broadly classified according to the manner in which pressure is developed (Fellows, 2003; Frame, 1994).

(a) Direct or plastic displacement and indirect or viscous - drag extruders

Direct extruders include the ram or piston type extruder and inter - meshing twin - screw extruder. The ram extruder has found major application in sausage stuffing operations and in extrusion of corn masa to make fried corn chips. It is desirable for these applications because virtually no shear occurs, and the properties of the extruded product are therefore essentially unchanged from those of the feed material. This type of extrusion is batch in nature because the piston must be retracted periodically to permit refilling of the chamber. Furthermore, the heat buildup in the in the extrudate is usually limited to the viscous energy dissipation in the die. It should be emphasized that in the extrusion process, the intensity of shear to which the food material is subjected and where the shear takes place are critical items. Intermeshing twin - screw extruders subject materials to some shear due to viscous drag between the intermeshing flights and also subjects the materials to a high degree of extensive mixing. They find major use in compounding operations such as manufacturing chewing gum or chocolate (Guy, 2001).

(b) Indirect or Viscous - drag type.

This type of extruder develops viscous drag and therefore modifies the characteristics of the extruded product (Farral, 1976). There are several types of indirect extruders. One type is the roller extruder, which is used to a great extent with very sticky materials which do not require high - pressure forming. Its primary application is in the confectionery industry. Other types are the single - screw extruder and the non - intermeshing multiple - screw extruder, which developed from the single - screw extruder. The non - intermeshing multiple - screw extruder operates on the same pumping principle as the single - screw extruder and is used for special application such as dough sheeting across a wide conveyor.

2.9.3 Functional Classification

Functionally classification refers to how much mechanical energy can be generated or the extent of shearing action in the food, Extruders can be classified as follows.

Pasta Extruder is used for forming macaroni, cookies and similar product from a dough. Of the five extruder types, it is the closest to the idealized extruder in that it has smooth barrel and no solid conveying section (dough feed) and usually has a constant screw geometry. It is also the closest to an isothermal extruder since it affects the lowest temperature rise. It operates at low screw speed and it is characterized by deep flighted screw in a smooth barrel (Starch Extrusion Lecture, 2001).

High – Pressure Forming Extruder is used for compressing and shaping a pregelatinized dough feed into products which normally require further processing such as deep fat frying (snacks) and gun puffing (cereals). The operation of this extruder is similar to that of the pasta extruder, except that its barrel is normally grooved to produce high pressure. The grooves require additional power and increase the temperature and amount of heat dissipated to the food due to viscous dissipation. The excess heat is removed by circulating water in jacket around the barrel

Low – Shear Cooking Extruder is used as continuous cooker for high moisture products or soft moist petfood (Rossen and Miller, 1973). This is a flexible unit and has a wide variety of applications. The cooked product must be further processed by forming drying etc. the applied shear is higher than that of the forming extruder, but due to the low viscosity (high moisture), most of the energy required for cooking is applied by external heating, despite the fact that deeply grooved barrels and compression screws (variable D/h or pitch) are normally used.

Collet Extruder cools, puffs, and forms dry granular feeds such as corn meal to produce puffed snack products such as corn curls (Starch Extrusion Lecture, 2001). This is a very high shear, short residence time extruder and characterized by short shallow flighted screw with length to diameter ratio of 3:1. A high rate of energy dissipation is produced by high applied shear rate, deeply grooved barrels, and high viscosity (low moisture).

Viscous dissipation can heat the product to 175°C. The subsequent high temperature causes violent flashing of the moisture at the die outlet, the material expands rapidly, creating a puffed, dry product. Starch is gelatinized and partially dextrinized. Although this machine

has the advantage of requiring little post – or pre – extrusion processing, it is quite inflexible and produce a narrow range of product from a narrow range of ingredients. This and the high – shear cooking extruder are the furthest from the idealized extruder. Large temperature rises, rheological changes, starved operations and variations in screw and barrel designs make analysis difficult.

High – Shear Cooking Extruder also called HTST extruders is similar in operation to the collet extruder except heat is removed by cooling the barrel. It is more flexible than the collet extruder in that it can produce many products such as puffed of dry ingredients and mixes. It is characterized by long barrels with length to diameter ratio of 15:1 and high compression ratio. The high – applied shear rate and long residence time provide good mixing within the extruder, so that water may be injected in the feed section to provide optimum process moisture. Since the feed moisture is generally higher than for the collet extruder, higher product moisture remains after flashing, which often require post – extrusion drying. The product temperature is lower than those for the collet shear rate, food moisture and cooling rate. These differences result in longer – time, lower temperature cook and less violent expansion than the collect extruder provides. The products are usually browner and harder in texture than those of the collet extruder and have more flavor development.

2.9.4 The Number and Relative Position of the Screws

Extruders with one screw are termed as single screw extruders while twin – screw extruders have two screws in the barrel. In twin screw extruders, the screws can be intermeshing or non intermeshing. For the intermeshing screws, the fit of the flights into the channel might be loose when the screws are non conjugated. On the other hand, the screws are conjugated when the flight of one is identical in size and shape to the channel of the other and hence, the flights fit tightly into the channel.

2.9.5 The Relative Direction of Rotation of the Screws

With respect to the twin screw extruders, the screws can be rotated in the same direction in which case, they are corotating. When they in opposite directions, they are counter – rotating. According to Sahay and Singh (1994), The main difference between the single screw extruder and twin screw extruder is the conveying mechanism. In single screw extruder, the conveying action is the result of friction effects, (1) the friction between screw and product, and (2) the friction between barrel and product.

2.9.6 Method of injection of steam or water

Segmented screw/barrel single-screw extruders are the most widely applied cooking extrusion design in the food, pet foods and feeds processing industries. 'Wet' means that steam and water can be injected into the barrel during processing. Typically, the barrels of these machines are also equipped with heating and cooling jackets. They process more tonnage of extruded products than any other extruder design. The products produced range from fully cooked, light density corn snacks, to dense, partially cooked and formed pastas.

The term 'dry' extrusion means that this type of extruder does not require an external source of heat or steam for injection or jacket heating, and all product heating is accomplished by mechanical friction. Dry extruders can process ingredients which have a wide range of moisture contents, i.e. 10-40%, depending on the premixed formula. If the ingredients have sufficiently low initial moisture content drying of the product after extrusion cooking may not be necessary. Moisture loss in dry extrusion is in the form of steam flash-off at the die, and the extent depends on initial moisture in the ingredients and product exit temperature. Dry extruders have the option of water injection during extrusion. Usually starchy material requires some moisture in order to gelatinize.

2.9.7 Moisture characteristics

Moisture contents of the feed greatly affect the operation of extruders and also the energy costs. On the basis of moisture characteristics extruders can be Low Moistured (< 20 %), Intermediate (20 to 28 %) and High (> 28 %) (Chinnaswamy and Hanna, 1988)

2.9.8 Cooking Ability

This comprise of cold extruders and extrusion cookers. For cold extruders, the product is extruded into strips without cooking or distortion of the food caused by expansion (Fellows, 2003). Food is heated in an extrusion cooker by a steam jacketed barrel and/or by a steam heated screw. In some designs, electric induction heating elements are used to heat the barrel directly. Heat is also generated by friction in the product, caused by the action of the screw and internal ribs on the barrel.

2.10 PARAMETERS OF EXTRUSION

2.10.1 Introduction.

The extrusion process operates in a dynamic steady equilibrium where the input variables are balanced with the output. Therefore, in order to obtain the required characteristics in an extrudate, the correct level to give the dependent physical conditions and chemical process changes must be applied. Mass, temperature, pressure, residence time and shear rate are the main 'system parameters' influencing the outcome of extrusion depending on extruder geometry, process parameters and raw material composition (Kitabataki and Cheftel, 1985). Process parameters such as type of extruder, length of the barrel, screw configuration and speed, barrel temperature, feed rate, die configuration, moisture content, formula etc can be attributed to the system parameters (Meuser *et al.*, 1987). Also, Lam and Flores (2003) identified viscosity, torque, extrusion pressure, mass flow rate and specific mechanical energy (SME) as momentum transfer parameters. Simplified flow diagrams in Figures 2.7 and 2.8 show key process variations to product quality and output and the interaction of raw material properties, process variables and product characteristics while Figure 2.9 shows system analyses for extrusion cooking.

In an extrusion system, for a given formulation, there are four major categories of variables, which affect product quality. These include the extruder screw configuration and length to diameter ratio, die design, diameter, shape, land length, number of dies on die plate; design of rotating knife and process variables that the operator can change during the run (Chessari *et al.*, 2001). The extruder configuration affects the degree of mixing, shear forces introduced, amount of heat generated by friction and the residence time distribution (RTD). All these factors affect the degree of cook, the melt rheology and product quality and uniformity. The length to diameter ratio affects the residence time and hence the degree of cooking. The die is a major component in the extruder apparatus. Understanding the material properties and the nature of the flow in the extruder die is of primary importance in controlling the extruder performance and extrudates quality.

The design of the die plays a role in controlling the texture of the final product. Another function of the die is to stabilize the flow coming out the extruder barrel and consequently shape it into a desirable product. Although the extruder screw configuration and length to diameter ratio die design, design of rotating knife all affect the product quality, none of these variables could be changed while the extruder is running.

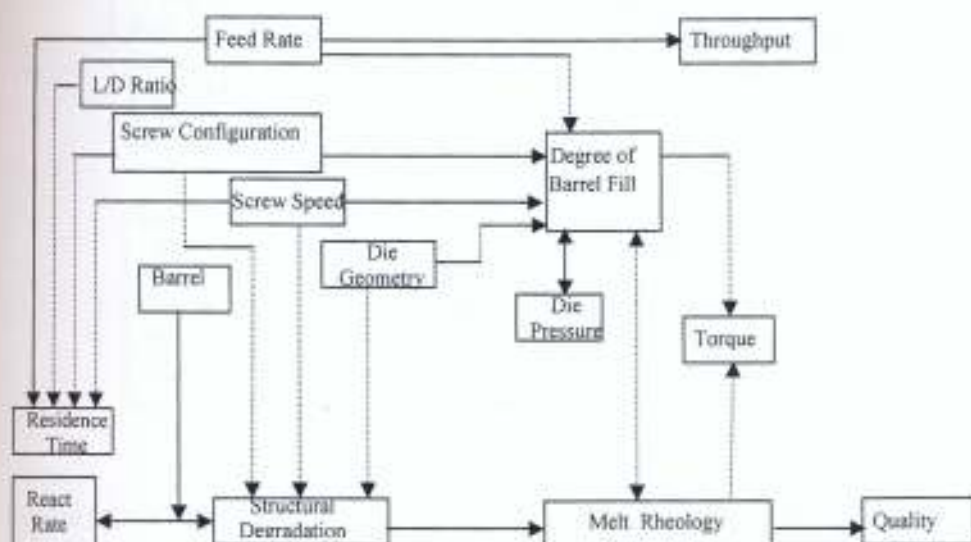


Figure 2.7: Key process variables to product quality and output (Frame, 1994)

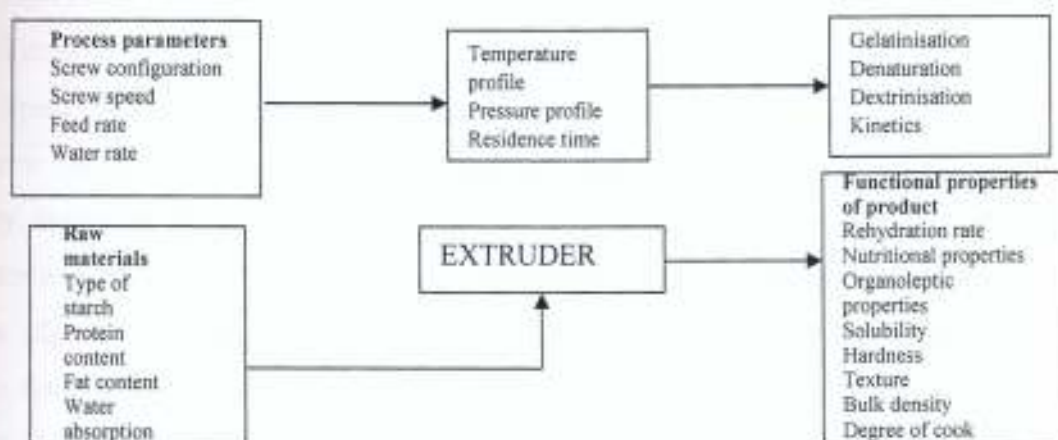


Figure 2.8: The interaction of raw material properties, process variables and product characteristics (Guy, 2001)

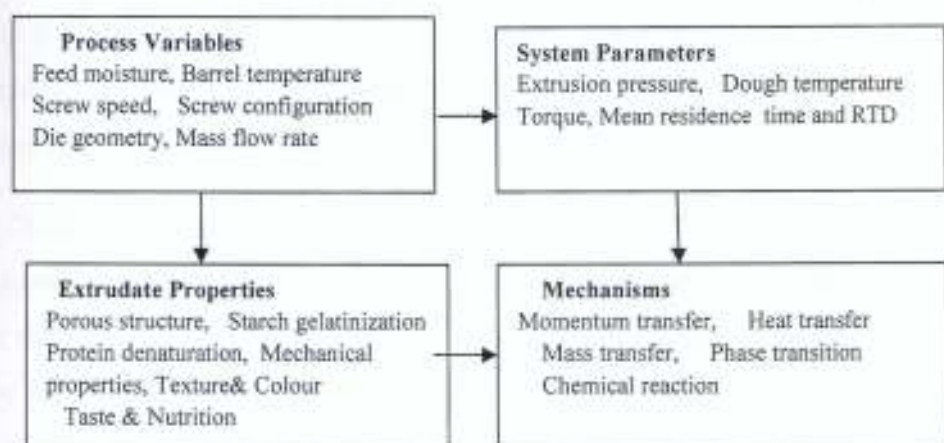


Figure 2.9: System analyses for extrusion cooking Chang and Halek (1991).

2.10.2 Process Variables

The following process variables could be changed when the extruder is operating:

- Screw speed
- Water injection rate/ moisture content
- Feed rate
- Temperature profile in the barrel
- Speed of rotating knife.

The screw speed affects the residence time, the amount of shear introduced, the melt viscosity, amount of frictional energy generated and the barrel fill. The pitch and diameter of the screw, the number of flights and the clearance between the flights and the barrel can each be adjusted to change the performance of the extruder. The screw is driven by a variable speed electric motor that is sufficiently powerful to pump the food against the pressure generated in the barrel. The screw speed is one of the main factors that influence the performance of the extruder: it affects the residence time of the product, the amount of frictional heat generated, heat transfer rate, and the shearing force on the product. Typical screw speeds are 150-600 rpm, depending on the application (Fellows, 2003). The moisture content controls frictional energy generated, and the melt viscosity. The feed rate controls the energy generated, the residence time and the barrel fill.

The temperature profile of the barrel affects the product temperature, which in turn affects degree of cook and the melt rheology. Product characteristics from starchy ingredients depend on physicochemical changes occurring during extrusion. The independent process

variables such as barrel temperature, screw speed and throughput along with screw configuration/and die geometry result in system parameters such as mechanical and thermal energy input, and residence time (Choudhury and Gautam, 1998). These intermediate process parameters induce reactions that affect product attributes.

Ficarella *et al.* (2006) identified shear rate, residence time, and mixing index as fluid – dynamic parameters. Increasing the fat content significantly decreased the degree of starch gelatinization of the extrudates. Increasing the initial moisture decreased the degree of starch gelatinization of the extrudates. Physical properties include apparent and true densities, expansion ratio and porosity (Sokhey *et al.*, 1997).

2.10.3 Product Quality Attributes

Extrusion cooking transforms low moisture cereals and starches into expanded crispy, porous and ready-to-eat food products. These types of expanded snack foods with different sizes, shapes and colors are available everywhere. The quality of these expanded foods depends on many factors. The most important factors considered in judging the quality of such expanded foods are texture and mouth feel. Both of these factors are directly related to the expansion properties. According to Gonzalez *et al.* (2001), the main difficulty is not the prediction of output or power consumption but to obtain the same product, which in the case of cereal cooking, implies the same degree of cooking. In order to obtain the same product characteristics, some of the so-called primary criteria (such as: residence time, mixing intensity and shear, product temperature and die pressure) have to be kept constant in the scaling up process. In dry cereal products, consumers consider crunchiness and crispness as signs of freshness, proper technology and good quality while gumminess, plasticity or sogginess is caused by increased moistness of the material. Water content correlated with water activity affects crispness, fragility and plasticity of cereal products (Agata *et al.*, 2004). Starch degradation leads to less expansion (Van Den Einde *et al.*, 2003).

2.10.3.1 Rheological and strength properties

The development of any machinery for harvesting and processing of agricultural material depends greatly on the physical and mechanical properties of such an agricultural product. Mechanical properties are essential attributes of soft solids, and this concerns primarily consistency during handling or eating, more so that physical stability often depends on

these properties (Walstra, 2003). Also, the rheological properties of foods play an important role in textural evaluation as well as in the selection of the correct equipment in operations involving the deformation of foods. Viscosity is one of the factors that determine acceptability of fabricated foods and to know or monitor the effect of any treatment on the starch. Also, the knowledge of the rheological properties of melted dough is very important in food extrusion systems because they affect extrudate expansion, texture, appearance and hydration properties as well as the thermal and mechanical energy input etc (Lo *et al.*, 1998a). The viscosity is influence by the process parameters. Accordingly, each alteration to an extrusion parameter always leads to a change in shearing stress and thus the viscosity of the mass. Therefore, by measuring viscosity value any alteration to an extrusion parameter will be monitored. A viscosity model equation for biological materials in an extruder was presented by Harper *et al.* (1971) as follows:

$$U_o = m(\dot{\gamma})^{(n-1)} e^{\left(\frac{\Delta E}{RT} + B_2 MC\right)} \dots\dots\dots (2.1)$$

Where U_o is the apparent viscosity ($N\ s/m^2$), m is the consistency coefficient (Ns^n/m^2), $\dot{\gamma}$ is the shear rate (sec^{-1}), n is the flow behavior index (dimensionless), ΔE is the activation energy of the material [$J\ (g\text{-}mol)^{-1}$], R is the gas constant [$8.314\ J(g\text{-}mol\text{-}K)^{-1}$], T is the product temperature (K), B_2 is a constant for moisture content ($\%^{-1}$), and MC is the moisture content of the material ($\%$, wb).

m can be determined as described by Lo *et al* (1998b) as follows if the extruder geometry, viscous dissipation power, and rotational speed are known:

$$Z_v = \sum_{i=1}^4 K (\dot{\gamma})^{(n+1)} V_i \dots\dots\dots (2.2)$$

Where n , K , and V_i are the flow behavior index, consistency coefficient and relative velocity, respectively. n can be expressed as the derivative of $\ln \sigma$ with respect to $\ln \dot{\gamma}$ with shear stress a function of the extruder geometry and the torque (M). Since shear stress and shear rate are proportional to motor torque and screw speed (SS):

$$n = \frac{d(\ln M)}{d(\ln SS)} \dots\dots\dots (2.3)$$

However, Diosady *et al* (1985) reported that the apparent viscosity of wheat starch melt in an extruder was calculated using the equation below:

$$U_o = 78.5(\dot{\gamma})^{-0.49} e^{\left(\frac{2500}{T}\right)} e^{-7.9MC} \dots\dots\dots (2.4)$$

Also, mechanical properties of agricultural products are most conveniently measured with the force - deformation curves (Lewis, 2000). From this curve, a number of mechanical properties can be determined, such as maximum force or energy to rupture, stiffness modulus and deformation (Khazaei and Mann, 2004). Linear limit, Young's modulus of elasticity and bio-yield point can as well be obtained from the force - deformation curve. Compression tests of biological materials provide an objective method for determining mechanical properties significant in quality evaluation and control, maximum allowable load for minimizing mechanical damage, and minimum energy requirement for size reduction. Determination of compressive properties requires the production of a complete force deformation curve (ASAE, 1982). From the force- deformation curve, stiffness, modulus of elasticity, modulus of deformability, toughness, force and deformation to points of inflection, to bioyield, and to rupture, and maximum normal contact stress or a stress index at low levels of deformation can be obtained. Knowledge of the force-deformation characteristics or breaking behaviour of extrudates will find applications in the design of its milling machines.

Compression force, impact force and shearing forces are all used for size reduction of extrudates. According to Maduemezea and Chike-obi (1990), strength is the ability or capacity of the material in a particular condition to resist or endure an applied force. Compressive strength or hardness characteristics of extrudates may be used as an index for sensory attributes such as crispness and brittleness. When stress (force) is applied to a food the resulting internal strains are first absorbed, to cause deformation of the tissues. On many occasions the strain does not exceed a certain critical level named the elastic stress limit (E). When the stress is removed, the tissues return to their original shape and release the stored energy as heat. As little as 1 % of applied energy may be used for size reduction. However, when the strain within a localized area exceeds the elastic stress limit E, the food is permanently deformed (Figure 2.10). Y is the yield point; B, breaking point; OE, elastic region; EY, inelastic deformation; YB, region of ductility, material 1 (curve 1) is hard, strong and brittle, material 2 (curve 2) is hard, strong and ductile, material 3 (curve 3) is hard, weak and brittle, material 4 Curve 4) is soft, weak and ductile, material 5 (curve 5) is soft, weak and brittle.

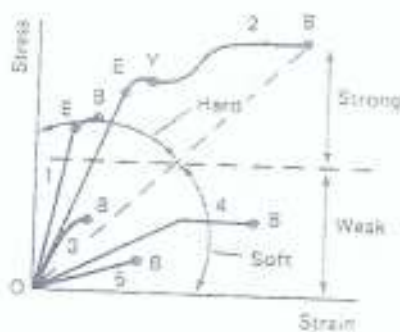


Figure 2.10 Stress- strain diagram for various foods.

Source: Fellows, (2003).

If the stress is continued, the strain reaches a yield point (Y), above which the food begins to flow known as region of ductility. Finally, the breaking stress is exceeded and the food fractures along a line of weakness. As the size of the piece is reduced, there are fewer lines of weakness available, and the breaking stress that must be exceeded increases. When no lines of weakness remain, new fissures must be created to reduce the particle size further and this requires an additional input of energy. The amount energy that is absorbed by food before it fractures is determined by its hardness and tendency to crack (friability) which in turn depends on the structure of the food. Harder foods absorb more energy and consequently require a greater energy input to create fractures. The more line of weakness in a food, the lower is the energy input needed fracturing. Materials taken above their elastic limit will be permanently deformed, once the stress is removed. Substances that elongate considerably after the elastic limit and undergo plastic deformation are termed ductile. Substances that break just after the elastic limit has been exceeded are termed brittle (Lewis, 2000). Some materials appear to have no yield point; they increase in length beyond the elastic limit as the load is increased, without the appearance of a plastic stage.

Strength and hardness are very important properties governing size reduction operations. A material breaks or cracks along defects in the structure. For a large piece, which has many defects, a small stress may cause breakage but, as the size is reduced, fewer defects remain and the breaking strength increases; this makes grinding operations more difficult as the particle size decreases. Over a reasonable range of shear forces, many materials are elastic. A further property of elastic materials is that, as soon as the shear stress is removed, the strain is instantaneously removed, i.e. there are no time dependent effects. Compression forces are used to fracture friable or crystalline foods, combined impact and shearing forces are necessary for fibrous foods, and shearing forces are used for fine grinding of heat

generated in the food therefore depend on both the size of the forces and the time that food is subjected to the force. Generally, breaking strength increased with decreasing temperature (Stanley, 1986) but the effect of moisture was much more pronounced at lower screw types. Food products are required to have specific properties e.g. crispness, strength, brittleness, stringiness and fracturability (Van Den Ende *et al.*, 2003).

2.10.3.2. Physical properties

Physical properties include apparent and true densities, expansion ratio, porosity, product moisture and colour. Porosity (number/distribution of air pockets) increased with increasing expansion and decreasing breaking strength. Expansion is negatively correlated to breaking strength. This is because with more expansion, the extrudate is filled with porous structure composed of air pockets surrounded by laminar sheets of gelatinized starch and thus leads to reduction in strength.

2.10.3.3. Functional and pasting properties

Functional and pasting properties of flour and starch products are important for their use in the food industry. Characteristics of products formulated with starch, such as food thickeners and other flour or starch based products, are greatly influenced by functional and pasting properties (Niba *et al.*, 2001). According to Osundahunsi (2005), pasting characteristics is necessary to determine the nature of food if it is to be in paste form. The ability of a starch-containing food to form a paste or a gel is one of the principal factors that determine the texture and the quality of that food product. Functional properties of starch such as pasting viscosities influence the textural and gross structure of the food products and they provide information that could be used to determine specific end use applications (Henshaw and Adebawale, 2004).

Cold viscosity refers to the viscosity of a starch-water suspension at room temperature (Sopade, 1991). Ungelatinised starch absorbs few water molecules at room temperature. The gelatinised starch, however, absorbs water rapidly to form a paste at room temperature with further heating. The viscosity of the paste to a large extent depends on the degree of gelatinization of the starch granules and the extent of their molecular breakdown. Cold viscosity is the viscosity of a starch-water suspension at room temperature. Ungelatinised starch absorbs few water molecules at room temperature. The gelatinised starch, however, absorbs water rapidly to form a paste at room temperature with further heating. The viscosity of the paste to a large extent depends on the degree of gelatinization of the starch granules and the extent of their molecular breakdown. Cold

viscosity is an important property if the extruded starch will be used as an ingredient in the foods that require cold thickening capacity, like instant soups, creams or sauces.

Water absorption index (WAI) and Water solubility index (WSI) comprise starch pasting functions which are useful for starch quality analysis. The changes in starch solubility under different conditions of temperature and shear rate are monitored by measuring the Water Absorption Index and the Water Solubility Index (Fellows, 2003). The WAI of cereal products generally increases with severity of processing. The viscosity of the paste is also monitored to assess the severity of processing and to establish suitable processing conditions. Water solubility, absorption and paste viscosity are important parameters in determining quality of carbohydrate-based fat substitutes.

These characteristics have been shown to influence gelling ability, water- and fat-binding ability, and slicing ability and, hence, textural quality of food products. When the sample is suspended in water at 50°C, the measured equilibrium viscosity is called cold paste viscosity. At this stage of the analysis the structure of the sample and the degree of gelatinization will not be changed. After stabilization of the viscosity the sample is heated to 90°C at a constant rate and kept for 30 minutes at this temperature. During this heating step the gelatinization will be complete (100%). Then the sample is cooled down to 50°C. After stabilization of the temperature the measured viscosity is called hot end viscosity.

Water absorption index (WAI) is the weight of gel obtained per g of dry sample. The WSI is the weight of dry solids in the supernatant expressed as a percentage of the original weight of sample. It is the amount of soluble carbohydrate that stays permanently in the water phase when starch is submerged in water. The WAI is the weight of gel obtained after removal of the supernatant per unit weight of original dry solids. It can also be measured as total carbohydrate in solution using the phenol sulphuric acid method of Dubois as described in Miladinov and Hanna (2000) and Fang and Hanna (2001). The WAI measures the amount of water absorbed by starch and can be used as an index of gelatinization. WSI, often used as an indicator of degradation of molecular components measures the amount of soluble components released from the starch after extrusion. Choudhury and Gautam (1998) calculated WSI% and WAI% as follows:

$$WAI\% = \frac{\text{Weight of dissolved solids in the supernatant}}{\text{Weight of dissolved solids in the supernatant}} \dots\dots\dots 2.5$$

$$WSI (\%) = \frac{\text{Weight of dissolved solids in supernatant}}{\text{Weight of dry sample in the original sample}} \dots\dots\dots 2.6$$

2.10.4 System Parameters

Extrusion system variables (torque, specific mechanical energy, die pressure, and product temperature) are important parameters as well as indicators of extrusion processes. They are the controlled variables in an extruder (Chessari and Sellahewa, 2001).

2.10.4.1 Specific mechanical energy (SME)

Shear helps in the breakdown/fragmentation of granules and the heating process helps quick shear to take place. Specific mechanical energy (SME) is a common measure of extrusion energy consumption. It is an indicator of the relative ease with which a material can be extruded and the relative cost of the extrusion operation. Specific mechanical energy (SME) is the most frequently used system parameter (Yeh and Jaw, 1999). It is related to the mass transformation leading to variation in expansion, density, and geometric characteristics. SME, product temperature, and residence time have been used to predict the properties of puffed products such as expansion index and sensory characteristics. A second-order equation has been developed using SME, die pressure, temperature, and starch gelatinization to estimate the product characteristics such as diameter, apparent specific volume, breaking strength, and water absorption index (WAI) of extrudates.

SME is calculated from the torque, which is measured continuously during extrusion. The torque required to turn the extrusion screw is related to speed, fill, and the viscosity of the food material in the screw channel. Increasing screw speed results in decrease of torque. Torque is negatively related to die temperature. Second-order equation using moisture content, barrel temperature, and die temperature as independent variables has been developed to describe torque for a single-screw extruder. It was pointed out in Yeh and Jaw (1999) that a screw configuration with low conveying efficiency resulted in increased barrel fill and torque. The feed rate and screw speed are the major variables that affect the barrel fill, operating characteristics and extrudate properties. Increasing feed rate raised the torque. The degree of fill is a function of the ratio of feed rate to screw speed ($Fr:Ss$) in log scale. ($Fr:Ss$) has the unit of kg/revolution, indicating the mass taken by the screw channel per revolution of screw, which is one of the operating characteristics of an extruder. The increase in screw speed and the decrease in feed rate resulted in a decrease in degree of fill.

The increase in SME resulted in higher degree of gelatinization. Both increasing screw speed and decreasing feed rate resulted in the increase in SME and the degree of

gelatinization. Increasing SME resulted in a decrease in intrinsic viscosity, an index of the degradation of the starch molecules. Low intrinsic viscosity indicates high extent of the degradation of starch molecules. Torque was a power law function with positive power law index. The SME in the single screw extruder depends on the barrel friction and the viscosity of the material. It is often used to quantify the amount of shear that is put on material during extrusion.

For continuously operated system, SME is closely related to the maximal stresses during the operation (but not identical to it). Torque provides a direct indication of the energy absorbed by the material due to the shear exerted by the extruder screw and die nozzle. Fluctuation in torque, and hence in energy indicates erratic feed and surging (Akdogan, 1996). Hence it is a very good indicator during extrusion operation. Specific mechanical energy is defined as a total input of mechanical energy per unit dry weight of extrudate. It is often used to quantify the amount of shear that is put on material during extrusion. For continuously operated system, SME is closely related to (but not identical to) the maximal stresses during the operation.

SME (W h kg^{-3}) is calculated as:

$$\text{SME} = 2 \times \left(\frac{n \cdot 60}{\text{MFR}} \right) \times \tau \quad \dots\dots\dots 2.7$$

Where n : screwspeed (rpm), τ : torque (N-m), and MFR : mass flow rate (kg h^{-1}).

Choudhury and Gautam (1998) calculated SME using the equation below:

$$\text{SME} = \frac{n(\text{actual})}{n(\text{rated})} \times \frac{\% \tau}{100} \times \frac{P(\text{rated})}{m} \quad \dots\dots\dots 2.8$$

Where n = screw speed (rpm), τ : net torque, defined as the measured torque less than the lost frictional torque, P : motor power (kJ/s) and m : feed rate (kg/s) = production capacity.

Mechanical energy input into the material is provided by an electric motor. The power transmitted by the drive motor to the screws can be expressed as:

$$Z = f(Q^2 \mu, \mu, N, n^2) / K_f \quad \dots\dots\dots 2.9$$

Where, Q = output ($\text{m}^3 \text{s}^{-1}$), μ = melt viscosity in the die (Pa s), μ = average viscosity in the filled channels (Pa s), N = number of filled flights, n = screw speed (s^{-1}), K_f = conductivity of the die (m^3). The equation above suggests that material viscosity inside the extruder and number of filled flights (degree of fill) are two main factors affecting SME input.

Govindasamy *et al.* (1997) calculated SME using the following formula:

$$SME = \frac{T\omega}{F_r} = \frac{2\pi TS}{60F_r} \dots\dots\dots 2.10$$

Where ω is the angular velocity (rad/s), T is Torque (Nm), S is screw speed (rpm), F_r is Feed rate (Kg/h)

SME was calculated as follows in Myllymäki *et al.* (1997):

$$SME = T \omega / m = T2\pi v / m \dots\dots\dots 2.11$$

Where ω = angular velocity (1/s), v = rotational speed of screw (1/s) and m = mass flow rate (kg/h).

2.10.4.2 Temperature

The temperature of a substance may be regarded as a measure of the average kinetic energy of the molecule. According to Mottaz *et al.* (2001), the temperature field in an extruder barrel is very important and fundamental in order to estimate the heat flow patterns. This is because thermomechanical processing of the material reflects the temperature of the barrel. Both temperature and concentration of water are key elements affecting the internal structure as well as the viscoelastic properties of extruded cereals (Chi-Chuang and Yen, 2004).

Product temperature measured before the die is one of the dynamically controlled variables usually taken to reflect and predict product quality in the food extrusion (Olkku *et al.*, 1980). It is a measure of the thermal energy input in the extruded mass and it is a suitable for a system analysis of extrusion cooking (Meuser *et al.*, 1987). As a system parameter it can be used to connect extrusion cooking conditions such screw speed, moisture content, screw configuration etc. and product conversion (Water Absorption index WAI, Water Solubility Index, WSI) and thus to optimize and scale up the process appropriately (Bouvier, 2001). Hence, controlling product temperature is a major objective of sizing and thermally optimizing an extruder. Also, product temperature is the main factor that affects viscosity; hence it was used to study thermal effect on viscosity (Lam and Flores, 2003). Die temperature also influenced the viscosity of rice starch during extrusion (Chi-Chuang and Yen, 2004).

2.10.4.3. Residence Time

Residence time distribution (RTD) is a measure of the length of time material spends in an extruder and can influence the extent of both physical and chemical interactions that can occur in the extruder. It has been reported that the mean residence time is reduced by increasing screw

speed and the spread of the RTD curve is reduced by increasing feed rate (Olkku *et al.*, 1980). The studies on RTD of food materials in an extruder are to understand the flow patterns and are enabling one to predict the performance of an extruder. Although only two pieces of information (flow rate and system volume) are necessary to calculate the average residence time, it is very difficult to obtain accurate data for an extrusion process (Chi Chuang and Yen, 2004). Residence time is considered to be a system parameter that is a link between process variables such as screw speed and moisture content and product parameters such as texture and taste.

RTD is also a useful tool for the scale-up and for the determination of optimal extrusion conditions. Residence time is considered to be system parameter that is a link between process variables such as screw speed and moisture content and product parameters such as texture and taste. Residence time is characterized by Mean residence time (MRT). MRT can be used more easily to develop links between the process variables and the product properties. The residence time distribution is measured by a tracer technique. SME, product temperature, and residence time have been used to predict the properties of puffed products such as expansion index and sensory characteristics (Chi Chuang and Yen, 2004).

The tracer concentration at the exit $E(t)$ can be calculated as described by Seker (2005) as:

$$E(t) = \frac{xC_i}{\sum_{i=0}^{\infty} xC_i \Delta t} \quad \dots\dots\dots 2.12$$

The accumulated quantity of tracer at the exit is represented by the $F(t)$ curve and given by the following equation as

$$F(t) = \frac{\sum_{i=0}^t x_i \Delta t}{\sum_{i=0}^{\infty} x_i \Delta t} = \frac{\sum_{i=0}^t C_i \Delta t}{\sum_{i=0}^{\infty} C_i \Delta t} \quad \dots\dots\dots 2.13$$

and the mean residence time is calculated by the following equation as:

$$\tau = \int_0^{\infty} tE(t)dt = \frac{\sum_{i=0}^{\infty} t_i C_i \Delta t}{\sum_{i=0}^{\infty} C_i \Delta t} \quad \dots\dots\dots 2.14$$

2.10.4.4 Extrusion Pressure

According to Janssen (1978), pressure changes over the screw of an extruder originate from two sources. One source is the pressure which is developed at the die. The other is the moving wall of the extruder and the flow which occurs within the barrel itself. Compression can be achieved by back pressure created in the die and by increasing the diameter of the screw and decreasing the

screw pitch. Die pressures vary from around 2000×10^3 Pa for low viscosity products to 17000×10^3 Pa for expanded snackfoods (Fellows, 2003). A typical pressure profile of an extruder is shown in Figure 2.11. Strain gauges was used in Sivakumaran *et al.* (1986) to measure the pressure applied to thick wall pressure vessels like the expeller cage.

Pressure built up in extruders can be controlled by altering screw pitch, pitch direction, length, number of leads into the screw, angle of offset, screw fill factor and so on. Back feeding problems at higher throughput can be reduced by reducing the compression in the inlet zone. Pulsation in flow of extrudate can be reduced by adopting conical end barrel sections to give pre- die pressure development. The die end is often the highest pressure zone and the outlet cross- sectional area and land length of the die is critical in controlling pressure. Higher back pressures caused by increased packing fraction in the non- pumped regions are sensitive to product quality. Higher viscosities cause greater back flow and the reduction in plug flow causes greater residence time deviations

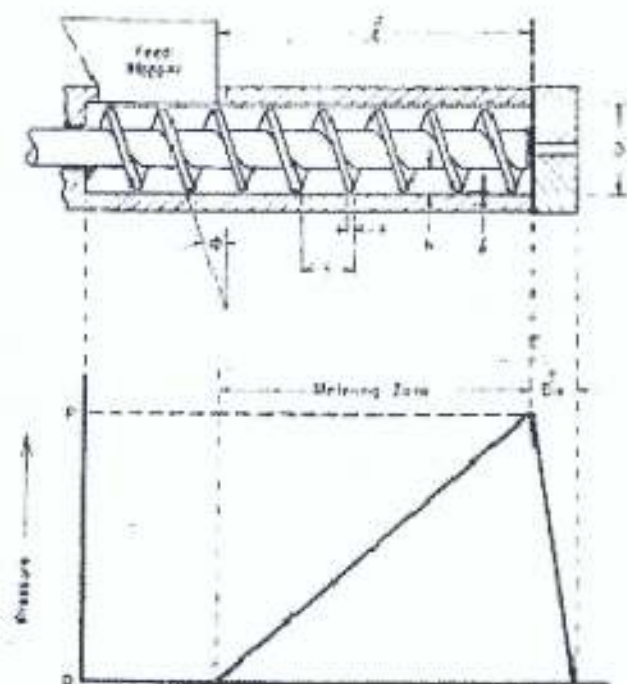


Figure 2.11: A typical pressure profile of extruders (Rossen and Miller, 1973)

3.0 DESIGN AND FABRICATION OF STARCH EXTRUDER

3.1. DESIGN CONSIDERATIONS

From the various cases of extrusion systems studied in the review of literature, the following could be considered for the effective design of the starch extruder. Particular attention was given to the following considerations:

- (a) Type of Extruder
- (b) Type of Product
- (c) Extruder Pressure
- (d) Length of Extruder
- (e) Extruder's drive mechanism
- (f) The frame
- (g) Aesthetic and design for safety during operation
- (h) Durability
- (i) Scale of Production.
- (j) Availability of materials

The extruder needed to be the dry type because of the simplicity of design.

For the research under consideration, the product was half product/pellets that could be further processed at any time up to at least one year (Guy, 2001). Since the machine was developed for food processing, it should be devoid of contaminants, as such the materials of the extruder were made corrosion resistant. All parts through which the feed material passed were made of hardened stainless steel to prevent contamination and to withstand frictional wear.

Compression was achieved by back pressure created in the die, by increasing the diameter of the screw and decreasing the screw pitch and by increasing the die length. Also, being highly viscous starch, a die pressure approaching to 17000×10^3 Pa was required (Fellows, 2003).

A major factor that determines the retention times of materials in extruder is the length of the extruder barrel. Considering the various conditions under which this extruder was subjected, it was expected that the equipment should be able to achieve a gelatinization temperature of most starchy crop, the highest of the crops under study being that of maize.

Also, according to Van Zuilichem *et al.* (1980), the length to diameter ratio (L/D) of biopolymer extruder should be shorter than that of chemical polymer so as to control chemical reactions such as burning of starches and denaturation of proteins. For food products, L/D ratios of 6 to 15 are required. Therefore, to be able to achieve a compression ratio necessary to attain to the required shear/friction necessary for gelatinization of starches on the extruder with the minimum power possible power requirement, a L/R ratio of 12 was chosen.

Fellows (2003) suggested typical screw speeds of between 150 and 600 rpm for food extruder, depending on the application. Therefore, a screw speed of 250 rpm was selected. Selection of bearings was based on axial load in one direction of the extruder, the back pressure created by the die and for combined radial and axial loads on the drive shafts. This arrangement helps in reducing the noise level of the machine to the barest minimum.

The frame forms the mounting support of all other units of the extruder. Hence stability and strength were the two major points of consideration.

Good and attractive, corporate appearance, styling and minimum noise and floor space occupancy but without compromise on functional attributes. Also, the size, shape and weight of the machine and its rigidity make it suitable for operation at any point in space. The machine could be easily dismantled and transported from one place to the other, and re-assembled together easily within a short time. the materials were selected such that the extruder cannot give sudden failure. Most moving parts were also guarded; there is minimum risk of hazards to the operator.

The strength of material, ruggedness and resistance to vibration, corrosion, and impact shock were considered in the material selection to guarantee the durability of the machine

The system (machine) was designed and constructed for small-scale/ laboratory operations. As a test rig, allowance was given for varying the screw configuration, feed rate, screw speed, die configuration and nozzle. The materials were chosen such that cost will be minimal to allow for fair market competition.

Every part of the machine was constructed with materials which could be obtained locally (except for the electric motors and gear box which are bought out components). This therefore gives the advantage of availability of spare parts when replacements are needed. The design was simple enough to make repairs easy for technicians.

3.2 DESCRIPTION AND OPERATION OF THE EXTRUDER

The dry type extruder is made up of three (3) main units namely the feeding unit, the compression and melting unit and the die unit all fabricated using locally available materials. A frame (illustrated in Drawing 3.9) fabricated from 5 mm mild steel U channel served as the mounting support for all the units. The feeding unit and the compression/melting unit are operated by one electric motor through a gear reducer and belt and pulley transmission system. As a test rig, allowance was given for varying the screw configuration, feed rate, screw speed, die configuration and nozzle. Speed regulation is done by varying the pulley ratios. All parts through which the feed material will pass were made of stainless steel to prevent food contamination and to withstand frictional wear.

3.2.1 The Feeding Unit

The feeding unit receives and transfers materials to be extruded in to the extruder and also serves to regulate the feed rate. The feeding unit is made up of a shaft which carried helicoid flightings on its surface, enclosed in a housing, bearing, a cap, pulley, hopper, tensioning plate and screw. The housing is held stationary while the rotation of the flightings causes the materials to move longitudinally. The feed rate of the extruder is regulated by changing the pulley ratio or speed of the feeding unit. The designed capacity of the conveyor is 0.53 ton/h. The extruder is kept starve fed by making the ratio of its capacity and that of the feeding screw 2:1. The unit is seated directly on top of the extruder worm. A pair of support plate made of 10 mm thick mild steel was used to keep the feeding conveyor and the extruder worm in position. The support plates also houses the bearings fixed on the extruder. It was made from 10 mm mild steel plate so that it can withstand all external loads applied to it. The unit terminates in a chute from where the conveyed food material is passed into the main extrusion unit. A cap at the outlet end of the conveyor serves to prevent overloading or clogging of the chute. The pitch of the flightings (40 mm) is made small relative to the diameter of the conveyor diameter to allow for easy movement of wet materials. The screw shaft diameter is 25 mm while the screw flight diameter is 66 mm. The outer diameter of the housing is 76 mm made from 2mm thick stainless steel pipe. The hopper was joined to the conveyor through a pair of flat bar welded on the sides of the conveyor housing. Figure 3.1 shows the sketch of conveyor screw and its housing.

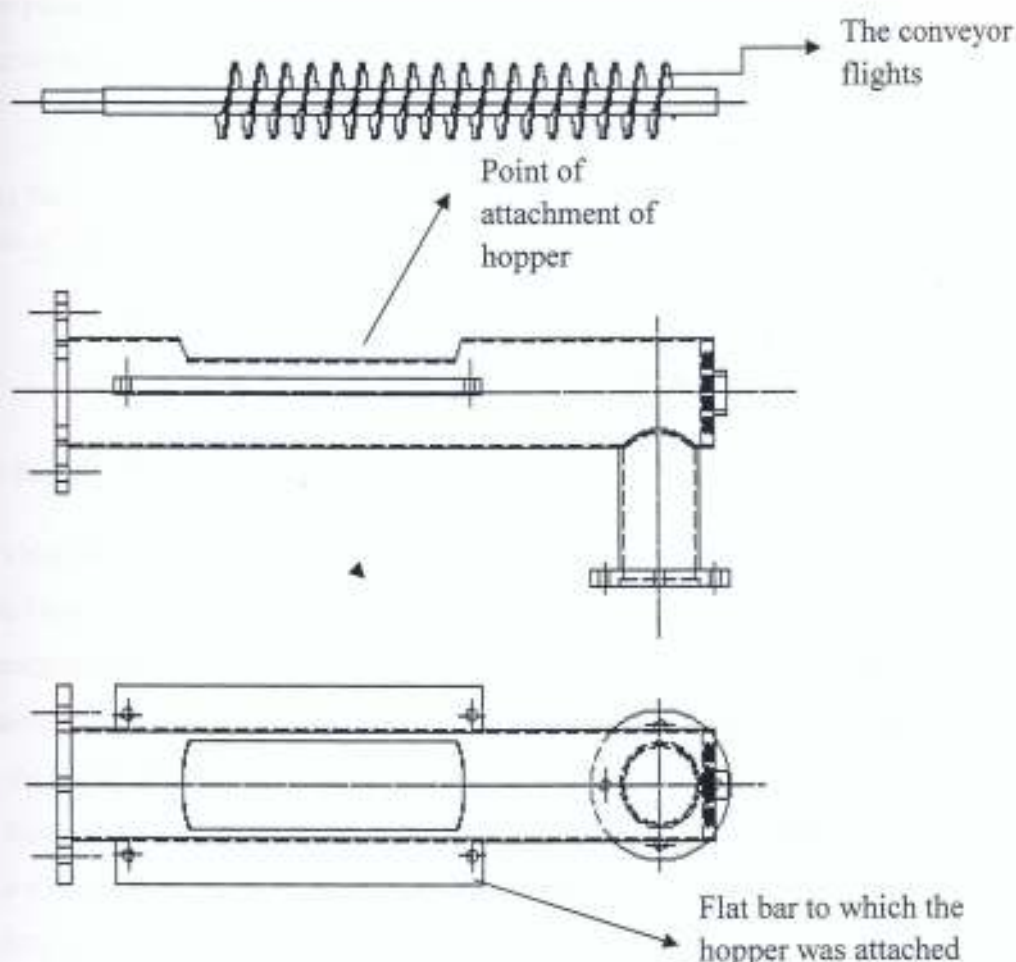


Figure 3.2: Sketch of conveyor housing showing the point of attachment of the hopper.

3.2.2 The Compression /Melting Unit

This unit subjects the food material simultaneously to mixing, heating and shear. It comprise of a screw, barrel, bearings, pulleys and locknut. The screw is of single flight, increasing diameter and tapering/decreasing pitch with a compression ratio of 4.5:1. The diameter of the final portion of the screw is reduced to a cone. This aid in pressure built up, easy conveyance of materials through the die and in reducing wear rate. The length to diameter ratio is 12:1. The screw (extruder worm) rotates in a barrel which has a hardened liner. The details of the extruder worm and its barrel are shown in Drawing 3.5. The barrel made from 80 mm diameter; 8 mm thick stainless steel hollow shaft is fixed with nuts on studs located on the support plates. An electric motor drives the screw through a gear reducer, and the backward thrust of the screw is absorbed by a thrust bearing. The Power is transmitted to the extruder shaft from the power train through a shaft suspended by a pair of taper roller bearing, mounted back to back. The bearing housing is welded to the support

plate at the pulley end of the extruder. The extruder worm is keyed into a cup provided on the extruder driving shaft. A sketch of the extruder driving shaft is shown in Figure 3.2.

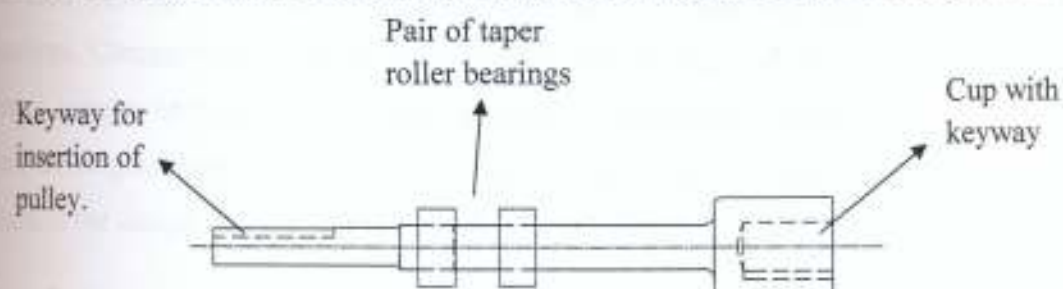


Figure 3.2: Sketch of the extruder driving shaft.

When it is close to the discharge end, i.e., near the die, the material being extruded has been transformed into a thermoplastic, viscoelastic materials at high pressure. It is worthy of note that the equipment performed excellently immediately it started operation because of the high precision attained during the fabrication of its components and in final assembly. The barrel and the screw/die configuration is typical of alimentary food production equipment. There are three speeds of the feeding conveyor and the extruder screw. The extruder is fitted with a switch that controls its starting. Also, tensioning of the extruder belt and pulley with a vertical tensioning provided on the motor - gear seat. All parts of the extruder are made replaceable.

3.2.3 The Die Unit

The die unit directs the compressed and viscoelastic material into the nozzle that forms its final shape. It also provides a resistance against which the screw must pump the extrudate. It is the outlet for the extruder. It consists of the die and a set of changeable nozzles. The die has a circular cross-section. The die unit is coupled to the compression unit through six bolts and nuts while the nozzle is screwed onto the die through the threadings provided on it. The extrudates were extruded as ribbons to be cut with a rotary cutter. The detailed Extruder Drawings are shown in Drawings 3.1 – 3.19.

3.3 DESIGN ANALYSIS OF EXTRUDER COMPONENTS

The food extruder was designed using conventional engineering principles and standard equations. Components of the extruder include the feeding conveyor, power transmission system, hopper, extruder die, bearing selection etc. Parameters designed for include shafts, sizes, die length, hopper capacity and dimension, pulley and belt sizes, belt tension, etc. The details of the design calculations are shown in Appendix 1.

3.3.1 Design of the Extruder Worm

3.3.1.1 Assumptions and data requirements

The design principle of power screw was applied in the design of this screw worm. Compression is achieved in the extruder by decreasing the screw's pitch along its length. According to Van Zuilichem *et al.* (1980), the L/D of biopolymer extruder should be shorter than that of chemical polymer so as to control chemical reactions such as burning of starches and denaturation of proteins. For food products, L/D ratios of 6 to 15 are required. Also, in order to effect good production of the parts, the following dimensions are chosen based on the limit of available materials locally. A minor diameter of 40mm was chosen. it will distort under arc welding. The clearance between the screw and the barrel is 1.3mm. The design is made similar to a continuous screw press/expeller. The relationship between the length of screw S , number of flights n and common difference in pitch d and the first pitch a is given by arithmetic progression

$$S_n = \frac{n}{2\{2a + (n-1)d\}} \dots\dots\dots 3.1$$

With length = 750mm, $n = 13.8$ mm, $d = - 1.5$

The pitch $U_n = a + (n-1) d$, maximum pitch = 45mm

Minimum pitch = 24. The last three pitches to bear similar size (Zuilichem *et al.*, 1980)

The screw is assumed to be a screw thread loaded as a cantilever beam. The detailed design of the extruder worm and its surrounding barrel is shown in Drawing 3.5

3.3.1.2 Determination of the compression ratio of the extruder

In view of the fact that heat will be provided through viscous dissipation for gelatinization of starch, compression was achieved by using a tapering shaft diameter and decreasing screw pitch (Fellows, 2003).

$$\text{Compression Ratio} = \frac{V_1}{V_2} \dots\dots\dots 3.2$$

Where V_1 = Volume of first pitch and

V_2 = Volume of the last pitch

The compression ratio was determined to be 4.437:1

3.3.1.3 Determination of the theoretical volumetric capacity

Theoretical volumetric capacity Q_t was calculated according to Srivastava et al. (1996) as

$$Q_t = \frac{\pi}{4} (d_f^2 - d_{ss}^2) l p n \dots\dots\dots 3.3$$

Where Q_t = theoretical volumetric capacity (m^3/s)

d_f = screw flight diameter (m)

d_{ss} = Screw shaft diameter (m)

$l p$ = Pitch length (m)

n = Screw rotational speed (rev/s)

The theoretical volumetric capacity, Q_t is calculated to be $3.6738 \times 10^{-4} \text{ m}^3/\text{s}$ while the mass flow rate = 1.059 ton/h. The torque on the shaft is calculated to be 305.66 Nm.

3.3.1.4 Determination of Power Requirement of Extruder

The power requirement for the extruder is calculated using the equation below according to PSGTECH (1982)

$$N = Q L \frac{W_0 \pm \sin \beta}{367} \frac{1}{\eta} \dots\dots\dots 3.4$$

Where N is Power (kW),

Q is the Volumetric capacity (ton/h),

L is length of screw (m),

W_0 is material factor (4 for powder),

β is angle of inclination of screw shaft to horizontal and

η is efficiency of gear reducer.

The power requirement of the extruder was calculated to be 1.083 kW. However, with a compression ratio of 4.437:1, the expected pressure generated at the die end of the extruder worm is $2.95 \text{ MN/m}^3 \times 4.437 = 13.1 \text{ MN/m}^2$. Therefore, the power required to cater for the back pressure created by the die due to the high compression ratio developed at the same Q , = 4.78 kW. Hence, the Power requirement of the extruder worm is 4.78 kW.

3.3.2 Design of Extruder Barrel

The barrel (cylinder) is designed on the basis of internal pressure. If the screw housing is treated as a thick wall cylinder, then using the standard and stress analysis technique applied to thick walled pressure vessels (Sivakumaran and Goodman, 1987), the tangential stress, σ , perpendicular to the axis of the cylinder is

$$\sigma = \frac{2P_c D_c^2}{(D_o^2 - D_c^2)} \dots \dots \dots 3.5$$

Where, P_c = designed Pressure in Extruder

D_o = outer diameter of cylinder

D_c = inner diameter of cylinder

The details of the design calculations are shown in Appendix 1.

3.3.3 Design of Hopper

The hopper is the housing where the material to be extruded are stored and fed into the machine at a determined rate. This hopper is to have a shape which facilitates loading, maximum volume utilization, a reliable and complete gravity discharge through the outlet. In predicting the lateral pressure in design of hoppers for gravity flow the coefficient of friction between granular materials is needed as a design parameter (Monsehnin, 1970). The coefficient of friction of coffee pulp, 0.73 which is similar to the materials to be studied in this work was selected. Hence, an angle exceeding $\tan^{-1} 0.75 = 36.12^\circ$ was used. An angle of inclination of 50° was selected for the hopper sides. The volume of the hopper which has the shape of a frustum = $1/3$ (Volume of Big Pyramid) – $1/3$ (Volume of Small Pyramid). The hopper was assumed to seat on $1/4$ of the circumference of the surface area of the cylinder. The top dimension of the hopper is 360 mm by 360 mm.

3.3.4 Design Analysis of Feeding Conveyor

The feeding conveyor was designed according to PSGTECH (1982) as follows:

Capacity of conveyor, $Q = 15\pi D^2 S n \psi \rho c \dots \dots \dots 3.6$

3.3.5 Design Analysis of Power Transmission System

The design analysis of power transmission system was carried out following the procedure of PSG TECH (1982). 'C' belt was selected for the extruder worm while 'A' belt was selected for the feeding conveyor. The relationships below were used to obtain necessary parameters.

The diameter of pulleys were determined using $d_2 n_2 = n_1 d_1 \eta$ 3.7

Where η the efficiency = 0.98

d_2 is the diameter of the driver pulley,

d_1 is the diameter of the driven pulley,

n_2 is the speed of the driver pulley and

n_1 is the speed of the driven pulley.

The nominal pitch length of belt L is given by

$$L = 2c + \pi/2 (d_2 + d_1) + (d_2 - d_1)^2 / 4c \dots\dots\dots 3.8$$

The actual value of the center distance c of pulley is given by the formula

$$C = A + \sqrt{A^2 - B} \dots\dots\dots 3.9$$

Where $A = L/4 - \pi d_2 + d_1$ and

$$B = \frac{(d_2 - d_1)^2}{8} \dots\dots\dots 3.10$$

$$\text{Number of belts, } N = \frac{P \times F_a}{kW \times F_c \times F_d} \dots\dots\dots 3.11$$

Where P is power required, correction factor for industrial service F_a , value of the correction factor, F_c , The value of the correction factor for the arc of contact, F_d .

The outer and inner sides of the extruder shaft driving belts are subjected to a tension of 450.68 N and 67.60 N respectively while the values for the feeder shaft are 275 N and 43.8 N. The center distance between the driving and driven pulley of the extruder shaft is 648 mm while that of the feeder shaft is 248 mm. Two belts were designed for the extruder worm while one was designed for the feeding conveyor. The details of the design calculations are shown in Appendix 1.

3.3.6 Screw Shaft Designs

Shaft design consists primarily of the determination of a correct diameter to ensure satisfactory strength and rigidity when the shaft is transmitting power under operating and loading conditions. Therefore, the shafts will be designed from the stand point of strength and rigidity.

worm while one was designed for the feeding conveyor. The details of the design calculations are shown in Appendix 1.

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3.3.6.1 The design of the extruder screw shaft

Total uniformly distributed load on extruder shaft = 3.08/m. The centrifugal force due to the belt on the extruder screw shaft was determined to be 0.219.N while the maximum torsional moment =

53.63 Nm. The maximum bending moment = 277.70 Nm. The required diameter for a solid shaft with little or no axial loading but having combined bending and torsional loads, is obtained as follows from ASME code equation:

$$D^3 = 16 / \pi S_s \sqrt{(K_b M_b)^2 + (K_t M_t)^2} \dots \dots \dots 3.12$$

Where d= diameter shaft

S_s = allowable stress

K_b = shock and fatigue factor applied to bending moment,

M_b = maximum bending moment,

K_t = shock and fatigue factor applied to torsional moment,

$$M_t = \text{Maximum torsional moment} = (T_1 - T_2)r \dots \dots \dots 3.13$$

T_1 = Belt tension on loose side

T_2 = Belt tension on tight side

R = inner radius of pulley (disc).

Diameter = 37.65 m

The details of the design calculations are shown in Appendix 1.

3.3.6.2 Feeder shaft design

Total uniformly distributed load of 219.145N was calculated to be acting on the conveyor shaft.

The centrifugal force due to the belt on the extruder screw shaft was determined to be 0.056 while the maximum torsional moment = 42.33 Nm. The radial force on the shaft from

The centrifugal force due to the belt on the extruder screw shaft was determined to be 0.056 while the maximum torsional moment = 42.33 Nm. The radial force on the shaft from the V – belt drive of pulley is 318.8N. The diameter is designed to be 25mm. The details of the design calculations are shown in Appendix 1.

3.3.7 Design of Extruder Die

The extruder die was design according to Frame (1994) using the following equation for a die of circular cross section,

$$Q = K_d \frac{P_d}{\mu} \dots\dots\dots 3.14$$

Where Q = volumetric flow rate,

P_d = Total pressure drop,

μ = Dough viscosity at the die

K_d = die constant which is a function of geometry

Also, die constant for cylindrical die is given by equation 3.38 as follows:

$$K_d = \frac{\pi R^4}{8L_d} \dots\dots\dots 3.15$$

Where R = nozzle radius,

L_d = length of die,

μ = viscosity of material,

P_d = pressure

The extrusion pressure P is also the P in the die equation and the Q for the die is the same as Q_{out} in the extruder. Pressure at the exit of die is assumed to be 0.

A die length of 10 mm was calculated. However, in order to increase/ improve on the operating die pressure, according to Sohkey *et al.* (1997), the die length was multiplied by 2. Hence a die length of 20 mm was selected. The details of the design calculations are shown in Appendix 1.

3.3.8 Bearing Selection

The following bearings were selected for this work.

- (1) Single thrust bearing: This was fixed on the extruder shaft to cater for axial load in one direction and the back pressure created by the die.
- (2) Taper roller bearing: A pair of these was mounted back to back on the extruder driving shaft for combined radial and axial loads. This arrangement helps in reducing the noise level of the machine to the barest minimum.
- (3) Self aligning ball bearings. This was mounted on conveyor screw shaft.

3.4 FABRICATION OF EXTRUDER COMPONENTS PARTS

The components were fabricated at the Agricultural Engineering Workshop of the Federal University of Technology, Akure and the Mechanical Workshop of the Rufus Giwa Polytechnic, Owo., Nigeria. The extruders worm was taper turned by the use of taper turning attachment on a central lathe and also by manipulation of the alignment of tail stock. The flights were formed and welded using the following procedure:

Firstly, 65 mm diameter solid rod was cut into 15mm length pieces with a power saw. Each piece was turned and surfaced by holding with a dependent 3 jaw chuck on the lathe to a consistent 625mm x 10mm thickness. A stencil of the flight was used to indicate the point on the shaft. The corresponding diameter of each point of the flight is noted. Then each prepared disc (flight) was drilled with 35mm drilling but on a turret heavy duty drilling machine before it urge bored to the required size of the flight on the tapered shaft. The disc was cut through reach the bored hole and drawn out with chain block. Thereafter each piece was in its corresponding position on the shaft beginning with the biggest end of the shaft. The flights were then tacked into place and full welding was done. Then the driver end of the shaft was step turned and a key way provided by a milling machine. Threading of the screw conveyor cap for locking purpose was done on the lathe. The thread was cut counter clockwise. The cap serves to prevent overloading or clogging of the extruder-feeding chute. The whole extruder conveyor was then position on the lathe to correct any distortion, wobbling and the diameter reduced to 61.5mm. Also the die was step turned to reduce its weight while the end of the die nozzle was threaded on the lathe.

The following equipment and machines were used in the fabrication and assembly of the extruder:

Guillotine was used to cut the cover plates, in complement with oxyacetylene flame cutting. Bending machine was used to bend then cover plates that required forming in shapes. Oxy-acetylene welding equipment set was used with the flame cutting nozzle to cut the extruder's support plates. Power saw was used to cut the extruder shaft, barrel, screw conveyor, its housing and motor seat while the conveyor flights and cover plates concave shapes were cut with a shear. Pulleys were cast using sand casting equipment, viz, sand moulds in cope and drag, furnace, pattern. Drilling machine was used to drill all bolt holes to facilitate assembly. Milling machine was used to cut the key ways on the extruder worm shaft, driving shaft and screw conveyor shaft.

The lathe machine was used produce the extruder's tapered shaft, the extruder worm's multi-pitch blades, screw conveyor shaft, driving shaft, hub finish machining of the pulleys and so on. Power saw was used to cut the solid shaft and angle iron frame members to their various sizes. Necessary mitering was done with hacksaw. Arc Welding Machine was used to join the subassemblies, i.e. the frame extruder worm barrel, extruder worm, base plate and motor seat and the inlet chute. Chain Block was used to draw the worm and conveyor blades. Also tools like scribe, try square and spirit levels were used to ensure perfect square.

In summary, the following processes were carried out during the fabrication of the extruder;

Taper turning by setting over the lathe machine tailstocks; taper turning by setting the compound slide; parallel turning; step turning; boring; milling, slotting, sand casting, oxyacetylene flame-cutting, drilling, arc welding, marking out, sawing and bending. Alignment of the extruder and hub support plates holes were done to eliminate vibration and safeguard the bearings. However, it was observed that a gearbox is required to improve the torque provided by the drive. Therefore, a speed reducing gear of ratio 25: 1 was incorporated and the corresponding diameters of the pulleys were to achieve 100, 150 and 200 rpm were estimated and provided.

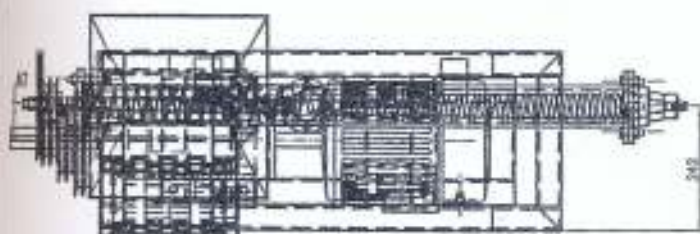
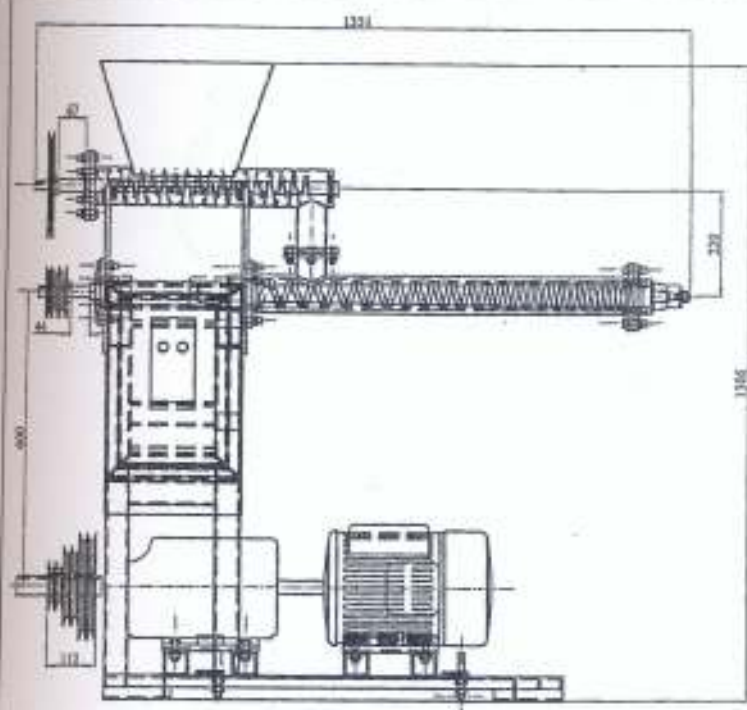
3.5 ASSEMBLY OF EXTRUDER

The machine was assembled and tested after fabrication. The detailed description of how the components of the extruder were assembled relative to one another is shown in Drawing 3.4. Provision was made for tensioning of pulley belts, which was in turn seated in the driving shaft hub the hub being screwed to the support plate. The three-bell-ways

pulley was keyed to the driving shaft. The electric motor and speed-reducing gearbox were secured on their seats with bolts and nuts and coupled together. Coupling was used to connect the pinion from electric motor to the speed reducer shaft. The motor pulley was keyed to the output of the gearbox; the belt was fixed and tensioned, properly aligning the two pulleys.

The cover plates were fastened to their positions with bolts and nuts the extruder worm barrel was fastened to the support plate with the aid of six studs and nuts. The die and nozzle are then attached. The screw conveyor was attached to its housing with the aid of a flange and bolts and nuts. The single belt pulleys were keyed to the screw conveyor at the rear. The belt was fixed, tensioned and aligned with the motor pulley. The inlet chute was attached to the screw conveyor housing which was in turn bolted to the extruder worm barrel.

**ENGINEERING
DRAWINGS OF
MACHINE**

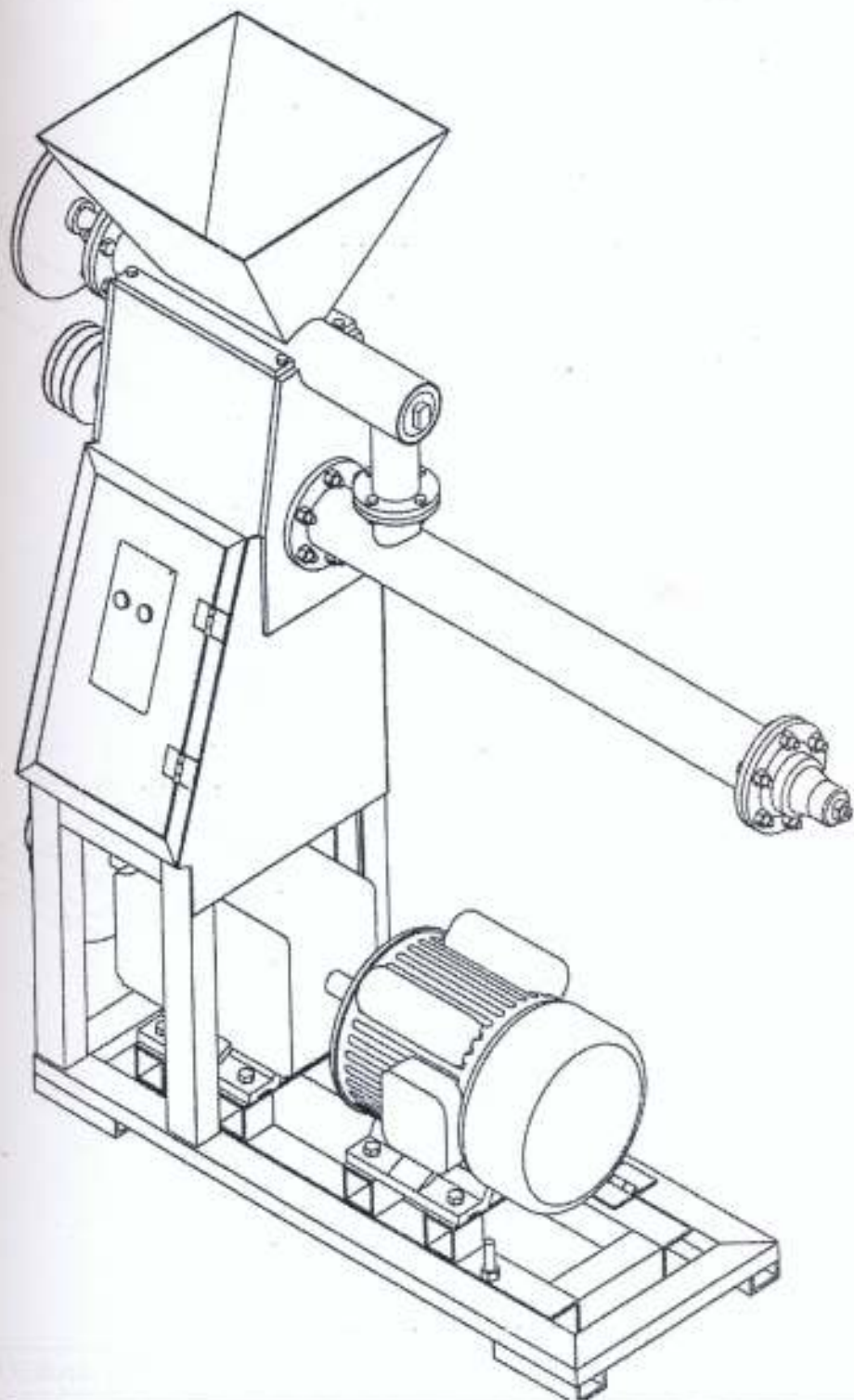


FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

Department AGRICULTURAL ENGINEERING

Description ORTHOGRAPHIC PROJECTION OF STARCH EXTRUDER

	Name	Signature	Date
Designed and Drawn by	ENGR. (MRS) F. T. FAYOSE		
Supervised by	(1) PROF. A. S. OGUNLOWO (2) DR. L. A. S. AGBETOYE		
Checked by	DR. L. A. S. AGBETOYE		
Approved by	PROF. A. S. OGUNLOWO		
Material	See detail drawing		
All Dimensions in mm	Drawing 3.1	Scale 1:7.5	Matrix No. 85/473

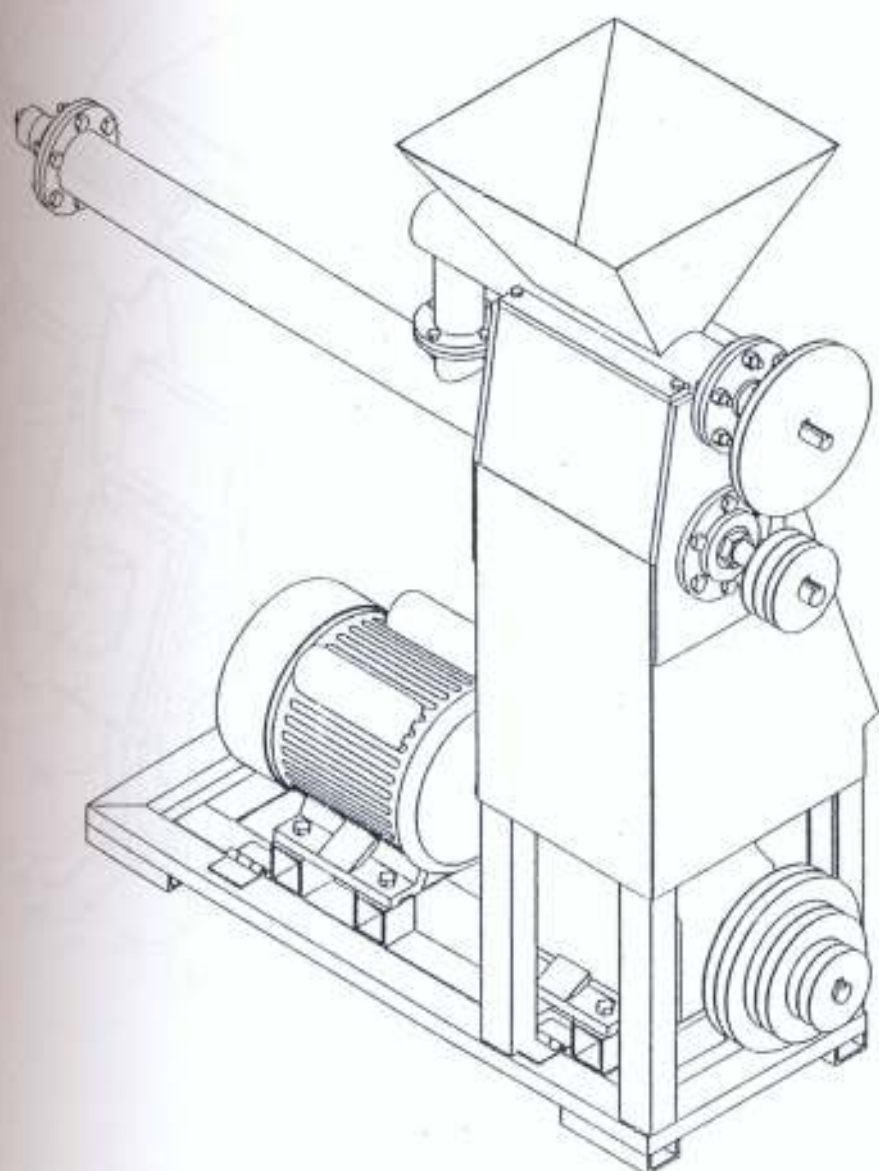


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Department AGRICULTURAL ENGINEERING

Description FIRST ANGLE ISOMETRIC VIEW OF STARCH EXTRUDER

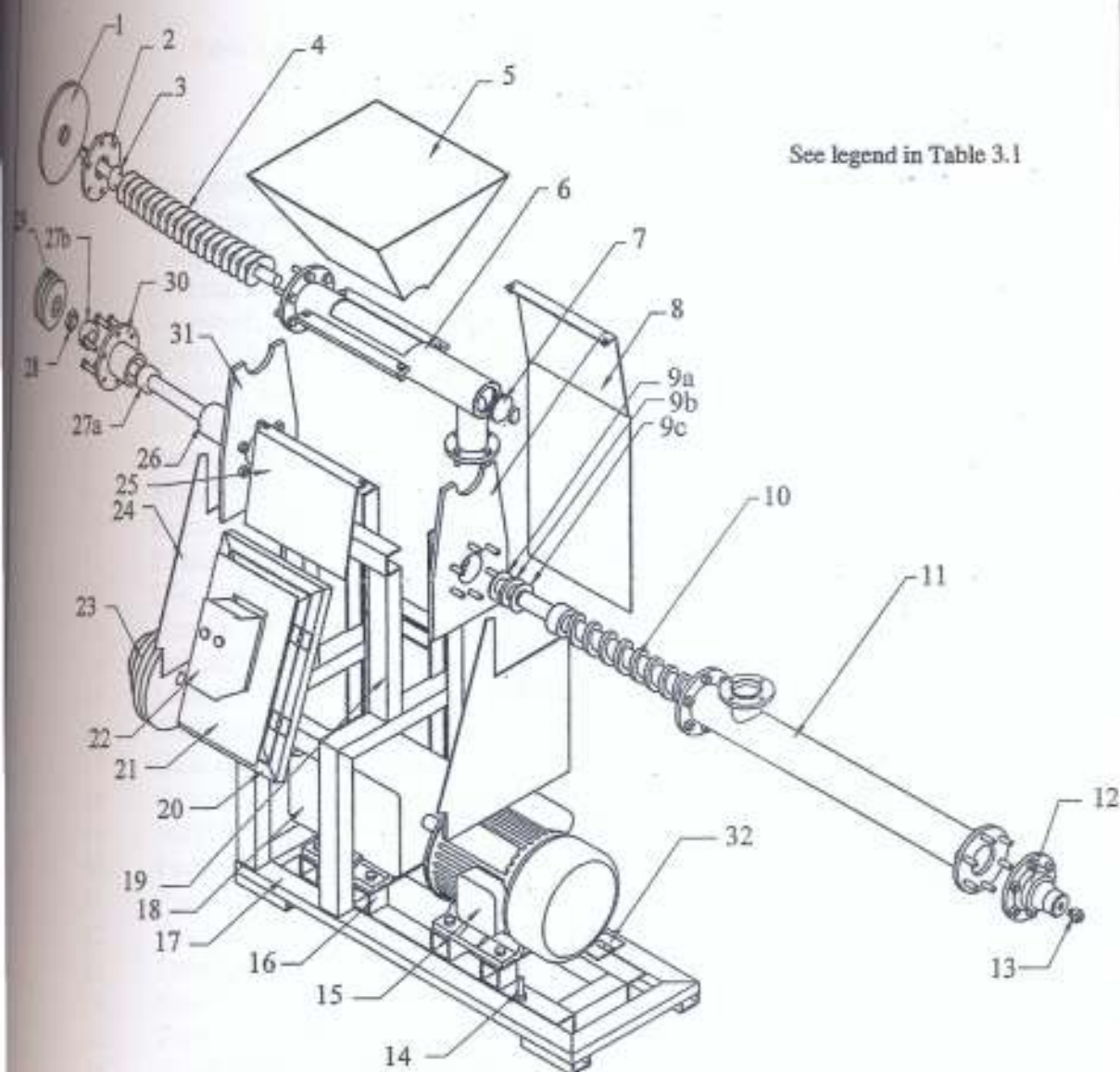
	Name	Signature	Date
Designed and Draws by	ENGR. (MRS) F. T. FAYOSE		
Supervised by	(1) PROF. A. S. OGUNLOWO (2) DR. L. A. S. AGBETOYE		
Checked by	DR. L. A. S. AGBETOYE		
Approved by	PROF. A. S. OGUNLOWO		
Material	See detail drawings		
All Dimensions in mm	Drawing 3.2	Scale 1:7.5	Matric No. 85/473



FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

Department	AGRICULTURAL ENGINEERING
Description	THIRD ANGLE ISOMETRIC VIEW OF STARCH EXTRUDER

	Name	Signature	Date
Designed and Drawn by	ENGR. (MRS) F. T. FAYOSE		
Supervised by	(1) PROF. A. S. OGUNLOWO (2) DR. L. A. S. AGBETOYE		
Checked by	DR. L. A. S. AGBETOYE		
Approved by	PROF. A. S. OGUNLOWO		
Material	See detail drawing		
All Dimensions in mm	Drawing 3, 1	Scale: 1:7.5	Matric No. 85/473



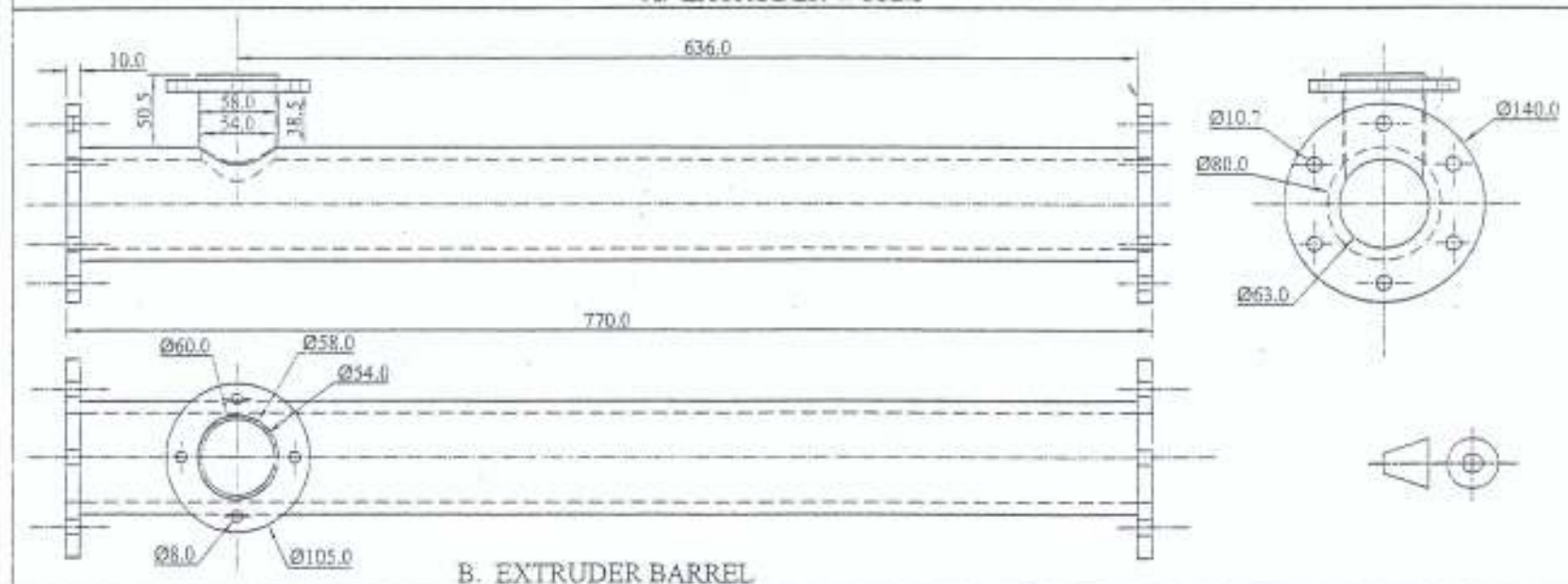
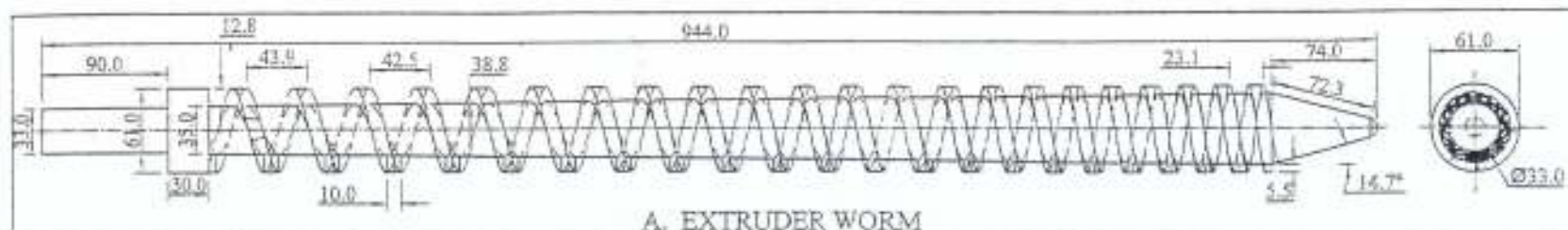
FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

Department	AGRICULTURAL ENGINEERING		
Description	DETAILED DRAWING OF STARCH EXTRUDER		
	Name	Signature	Date
Designed and Drawn by	ENGR. (MRS) F. T. PAYOSE		
Supervised by	(1) PROF. A. S. OGUNLOWO (2) DR. L. A. S. AGBETOYE		
Checked by	DR. L. A. S. AGBETOYE		
Approved by	PROF. A. S. OGUNLOWO		
Material	See detail drawings		
All Dimensions in mm	Drawing No. 4	Scale: 1:12.5	Matric No. 85473

Table 3.4 List of the component parts

LEGEND

Item	Description	Qty
1	Conveyor pulley, Sect.A 214 ϕ	1
2	Flange, 140 ϕ	1
3	Bearing, 20 ϕ	1
4	Conveyor, S.S plate, 75 mm ϕ	1
5	Hopper, 2mm S.S plate,	1
6	Housing, 76mm ϕ Inner, 80mm ϕ outer	1
7	Housing Plug, 10mm thick S.S Plate	1
8	Rear Cover Sheet, 3mm thk. S.S Plate	1
9	Thrust Bearing, 30 ϕ	1
10	Extruder worm, 61 ϕ see drawing 1	1
11	Extruder Barrel, 63mm ϕ 80mm ϕ X 75mm Lng. S.P.	1
12	Die, Stainless Steel Plate	1
13	Nozzle, 6mm ϕ Die Stainless Sheet Rod	1
14	Belt Adjuster, M  X 90 Lng	1
15	Motor, 3 Phase, 4 KW Electric Motor	1
16	Gear Seat, 4mm thick < bar	1
17	Base Frame, 5mm thick M.S U-Channel	1
18	Gear Box, 25.1 Speed reducing Gearbox	1
19	Main Frame, M.S U 50mm thick U-Channel	1
20	Panel Frame, M  25mm	1
21	Panel Cover Sheet, M.S Sheet G.16	1
22	Control Switch,	1
23	Driver Pulley (B-belt), B, 100 ϕ , 126 ϕ	3
24	Side Cover Sheet, 3mm M.S Plate	1
25	Front Cover Sheet, 3mm M.S Plate	1
26	Shaft With Cup, M.S Rod 60 ϕ	1
27	Taper Roller Bearing, ϕ 30	2
28	Lock Nut, 32 ϕ	1
29	Extruder Pulley, (A&B belts), Sect. (A&B) 107 ϕ	3
30	Hub, M.S Plate	2
31	Hub Support Plate, 10mm M.S Plate	2
32	Hinge, 50mm	2

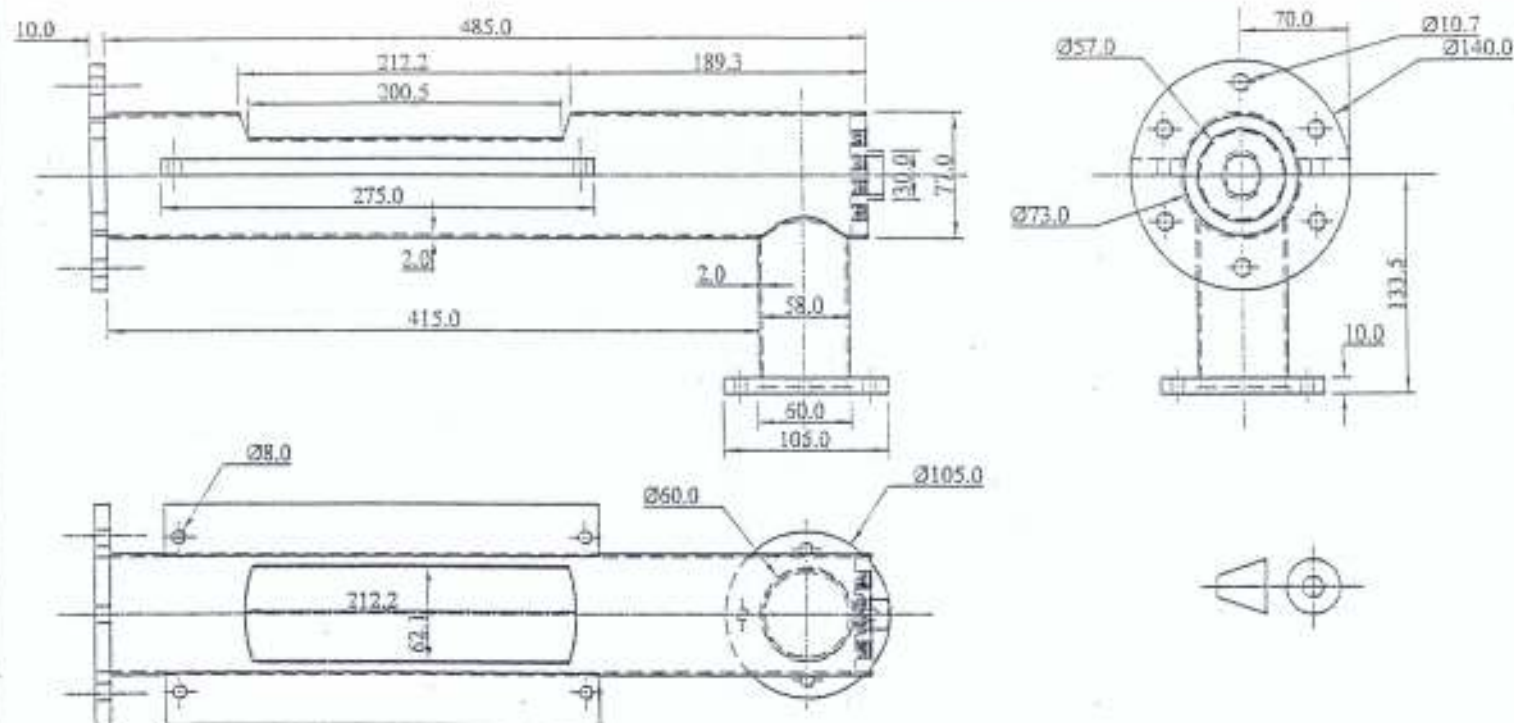


FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

Department: AGRICULTURAL ENGINEERING

Description: EXTRUDER AND EXTRUDER HOUSING

	Name	Signature	Date
Designed and Drawn by:	ENGR. (MRS) F. T. FAYOBE		
Supervised by:	(1) PROF. A. S. OGUNLOWO (2) DR. L. A. S. AGBETOYE		
Checked by:	DR. L. A. S. AGBETOYE		
Approved by:	PROF. A. S. OGUNLOWO		
Material:	Stainless steel, mild steel, brass and flange		
All dimensions in mm	Drawings: 3:1	Scale: 1:1	Main No: BSMTT

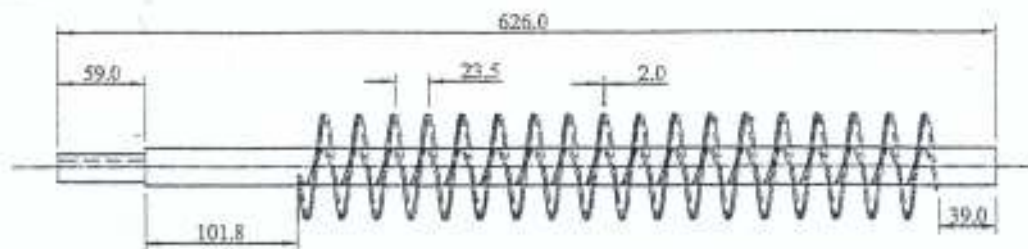


FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

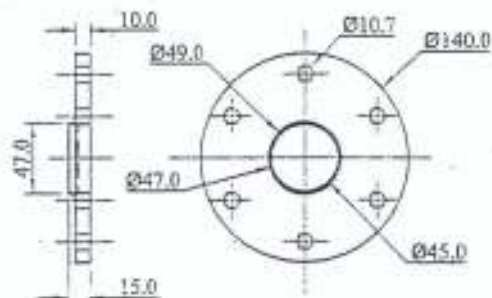
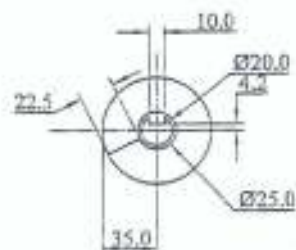
Department AGRICULTURAL ENGINEERING

Description CONVEYOR HOUSING

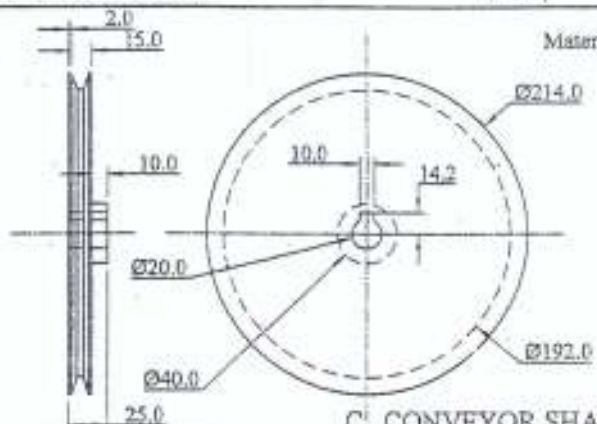
	Name	Signature	Date
Designed and Drawn by	ENGR. (MRS) F. T. FAYOSE		
Supervised by	(1) PROF. A. S. OGUNLOWO (2) DR. L. A. S. AGBETOYE		
Checked by	DR. L. A. S. AGBETOYE		
Approved by	PROF. A. S. OGUNLOWO		
Material	2mm thick stainless steel hollow pipe		
All Dimensions in mm	Drawing 2.0	Scale 1:1	Matric No. 85/473



A. CONVEYOR SCREW



B. CONVEYOR SCREW SUPPORT FLANGE



C. CONVEYOR SHAFT PULLEY

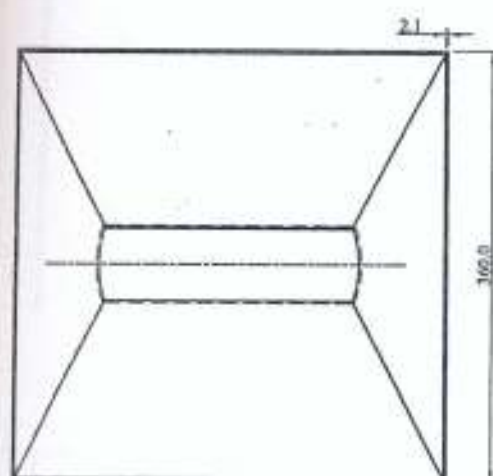
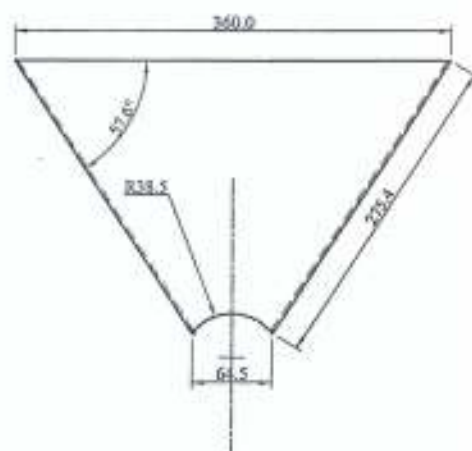
Material: Cast Steel

FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

Department AGRICULTURAL ENGINEERING

Description CONVEYOR DETAILS

	Name	Signature	Date
Designed and Drawn by	ENGR. (MRS) F. T. FAYOSE		
Supervised by	(1) PROF. A. S. OGUNLOWO (2) DR. L. A. S. AGBETOYE		
Checked by	DR. L. A. S. AGBETOYE		
Approved by	PROF. A. S. OGUNLOWO		
Material	Stainless steel sheet, shaft and flange (C not included)		
All Dimensions in mm	Drawing 3:1	Scale 3:1	Matrix No. RS/473

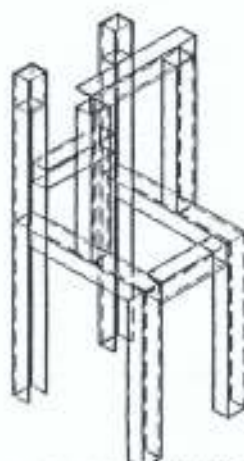
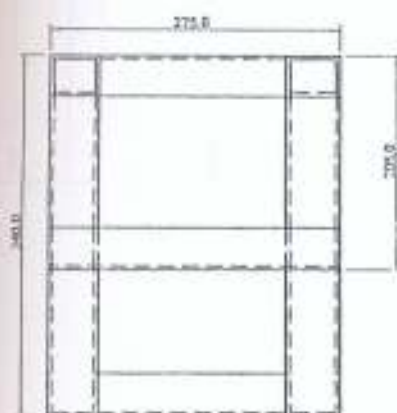
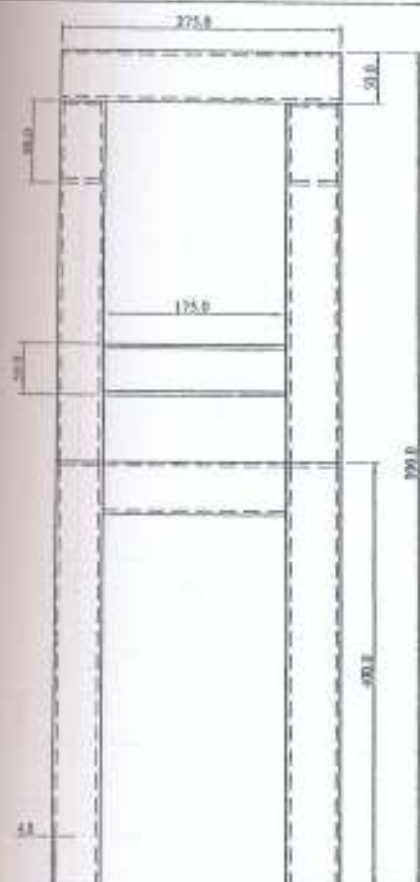


FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

Department AGRICULTURAL ENGINEERING

Description HOPPER

	Name	Signature	Date
Designed and Drawn by	ENGR. (MRS) F. T. FAYOSE		
Supervised by	(1) PROF. A. S. OGILLOWO (2) DR. L. A. S. AGHETOYE		
Checked by	DR. L. A. S. AGHETOYE		
Approved by	PROF. A. S. OGILLOWO		
Material	Stainless steel sheet		
All Dimensions in mm	Drawing 3. 8	Scale 1:5	Matric No. 85/473

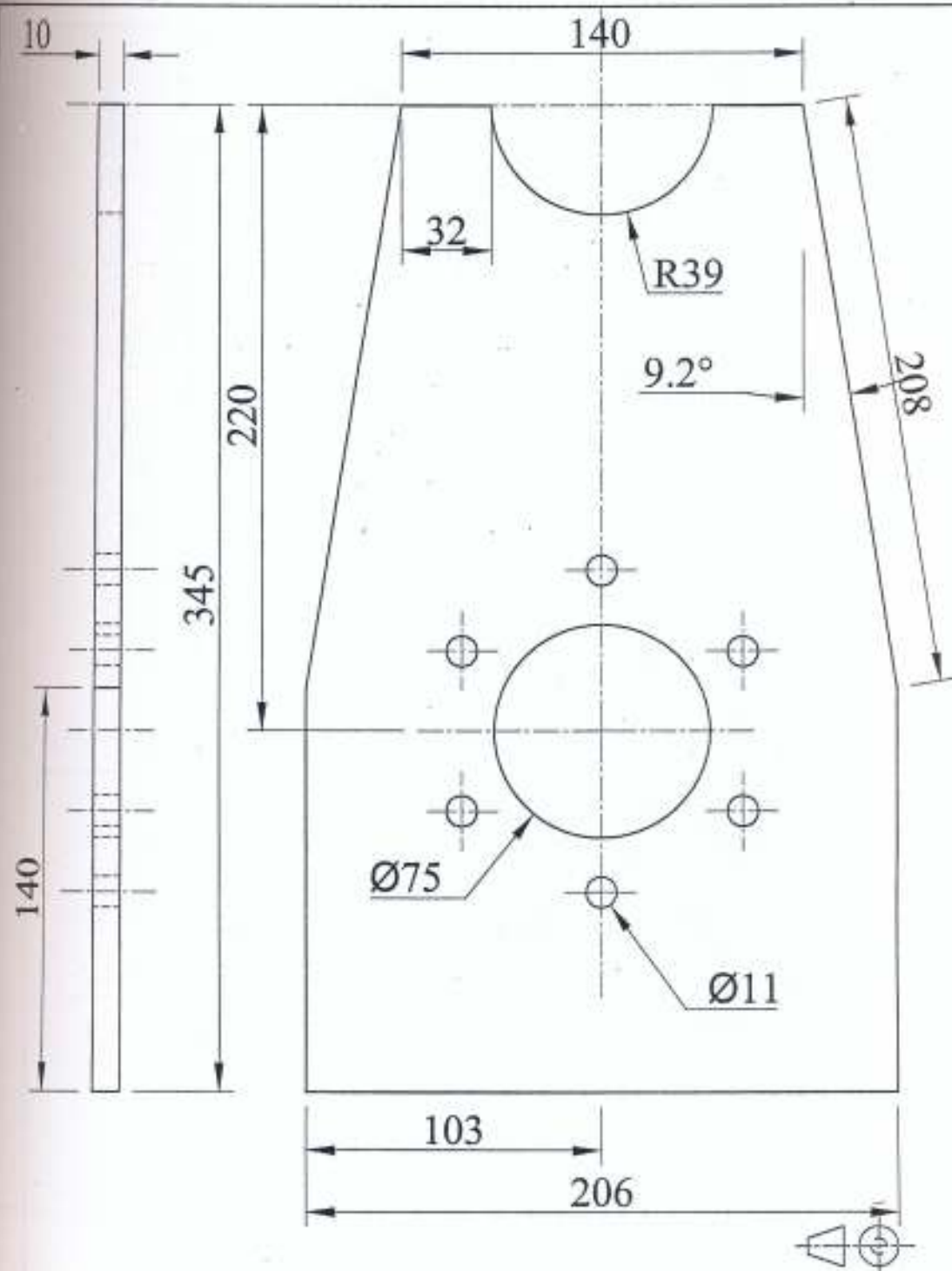


ISOMETRIC VIEW

FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

Department: AGRICULTURAL ENGINEERING
Description: MAIN FRAME

	Name	Signature	Date
Designed and Drawn by	ENGR. (MRS) F. T. FAYOSE		
Supervised by	(1) PROF. A. S. OGUNLOWO (2) DR. L. A. S. AGBETOYE		
Checked by	DR. L. A. S. AGBETOYE		
Approved by	PROF. A. S. OGUNLOWO		
Material	Mild steel U channel		
All Dimensions in mm	Drawing 3.9	Scale 1:4.5	Matric No. ES/473

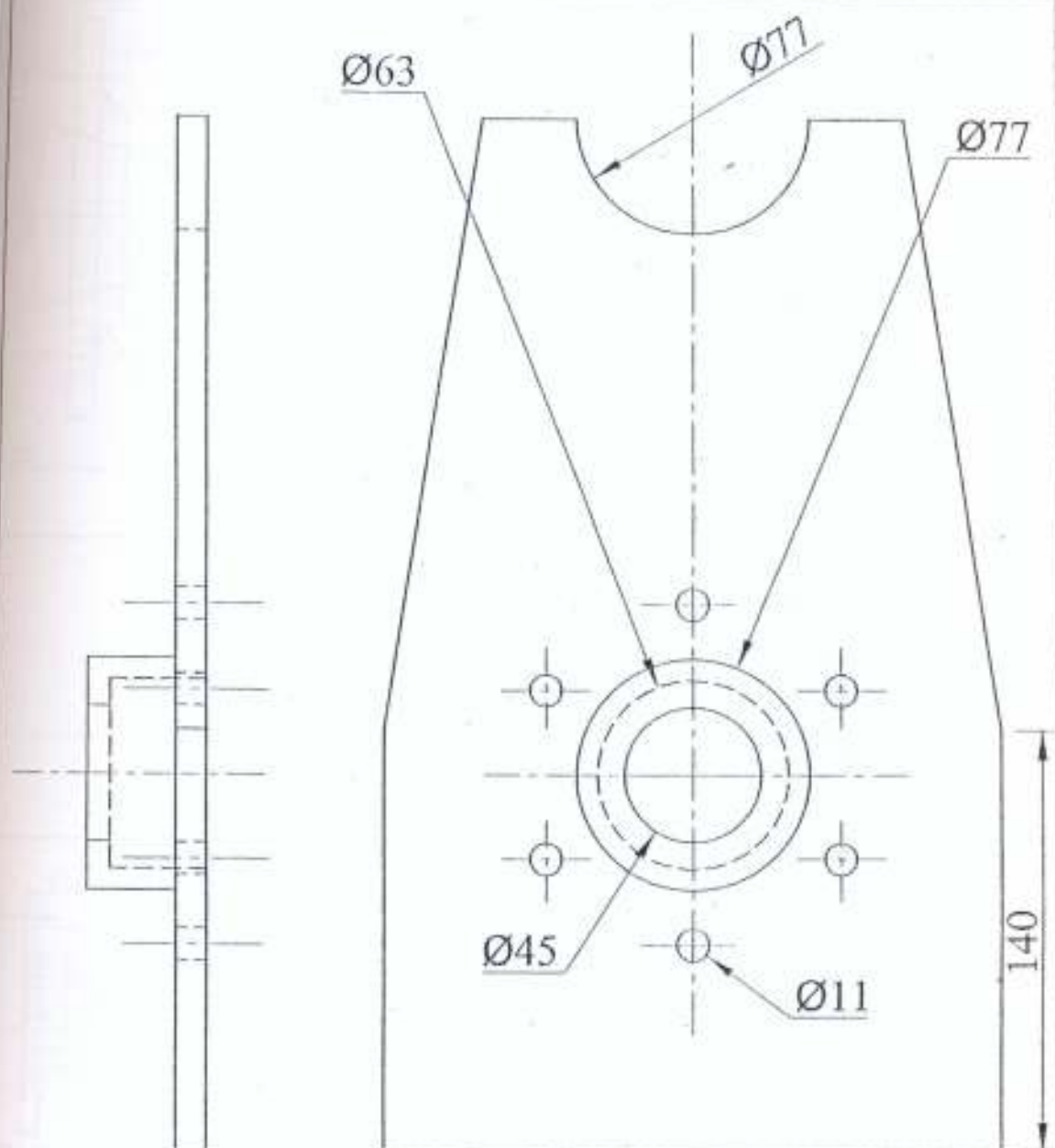


FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

Department: AGRICULTURAL ENGINEERING

Description: HUB SUPPORT PLATE

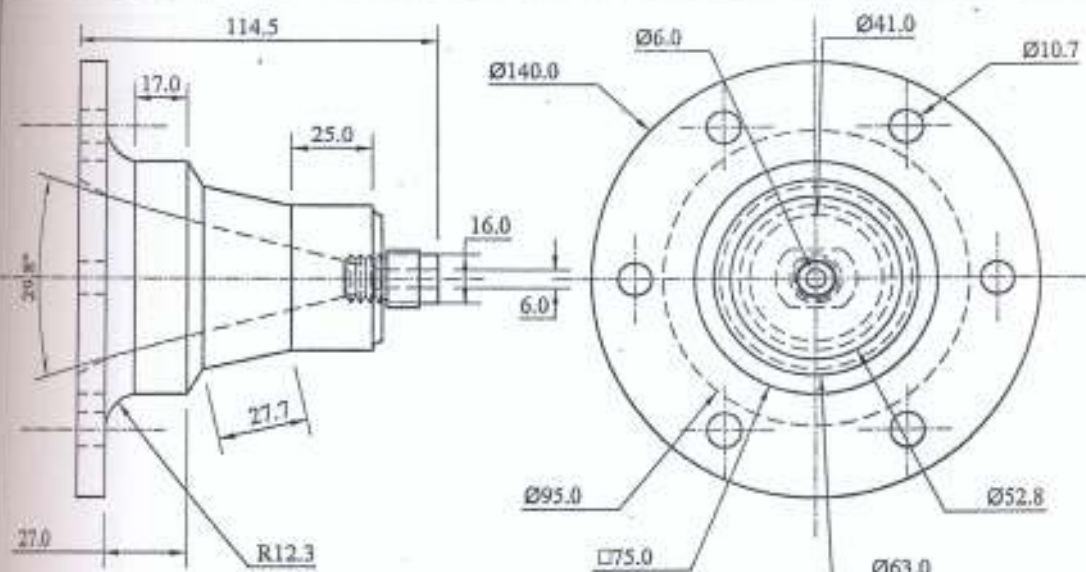
	Name	Signature	Date
Designed and Drawn by	ENGR. (MRS) F. T. FAYOSE		
Supervised by	(1) PROF. A. S. OGUNLOWO (2) DR. L. A. S. AGBETOYE		
Checked by	DR. L. A. S. AGBETOYE		
Approved by	PROF. A. S. OGUNLOWO		
Material	10mm thick mild steel plate		
All Dimensions in mm	Drawing 3.10	Scale 1:2	Matric No. 85/473



FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

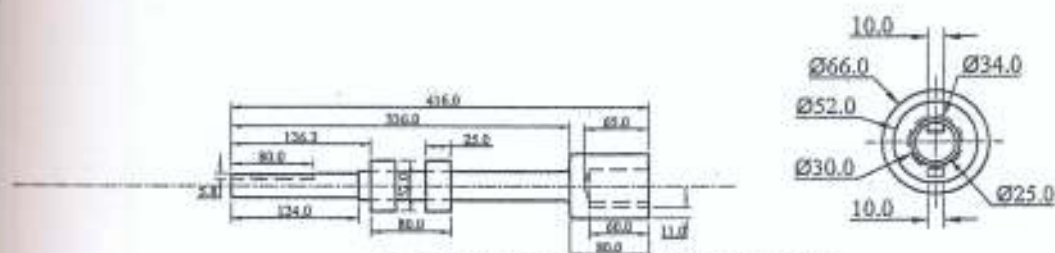
Department: AGRICULTURAL ENGINEERING
Description: EXTRUDER SUPPORT PLATE WITH BEARING HOUSING

	Name	Signature	Date
Designed and Drawn by	ENGR. (MRS) F. T. FAYOSE		
Supervised by	(1) PROF. A. S. OGUNLOWO (2) DR. L. A. S. AGBETOYE		
Checked by	DR. L. A. S. AGBETOYE		
Approved by	PROF. A. S. OGUNLOWO		
Material	Mild steel plate		
All Dimensions in mm	Drawing 3.11	Scale 1:2	Melec No. 85473

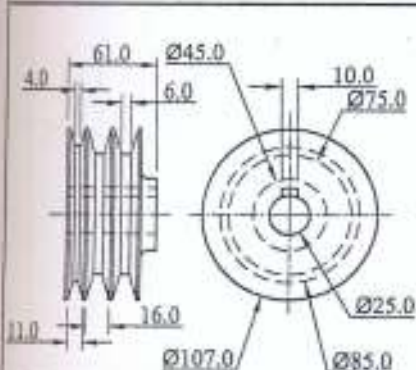


A. DIE

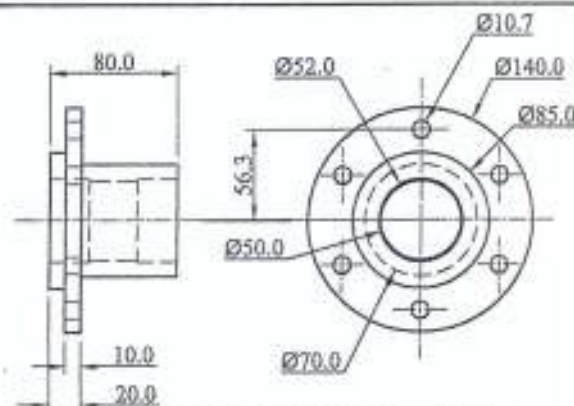
Scale 1:2



B. EXTRUDER DRIVING SHAFT



C. EXTRUDER DRIVING SHAFT PULLEY

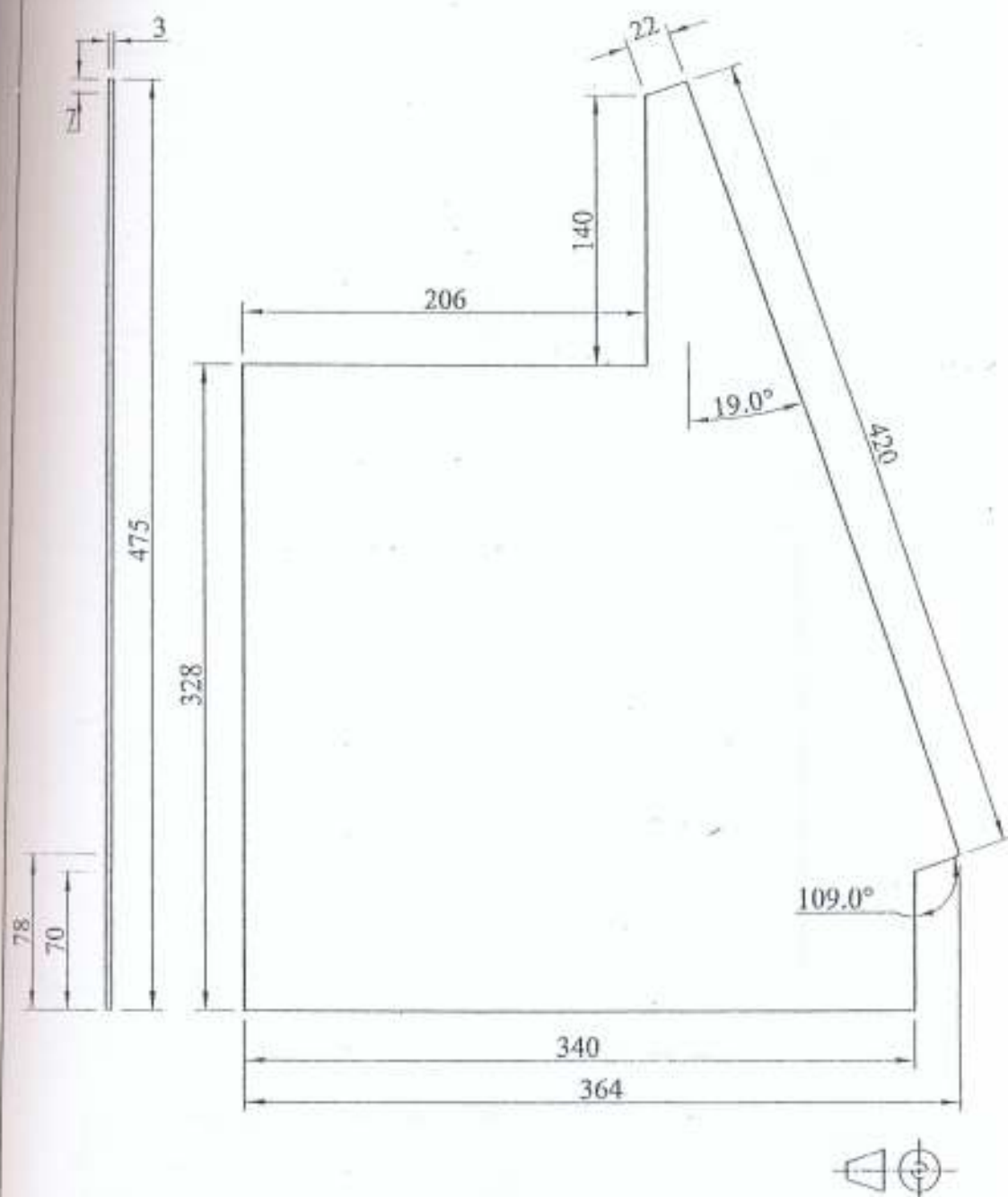


D. EXTRUDER DRIVING SHAFT HUB

FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

Department: AGRICULTURAL ENGINEERING
Description: DIE AND EXTRUDER DRIVING SHAFT, PULLEY AND HUB

	Name	Signature	Date
Designed and Drawn by	ENGR. (MRS) F. T. FAYOSE		
Supervised by	(1) PROF. A. S. OGUNLOWO (2) DR. L. A. S. AGBETOYE		
Checked by	DR. L. A. S. AGBETOYE		
Approved by	PROF. A. S. OGUNLOWO		
Material	A. Stainless steel, B & D Mild steel and C. Cast steel		
All Dimensions in mm	Drawing 3/12	Scale 1:4	Matric No. 85/473

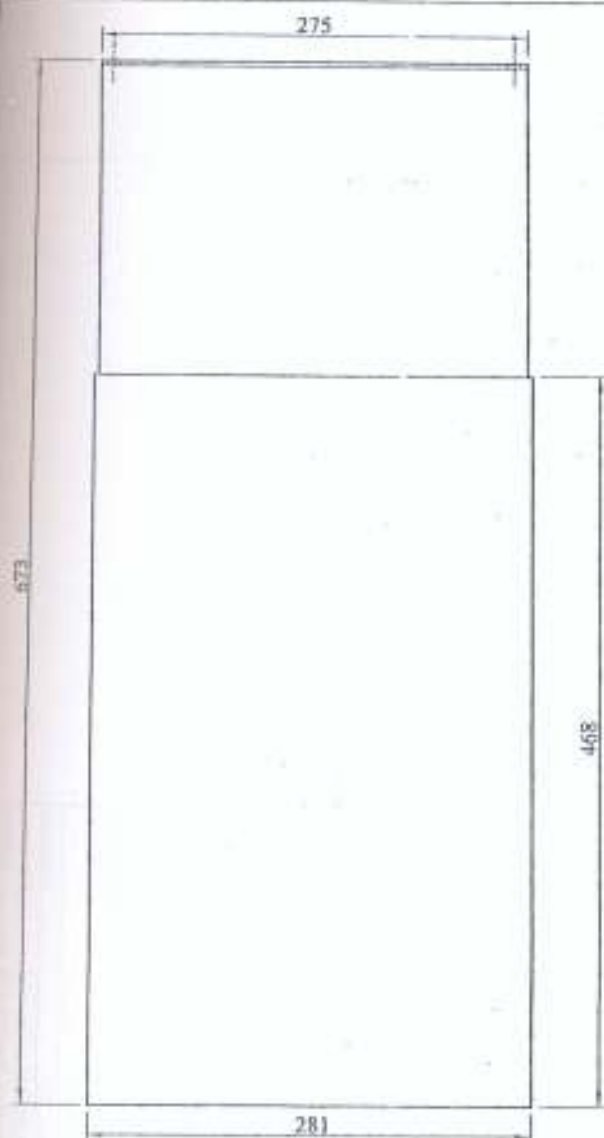


FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

Department: AGRICULTURAL ENGINEERING

Description: SIDE COVER SHEET

	Name	Signature	Date
Designed and Drawn by	ENGR. (MRS) F. T. FAYOSE		
Supervised by	(1) PROF. A. S. OGUNLOWO (2) DR. L. A. S. AGBETOYE		
Checked by	DR. L. A. S. AGBETOYE		
Approved by	PROF. A. S. OGUNLOWO		
Material	3mm thick mild steel sheet (2Nos)		
All Dimensions in mm	Drawing 3.13	Scale: 1:3	Matric No. 85/673

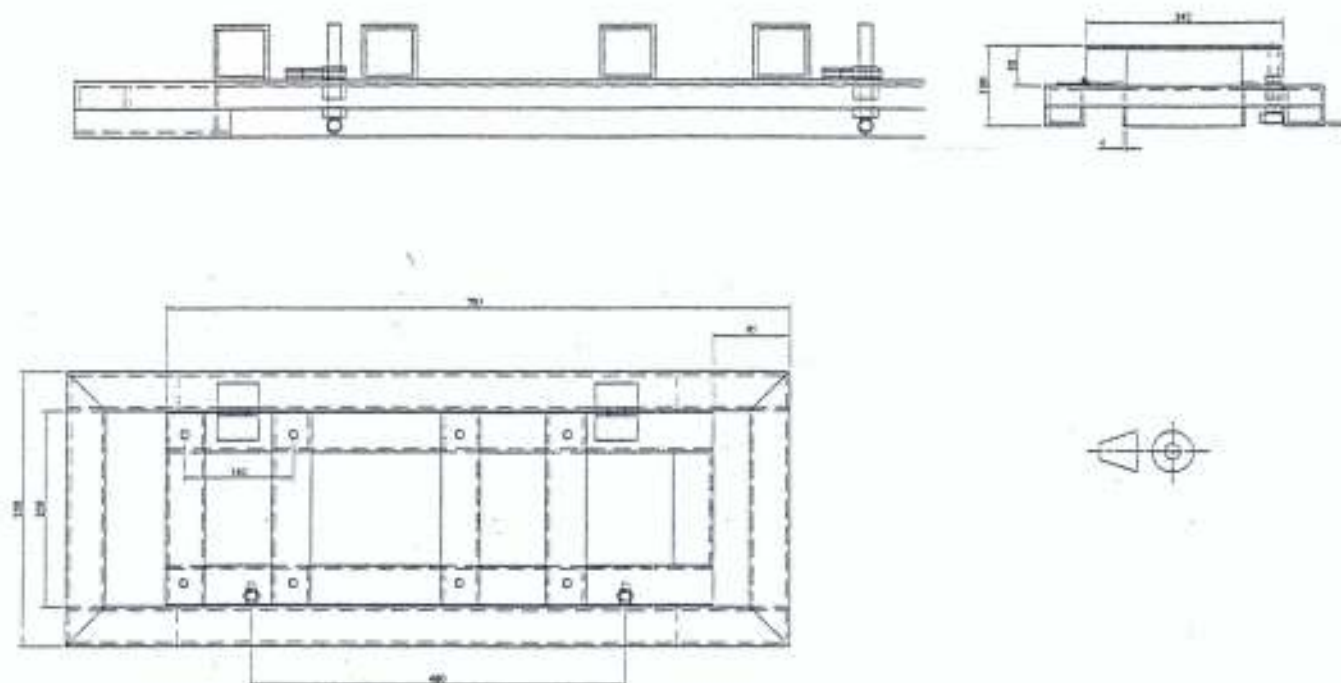


FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

Department AGRICULTURAL ENGINEERING

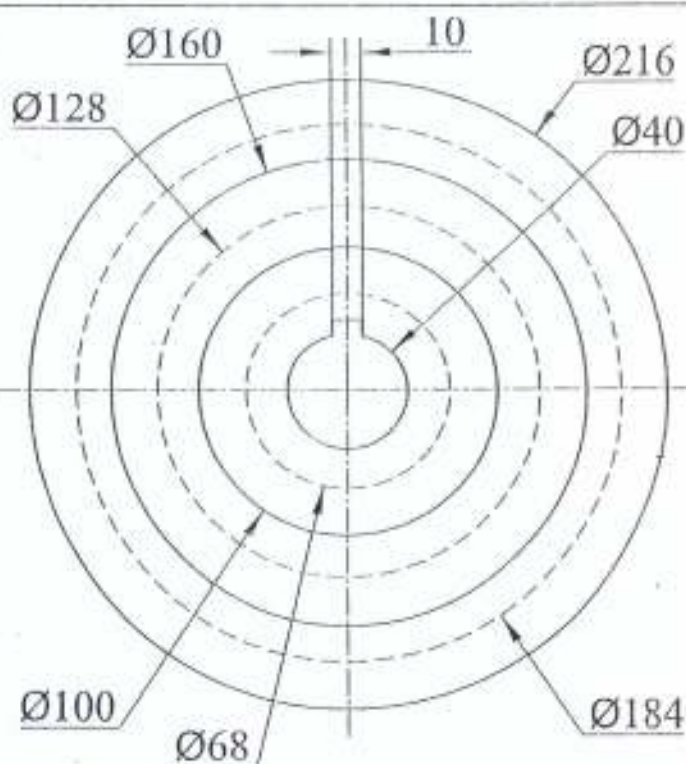
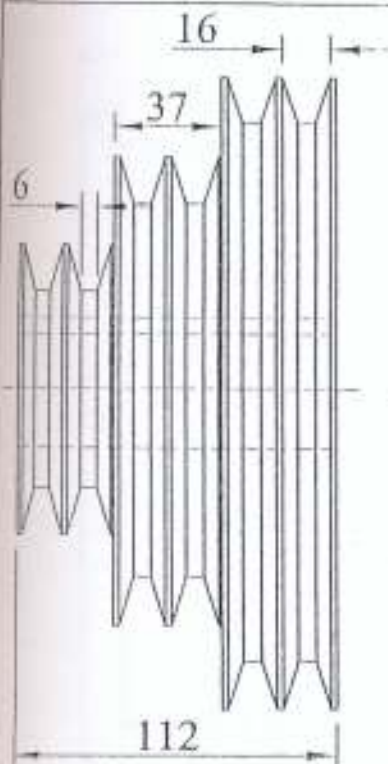
Description REAR COVER SHEET

	Name	Signature	Date
Designed and Drawn by	ENGR. (MRS) F. T. FAYOSI		
Supervised by	(1) PROF. A. S. OGUNLOWO (2) DR. L. A. S. AGBETOYE		
Checked by	DR. L. A. S. AGBETOYE		
Approved by	PROF. A. S. OGUNLOWO		
Material	3mm and 2mm thick mild steel sheet		
All Dimensions in mm	Drawing 3.14	Scale 1:4	Matric No. 85/673



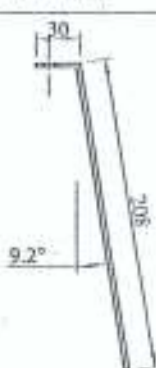
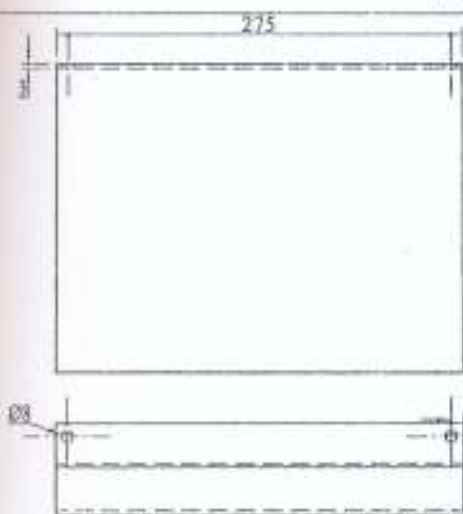
FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

Department	AGRICULTURAL ENGINEERING		
Description	BASE FRAME WITH MOTOR AND GEAR SEAT		
	Name	Signature	Date
Designed and Drawn by	ENGR. (MRS) F. T. FAYOGE		
Supervised by	(1) PROF. A. S. OGUNLOWO (2) DR. L. A. S. AGBETOYE		
Checked by	DR. L. A. S. AGBETOYE		
Approved by	PROF. A. S. OGUNLOWO		
Material	3mm thick mild steel (1) channel and 4mm thick angle bar		
All Dimensions in mm	Drawing 0.15	Scale: 1:10	Matrix No. 85/AT/1



A. DRIVER PULLEY

Scale 1:2



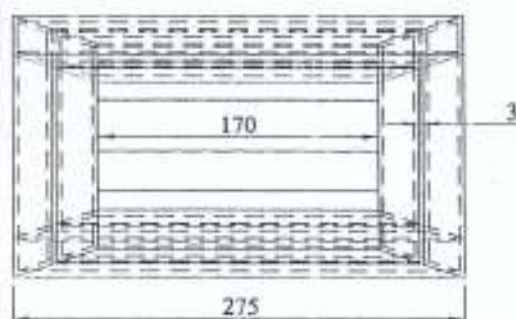
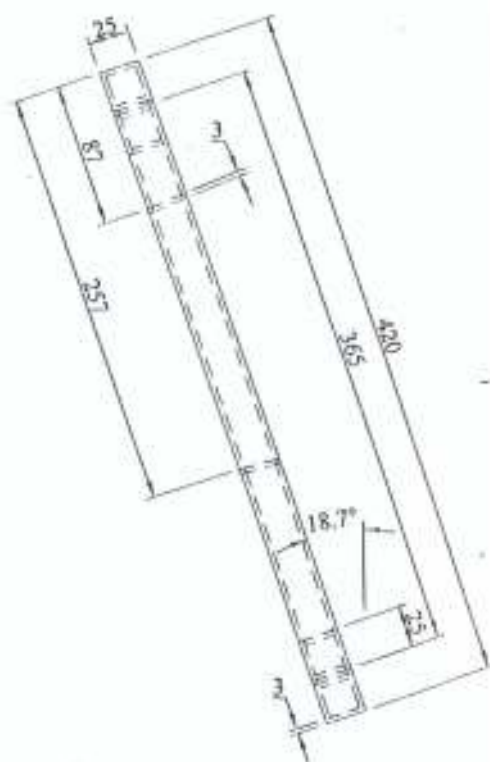
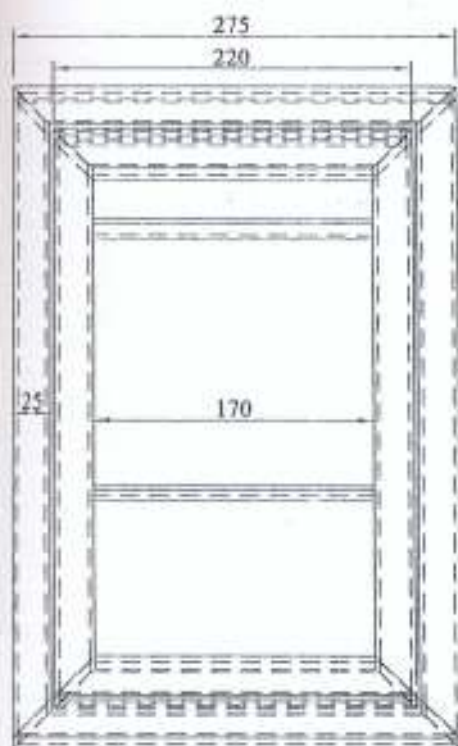
Scale 1:4

B. FRONT COVER SHEET



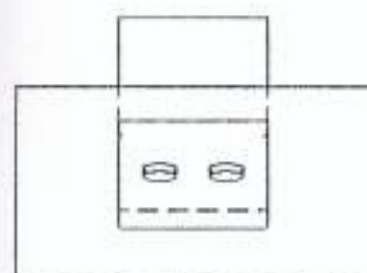
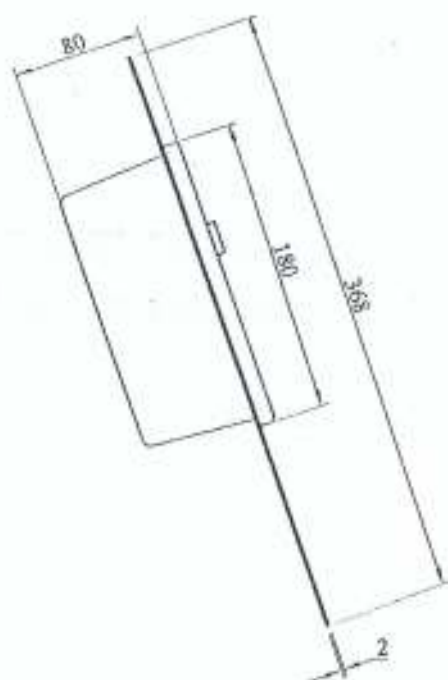
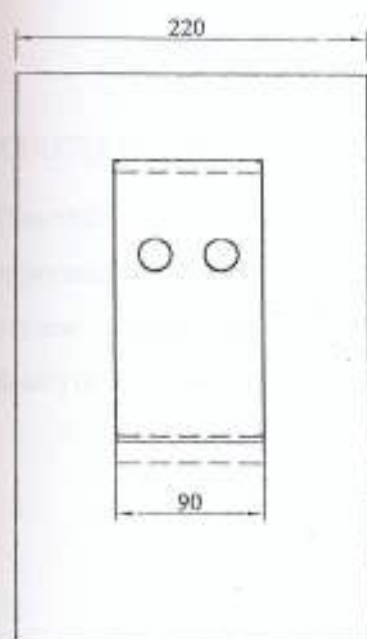
FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

Department	AGRICULTURAL ENGINEERING		
Description	DRIVER PULLEY AND FRONT COVER SHEET		
Designed and Drawn by	Name	Signature	Date
Supervised by	(1) PROF. A. S. OGUNLOWO (2) DR. L. A. S. AGBETOYE		
Checked by	DR. L. A. S. AGBETOYE		
Approved by	PROF. A. S. OGUNLOWO		
Material	Cast steel		
All Dimensions in mm	Drawing 3.16	Scale	Metric No. 85/473



FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

Department	AGRICULTURAL ENGINEERING		
Description	SUFORT FRAME FOR CONTROL PANEL		
	Name	Signature	Date
Designed and Drawn by	ENGR. (MRS) F. T. FAYOSE		
Supervised by	(1) PROF. A. S. OGUNLOWO (2) DR. L. A. S. AGBETOYE		
Checked by	DR. L. A. S. AGBETOYE		
Approved by	PROF. A. S. OGUNLOWO		
Material	25mm mild steel square pipe		
All Dimensions in mm	Drawing 3.17	Scale 1:4	Matric No. 85/473



FEDERAL UNIVERSITY OF TECHNOLOGY, AKURE

Department AGRICULTURAL ENGINEERING
Description CONTROL PANEL COVER SHEET

	Name	Signature	Date
Designed and Drawn by	ENGR. (MRS) F.T. FAYOSE		
Supervised by	(1) PROF. A. S. OGUNLOWO (2) DR. L. A. S. AGBETOYE		
Checked by	DR. L. A. S. AGBETOYE		
Approved by	PROF. A. S. OGUNLOWO		
Material	1.5mm thick mild steel sheet		
All Dimensions in mm	Drawing 3.18	Scale 1:4	Matric No. 85/473

3.6 PRODUCTION COST

The cost of the extruder was obtained by determining the costs of the bought out components, cost of components and parts fabricated, cost of machining and non machining jobs, transportation and workmanship. A unit of the machine costs ₦ 470, 390.00.00 as at April 2007. The details of the cost of production are shown in Appendix 2.

EVALUATION METHODOLOGY

Series of experiments were carried out to evaluate the performance of the equipment. Product quality characterization of the extrudates from the extruder was also carried out.

4.1 EXPERIMENTAL PLAN

This experiment was conducted using a factorial design comprising of five levels of Product classification, three levels of initial moisture content, three levels of screw speed and five levels of duration of operation of machine. The four independent variable levels were pre-selected based on the results of preliminary tests.

4.1.1 Test Parameters

The performance criteria considered are product temperature, product moisture content, hot paste viscosity (HPV), cold paste viscosity (CPV), specific mechanical energy (SME), residence time, expansion ratio, torque, compressive strength, water absorption index and water solubility index.

The performance variables comprise of constant variables (Feed rate, moisture content, die hole diameter, screw configuration) and running variables selected as described below:

- (1) 3 levels of barrel temperature: One level will be below the gelatinization temperature of both corn and cassava (58-72°C, 45°C, others at 90°C and 135°C (Meuser *et al.*, 1987). This temperature level will be built up with time/ duration of sampling.
- (2) 3 levels of screw speed, 100 rpm, 150 rpm and 200 rpm as explained in the design consideration (page 63).
- (3) 3 levels of moisture contents, 25, 30 and 40% (w.b)

The 5 levels of product classification include cassava starch, cassava flour, maize starch, maize flour and wheat flour. This was done to vary the starch content of samples.

Each treatment was replicated thrice. ANOVA, least significant follow up tests, and stepwise multiple regression analysis were carried out using Statistical Package for Social Scientists (SPSS 13.0) software while response surface regression and correlation analysis were carried out using the data analyst and response surface regression procedures of Statistical Analysis System (SAS) software v.9.R₁ (2003). Microsoft excel © 2007 was used

for plotting graphs. Regression analyses were employed to fit the experimental data to second-order polynomials.

In order to get the best model fit for the variables studied, the following steps were taken. Firstly, the data was analyzed using stepwise multiple linear regression method. This showed the entered variables in their order of importance in the model. In a situation where the $R^2 > 80\%$, an indication that may be that the relationship is not best described by a linear model, or where the significant F change is very significant showing that there is yet a relationship that has not been clearly indicated, then a response surface regression analysis was carried out to see if there will be improvement in model. Also, variables were analyzed with and without their interaction to see if there will be any improvement in the model fit. Significance level was defined as $P \leq 0.05$. Finally, the response of the products under study to the process of extrusion was compared.

4.1.2 The Response Surface Analysis

The response surface analysis of the extrusion data was used to identify the change pattern in the extrusion variables and identify the interaction conditions that can yield an optimum result. Also, response surface methodology was applied to the extrusion data using a second order polynomial as fitted to the data to obtain regression equations showing the importance of each independent variable and their interactions on the response variables considered. Response surface regression was used to find optimum combinations among the given sets of data and to discover which values of the given factor variables optimize a response.

Since each factor was measured at three or more values, a quadratic response surface was estimated by least-squares regression. The predicted optimal value was found from the estimated surface. If the estimated surface is more complicated, or if the predicted optimum is far from the region of experimentation, then the shape of the surface can be analyzed to indicate the directions in which further experiments for optimization should be performed. Hypothesis tests were used to gain a rough idea of importance of the effects. Statistical significance of the terms was examined. The detailed result of the analysis for all response functions under study is presented in Appendix 5-15.

The steps in the analysis of the data are:

Model Fitting and Analysis of Variance: The first task in analyzing the response surface was to estimate the parameters of the model by least-squares regression and to obtain

information about the fit in the form of an analysis of variance. The estimated surface is typically curved: a "hill" whose peak occurs at the unique estimated point of maximum response, a "valley," or a "saddle-surface" with no unique minimum or maximum. The ANOVA table with sources labeled "Regression" addresses the contribution of each type of effect - linear, quadratic, and cross product - to the statistical fit.

The ANOVA table with sources labeled "Factor" addresses the contribution of each factor variable to the statistical fit and whether or not the response can be predicted as well if the variable is removed. The test for lack-of-fit compares the variation around the model with "pure" variation within replicated observations. This measures the adequacy of the response surface model.

Estimation and Analysis of Variance

- 1 The Response Mean: This is the mean of the response variable in the sample.
- 2 The Root MSE estimates the Standard deviation of the response variable and is calculated as the square root of the total error mean square.
- 3 The R-Square value is R^2 , or the coefficient of determination. R^2 measures the proportion in the response that is attributed to the model rather to random error.
- 4 The Coef. of variation is 100 times the ratio of the Root MSE to the response Mean
- 5 Terms are brought into the regression in four steps;(1) the intercept (2) Linear terms like Proco, Staco, etc , (3) pure quadratic terms like Proco*Proco or Staco*Staco and (4) Cross product terms like Proco*Staco.
- 6 The Degrees of freedom should be the same as the number of corresponding parameters unless one or more of the parameters are not estimable.
- 7 Type 1 Sums of Squares, also called the sequential sums of squares, measure the reduction in the error sum of squares as sets of terms (Linear, Quadratic, and so forth) are added to the model.
- 8 These R-squares measure the portion of total R^2 contributed as each set of terms (Linear, Quadratic and so forth) is added to the model.
- 9 Each F-ratio test the null hypothesis that all parameters in the term are zero using the total Error mean square as the denominator
- 10 Prob>F is the significance value or probability of obtaining at least as great an F Ratio given that the null hypothesis is true.
- 11 The total Error Sum of Squares can be partitioned into Lack of Fit and Pure Error. When Lack of Fit is Significant, there is variation in the model other than random error
- 12 The total error Mean Square estimates the variance.

- 13 The parameter Estimates are the parameter based on values of the factor variables. If an effect is a linear combination of previous effects, the parameter for the effect is not estimable.
- 14 The Standard Error column contains the estimated standard deviations of the parameter estimates.
- 15 The column headed T for H_0 : parameter = 0 contains t values of a test of the null hypothesis that the true parameter is zero.
- 16 Prob. >|T| gives the significance value or probability of a greater absolute t ratio.
- 17 The parameter estimates from Coded Data are the parameter estimates based on the coded values of the factor variables. These are the estimates used in the subsequent canonical and ridge analyses.
- 18 The test on the factor, say Proco, is a joint test on all the parameters involving that factor. For example, the test for Proco tests the null hypothesis that the true parameters for Proco, Proc*Proco, and Proco*Staco are all zero.

4.2 SAMPLE PREPARATION

Samples of flour and starch of the maize and cassava under study were sourced and prepared from the same varieties grown under the same cultivation practices. This was done to give room for basis of comparison of results.

Samples of white maize, EV8363-SR QPM was sourced from the International Institute of Tropical Agriculture, (IITA) Ibadan and processed into flour and starch respectively. Maize samples were sourced from IITA breeder's seed, thus making it an authentic/ unadulterated/ true seed. Samples of cassava tubers (*Manihot esculenta* Crantz) TMS 30572, were sourced from experimental plots at the Federal College of Agriculture, Akure and processed into flour and starch respectively within 48 hours of harvesting. Wheat flour sample was obtained from hard durum wheat flour (*Triticum aestivum*) which was purchased from Akure main market.

During the preparation of starch from maize, cleaned corn was steeped in water for 48 hours at room temperature. To prevent fermentation, the steeped grains were washed and the water replaced at six hours intervals as described by Akanbi *et al* (2003). They were subsequently wet-milled using a commercial corn mill and starch extracted by wet sieving using the Wet sieving machine developed by Fayose (2005) with a 212 μ m sieve. The slurry was allowed to settle for 6 hr, the starch recovered and dried at 40°C in an air oven (Labcon fsoml, Laboratory marketing Services, Maraiburg).

For the preparation of maize flour, cleaned corn was dehulled in a rice mill; the hulls were blown off manually while the remaining content was milled in a heavy duty commercial mill.

During the preparation of Cassava, cassava roots were harvested manually and processed into flour and starch according to International Starch Institute standards(2005).The products were dried at 40°C in an air oven (Labcon fsoml, Laboratory marketing Services, Maraiburg). The samples were milled and passed through a 300 μ m sieve separately. Thereafter, their proximate analysis and moisture contents were determined as described by AOAC (1995) approved method and the amount of water needed to bring the samples to the required moisture content were calculated and added slowly while being stirred in a mixer.

Official methods of the Association of Official Analytical Chemists, AOAC (1995) were used for moisture, ash, protein, fat and crude fibre. The micro- kjedhal method (AOAC 1995) was used for the determination of crude protein content. Extraction of the fat was carried out by soxhlet method using ether petroleum ether (BP 40 - 60 °C) as solvent. The carbohydrate content was determined by difference.

Moisture contents of native starch samples were determined on a dry basis by an oven method using the AOAC (1995) method. Approximately 2g each sample was placed in an air oven at $100 \pm 2^{\circ}\text{C}$ for 16 to 18 hours. The weighing balance used was Mettler Toledo Type: PR203, Switzerland, The loss in weight represents the moisture loss.

The moisture content (wet basis) was calculated according to Lewis, (2000) as:

$$\text{Moisture content} = \frac{\text{Mass of Water}}{\text{Mass of Sample}} \times 100 \quad \dots\dots\dots 4.1$$

The moisture content of each sample was an average of triplicate analysis. After removal from the oven, the samples were cooled in a desiccator over calcium sulfate (0% RH) and reweighed. Mixing was performed in a Kenwood planetary mixer (Kenwood Ltd., Havant, UK) fitted with a 'K'-beater, at set speed 3 according to Cheyne *et al.* (2005). However, due to power failure, some of samples were manually mixed with hand. The samples were then divided into equal weighed portions, prepared and labeled according to treatments and replicates.

The machine was test run to effect all necessary adjustments, alignment, tensioning and greasing. A, 2800 rpm, 4 kW three phase electric motor was used as the drive. Also, a 25:1 ratio speed reducer gear box for both the extruder unit and the feeding conveyor was incorporated. The electric motor rotated clock wise. A and B-belts tensioning was achieved using screw adjuster by lifting the drive train (electric motor + gear box) vertically, either up or down as applicable. Also, an idler pulley welded to the frame of extruder was provided for tensioning the feeder driver belt. The pulley and belt was preferred to other types of transmission like chain and sprockets because it served the dual purpose of power transmission and control of misalignment of the screw shaft. If there is any alignment along the drive train, the belt tends to slip thereby the bearings and screw worm/barrel will not wear away easily. Also, this leads to uniform flow of output.

The bearings were well lubricated with grease. K type copper- constantan thermocouple was installed with acyanoacrylate adhesive towards the outlet end of the barrel to measure the highest barrel temperature. The result was obtained from a read out digital meter. Other measuring instruments such as probe thermometer, tachometer, stopwatch, analytical balance, measuring cylinders, blenders, were used for immediate measurement of product temperature, actual screw speed, duration of sampling, weights of samples and other parameters under the study. Data were read simultaneously by two observers, each person taking specified instruments simultaneously. It is worthy of note that the equipment performed excellently immediately it started operation without load because of the high precision attained during the fabrication of the components and in final assembly.

The extruder was therefore subjected to rigorous preliminary tests in order to identify its functional defects and correct them before experimentation. The extruder was run when the material was unloaded and under loading conditions. The extruder was run under unloading conditions for one hour. Thereafter, it was loaded with the products under study and run until steady state was attained. Samples were fed at room temperature into the extruder at a constant feed rate of 10 kg/h. A steady state extrusion condition was assumed to have been reached where there was no visible drift in barrel temperature and by a steady extrusion rate (Alves *et al.*, 1999).

Moisture content values from 15 to 70% (w.b.) were tried for all products under study to see which will allow for easy flow of the samples through the extruder. Screw speeds ranging from 80 to 200 rpm were tested during the operation of machine. However, data could not be collected when the machine was operated at screw speed of 200 rpm due to misalignment. Therefore, computational techniques such as extrapolation and graphing were employed in generating data for the extruder at screw speed of 200 rpm. Finally, the sizes of die that would allow for easily passage of materials were selected.

4.4 EXPERIMENTAL PROCEDURE

Samples were fed at room temperature into the extruder at a constant feed rate 10 kg/h. The feeding section of the extruder was maintained at room temperature. The extruder was operated at steady state for each set of condition. Steady state extrusion conditions was assumed to have been reached where there was no visible drifts in products temperature and torques required to turn the screw and by a steady extrusion rate (Alves *et al.*, 1999). The test samples were made large enough to guarantee equilibrium within the extruder before

the extrudate to be used for analysis were collected. Reading of extrusion time starts when the extruder was loaded with material.

The extruded samples were prepared for analysis by drying them at 45°C for 16-24 h to bring the final products to approximately the same moisture content (5-7% w.b) according to Iwe et al. (1999). A portion of the dried materials were coarsely ground in a High speed laboratory blender (Waring Commercial Heavy Duty Blender, New Hartford, Conn. U.S.A) and milled in a domestic blender (Martex, Dawan) to pass through a 300µm sieve. These materials were used in further analysis.

4.5 PERFORMANCE EVALUATION OF THE EXTRUDER

4.5.1 System Parameters

4.5.1.1 Product temperature

Product temperature was determined as described by Chessari and Sellahewa (2001). Product temperature was measured with Portec CAI 001 thermometer probe (Portec instrumental, Milton Keynes, UK) inserted into the melt immediately before passage of the mass out of the die. This represents the thermal energy in the mass.

4.5.1.2 Mean residence time

Residence time is characterized by mean residence time (MRT) which can be used more easily to develop links between the process variables and the product properties. MRT was determined by the monitoring of potassium permanganate using an Atomic Absorption/Emission Spectrophotometer (type: Buck scientific 2.0).

The MRT was measured by a tracer technique and as described by Seker (2005) but with modification. The modification was in the use of Atomic Absorption/Emission Spectrophotometer (AAS) as against a CM-2002 spectrophotometer. A 2g of Potassium permanganate (KMnO_4) was added at $t = 0$ into extruder through the feed port as a tracer. Extrudates were collected at regular intervals of 30 sec. until the samples were exhausted from the extruder. Extrudates samples were dried in an oven. Thereafter, according to Perkin (1982), 0.2 g of each samples was put in a furnace at 550 °C until fully ashed to remove any/all organic compounds. The ash was then dissolved in 10 ml of 0.1 M Hydrochloric acid (Hcl) and made up to 50 mls with distilled water. The solution filtered with filter paper to make a clear solution. Finally, the amount of Mn ions in this solution was measured by

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4.5.1.4 Specific mechanical energy requirement (SME)

Specific mechanical energy requirement (SME) is an important index in terms of the cost of manufacturing extruded products. Since extrusion is a melting, mixing and pressing process, when mixing two or more polymers, mechanical energy is used in mixing and it is also transformed into thermal energy for cooking the products. SME is a measure of the work done on the feed material by the extruder.

The SME was calculated using the equation described by Chi- Chuang and Yeh, (2004):

$$SME = \frac{2\pi \times \tau \times S_s / 60}{F_r} \times 3.6 [kJ/kg] \dots\dots\dots 4.2$$

τ is the corrected torque (N m), S_s the screw speed (rpm), F_r the feed rate (kg/h) and equivalent to the product output at stable conditions.

The measured torque was the total torque required to turn the screw that has two components: torque required to work the product, the net torque, and the torque-required to turn the screw, the no load torque. By running the extruder with water at operating temperatures and screw speeds, the no load torque was measured. Usually the no load torque consisted of 11% to 72% of the total torque, depending on the operating condition. The torque T required to drive the screw was calculated using the equation below according to Khurmi (2006).

$$T = \frac{60P}{2\pi N} \dots\dots\dots 4.3$$

4.5.2 Extruder's Efficiency

Extruder efficiency is considered the theoretical power required divided by the actual power consumed. The extruder efficiency, η , is defined as:

$$\eta = \frac{P_{th}}{P} \dots\dots\dots 4.4$$

Where P is the input power and P_{th} is the theoretical power. The theoretical power required in an extruder, P_{th} , can be expressed as:

$$P_{th} = Q \int_0^p C_p \delta T + \frac{Q \Delta p}{D} + Q \Delta H \dots\dots\dots 4.5$$

Where Q is a mass flow, T_o and T_i are inlet and outlet materials temperature C_p is the specific heat of the polymer, p is discharged pressure, D is the specific density of polymer, and H is the enthalpy changes associated with starch gelatinization and protein denaturization per unit weight of extruder.

Specific heat was calculated mathematically as follows:

$$C_p = 1.424m_c + 1.549m_p + 1.675m_f + 0.837m_a + 4.187m_m \dots\dots\dots 4.6$$

Where m is the mass fraction and the subscripts denote carbohydrate, protein, fat, ash and moisture.

The phase change (enthalpy), ΔH was estimated using the following equation (Liang *et al.* 2002):

$$\Delta H = 14X_s + 95X_p \dots\dots\dots 4.7$$

Where X_s and X_p are mass fraction of starch and protein, respectively.

The extruder output was measured by collecting the sample of extrudates for 2 minutes and weighing after drying at 60°C for 24 h. Extrudate mass flow rate (on dry weight basis) was calculated in terms of kg/h. The flow rate, on a volume basis, was then calculated as described by Sokhey *et al.* (1997) as:

$$\text{Volumetric flow rate} = \frac{\text{mass flow rate}}{\text{the solid density}} \dots\dots\dots 4.8$$

The density of the extrudates was determined according to Liang *et al.* (2002) by conducting dead stop extrusion runs of each sample. The extrusion operation was intentionally shut down after reaching steady state. The die plate was opened immediately and very dense, solid chunk pieces of extrudates about 10 to 20 g each were collected from

the space between the screw top and die. The dough sample was immediately wrapped using a plastic film, weighed, and submerged for measurement of its volume by water displacement as described by Muzilla *et al.* (1990) and Cha *et al.* (2003). A known mass of sample was added to a 60 ml volumetric flask which was filled with distilled water at room temperature. Density was calculated using the following equation.

$$D = \frac{M}{60 - V} \dots\dots\dots 4.9$$

Where D = density (g/ml), M = mass of sample (g) and V = volume of water added (ml).

In the absence of an appropriate die pressure measuring device, equation 3.14 was used to estimate the die pressure, i.e

$$Q = K_d \frac{P_d}{\mu}$$

4.6. EXTRUDATES' CHARACTERIZATION OF THE EXTRUDER

4.6.1 Product Moisture Content

Moisture contents of native starch samples were determined on a dry basis by an oven method using the AOAC (1995) method. The moisture content of each extrudate was determined immediately after extrusion according to AOAC method 950.46. Approximately 2g each sample was placed in an air oven at $100 \pm 2^\circ\text{C}$ for 16 to 18 hours. The weighing balance used was Mettler Toledo Type: PR203, Switzerland. The loss in weight represented the moisture loss. The moisture content of each sample was an average of triplicate analysis. After removal from the oven, the samples were cooled in a desiccator over calcium sulfate (0% RH) and reweighed.

4.6.2 Expansion Ratio

Expansion ratio of extrudates was calculated according to Choudhury and Gautam (1998). Extrudates were measured using a caliper. Radial expansion ratios of the extrudates were calculated as:

$$\frac{D^2}{d^2} \dots\dots\dots 4.10$$

where D is the extrudate's diameter while d is the diameter of the die. Each value of extrudate diameter was an average of three readings. Also, the photographs of the expanded extrudates were taken.

4.6.3 Compressive Strength

According to Guan and Hanna (2004), Guan *et al.* (2005) and Sopade (1991) compression strength, which was used as a measure of the hardness of the extrudates, was measured using the Testometrics Universal Testing machine 500-532 (Testometric, Co Ltd. Unit, Lincoln, Business Park, Lancashin, England.) at the National Centre for Agricultural Mechanization (NCAM), Ilorin, Kwara State of Nigeria. The machine has an accuracy of 0.1 kN and a maximum capacity of 50 kN. Also, the bending strengths were determined. This computerized UTM- AX has been designed to be used as a complete stand-alone tester to enable the operator to perform a series of user-designed tests and by direct connection to a printer, produces print-outs including test results and graphical analysis. The UTM operates by the principles of screw movement and moves at displacement/Extension rate. It has a cross head which is used as the Extensometer and a cell 50kN.

Dried extruded products 20 mm long with carefully aligned out surfaces (illustrated in Plate 4.1) were compressed using the compression jaw/rig (plate) of the UTM at a loading rate of 1cm/min until failure occurs. The load cell which sent the pressure transmitted to the console or PC monitor was sandwiched between the upper jaw and the cross head which

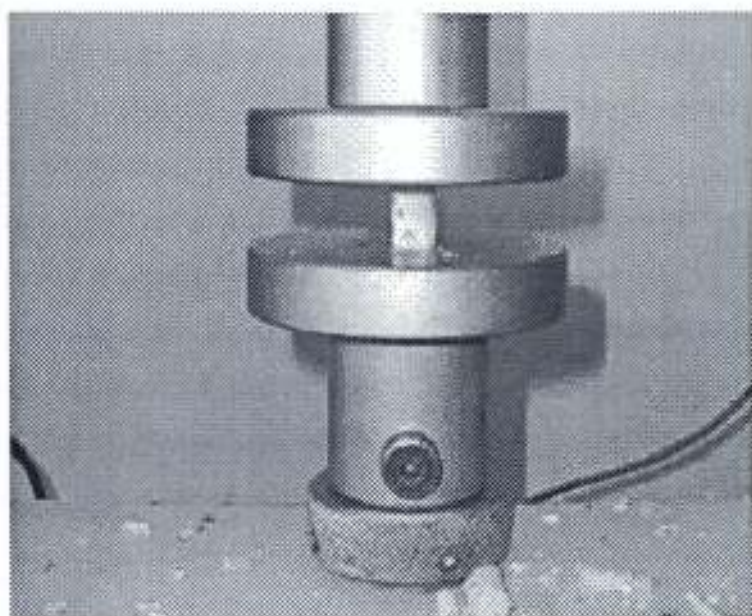


Plate 4.1 Position of the extrudate on the compression jaws of the UTM

were driven by a screw press. When the upper jaw was lowered well enough to grip the samples, the laboratory thumb was withdrawn and the start button was pressed to commence the test.

Compression force was exerted and the biomaterial failed as it was accompanied by a "crack sound" and a corresponding drop on the force-deformation graph, which was plotted concurrently on the PC monitor. When the sample thus failed, the "end test" button was pressed on the console. The PC monitor displayed the results of linear limit, Young's modulus of elasticity and bioyield point, readings. Deflection at peak, strain at peak, energy at peak, Young Modulus, Load at yield, Deflection at yield, strain at yield, energy at yield were thereafter printed out. The peak load was reported as the compressed strength. The peak force was defined as the height of the first peak. The peak force represents the resistance of extrudate to initial penetration and is believed to be the hardness of extrudate. Each sample was measured three times and reported as an average of three.

4.6.4 Melt Viscosity

The viscosity of the melts was determined with Capillary Viscometer Method, AOAC (1995) using the equation below:

$$\frac{\text{Flow rate of sample solution at } 20^{\circ}\text{C} \times \text{specific gravity of sample solution} \times 4.11}{\text{Flow rate of water} \times 1.002 (\text{specific gravity of water})}$$

4.6.5 Hot Paste Viscosity (HPV) and Cold Paste Viscosity (CPV)

The instrument used to measure the pasting viscosity of the extrudates is the Rion viscotester (VT - O4E - Japan). This viscotester operates on the principle of coaxial rotational viscometers. A rotor turning at constant speed is inserted into the test fluid. Pasting Properties (Hot and Cold paste viscosity) were determined as described by Amani *et al.* (2004). 2 g of each extrudate was weighed in a balance. 17 ml of distilled water was added to the sample to make a concentration of 35 % and stirred at room temperature until completely dissolved. The solution was then heated at a constant rate and stirred simultaneously until a temperature of 90°C was attained. The sample was thus removed from the stove and poured into the viscometer cup and the HPV determined. The samples were heated to 90°C because all the materials under study had a gelatinization temperature much less than 90°C. The test fluid was then cooled at a constant rate to 30°C. This value represents the CPV at which temperature the product is normally eaten or the room temperature.

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4.6.5 Hot Paste Viscosity (HPV) and Cold Paste Viscosity (CPV)

The instrument used to measure the pasting viscosity of the extrudates is the Rion viscotester (VT-04E – Japan). This viscotester operates on the principle of coaxial rotational viscometers. A rotor turning at constant speed is inserted into the test fluid. Pasting Properties (Hot and Cold paste viscosity) were determined as described by Amani *et al.* (2004). 2 g of each extrudate was weighed in a balance. 17 ml of distilled water was added to the sample to make a concentration of 35 % and stirred at room temperature until completely dissolved. The solution was then heated at a constant rate and stirred simultaneously until a temperature of 90°C was attained. The sample was thus removed from the stove and poured into the viscometer cup and the HPV determined. The samples were heated to 90°C because all the materials under study had a gelatinization temperature much less than 90°C. The test fluid was then cooled at a constant rate to 30°C. This value represents the CPV at which temperature the product is normally eaten or the room temperature.

4.6.6 Water absorption index (WAI) and water solubility index (WSI)

The water absorption index (WAI) and water solubility index (WSI) were determined using the procedure by Danshy and Bovell (2003). Ground extrudates (1g) was suspended in 10 ml distilled water in a centrifuge tube. The suspension was stirred with a glass rod to break up any lumps, mixed for 5 minutes with a mixer at room temperature, centrifuged at 3000 rpm for 10 minutes and the supernatant preweighed in petri dishes.

The centrifuge used is the centrifuge (type: KA1000, Japan) of 4000 rpm capacity. This is a device used to produce large forces on objects by whirling them in a circle. The centrifuge is used to whirl test tubes containing a solid in suspension. The force produced on the particles of the solid makes them settle to the bottom of the test tube. As the test tube turns, the contents

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$$WAI\% = \frac{\text{Weight of dissolved solids in the supernatant}}{\text{Weight of dissolved solids in the supernatant}}$$

$$WSI (\%) = \frac{\text{Weight of dissolved solids in supernatant}}{\text{Weight of dry sample in the original sample}}$$

RESULTS AND DISCUSSIONS

5.1 PRELIMINARY EXPERIMENT RESULT

Several extrusion trials were performed to evaluate the performance of the extruder and the parameters ranges used in this research work. Below is the summary of the outcome of the trials and the range selected for further investigation while Table 5.1 shows the result of preliminary testing of the extruder.

5.1.1 Feed Moisture Content

Moisture content values from 15 to 60 % wet basis (w.b.) were tried for cassava flour. With all conditions, feed moisture ≤ 20 % blocked the rotation of the screw as there was no transition from the original floury nature to a melted state typical of most extrusion processing. This condition also applied for wheat flour and cassava starch. This may be because the moisture content was not sufficient to solvate the starch polymers and allow them to move freely in the mass, hence there was resistance to deformation. The minimum moisture necessary to obtain steady flow of extrudate was 25%. For maize, however, minimum moisture of 30 % was selected. Extrusion processing using feed moisture $\geq 70\%$ resulted in adherence of cassava flour paste to the hopper while 55 % moisture was observed for others. Therefore a range of feed moisture from 25 - 45% w.b. was selected for cassava flour, starch and wheat flour while 30 - 50% was selected for maize for further investigation. This problem of getting stocked at lower moisture levels can be overcome by improving the torque. Low-moisture materials require more mechanical energy to cause flow. Generally, there is higher torque at smaller speed. Torque decreases with increasing speed. A possible explanation for this is that increasing screw speed at a constant speed would improve the pumping effect of the extruder screws, leading to a decrease in barrel fill and resulting in a decrease in torque. Also, increasing screw speed would induce shear thinning behavior of starch melt, resulting in a reduction in melt viscosity and consequently, the torque (Yuliani *et al.*, 2006). Increasing screw speed causes a decrease in melt viscosity since at higher screw speed the shear rate is higher. The viscosity also resulted in a decline in the torque because there is less resistance to the rotation of the screw shaft. Also, from equation 4.2, speed is inversely proportional to torque, since N is directly proportional to the diameter of pulley (note: Smaller diameter produces more rpm than bigger pulleys when

running at the same speed). From the above observation, it can be deduced that to develop higher torque, a bigger pulley should be used. For better ability to propel the extruder therefore, the pulley on the extruder shaft must be bigger than that of the driver pulley to increase its torque force. It is therefore advisable to select high speed prime mover and attempt to step down its speed on the extruder by using a bigger pulley. This will improve the propelling force and reduce the tendency for belt slippage.

5.1.2 Temperature.

Because of the similarity in trends, only result for cassava flour at screw speed 100 rpm will be reported. Figure 5.1 shows the variation of highest barrel temperature with extrusion time at moisture contents 25, 30 and 40% (w.b).

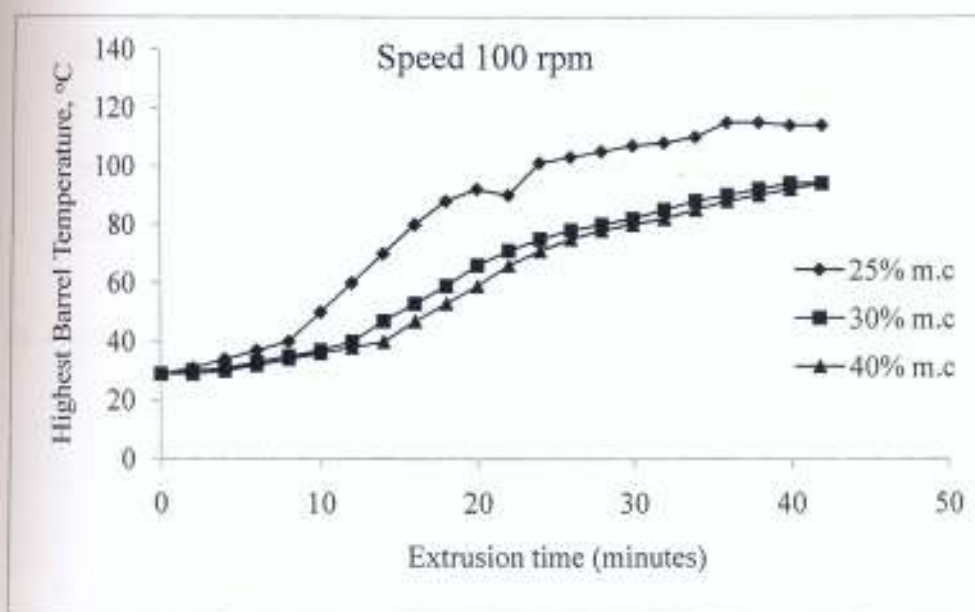


Figure 5.1: Variation of highest barrel temperature with extrusion time at different moisture contents of cassava flour and screw speed 100 rpm.

The graph shows that barrel temperature varies directly with extrusion time in a polynomial trend. The barrel temperature increased with increase in extrusion time. A maximum temperature of 114°C was attained in 30 minutes through viscous dissipation at 25% moisture content. Steady state condition was attained within 15 minutes for moisture content 25% while it took longer period for those of 30% and 40% moisture contents to attain steady state.

Table 5.1: Result of preliminary running of machine.

MC	Dt	Die Φ	OBSERVATION	REMARK
15	2	6-12	Got stocked	Not selected
25	30	12	formed but no expansion	Not selected
		6	maize got stocked, others well formed	Selected
30	30	12	formed but no expansion	Not selected
		6	well formed	selected
40	30	12	formed but no expansion	Not selected
		6	well formed	selected
50	30	6-12	maize flour well formed, others also formed but no expansion	selected for maize
60	30	6-12	maize flour well formed with no expansion, other sample adhere to the surface of container	Not selected
70	30	6-12	all samples adhere to the surface of container	Not selected

Mc – Moisture content, Ss- screw speed, Dt- Duration of operation. Φ - Diameter

Temperature of a substance may be used as a measure of the average kinetic energy of the molecule. Temperature, both of the barrel and product were varied by continuous running of the machine, thereby building up the temperature. A major reason why heat is better generated through viscous dissipation than that added or removed through the barrel walls is because if heat is generated by drive unit (through viscous dissipation) it is by far dominant and more cost efficient (Liang *et al.*, 2002). It is necessary to determine the product temperature in these preliminary studies of this extruder so as to understand and know the temperature profile under any condition and to be able to control it effectively for any particular application. Also, long term trends such as wear can be more closely monitored by observing extruder temperature data, thus providing management data. Since barrel temperature varies with duration of operation, duration of operation was observed as an independent variable. Temperature was controlled by removing and dipping the barrel and screw in a bath of cold water each time the extruder is to be fed with samples. The first range of temperature selected was 40 – 45°C. At this temperature, all feed materials had started to form, although not fully cooked. At 65 – 70°C, most materials under study had started to expand. Extrudates were stable and producing regular and puffed products. By the time a barrel temperature range of 87-94°C was attained virtually all the materials had reached their maximum expansion with the onset of either collapse or reduction beyond 95°C. Thus, Extrudates were selected at these ranges of barrel temperature for further investigation.

5.1.3 Screw Speed

Three screw speeds were selected. These are 100, 150 and 200 rpm to be able to characterize the extruder and know the optimum speed ratios. Because of the similarity in trends, only result for cassava flour at screw speed 100 rpm will be reported and compared with other speeds. Figure 5.2 shows the variation of actual extruder screw speed with extrusion time at moisture contents 25, 30 and 40% (w.b) of cassava flour. From the graph, actual extruder screw speed varies inversely with duration of operation and it is best fitted with a polynomial trend. Actual extruder screw speed decreased with with increase in duration of operation.

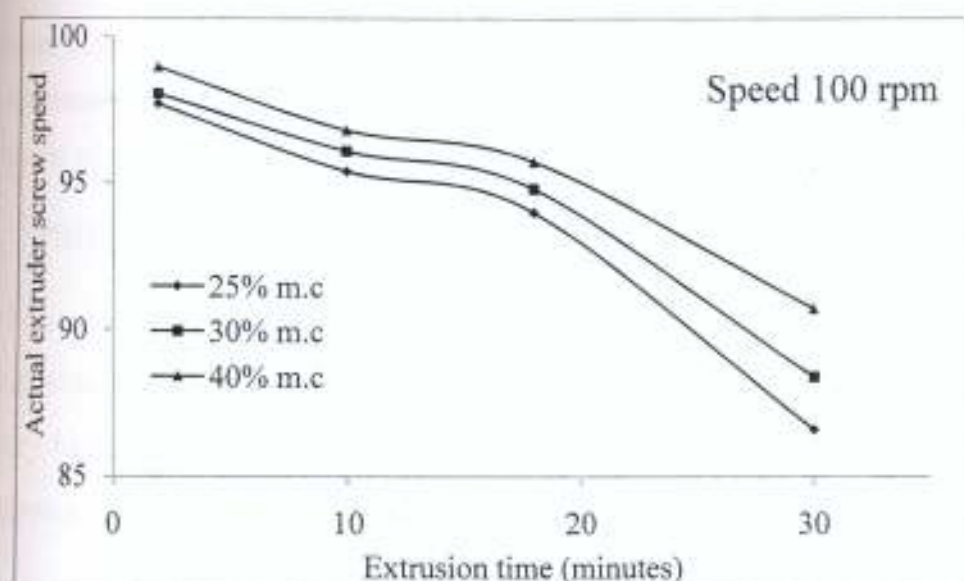


Figure 5.2: Variation of actual extruder screw speed with extrusion time at different moisture contents of cassava flour.

An increase in screw speed at a constant feed rate generally increased the percent torque and die pressure, but decreased the specific mechanical energy (SME). Increasing screw speed at a constant feed rate increased the number of flights of the extruder that were filled. This would increase the resistance to turn the screw and hence require more mechanical power to dissipate into the material. The common practice to avoid such occurrence is to maintain a constant percentage filled flight of the extruder by determining the appropriate feed rate at each screw speed. The ratio of the feed rate to screw speed required to maintain a constant percentage filled flight is called Specific Feeding Load (SFL). At fixed feed rate, an increase in screw speed decreased the amount of feed conveyed per flight by the screw and therefore decreased the filling ratio in the screw elements. Also, mechanical energy addition to feed was reduced, thus lowering the product and barrel temperature with corresponding reduced diametric extrudates. The reason for the difference between the actual screw speed and the rated screw speed was because as the extrusion time increased, the temperature of the sample increased with a consequent increase in viscosity thereby increasing the resistance of the material to flow.

5.1.4 Choice of Die Diameter

From preliminary experiments conducted, it was discovered that cassava and maize flour at 25 % moisture content could not flow out of the extruder when a restriction was placed on

its outlet. However, when the hole was 12 mm, it flowed very easily, but without expansion. An optimum die diameter of 6 mm was selected so as to allow for maximum flow and expansion of extrudates.

5.2 PROXIMATE COMPOSITION OF RAW MATERIALS STUDIED

The Proximate composition of all the materials under study is presented in Figure 5.3. One very important observation made is that the protein content of this variety of cassava flour is very high when compared with result from previous studies (Badrie and Mellowes, 1991a; Badrie and Mellowes, 1991b; Mali and Grossman, 2001).

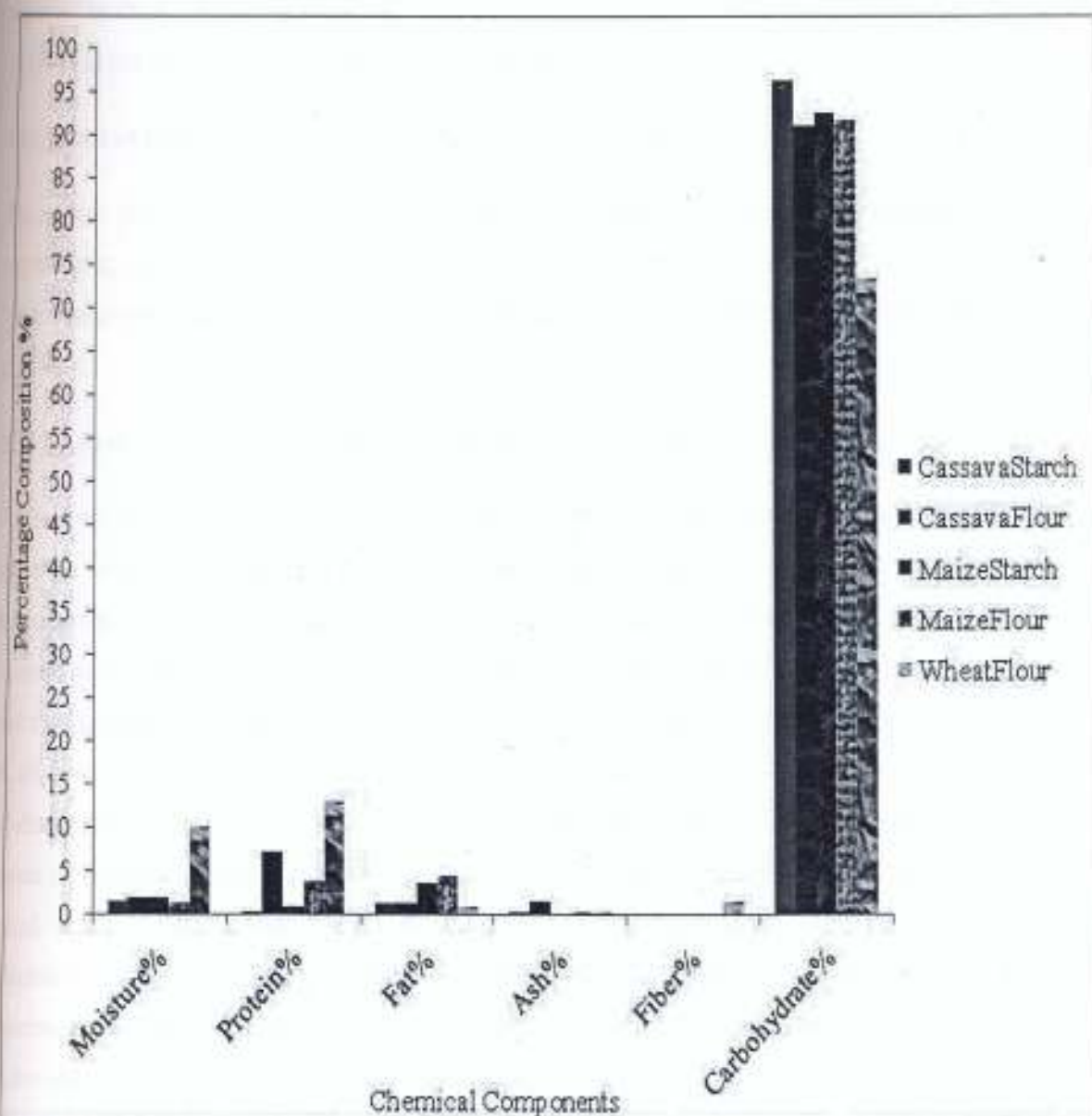


Figure 5.3: Proximate compositions of samples.

This result shows that the protein content of TMS 30572 variety of cassava is high when compared with other varieties used in previous studies. Efforts to improve cassava have been focused on increasing yield, dry matter content, nutritional and protein content as a means to contribute to a sustainable and cost effective solution to malnutrition (Dixon *et al.*, 2007).

5.3 RESULT AND DISCUSSION ON EXTRUSION PARAMETERS

The effect of extrusion variables under study were quantified using some system and product quality parameters. The detailed results of the effect of extrusion variables on each product studied are presented in Figures A.1 – A.68 (Appendix 4) while the result of stepwise multiple linear regression analysis showing the order of importance of the variables in the model is presented in Appendix 5.

5.3.1 Effect of Extrusion Variables on System Parameters

The system parameters studied includes product temperature, specific mechanical energy requirement, motor torque and mean residence time. Product temperature is a suitable system parameter for a system analysis of extrusion cooking (Olkku *et al.*, 1980; Meuser *et al.*, 1987).

5.3.1.1 Effect of extrusion variables on product temperature

Figure 5.4 - 5.6 show the effect of extrusion variables (initial moisture content, duration of operation and screw speed) on product temperature. The graph shows that product temperature varies directly with duration of operation. Product temperature increased with increase in duration of operation. Also, Product temperature increased from 100 to 150 rpm and then decreased at 200 rpm. Extruder's performance improved from 100 to 150 rpm but at 200 rpm there was a change over in the performance of the extruder. For instance, the product temperature reduced at 200 rpm than at 150 rpm. Also, the SME decreased as screw speed increased. There is the need for proper and commensurate feeding at each screw speed to maintain uniform pressure, temperature, throughput and extrudate expansion (Badrie and Mellows, 1991). The reduction of SME is due to the decrease of mean residence time due to increase in screw speed. The shorter the time the feed material stays in the extruder, the less energy it receives from the process, at constant feed rate. This was what brought about Specific feeding load (SFL) in previous studies (Frame, 1994; Lo *et al.*, 1998).

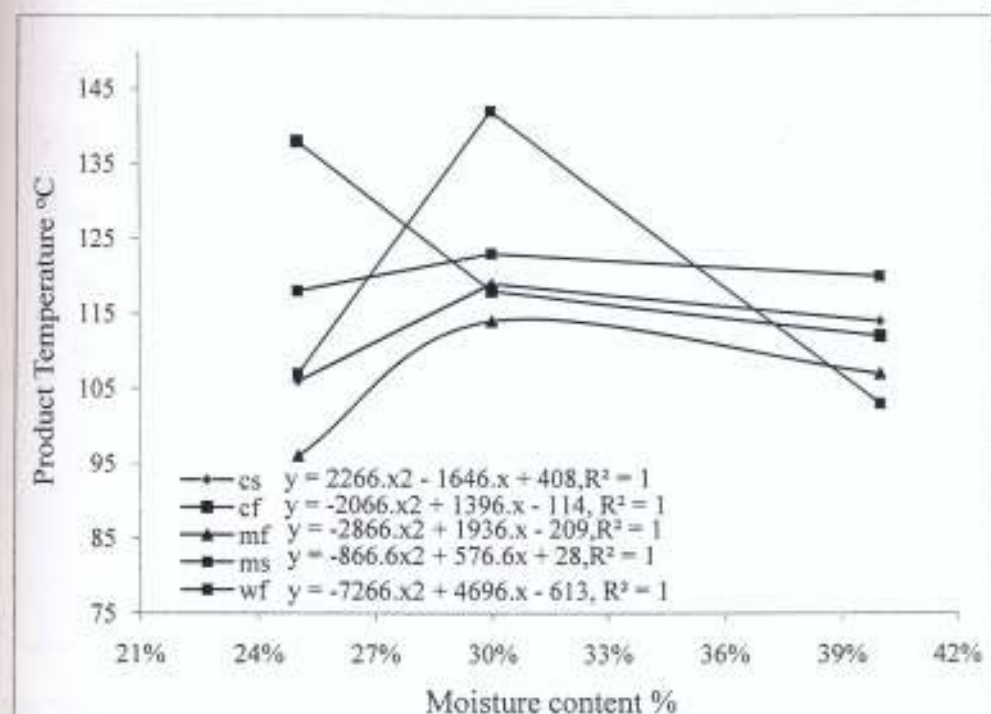


Figure 5.4: Variation of product temperature with initial moisture content at extrusion time 30 minutes and screw speed 100 rpm.

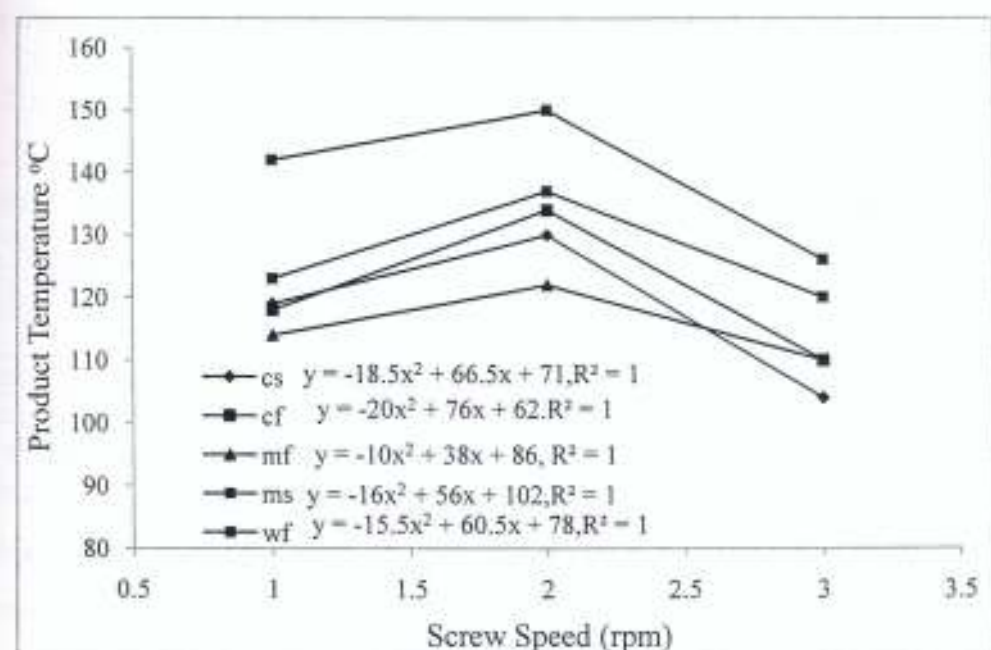


Figure 5.5: Variation of product temperature with screw speed at 30 minutes extrusion time and 30% initial moisture content.

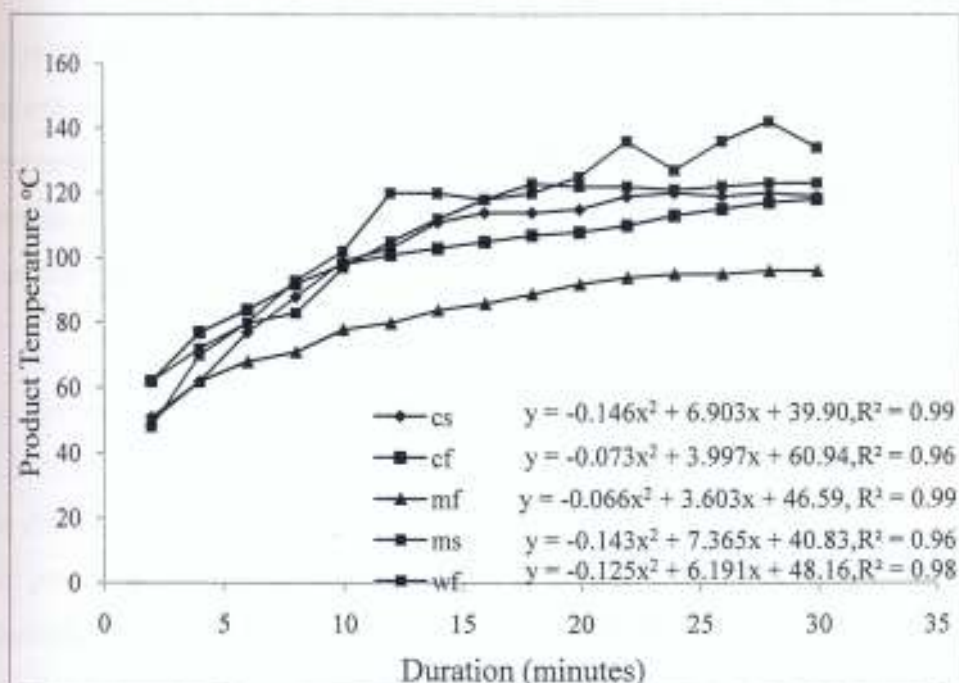


Figure 5.6: Variation of product temperature of products with duration of operation at 100 rpm screw speed and 30% initial moisture content.

Table 5.2 shows a simple statistics showing the maximum and the minimum values of system parameters under study.

Table 5.2: Simple Statistics of System parameters

Response Variable	Maximum		Minimum	
	Product	Value	Product	Value
Product Temperature °C	Pc ₃ Ss ₂ Mc ₂ Dt ₁₅	150	Pc ₄ Ss ₃ Mc ₂ Dt ₁	43
SME kJ/kg	Pc ₁ Ss ₂ Mc ₂ Dt ₁₅	241.71	Pc ₃ Ss ₁ Mc ₃ Dt ₁₅	4.7
Torque	Pc ₁ Ss ₁ Mc ₁ Dt ₁₅	105.10	Pc ₅ Ss ₃ Mc ₃ Dt ₁₅	0.83
Mean residence time, sec	Pc ₁ Ss ₁ Mc ₂ Dt ₁₅	58.00	Pc ₅ Ss ₂ Mc ₁ Dt ₁₅	14

Pc- Product classification, 1- Cassava starch, 2- Cassava flour, 3- Maize starch, 4- Maize flour, 5- wheat flour; Ss- screw speed 0, 1, 2, 3; Mc – moisture content, 1, 2, 3; Dt - duration of sampling 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15.

From Table 5. 2, the highest temperature was observed for maize starch while the minimum temperature was that of maize flour. A maximum temperature of 150°C was attained in 30 minute through viscous dissipation at 150 rpm and 30% moisture content. The product temperature at 30 % moisture content was higher than at 25 and 40% moisture content. Steady state condition was attained within 15 minutes for samples 30% moisture content while it took longer time for samples with 25% and 30% moisture contents. This result agrees with those of Fletcher *et al.* (1985) who investigated the extrusion cooking of maize

flour for typical operating conditions: Throughput = 30 kg h⁻¹, screw speed = 300 rpm and 400 rpm, and moisture content = 25 to 83% (wet basis). They measured the mechanical power, temperature and pressure in the material along the extruder, and the characteristics of the product as it leaves the die. They show that the presence of the die causes a sudden rise in pressure and temperature. The product temperature attained to was between 75 and 130°C.

However, for cassava flour the product temperature decreased with increase in moisture content from 25 to 40%. The difference observed between cassava starch and cassava flour might be due to the differences in their carbohydrate and protein contents. For example, the increased protein content of cassava flour when compared with that of cassava starch might be responsible for the difference in their product temperature. The result of the statistical analysis showing the order of importance of variables is presented in Table 5.3. The interaction term improved the model.

Table 5.3: Stepwise Regression of Product temperature for all Product Classification

Models	Coefficients		T-test	Prob	Adjusted R ²	F value	Prob	VIF
1	B ₀	63.785	57.440	.000	.627	1158.038	.000	1.000
	Dt	2.081	34.030	.000				
2	B ₀	73.537	41.755	.000	.652	643.770	.000	1.000
	Dt	2.082	35.214	.000				
	sm	-.002	-6.986	.000				

From Table 5.2, the Duration of sampling has the highest contribution, 62.8%, to R² of Product temperature. The interaction term of screw speed and moisture content (sm) improved the model R² by 2.5%, The Variance Inflation Factor (VIF) value for all parameter estimates were 1.0. Therefore, it can be concluded that multicollinearity is not a problem in this case. The more strongly correlated the independent variables are, the greater the need for controlling the confounding effects. However, the greater the intercorrelation of the independent variables, the less the reliability of the relative importance indicated by the partial regression coefficients. The estimated coefficients reflect how changes in the predictors affect the response. The interaction term improved the model.

The coefficients in the regression equation can be used to examine the significance of each term relative to each other. Hypothesis tests can be used to gain a rough idea of importance of the effects. The F-test tool provides the result of a test of the null hypothesis that these two samples come from distributions with equal variances, against the alternative that the variances are not equal in the underlying distributions. The tool calculates the value f of an F-statistic (or F-ratio). The alpha level is a significance level that is related to the probability of having a type I error (rejecting a true hypothesis). A value of f close to 1 provides evidence that the underlying population variances are equal. In the output table, if $f < 1$ "P(F $\leq f$) one-tail" gives the probability of observing a value of the F-statistic less than f when population variances are equal, and "F Critical one-tail" gives the critical value less than 1 for the chosen significance level, Alpha. If $f > 1$, "P(F $\leq f$) one-tail" gives the probability of observing a value of the F-statistic greater than f when population variances are equal, and "F Critical one-tail" gives the critical value greater than 1 for Alpha.

Collinearity (or multicollinearity) is the undesirable situation when one independent variable is a linear function of other independent variables. Eigenvalues of the scaled and uncentered cross-products matrix, condition indices, and variance-decomposition proportions are displayed along with variance inflation factors (VIF) and tolerances for individual variables. Multicollinearity refers to the situation in which some or all of the independent variables are very highly inter-correlated. The variance inflation factors (VIF) were used to detect the presence of multicollinearity. VIF measures how much the variances of the estimated regression coefficient are inflated as compared with when the independent variables are not linearly related (Neter *et al.*, 1990). According to Neter *et al.* (1990) maximum VIF value in excess of 10 is often taken as an indication that multicollinearity may be duly influencing the least squares estimates.

T test value in the table shows the extent (%) of the influence of the independent variable on the performance of the response variable. If positive, it indicates that an increase in the independent variable is contributing a positive percentage to the response variable. If negative, then a unit increase of the independent variable is decreasing the response variable. The F value indicates the significance of the total model. In this study, a unit increase in Dt is contributing 35.214% to PT while a unit increase in sm is decreasing PT by 6.99%.

Product temperature measured before the die is one of the dynamically controlled variables usually taken to reflect and predict product quantity in the food extrusion. It is a measure of the thermal energy input in the extruded mass. (Olkku *et al.*, 1980; Meuser *et al.*, 1987). Product temperature is a suitable system parameter for a system analysis of extrusion cooking. As a system parameter it can be used to connect extrusion cooking conditions such as screw speed, moisture content, screw configuration *e.t.c* and product conversion (Water Absorption index, Water Solubility Index) and thus to optimize and scale up the process appropriately (Bouvier, 2001), hence, controlling product temperature is a major objective of sizing and thermally optimizing an extruder. Also after constant moisture content, barrel temperature is the most significant factor affecting starch gelatinization during extrusion, followed by feed rate and screw speed (Ibanoglu, *et al.*, 1996).

For corn meal, dough temperature studied at various extrusion conditions (Chang and Halek, 1991) increased with increased barrel wall temperature zone 5, the most important factor that accounted for nearly 0.96 of the total R^2 . Food moisture or screw speed showed a slight effect. Also, food moisture and screw speed did not represent high R^2 but are yet significant. It was speculated that since increase in screw speed reduced residence time, degree of fill and filled length, increases in viscous heating would be balanced by reduced barrel heat transfer. This was confirmed by the fact that dough temperature for screw speed 200 rpm only differed from that for 100 rpm slightly.

For wheat starch, Van Zuilichem and Stolp (1987) reported a similar case that a temperature of 95°C was attained in 44 minutes with an extruder of the following configuration: screw L/D: 1/12, compression ratio: 2.94 screw speed: 100 rpm and moisture content: 15.9 - 16.7%. The viscosity attained to within the period was 18×10^2 BU. However when the time of operation was extended beyond one hour to one hundred and three minutes the temperature decreased. Also, a decrease in die diameter as well as in the moisture content led to an increase in Product temperature for wheat starch (Meuser *et al.*, 1987; O' Connor, 1987).

5.3.1.2 Effect of extrusion variables on specific mechanical energy (SME)

Figure 5.7 - 5.9 show the effect of extrusion variables (initial moisture content, duration of operation and screw speed) on SME. The graph shows that SME varies directly with duration of operation. SME decreased with increase in duration of operation. Also, it increased from 100 to 150 rpm and then decreased at 200 rpm. Extruder's performance improved from 100 to 150 rpm but at 200 rpm there was a change in the performance of the extruder. For instance, the product temperature reduced at 200 rpm than at 150 rpm. Also, the SME decreased as screw speed increased. Also, SME decreased with increasing speed from 100 to 200 rpm and increase in moisture content from 25 to 40%. Maximum SME of 241.71 kJ/kg was attained in 30 minutes through viscous dissipation at 150 rpm and 30% moisture content while a minimum of 24.79 kJ/kg occurred at 200 rpm and 40% moisture content. However, SME varies inversely with duration of operation for all cereal products under consideration. The stepwise regression data analysis of SME is shown Table 5.4. The interaction term S_m has the highest contribution 15.9%, to R^2 of SME. The variable, starch content accounted for 2.9%, duration of sampling, 3.9% of the total variation in R^2 and dsm accounted for only 1.4%.

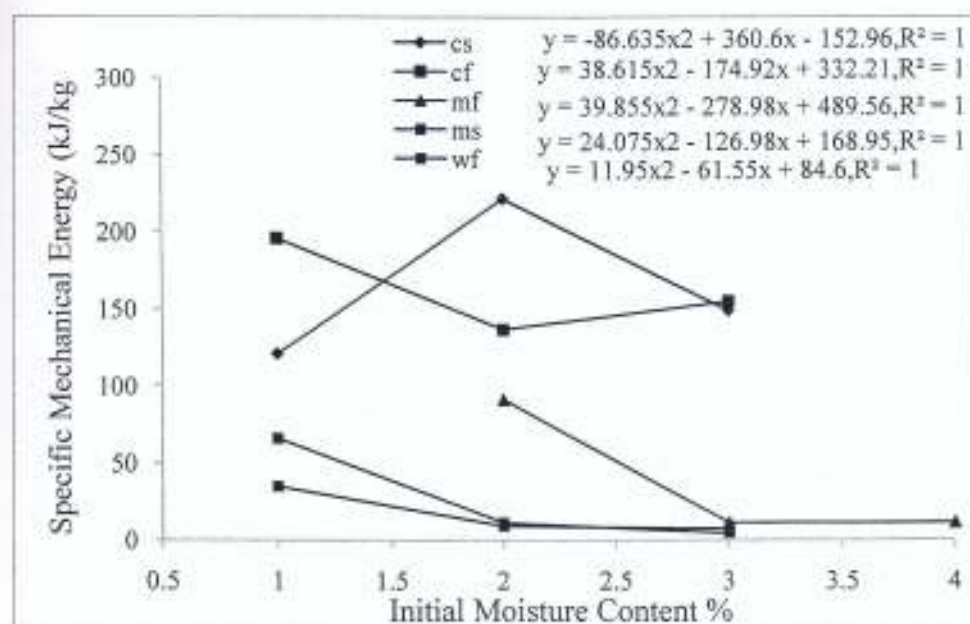


Figure 5.7: Variation of specific mechanical energy with initial moisture content at 30 minutes extrusion time and 100 rpm screw speed.

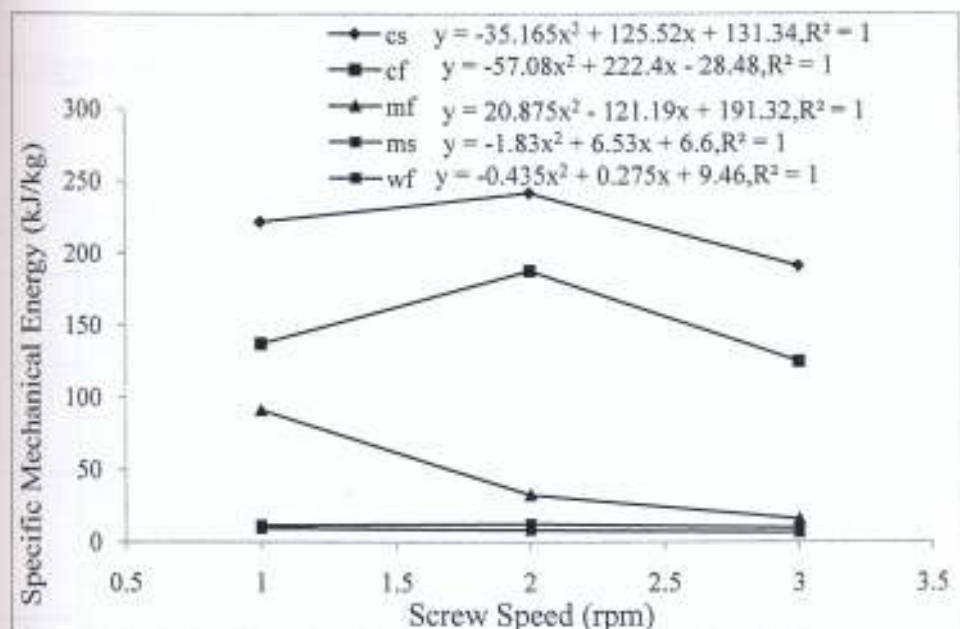


Figure 5.8: Variation of specific mechanical energy with screw speed at 30 minutes extrusion time and 30% initial moisture content.

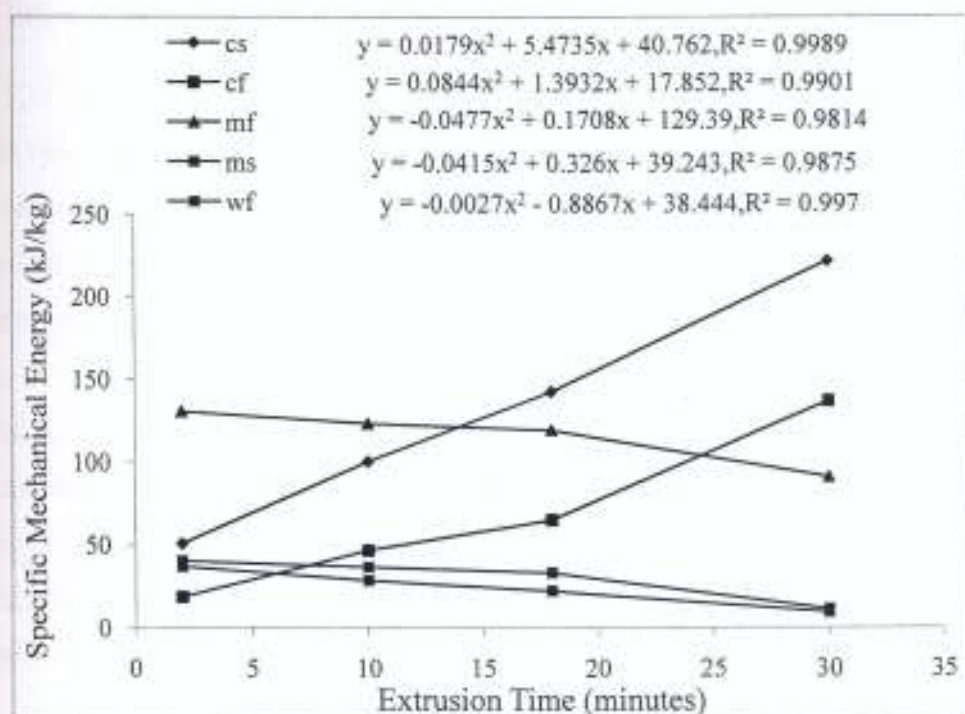


Figure 5.9: Variation of specific mechanical energy with duration of operation at 100 rpm screw speed and 30% initial moisture content.

Table 5.4: Stepwise regression of specific mechanical energy for all Product Classification

Models	Coefficients		T-test	Prob.	Adjusted R	F value	Prob.	VIF
1	Bo	30.411	0.302	0.764	0.159	33.368	0.000	1.000
	Sm	-0.003	7.768	0.000				
2	Bo	30.411	0.562	0.578	0.278	35.018	0.000	1.001
	sm,	-0.004	15.316	0.000				
	Sc	0.690	-9.198	0.000				
3	Bo	-35.892	0.610	0.546	0.317	28.394	0.000	1.001
	sm,	2.411	15.316	0.000				
	Sc,	0.000	-3.890	0.000				
	Dt,	-0.004	-2.627	0.013				
4	Bo	0.752	0.681	0.501	0.331	22.857	0.000	3.100
	Sm,	4.390	6.453	0.000				
	Sc,	0.000	1.728	0.094				
	Dt,	-0.016	-3.758	0.001				
	dsm	-0.062	-2.972	0.006				

5.3.1.3 Effect of extrusion variables on torque

Figure 5.10 - 5.12 show the effect of cassava starch moisture content on torque at 100, 150 and 200 rpm screw speed and 30 minutes duration of operation. The graph shows that torque varies directly with duration of operation. Torque increased with increase in duration of operation for cassava products while it decreased with increase in duration of operation for cereal products. Also, Torque decreases with increasing speed from 100 to 200 rpm and increase in moisture content from 25 to 40%. Maximum torque of 105 Nm per 30 minutes was attained through viscous dissipation at 100 rpm and 25% moisture content while a minimum of 3.35 Nm occurred at 200 rpm and 40% moisture content. The above results of decrease in SME and torque with increase in moisture content were because water acts as a plasticizer that decreases viscosity. The result of the statistical analysis is presented in Table 5.5. The interaction term improved the model.

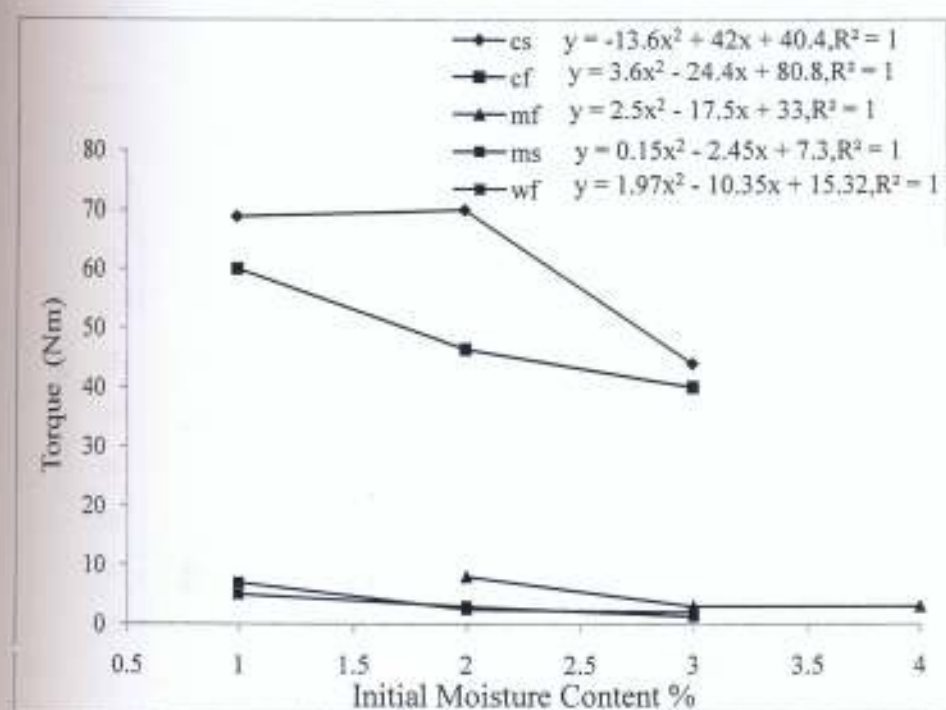


Figure 5.10: Variation of specific mechanical energy with initial moisture content at 30 minutes extrusion time and 100 rpm screw speed.

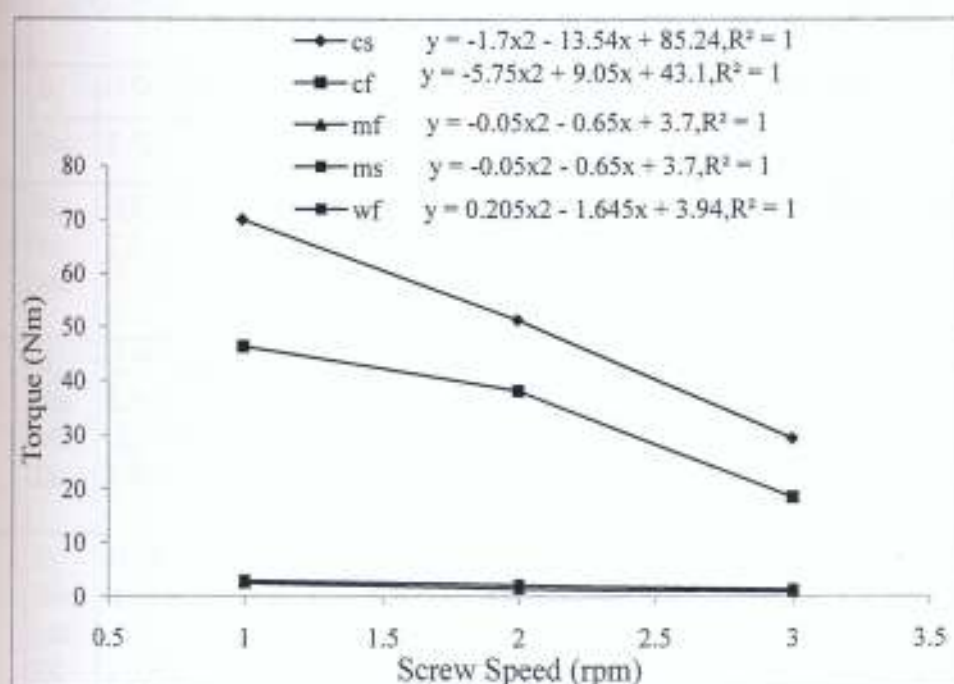


Figure 5.11: Variation of specific mechanical energy with screw speed at 30 minutes extrusion time and 30% initial moisture content.

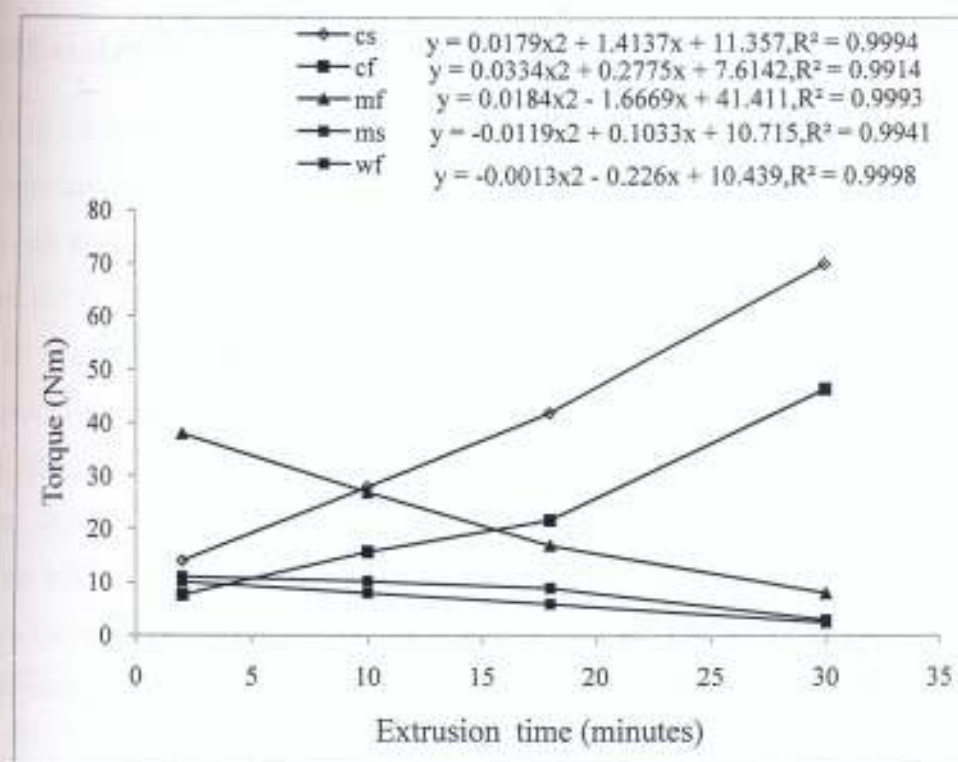


Figure 5.12: Variation of specific mechanical energy with duration of operation at 100 rpm screw speed and 30% initial moisture content.

Table 5.5: Stepwise regression of torque for all product classification

Models	Coefficients		T-test	Prob	Adjusted R	Std. Error	F value	Prob	VIF
1	B ₀	-156.761	-4.088	.000	.149	45.217	32.045	.000	1.000
	Sm	2.424	5.661	.000					
2	B ₀	-88.537	-2.357	.204	.272	41.826	34.071	.000	1.003
	Sm	2.534	6.391	.000					
	Mc	-2.337	-5.540	.001					
3	B ₀	-105.324	-2.865	.005	.315	40.570	28.143	.000	1.000
	Sm	2.548	6.625	.000					
	Mc	-2.329	-5.692	.000					
	Dt	1.014	3.464	0.000					
4	B ₀	-124.315	-3.346	0.001	0.333	40.044	23.067	0.000	1.003
	Sm	2.548	6.712	0.000					
	Mc	-1.759	-3.742	0.000					
	Dt	2.280	3.752	0.000					
	dsm	0.000	-2.368	0.019					

5.3.1.4 Effect of extrusion variables on mean residence time (MRT)

Figure 5.13 - 5.15 show the effect of extrusion variables (initial moisture content, duration of operation and screw speed) on mean residence time. Mean residence time (MRT) varies directly with duration of operation. Also, MRT decreased with increasing speed from 100 to 200 rpm and decrease in moisture content from 25 to 30% and an increase at 40%. The reason for this was because at higher moisture content i.e. 40%, the mash tend to adhere to the surface of the barrel, hence could not be conveyed easily. This is contrary to the report of Sohkey, *et al.* (1997) that moisture content improved the conveying capacity of an extruder. This is probably due to the differences in the screw configurations used. Maximum MRT of 58 sec was attained in 30 minute through viscous dissipation at 150 rpm and 25% moisture content while a minimum of 21.5 sec occurred at 200 rpm and 30% moisture content. The stepwise regression data analysis of MRT is shown Table 5.6

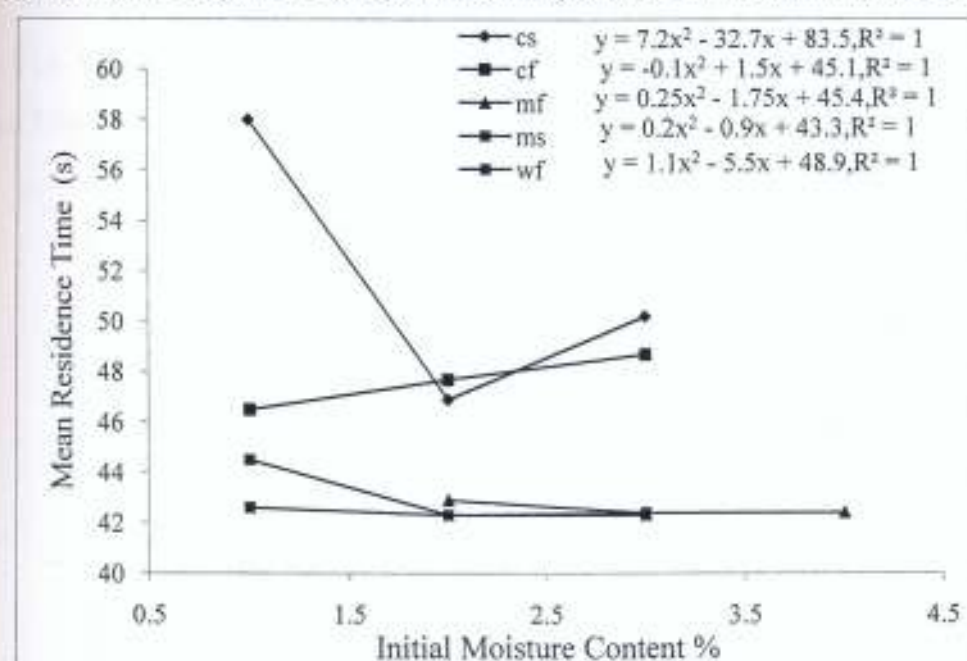


Figure 5.13: Variation of mean residence time with initial moisture content at 30 minutes extrusion time and 100 rpm screw speed.

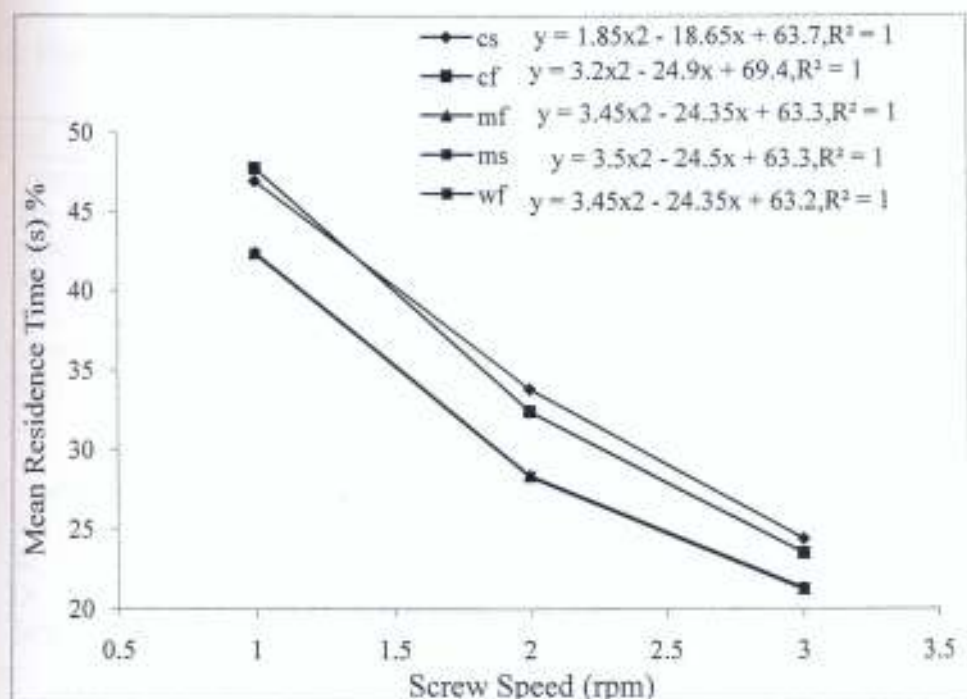


Figure 5.14: Variation of mean residence time with screw speed at 30 minutes extrusion time and 30% initial moisture content.

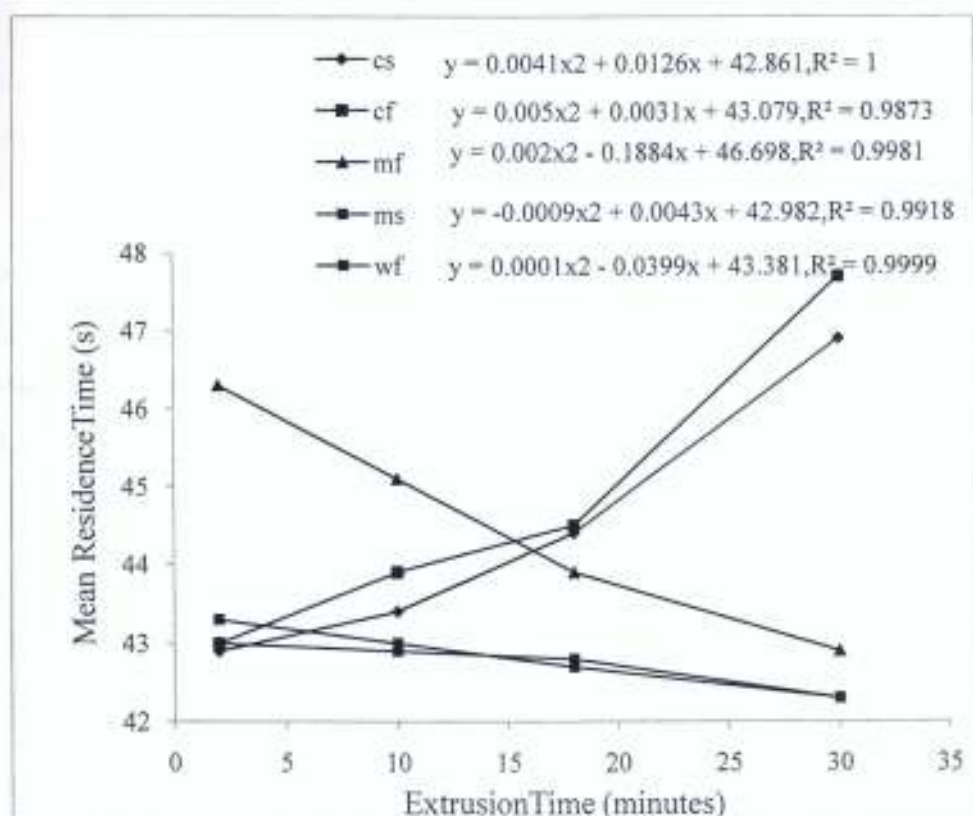


Figure 5.15: Variation of mean residence time with duration of operation at 100 rpm screw speed and 30% initial moisture content.

Table 5.6: Stepwise regression of MRT for all product classification

Model	Coef.	T test	Prob.	R ²	F value	Prob.	VIF
1 Constant	66.07	78.812	.000	.910	1784.25	.000	
Sm	-.227	-42.240	.000				1.000
2 constant	58.04	22.687	.000	.916			
Sm	-.227	-43.370	.000		948.13	.000	1.000
Sc	.090	3.312	.001				1.000
3 Constant	60.78	23.192	.000	.921			
Sm	-.227	-44.621	.000		672.09	.000	1.000
Sc	.094	3.569	.000				1.003
Dt	-.093	-3.325	.001				1.003
4 Constant	67.92	15.762	.000	.922	514.75	.000	
Sm	-.274	-11.826	.000				21.138
Sc	.093	3.571	.000				1.003
Dt	.848	-2.887	.004				8.849
dsm	.000	2.078	.039				10.902

5.3.2 Product Quality Attributes

Product quality attributes studied include product moisture content, expansion ratio, compressive strength, water absorption index, water solubility index, cold paste viscosity and hot paste viscosity. Table 5.7 shows the simple statistics of the maximum and minimum values of the product quality attributes.

Table 5.7: Simple statistics of product quality attributes

Response Variable	Maximum		Minimum	
	Product	Value	Product	Value
Product moisture, %	Pc ₃ Ss ₃ Mc ₃ Dt ₁	39.52	Pc ₂ Ss ₃ Mc ₂ Dt ₁	10.60
Expansion ratio	Pc ₁ Ss ₂ Mc ₂ Dt ₇	11.57	Pc ₃ Ss ₁ Mc ₃ Dt ₁₅	0.985
Compressive strength, N	Pc ₁ Ss ₃ Mc ₁ Dt ₁	3050.00	Pc ₅ Ss ₃ Mc ₃ Dt ₁₅	0
Relative melt viscosity, 0.001Pa.s	Pc ₁ Ss ₁ Mc ₂ Dt ₁₂	10.45	Pc ₅ Ss ₂ Mc ₁ Dt ₁₅	2.8
Water absorption index, g/g	Pc ₁ Ss ₁ Mc ₂ Dt ₁₅	9.00	Pc ₃ Ss ₂ Mc ₂ Dt ₁₅	1.62
Water solubility index, g/g	P ₃₁ Ss ₀ Mc ₂ Dt ₁₅	-	Pc ₃ Ss ₂ Mc ₂ Dt ₁₅	-
Hot paste viscosity, dPa.s	Pc ₁ Ss ₀ Mc ₁ Dt ₀	9.7	Pc ₃ Ss ₂ Mc ₂ Dt ₁₅	0.1
Cold paste viscosity, dPa.s	Pc ₁ Ss ₀ Mc ₁ Dt ₀	16.47	Pc ₃ Ss ₂ Mc ₂ Dt ₁₅	0.15

Pc- Product classification, 1- Cassava starch, 2- Cassava flour, 3- Maize starch, 4- Maize flour, 5- wheat flour; Ss- screw speed 0, 1, 2, 3, 4, 5; Mc – moisture content, 1, 2, 3; Dt - duration of sampling 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15.

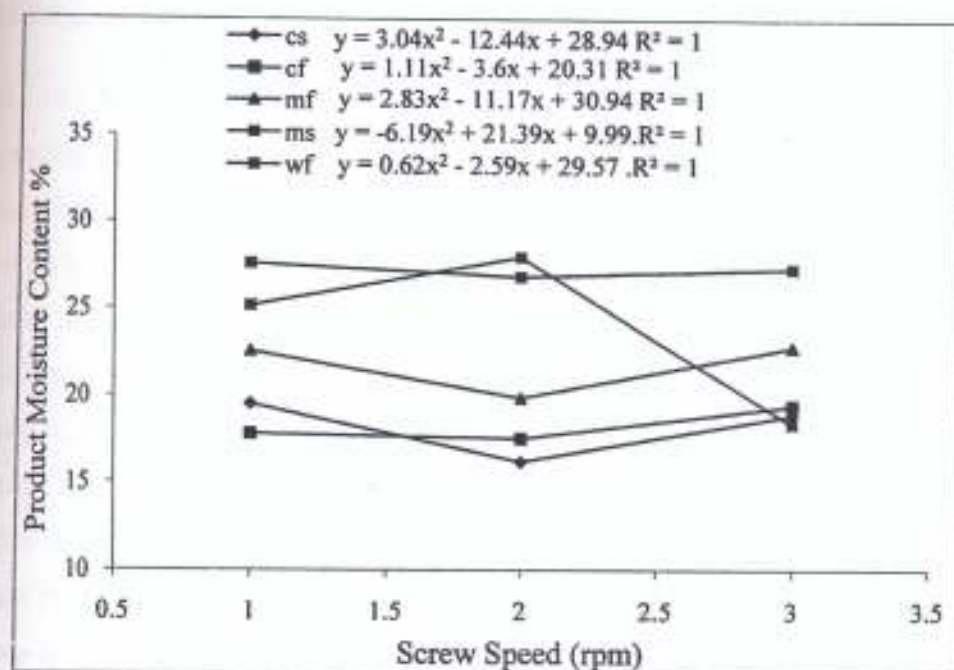


Figure 5.17: Variation of product moisture contents with screw speed at 30 minutes extrusion time and 30% initial moisture content.

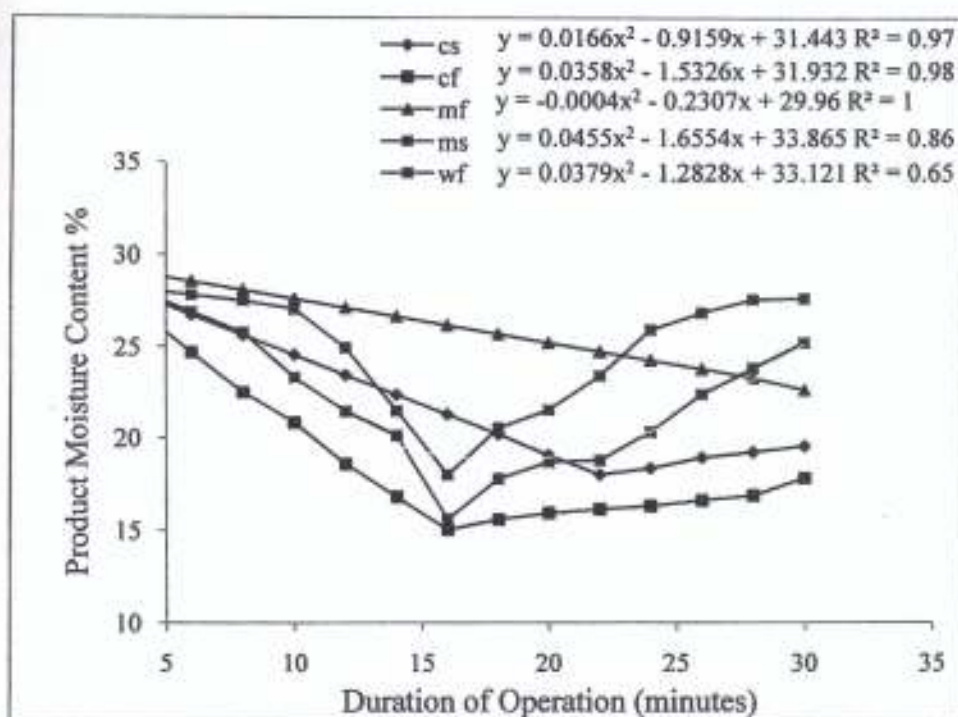


Figure 5.18: Variation of product moisture content with duration of operation at screw speed 100 rpm and initial moisture content 30%.

The best reaction was obtained at 30% moisture content for maize starch, cassava starch and wheat flour, 25% for cassava flour and 40% for maize flour.

5.3.2.1 Effect of extrusion variables on product moisture content

Figure 5.16 - 5.18 show the effect of extrusion variables (initial moisture content, duration of operation and screw speed) on product moisture content. Product moisture varies inversely with duration of operation. An increase in extrusion time decreased moisture content up to a critical value of above which it started to increase again. As feed moisture increased, higher extrudate moisture was obtained. Lo *et al.* (1998) reported similar result with yellow corn maize. Also, product moisture decreased from 100 to 150 rpm and then increased at 200 rpm. The extrudates' moisture loss is directly proportional with expansion. Increasing feed moisture content caused a decrease in transverse expansion and increase in extrudate moisture content. A high process temperature produced extrudates with low moisture content. The minimum product moisture of 10.6% indicating maximum moisture loss was attained at 150 rpm and 25% moisture content by cassava flour. A maximum moisture loss of 57.6% was obtained. The mass temperature fell with increasing extrudate moisture. Thus on increasing feed moisture of cassava and other products, the drop in barrel temperature created lower vapour pressure in the dough resulting in less flashing of moisture and reduced expansion.

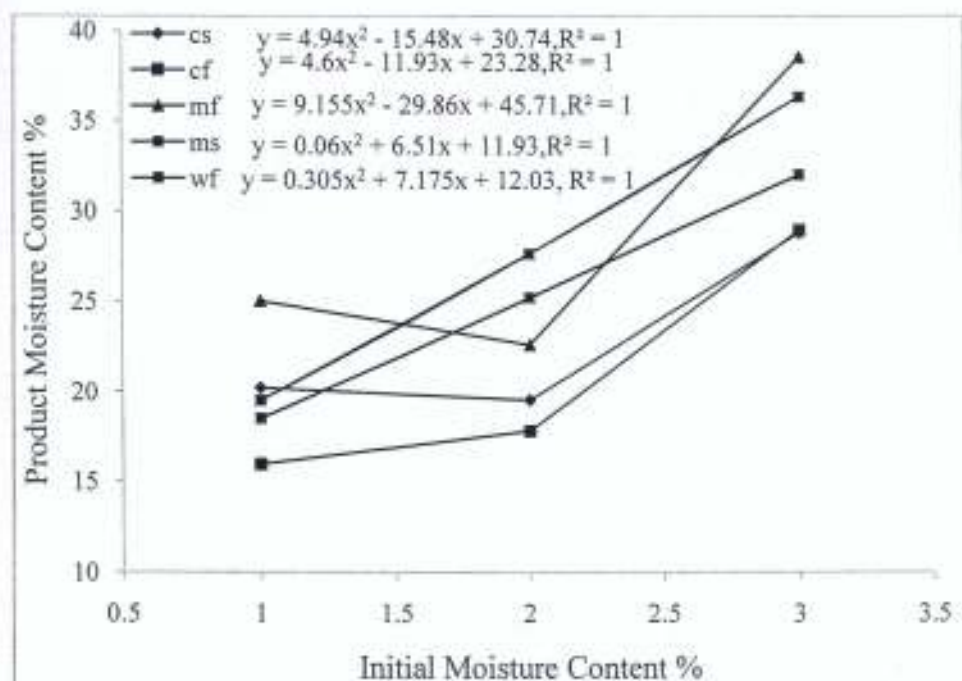


Figure 5.16: Variation of product moisture content with initial moisture content at 30minutes extrusion time and 100 rpm screw speed.

The best reaction was obtained at 30% moisture content for maize starch, cassava starch and wheat flour, 25% for cassava flour and 40% for maize flour.

From every indication, cassava flour has a lower and faster moisture loss than cassava starch. This difference obtained between cassava flour and its starch may be due to difference between their viscosities at high temperature/shear environment. An increase in extrusion time decreased moisture content up to a critical value of above which it started to increase again. The maximum value for the peak occurs where the cellulose is least i.e. starch. For higher concentration as contained in flour it decreased. This may be due to the fact that cellulose, being a major component of flour does not develop viscosity (Arambula, et al. 2002). Cassava starch therefore could not dry faster than its flour because of its higher viscosity. The stepwise regression data analysis of Product moisture is shown Table 5.8. The moisture content has the highest contribution, 71.2%, to R^2 of Product moisture. The interaction term dm accounted for 6.8%, starch content for 0.6% and protein content 2.7% of the total variation in R^2 . The VIF value for all parameter estimates were 1.0. Therefore, it can be concluded that multicollinearity is not a problem in this case.

Table 5.8: Stepwise regression of product moisture for all product classification

Models	Coefficients	T-test	Prob	Adjusted R^2	F value	Prob	VIF
1	B_0 -3.300	-4.328	.000	0.712	1709.93	.000	1.000
	Mc 0.928	41.351	.000				
2	B_0 -3.285	-4.932	.000	0.780	1228.08	.000	1.000
	Mc 1.045	49.397	.000				
	dm .007	-14.672	.001				
3	B_0 3.939	2.297	.022	0.786	849.19	.000	1.000
	Mc 1.050	50.260	.000				
	dm -0.007	-14.882	.000				
	Sc -0.083	-4.561	0.000				
4	B_0 42.042	10.139	0.000	0.813	752.70	0.000	1.169
	Mc 1.054	53.939	0.000				
	dm -0.007	-15.906	0.000				
	Sc -0.471	-11.083	0.000				
	Pc -0.728	-0.965	0.000				

5.3.2.2 Effect of extrusion variables on expansion ratio

Figures 5.19 - 5.21 show the effect of extrusion variables (initial moisture content, duration of operation and screw speed) on expansion ratio. Expansion ratio varies directly with duration of operation. Also, expansion ratio increased from 100 to 150 rpm and then decreased at 200 rpm. A maximum expansion ratio of 11.57% was attained through viscous dissipation in 30 minutes at 150 rpm and 30% moisture content by cassava starch. Expansion is negatively correlated to compressive strength. This was because with more expansion, the extrudate is filled with porous structure composed of air pockets surrounded by laminar sheets of gelatinized starch and thus leads to reduction in strength. The physical appearance of the extrudates arranged in order of duration of sampling and degree of expansion are shown in Plates 5.1 – 5.12.

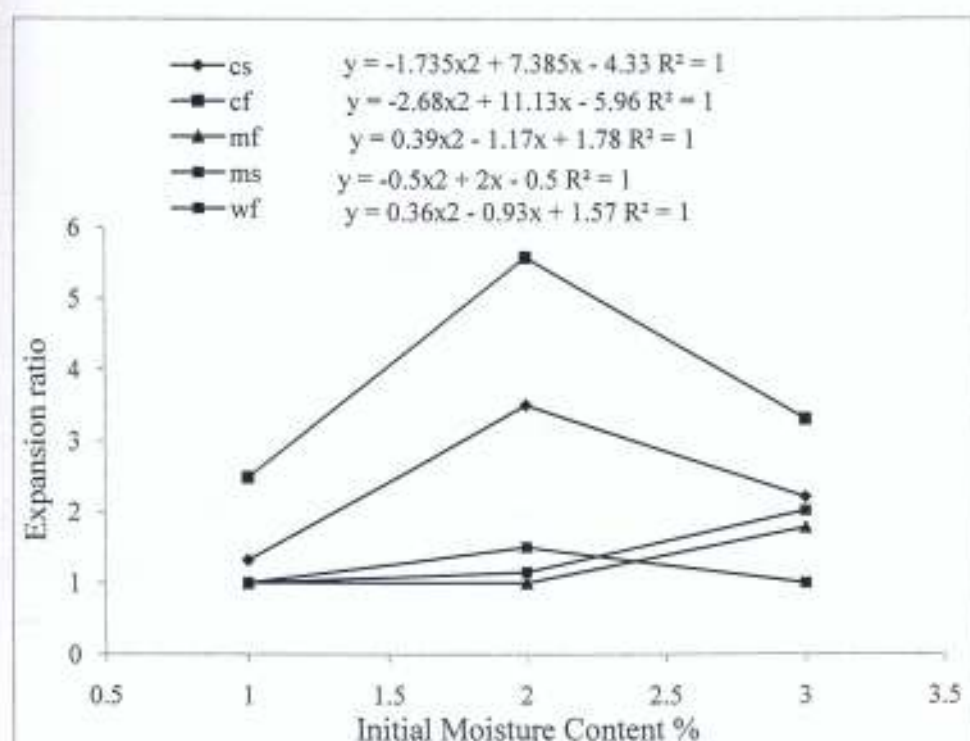


Figure 5.19: Variation of expansion ratio with initial moisture content at 30minutes extrusion time and 100 rpm screw speed.

An increase in extrusion time increased expansion up to a critical value of above which it started to decrease again. This was because increase in extrusion time leads to starch degradation with a consequent reduced expansion. All extrudates of maize starch at higher product temperature were characterized by their appearance, porous structure and fragility.

product temperature were characterized by their appearance, porous structure and fragility. Increase in temperature of maize starch to make it possible to obtain a texture with higher porosity and greater fragility. These changes in product characteristics are a result of modification of the starch and protein components under high temperature.

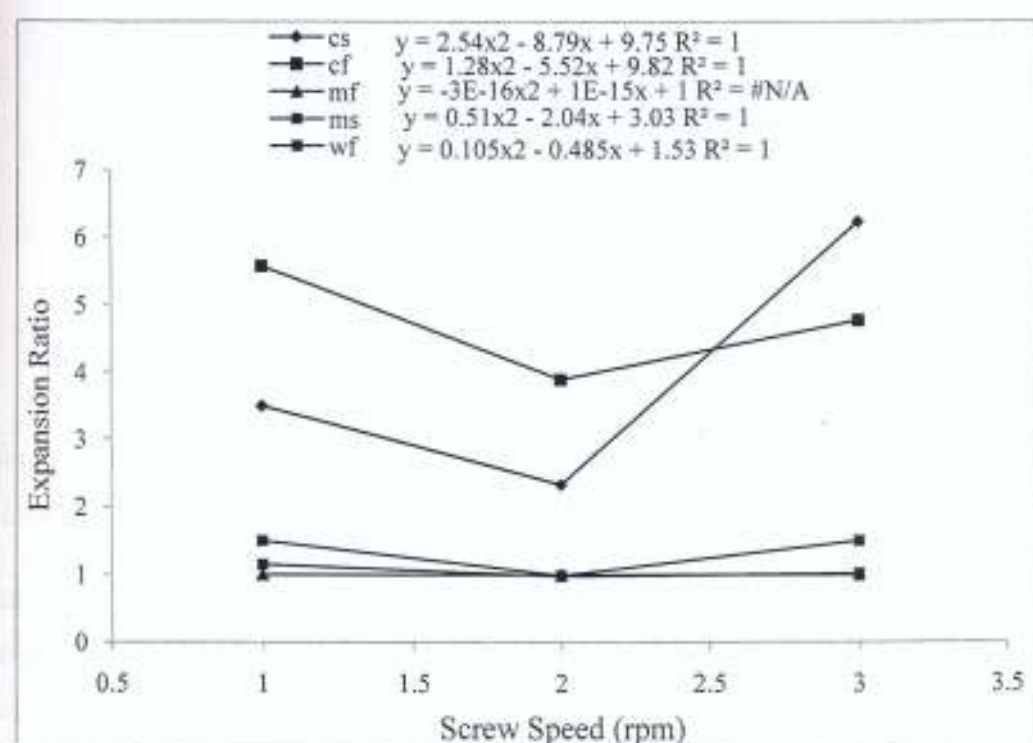


Figure 5.20: Variation of expansion ratio with screw speed at 30 minutes extrusion time and 30% initial moisture content.

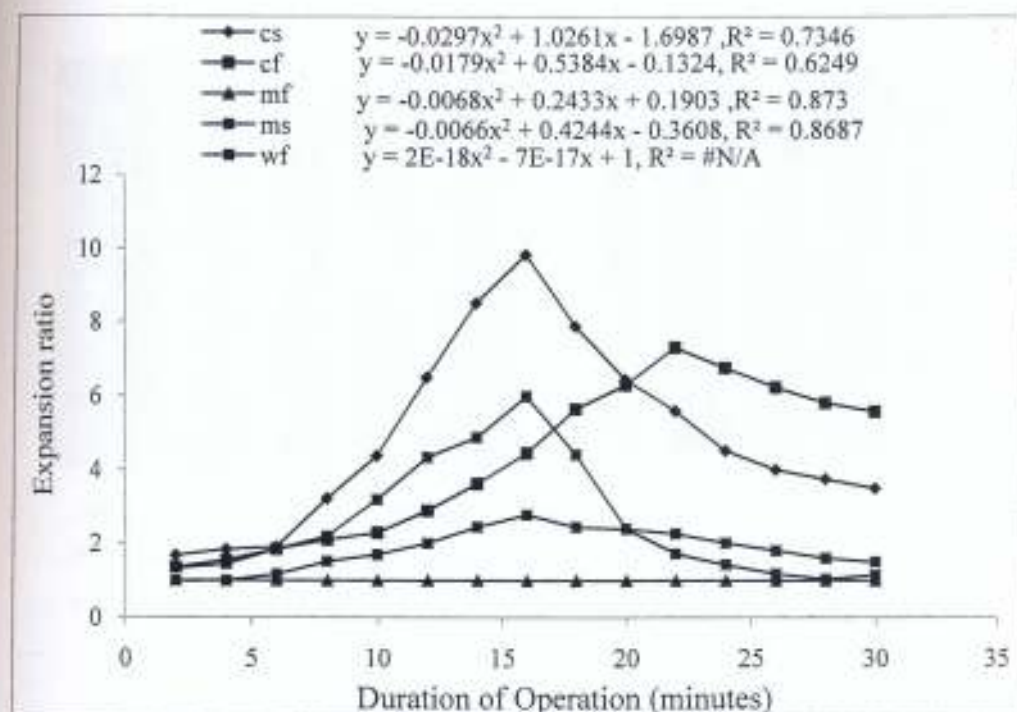


Figure 5.21: Variation of product expansion ratio with duration of operation at screw speed 100 rpm and initial moisture content 30%.

Maize starch even though was observed to start puffing even before maize flour but could not expand as much as maize flour probably because It does not develop sufficient strength /structure and adhesiveness to form a continuous matrix hence there were lots of bubbles even in the surfaces of the extrudates making them very, very weak to touch. However, this quality makes it very suitable as ready to eat snacks product, because since it is very weak and brittle, masticating it will be very easy. Gujska and Khan (1991) have suggested that the degree of expansion affects density, fragility and softness of extruded products. Hence, the degree of expansion is an important factor to monitor, especially if the extruded product is to be used as a snack. All products at low extrusion time are smooth and can be suitable for pasta products.

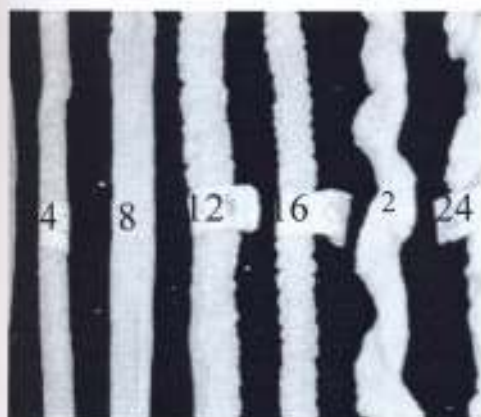


Plate 5.1 Cassava flour@ moisture content 25% and screw speed 100 rpm arranged in order of duration of operation.



Plate 5.2 Maize flour @ moisture content 40% screw speed 100 rpm arranged in order of operation.

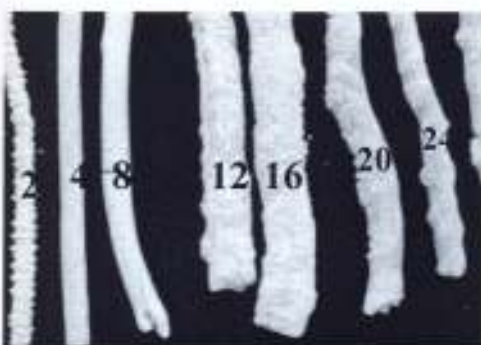


Plate 5.3 Wheat flour@ moisture content 30% and screw speed 100 rpm arranged in order of duration of operation.



Plate 5.4 Wheat flour @ moisture content 40% screw speed 100 rpm arranged in order of operation.

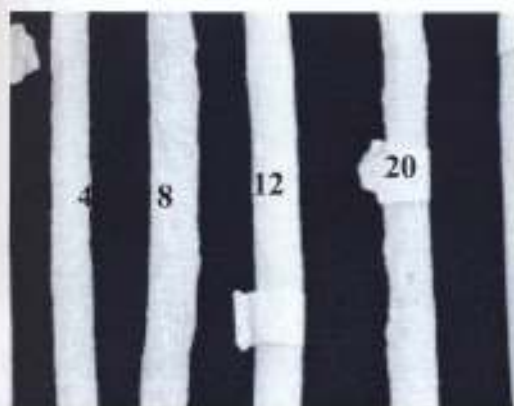


Plate 5.5 Maize flour@ moisture content 30% and screw speed 100 rpm arranged in order of duration of operation.



Plate 5.6 Maize starch @ moisture content 40% screw speed 100 rpm arranged in order of operation.



Plate 5.7 Cassava flour@ moisture content 30% and screw speed 100 rpm arranged in order of duration of operation.



Plate 5.8 Cassava starch @ moisture content 40% screw speed 100 rpm arranged in order of operation.

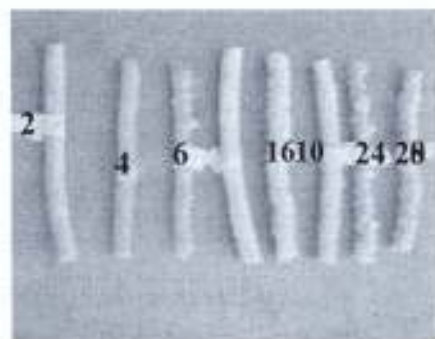
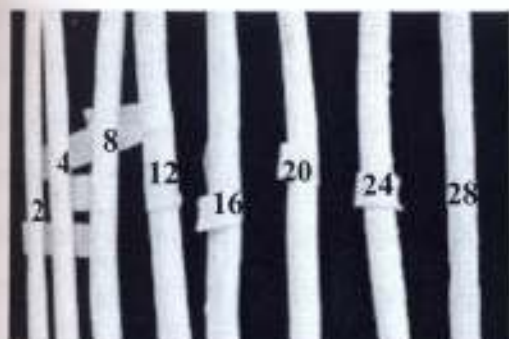


Plate 5.9 Cassava starch @ moisture content 30% and screw speed 100 rpm arranged in order of duration of operation.

Plate 5.10 Maize starch @ moisture content 30% screw speed 100 rpm arranged in order of operation.

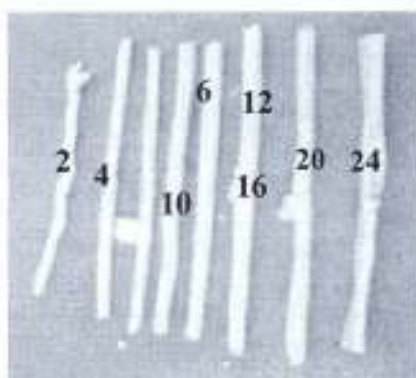
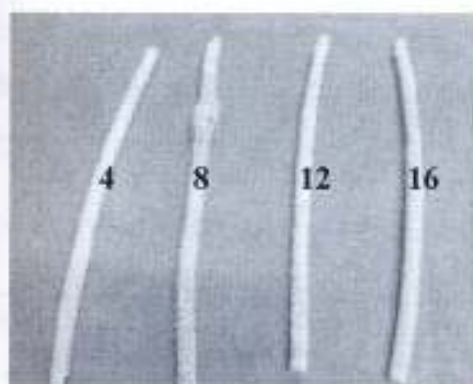


Plate 5.11 Maize flour @ moisture content 30% and screw speed 100 rpm arranged in order of duration of operation.

Plate 5.12 Cassava flour @ moisture content 40% screw speed 100 rpm arranged in order of operation.

The stepwise regression data analysis of expansion ratio is shown Table 5.9. From the stepwise linear multiple regression analysis conducted, the R^2 was very low. But a high R^2 was obtained for the plot (Graph) when fitted to a sixth order polynomial trend. The interaction term Sm has the highest contribution, 6%, to R^2 of product moisture. The variable, starch content accounted for only 1.3% and protein content 13.1% of the total variation in R^2 . This low R^2 for expansion ratio is an indication that the relationship is not best described by a linear model. The (VIF) value for all parameter estimates were 1.0. Therefore, it can be concluded that multicollinearity is not a problem in this case. The VIF value for some parameter estimates (ds, Mc, dsm) were 1.0. Therefore, it can be concluded that multicollinearity is not a problem in this case. However, for the 3rd model of the interaction terms ds and dsm, the VIF value of 26.79 and above can be an indication that at least one of the independent variables is a perfect linear function of one or more other independent variable in the equation.

The more strongly correlated the independent variables are, the greater the need for controlling the confounding effects. However, the greater the intercorrelation of the independent variables, the less the reliability of the relative importance indicated by the partial regression coefficients.

Table 5.9: Stepwise Regression of expansion ratio for all product classification

Models	Coefficients		T-test	Prob	Adjusted R	F value	Prob	VIF
1	B ₀	1.692	12.222	.000	.067	51.706	.000	1.000
	sm	1.04E-005	7.191	.000				
2	B ₀	-1.132	-1.270	.204	.080	31.332	.000	1.000
	sm	1.04E-005	7.192	.000				
	Sc	.032	3.208	.001				
3	B ₀	-23.608	-10.602	.000	.211	63.682	.000	1.000
	Sm	1.03E-005	7.685	.000				
	Sc	.260	11.345	.000				
	Pc	.428	10.869	0.000				

5.3.2.3 Effect of extrusion variables on compressive strength

Figures 5.21 - 5.23 show the effect of extrusion variables (initial moisture content, duration of operation and screw speed) on product temperature. Compressive strength varies inversely with duration of operation for cassava products. Product compressive strength decreased as the duration increased. Maximum compressive strength of 3050 N per 30 minute was attained through viscous dissipation at 200 rpm and 25% moisture content while a minimum of 506 N occurred at 150 rpm and 25% moisture content. It increased with increase in moisture content from 25 to 40%. The increase in compressive strength might be the result of reduced expansion caused by the increase in moisture content. This result agrees with those of Liu *et al.* (2000). However, for maize flour, as shown in Figure 3, the rate of change of compressive strength with duration of operation increased as the duration increased up to a critical value above which it decreased. Also, compressive strength decreased from 314.3 N at 100 rpm to 291.5 N at 150 rpm and then increased at 200 rpm to 530 N. This might be because of the rise in temperature of extrudates from 100 rpm to 150 rpm which might have reduced the viscosity (Lo *et al.*, 1998).

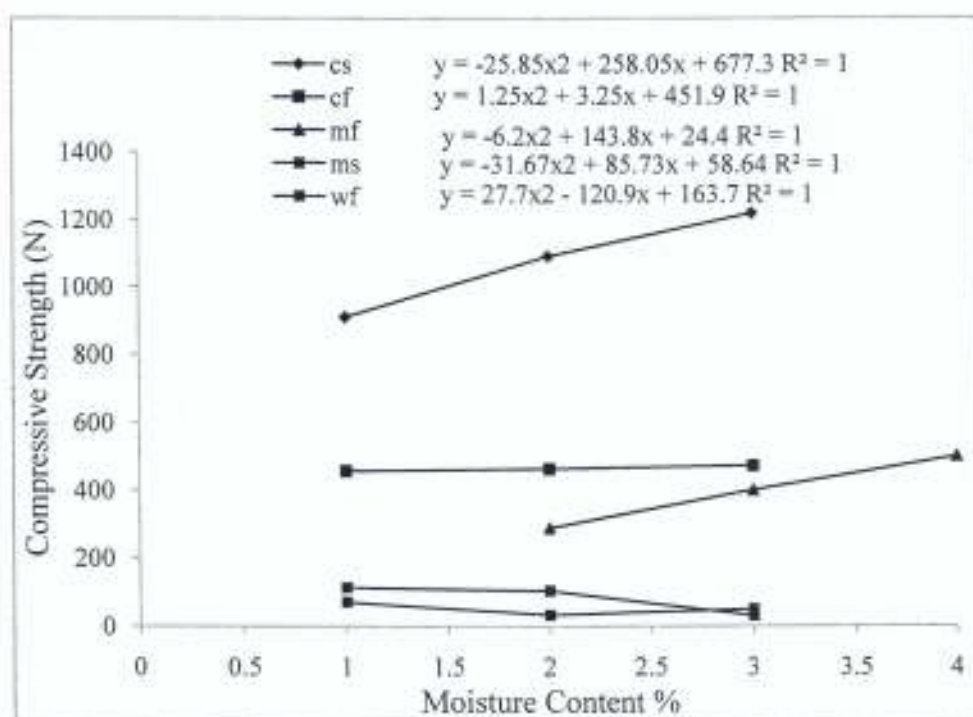


Figure 5.22: Variation of compressive strength with initial moisture content at 30 minutes extrusion time and 100 rpm screw speed.

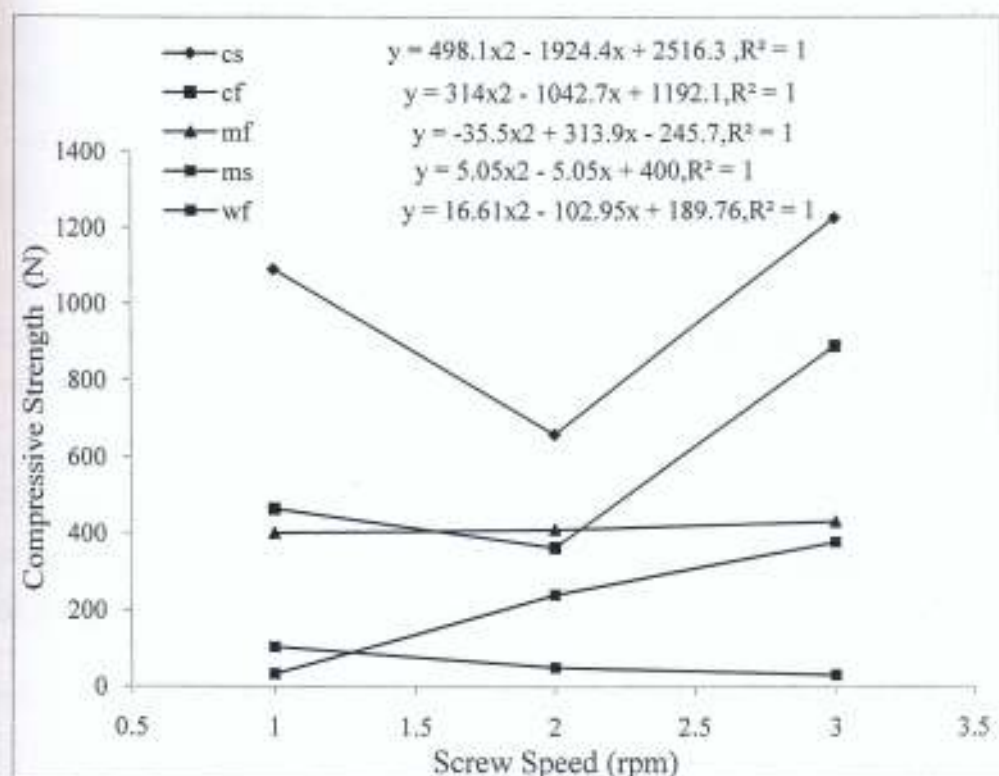


Figure 5.23: Variation of product temperature with screw speed at 30 minutes extrusion time and 30% initial moisture content.

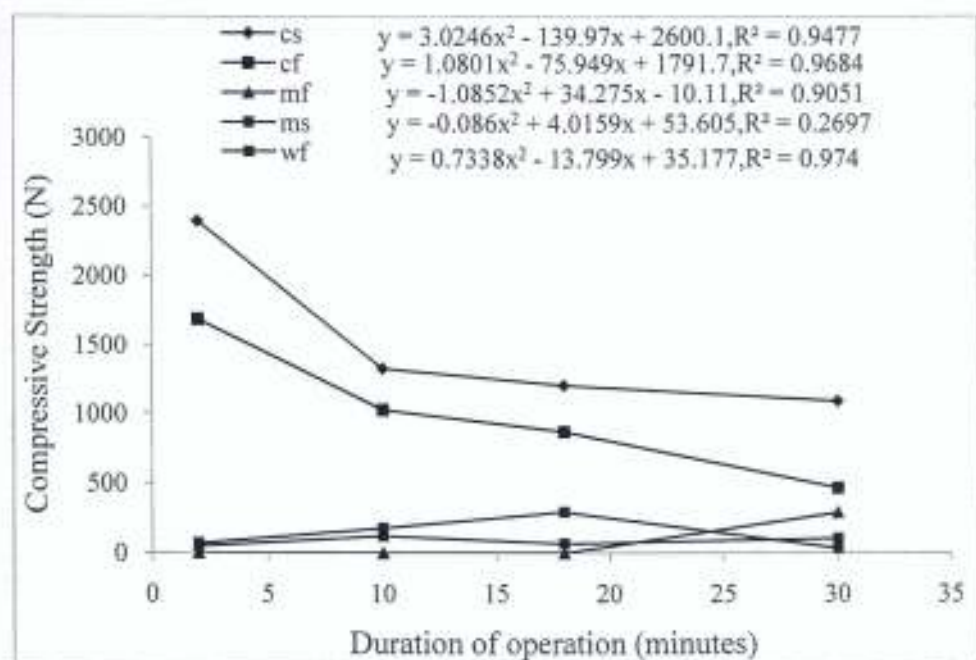


Figure 5.24: Variation of compressive strength with duration of operation at screw speed 100 rpm and initial moisture content 30%.

Maximum compressive strength of 207 N was attained by maize starch through viscous dissipation in 30 minutes at 100 rpm and 40% moisture content while a minimum of 18.1 N occurred at 150 rpm and 40% moisture content. Compressive strength increased with increase in moisture content from 25 to 40%.

When considered for aquatic pellets, soft pellets, typical of pelletizers tends to dissolve in water and wasted if not picked up immediately by the fish. Hard pellets which were produced from this extruder will either float or sink depending on the extrusion condition. Hard pellet tend to be denser than soft pellets. However, maize samples floated in water while cassava samples sank. Generally, from this study all maize samples processed at high temperatures floated in water and are not easily dissolved in water. Figures 5.24 to 5.28 show the Force – Deformation curves of products at variable extrusion conditions.

The average results of the rheological properties of the cassava starch, cassava flour, maize starch, maize flour and wheat flour at variable extrusion conditions are presented in Figures 5.24 to 5.28. Figure 5.24 shows the Force-Deformation curve of cassava starch of 30 % moisture content (w.b) at 2 minutes and 30 minutes duration of sampling and 100 rpm screw speed. The graph representing the 2 minutes duration shows that up to Pt. A, cassava

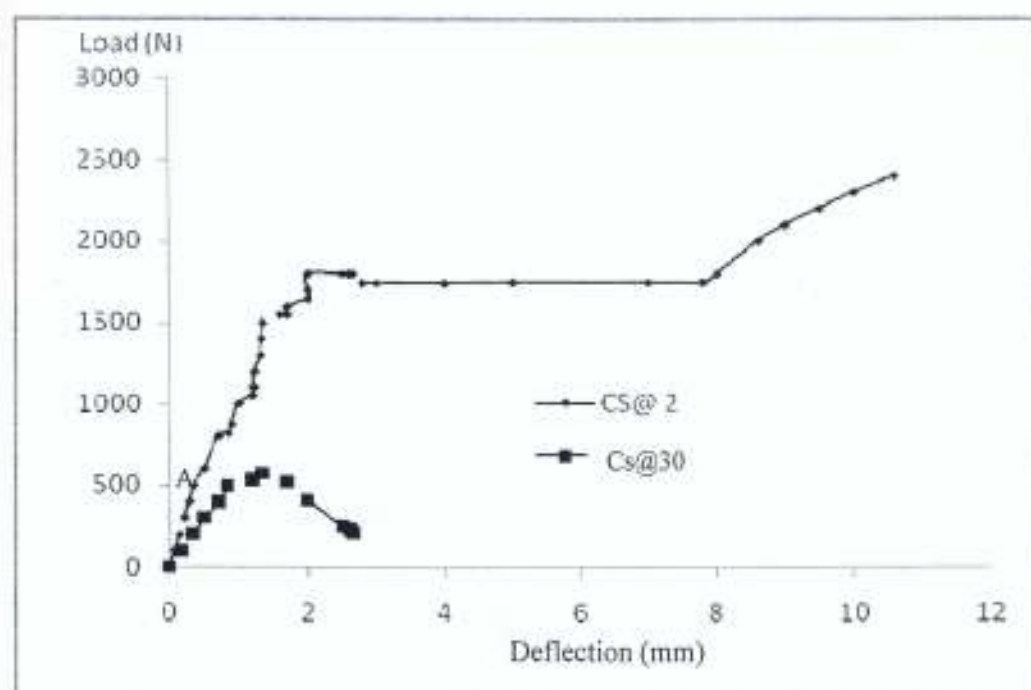


Figure 5.25: Force – Deformation curve of (a) cassava starch @ 30% moisture content, 2 minute duration of operation, (b) cassava starch @ 30 % moisture content and 30 minutes duration of operation.

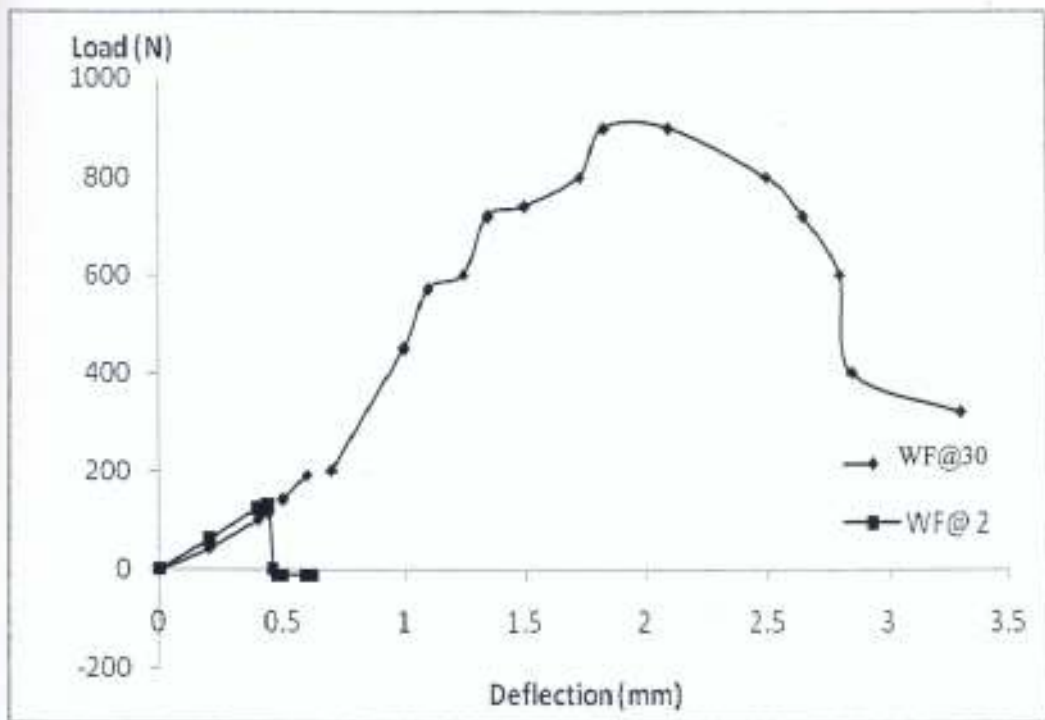


Figure 5.26: Force – Deformation curve of wheat flour @ (a) 40% moisture content, low duration of sampling, (b) 40 % moisture content high duration of sampling extrusion conditions.

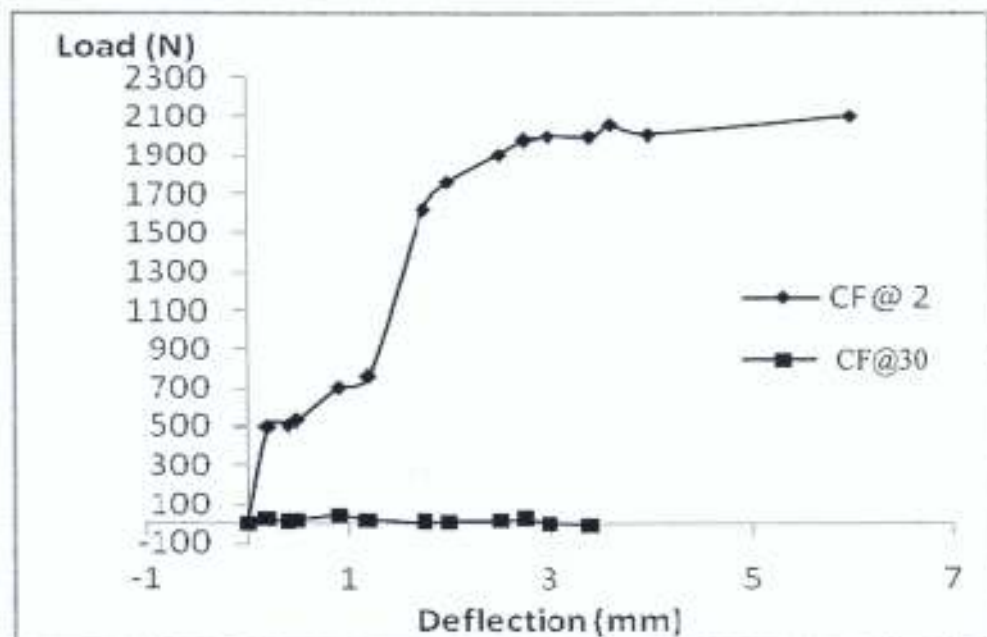


Figure 5.27: Force – Deformation curve of (a) cassava flour @ 25% moisture content, 2 minunte duration of operation, (b) cassava starch 25 % moisture content and 30 minute duration of operation.

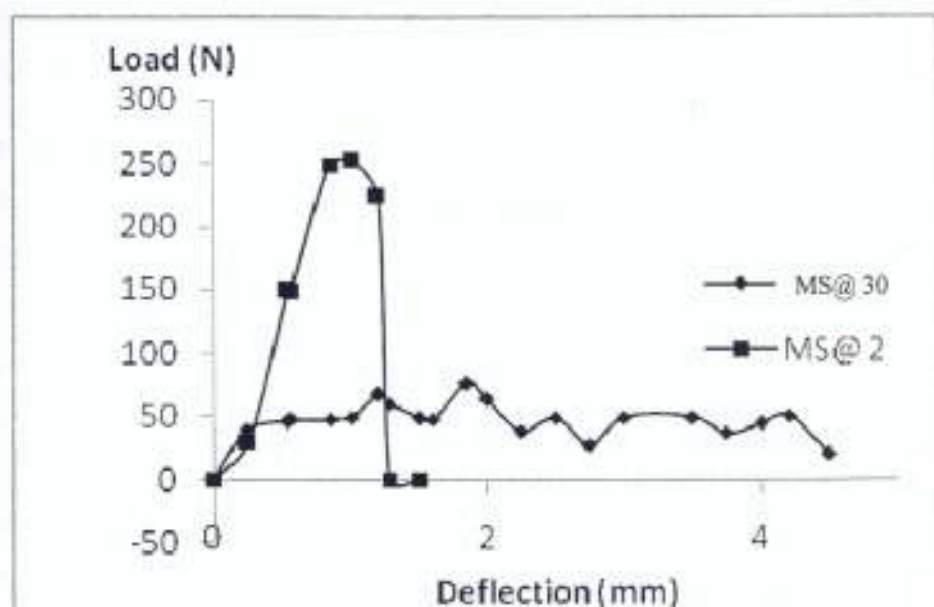


Figure 5.28: Force – Deformation curve of (a) maize starch @ 30 % moisture content, 2 minute duration of operation, (b) maize starch 30 % moisture content and 30 minutes duration of operation.

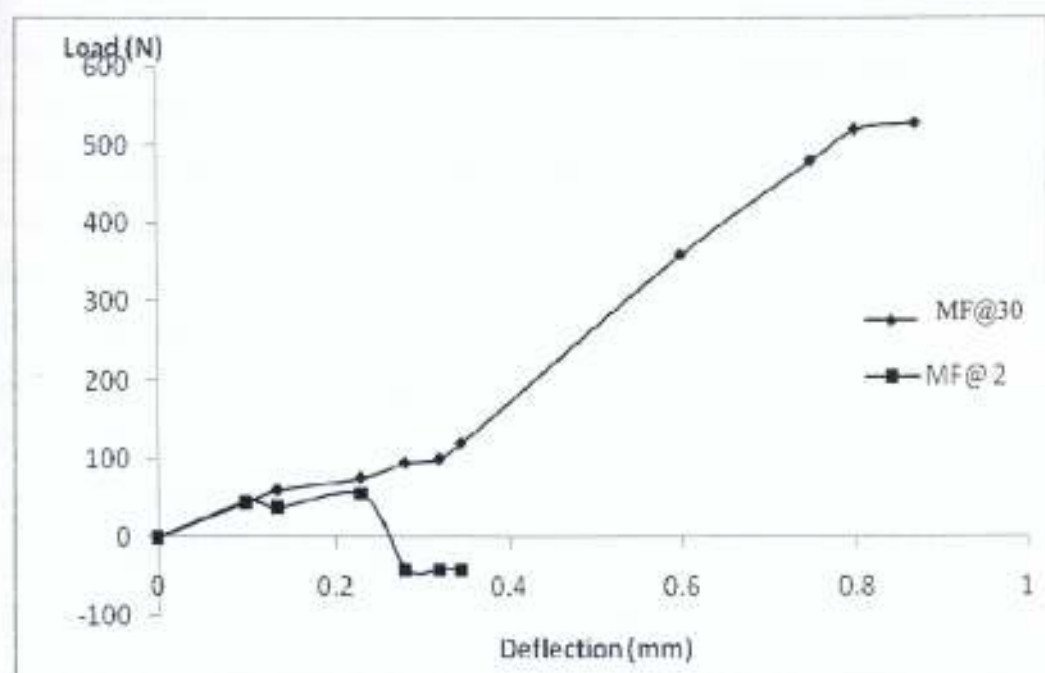


Figure 5.29: Force – Deformation curve of (a) maize flour @ 40% moisture content, 2 minute duration of operation, (b) maize flour 40 % moisture content and 30 minute duration of operation.

extrudate obeyed Hook's law while it manifested plastic deformation as from pt. B. The 30 minute graph however showed that the material is brittle.

From these figures, it is evidenced that cassava products are generally elastic at low temperature/ duration of operation with higher deformation values while at higher duration of operation/ temperature, the rate of deformation is low. For cereal products, however, extrudates are soft at low duration of operation with low deformation. Also, cassava products are weaker at higher extrusion times while cereal products grew stronger. Samples without load at yield are very brittle. Those with fibres e. g maize flour tend to be more ductile at low extrusion time while those without fibre are brittle e.g. maize starch. From figure 5.28, for maize starch at 30 minutes duration of operation, the fluctuations (rise and fall) in the deformation curve is an evidence of the voids formed in the extrudates during extrusion. Also, there are clear indications that the curves all concave towards the deformation axis. Moreover, the force-deformation curves obtained from the compression tests follow the usual pattern or shapes (sigmoid) of curves obtained for visco -elastic substances such as biomaterials (Mohsenin, 1970).

Hard pellets, typical of cassava products will either float or absorb water and sink. Hard pellet tend to be denser than soft pellets. Also cassava products are generally elastic at low temperature/ duration of operation with higher deformation values while at higher duration of operation/ temperature, the rate of deformation is low. For cereal products, however, extrudates are soft at low duration of operation with low deformation. Samples without load at yield are very brittle. Those with fibres e. g maize flour tend to be ductile while those without fibre are brittle. e.g. maize starch. Fibers are difficult to compress but when they are present in sufficiently fine strands in the pellet, they give toughness to the product (Anderson *et al.*, 1981; Artz *et al.*, 1990). Such foods are of interest to the consumer due to their health benefits, as fibre in the diet helps to reduce the risk of gastrointestinal and coronary illnesses (Slavin, 1987; Hsieh *et al.*, 1989; Sacks 1991).

The stepwise regression data analysis of compressive strength is shown Table 5.10. The starch content has the highest contribution, 91.2 %, to R^2 of compressive strength. The variable, screw speed accounted for only 6 % and the interaction term only 2.7 % of the total variation in R^2 .

Table 5.10: Stepwise regression of compressive strength for all product classification.

Model		T test	Prob.	R2	F value	Prob.	VIF
1 Constant)	-2725.084	78.812	.000	.910	1784.29	.000	
Sc	37.214	-42.240	.000				1.00
2 Constant)	-3262.299	22.687	.000	.916			
Sc	37.458	-43.370	.000		948.137	.000	1.00
Ss	3.430	3.312	.001				1.00
3 Constant)	-3273.737	23.192	.000	.921			
Sc	37.609	-44.621	.000		672.088	.000	1.00
Ss	4.490	3.569	.000				1.00
dsm	-.002	-3.325	.001				1.00

5.3.2.4 Effect of extrusion variables on relative melt viscosity

Figure 5.30 - 5.31 show the effect of extrusion variables (initial moisture content, duration of operation and screw speed) on product temperature. Relative Melt Viscosity increased positively as the duration increased. The Maximum Relative Melt Viscosity of 10.45 (0.001Pas) was attained at 30% moisture content. The minimum Relative Melt Viscosity of 2.86 (0.001Pas) was attained at 25% moisture content. The Relative Melt Viscosity at 30% moisture content was higher than at 25 and 40% moisture content. On the difference obtained between the viscosity of cassava flour and its starch, the maximum value for the peak occurs where the cellulose is least i.e. starch. For higher concentration as contained in flour it decreased. This may be due to the fact that cellulose, being a major component of flour does not develop viscosity (Arambula, *et al* 2002).

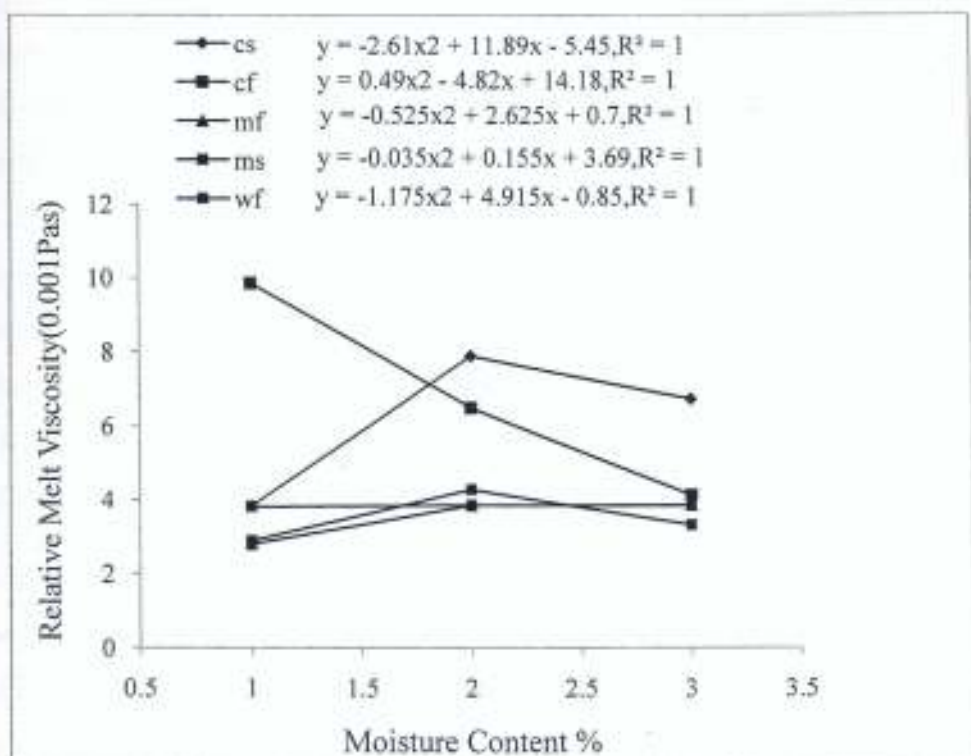


Figure 5.30: Variation of specific mechanical energy with initial moisture content at 30 minutes extrusion time and 100 rpm screw speed.

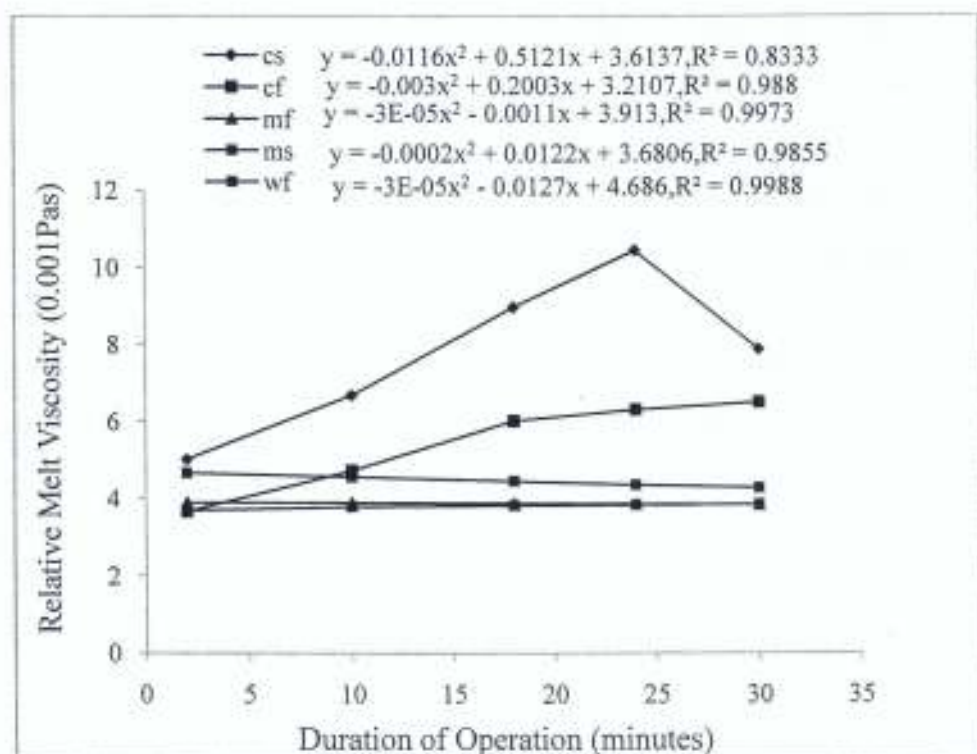


Figure 5.31: Variation of relative melt viscosity with duration of operation at screw speed 100 rpm and initial moisture content 30%.

For cereal products, viscosity decreases with duration of operation, product temperature and moisture content. This can be due to the fact that within normal operating ranges starches and protein rich material are shear thinning (Van Zuilichem, *et al.* 1987). This justifies the use of a power law constitutive equation for the shear dependency of viscosity. However, the result of relative viscosity for cassava products generally showed a deviation from above concept. Only at extreme temperature does the equation above applied to cassava product and by this time the cassava is already becoming dextrinized. Also, it has been reported (Lo *et al.*, 1998) that as the temperature of the dough rises above the gelatinization range the starch granules undergo swelling. The force may have been great enough to break these fragile granules into smaller fragments thereby causing a reduction in viscosity.

For cassava products, the rise in viscosity with temperature before a decline maybe due to the fact that it requires greater force to break the strong binds that exists between the starch molecules than those of cereals because of their higher amyl pectin contents than those of cereals starches (National Starch and Chemical Industry). Also, it is known that the gelatinization temperature for cassava is lower than that of maize and wheat. (Ihekoronye, 1985; Zuilichem and Stolp, 1987) it was easier for cassava to cook/gelatinize under the heat provided by the extruder, hence, a higher solubility and viscosity. This minimum temperature required to cook the cassava sample shows that the use of this extruder is by far more cost efficient than for other products i.e. Maize and wheat. As food, the extrudates with low relative melt viscosity can easily be eaten by infants while those with high viscosity can only be eaten easily by adults because they tend to be hard and cohesive in texture than samples with low viscosities. The stepwise regression data analysis of relative melt viscosity is shown Table 5.11. The Duration of sampling has the highest contribution, 52.8 %, to R^2 of relative melt viscosity. The variable, moisture content accounted for 18.8 % and screw speed only 2.7 % of the total variation in R^2 . This low R^2 for relative melt viscosity is an indication that the relationship is not best described by a linear model. The interaction terms did not improve the model R^2 , therefore they were dropped.

Table 5.11: Stepwise regression of melt viscosity for all product classification

Models	Coefficients		T-test	Prob	Adjusted R ²	F value	Prob	VIF
1	B ₀	-577	-0.287	-0.775	0.068	6.396	0.014	1.000
	Sc	0.057	2.529	0.014				
2	B ₀	-13.493	-2.578	0.012	0.139	6.986	0.002	6.224
	Sc	0.188	3.487	0.001				6.224
	Pc	0.246	2.655	0.010				
3	B ₀	-14.095	-2.751	0.008	0.178	6.341	0.001	6.224
	Sc	0.188	3.568	0.001				6.224
	Pc	0.246	2.716	0.008				1.000
	Dt	0.036	2.096	0.040				
4	B ₀	-14.645	-2.939	0.004	0.224	6.355	0.000	6.239
	Sc	0.194	3.783	0.000				6.228
	Pc	0.251	2.857	0.006				6.201
	Dt	0.123	2.966	0.004				6.206
	dm	-0.003	-2.292	0.025				

5.3.2.5 Effect of extrusion variables on water absorption index

Figures 5.32 - 5.33 show the effect of extrusion variables (initial moisture content, duration of operation and screw speed) on product temperature. Water Absorption Index change with duration of operation does not show a consistent pattern. While some increased positively as the duration increased and decreases with increase in moisture content from 25 to 30% but increased at 40%, some others decreased. This may be due to experimental error. Badrie and Mellowes (1991a), studying the characteristics of extruded products made from mixtures of cassava flour, showed that as the proportion of cassava starch increased, the concentration of proteins, lipids and fibre decreased, while the concentration of carbohydrates increased. Associated with the increase in carbohydrate and consequent increase in reducing sugars, the water solubility index of the products increased, whereas the water absorption index decreased (Chang *et al.*, 1997). Maximum Water Absorption Index of 6.456 g/g was attained at 25% moisture content. The minimum Water Absorption Index of 1.67 g/g was attained when the cassava starch was not run through the extruder.

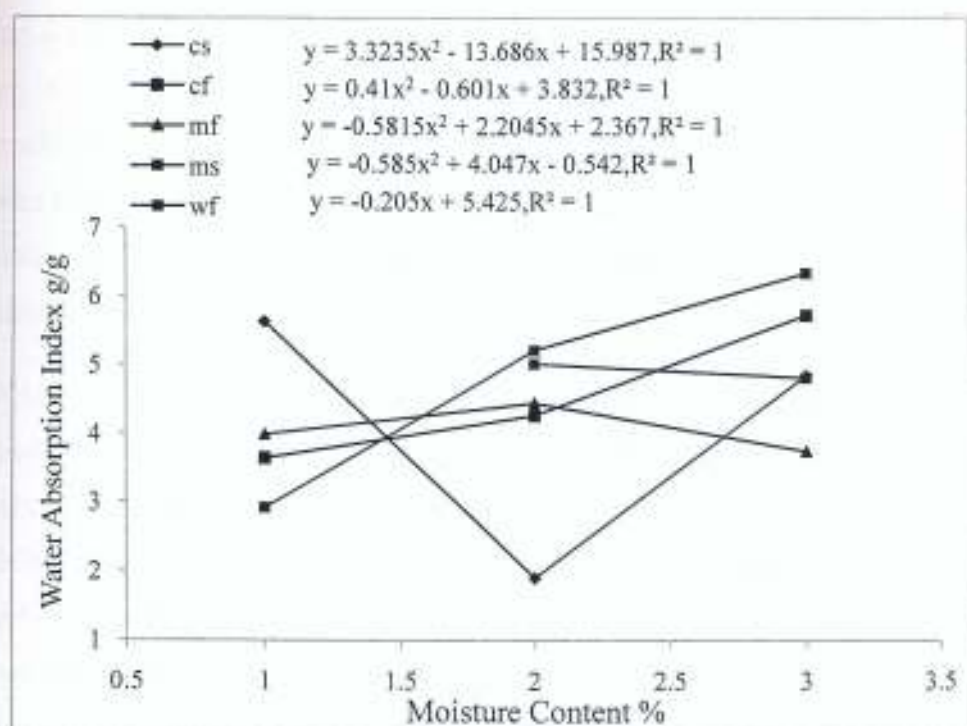


Figure 5.32: Variation of water absorption index with initial moisture content at 30 minutes extrusion time and 100 rpm screw speed.

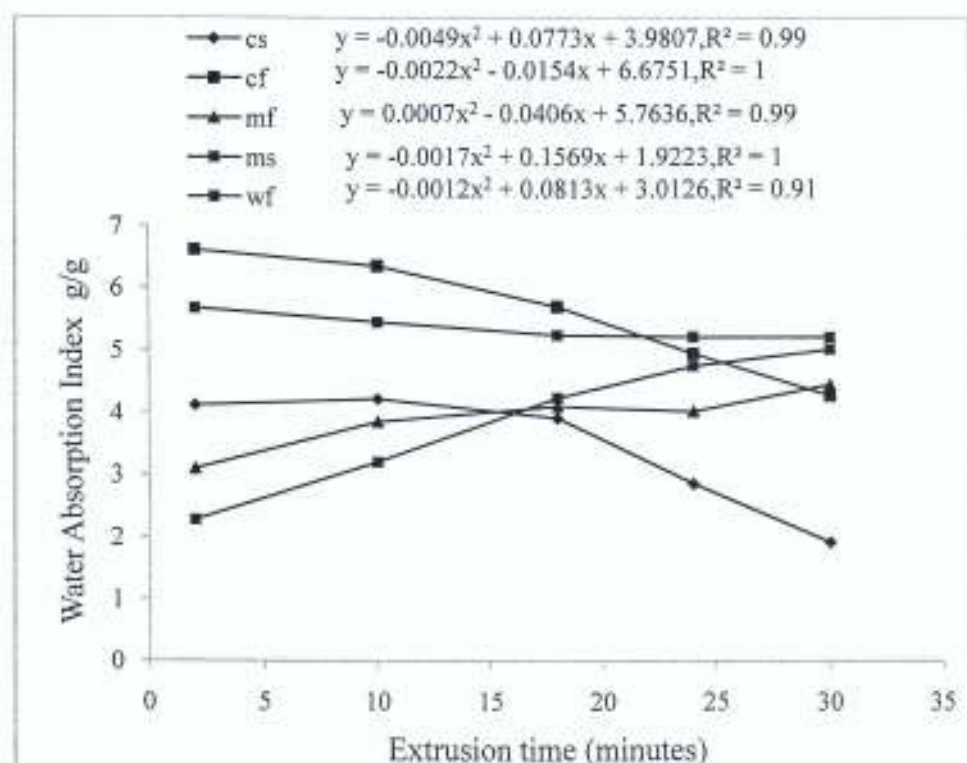


Figure 5.33: Variation of water absorption index with duration of operation at screw speed 100 rpm and initial moisture content 30%.

However, a minimum WAI of 1.91 g/g was attained at 30% and 30 minutes duration of operation. All extruded products had more than triple the WAI of non-extruded samples. These results agree with those of Gujska and Khan (1990) who reported that heat processing of different kinds of flours is higher WAC than in the raw flour. Protein denaturation, starch gelatinization and swelling of the crude fiber, which occurred during extrusion, could all be responsible for the increased WAI of extruded products.

High WAI is an indication of high yield. It is desirable in food systems to improve yield and consistency and give body to the food. However, if the extrudates were to be considered for aquatic feeding, high WAI of extrudates shows that the extrudates will absorb water and sink, while extrudates with low WAI will be very good as floating feeds. Generally, all maize and cassava flour extrudates will be very good as floating aquatic feeds. In particular, all maize samples processed at 8 minutes extrusion time and above floated in water. Cassava flour processed between 10 minutes and 26 minutes extrusion time floated in water. However, all cassava starch samples sank in water. The stepwise regression data analysis of water absorption index is shown Table 5.12.

Table 5.12: Stepwise regression of water absorption index for all product classification

Models	Coefficients		T-test	Prob	Adjusted R	F value	Prob	VIF
1	B ₀	1.911	-1.350	.181	.050	4.571	.036	1.000
	staco	.082	2.138	.036				
2	B ₀	-2.017	-5.266	.000	.305	15.937	.000	1.008
	staco	.085	5.646	.000				
	Pc	.042	5.062	.000				
3	B ₀	14.893	-5.443	.000	.345	12.939	.000	1.009
	staco	0.084	5.713	.000				
	Pc	.174	5.123	.000				
	Dt	.242	2.238	0.029				
4	B ₀	-2.057	-5.644	.000	.402	12.440	0.000	5.256
	staco	.022	5.920	.000				
	Pc	.034	5.396	.000				
	Dt	.011	3.367	.001				
	dm	.000	-2.688	0.009				

5.3.2.6 Effect of extrusion variables on water solubility index

Figures 5.34 - 5.35 show the effect of extrusion variables (initial moisture content, duration of operation and screw speed) on product temperature. Water Solubility Index (WSI) shows a similar result as WAI. While some varies directly with duration of operation, others showed the opposite. The increase was caused perhaps by greater shear degradation of starch during extrusion at higher temperature. WSI increases from 25% moisture content to a peak at 30% moisture content and then decreased at 40%. Grossmann *et al.* (1988) determined that under milder extrusion conditions (low temperature and high moisture content), the destruction of the organized structure of cassava starch was only partial, characterized by increases in the WAI and WSI. On the other hand, under more drastic conditions (high temperature and low moisture content), starch dextrinisation probably occurred, and indicated by decreases in the WAI and increases in the WSI.

High WSI implies that the material will dissolve easily in water and hence will be wasted as feed fish. However, High WSI will be very good in forming solutions. The result of the water absorption index and water solubility index for all the products under study does not show a consistent pattern. Therefore, further study is required to determine the pattern of variation of the two properties with time. The stepwise regression data analysis of WSI is shown Table 5.13. The Duration of sampling has the highest contribution, 52.8%, to R^2 of WSI. The variable, moisture content accounted for 18.8% and screw speed only 2.7% of the total variation in R^2 . This low R^2 for expansion ratio is an indication that the relationship is not best described by a linear model.

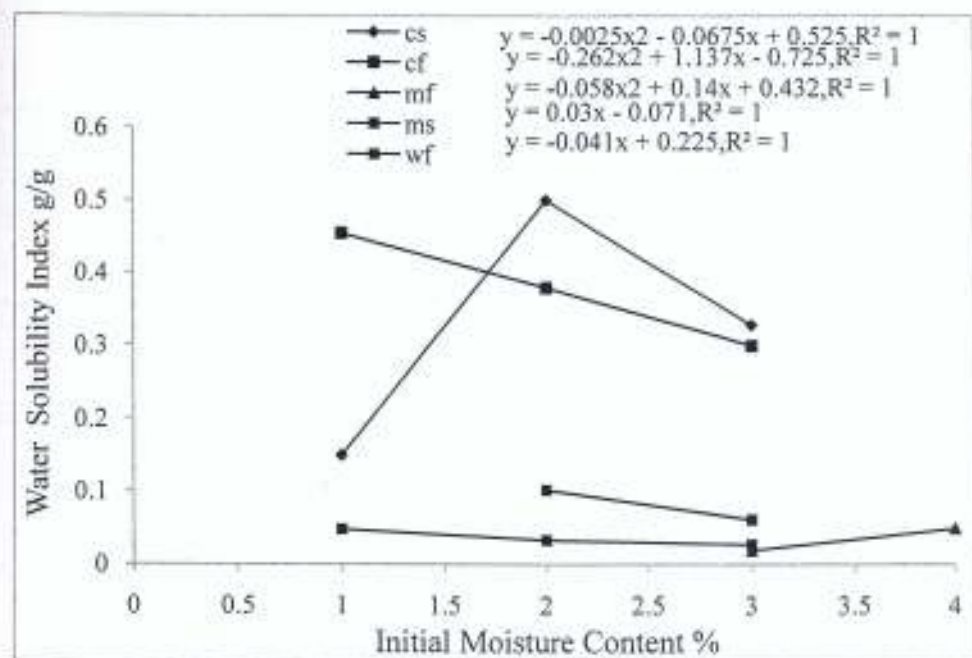


Figure 5.34: Variation of water solubility index with initial moisture content at 30 minutes extrusion time and 100 rpm screw speed.

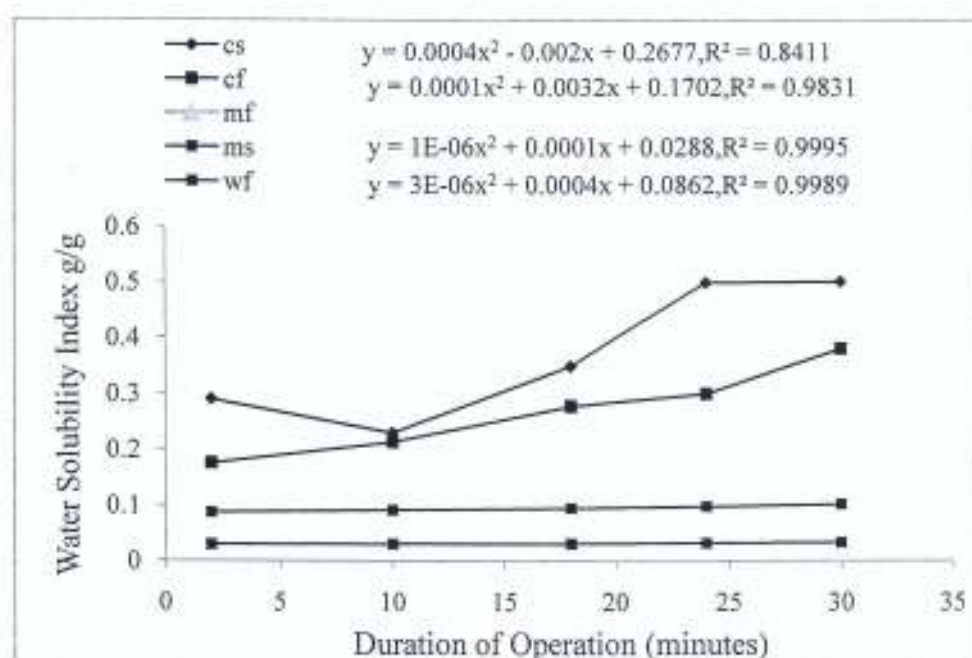


Figure 5.35: Variation of water solubility index with duration of operation at screw speed 100 rpm and initial moisture content 30%.

Table 5.13: Stepwise regression of water solubility index for all product classification

Models	Coefficients		T-test	Prob	Adjusted R	F value	Prob	VIF
1	B ₀	-577	-0.287	-0.775	0.068	6.396	0.014	1.000
	Sc	0.057	2.529	0.014				
2	B ₀	-13.493	-2.578	0.012	0.139	6.986	0.002	6.224
	Sc	0.188	3.487	0.001				6.224
	Pc	0.246	2.655	0.010				
3	B ₀	-14.095	-2.751	0.008	0.178	6.341	0.001	6.224
	Sc	0.188	3.568	0.001				6.224
	Pc	0.246	2.716	0.008				1.000
	Dt	0.036	2.096	0.040				
4	B ₀	-14.645	-2.939	0.004	0.224	6.355	0.000	6.239
	Sc	0.194	3.783	0.000				6.228
	Pc	0.251	2.857	0.006				6.201
	Dt	0.123	2.966	0.004				6.206
	dm	-0.003	-2.292	0.025				

5.3.2.7 Effect of extrusion variables on hot paste viscosity

Figure 5.36 - 5.37 show the effect of extrusion variables (initial moisture content, duration of operation and screw speed) on product temperature. Hot Paste Viscosity (HPV) varies inversely with duration of operation i.e HPV decreases with increase in duration of operation and decrease with increase in moisture content from 25 to 30% and an increase at 40%. Maximum (HPV) of 9.1 dPas was attained at 25%. An (HPV) of 9.7 dPas was attained at 0 duration of operation (i.e. when the cassava starch was not run through the extruder). However, a minimum (HPV) of 0.217 dPas was attained at 30% and 30 minutes duration of operation. The stepwise regression data analysis of HPV is shown Table 5.14. The Duration of sampling has the highest contribution, 52.8 %, to R^2 of HPV. The variable, moisture content accounted for 18.8 % and screw speed only 2.7 % of the total variation in R^2 . The interaction terms did not improve the model R^2 , therefore they were dropped.

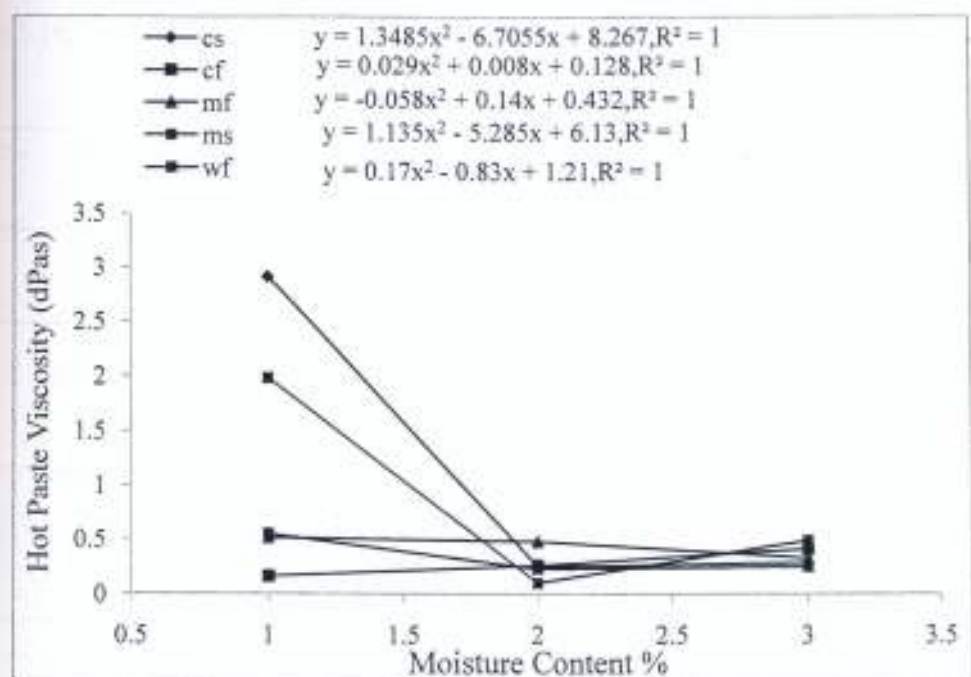


Figure 5.36: Variation of hot paste viscosity with initial moisture content at 30 minutes extrusion time and 100 rpm screw speed.

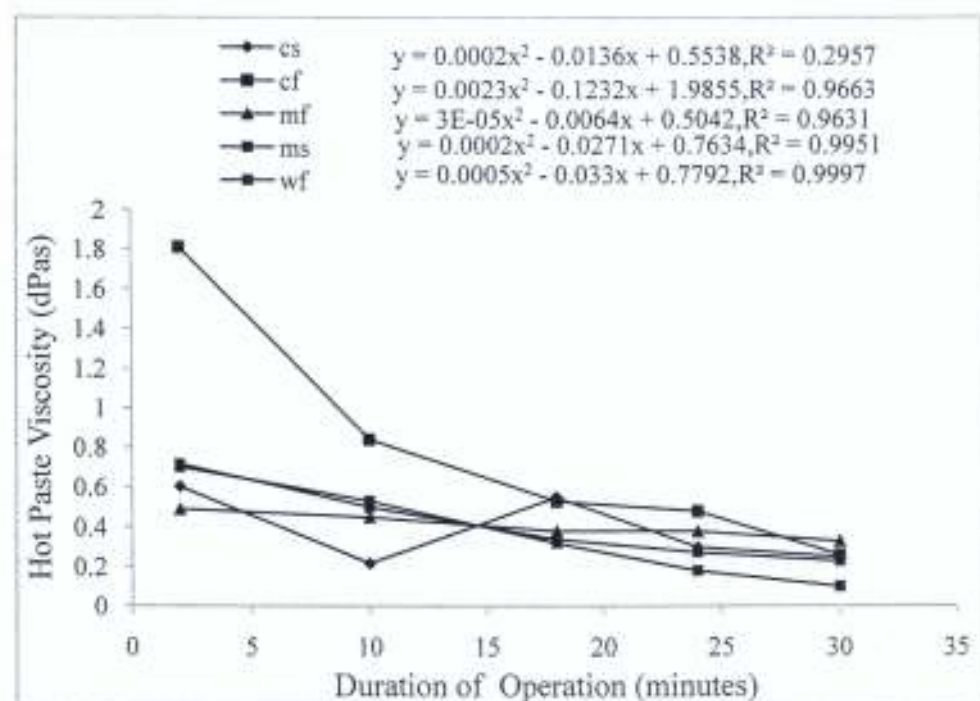


Figure 5.37: Variation of hot paste viscosity with duration of operation at screw speed 100 rpm and initial moisture content 30%.

Table 5.14: Stepwise regression of hot paste viscosity for all product classification

Models	Coefficients		T-test	Prob.	Adjusted R	F value	Prob.	VIF
1	B ₀	4.810	8.251	0.000	0.068	6.396	0.014	1.000
	dm	-0.004	-4.666	0.000				
2	B ₀	5.838	9.270	0.000	0.139	6.986	0.002	1.001
	dm	-0.004	-4.666	0.000				
	Pc	-0.237	-3.291	0.002				
3	B ₀	8.479	5.907	0.000	0.178	6.341	0.001	1.188
	dm	0.003	-3.766	0.000				
	Pc	-0.227	-3.183	0.002				
	Mc	-0.092	-2.037	0.045				
4	B ₀	14.134	5.950	0.000	0.224	6.355	0.000	23.968
	dm	0.007	1.953	0.055				
	Pc	-0.227	-3.380	0.001				
	Mc	-0.258	-3.612	0.001				
	Dt	-0.370	-2.908	0.005				

5.3.2.8 Effect of extrusion variables on cold paste viscosity

Figure 5.38 - 5.39 show the effect of extrusion variables (initial moisture content, duration of operation and screw speed) on product temperature. Cold Paste Viscosity (CPV) varies inversely with duration of operation and decrease with increase in moisture content from 25 to 30 % and an increase at 40%. Maximum CPV of 12.98 dPas was attained at 25% moisture content. A CPV of 16.47 dPas was attained at 0 duration of operation (i.e. when the cassava starch was not run through the extruder). However, a minimum CPV of 0.477 dPas was attained at 25% and 30 minutes duration of operation. The stepwise regression data analysis of CPV shown in Table 5.15. The Duration of sampling has the highest contribution, 52.8%, to R^2 of CPV. The variable, moisture content accounted for 18.8% and screw speed only 2.7% of the total variation in R^2 .

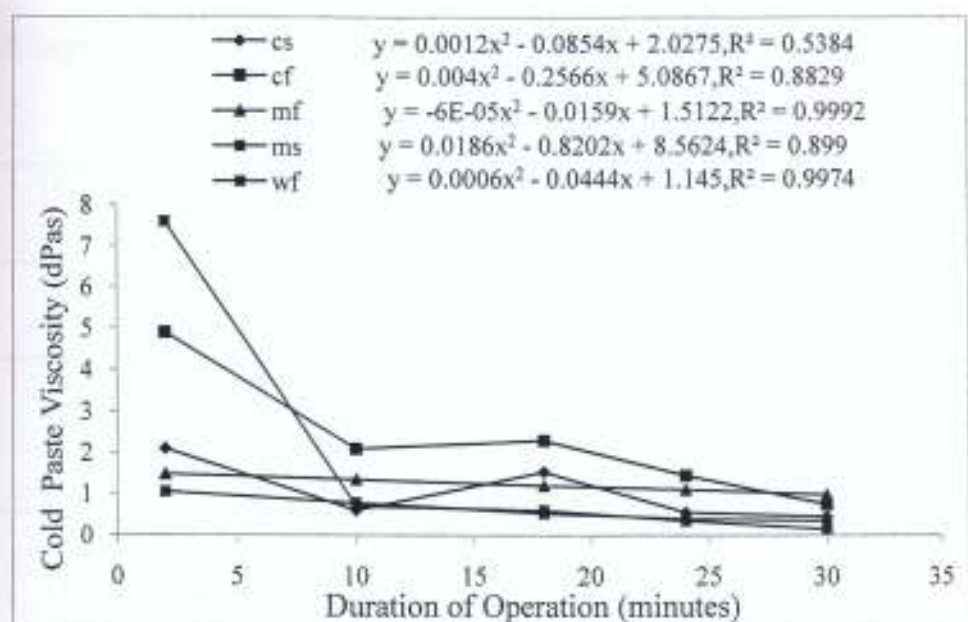


Figure 5.38: Variation of cold paste viscosity with initial moisture content at 30 minutes extrusion time and 100 rpm screw speed.

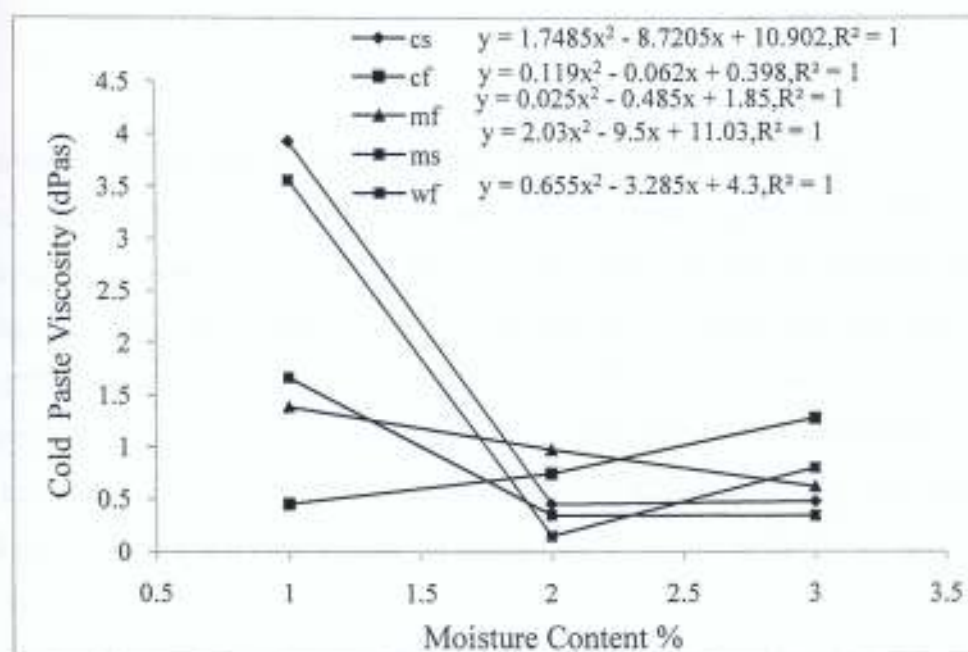


Figure 5.39: Variation of cold paste viscosity with duration of operation at screw speed 100 rpm and initial moisture content 30%.

Table 5.15: Stepwise regression of cold paste viscosity for all product classification

Models	Coefficients		T-test	Prob.	Adjusted R	F value	Prob.	VIF
1	B ₀	4.810	8.251	0.000	0.068	6.396	0.014	1.000
	dm	-0.004	-4.666	0.000				
2	B ₀	5.838	9.270	0.000	0.139	6.986	0.002	1.001
	dm	-0.004	-4.666	0.000				
	Pc	-0.237	-3.291	0.002				
3	B ₀	8.479	5.907	0.000	0.178	6.341	0.001	1.188
	dm	0.003	-3.766	0.000				
	Pc	-0.227	-3.183	0.002				
	Mc	-0.092	-2.037	0.045				
4	B ₀	14.134	5.950	0.000	0.224	6.355	0.000	23.968
	dm	0.007	1.953	0.055				
	Pc	-0.227	-3.380	0.001				
	Mc	-0.258	-3.612	0.001				
	Dt	-0.370	-2.908	0.005				

Table 5.16 shows the stability of the extrudates. From the differences obtained between the two charts, if the difference between HPV and CPV is low, it means the sample is very stable. Hence, it can be deduced that MS is least stable, having the highest difference between its CPV and HPV values. This is followed by CS. Also, the most stable of the products is MS, followed by WF, and then CS. If the HPV and CPV are far apart indicating lower stability then its tendency for retrogradation is very high. Where as product with high WSI will have cooking losses because part of the product would have gone into solution but those with low WSI have minimum cooking losses.

Table 5.16: Differences in pasting characteristics of extrudates at the various moisture contents

	25%mc	30%mc	40%mc	Not extruded
cs	1.02	0.205	0.19	7.5
cf	0.29	0.49	0.87	10.09
mf	0.88	0.5	0.29	5.66
ms	1.58	0.05	0.31	0.38
wf	1.12	0.12	0.11	1.54

From the Table 5.16 above, there is generally an improvement in the stability of the extruded products when compared to the raw samples. The stability of cassava products were improved better than cereal products. According to Chang *et al.*, (1997), starch with low moisture content extruded at a high temperature results in an extrudate characterised by a low degree of retrogradation, while starch with a moderate to high moisture content (190-260 g kg⁻¹) extruded at a moderate temperature (125-190°C) produces an extrudate with a high degree of retrogradation. In this work, retrogradation decreased with increasing extrusion time and moisture content.

5.4. EXTRUDER'S EFFICIENCY

For the extruder efficiency evaluation, the densities of the samples under study were higher than 1450kg/m³ used by van Zuilichem and others (1987) for corn meal, but similar to 1400 to 1500 kg/m³ reported by Liang *et al.*, (2002) for corn starch. The enthalpy changes associated with starch gelatinization and protein denaturation and specific heat capacities (Cp) of the materials studied are given in Table 5.17

Table 5.17: Specific heat capacities and enthalpy change of materials under study

	CS	CF	MS	MF	WF
Cp (kJ ⁻¹ kg ⁻¹ K ⁻¹)	2.254	2.306	2.2541	2.292	2.235
ΔH ((kJ ⁻¹ kg ⁻¹)	9.53	9.53	9.16	9.18	8.72

These Cp values are higher than that reported for corn meal ($1.945 \text{ kJ kg}^{-1} \text{ K}^{-1}$) by Liang *et al.* (2002) probably due to the higher moisture levels considered in this study. The Specific heat energy (SHE) for all extrusion condition in this study was zero since heat was generated through viscous dissipation. Figure 5.40 shows the extruder efficiency against duration of sampling at screw speed 100 rpm and 30 % moisture content for all the five products under consideration while Figure 5.41 shows the highest efficiency attained when various products were processed by the machine.

The result of the efficiency of the extruder for the various materials processed show that it is more efficient processing cereal products than cassava products. This may be due to the fact that, being a dry type extruder, highly viscous materials typical of cassava products is hard to process through this extruder type. It may therefore be necessary to introduce heat treatment to reduce viscosity of cassava at higher extrusion times in order to improve the performance of the extruder with cassava products. Power input in an extrusion system comes mainly from the extruder drive motor. Lower screw speeds also make less efficient use of motor drive, unless it is geared to operate at high speeds to keep the displacement power factor near unity. For a given torque, power output rises in proportion to motion speed, while electric losses are generally constant. Efficiency therefore, rises with speed. However, extruders are usually not allowed to run over their rated maximum screw speed, also it cannot be expected to run at 100 % efficiency. At a fixed feed rate, the maximum efficiency was obtained at a maximum screw speed of 200 rpm for maize starch. That is 91.93% while the maximum extruder efficiency occurred at screw speed 150 rpm for cassava starch at 30 moisture content and highest duration of 30 minutes. It was observed that the efficiency decreased generally at a screw speed of 150 rpm for all the crops under study apart from WF, this was because of the influence of specific mechanical energy input, which is a very good determinant of extruders' efficiency. Also, from Figure 5.40 extruder efficiency increased with duration of operation for cereal product (maize and wheat) while it decreases with duration of operation for cassava products.

Energy consumption and extruder efficiency are two important considerations for extrusion processes. They were found to be significantly correlated with feed rate, screw speed and their ratio, Specific feed ratio SFL (Liang *et al.*, 2002). Among them SFL appeared to be the most important factor influencing the energy consumption and extruders are usually not allowed to run over their rated maximum die pressure. This makes it important to know

what horsepower the motor should deliver throughout its duty cycle and how the motor load and screw speed should be matched closely to achieve both energy economy and extruder efficiency with acceptable product quality. In addition, an extruder cannot be expected to run at 100% efficiency, since the extruder is not completely adiabatic and the system itself consumes power, plus the external energy consumption.

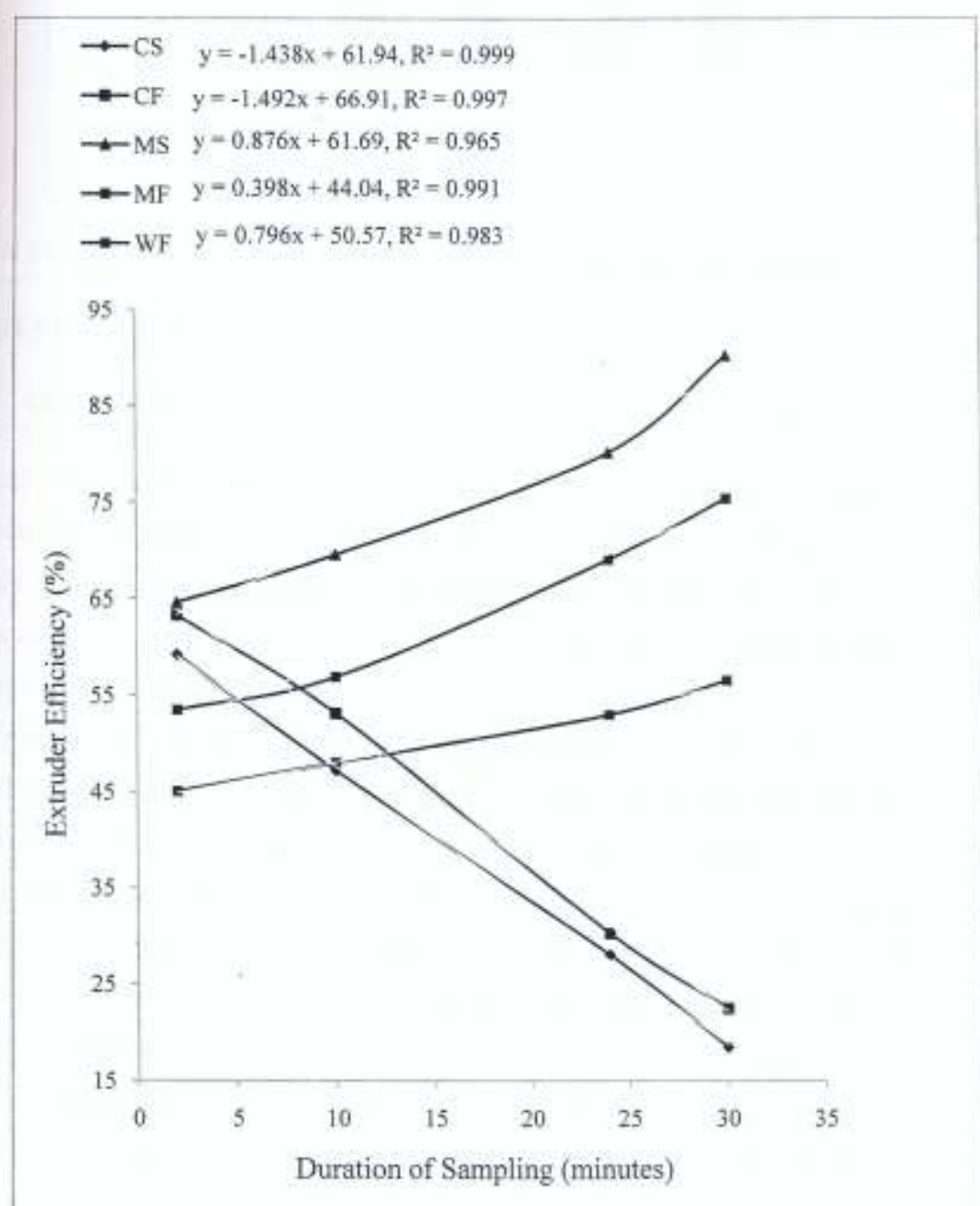


Figure 5.40: The extruder's efficiency compared among the product classification

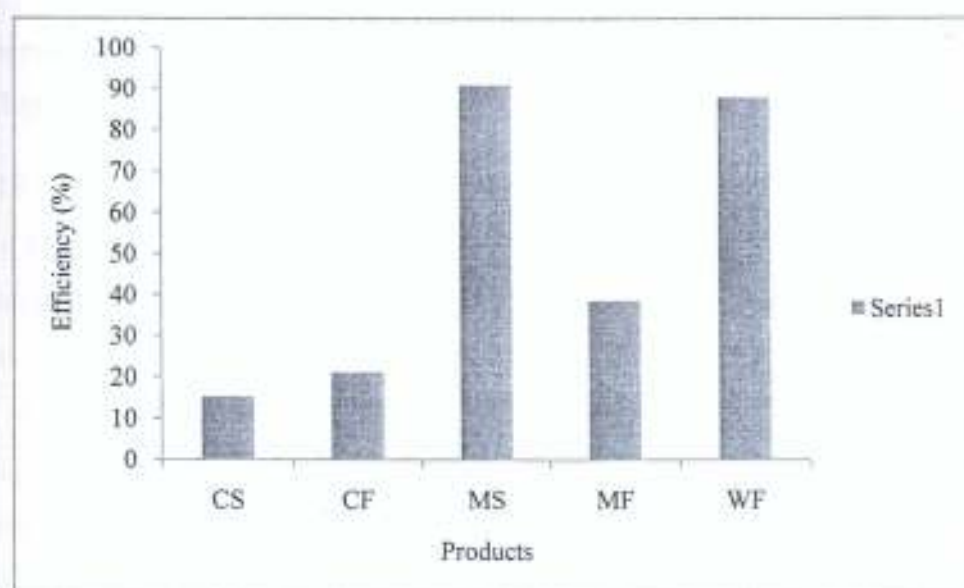


Figure 5.41: Highest efficiencies attained with various products by the machine

5.5. STATISTICAL ANALYSIS

5.5.1 One Way Analysis of Variance

This is the statistical technique that assesses the effects of one or more categorical independent variables, measured at any level upon a continuous dependent variable that is usually assumed to be measured at an interval level. In this study, the samples were subjected to one way analysis of variance to assess the effect of moisture content, MC at 30 minutes duration upon the response variables at three different screw speeds, SS. The cases were divided into groups GRP based on their values for each of the moisture contents and the differences between the means of the moisture contents on each response variable were tested for statistical significance. The results are as shown in Appendix 7, the result of one way analysis of variance for maize starch shows that product temperature is significantly different at 95% confidence interval for 100 and 150 rpm but not at 200 rpm. This can be due to the fact that there was interaction between speed and moisture content, but the effect of speed dominated that of moisture content. Hence, moisture content is not significant. Also, for maize flour product temperature is significantly different at 95% confidence interval for 100 and 200 rpm but not at 150 rpm. This was due to the fact that maize flour being the densest of all materials under this study requires minimum moisture content 40% to flow through the extruder.

5.5.2 Correlation Coefficients of Extruder's System Parameters and Extrudates Characteristics

Table 5.18 shows the bivariate correlation result of the extrusion data. Bivariate correlation provide a single member which summaries the relationship between two variables. These correlation coefficients indicate the degree to which variation (or change) in one variable is related to variation (change) in another. A correlation coefficient not only summaries the strength of association between a pair of variables, but also provides an easy means for comparing the strength of relationship between one pair of variables and a different pair. From the Persons correlation analysis conducted as shown in Table 5.89, protein content is highly significantly negatively correlated to starch content, torque, SME, HPV, CPV and compressive strength with the following values: (-0.91615), (-0.281), (-0.303), (0.419), (0.303), (-0.274). Starch content and compressive strength have significant correlation up to 41%. Screw speed and actual speed have very significant correlation of 98.31%. Also, MRT have very significant negative correlation of 95.36% with screw speed and 92.2% with moisture content. Also, SME and Starch have significant correlation up to 40%. This is the same relationship between Torque and starch content. Torque and SME are strongly correlated with a expected value of 95.33% also MRT and torque and correlated with 0.45% value. Product Temperature and duration are strongly correlated with a value of 0.81%. Also, product temperature is correlated with moisture content.

Table 3.18: Correlation analysis of extrusion variation

	Pc	Sc	Mc	Ss	Dt	PT	ER	PM	Tq	SME	MRT	Cs	WAI	WSI	MV	CPV	HPV
Pc	1	-.916**	-.026	.000	.000	.055	.016	-.018	-.281**	-.303**	-.074	-.24**	.034	-.07	-.048	-.303*	-.419**
Sc	-.916**	1	.037	.000	.000	-.039	.148*	-.036	.369**	.415**	.088	.418**	.047	.135	.132	.262*	.343*
Mc	-.026	.037	1	.000	.007	-.083	.130*	.851**	-.286**	-.345**	-.067	-.073	-.363**	.413**	-.341**	-.404**	-.314*
Ss	.000	.000	.000	1	.000	-.093	.062	.008	-.318**	-.123	-.951**	.198**	(a)	(a)	(a)	(a)	(a)
Dt	.000	.000	.007	.000	1	.830**	.220**	-.290**	.187**	.197**	.028	-.147*	-.088	.007	.148	-.367**	-.326*
PT	.055	-.039	-.083	-.093	.830**	1	.351**	-.409**	.185**	.196**	.087	-.140*	-.021	-.170	.355**	-.423**	-.431**
ER	.016	.148*	.130*	.062	.220**	.351**	1	-.274**	.196**	.326**	-.036	.242**	-.217	.019	.407**	-.316**	-.415**
PM	-.018	-.036	.851**	.008	-.290**	-.409**	-.274**	1	-.363**	-.470**	-.065	-.090	-.282*	.368**	-.493**	-.155	.000
Tq	-.281**	.369**	-.286**	-.318**	.187**	.185**	.196**	-.363**	1	.800**	.486**	.137*	.157	-.156	.448**	.177	
SME	-.303**	.415**	-.345**	.123	.197**	.196**	.326**	-.470**	.800**	1	.245**	.238**	.057	-.013	.562**	-.002	.210
MRT	-.074	.088	-.067	-.951**	.028	.087	-.036	-.065	.486**	.245**	1	-.128	.138	-.190	.323**	.364**	
Cs	-.24**	.418**	-.073	.198**	-.147*	-.140*	.242**	-.090	.137*	.238**	-.128	1	.138	-.211	.474**	-.153	-.258
WAI	.034	.047	-.363**	(a)	-.088	-.021	-.217	-.282*	.157	.057	.138	.262*	1	-.824**	.353**	.325**	-.008
WSI	-.071	.135	.413**	(a)	.007	-.170	.019	.368**	-.156	-.013	-.190	-.211	-.824**	1	-.639**	-.342**	
MV	-.048	.132	-.341**	(a)	.148	.355**	.407**	-.493**	.448**	.562**	.323**	.474**	.353**	-.639**	1	-.063	.388**
CPV	-.303*	.262*	-.404**	(a)	-.367**	-.423**	-.316**	-.155	.177	-.002	.364**	-.153	.325**	-.342**	-.063	1	.129
HPV	-.419**	.343*	-.314*	(a)	-.326*	-.431**	-.415**	.000	.210	-.008	.388**	-.258	.129	-.311*	-.395**	.886**	1

Significant at * $p \leq 0.05$; ** $p \leq 0.01$, pc - protein content, sc - starch content, Mc - Moisture content, Ss - screw speed Dt - duration of operation, PT Product temp($^{\circ}$ C), SME- Specific Mechanical Energy, (KJ/Kg), MRTs- Mean Residence Time (sec.), MV-Relative Melt Viscosity(0.01Dpa.S), HPV-Hot Paste Viscosity (dPa.S), PM-Product Moisture(%),WSI-Water Solubility(g/g).CS-Comp Strength (N), CPV- Cold Paste Viscosity (dPa.S), WAI-Water Absorption Index, (g/g), (a) - not determined

5.4.6.1 The result of the response surface analysis

Response surface methodology (RSM), a useful steady state optimization analysis, has been useful to relate process and design parameters on process performance such as product quality characteristics (Alves *et al.*, 1999; Stanley, 1986; Guan *et al.*, 2005). The detailed statistical analysis using response surface methodology (RSM) generated the coefficients of the second order polynomials for the response functions. Table 5.19 shows the coefficients of the Polynomials relating the response functions and extrusion variables. Generally, there is an improvement in the R^2 of the response surface regression model than for the stepwise regression model. The estimated coefficients in Table 5.19 reflect how changes in the predictors affect the response. The coefficients in the regression equation can also be used to examine the significance of each term relative to each other (Ibanoglu *et al.*, 1996).

Table 5.19: Coefficients of the Polynomials relating the response functions and extrusion variables

Coefficients	PT	ER	PM	WAI	SME	WSI	MRTs	CS	MV	CPV	HPV
B0	-469.72	-76.97**	48.41	27.99	-1391.18	-7.093	68.799	-37600	-91.909	140.008	42.133 ^{NS}
B1	-32.24**	2.99*	7.50**	-8.212*	165.21**	0.059 ^{NS}	3.949 ^{NS}	1118.8 ^{NS}	3.480 ^{NS}	-14.353*	-6.463 ^{NS}
B2	4.12**	0.73**	-0.38 ^{NS}	-0.253 ^{NS}	15.430*	0.072**	0.480 ^{NS}	396.02**	0.895*	-1.0276 ^{NS}	-0.172 ^{NS}
B3	14.80**	1.65**	-0.70 ^{NS}	-1.204 ^{NS}	-3.377 ^{NS}	0.093 ^{NS}	-0.509*	206.73 ^{NS}	2.264*	-4.0873*	-1.688 ^{NS}
B4	1.65**	-0.056 ^{NS}	-0.11 ^{NS}	ND	3.186 ^{NS}	ND	-0.712**	-62.56**	ND	ND	ND
B5	11.56**	-1.19**	1.405*	1.128*	-47.097**	-0.067*	-1.404**	375.48**	-0.937 ^{NS}	-0.05 ^{NS}	-0.024 ^{NS}
B1*B1	0.84**	0.01 ^{NS}	-0.20**	0.186*	-1.874 ^{NS}	0.007 ^{NS}	-0.035 ^{NS}	25.056*	0.0032 ^{NS}	0.264 ^{NS}	0.154 ^{NS}
B1*B2	0.40**	-0.025 ^{NS}	-0.083**	0.071*	-1.656**	-0.000 ^{NS}	-0.047 ^{NS}	-10.57 ^{NS}	-0.0236 ^{NS}	0.105 ^{NS}	0.046 ^{NS}
B3*B2	-0.26**	-0.025**	0.04 ^{NS}	0.021 ^{NS}	0.117 ^{NS}	-0.001 ^{NS}	0.013 ^{NS}	-3.361 ^{NS}	-0.0418 ^{NS}	0.075**	0.027 ^{NS}
B3*B1	-0.15**	-0.014**	0.015**	0.012 ^{NS}	-0.012 ^{NS}	-0.001 ^{NS}	-0.000 ^{NS}	-1.624 ^{NS}	-0.0192*	0.026 ^{NS}	0.007 ^{NS}
B3**	-0.004 ^{NS}	-0.005 ^{NS}	0.004 ^{NS}	0.002 ^{NS}	0.022 ^{NS}	0.000 ^{NS}	0.003 ^{NS}	-0.028 ^{NS}	-0.0038 ^{NS}	0.017*	0.012*
B4*B2	-0.007 ^{NS}	0.0015 ^{NS}	0.0004 ^{NS}	ND	-0.026 ^{NS}	ND	0.001 ^{NS}	0.595 ^{NS}	ND	ND	ND
B4*B1	-0.001 ^{NS}	0.0011 ^{NS}	0.0002 ^{NS}	ND	0.019 ^{NS}	ND	-0.001 ^{NS}	0.595*	ND	ND	ND
B4*B3	-0.0005 ^{NS}	0.0003 ^{NS}	-0.0004 ^{NS}	ND	0.008 ^{NS}	ND	0.002**	-0.321**	ND	ND	ND
B4*	-0.005**	-0.0002**	0.0004**	ND	-0.006*	ND	0.016**	0.073*	ND	ND	ND
B5*B2	-0.12**	0.021**	-0.022*	-0.013*	0.737**	0.001*	0.020*	-6.352**	0.0202 ^{NS}	0.0014 ^{NS}	0.002 ^{NS}
B5*B1	-0.062**	0.014**	-0.019**	-0.011 ^{NS}	0.531**	0.001*	0.016**	-4.142**	0.0136*	-0.006 ^{NS}	-0.003 ^{NS}
B5*B3	-0.006 ^{NS}	0.004**	-0.010**	-0.001 ^{NS}	-0.083*	-0.000 ^{NS}	0.004 ^{NS}	0.604 ^{NS}	-0.007*	0.0075 ^{NS}	0.005 ^{NS}
B5*B4	-0.0003 ^{NS}	0.0003 ^{NS}	-0.0003 ^{NS}	ND	-0.006 ^{NS}	ND	-0.000 ^{NS}	-0.084 ^{NS}	ND*	ND	ND
B5**	-0.097**	-0.009**	0.0155**	-0.003 ^{NS}	0.022 ^{NS}	0.000 ^{NS}	0.002 ^{NS}	0.249 ^{NS}	-0.003 ^{NS}	0.005 ^{NS}	0.0015 ^{NS}
R ²	0.8580	0.45	0.8526	0.542	0.6567	0.8085	0.9711	0.776	0.6342	0.713	0.611

Significant at * $p \leq 0.05$; ** $p \leq 0.01$, NS-Non significant at $p=0.05$, Coef – Coefficients: B₀-(constant term) b₁, b₂, b₃, b₄, b₅ linear effect of protein content, starch content, Moisture content, screw speed and duration of operation respectively. ND - Not determined, Resp. Var - Response variables: PT Product temperature (°C), SME– Specific Mechanical Energy, (kJ/kg), MRTs– Mean Residence Time (sec.), MV–Relative Melt

The equations are represented in equations 5.1 – 5.11

Product Temperature

$$Y = 4.12X_2 + 14.80X_3 + 1.65X_4 + 11.56X_5 - 32.24X_1 + 0.84X_1^2 + 0.4X_{12} - 0.26X_{23} \\ - 0.15X_{31} - 0.004X_3^2 - 0.007X_{42} - 0.001X_{41} - 0.0005X_{43} - 0.003X_4^2 \dots\dots\dots 5.1 \\ - 0.12X_{52} - 0.062X_{51} - 0.006X_{53} - 0.0003X_{45} - 0.097X_5^2 - 469.72$$

Specific Mechanical Energy

$$Y = 165X_1 - 15.43X_2 - 3.38X_3 + 3.18X_4 - 47.097X_5 - 1.87X_1^2 - 1.66X_{12} + 0.117X_{32} \\ - 0.012X_{31} + 0.022X_3^2 - 0.026X_{42} + 0.019X_{41} + 0.008X_{43} - 0.006X_4^2 \dots\dots\dots 5.2 \\ + 0.737X_{52} + 0.53X_{51} - 0.083X_{53} - 0.006X_{54} + 0.022X_5^2$$

Mean Residence Time

$$Y = 3.949X_1 + 0.480X_2 - 0.00X_3 - 0.712X_4 - 1.404X_5 - 0.035X_1^2 - 0.047X_1X_2 \\ + 0.013X_3X_2 - 0.000X_3X_1 + 0.003X_3^2 + 0.001X_4X_2 - 0.001X_4X_1 + 0.002X_4X_3 \dots\dots\dots 5.3 \\ + 0.016X_4 + 0.020X_5X_2 + 0.016X_5X_1 + 0.004X_5X_3 - 0.000X_5X_4 + 0.002X_5^2$$

Expansion Ratio

$$Y = 2.99X_1 + 0.73X_2 + 1.65X_3 - 0.056X_4 - 1.19X_5 - 0.01X_1^2 - 0.025X_1X_2 \\ - 0.025X_3X_2 - 0.014X_3X_1 - 0.005X_3^2 + 0.0015X_4X_2 + 0.0011X_4X_1 \dots\dots\dots 5.4 \\ + 0.0003X_4X_3 - 0.0002X_4 + 0.021X_5X_2 + 0.014X_5X_1 + 0.004X_5X_3 \\ + 0.0003X_5X_4 - 0.009X_5^2$$

Product Moisture

$$Y = 7.50X_1 - 0.38X_2 - 0.70X_3 - 0.11X_4 + 1.405X_5 - 0.20X_1^2 - 0.083X_1X_2 \\ + 0.04X_3X_2 + 0.015X_3X_1 + 0.004X_3^2 + 0.0004X_4X_2 + 0.0002X_4X_1 \dots\dots\dots 5.5 \\ - 0.0004X_4X_3 + 0.0004X_4 - 0.022X_5X_2 - 0.019X_5X_1 - 0.010X_5X_3 \\ - 0.0003X_5X_4 + 0.0155X_5^2$$

Water Absorption Index

$$Y = - 8.212X_1 - 0.253X_2 - 1.204X_3 - + 1.128X_5 + 0.186X_1^2 + 0.071X_1X_2 \\ + 0.021X_3X_2 + 0.012X_3X_1 + 0.002X_3^2 + 0.013X_5X_2 - 0.011X_5X_1 \dots\dots\dots 5.6 \\ - 0.001X_5X_3 - 0.003X_5^2$$

Water Solubility Index

$$Y = 0.059X_1 + 0.072X_2 + 0.093X_3 - 0.067X_5 + 0.007X_1^2 - 0.000X_1X_2 \\ - 0.001X_3X_2 - 0.001X_3X_1 + 0.000X_3^2 + 0.001X_5X_2 + 0.001X_5X_1 \dots\dots\dots 5.7 \\ - 0.000X_5X_3 + 0.000X_5^2$$

Compressive Strength

$$Y = 1118.8X_1 + 396.02X_2 + 206.73X_3 - 62.56X_4 + 375.48X_5 + 25.056X_1^2 \\ - 10.57X_1X_2 - 3.361X_3X_2 - 1.624X_3X_1 - 0.028X_3^2 + 0.595X_4X_2 \dots\dots\dots 5.8 \\ + 0.595X_4X_1 - 0.321X_4X_3 + 0.073X_4 - 6.352X_5X_2 - 4,142X_5X_1 \\ + 0.604X_5X_3 - 0.084X_5X_4 + 0.249X_5^2$$

Melt Viscosity

$$Y = 3.480X_1 + 0.895X_2 + 2.264X_3 - 0.937X_5 + 0.0032X_1^2 - 0.0236X_1X_2 \\ - 0.0418X_3X_2 - 0.0192X_3X_1 - 0.0038X_3^2 + 0.0202X_5X_2 + 0.0136X_5X_1 \dots\dots\dots 5.9 \\ - 0.007X_5X_3 - 0.003X_5^2$$

Cold Paste Viscosity

$$Y = -14.353X_1 - 1.0276X_2 - 4.0873X_3 - 0.05X_5 + 0.264X_1^2 + 0.105X_1X_2 \\ + 0.075X_3X_2 + 0.026X_3X_1 + 0.07X_3^2 + 0.0014X_5X_2 \dots\dots\dots 5.10 \\ - 0.006X_5X_1 + 0.0075X_5X_3 + 0.005X_5^2$$

Hot Paste Viscosity

$$Y = -6.463X_1 - 0.172X_2 - 1.688X_3 - 0.024X_5 + 0.154X_1^2 + 0.046X_1X_2 \\ + 0.027X_3X_2 + 0.007X_3X_1 + 0.012X_3^2 + 0.002X_5X_2 - 0.003X_5X_1 \dots\dots\dots 5.11 \\ + 0.005X_5X_3 + 0.0015X_5^2$$

5.4.6.2 Estimated Ridge of Maximum Response for Variables

From the summary result of estimated ridge of maximum response for variables in table 5.20, the following observations were made at constant feed rate for each response variable considered.

Table 5.20: Summary Result for Estimated Ridge of Maximum Response for Variables

S/N	Response Variable	Estimated Response	Standard Error	Pc	Uncoded Factor Value			
					Sc	MC	SS	t
1	PT	156.691	5.378	12.205	89.038	33.872	147.502	17.890
2	ER	8.592	0.826	10.598	92.706	34.621	155.334	20.147
3	PM	46.254	0.971	6.484	81.739	48.153	149.002	9.783
4	WSI	0.819	0.166	12.020	90.631	35.883	ND	17.085
5	SME	148.142	10.109	6.630	94.900	34.928	145.988	22.161
6	MRT	42.297	0.445	7.195	87.278	36.522	101.453	16.431
7	Cs	3338.541	479.676	11.679	91.515	36.731	154.246	13.562
8	WAI	18.611	3.102	12.224	90.065	39.435	ND	14.128
9	MV	7.892	1.473	9.609	91.969	31.227	ND	20.864
10	CPV	18.221	5.690	12.195	89.726	40.551	ND	14.446
11	HPV	9.113	4.217	12.362	89.468	39.750	ND	14.701

The abbreviations used on the table include Pc - protein content, Sc - starch content, Mc - Moisture content, Ss- screw speed and t - duration of operation respectively. ND-Not determined .PT Product temperature ($^{\circ}\text{C}$), SME- Specific Mechanical Energy, (kJ/kg).MRTs- Mean Residence Time (sec.), .MV-Relative Melt Viscosity (0.01DPa.S), HPV-Hot Paste Viscosity (dPa.S), .PM-Product moisture content (%), WSI-Water solubility index (g/g).CS-Compressive Strength (N), CPV-Cold Paste Viscosity(dPa.S) and WAI-Water absorption index, (g/g).

Product temperature :- The canonical analysis indicates that the predicted response surface is shaped like a saddle. The eigenvalue of 44.22 shows that the valley orientation of the saddle is less curved than the hill orientation, with eigenvalue of 0.97. The coefficients of the associated eigenvectors show that the value is more aligned with PC and the hill with

Duration. Because the canonical analysis resulted in a saddle point, the estimated surface does not have a unique optimum. However, the ridge analysis indicates that maximum PT will result from high Pc and Sc but with moderate, MC, SS and Duration. Note from the analysis of variance for the model that the test for the Sc, MC and SS factors are highly significant. If further experimentation is undertaken, it might be best to fix these factors at a moderate to high values and to concentrate on the effect of Duration. Both Linear and Quadratic models fit the data very well, the Product temperature is negatively related ($p \leq 0.001$) to the linear effect of protein content and cross product effects of moisture content and starch content which indicates that an increase in these variables decrease the temperature values. Etc. Also, the analysis of variance showed that the effect of all input variables (Protein content, starch content, moisture content, screw speed and duration of operation of samples were highly significantly different on product temperature.

Product moisture content :- From Appendix 3, the canonical analysis for product moisture content indicates that the predicted response surface is shaped like a saddle. The eigenvalue of 4.08 shows that the valley orientation of the saddle is less curved than the hill orientation, with eigenvalue of 0.93. The coefficients of the associated eigenvectors show that the value is more aligned with Duration and the hill with Pc. From the canonical analysis, all terms in the regression model are significant. Also, the estimated surfaces are shaped like a saddle with no unique minimum or maximum. However, the ridge analysis (Table 5.20) indicates that maximum PM will result from relatively high Pc, Sc, MC, SS and low Duration. Note from the analysis of variance for the model that the test for the Sc, MC and SS factors are not significant. If further experimentation is undertaken, it might be best to fix these factors at a moderate to high values and to concentrate on the effect of Duration. Both Linear and Quadratic models fit the data very well.

Water absorption index :- The canonical analysis indicates that the predicted response surface is shaped like a saddle. The eigenvalue of 8.50 shows that the valley orientation of the saddle is less curved than the hill orientation, with eigenvalue of 0.47. The coefficients of the associated eigenvectors show that the value is more aligned with Pc and the hill with Duration. Because the canonical analysis resulted in a saddle point, the estimated surface does not have a unique optimum. However, the ridge analysis indicates that maximum WAI will result from high Protein content, Starch content and moderate MC, Duration. Note from the analysis of variance for the model that the test for the Sc and MC factors are not significant.

Expansion ratio:- The canonical analysis indicates that the predicted response surface is shaped like a saddle. The eigenvalue of 3.32 shows that the valley orientation of the saddle is downward curved than the hill orientation, with eigenvalue of 0.99. The coefficients of the associated eigenvectors show that the value is more aligned with Duration and the hill with SS. Because the canonical analysis resulted in a saddle point, the estimated surface does not have a unique optimum. However, the ridge analysis indicates that maximum ER will result from relatively high Pc, Sc, moderate MC, high SS and moderate Duration. Note from the analysis of variance for the model that the test for the SS is not significant.

Water solubility index:- The canonical analysis indicates that the predicted response surface is shaped like a saddle. The eigenvalue of 0.32 shows that the valley orientation of the saddle is less curved than the hill orientation, with eigenvalue of 0.086. The coefficients of the associated eigenvectors show that the value is more aligned with Pc and the hill with Duration. Because the canonical analysis resulted in a saddle point, the estimated surface does not have a unique optimum. However, the ridge analysis indicates that maximum WSI will result from relatively high Protein content, Starch content, moderate moisture content and duration. Note from the analysis of variance for the model that the test for the Protein content and moisture content factors are not significant.

SME:- The canonical analysis indicates that the predicted response surface is shaped like a saddle. The eigenvalue of 128.26 shows that the valley orientation of the saddle is downward curved than the hill orientation, with eigenvalue of 50.36. The coefficients of the associated eigenvectors show that the value is more aligned with protein content and the hill with moisture content. Because the canonical analysis resulted in a saddle point, the estimated surface does not have a unique optimum. However, the ridge analysis indicates that maximum SME will result from relatively high protein content, starch content and screw speed moderate moisture content and duration. Note from the analysis of variance for the model that the test for the moisture content and screw speed factors are not significant.

MRT:- The canonical analysis indicates that the predicted response surface is shaped like a saddle. The eigenvalue of 4.06 shows that the valley orientation of the saddle is less curved than the hill orientation, with eigenvalue of 1.67. The coefficients of the associated eigenvectors show that the value is more aligned with SS and the hill with Duration. Because the canonical analysis resulted in a saddle point, the estimated surface does not

have a unique optimum. However, the ridge analysis indicates that maximum MRTs will result from relatively high P_c , S_c , moderate MC and Duration and low SS. Note from the analysis of variance for the model that the test for the P_c , S_c and MC factors are not significant.

CS:- The canonical analysis indicates that the predicted response surface is shaped like a saddle. The eigenvalue of 1178.26 show that the valley orientation of the saddle is less curved than the hill orientation, with eigenvalue of 487.24. The coefficients of the associated eigenvectors show that the value is more aligned with P_c and the hill with SS. Because the canonical analysis resulted in a saddle point, the estimated surface does not have a unique optimum. However, the ridge analysis indicates that maximum CS will result from relatively high P_c , S_c and SS, moderate MC and low Duration. Note from the analysis of variance for the model that the test for the P_c and MC factors are not significant.

RMV:- The canonical analysis indicates that the predicted response surface is shaped like a saddle. The eigenvalue of 3.08 show that the valley orientation of the saddle is downward curved and the hill orientation, with eigenvalue of 2.23. The coefficients of the associated eigenvectors show that the value is more aligned with MC and the hill with Duration. Because the canonical analysis resulted in a saddle point, the estimated surface does not have a unique optimum. However, the ridge analysis indicates that maximum MV will result from relatively high P_c , S_c and moderate MC and Duration. Note from the analysis of variance for the model that the test for the P_c and Duration factors are not significant. If further experimentation is undertaken, it might be best to fix these factors at a moderate to high values and to concentration on the effect of Duration. Both Linear and Quadratic models fit the data very well.

CPV:- The canonical analysis indicates that the predicted response surface is shaped like a saddle. The eigenvalue of 12.99 show that the valley orientation of the saddle is less curved than the hill orientation, with eigenvalue of 2.12. The coefficients of the associated eigenvectors show that the value is more aligned with P_c and the hill with Duration. Because the canonical analysis resulted in a saddle point, the estimated surface does not have a unique optimum. However, the ridge analysis indicates that maximum CPV will result from relatively high P_c , S_c MC and moderate Duration. Note from the analysis of variance for the model that the test for the S_c and Duration factors are not significant.

HPV:- The canonical analysis indicates that the predicted response surface is shaped like a saddle. The eigenvalue of 6.88 show that the valley orientation of the saddle is less curved than the hill orientation, with eigenvalue of 1.73. The coefficients of the associated eigenvectors show that the value is more aligned with Pc and the hill with Duration. Because the canonical analysis resulted in a saddle point, the estimated surface does not have a unique optimum. However, the ridge analysis indicates that maximum PM will result from relatively high Pc, Sc, MC and moderate Duration. Note from the analysis of variance for the model that the test for the Pc, Sc, MC and SS factors are not significant.

It is obvious that extrusion characteristics and product attributes are interrelated. The linear interrelationship between the system parameters and the product attributes under study is shown in Table 5.21.

Table 5.21: Interrelationship between Product Quality Attributes and Extrusion Performance Variables

ER	1	$y = 0.27 \text{ PT} - 0.443$
	2	$y = 0.008 \text{ SME} + 0.007 \text{ PT} - 0.630$
$R^2_{\text{adj}} = 0.210$, Std. Error = 1.42, $P < 0.000$		
PM	1	$y = 33.664 - 0.087 \text{ SME}$
	2	$y = 43.664 - 0.073 \text{ SME} - 0.115 \text{ PT}$
$R^2_{\text{adj}} = 0.321$, Std. Error = 7.14		
Cs	1	$y = 4.201 \text{ SME} + 357.008$
	2	$y = 0.003 \text{ SME} - 0.010 \text{ Na} - 0.94$
$R^2_{\text{adj}} = 0.123$, Std. Error = 579.93, $P < 0.011$		
WAI	1	$y = 5.46 - 0.009 \text{ SME}$
	2	$y = 5.51 - 0.020 \text{ SME} - 0.030 \text{ Tq}$
$R^2_{\text{adj}} = 0.202$, Std. Error = 1.15, $P < 0.000$		
WSI	1	$y = 0.023 + 0.002 \text{ SME}$
	2	$y = 0.003 \text{ SME} - 0.010 \text{ Na} - 0.94$
	3	$y = 0.003 \text{ SME} - 0.019 \text{ Na} - 1.86$
$R^2_{\text{adj}} = 0.697$, Std. Error = 0.073, $P < 0.000$		
MV	1	$y = 3.078 + 0.022 \text{ SME}$
	2	$y = 0.032 \text{ SME} + 0.111 \text{ Na} - 8.015$
	3	$y = 0.030 \text{ SME} + 0.105 \text{ Na} + 0.014 \text{ PT} - 8.634$
$R^2_{\text{adj}} = 0.559$, Std. Error = 1.06, $P < 0.000$		
CPV	1	$y = 7.17 - 0.050 \text{ PT}$
	2	$y = 27.00 - 0.055 \text{ PT} - 0.21 \text{ Na}$
	3	$y = 89.84 - 0.037 \text{ PT} - 0.85 \text{ Na} - 0.19 \text{ Tq}$
$R^2_{\text{adj}} = 0.585$, Std. Error = 1.81, $P < 0.000$		
HPV	1	$y = 14.46 - 0.14 \text{ Na}$
	2	$y = 58.89 - 0.58 \text{ Na} - 0.13 \text{ Tq}$
	3	$y = 57.29 - 0.56 \text{ Na} - 0.10 \text{ Tq} - 0.013 \text{ SME}$
	4	$y = 194.67 - 1.31 \text{ Na} - 0.05 \text{ Tq} - 0.024 \text{ SME} - 1.49 \text{ MRT}$
	5	$y = 185.75 - 1.23 \text{ Na} - .05 \text{ Tq} - 0.02 \text{ SME} - 1.43 \text{ MRT} - 0.01 \text{ PT}$
$R^2_{\text{adj}} = 0.619$, Std. Error = 1.12, $P < 0.000$		

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

A single screw starch extruder has been developed using locally available materials as a means of arresting post harvest losses of starch based crops in Nigeria. It has been evaluated for performance in terms of the system parameters and extrudates' quality. Furthermore, the products have been well characterized. The research facilitated the development of an indigenous starch extruder adaptable to local conditions. Also, it provided a test rig which will be useful in further research and training.

Different parameters involved during the process of extrusion cooking of the products (duration of operation of extruder, moisture content of the product before extrusion, extruder screw speed) are important and interrelated. Generally, the study revealed that it is better to fix the extrusion variables at a moderate to high values to enhance the extrusion performance. Both linear and quadratic coefficients fit the data very well. However, the quadratic with R^2 (0.61- 0.86) have better fit than the linear. The developed models are a useful tool for proper design of extrusion control systems.

Generally, it was easier for cassava to cook/gelatinize under the heat provided by the extruder, hence, a higher solubility and viscosity. Maize starch requires more shear/cooking to form than cassava starch. However, the highest extruder efficiency of the machine when operated at 100 rpm, 89.40 % was attained with maize starch at a longer duration. Also, there is generally an improvement in the stability of the extruded products when compared with the raw samples.

Product quality attributes of maize and wheat were less sensitive to changes in extrusion variables when compared to cassava. This minimum temperature required to cook the cassava sample shows that the use of this extruder is by far more cost effective for cassava than other products i.e. maize and wheat. The resultant polynomial coefficients for response surface regression compared favourably with previous works (Guan,et al ,2004; Guan,et al, 2005).

Database on extrusion of the crops under study which are of benefit in food and feed processing were established. Specific end uses to which the products at different extrusion

conditions can be put were identified. Also, the canonical analysis of the response surface analysis resulted in a saddle point; the estimated surface does not have a unique optimum. However, directions on further experimentation for optimization were suggested.

With the adoption of the developed machine, more food with balanced diet will be produced from basic ingredients with value addition and market for crops produced, sustained production and improved standard of living of the producers. Prediction equations for the studied functional, physicochemical and extrusion system parameters of extruded starches can help in selecting processing conditions for specific food and feed applications. Within the limits of this present study, each response variable was best explained by a second order polynomial non linear regression model. This indigenous starch extruder will enhance the development and operation of starch screw extruder at minimized production cost and energy consumption.

6.2 RECOMMENDATION

The following are recommended for further study on the extruder:

- i. Incorporation of a heat control system with the extruder,
- ii. Evaluation of the improvement of the torque to improve the pumping ability of the extruder,
- iii. Effect of extrusion variables on chemical composition, melt viscosity and nutrition of the products,
- iv. Evaluation of the effect of extrusion variables on the die pressure,
- v. Numerical study can be performed to validate the empirical results and
- vi. Further studies should be done on the microstructure of the extrudates.

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**LIST OF
APPENDICES**

DESIGN ANALYSIS OF EXTRUDER COMPONENTS

1.1 Design of the Extruder Worm

1.1.1 Assumptions and data requirements

The design principle of power screw was applied in the design of this screw worm. Compression is achieved in the extruder by decreasing the screw's pitch along its length. According to Van Zuilichem *et al.* (1980), the L/D of biopolymer extruder should be shorter than that of chemical polymer so as to control chemical reactions such as burning of starches and denaturation of proteins. For food products, L/D ratios of 6 to 15 are required. Also, in order to effect good production of the parts, the following dimensions are chosen based on the limit of available materials locally. A minor diameter of 40mm was chosen. it will distort under arc welding. The clearance between the screw and the barrel is 1.3mm. The design is made similar to a continuous screw press/expeller. The relationship between the length of screw S , number of flights n and common difference in pitch d and the first pitch a is given by arithmetic progression

$$Sn = \frac{n}{2[2a + (n-1)d]}$$

With length = 750mm, $n = 13.8$ mm, $d = -1.5$

The pitch $U_n = a + (n-1)d$, maximum pitch = 45mm

Minimum pitch = 24. The last three pitches to bear similar size (Zulichem *et al.*, 1980)

The screw is assumed to be a screw thread loaded as a cantilever beam.

1.1.1.2 Determination of the compression ratio of the extruder

In view of the fact that heat will be provided through viscous dissipation for gelatinization of starch, compression was achieved by using a tapering shaft diameter and decreasing screw pitch (Fellows, 2003).

$$\text{Compression Ratio} = \frac{V_1}{V_2}$$

Where V_1 = Volume of first pitch and

V_2 = Volume of the last pitch

$U_1 = 45$ mm, $D_1 = 63$ mm, $D_o = 35$ mm

$$V_1 = \frac{P_1 \times \pi \times (D_1 - D_0)}{4}$$

$$V_1 = 96980.97 \text{ mm}^3$$

V_2 = Volume of the last pitch

$$U_2 = 22 \text{ mm}, D_2 = 50 \text{ mm}$$

$$V_2 = \frac{U_2 \times \pi \times (D_1 - D_2)}{4}$$

$$V_2 = 21857.63 \text{ mm}^3$$

$$\text{Compression Ratio} = \frac{96980.97 \text{ mm}^3}{21857.63 \text{ mm}^3} = 4.437:1$$

1.1.1.3 Determination of the theoretical volumetric capacity

Specific weight of starch is 7.853×10^{-6} (Perry, 1986)

$$\text{Therefore, specific mass} = \frac{7.853 \times 10^{-6}}{9.81} = 800.51 \text{ kg/m}^3$$

Theoretical volumetric capacity Q_t was calculated according to Srivastava *et al.* (1996) as

$$Q_t = \frac{\pi (d_{sf}^2 - d_{ss}^2) l p n}{4}$$

Where Q_t = theoretical volumetric capacity (m^3/s)

d_{sf} = screw flight diameter (m)

d_{ss} = Screw shaft diameter (m)

lp = Pitch length (m)

n = Screw rotational speed (rev/s)

$$d_{sf} = \text{screw flighting diameter (m)} = 0.061$$

$$d_{ss} = \text{Screw shaft diameter (m)} = 0.035$$

$$lp = \text{Pitch length (m)} = 0.045$$

$$n = \text{Screw rotational speed (rev/s)} = 4.1667$$

$$Q_t = \frac{(61^2 - 35^2) \times 3.14 \times 45 \times 250}{4 \times 60}$$

$$Q_t \text{ is calculated to be } 3.6738 \times 10^{-4} \text{ m}^3/\text{s}$$

$$\text{Mass flow rate} = 800.51 \text{ kg/m}^3 Q_t$$

$$= 3.6738 \times 10^{-4} \text{ m}^3/\text{s} \times 800.51 \text{ kg/h} \times 3600$$

$$= 1.059 \text{ ton/h}$$

1.1.1.4 Determination of Power Requirement of Extruder

The power requirement for the extruder is calculated using the equation below according to PSGTECH (1982)

$$N = QL \frac{W_0 \pm \sin \beta}{367}$$

Where N is Power (kW),

Q is the Volumetric capacity (ton/h),

L is length of screw (m),

W_0 is material factor (4 for powder),

β is angle of inclination of screw shaft to horizontal and

η is efficiency of gear reducer.

$$\text{Power, } N = \frac{1.059 \times 0.75 (4) 1/0.2}{367} = 1.083 \text{ kW}$$

The power requirement of the extruder was calculated to be 1.083 kW. However, with a compression ratio of 4.437:1, the expected pressure generated at the die end of the extruder worm is $2.95 \text{ MN/m}^2 \times 4.437 = 13.1 \text{ MN/m}^2$. Therefore, the power required to cater for the back pressure created by the die due to the high compression ratio developed at the same Q , = 4.78 kW. Hence, the Power requirement of the extruder worm is 4.78 kW.

1.2 Design of Extruder Barrel

The barrel (cylinder) is designed on the basis of internal pressure. If the screw housing is treated as a thick wall cylinder, then using the standard and stress analysis technique applied to thick walled pressure vessels (Sivakumaran and Goodman, 1987), the tangential stress, σ , perpendicular to the axis of the cylinder is

$$\sigma = \frac{2P_c D_c^2}{(D_o^2) - (D_c^2)}$$

Where, P_c = designed Pressure in Extruder

D_o = outer diameter of cylinder

D_c = inner diameter of cylinder

Allowable tangential stress is assumed to be $140 \times 10^6 \text{ Nm}$ (Sivakumaran and Goodman, 1987).

$$\text{Therefore, } 140 \times 10^6 = \frac{2 \times 114.7 \times 10^6 \times (0.063)^2}{(D_o^2) - (0.063^2)}$$

$$= \frac{9104886}{(D_o^2) - (0.063^2)}$$

$$(D_o^2) - (0.063^2) = 6.5 \times 10^{-3}$$

$$(D_o^2) = 3.97 \times 10^{-3}$$

$$\begin{aligned}
&= \frac{9104886}{(D^1_c)^2 - (0.063^2)} \\
(D^1_c)^2 - (0.063^2) &= 6.5 \times 10^{-3} \\
(D^1_c)^2 &= 3.97 \times 10^{-3} \\
&= 0.0105 \\
(D^1_c)^1 &= 0.013\text{m} \\
&= 130 \text{ mm}
\end{aligned}$$

1.3 Design of Hopper

The hopper is the housing where the material to be extruded are stored and fed into the machine at a determined rate. This hopper is to have a shape which facilitates loading, maximum volume utilization, a reliable and complete gravity discharge through the outlet. In predicting the lateral pressure in design of hoppers for gravity flow the coefficient of friction between granular materials is needed as a design parameter (Monsehnin, 1970). The coefficient of friction of coffee pulp, 0.73 which is similar to the materials to be studied in this work was selected. Hence, an angle exceeding $\tan^{-1} 0.75 = 36.12^\circ$ was used. An angle of inclination of 50° was selected for the hopper sides.

1 Determination of the volume of hopper

The volumetric capacity of the extruder $= 3.674 \times 10^{-4} = 1322640000 \text{ mm}^3/\text{h}$

Since the extruder is to be starve fed, the capacity of the feeder is halved $= 661320000 \text{ mm}^3/\text{h}$ which is the volume of material charged in 1 hour.

The ideal volume of a pyramid $= 1/3 \times \text{Base Area} \times \text{Height}$

The volume of the hopper which has the shape of a frustum

$= 1/3 (\text{Volume of Big Pyramid}) - 1/3 (\text{Volume of Small Pyramid})$

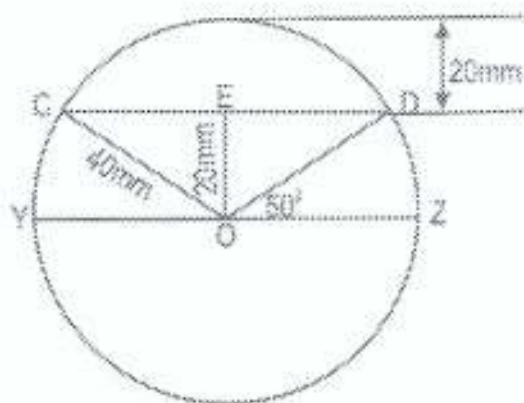
i.e. Volume of frustum, ABCDHIFG = Volume ABCDIJ - Volume EFGHIJ.

The configuration of the hopper is estimated as follows:

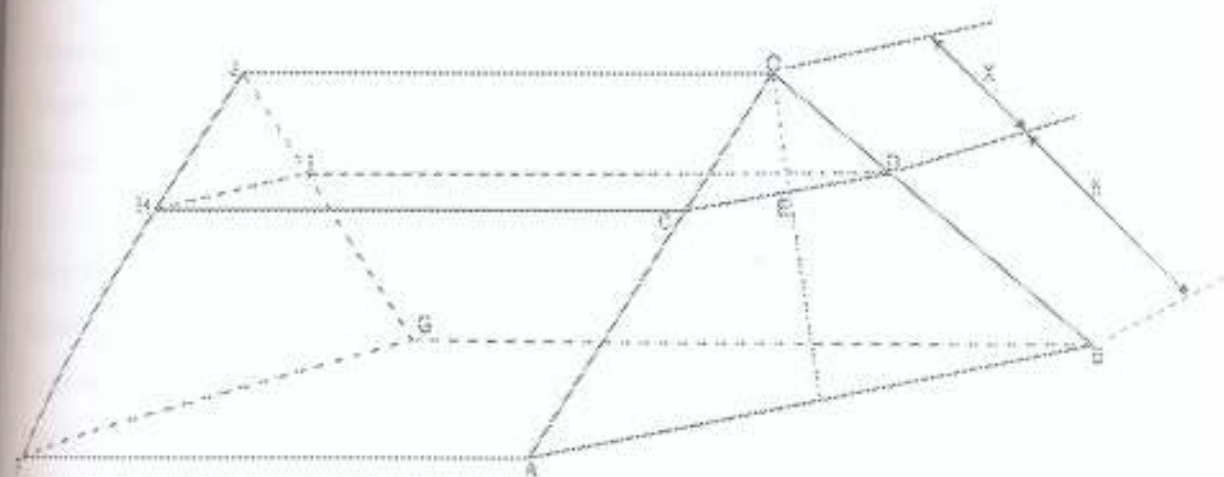
2 Determination of the width of hopper base.

The diameter of the designed feeding conveyor $= 80 \text{ mm}$

Assuming that the hopper is made to seat on $1/4$ of the circumference of the surface area of the cylinder as shown in Figure A.1a



(a)



(b)

Figure A.1 Extruder hopper dimensions

From figure A.1a, considering triangle CEO,

$$CO^2 = CE^2 + EO^2$$

$$CE^2 = CO^2 - EO^2$$

$$CE = 35\text{mm}$$

CD = 70mm, which is width of hopper base.

3 Determination of the top dimensions of the hopper

Analyzing from Figure A.1b,

Center O is common to both the small and big pyramids.

$$X = \frac{35}{\cos 50} = 54.45$$

Assuming h is in multiples of x, for instance, $h = 4x$

From similar triangles ODE and OAB

$$\frac{X}{CD} = \frac{x + 4x}{AB}$$

$$AB = 350 \text{ mm}$$

When, $h = 233$, then $AB = 362 \text{ mm}$.

Therefore, when $h = 233$, the top dimensions of the hopper is 360 mm by 360 mm.

1.4 Design Analysis of Feeding Conveyor

The feeding conveyor was designed according to PSGTECH (1982) as follows:

1 Determination of conveyor speed, n

$$\text{Capacity of conveyor, } Q = 15\pi D^2 S n \psi \rho c$$

Where D is conveyor diameter, S is the screw pitch, n is conveyor speed, ψ is loading efficiency, c is factor inclination to horizontal, ρ is density.

$$\text{The extruder's capacity} = 1.059 \text{ ton/hr}$$

Since the extruder is to be starve feed, therefore the capacity of the feeding conveyor is halved 0.5295 ton/hr (Frame, 1994).

Loading efficiency = 0.4, assuming pitch = screw diameter = 0.076m

Density of starch is taken to be $790 \times 10^{-3} \text{ ton/m}^3$ (PSG TECH, 1982).

Density of water = $1000 \times 10^{-3} \text{ ton/m}^3$.

Maximum moisture content of starch – water mixture to be studied = 40 %

Therefore, density of starch- water mixture

$$= 0.60 \times 790 \times 10^{-3} + 0.40 \times 1000 \times 10^{-3}$$

$$= 0.474 + 0.4$$

$$= 0.874 \text{ ton/m}^3$$

Factor inclination to horizontal, $c = 1$

$$\text{Therefore, conveyor speed, } n = \frac{0.5295}{15 \times (0.076)^3 \times 0.8 \times 0.4 \times 0.874}$$

$$= 91.52 \text{ rpm}$$

2 Power required for driving the screw, N

$$N = \frac{QL}{367} \times 4.0 \times \frac{1}{0.2} \dots\dots\dots 3.9$$

$$= \frac{0.5295 \times 0.5}{367} \times 4.0 \times \frac{1}{0.2}$$

$$= 0.0144 \text{ kW}$$

3 Torque on screw shaft, M

$$M = 975 \frac{N}{n} \text{ kgfm} \dots\dots\dots 3.10$$

$$= 0.153 \text{ kgfm.}$$

4 Load propulsion Speed, V

$$V = \frac{Sn}{60} \text{ m/s} \dots\dots\dots 3.11$$

$$= \frac{0.0608 \times 91.52}{60}$$

$$= 0.093 \text{ m/s}$$

5 Load per meter length of conveyer, q

$$q = \frac{Q}{3.6V} \text{ kg f/m} \dots\dots\dots 3.12$$

$$= \frac{0.5295}{3.6 \times 0.093}$$

$$= 1.582$$

6 Axial thrust on screw, p

$$p = ql\mu \dots\dots\dots 3.13$$

$$= 1.582 \times 0.5 \times 0.6$$

$$= 0.477 \text{ kg f}$$

7 Area of outlet, A

$$Q = \rho V a \dots\dots\dots 3.14$$

$$A = Q / \rho v$$

$$\text{But } V = 0.093 \text{ m/s}$$

$$= 0.093 \times 3600 \text{ m/h}$$

$$= 334.8 \text{ m/h}$$

$$\text{Therefore, } A = \frac{0.5295}{0.874 \times 334.8}$$

$$1.81 \times 10^{-3} \text{ m}^2$$

8 The diameter of the outlet orifice, d_o

$$\text{From } A = \left(\frac{\pi}{4} d_o\right)^2$$

$$d_o = 2.3 \times 10^{-3} \text{ m}$$

$$= 2.3 \text{ mm.}$$

1.5 Design Analysis of Power Transmission System

The design analysis of power transmission system was carried out following the procedure of PSG TECH (1982)

1.5.1 Motor – intermediate V – belts and pulleys

1 Determination of the diameter of pulleys

Motor speed = 1420rpm = 23.67rps

Required intermediate speed = 500rpm

Belt selection: C V – Belt with the power range of 7.5 – 75 cross – section with as shown in figure A.2 is selected.

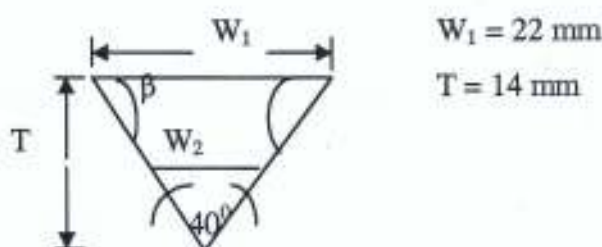


Figure A.2 'C' V- Belt cross section

The recommended minimum pulley pitch diameter, $d_p = 0.200\text{m}$ (PSG TECH, 1982)

$$\text{Belt speed, } S = d_p n = \pi \times 0.200 \times 23.67 \text{ rps} \\ = 14.872.$$

$$\text{Speed ratio} = \frac{1420}{500} = 2.84$$

Small diameter correction factor, $F_b = 1.13$

$$\text{Equivalent pitch diameter, } d_e = d_p \times F_b = 0.200 \times 1.13 = 0.226\text{m}$$

The pulley diameters are as shown in figure 3.3.

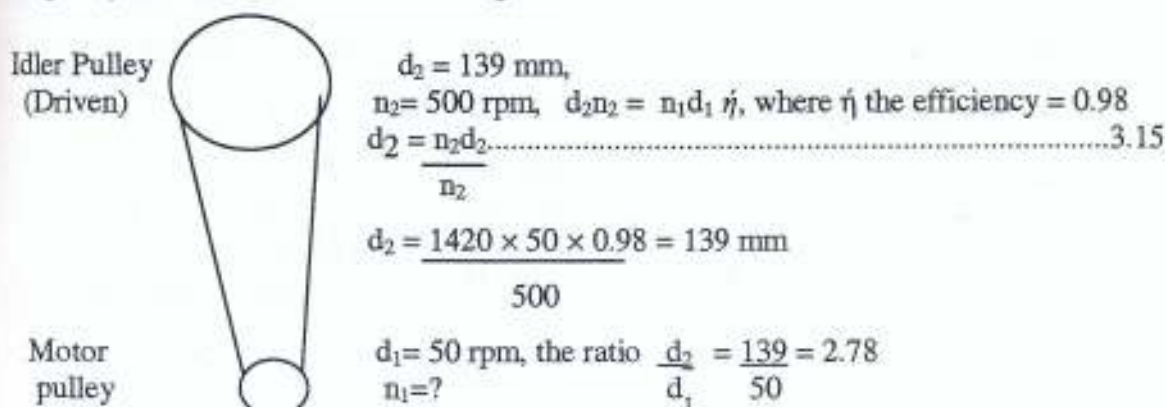


Figure A.3 Motor – Intermediate V – belt and pulley

2 Determination the centre distance c , of belt

Recommended c/d ratio = 1.0 i.e. $c = 1.0 \times 139 = 139$

$$c_{\min} = 0.55 (d_5 + d_4) + T \dots\dots\dots 3.16$$

$$= 0.55 (102) + 14 = 117.95$$

$$c_{\max} = 2(d_2 + d_1) \dots\dots\dots 3.17$$

$$= 378 \text{ mm}$$

3 Determination of the length of belt, L

The nominal pitch length of belt L is given by

$$L = 2c + \pi/2 (D+d) + (D-d)^2/4c \dots\dots\dots 3.18$$

$$= 589.15 \text{ mm}$$

The closest value to this calculated nominal pitch length is belt = 610 mm,

$$\text{The actual value of } c \text{ is given by the formula } A + \sqrt{A^2 - B} \dots\dots\dots 3.19$$

$$\text{Where } A = L/4 - \pi d_2 + d = \frac{610}{4} - \frac{74.22}{4} = 78.28 \text{ mm}$$

$$\text{Therefore, } c = 78.28 + \sqrt{(78.28)^2 - 990.25} = 78.22 \text{ mm}$$

4 Determination of the number of belts

The correction factor for industrial service $F_a = 1.4 + 0.2 = 1.6$

The value of the rating for the 'C' V - belt,

The value of the correction factor, $F_c = 0.8$

The value of the correction factor for the arc of contact, $F_d = 0.77$

$$\text{Arc of contact angle} = 180^\circ - 60^\circ(d_2 - d_1) \dots\dots\dots 3.20$$

$$\text{Arc of contact angle} = 106.8^\circ$$

$$\text{Number of belts, } N = \frac{P \times F_a}{\text{kW} \times F_c \times F_d} \dots\dots\dots 3.21$$

Where P is power required.

$$N = \frac{7.50 \times 1.6}{7.58 \times 0.8 \times 0.7}$$

Therefore number of belts = 3

1.5.2 Intermediate – extruder V belt and pulley: Speed 1

1 Determination of the diameter of pulleys

Required intermediate speed = 500 rpm = 8.33 rps

Belt selection: 'C' V – belt

Required extruder speed 1 = 200rpm

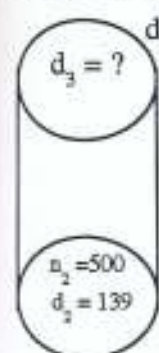
$$d_p = 0.2$$

Belt speed $s = 5.234$ m/s

$$\text{Speed ratio} = \frac{500}{200} = 2.5; F_b = 1.13$$

$$d_p = 226\text{mm}, \text{ kW} = 3.30\text{kW}$$

The pulleys diameters are as shown in Figure A.4.



$$d_3 n_3 = n_2 d_2 \Rightarrow d_3 = \frac{n_2 d_2}{n_3} = \frac{500 \times 139}{200} = 347.5 \approx 348\text{mm}$$

$$\text{The ratio } d_3/d_2 = 348/139 = 2.496$$

$$\text{Recommended } c/d \text{ ratio} = 1; c = 348\text{mm}$$

$$c_{\max} = 0.55 (480) + 7 = 278\text{mm}$$

$$c_{\min} = 2(480) = 960\text{mm}$$

Figure A.4 Intermediate – extruder V belt and pulley

2 Determination the centre distance c , of belt

The nominal pitch length of belt

$$L = 2c + \pi/2 (D + d) + (D - d)^2/4 \times c$$

$$\begin{aligned} L &= 2 \times 348/408\text{mm} + \pi/2 \frac{(480) + (202)^2}{4 \times 408} \\ &= 816 + 754 + 29.915 \\ &= 1590\text{mm} \end{aligned}$$

The closest value for $L = 1473$ mm; $F_c = 0.80$

The actual value of $c = A + \sqrt{A^2 + B}$

$$\begin{aligned} A &= 1473/4 - \pi (489/8) = 368.25 - 188.57 \\ &= 179.79 \text{ mm} \end{aligned}$$

$$B = (202)^2 = 5100.5\text{mm}$$

$$\begin{aligned} c &= A + \sqrt{A^2 + B} = 208.03 + \sqrt{43276.5 - 5100} \\ &= 180 + 195.4 \\ &= 375.15\text{mm} \end{aligned}$$

3 Determination of the number of belts

The correction factor for industrial service $F_a = 1.3$

The value of the rating for the V – belt = 3.60kW

Arc of contact angle = $180^\circ - 60^\circ (202/408) = 150.3^\circ$

Correction factor for arc of contact, $F_d = 0.93$

No of belts = $330 \times 1.3 / 3.6 \times 0.8 \times 0.93 = 1.6 = 2$ belts

1.5.3 Extruder – feeder V – belt and pulley A

1 Determination of the diameter of pulleys

Belt selection 'C' belt

Speed ratio = $500/100 = 5$,

$n_3 = 500\text{rpm} = 8.33\text{rps}$

Belt speed = 5.234m/s , $F_b = 1.12$

$d_e = 224$; kW = 3.30 kW

$d_3 n_3 = d_4 n_4$, $d_5 = d_4 n_4 \dot{\eta} / n_5 = 367.5$

The ratio $d_5/d_4 = 367.5/n_5 = 4.9$

2 Determination the centre distance c, of belt

$c/d_5 = 0.9$; $c = 0.9 \times 368\text{mm} = 331.2$

$c_{\min} = 0.55 (d_5 + d_4) + T = 0.55 (368 + 75) + 7$
 $= 257.65\text{m}$

$c_{\max} = 2(443) = 886\text{mm}$

3 Determination of the length of belt

The normal pitch length of belt L ,

$L = 2c \times \pi / 2 (d_5 + d_4) + (d_5 - d_4)^2 / 4c$

$= 2 \times 331.2 + \pi / 2 (443) + (293)^2 / 4 \times 331.2$

$= 662.4 + 695.9 + 64.8$

$= 1423.1$

The closet value to $L = 1422\text{mm}$, $F_e = 0.87$

$A = 1422 / 4 - \pi / 8 (443) = 51274 - 173.96$
 $= 338.15$

$B = (293/8)^2 = 10731.13$

$$C = 660.04$$

4 Determination of the number of belts

$$F_s = 1.2$$

The value of the rating for the 'C' V belts = 3.60 kW

$$\text{Arc of contact angle} = 180^\circ - 60^\circ (293/600) = 153^\circ$$

$$F_d = 0.93$$

$$\text{Number of belts, } N = 3.30 \times 12 / 3.60 \times 0.93 \times 0.87 = 1.35 = 2 \text{ belts}$$

The c to be chosen must exceed that of the extruder pulley since that feeder will be mounted on the extruder. Therefore the center distance chosen must be greater than $(408 + 240\text{mm}) = 648\text{mm}$. Therefore 660mm was chosen.

1.5.4 Design of intermediate – extruder V Belts and pulley: Speed 2

1 Determination of the diameter of pulleys

$$\text{Intermediate speed} = 500\text{rpm} = 8.33 \text{ rps}$$

Belt selection: 'C' V – belt

$$\text{Required extruder speed } 2 = 250\text{rpm}$$

$$d_p = 0.2 \text{ m}$$

$$\text{Belt speed, } S = \pi d_p n = 5.234\text{m/s}$$

$$\text{Speed ratio} = 500/250 = 2, F_b = 1.13$$

$$d_e = 226\text{mm}, \text{ kW} = 3.30\text{kW}$$

$$d_3 n_3 = n_2 d_2 \dot{\eta}, d_3 = 68110/250 = 273.5\text{m}$$

2 Determination the centre distance c , of belt

$$\text{Recommended } C = 327.6\text{mm}$$

$$c_{\min} = 0.55 (412) + T = 240\text{mm}$$

$$c_{\max} = 2(412) = 824\text{mm}$$

Since the 1st C on the design is 408mm

Therefore, 408 mm was chosen in this case

3 Determination of the length of belt

The normal pitch length of belt,

$$L = 2c + \pi/2 (D + d) + (D - d) / 408$$

$$= 2 \times 408 + \pi/2 (412) + 11.00 = 816 + 647.17 + 11$$

$$= 1474.17 \text{ mm}$$

4 Determination of the number of belts

The closet value to $L = 1473$, $F_a = 0.80$

The correction factor for industrial service $F_e = 1.3$

The value of the ratio for the 'C' v – belt = 3.60 kW

$$\text{Arc of contact angle} = 180^\circ - 60^\circ (134/408) = 160.29^\circ$$

$$F_d = 0.98$$

$$\text{Number of belts, } N = 3.00 \times 12/3.60 \times 0.80 \times 0.95 = 1.45 = 2 \text{ belt}$$

1.5.5 Extruder – feeder V – belt and pulley (B)

1 Determination of the diameter of pulleys

Belt selection 'C' V – belt

$$\text{Speed ration} = 500/125 = 4$$

$$n_3 = 500 \text{ rpm} = 8.33 \text{ rps}$$

$$\text{Belt speed} = 5.234 \text{ m/s}; F_b = 1.12$$

$$d_5 n_5 = d_4 n_4 \eta, d_5 = d_4 n_4 \eta / n_5 = 500 \times 88 \times 0.98 / 125 = 345 \text{ mm}$$

2 Determination the centre distance c, of belt

$$c/d_5 = 0.95, c = 0.95 \times 345 = 327.75 \text{ mm}$$

$$c_{\min} = 0.55 (D + d) + T = 0.55 (417.75) + 14 = 242.66 \text{ mm}$$

$$c_{\max} = 2(d_5 + d_4) = 835.5 \text{ mm}$$

However since 660mm was chosen for the other speeds values.

Therefore, 660 mm was selected

3 Determination of the length of belt

$$L = 661.22 + 656.2 + 2572 = 1367.37$$

The closet value to $L = 1981$, $F_c = 0.87$

4 Determination of the number of belts

$$F_a = 1.2$$

The value of the ration for the V – belt = 3.60kW

$$\text{Arc of contact, } p = 1800 - 600 (257/660) = 157$$

$$F_d = 0.94$$

$$\text{Number of belt, } N = 3.30 \times 1.2 / 3.60 \times 0.87 \times 0.94 = 1.33$$

$$\text{Number of belt} = 1$$

1.5.6 Intermediate – extruder V – belts and pulley: Speed 3

1 Determination of the diameter of pulleys

$$\text{Intermediate} = 500\text{rpm} = 8.33$$

$$\text{Required Extruder speed} = 300\text{rpm}$$

Belt selected: 'C' V belt

$$d_p = 0.200$$

$$\text{Belt speed, } S = 5.234$$

$$\text{Speed ratio} = 500/300 = 1.67$$

$$\text{Small diameter correction factor, } F_n = 1.12$$

$$d_3 = 204\text{mm}$$

$$d_3 n_3 = n_2 d_2 = d_3 = n_2 d_2 / n_3 = 68110/300 = 227.03$$

2 Determination the centre distance c, of belt

$$\text{The ratio } d_3/d_2 = 227/139 = 1.633$$

$$\text{Recommended } c/d \text{ ratio} = 1.2 = c = 1.2 \times 227 = 272.4\text{mm}$$

$$c_{\min} = 0.55(D + d) + T = 0.55(227 + 139) + 14 = (336 \times 0.55) + 14 = 215.3\text{mm}$$

$$c_{\max} = 2(336) = 672\text{mm}$$

c for the 1st Inter – Extruder pulley (1), 408mm is chosen.

3 Determination of the length of belt

Nominal pitch length of belt, L

$$L = 2 \times 408 + (336) + (88)2 = 1348.5\text{m}$$

4 Determination of the number of belts

The correction factor for industrial services

$$F_a = 1.3$$

The value of the rating for the 'C' V – belt = 3.60kW

$$\text{Arc of contact angle} = 180^\circ - 60^\circ (88) = 167.06^\circ$$

$$F_d = 0.97$$

$$\text{Number of belts } N = 3.30 \times 1.3 / 3.6 \times 0.8 \times 0.97 = 1.536$$

Number of belts = 2 belts

1.5.7. Extruder – Feeder V – belts and pulley C

1 Determination of the diameter of pulleys

Belt selection : 'C' V – Belt

$$\text{Speed Ratio} = 500 / 150 = 3.33$$

$$n_3 = 500 \text{rpm} = 8.33 \text{rps}$$

$$\text{Belt Speed} = 5.234 \text{m/s}, F_b = 1.12$$

$$d_e = 224 \text{ mm}, \text{ kW} = 3.30 \text{ kW}$$

$$d_3 n_3 = d_4 n_4, d_5 = d_4 n_4 / n_5$$

$$= 500 \times 100 \times 0.98 / 150 = 327$$

2 Determination the centre distance c, of belt

$$\text{The ratio} = d_5 / d_4 = 3.27$$

$$c / d_4 = 0.95 ; C = 0.95 \times 227 = 310.67 \text{mm}$$

$$c_{\min} = 0.55 (d_5 + d_4) + T = 0.55(327 + 100) + 14 = 248.85$$

$$c_{\max} = 2(d_5 + d_4) = 854 \text{mm}, \text{ Since } C \text{ for the first belt is } 660 \text{mm is chosen}$$

3 Determination of the length of belt

The nominal pitch length of belts, 660mm that been selected for other

$$L = 2c + \pi/2 (d_5 + d_4) + (d_5 - d_4/4c) 2$$

$$= 1320 + 670.73 + \frac{(227)^2}{19.81}$$

$$= 2010.25$$

$$\text{The closet value to } L = 19.81 \text{mm}, F_e = 0.17$$

4 Determination of the number of belts

$$F_a = 1.2$$

The value of the rating for the C V – belts = 3.80kW

$$\text{Arc of contact angle,} = 1800 - 600 (227/660) = 138.80$$

$$F_d = 0.97$$

$$\text{Number of belts, } N = 3.30 \times 1.2 / 3.60 \times 0.87 \times 0.92 = 1.30 = 2 \text{ belts}$$

1.6 Screw Shaft Designs

Shaft design consists primarily of the determination of a correct diameter to ensure satisfactory strength and rigidity when the shaft is transmitting power under operating and loading conditions. Therefore, the shafts will be designed from the stand point of strength and rigidity.

1.6.1 The design of the extruder screw shaft

$$1 \quad \text{Time to cover distance } L_t = L/v \quad 3.21$$

$$= 0.750/0.3463 = 2.17s$$

$$2 \quad \text{Weight of material conveyed distributed in the worm} = Q \cdot t \quad 3.22$$

$$= Q \cdot L/v = 1.059 \times 2.17 = 2.30$$

$$3 \quad \text{Uniformly distributed load due to material} = Q \cdot L/V \cdot L \text{ (per unit length)} \quad 3.23$$

$$= 1.059/0.3463$$

$$= 3.06$$

$$4 \quad \text{Uniformly distributed load due to the auger } q$$

$$q = Q/3.6v \quad 3.24$$

$$= 1.059/3.6 \times 0.34625 = 0.29$$

$$5 \quad \text{Total uniformly distributed load}$$

$$= Q/v + q \quad 3.25$$

$$= 3.06 + 0.29$$

$$= 3.08/m$$

$$6 \quad \text{Determination of forces due to the pulley (made of aluminum)}$$

Volume of pulley covered by V – belt groove

= belt cross – sectional area $\times$ thickness

Given:

Top width of belt = 22mm

Nominal depth of belt, $T = 14\text{mm}$

Sheave groove angle = 40°

Density of leather belt = 970kg/m^3

Friction between the pulley and belt $U = 0.25$

The bottom width of belt β

$$\beta = (180 - \square) / 2 \quad 3.26$$

$$= (180^\circ - 40^\circ) / 2 = 70^\circ$$

$$T = \frac{1}{2} W_1 \tan \beta^\circ \quad 3.27$$

$$= 8.5 \tan 70^\circ = 30.22$$

$$\text{By similar triangles, } W_2 = (T \times W_1) / T = 14 \times 22 / 30.22 \\ = 10.20$$

The belt cross – sectional area can be obtained as

$$A = [(W_1 + W_2) / 2] T \quad 3.28$$

$$= [(22 \times 10.2) / 2] 14$$

$$= 225.34 \times 10^{-6} \text{ m}^2$$

$$\text{Mass per unit length, } m = \rho \times A \quad 3.29$$

$$= 970 \text{ kg / m}^3 \times 225.34 \times 10^{-6}$$

$$m = 0.219 \text{ kg/m}$$

7 Determination of the weight of pulley (assumed to be made aluminum)

Volume of pulley covered by V – belt groove (3 in No)

= belt cross sectional area x thickness

$$= 225.34 \times 10^{-6} \times 14 \times 10^{-3}$$

$$= 1.6 \times 10^{-4} \text{ m}^3 \times 3 = 4.92 \times 10^{-3}$$

A small hole of 138 mm diameter at the center of the pulley for the insertion of angler shaft volume of pulley taken among by the hole

$$\pi r^2 \times W_1 \times 3 = \Pi (69 \times 10^{-3}) \times 22 \times 10^{-3} \times 3 \\ = 4.55 \times 10^{-3} \text{ m}^3$$

8 Gross volume of aluminum disc for the pulley

$$= (22/7 \times (227 \times 10^{-3} \times 22 \times 10^{-3} + (22/7 \times (341 \times 10^{-3})^2 + 22/7 (273 \times 10^{-3})^2 \times 22 \times 10^{-3} \\ = 0.0036 + 0.00801 + 0.00515 = 0.01676 \text{ m}^3 = 1.68 \times 10^{-2} \text{ m}^3$$

9 Net volume of aluminum used for the pulley

$$= 1.68 \times 10^{-2} - 4.55 \times 10^{-3} - 4.92 \times 10^{-4}$$

$$= 1.17 \times 10^{-2} \text{ m}^3$$

$$\therefore \text{Mass of pulley} = 2700 \times 1.17 \times 10^{-2} = 31.59 \text{ kg}$$

$$\text{Weight} = 309.9 \text{ N}$$

10 Determination of the arc of contact of belt

$$n_1 = 500$$

$$r_c = 37.5$$

$$C = 660$$

$$n_2 = 100 = 100/60 \text{ rps}$$

$$r_2 = 183.5$$

$$\alpha_1 = 180 - 2 \sin^{-1} (r_2 - r_1)/c \quad 3.30$$

$$= 180 - 2 \sin^{-1} (183.5 - 37.5)/660 = 2$$

$$= 180 - 2 \sin^{-1} 2.43 \times 10^{-1} = 180 - 31.253$$

$$= 148.75$$

$$\alpha_2 = 180^\circ + 2 \sin^{-1} (r_2 - r_1)/c \quad 3.31$$

$$= 180^\circ + 31.253 = 221.25$$

$$\text{Max tension } T_1 = 2 \times 10^6 \text{ N/m}^2 \times 225.34 \times 10^{-6} = 450.68 \text{ N}$$

$$\text{Allowable tension ratio } R = \frac{\mu}{\sin \theta} \quad (\mu \propto \csc \theta/L) \quad 3.32$$

$$= \frac{\mu}{\sin \theta} (0.25 \times 148.75 \times \pi/180 / \sin 200)$$

$$= 6.685$$

$$\text{Belt speed } v = \pi d_2 n_2 \quad 3.33$$

$$= \pi \times 0.184 \times 100/60$$

$$= 0.96 \text{ m/s} = 1 \text{ m/s}$$

The centrifugal force on the belt, T_c

$$T_c = mv^2 \quad 3.34$$

$$T_c = 0.219 \times 1^2 = 0.219 \text{ N}$$

The belt tension on the slack side, T_2

$$T_1 - T_c / T_2 - T_c = R \quad 3.35$$

$$= T_2 = T_1 - T_c / R + T_c$$

$$= 450.68 - 0.219/6.685 + 0.219 = 67.603 \text{ N}$$

The highest belt tension attainable is due to pulley C is 91.154 N. Therefore, the radial force on the shaft from the V - belt drive is $T = T_1 + T_2 = 450.68 + 91.154 \text{ N}$

$$T_r = 541.834 \text{ N}, T_h = 0$$

$$\text{Total load acting on the pulley} = 309.9 + 541.834 \text{ N} = 851.732 \text{ N}$$

11 Determination of the weights on the screw shaft

(a) Weight of barrel

Volume of barrel = $0.75 (D - d)^2 / 4 \times N$ (thickness = 7mm)

$$= 0.75 \times \pi \times \{(14 \times 10^{-3})^2\} / 4$$

$$= 1.15 \times 10^{-4} \text{ m}^3$$

Mass of barrel = Density $\times$ volume

$$= 7840 \times 1.16 \times 10^{-4}$$

$$= 0.905 \text{ kg}$$

$$\text{Weight of barrel} = 0.905 \times 9.81 = 8.89 \text{ N}$$

(b) Determination of the weight of die

Volume of die material (Figure 3.5)

$$= \text{Total volume} - (\text{Volume of cone entrance} + \text{volume of nozzle})$$

Assuming a lead in angle 45° , the required $x = 0.02065$

$$\text{Volume of cone} = 0.000008806$$

$$\text{Volume of nozzle} = \pi r^2 h = 0.000000405$$

$$\text{Volume of cone} + \text{volume of nozzle} = 0.0000008394$$

$$\text{Volume of die} = 0.0002077 \text{ m}^3$$

$$\text{Mass of die} = 7840 \times 0.0002077 \text{ m}^3$$

$$= 1.627 \text{ kg}$$

$$\text{Weight} = 15.97 \text{ N}$$

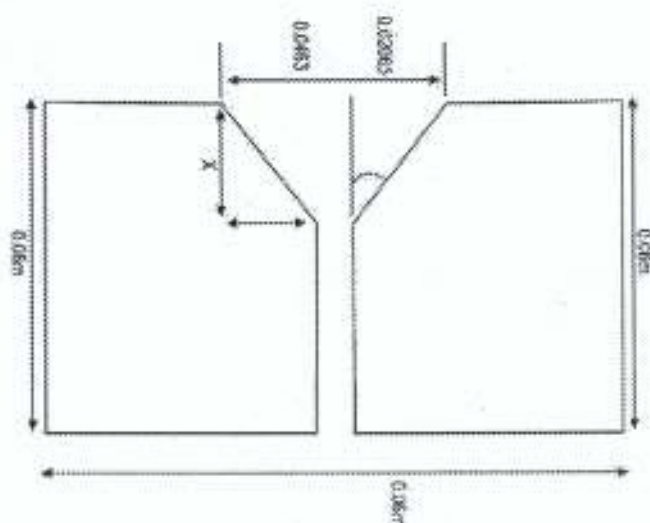


Figure A.5: Design of extruder die

Since the extruder is being considered as a cantilever, the weight of barrel + weight of die goes together = $8.89 + 15.97 \text{ N} = 24.86 \text{ N}$. The vertical forces acting on extruder shaft are shown in Figure 3.6.

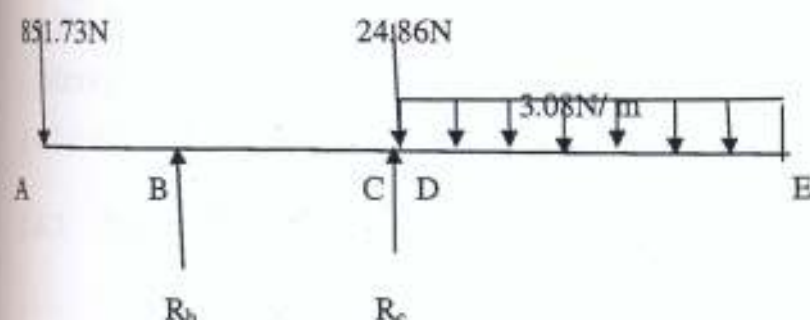


Figure A.6. Vertical Forces acting on extruder shaft

Taking moment about B

$$438.35(0.750)^2/2 - R_c \times 0.5 + 24.86 \times 0.6 - 851.732 \times 0.2 = 0$$

$$123.29 - 0.5R_c + 14.92 - 170.35 = 0$$

$$0.5R_c = -170.35 + 123.29 + 14.92$$

$$R_c = -32.85 \times 2 = 65.7 \text{ N}$$

$$R_b = 851.732 + 24.86 + 328.76 = 1141.072 \text{ N}$$

Moment at Pt A = 0

$$\text{Moment at Pt B } 851.732 \times 0.2 = 170.35$$

$$\text{Moment at pt C } 851.732 \times 0.7 - 570.54 - 0.328.76 \times 0.375$$

$$M_c = -277.70, \text{ Moment at pt D; } M_d = 0$$

The maximum bending moment occurs at C = 277.70

For the belt drive the higher torsional moment

$$M_t = 0.750 (450.68 - 91.154) \text{ N} = 53.93$$

13 Determination of shaft diameter

For the solid shaft with little or no axial loading but having combined bending and torsional loads, the required diameter D is obtained as follows from ASME code equation:

$$D^3 = 16/\pi S_s \sqrt{(K_b M_b)^2 + (K_t M_t)^2} \quad 3.36$$

Where d = diameter shaft

$$S_s = \text{allowable stress} = 40 \times 10^{-6} \text{ N/m}^2 \text{ for steel}$$

$$K_b = \text{shock and fatigue factor applied to bending moment} = 1.5$$

$$M_b = \text{maximum bending moment} = 277.70$$

$$K_t = \text{shock and fatigue factor applied to torsional moment} = 1$$

$$M_t = \text{Maximum torsional moment} = 53.93 \text{ N}$$

$$D^3 = 16/\pi (40 \times 10^{-6}) \left[(1.5 \times 277.70)^2 + (1 \times 53.93)^2 \right]$$

$$= 1.27 \times 10^{-7} \sqrt{173513.903 + 2908.33}$$

$$= 1.27 \times 10^{-7} \sqrt{176422.8325}$$

$$= 0.00005334$$

$$d = \sqrt[3]{0.00005334345} = 0.03765 \text{ m} = 37.65 \text{ mm}$$

1.6.2 Feeder shaft design

1 Time to cover distance $L_t = l/V = 0.5 / 0.3463$
 $= 1.444$

2 Weight of material conveyed / distributed in the worm, Q_t
 $= 59.392 \times 1.44 = 85.752$

3 Uniformly distributed load due to the material
 $= Q/v$ (per unit length) $= 59.392 / 0.363 = 171.505$

4 Uniformly distributed load due to the auger q
 $Q = Q/3.6v = 59.392 / 3.6 \times 0.34625 = 47.64$

5 Total uniformly distributed load $= Q/v + q$
 $= 171.505 + 47.64 = 219.145$

6 Weight of pulleys

Gross volume of aluminum disc for the pulley =

$$= (22/7 \times (75 \times 10^{-3})^2 \times 22 \times 10^{-3}) + (22/7 \times (88 \times 10^{-3})^2 \times 22 \times 10^{-3})$$

$$+ (22/7 \times (100 \times 10^{-3})^2 \times 22 \times 10^{-3})$$

$$= 3.89 \times 10^{-4} + 5.35 \times 10^{-4} + 6.9 \times 10^{-4}$$

$$= 1.62 \times 10^{-3}$$

Net volume aluminum used for the pulley

$$1.17 \times 10^{-2} = 2.39 \times 10^{-3}$$

$$\text{Mass of pulley} = 2700 \times 2.39 \times 10^{-3} = 6.4531$$

$$\text{Weight} = 6.453 \times 9.81 = 63.3 \text{ N}$$

$$\text{Cross-sectional area of belt } A = 137.5 \times 10^{-6} \text{ m}^2$$

$$\text{Mass per unit length of belt } A, m = 0.133 \text{ kg/m}$$

$$r^2 = 163.5 \text{ mm}, \text{ belt speed} = 0.43 \text{ m/s}, T_c = 0.056$$

$$\text{Max. Tension, } T_1 = 275 \text{ N},$$

7 Determination of the arc of contact of belt

$$\alpha_1 = 180^\circ - 2 \sin^{-1} [(r_2 - r_1)/c]; \alpha_2 = 180^\circ + 2 \sin^{-1} (r_2 - h/c)$$

$$\alpha_1 = 180^\circ - 2 \sin^{-1} (57.5 - 25/500); \alpha_2 = 180^\circ + (57.5 \cdot 25/500)$$

$$= 180^\circ - 7.454; \alpha_2 = 180^\circ + 74.54$$

$$\alpha_1 = 172.55; \alpha_2 = 187.454$$

8 Determination of the allowable tension rating for the V - belt

$$R_1 = e^{(U \cdot 1 \cdot \csc \theta / 2)}$$

$$R_2 = e^{(U \cdot 2 \cdot \csc \theta / 2)}$$

$$= e^{(0.25 \times 172.55 + \pi/180)}$$

$$R_2 = e^{(0.15 \times 187.454 \times \pi/180 / \sin 20)}$$

$$= e^{126.18}$$

$$= e^{137.07}$$

$$= 6.28$$

$$= 3.38$$

$$T_1 = 43.8 \text{ N}$$

The radial force on the shaft from the V - belt drive of pulley,

$$T_R = T_1 + T_2 = 275 + 43.8 = 318.8 \text{ N}, T_h = 0$$

9 Total load acting due to the pulley

$$\text{Weight of pulley} + \text{radial force} = 63.3 + 318.8 = 382.1 \text{ N}$$

10 The vertical forces acting on extruder shaft are shown in figure 3.7.

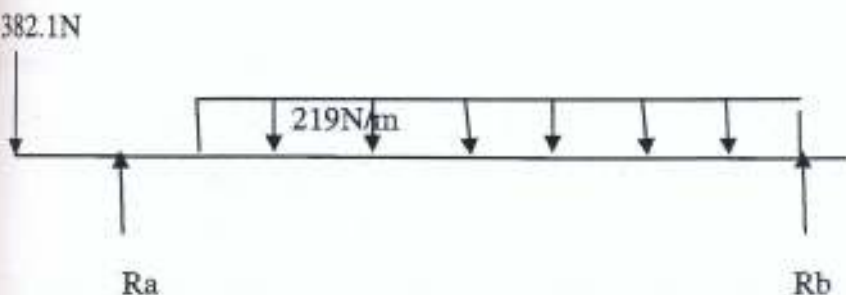


Figure A.7 Vertical Forces acting on feeder shaft

10 Determination of shaft diameter

$$\text{From eqn 3.35, } D_3 = 16 / \pi S_e \sqrt{(K_b M_b)^2 + (K_t M_t)^2}$$

$$S_e = \text{allowable stress} = 46 \times 10^6 \text{ N/m}^2 \text{ for steel}$$

$$K_b = 1.5; M_b = 45.0195 \text{ Nm}; K_t = 1, M_t = 53.93 \text{ N}$$

$$d_3 = 16 / \pi (40 \times 10^6) \sqrt{(1.5 \times 45.0195)^2 + (1 \times 53.93)^2} \text{ N}$$

$$= 1.27 \times 10^{-7} \sqrt{4560.20 + 2908.83}$$

$$= 1.27 \times 10^{-7} \sqrt{7469.03} = 1.0978 \times 10^{-5}$$

$$\begin{aligned}
 d_1 &= 16 / \pi (40 \times 10^{-6}) \sqrt{(1.5 \times 45.0195)^2 + (1 \times 53.93)^2} \text{ N} \\
 &= 1.27 \times 10^{-7} \sqrt{4560.20 + 2908.83} \\
 &= 1.27 \times 10^{-7} \sqrt{7469.03} = 1.0978 \times 10^{-5} \\
 d &= 2.2 \times 10^{-2} = 22.22 \text{ mm} \approx 25 \text{ mm}
 \end{aligned}$$

1.7 Design of Extruder Die

1 Determination of die pressure

According to Frame (1994), for a die of circular cross section,

$$Q = K_d \frac{P_d}{\mu} \quad 3.37$$

Where Q = volumetric flow rate,

P_d = Total pressure drop,

μ = Dough viscosity at the die

K_d = die constant which is a function of geometry

Also, die constant for cylindrical die is given by equation 3.38 as follows:

$$K_d = \frac{\tau R^4}{8L_d} \quad 3.38$$

Where R = nozzle radius,

L_d = length of die,

μ = viscosity of material,

P_d = pressure

The extrusion pressure P is also the P in the die equation and the Q for the die is the same as Q_{net} in the extruder.

From the design analysis of the extruder worm (pg 82), the volumetric flow rate

$$Q = 3.6738 \times 10^{-4} \text{ m}^3/\text{s}.$$

$$\begin{aligned}
 \text{Pressure} &= \frac{\text{power}}{Q} \\
 &= \frac{4780 \text{ W}}{3.6738 \times 10^{-4} \text{ m}^3/\text{s}}
 \end{aligned} \quad 3.39$$

$$\text{Die pressure} = 13.01 \text{ MN/m}^2$$

Pressure at the exit of die reduces instantly to 0.

2 Determination of the radius of the nozzle and length of the die

According to Frame (1994), for a die of circular cross section equations 3.37 and 3.38 were used.

Apparent viscosity was calculated according to Alvarez - Martinez *et al.* (1987) as follows:

$$U_o = 78.5(\gamma)^{-0.49} e^{\left(\frac{1500}{T}\right)} e^{-7.9M} \quad 3.40$$

$$\text{And } \gamma = \frac{\pi DN}{H} = \text{shear rate (s}^{-1}\text{)} \quad 3.41$$

Where U_o = dough viscosity at the die (Pa.s),

T = Barrel temperatures $^{\circ}\text{C}$,

M = Moisture fraction of the feed,

D = Barrel diameter (m),

N = Screw speed (rpm),

H = average screw channel length over the active volume (m).

The highest viscosity will be obtained at the following values

Moisture content 22 % (w.b),

Temperature 45°C ,

Screw speed 200 rpm,

Barrel diameter, $D = 61 \text{ mm}$

Screw depth, $H = 14 \text{ mm}$

$$\begin{aligned} \gamma &= \frac{\pi DN}{H} = \frac{\pi \times 61 \times 10^{-3} \times 200}{14 \times 10^{-3} \times 60} \\ &= 93.064 \text{ sec}^{-1} \end{aligned}$$

$$\begin{aligned} U_o &= 78.5(93.064)^{0.49} \times 1.235 \times e^{(-7.9 \times 20\%)} \\ &= 78.5 \times 9.22 \times 1.235 \times 12.482 \\ &= 11,157.11 \text{ N.s/m}^2 \end{aligned}$$

$$\therefore Q_{die} = \frac{r^4}{8\eta} \times \frac{P}{U_o}$$

$$\begin{aligned} 3.6738 \times 10^{-4} \text{ m}^3/\text{s} &= \frac{13.01 \times 10^6 \times \pi \times R^4}{11,157.11 \times L_d} \\ &= 1166.07 \frac{R^4}{L_d} \end{aligned}$$

Assuming a radius of $5 \text{ mm} = 5 \times 10^{-3} \text{ m}$

$$\begin{aligned}
 \therefore L_d &= \frac{1166.07 \times (5 \times 10^{-3})^4}{3.6738 \times 10^{-4}} \\
 &= \frac{7.2879 \times 10^{-7}}{3.6738 \times 10^{-4}} \\
 &= 0.984 \times 10^{-3} \text{ m} \\
 &= 10 \text{ mm.}
 \end{aligned}$$

In order to increase/ improve on the operating die pressure, according to Sohkey et al. (1997), the die length was multiplied by 2. Hence a die length of 20 mm was selected.

APPENDIX 2

A.2.1 Bought Out Components

Table 3.1 Bought Out Components (A)

Table 3.1 Bought Out Components (A)					
Sl	Name	Specification	Quality	Unit cost (₹)	Total Cost (₹)
1	Electric motor	4.0 kW, 2800 rpm three phase	1	25,000	25,000
2	Speed reducing gear	2800 rpm, speed ratio 1:25	1	50,000	50,000
3	Taper roller bearing	D = 62, d = 30, B = 25	2	250	500
4	Stainless Electrodes	G10	2 packets	4,500	9,000
5	Thrust bearing	D = 52, d = 30, h = 6	1	1,500	1,500
6	Saw blade		2 Rolls	1,780	3,400
7	Sealed self aligning ball bearing	Φ20 mm	1	150	150
8	B. V- Belt 68	B	2	200	400
	B. V- Belt 60	B	2	200	400
	B. V- Belt 58	B	2	200	400
	A. V- Belt 30	A	1	100	200
9	Hinge	76 mm	2	100	200
10	Lock nut	Φ 32	1	100	100
11	Control switch		1	7500	7500
12	Stainless steel flange	Φ 140 X 10 mm	10	840	8400
13	Bolts and Nuts	M10 long	4	80	320
		M10 short	24	80	1,920
		M6	8	50	400
TOTAL					109,790.00

A.2.2 Component and Parts Fabricated

Table A.2 Component and Parts Fabricated (B)

COMPONENT					
S/N	NAME	SPECIFICATION	QTY	NAME	COST(₦)
1	Thrust Bearing	φ 76mm rod	1	m.s rod	400
	housing	φ 100mm rod	2	Stainless steel	500
	Hub	φ 25mm rod		rod	7,200
	Die nozzle }	φ55mm rod	1	Stainless steel	
	Conveyor shaft }	φ65 mm rod	1	Hollow pipe	24,000
	Extruder main	φ60mm	1	Stainless steel	
	Extruder worm	φ80mm, cut	1	rod	18,000
	Extruder feed chute	φ76mm	1	Hollow pipe	500
	Conveyor housing	Exφ80mm, Int		Stainless steel	7,200
	Extruder barrel	φ63m		pipe	12,000
			1		
	Die	φ80mm rod	1		
	Support frame	50 mm X 25.4 mm	1	Stainless steel	4000
		50 mm X 25.4 mm	1	rod	
	Base frame	76mm X 4mm		Ms U channel	15,000
	Motor seat	25.4mm	4	Ms U Channel	
	Control panel		2	Angle Iron	
	Support frame	3mm	4	Stainless plate	6,000.00
		3mm	1	m.s. plate	
	Conveyor screw	50mmX3mm		Square pipe	300
	Hopper support	3mm	1	m.s. plate	
	Body cover	3mm			15,000
	Transmission cover		1	stainless steel	10,000
	Control panel cover	3mm		flat bar	
	sheet			m.s.sheet	14,000
	Extruder support plate	10mm m.s. plate	2	m.s. plate	3,000
	Pulleys.			m.s plate	
		φ220mm X 25mm	1		2000
		φ140mm X 37mm	1	cast materials	3000
		φ180mm X 37mm	1		3000
		φ240mmX37mm	1		3000
		Total			117,100

A.2.3 Machining and Non Machining Jobs

Table A.3 Machining and Non Machining Jobs, C

TYPE OF JOB	MACHINE USED	MATERIAL	COST ₦
1. Lathe work with generator (Boring, threading, turning)	Industrial lathe	Stainless rod; ms Rods;	80,000
2. cutting	Power saw		
3. cutting	Hack saw		1,000
4. cutting	Guillotine	pulleys	5,000
5. drilling			
6. milling		Stainless rod; ms	not
7. punching	Table & Hand grinding	Rods; pulleys	costed
8. bending		Shaft	
9. grinding			
10. Oxy acetylene cutting	Oxy-acetylene		
11. arc welding (with generator)	Bastard file, round etc.		10,000
12. filling		units pipe, plastic frameset	10,000
		Rods, pipe, pulleys	10,000
		Sheets, plates, pipes, frames etc	2,000
		Sheets & plates	10,000
		Rods, sheets, plates	20,000
		etc.	10,000
		Plates	20,000
		Sheets, plates, rods.	5,000
		Total	<u>183,000</u>

A.2.4 Total Cost of Production

Other costs

1.	Transportation	20,500
2.	Workmanship	40,000
	TOTAL	<u>60,500</u>

Total cost of production = A+B+C+D

$$= 109,790 + 117,100 + N183,100 + 60,500$$

$$\text{N} 470,390.00$$

TableA.4 Determination of Proximate Composition of Materials studied

MOISTURE CONTENT				
	W1	W2	W3	% Mc
Cs (a)	43.086	48.028	47.956	1.46
(b)	41.932	46.867	46.794	1.48
Fc (a)	42.680	46.095	46.033	1.82
(b)	42.669	46.130	46.062	1.97
Ms (a)	42.692	46.329	46.255	2.04
(b)	43.894	47.669	47.592	2.09
Mf (a)	43.882	49.236	49.168	1.27
(b)	43.239	48.599	48.528	1.32
ASH				
	W1	W2	W3	%ASH
Cs (a)	8.171	9.785	8.174	0.19
(b)	12.056	13.508	12.059	0.21
Fc (a)	17.916	19.356	17.939	1.60
(b)	14.740	16.085	14.765	1.64
Ms (a)	12.128	13.281	12.129	0.17
(b)	12.191	13.074	12.197	0.11
Mf (a)	30.708	32.783	30.716	0.39
(b)	9.321	10.403	9.325	0.37
FAT				
	W1	W2	W3	%Fat
Cs (a)	0.428	1.733	1.710	1.724
(b)	0.433	1.309	1.264	1.268
Fc (a)	0.415	1.487	1.434	1.439
(b)	0.450	1.351	1.317	1.364
Ms (a)	0.294	1.217	1.188	3.14
(b)	0.264	0.871	0.847	3.95
Mf (a)	0.280	1.102	1.065	4.50
(b)	0.341	0.985	0.957	4.35
FIBRE				
	W1	W2	W3	% Fibre
Cs (a)	5.000	18.210	18.201	0.18
(b)	5.000	18.682	18.671	0.22
Ms (a)	5.000	18.648	18.634	0.28
(b)	5.000	10.332	10.317	0.30
Mf (a)	3.000	10.428	10.417	0.37
(b)	5.000	16.216	16.199	0.34
Fc (a)	5.000	28.495	28.483	0.24
(b)	5.000	22.215	22.203	0.24

PROTEIN				
	Wt used	Titre value	% Protein Content	
Cs	0.573	(a) 0.20	0.31	
		(b) 0.20	0.31	
Ms	0.590	(a) 0.60	0.86	
		(b) 0.60	0.86	
Mf	0.614	(a) 2.60	3.85	
		(b) 2.70	4.00	
Fc	0.547	(a) 4.60	7.36	
		(b) 4.50	7.20	

$$\%N = \frac{\text{Titre value} \times 0.01\text{MHCl} \times 0.014 \times 50 \times 100}{\text{wt} \times 5}$$

$$\% \text{Protein} = \%N \times 6.25$$

THE EFFECT OF EXTRUSION VARIABLES ON PRODUCT CLASSIFICATION

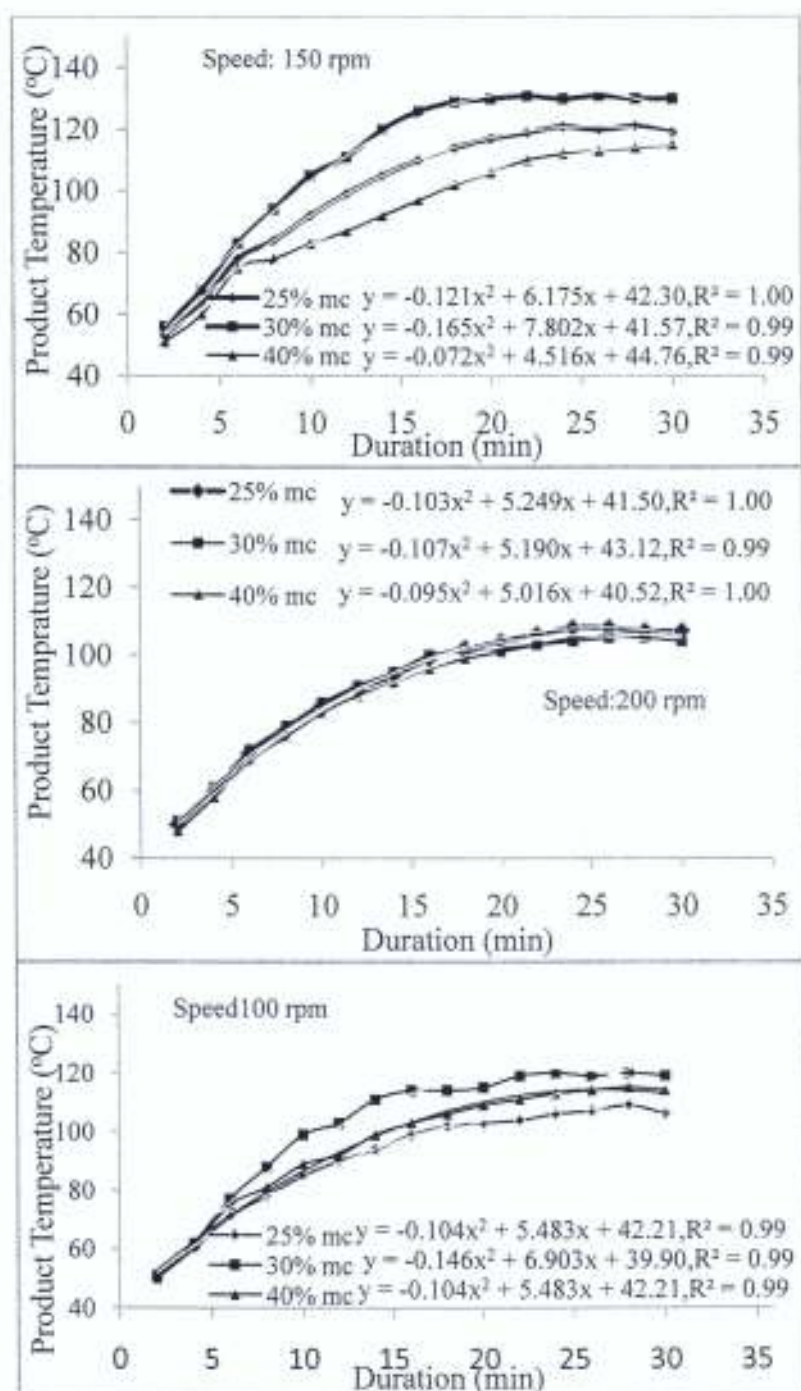


Figure A.8: Product temperature response of cassava starch to variable extrusion conditions.

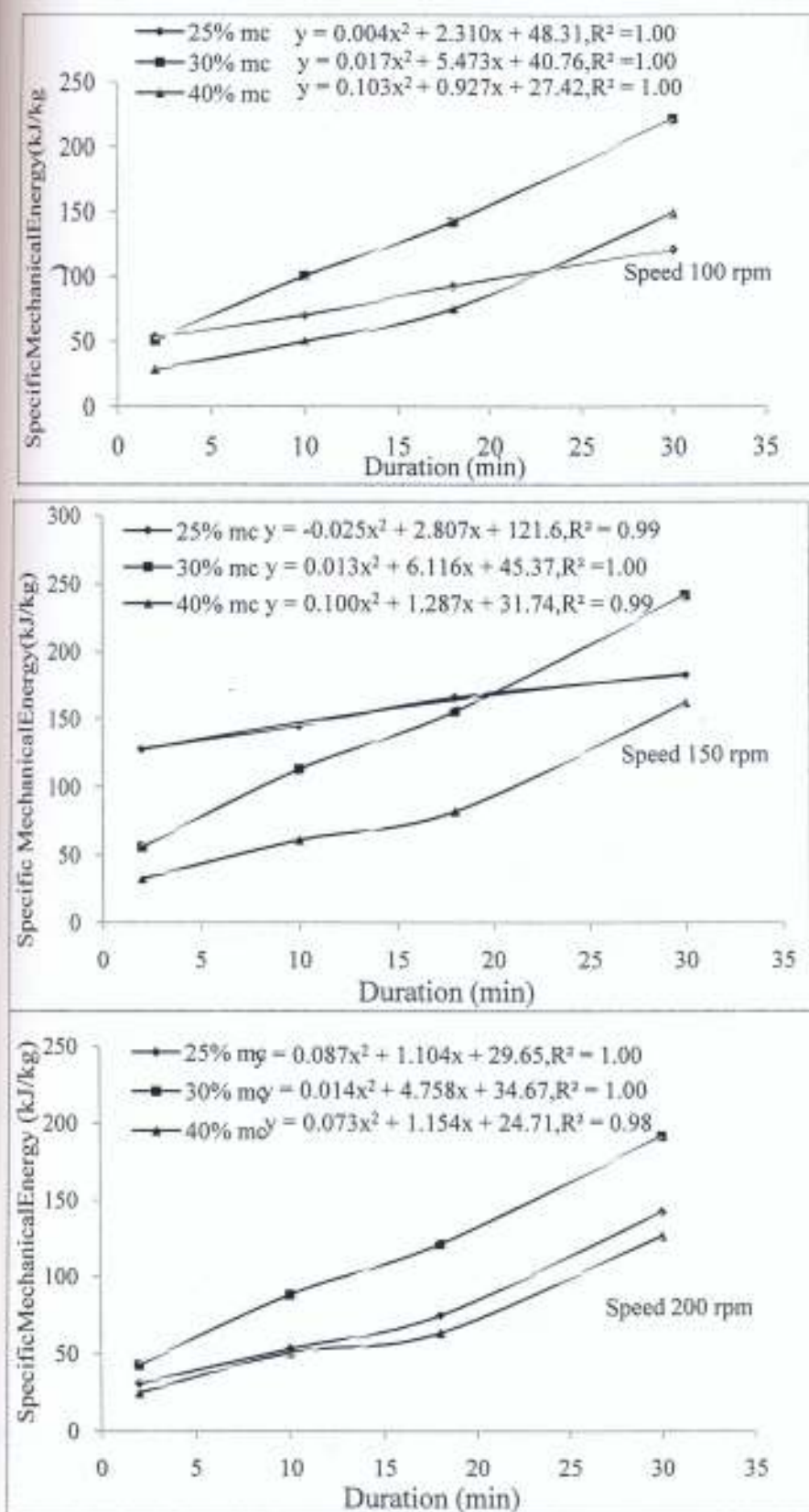


Figure A.9: Specific mechanical energy response of cassava starch to variable extrusion conditions

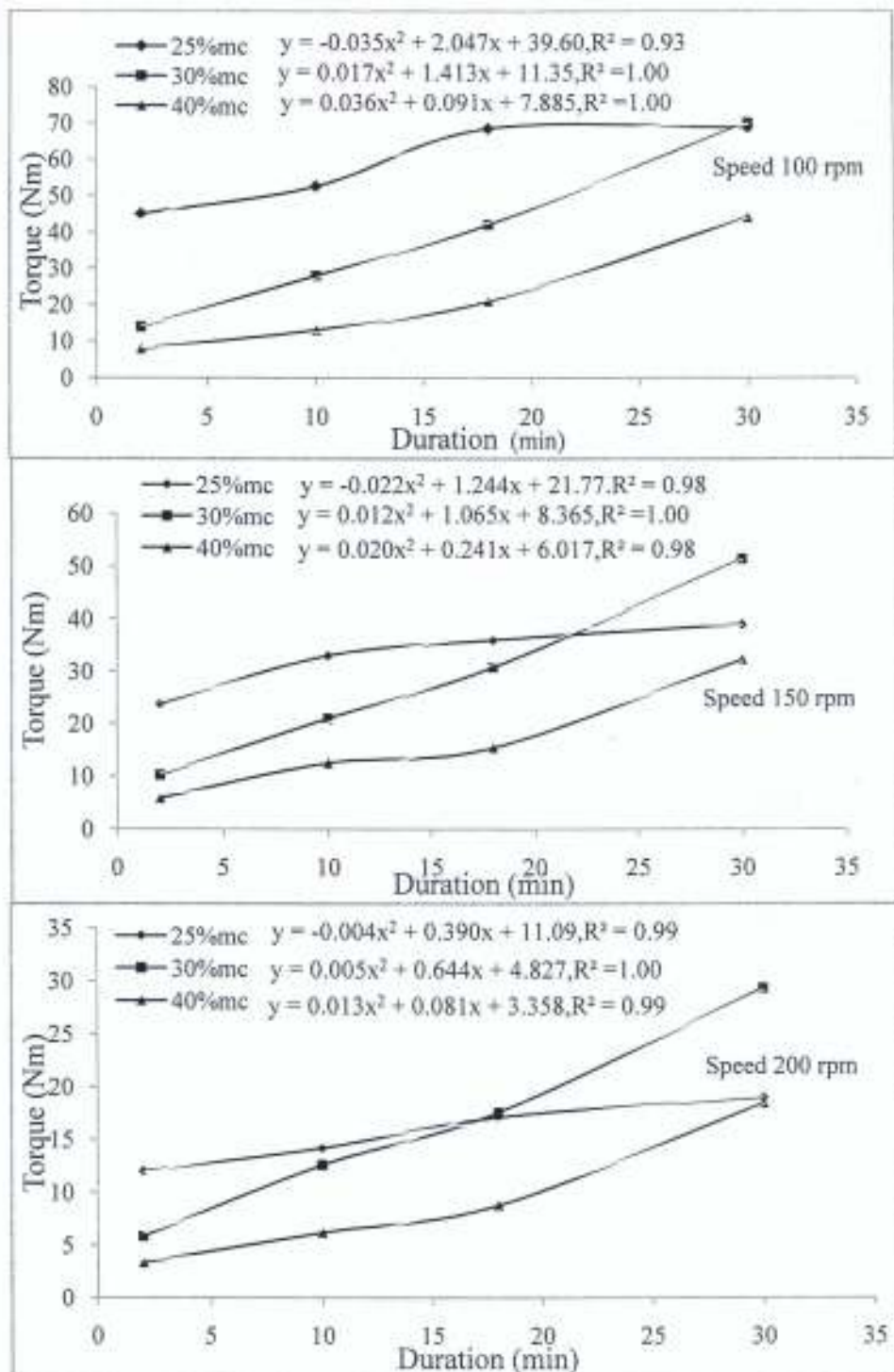


Figure A.10: Motor torque response of cassava starch to variable extrusion conditions

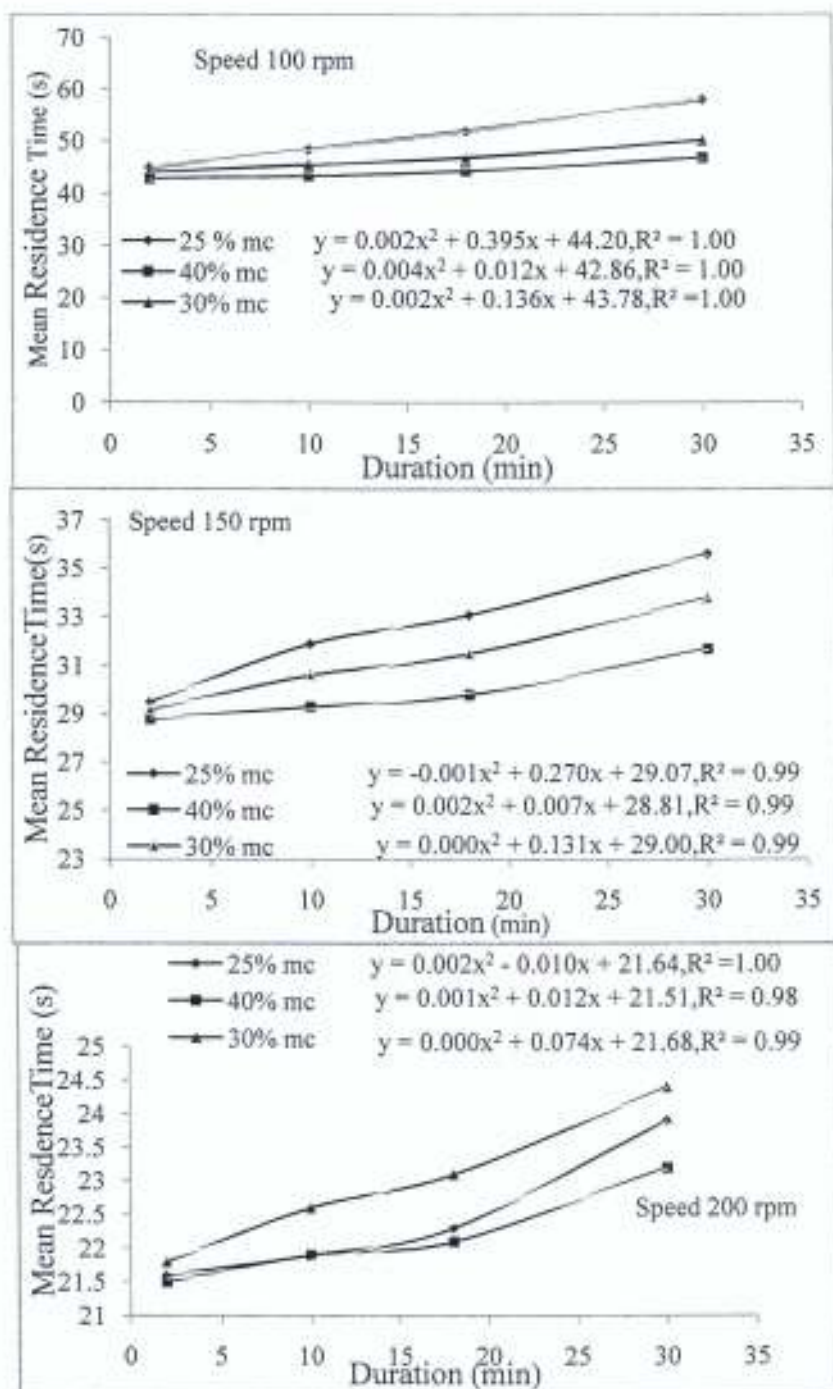


Figure A.11: Mean residence time (MRT) response of Cassava starch to variable extrusion conditions

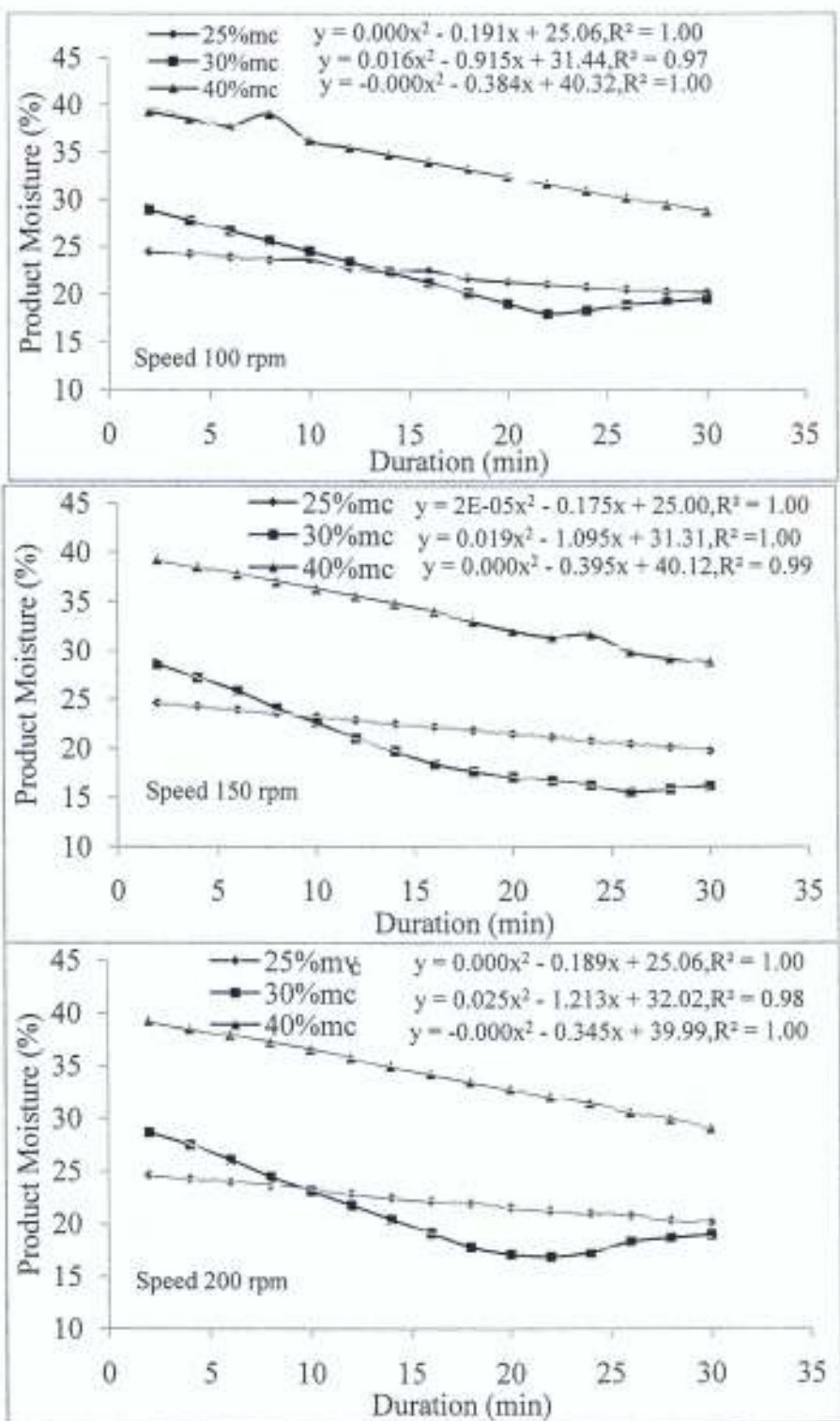


Figure A.12: Product moisture response of cassava starch to variable extrusion conditions

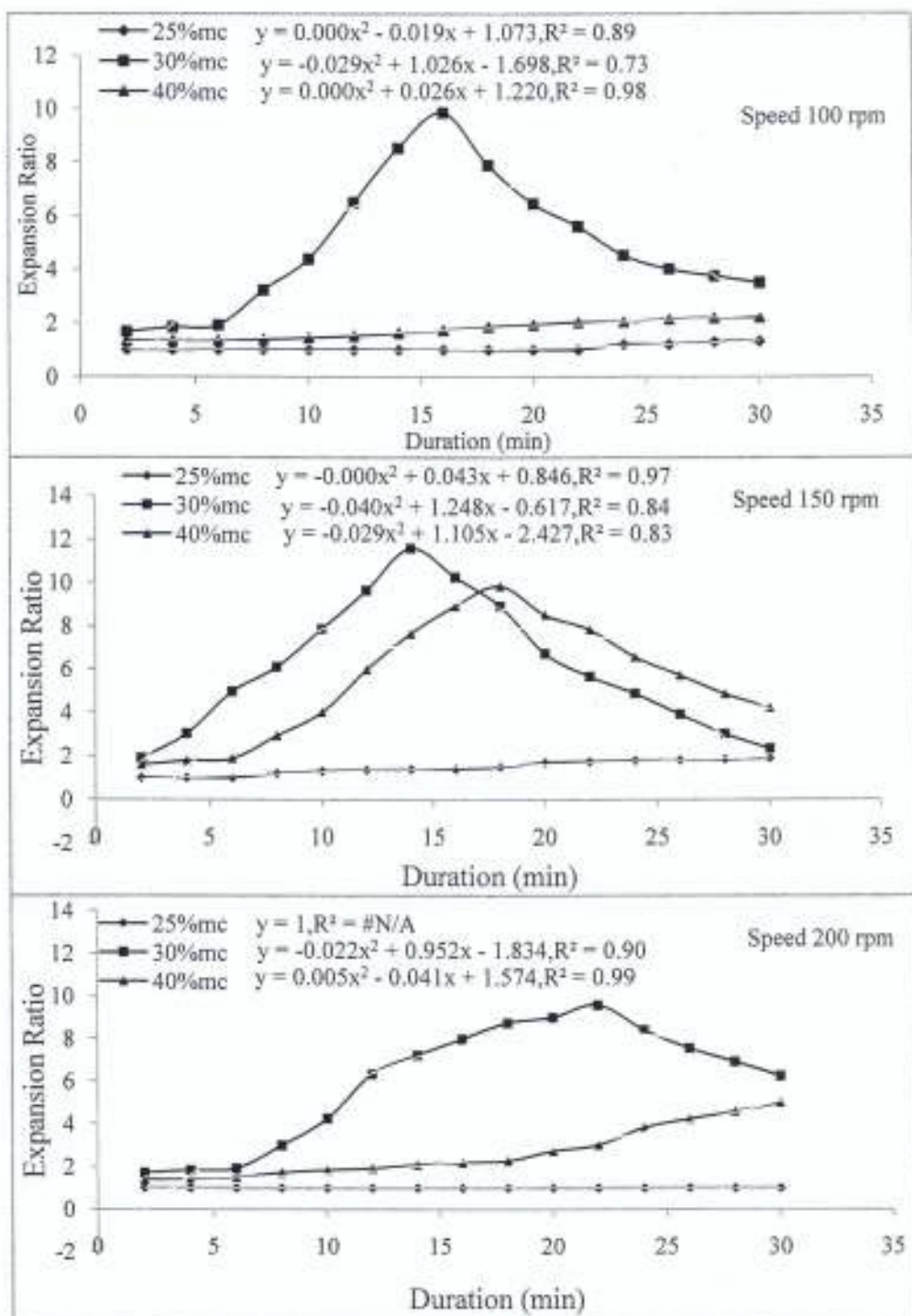


Figure A.13: Expansion ratio response of cassava starch to variable extrusion conditions

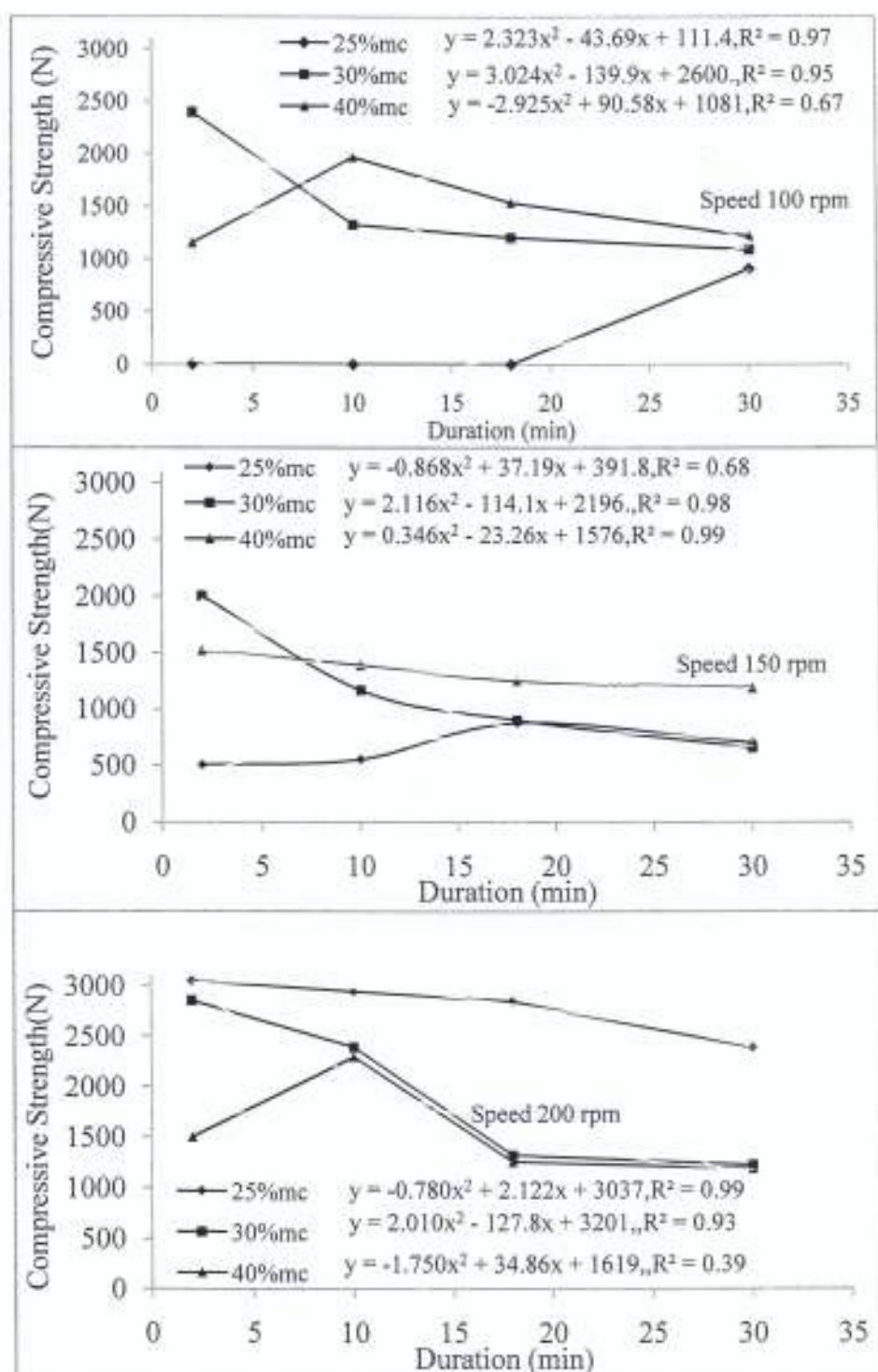


Figure A.14: Compressive strength response of cassava starch to variable extrusion conditions

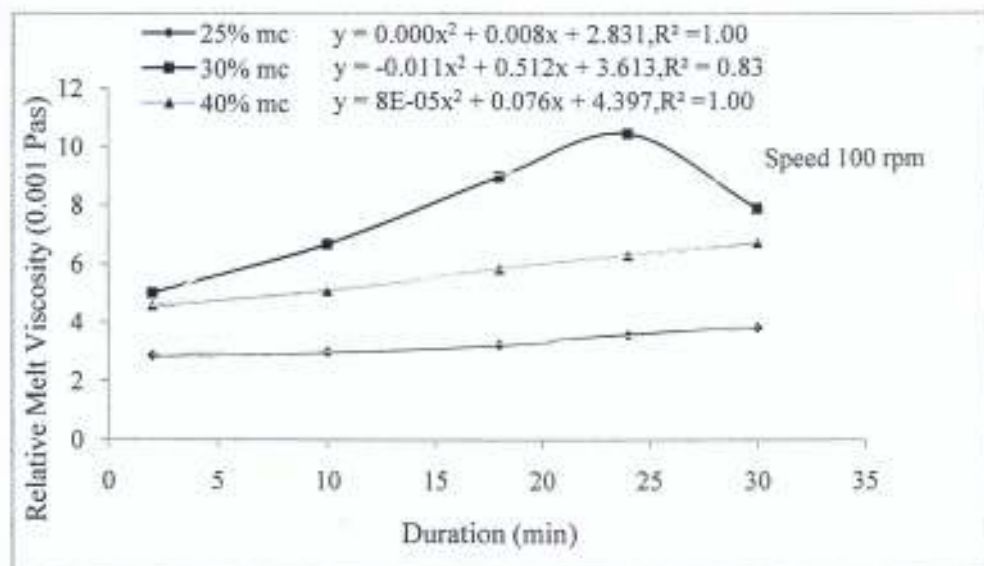


Figure A.15: Relative melt viscosity response of Cassava starch to variable extrusion conditions

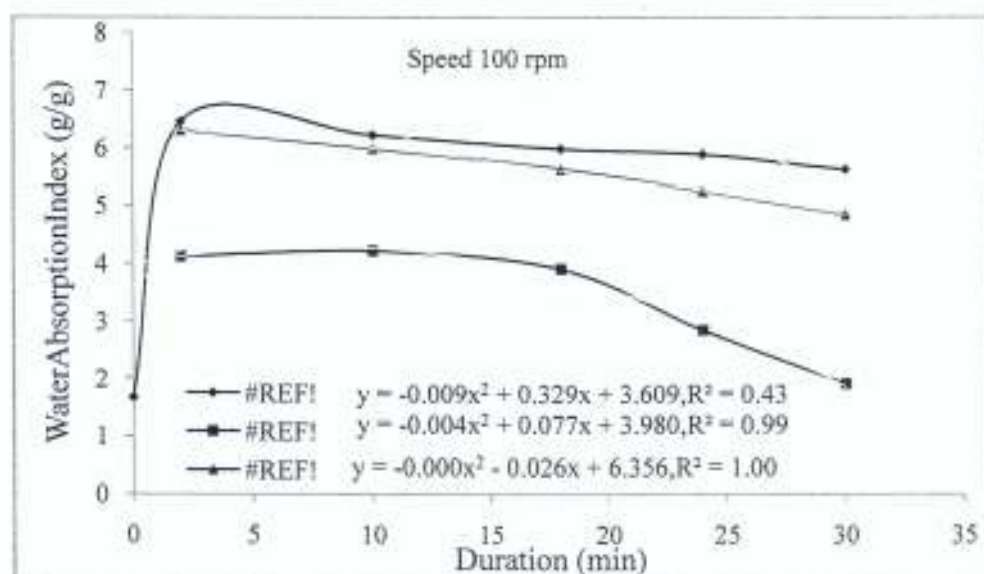


Figure A.16: Water absorption index response of Cassava starch to variable extrusion conditions

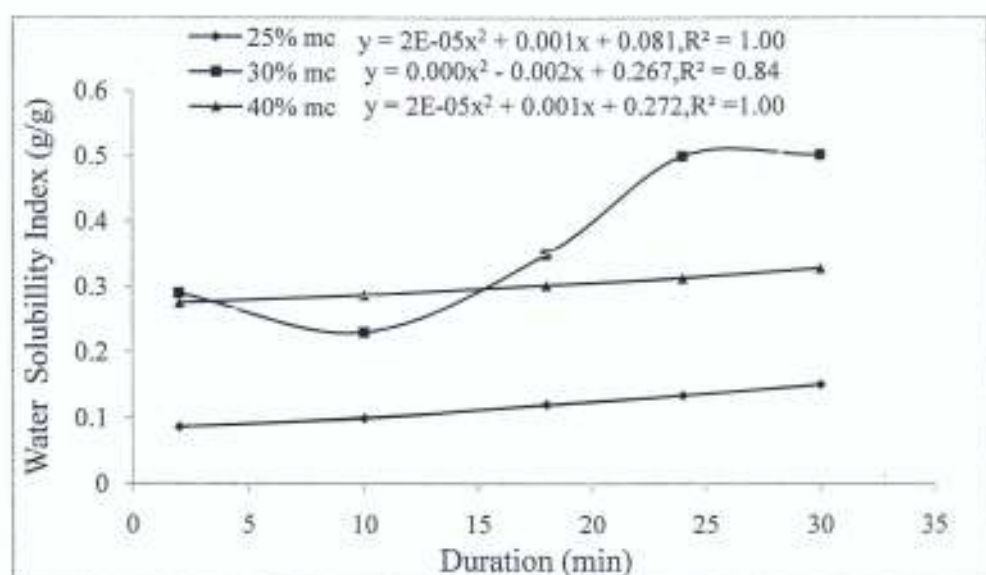


Figure A.17: Water solubility index response of cassava starch to variable extrusion conditions.

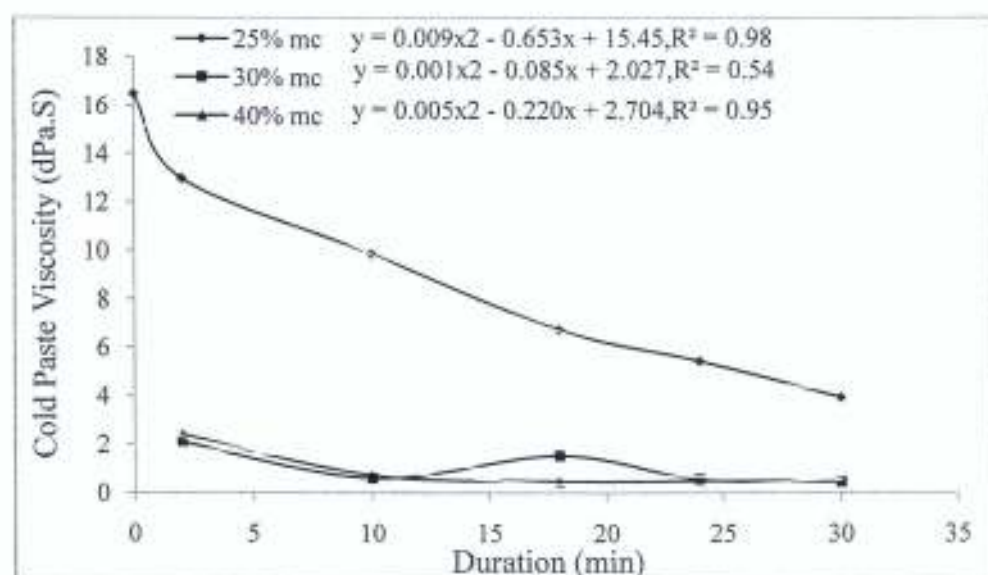


Figure A.18: Cold paste viscosity response of cassava starch to variable extrusion conditions.

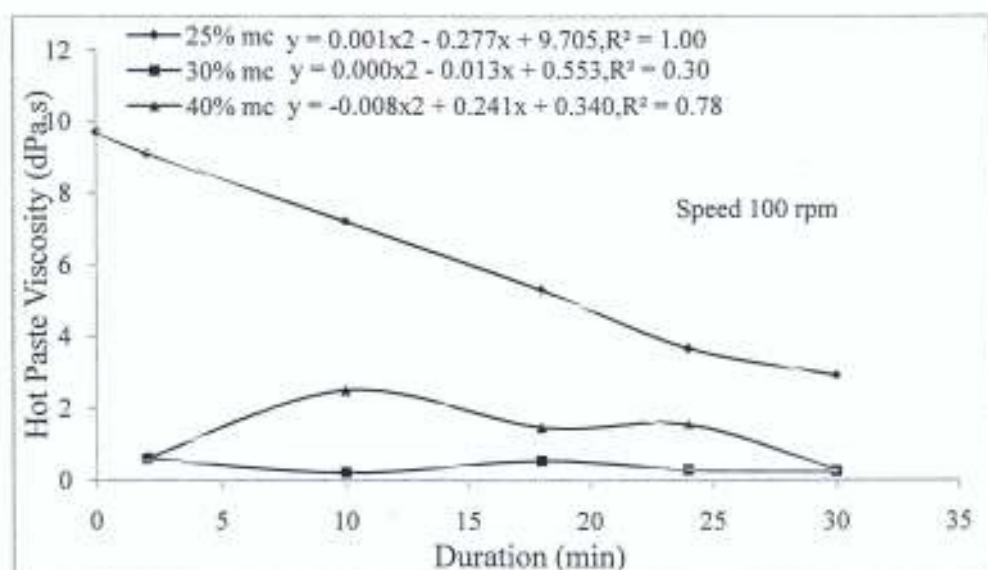


Figure A.19: Hot paste viscosity response of cassava starch to variable extrusion conditions.

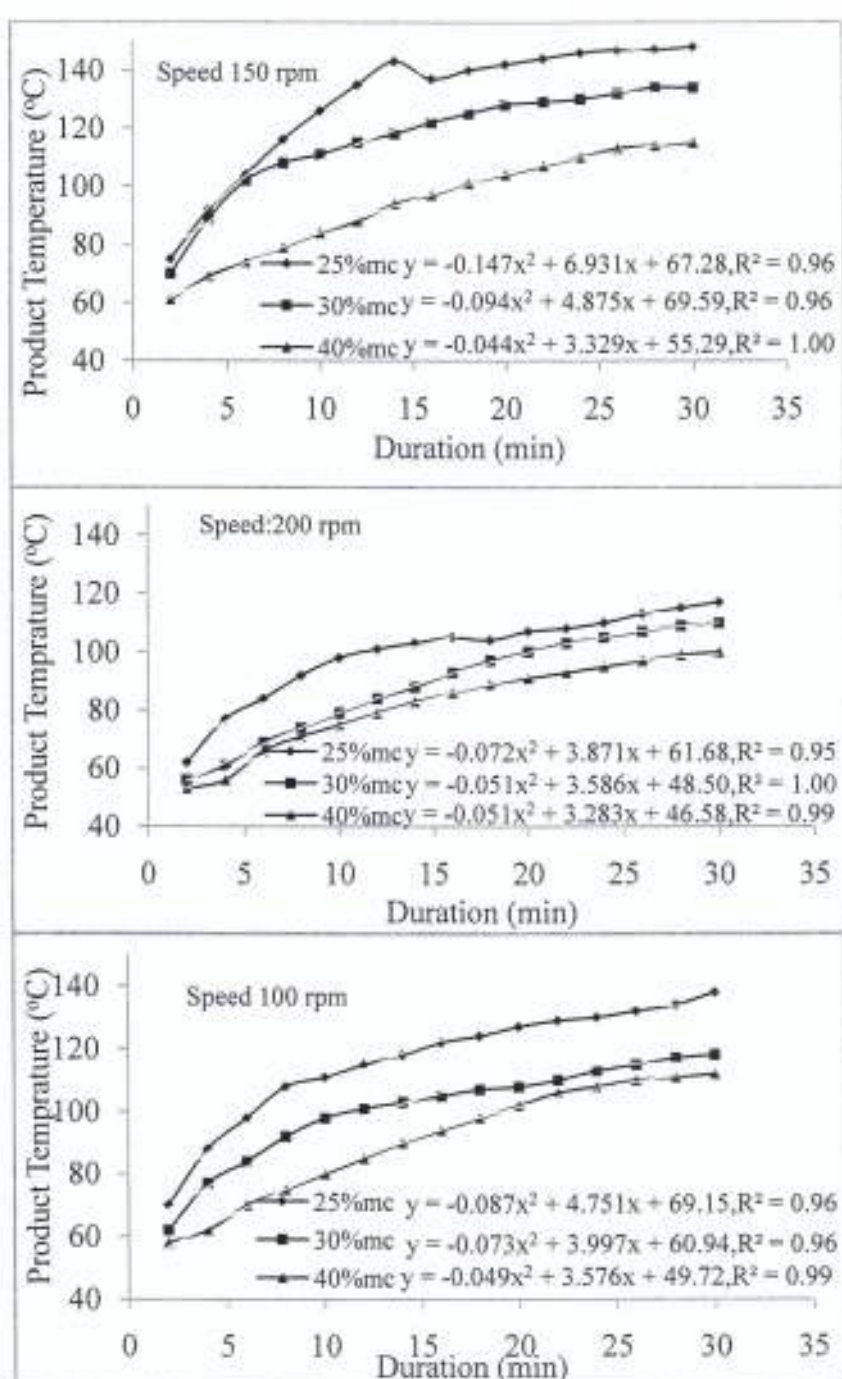


Figure A.20: Product Temperature response of cassava flour to variable extrusion conditions.

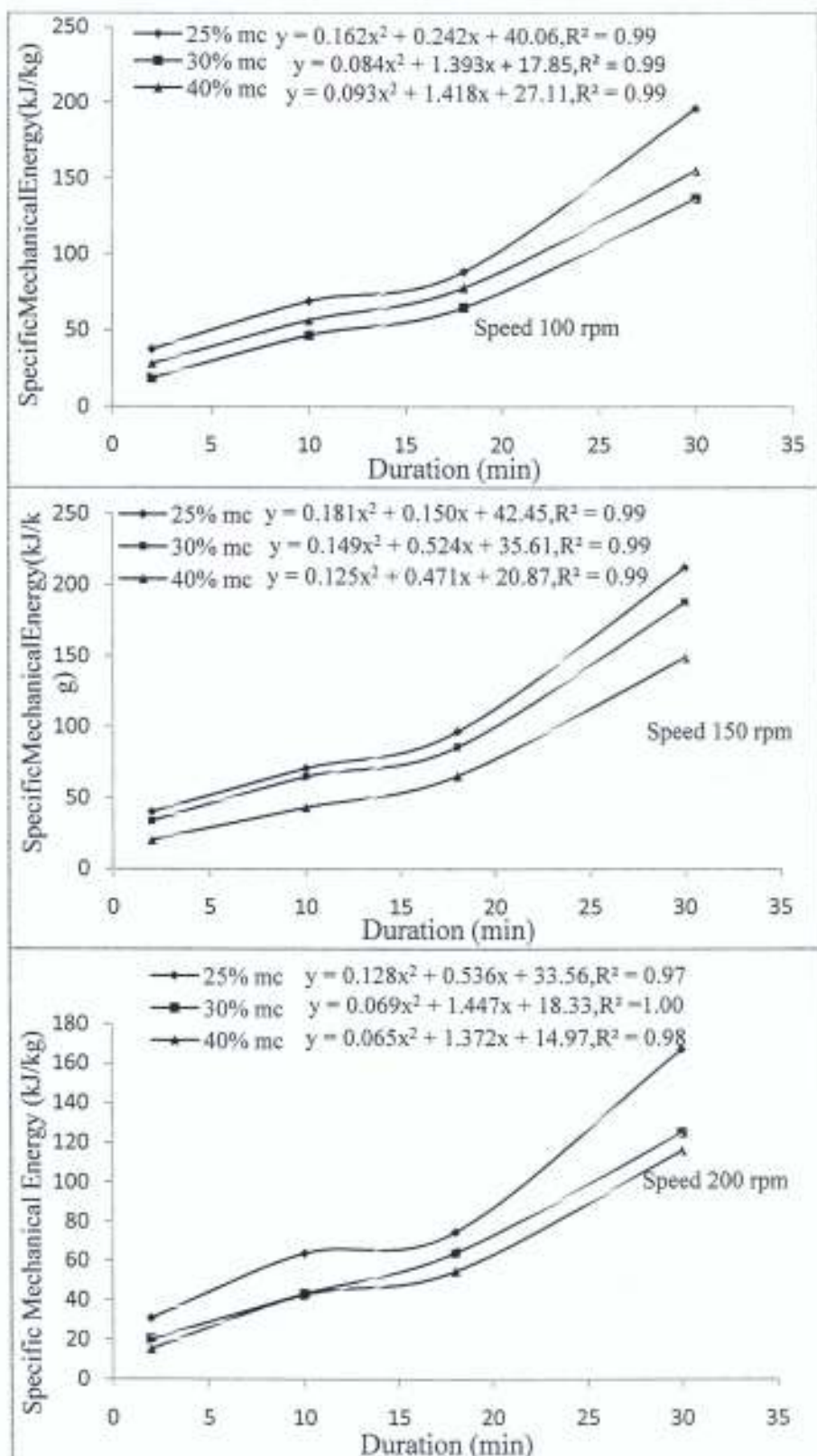


Figure A.21: Specific mechanical energy response of cassava flour to variable extrusion conditions.

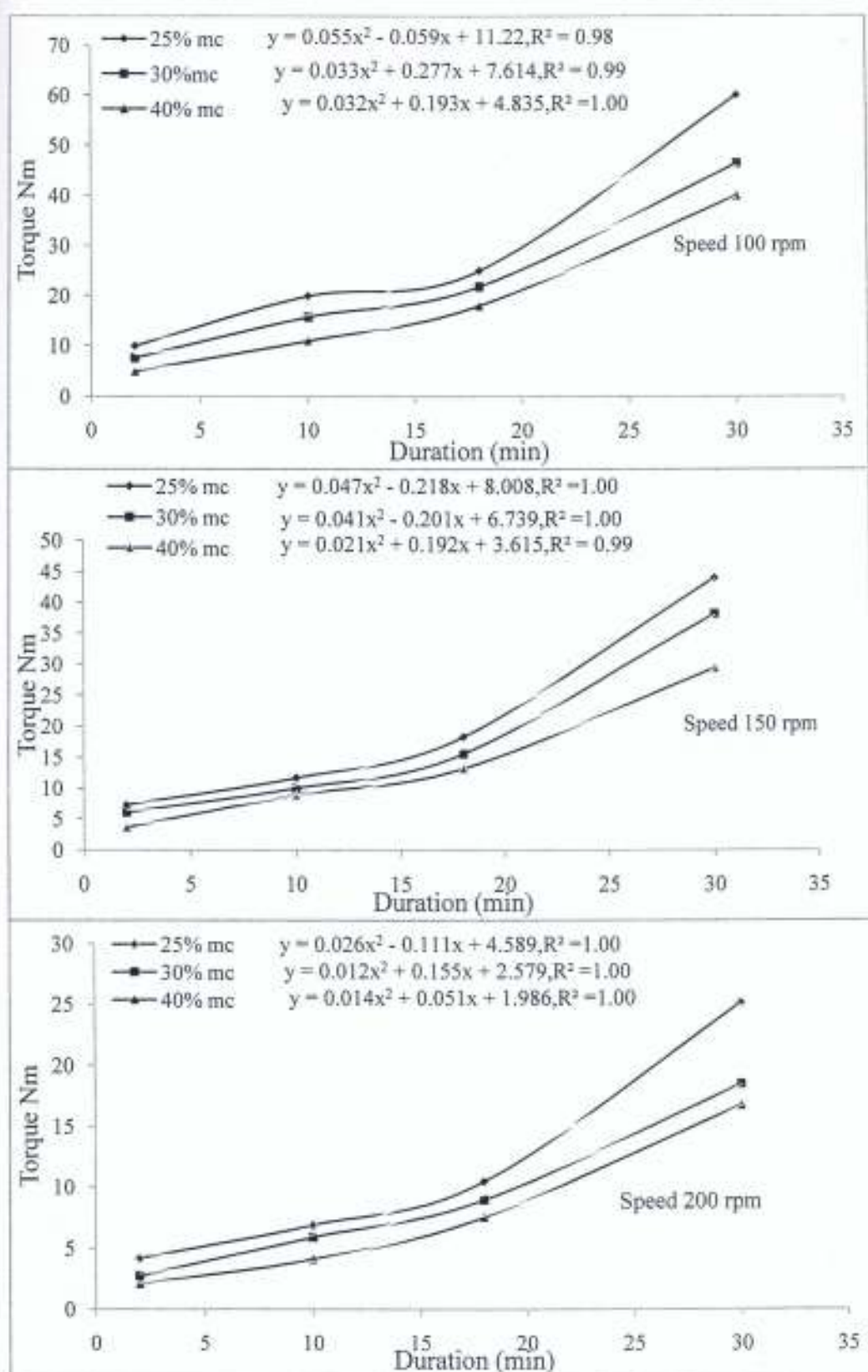


Figure A.22: Motor torque response of Cassava flour to variable extrusion conditions.

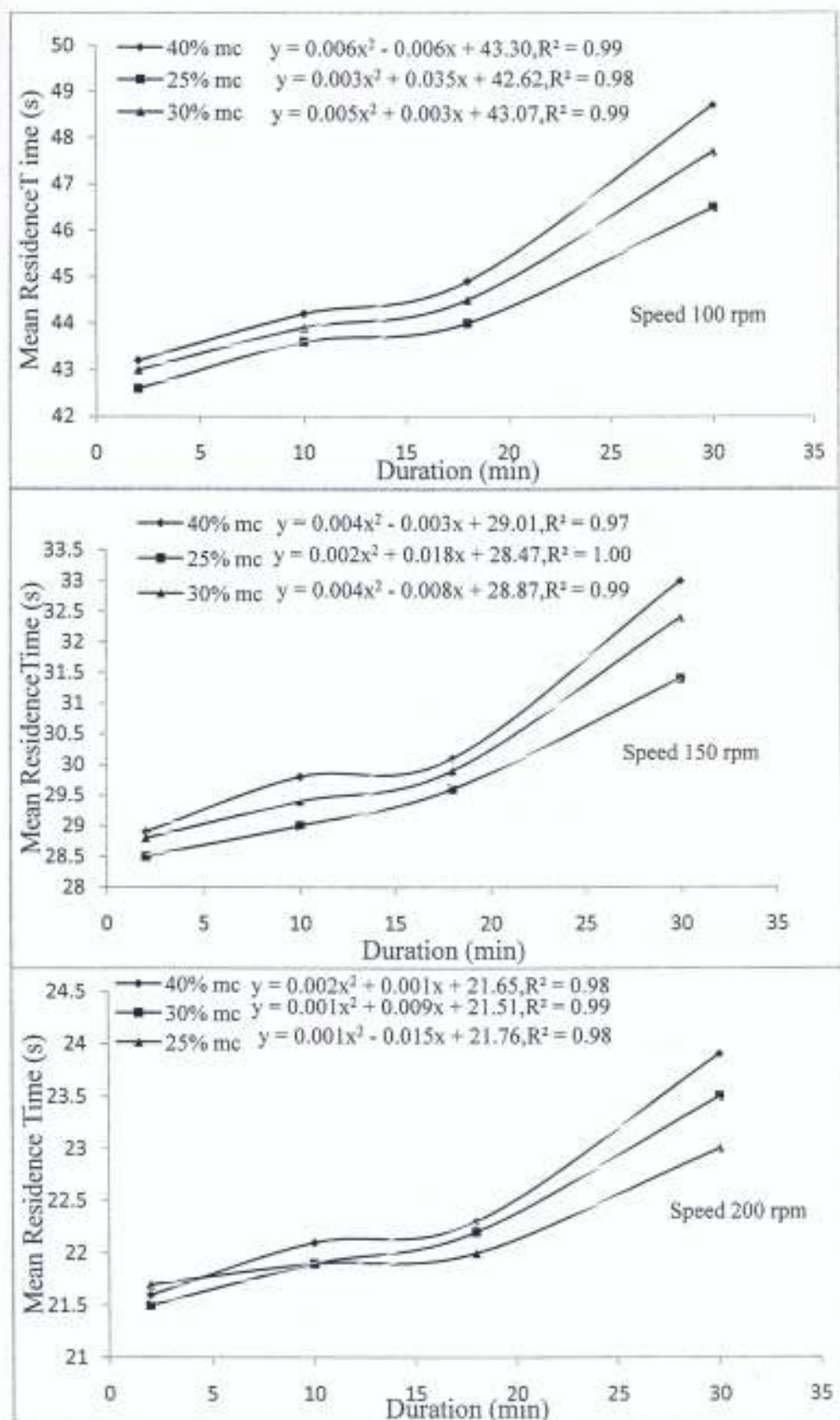


Figure A.23: Mean residence time response of Cassava flour to variable extrusion conditions.

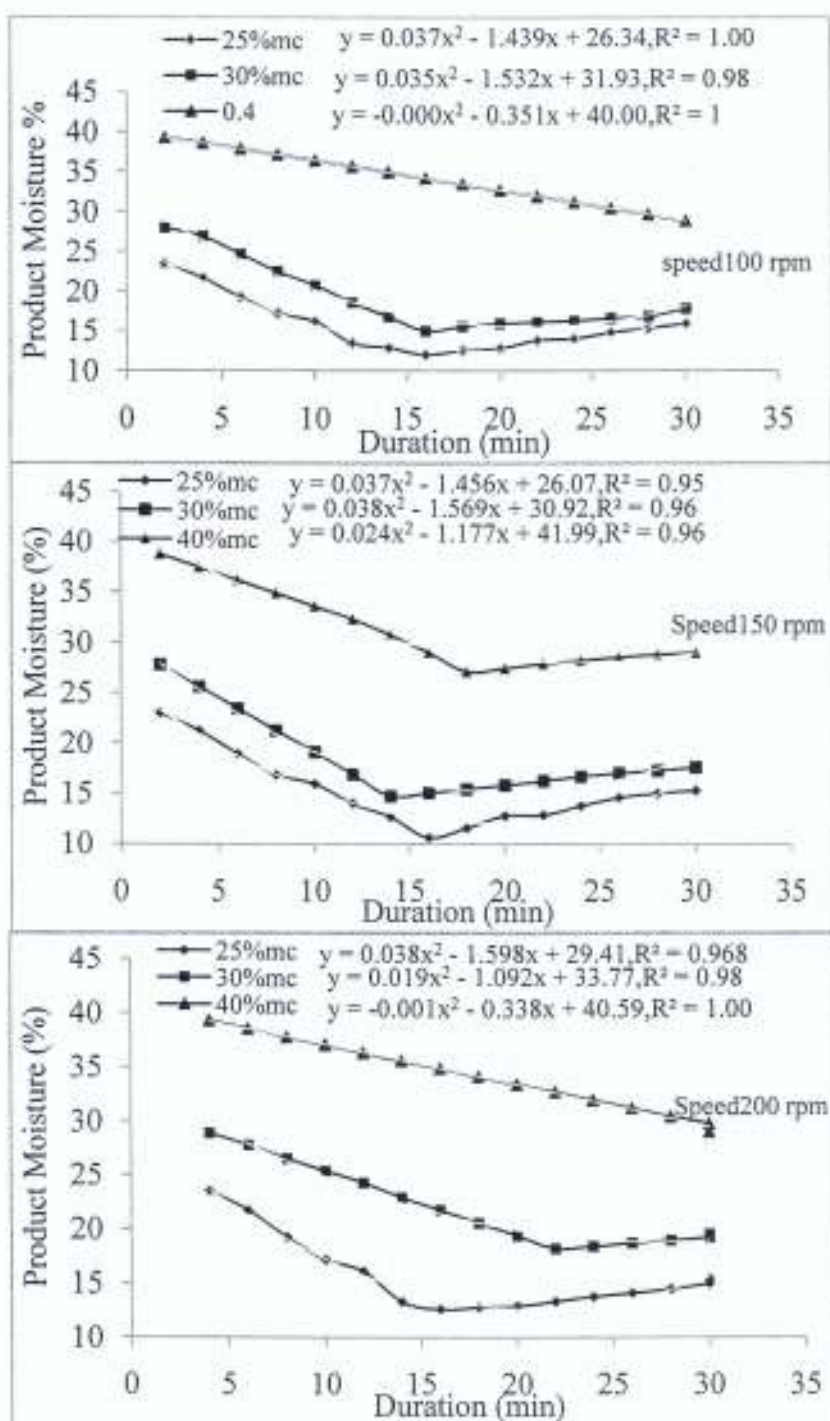


Figure A.24: Product moisture response of cassava flour to variable extrusion conditions.

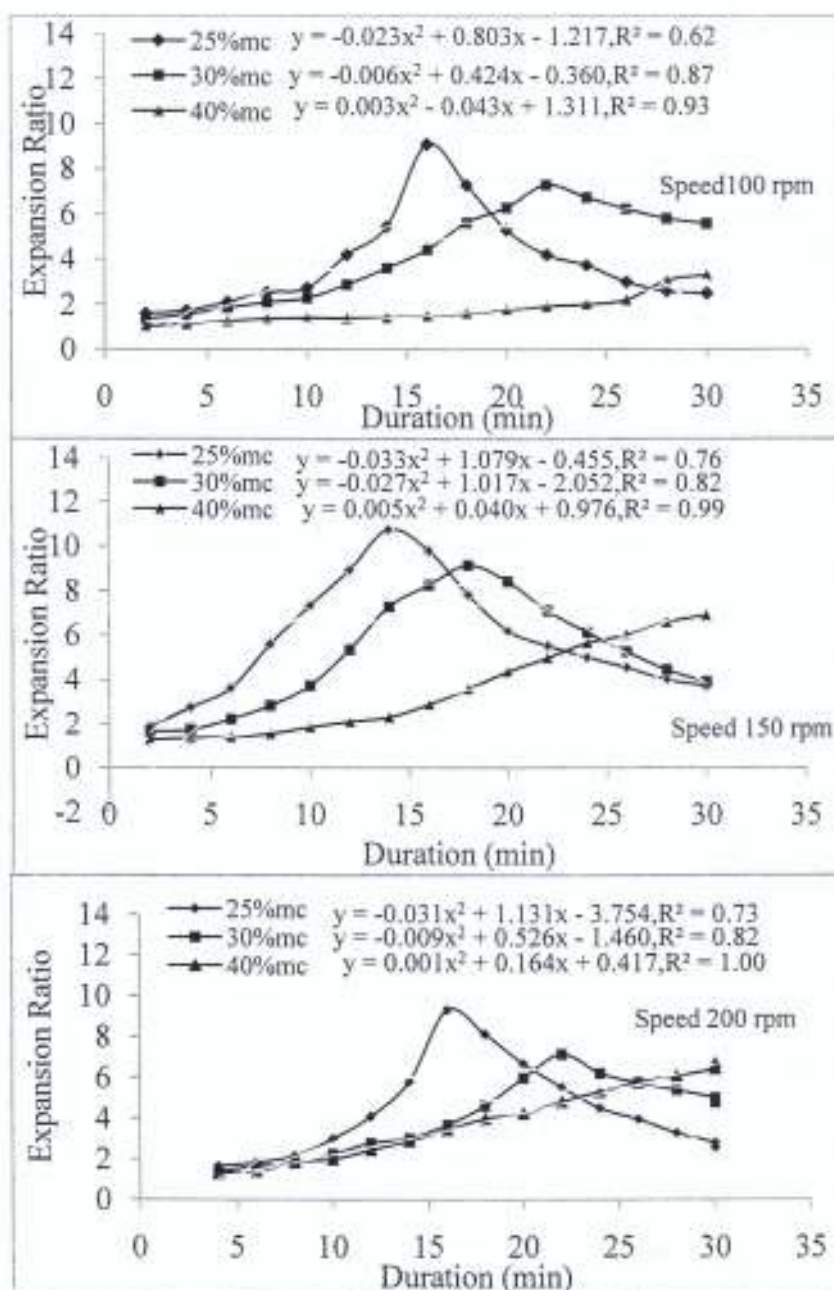


Figure A.25: Expansion ratio response of cassava flour to variable extrusion conditions.

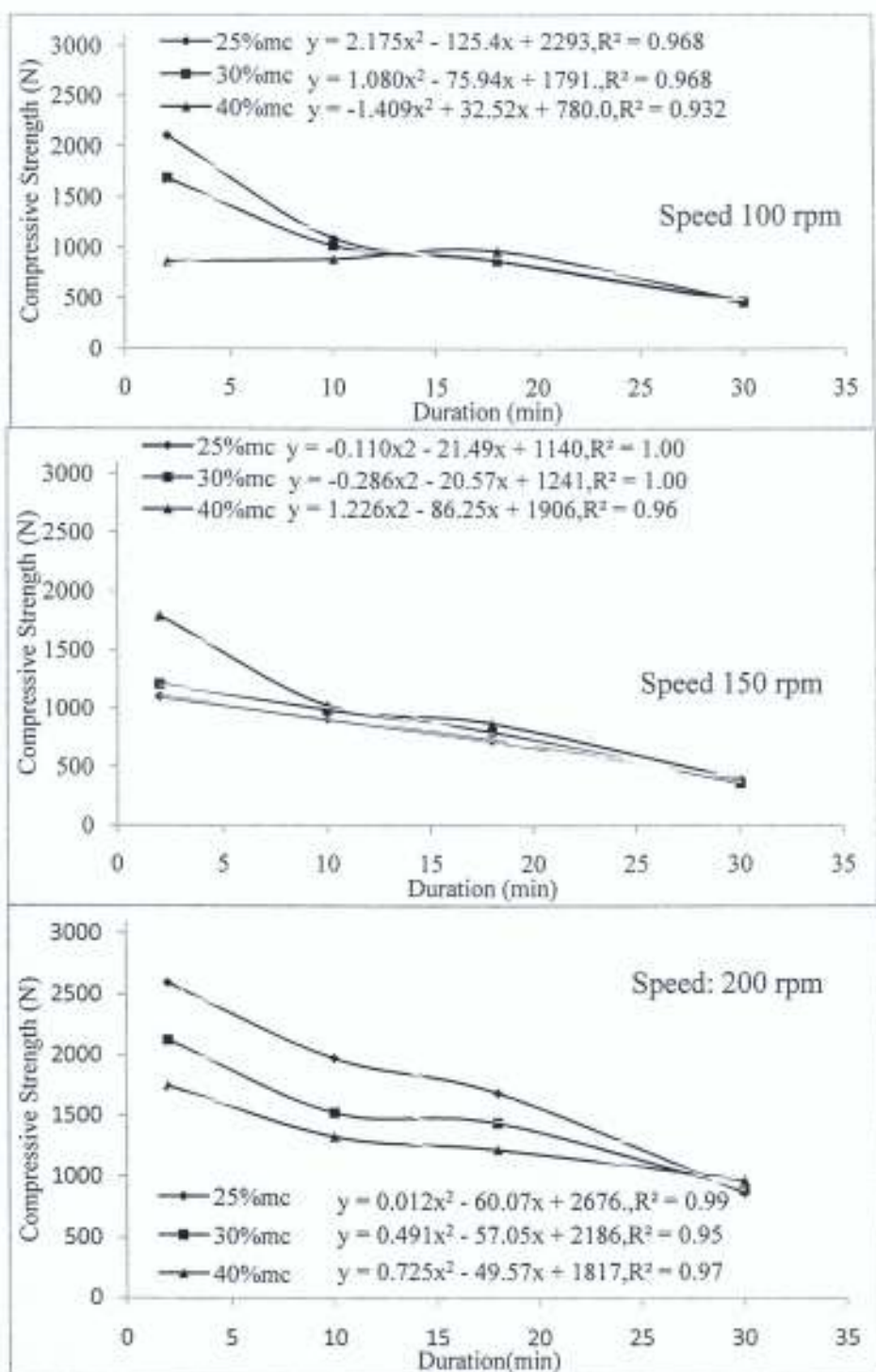


Figure A.26: Compressive strength response of cassava flour to variable extrusion conditions.

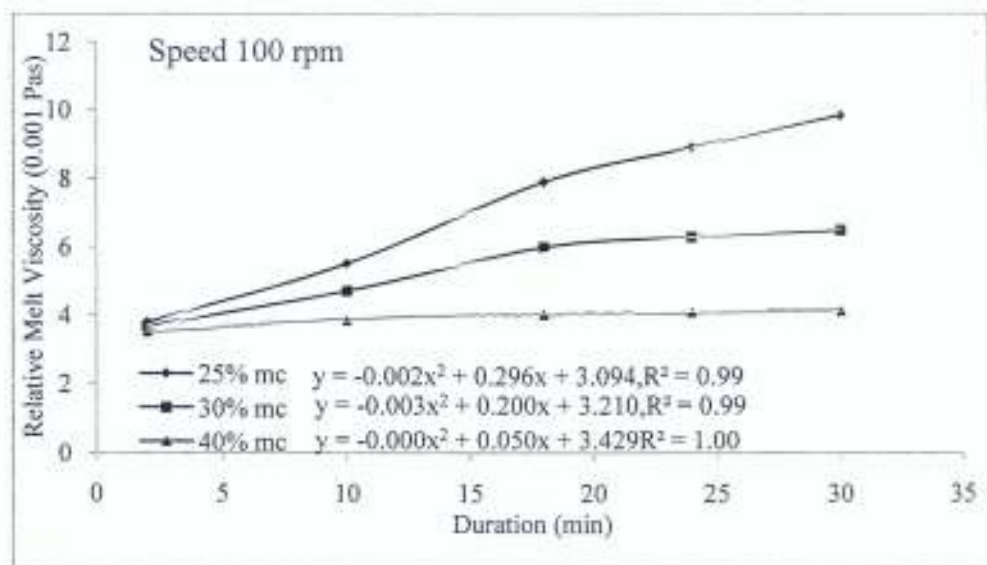


Figure A.27: Relative melt viscosity response of cassava flour to variable extrusion conditions.

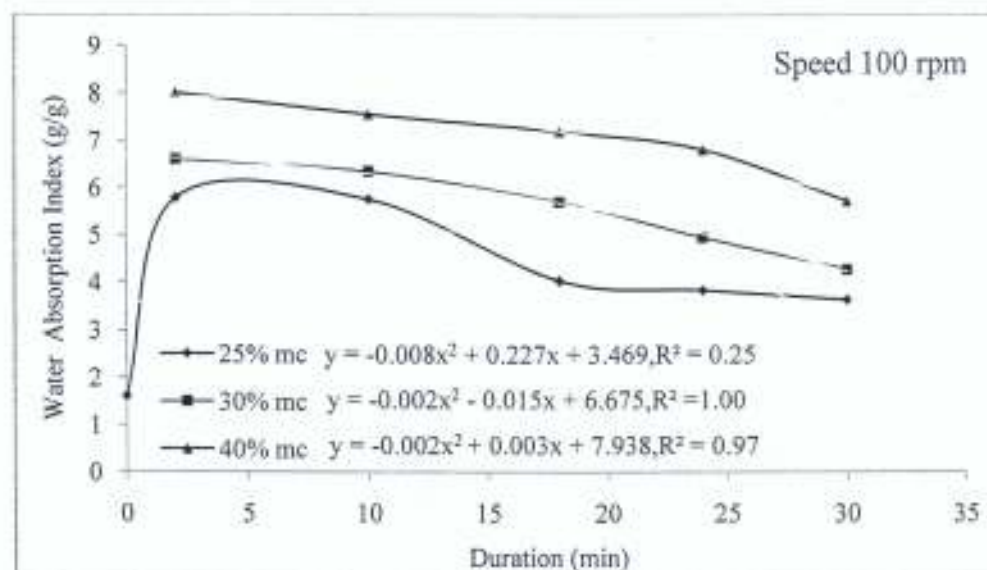


Figure A.28: Water absorption index response of cassava flour to variable extrusion conditions.

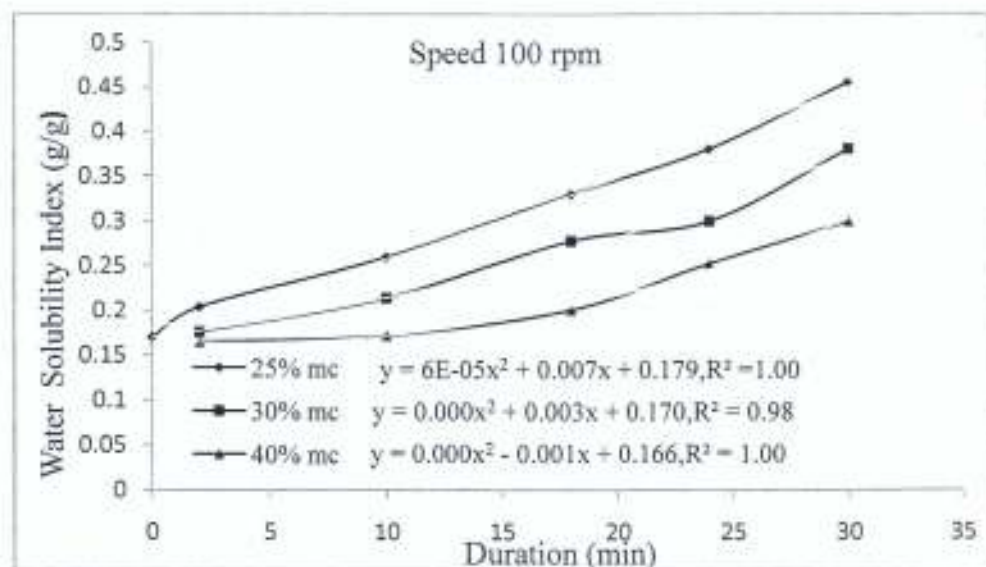


Figure A.29: Water solubility index response of cassava flour to variable extrusion conditions.

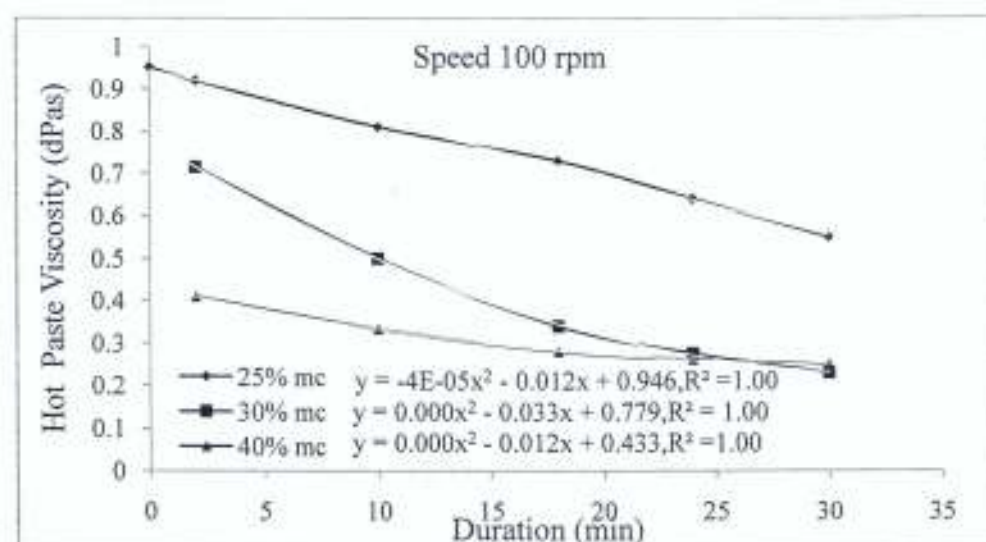


Figure A.30: Variation of hot paste viscosity with duration of sampling for cassava flour at different moisture contents.

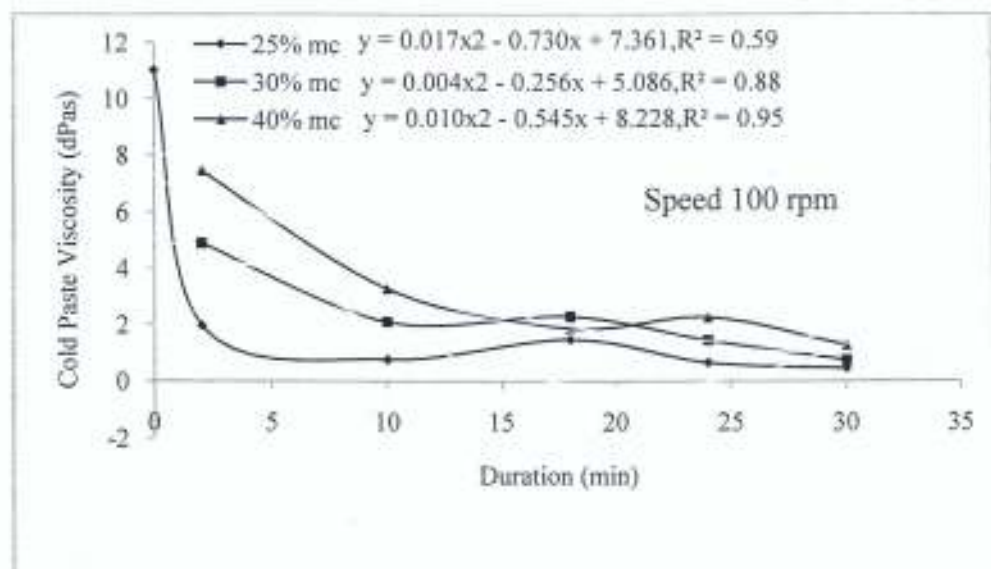


Figure A.31: Variation of cold paste viscosity with duration of sampling for cassava flour.

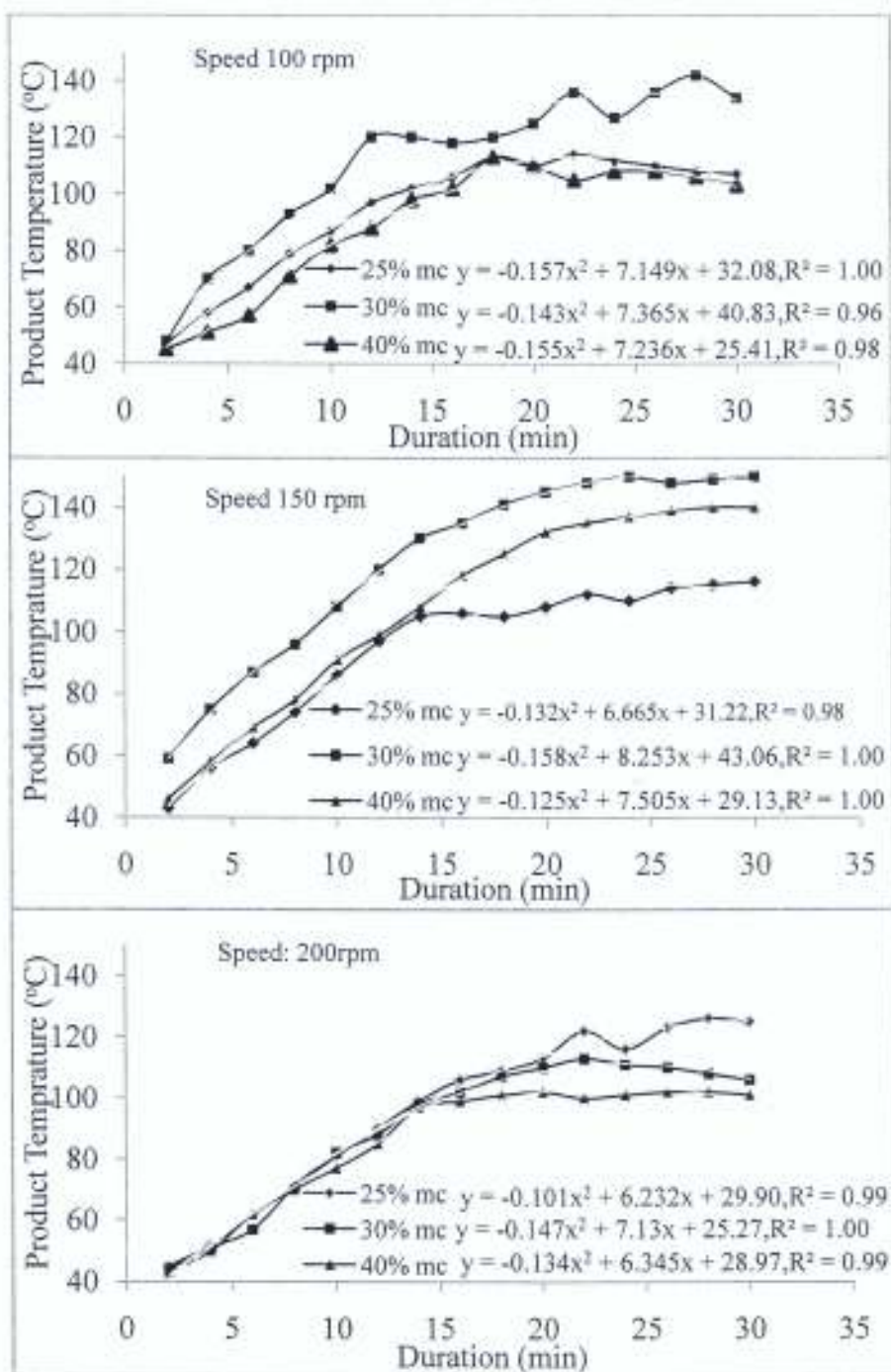


Figure A.32: Product temperature response of maize starch to variable extrusion conditions

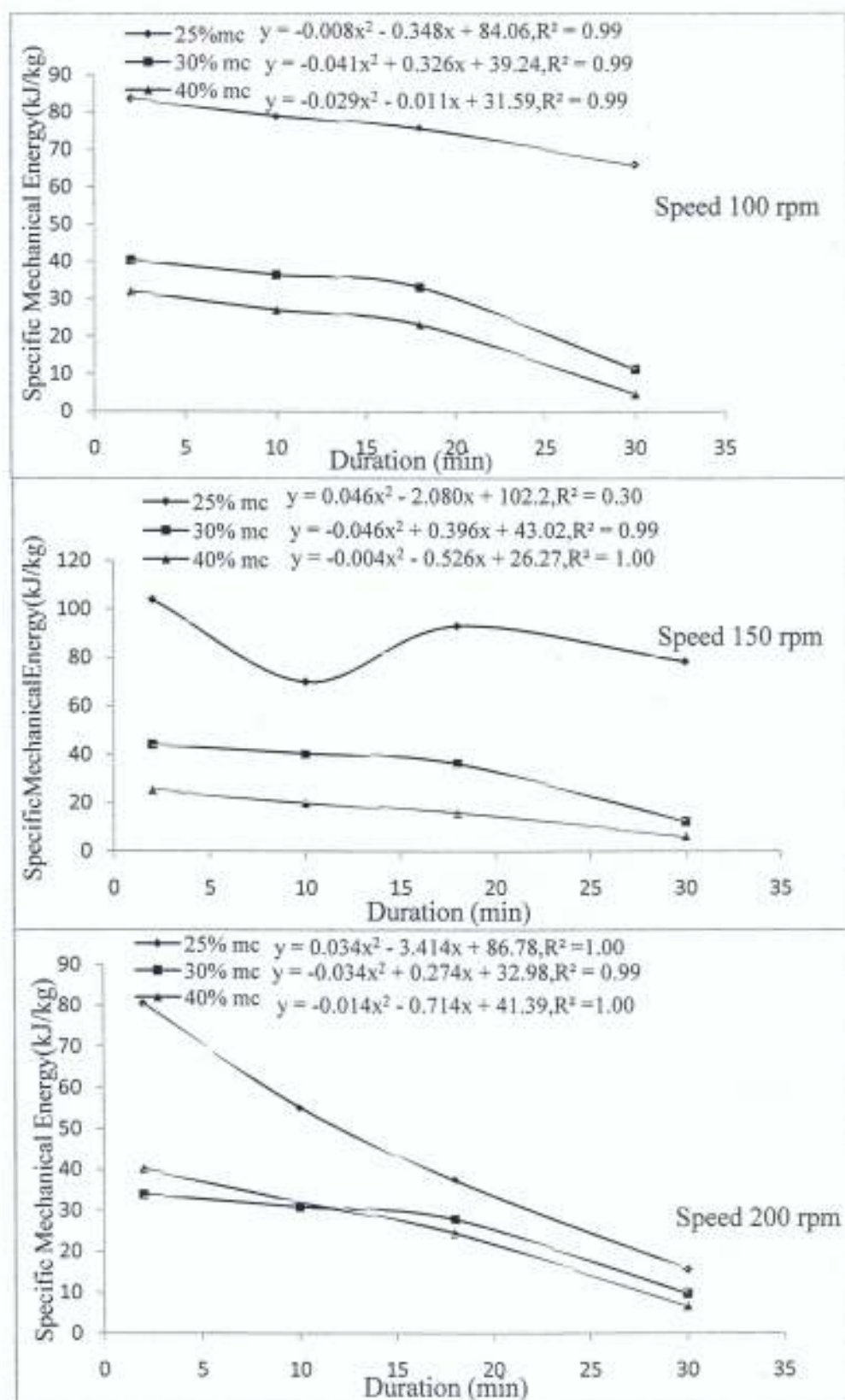


Figure A.33: Specific mechanical energy response of maize starch to variable extrusion conditions.

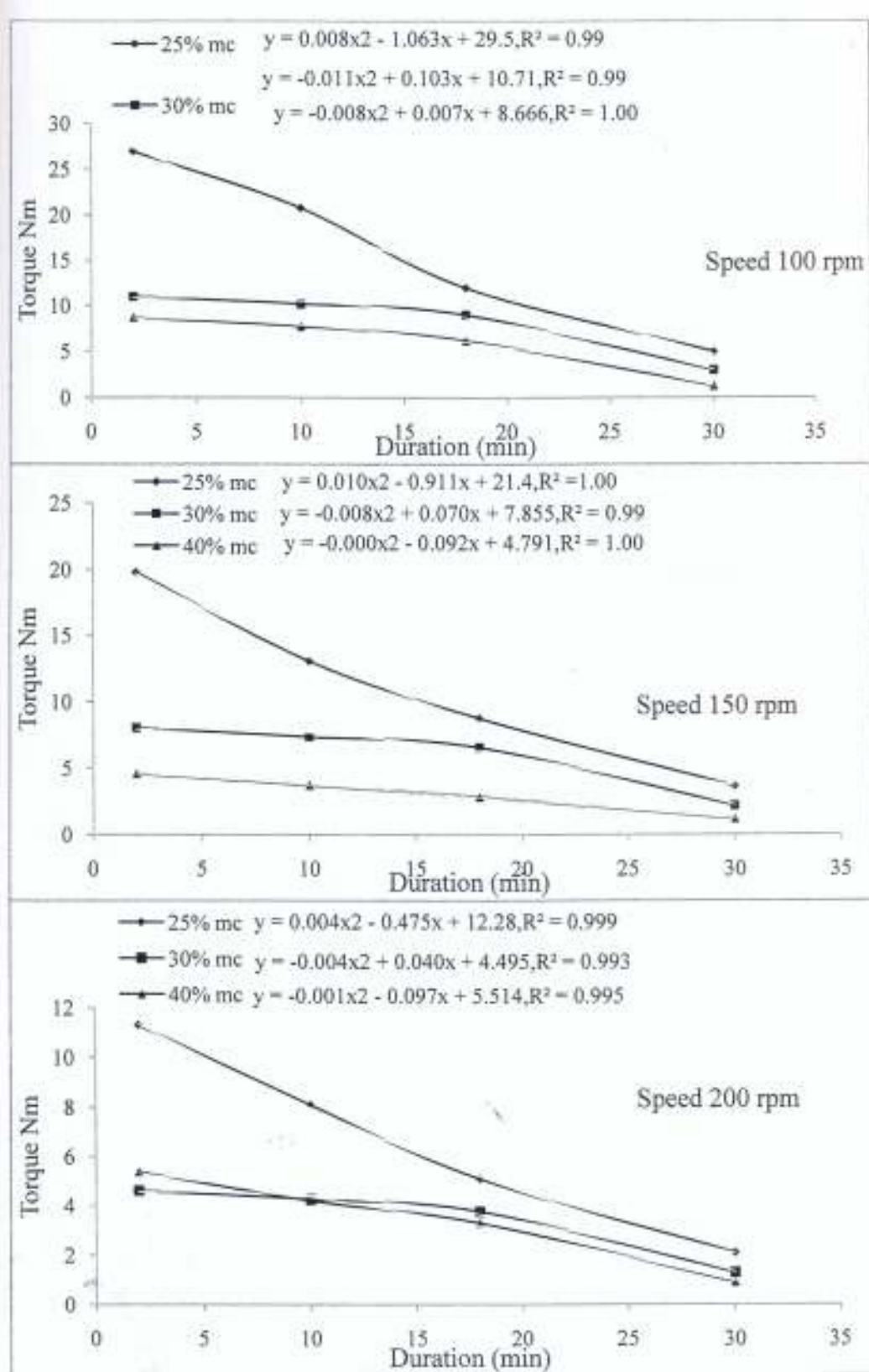


Figure A.34: Motor torque response of maize starch to variable extrusion conditions.

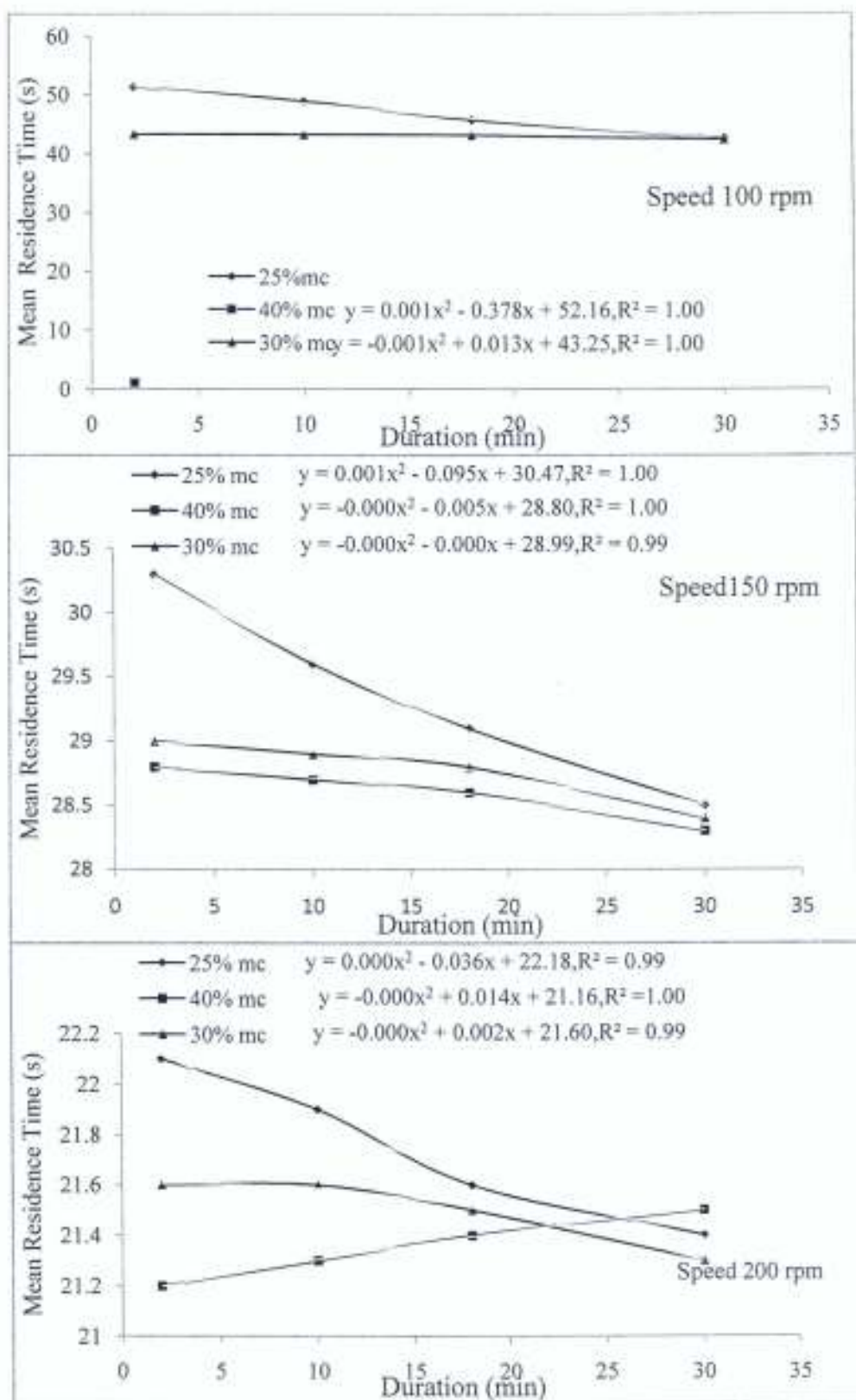


Figure A.35: Mean residence time response of maize starch to variable extrusion conditions.

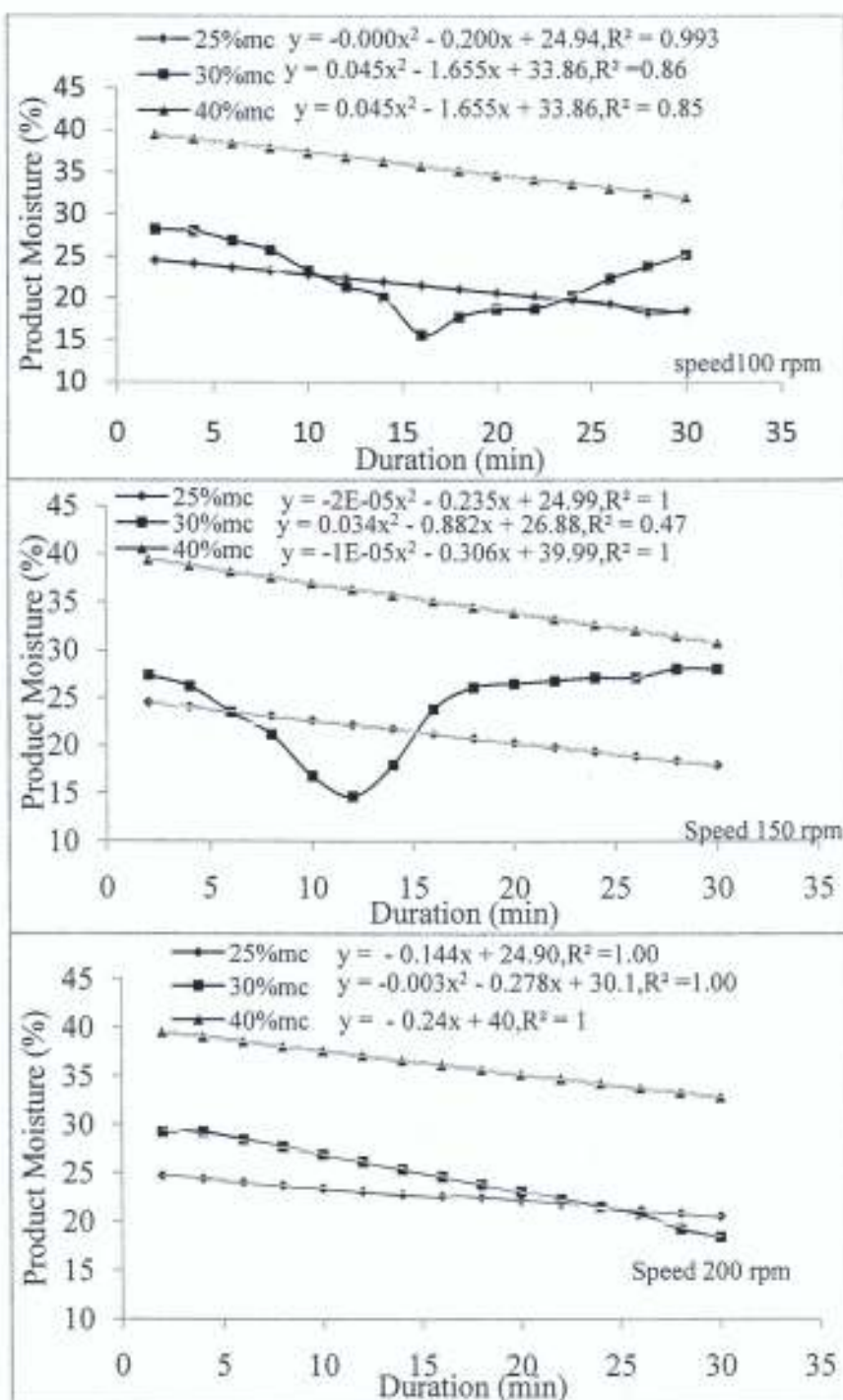


Figure A.36: Product moisture response of maize starch to variable extrusion conditions.

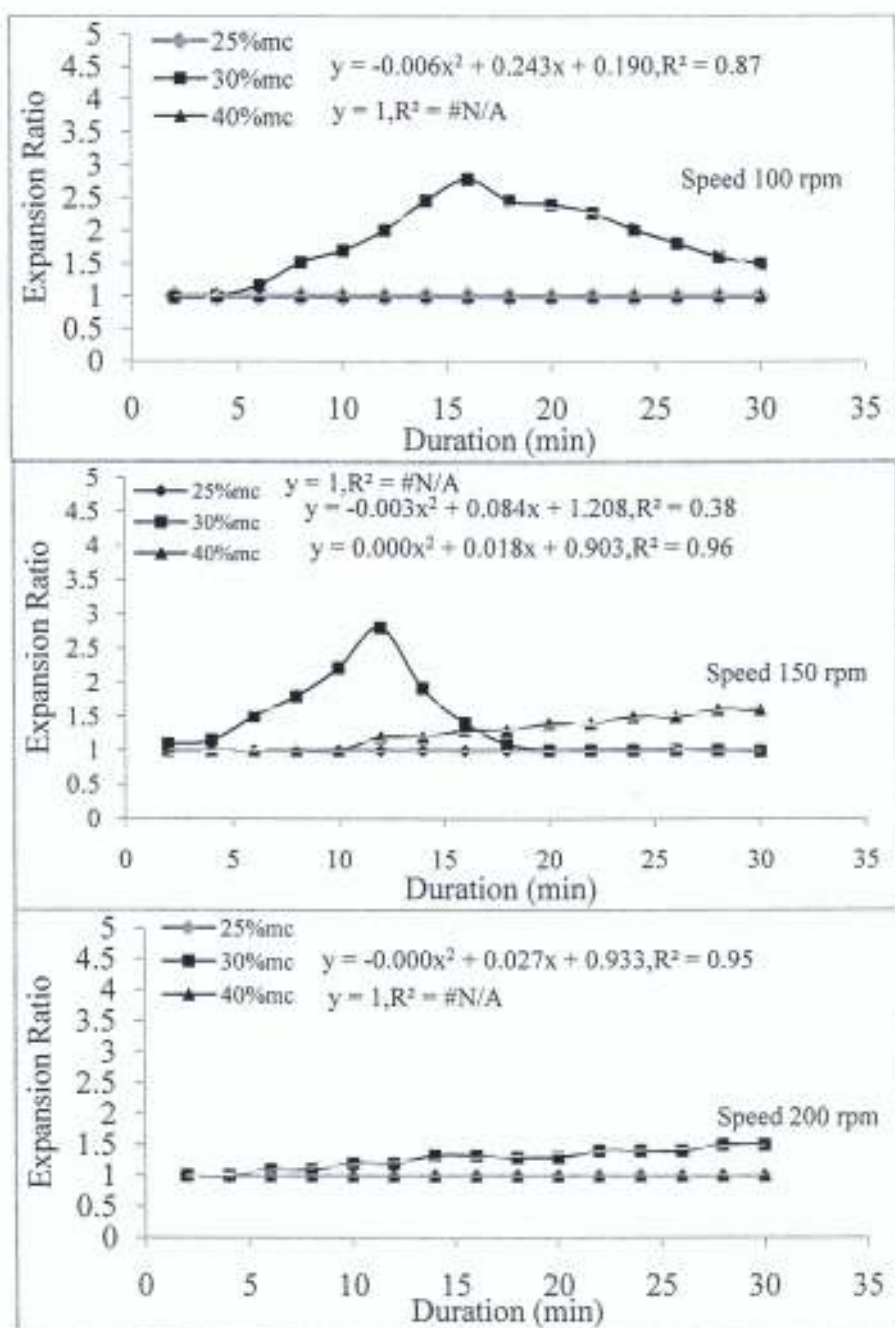


Figure A.37: Expansion ratio response of maize starch to variable extrusion conditions.

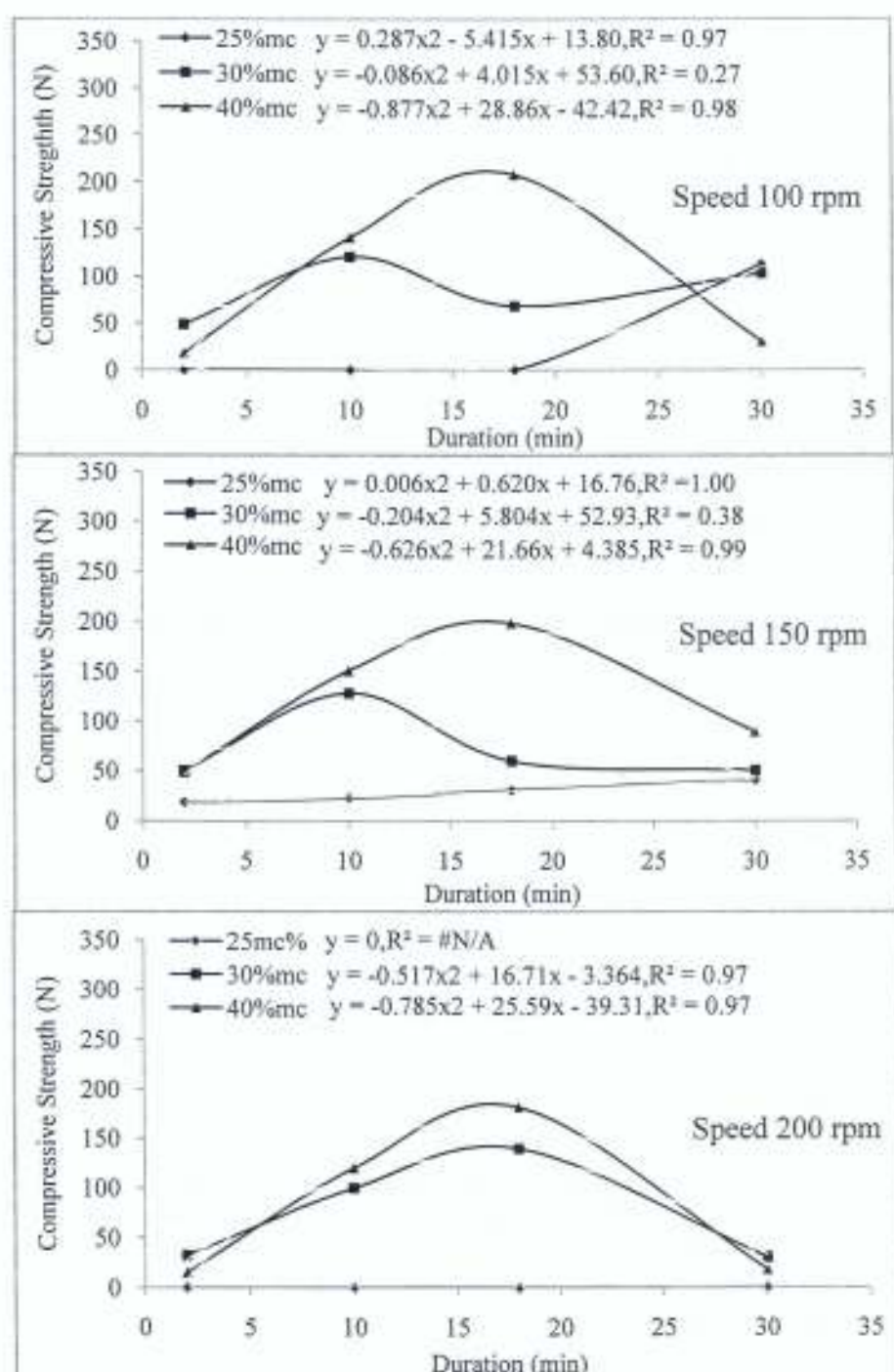


Figure A.38: Compressive strength response of maize starch to variable extrusion conditions.

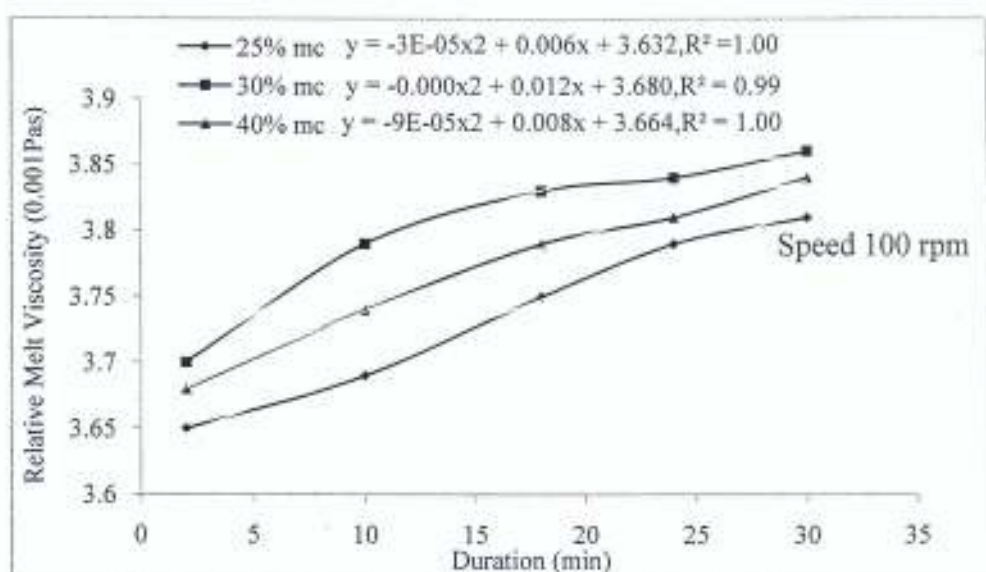


Figure A.39: Relative melt viscosity response of maize starch to variable extrusion conditions.

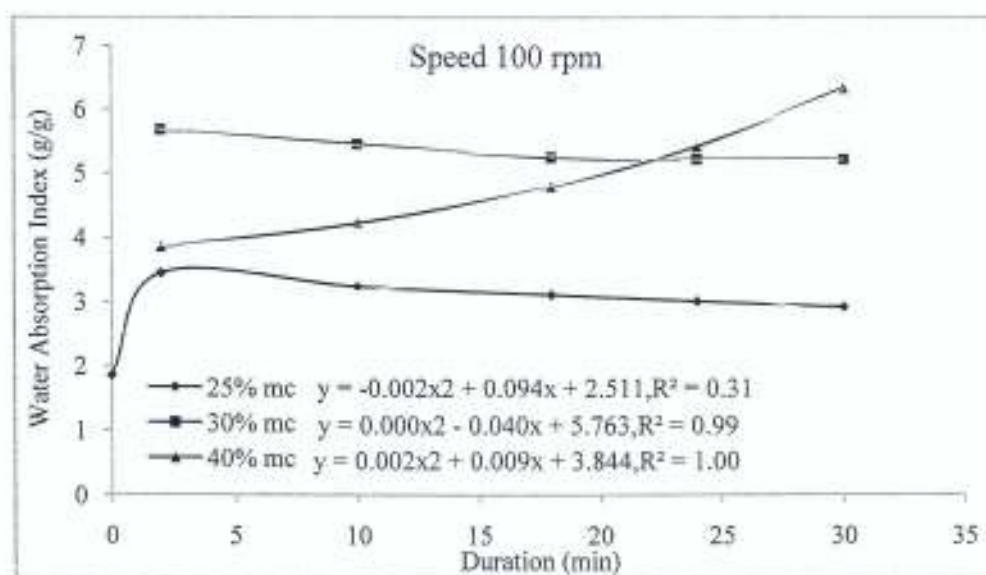


Figure A.40: Water absorption index response of maize starch to variable extrusion conditions.

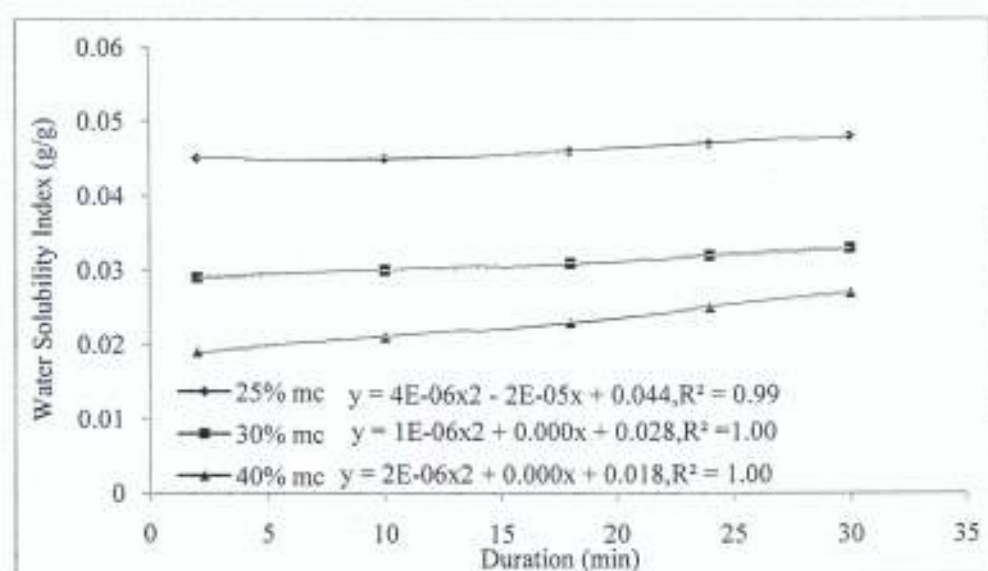


Figure A.41: Water solubility index response of maize starch to variable extrusion conditions.

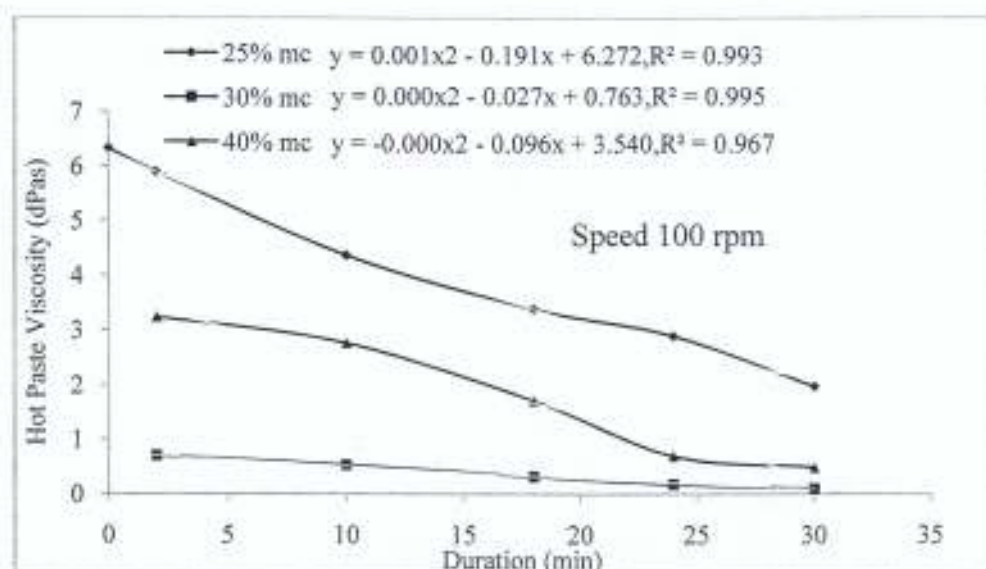


Figure A.42 Hot paste viscosity response of maize starch to variable extrusion conditions.

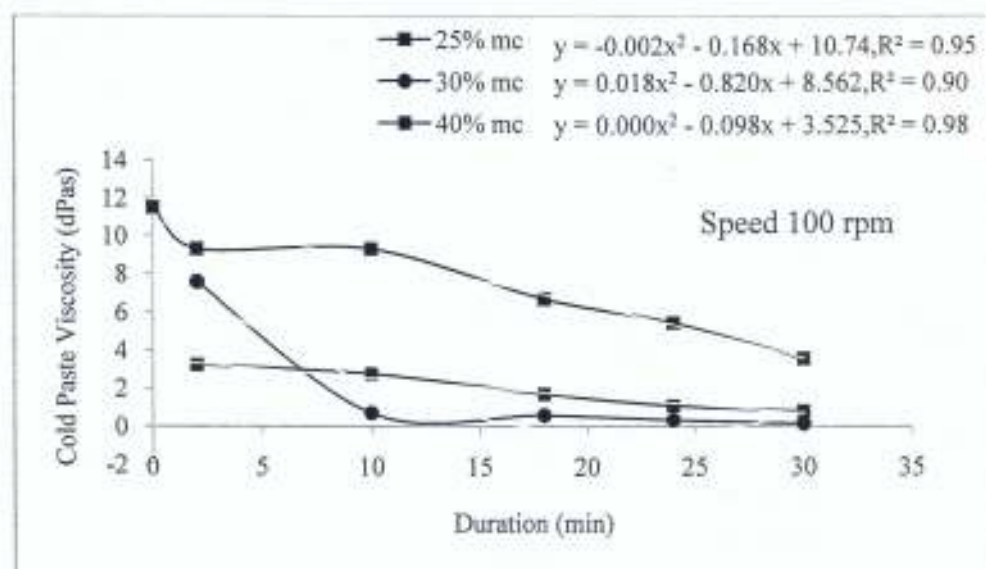


Figure A.43: Cold paste viscosity response of maize starch to variable extrusion conditions.

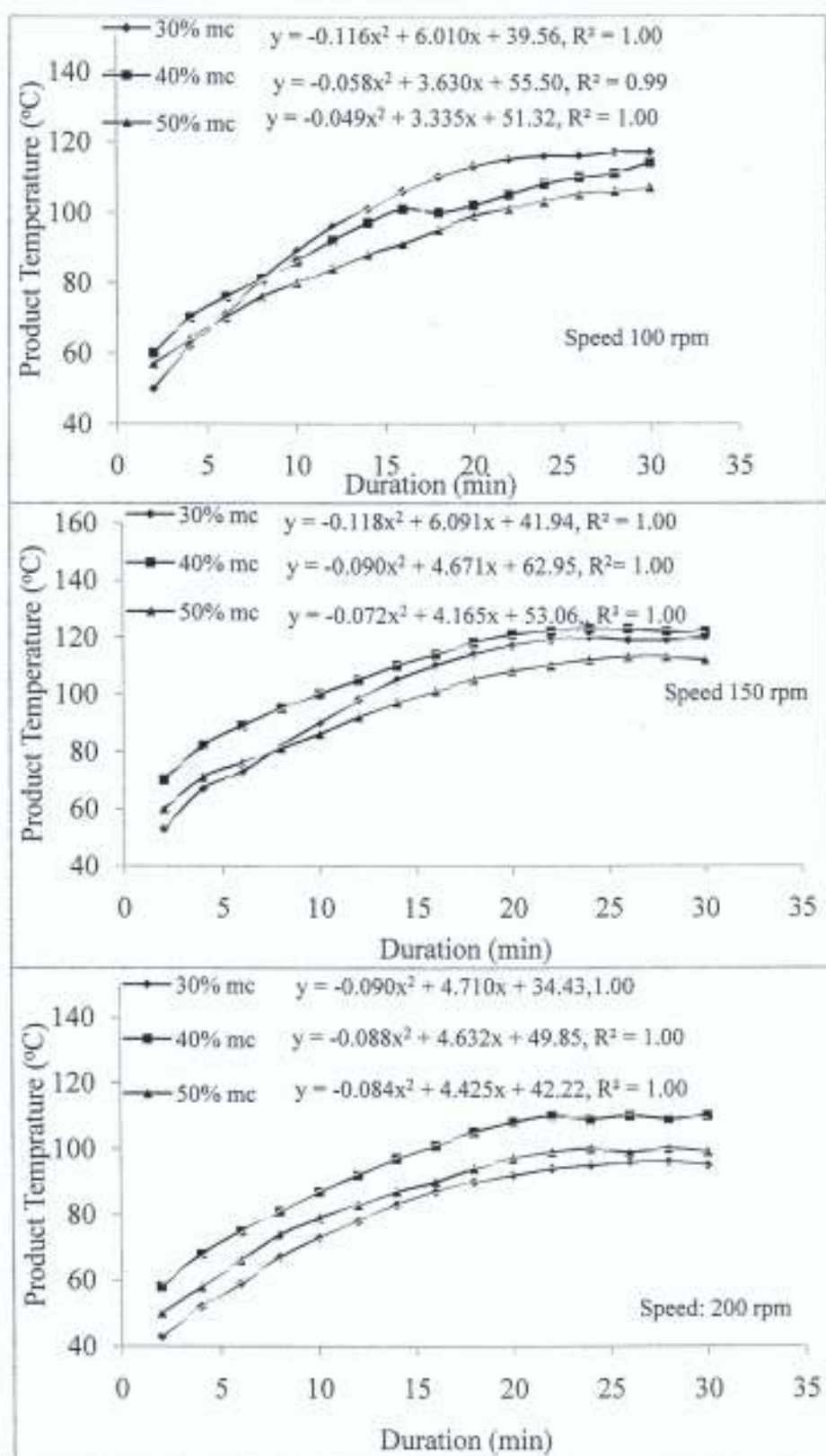


Figure A.44: Product temperature response of maize flour to variable extrusion conditions.

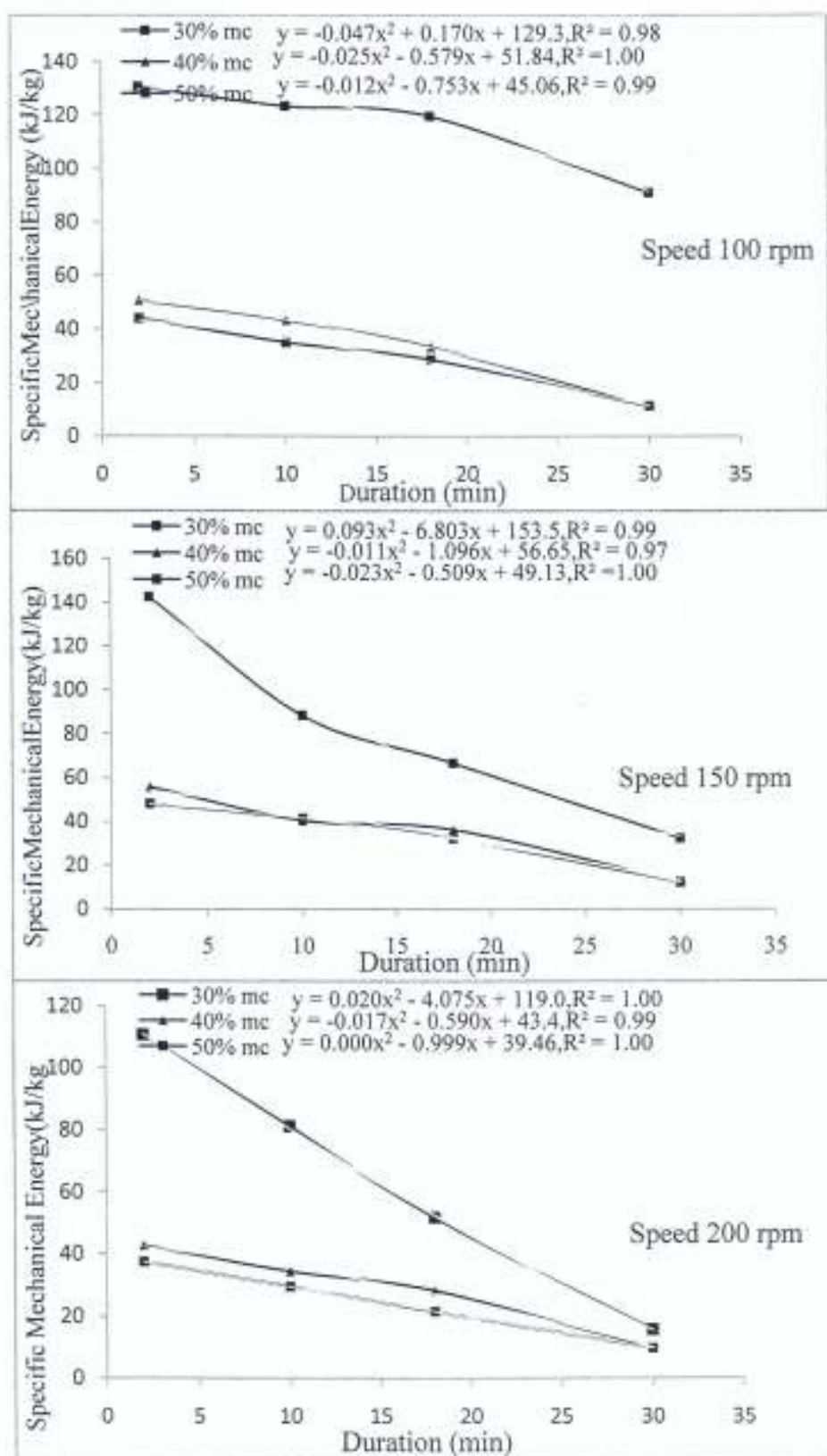


Figure A.45: Specific mechanical energy response of maize flour to variable extrusion conditions.

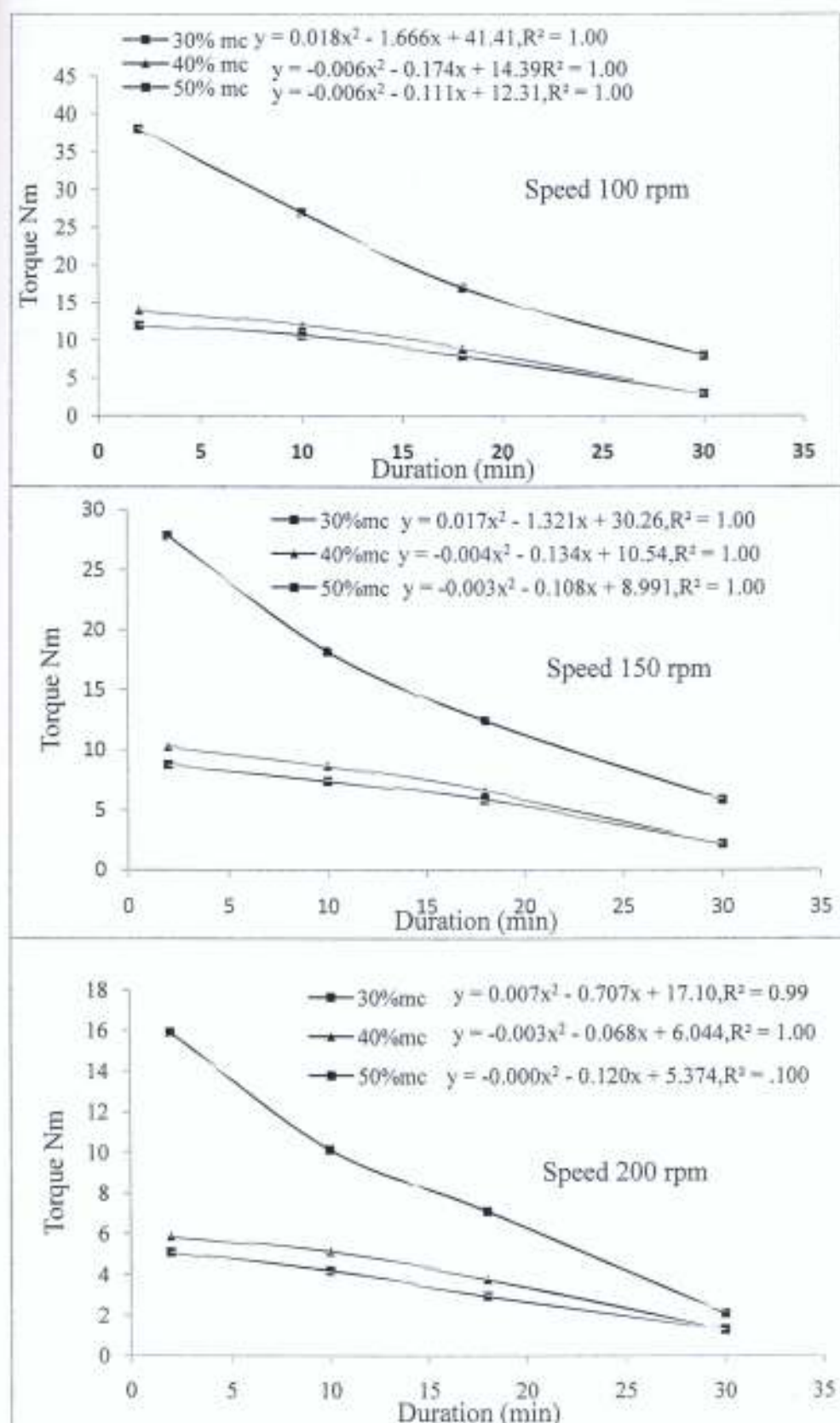


Figure A.46: Motor torque response of maize flour to variable extrusion conditions.

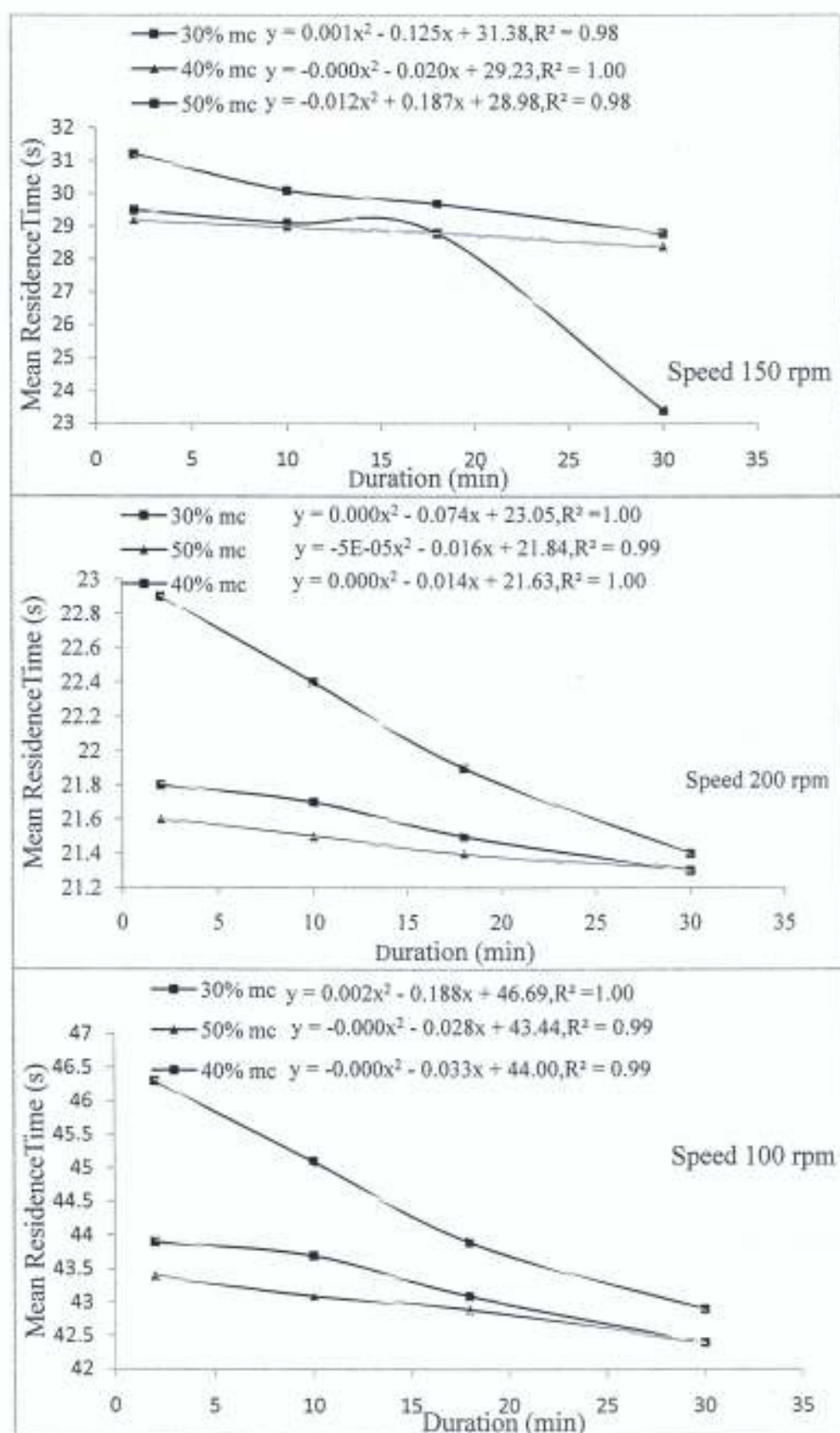


Figure A.47: Mean residence time response of maize flour to variable extrusion conditions.

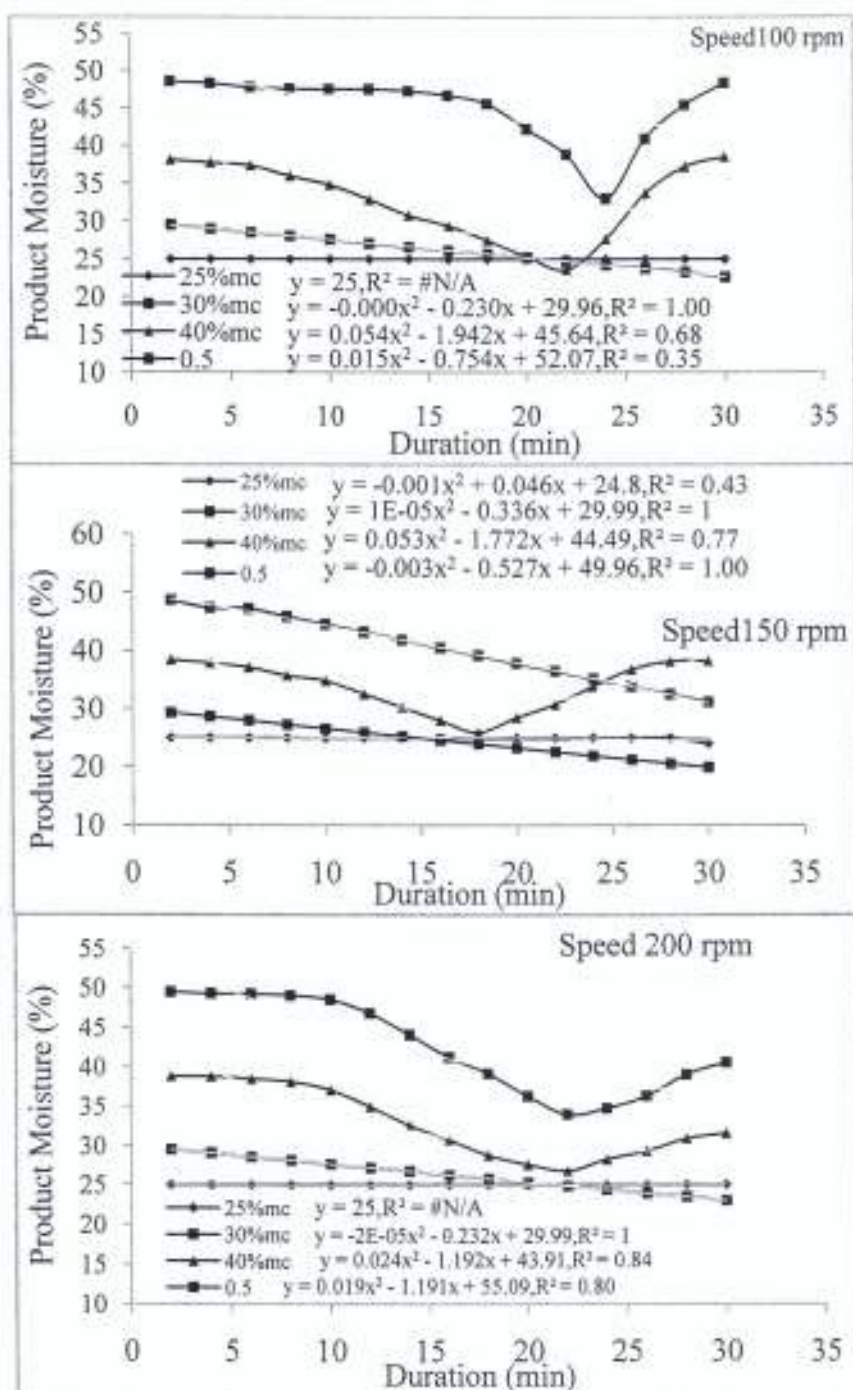


Figure A.48: Product moisture response of maize flour to variable extrusion conditions.

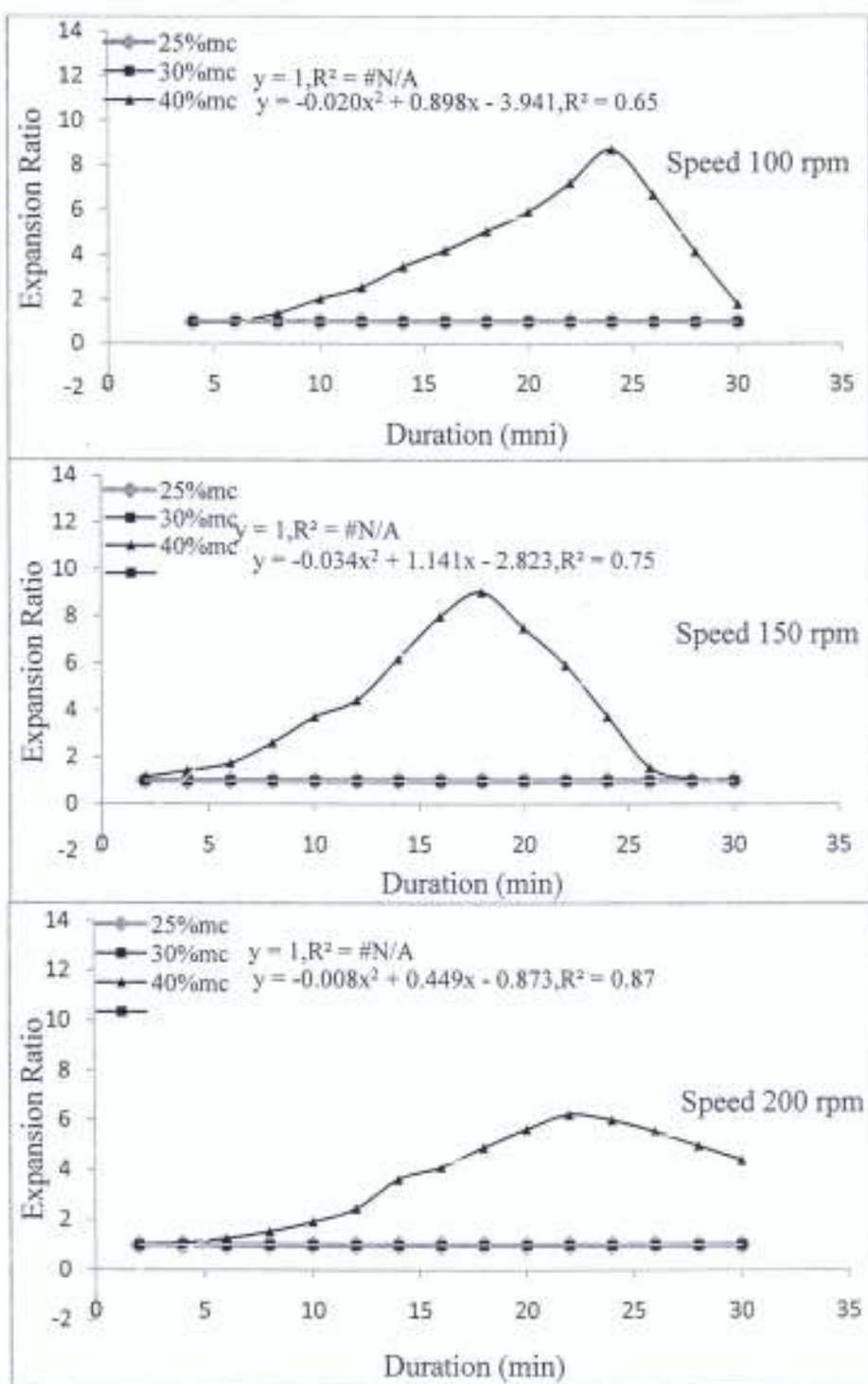


Figure A.49: Expansion ratio response of maize flour to variable extrusion conditions.

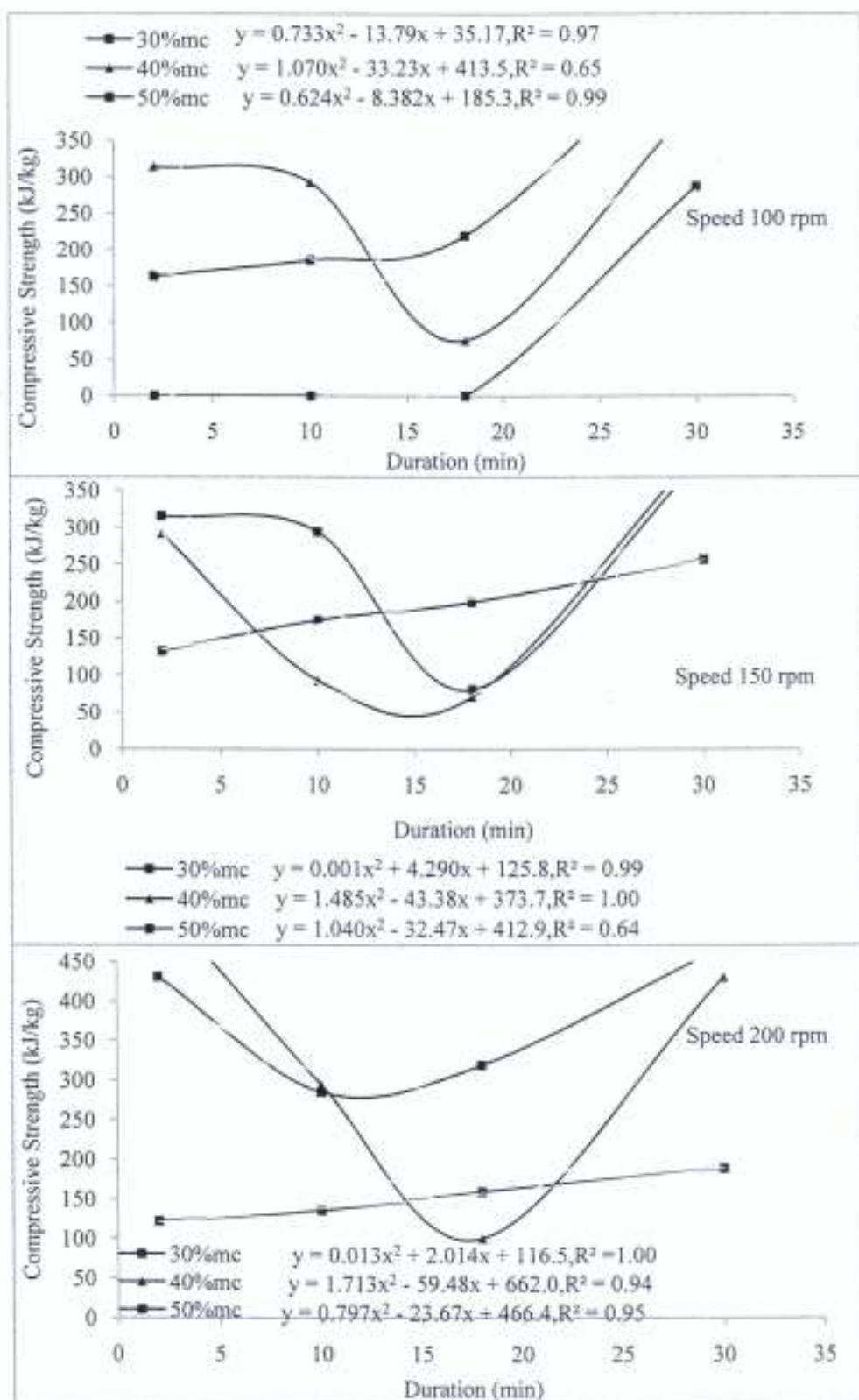


Figure A.50: Compressive strength response of maize flour to variable extrusion conditions.

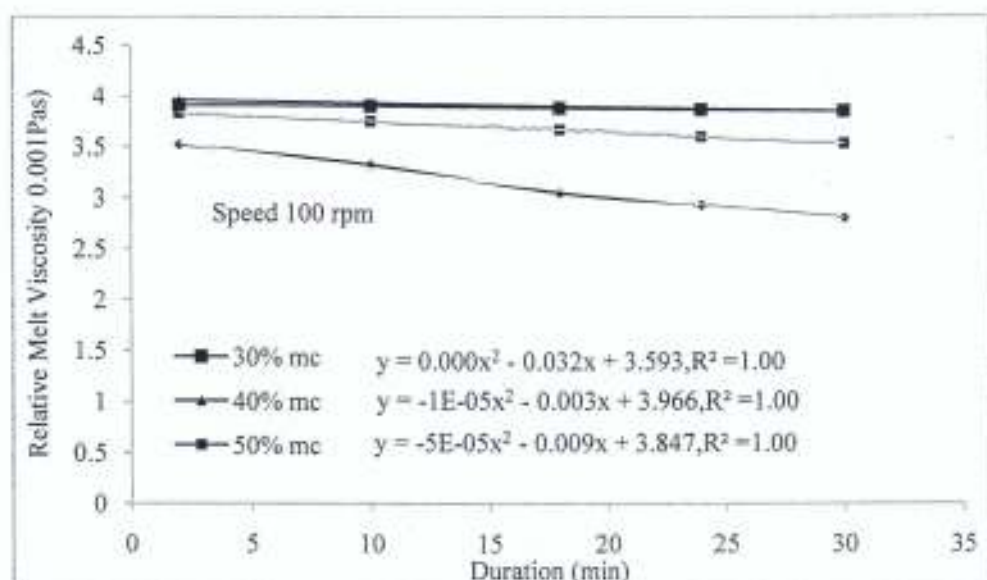


Figure A.51: Relative melt viscosity response of maize flour to variable extrusion conditions.

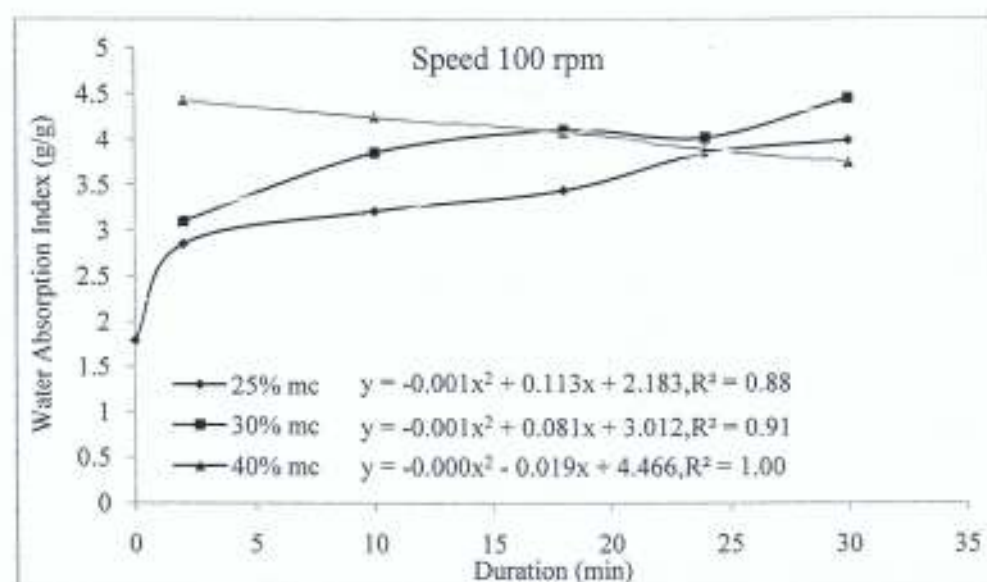


Figure A.52: Water absorption index response of maize flour to variable extrusion conditions.

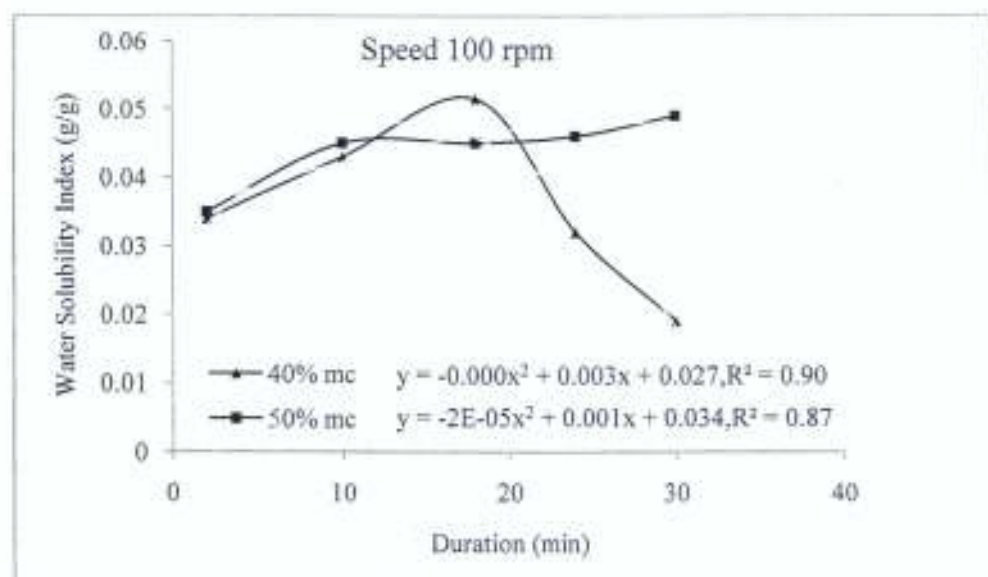


Figure A.53: Water solubility index response of maize flour to variable extrusion

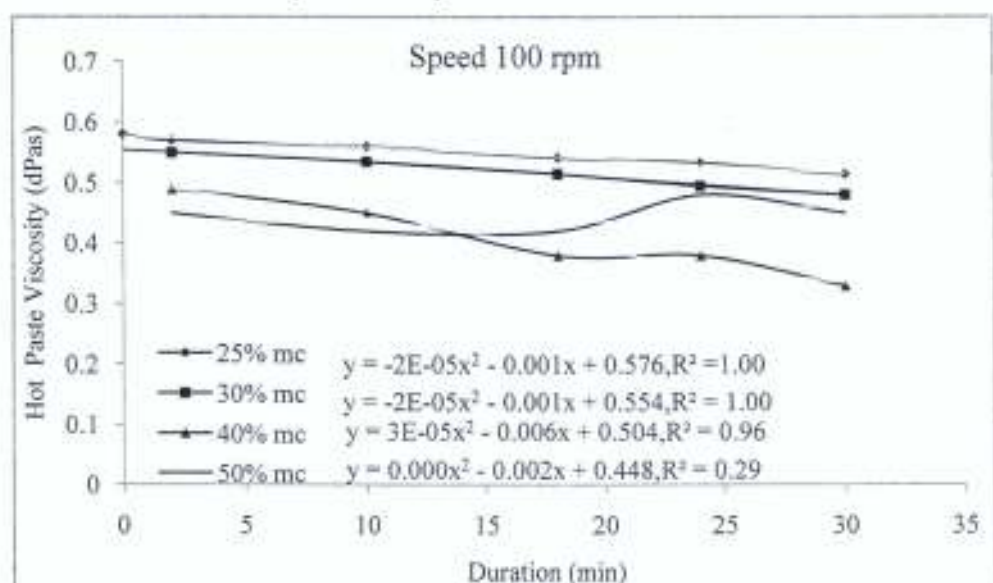


Figure A.54: Hot paste viscosity response of maize flour to variable extrusion conditions.

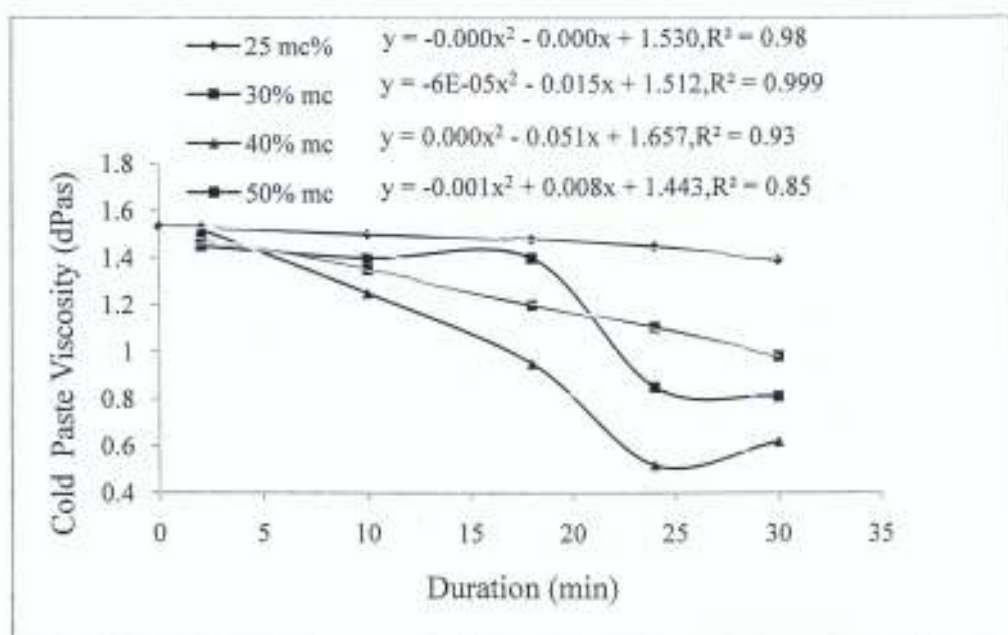


Figure A.55: Cold paste viscosity response of maize flour to variable extrusion conditions.

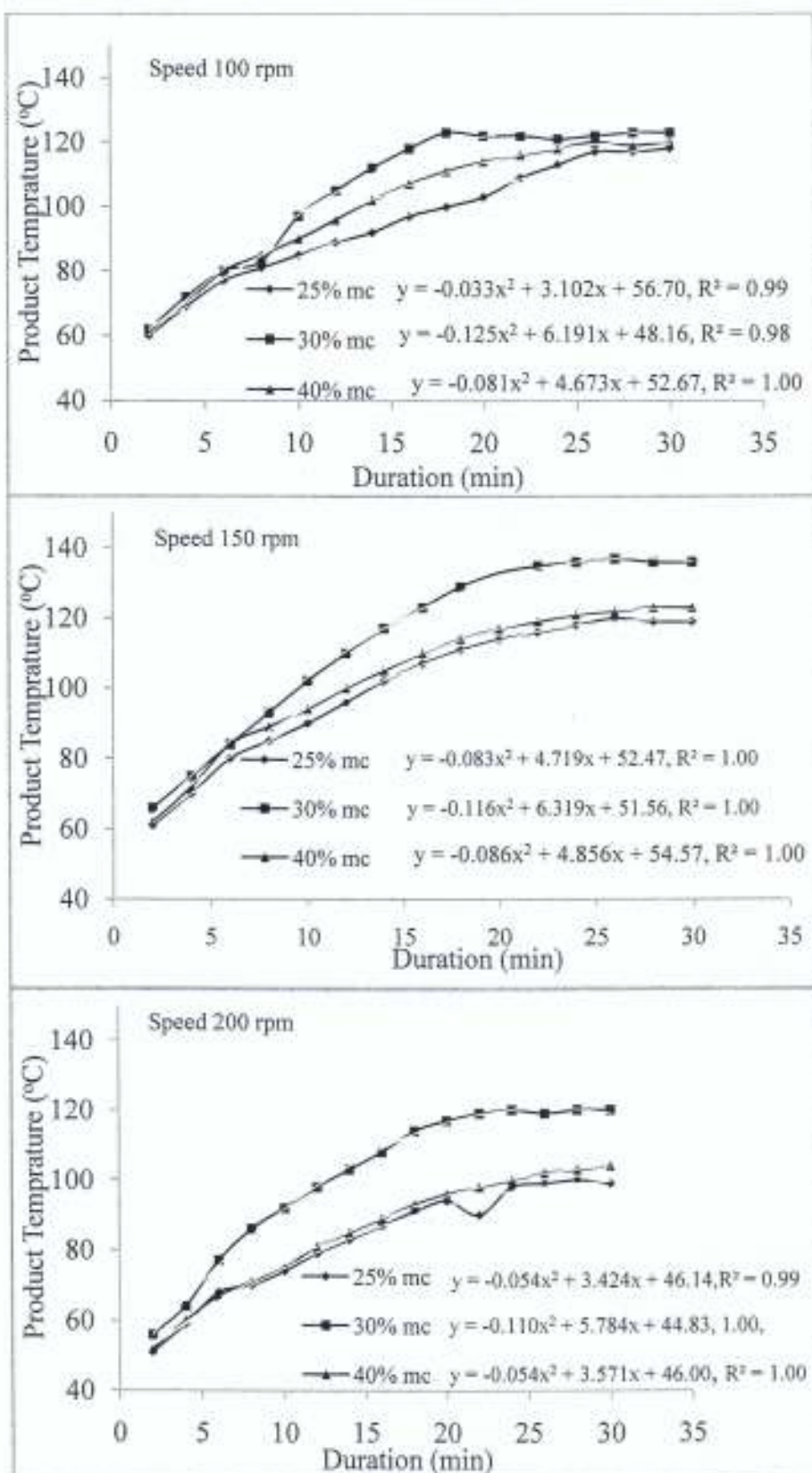


Figure A.56: Product Temperature response of wheat flour to variable extrusion conditions.

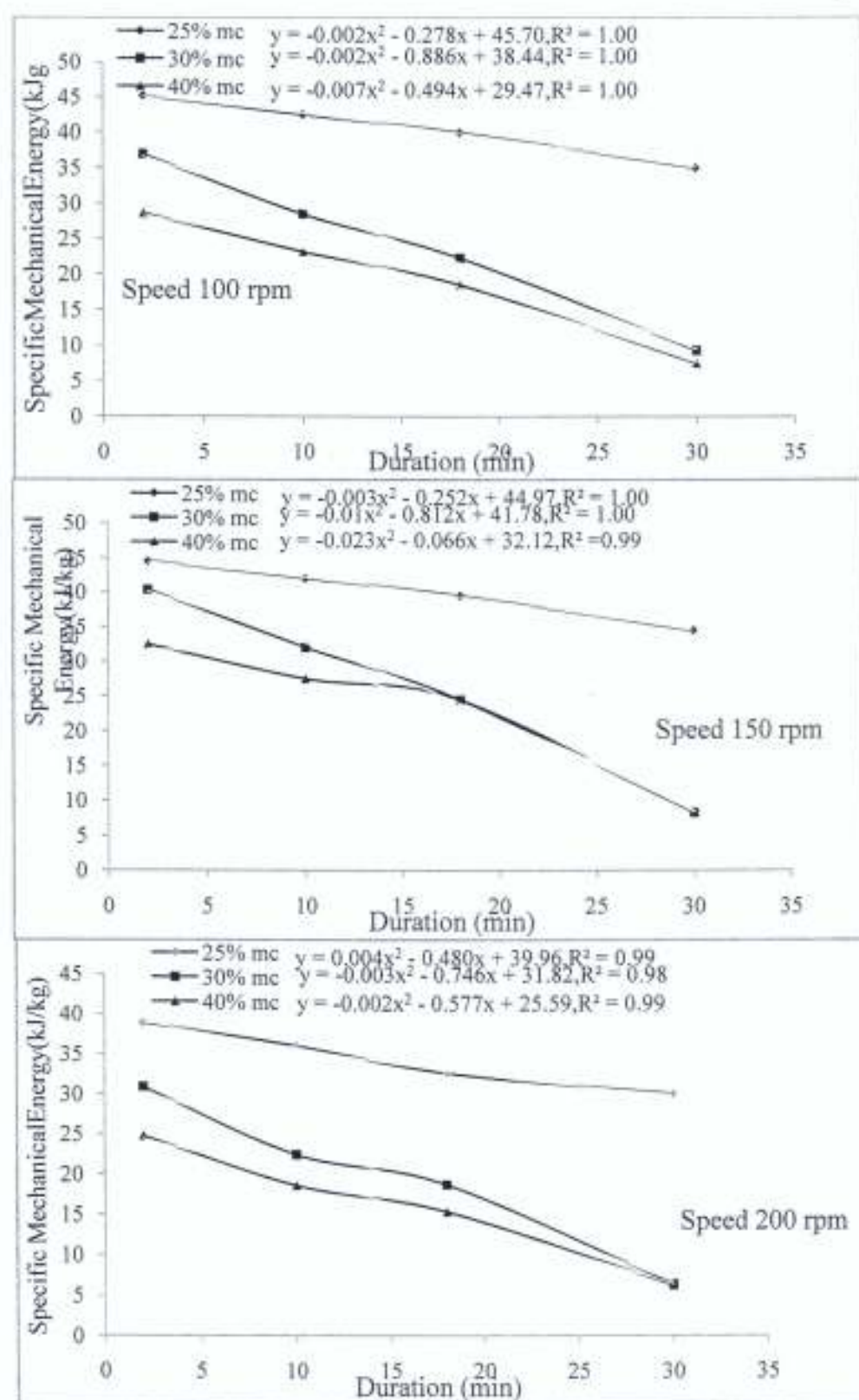


Figure A.57: Specific mechanical energy response of wheat flour to variable extrusion conditions.

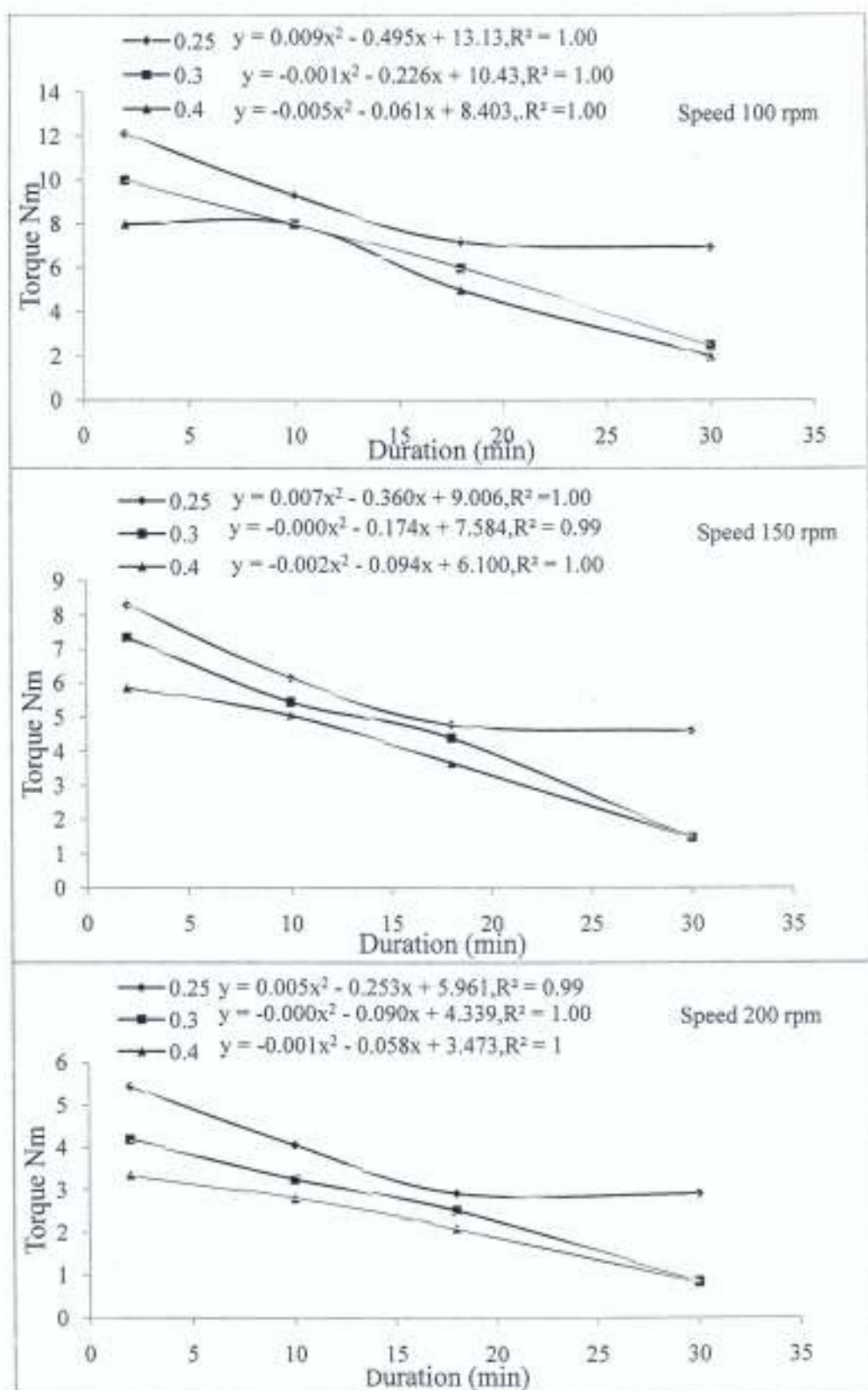


Figure A.58: Motor torque response of wheat flour to variable extrusion conditions.

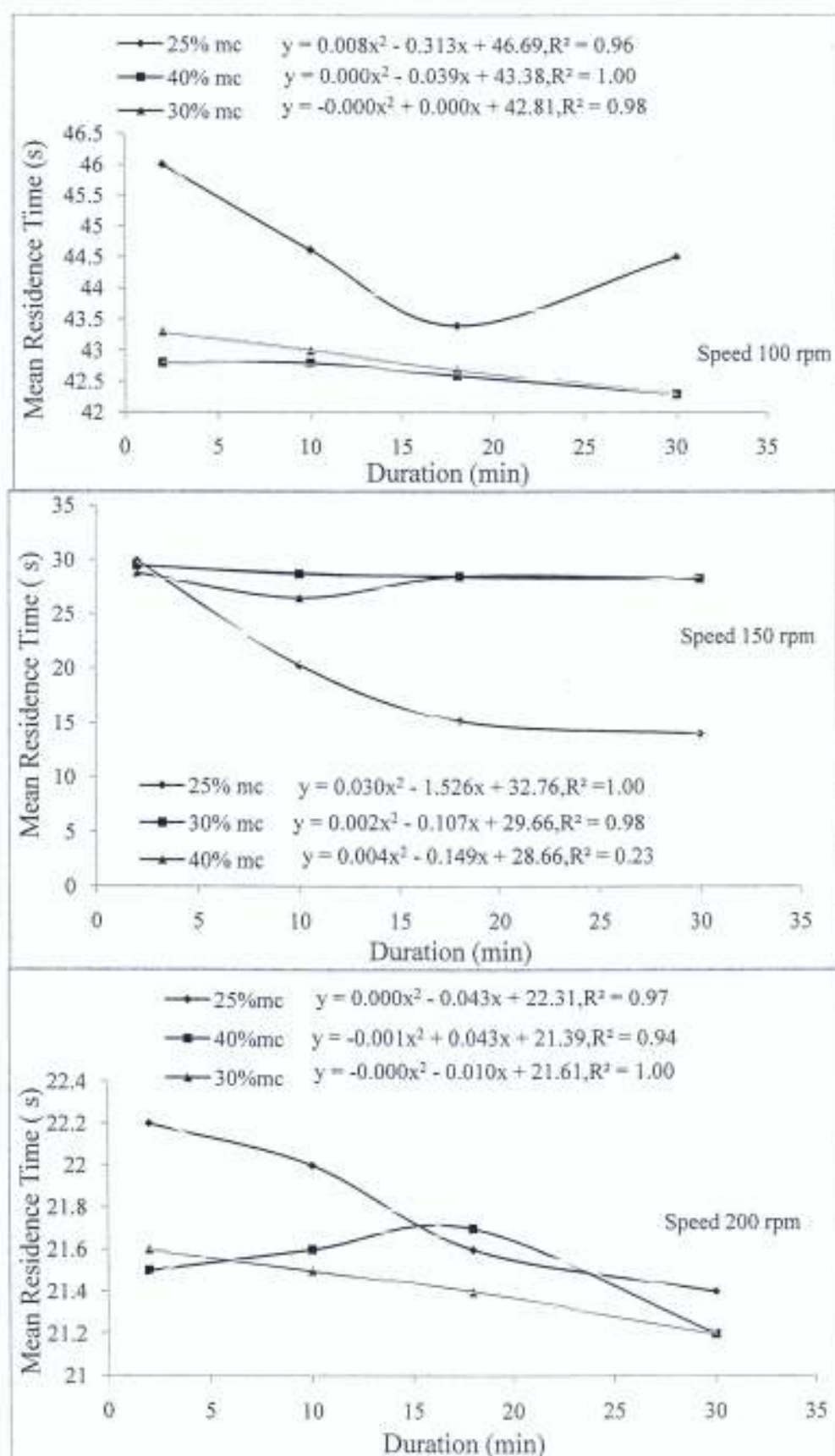


Figure A.59: Mean residence time response of wheat flour to variable extrusion conditions

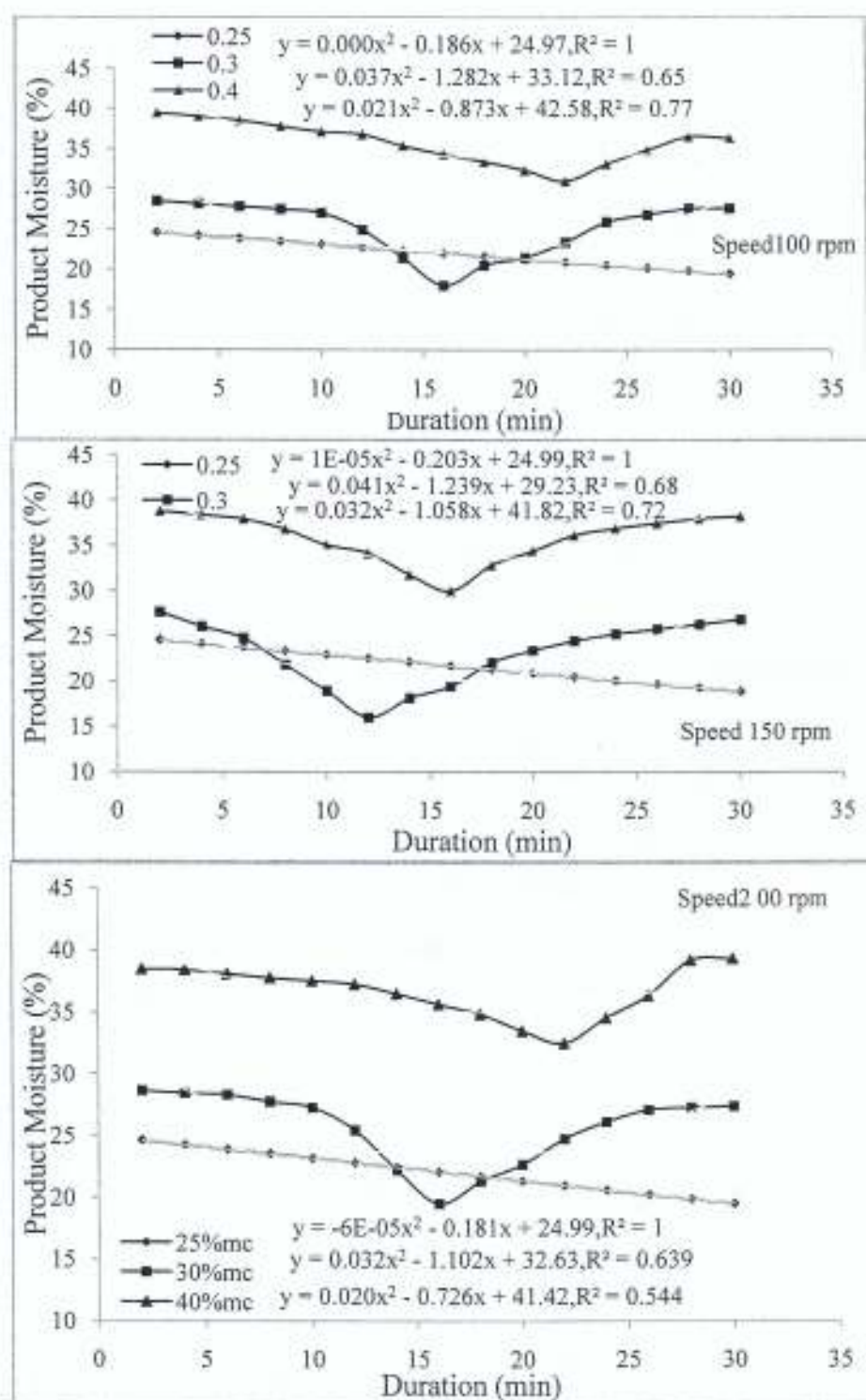


Figure A.60: Product moisture response of wheat flour to variable extrusion conditions.

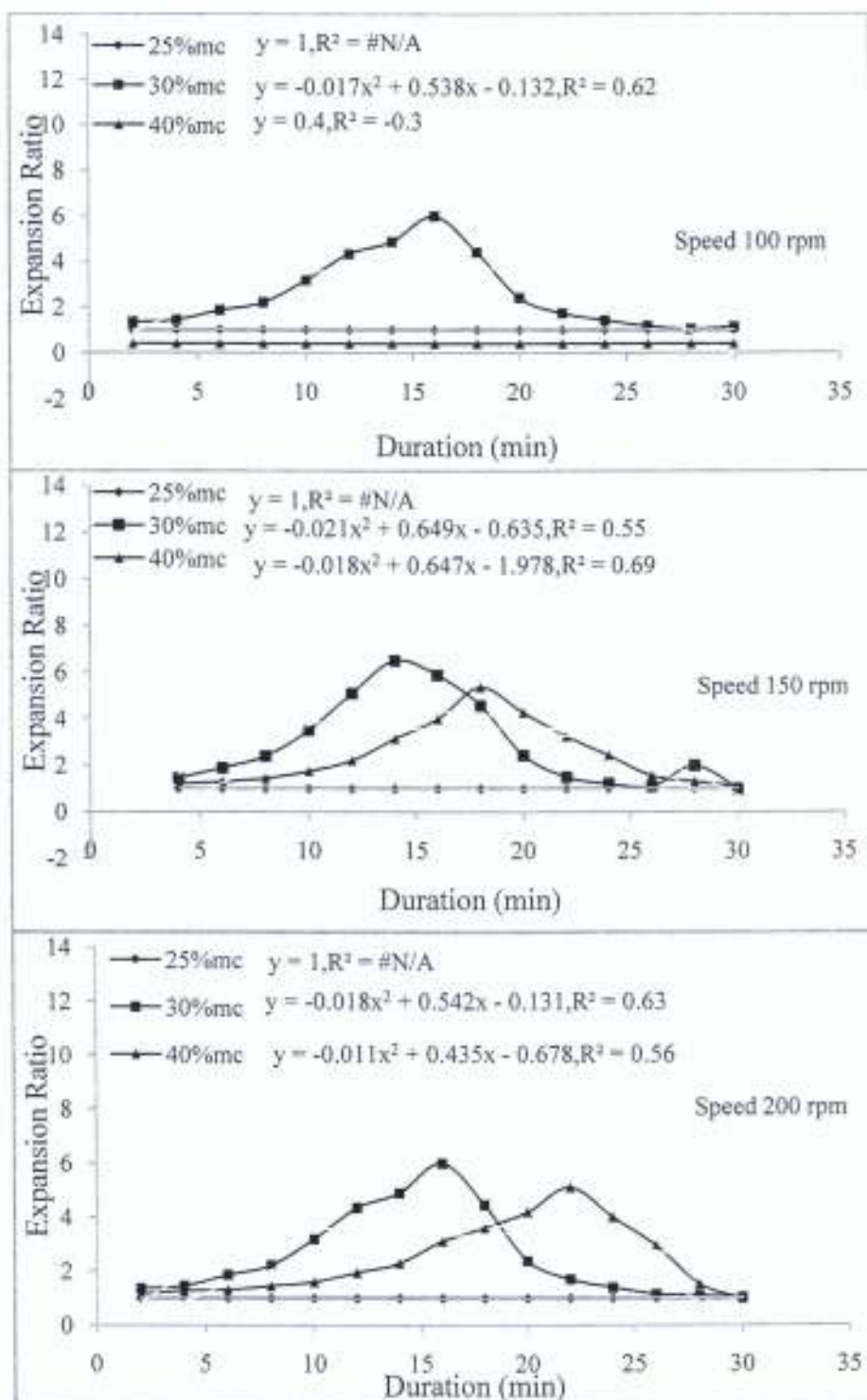


Figure A.61: Expansion ratio response of wheat flour to variable extrusion conditions.

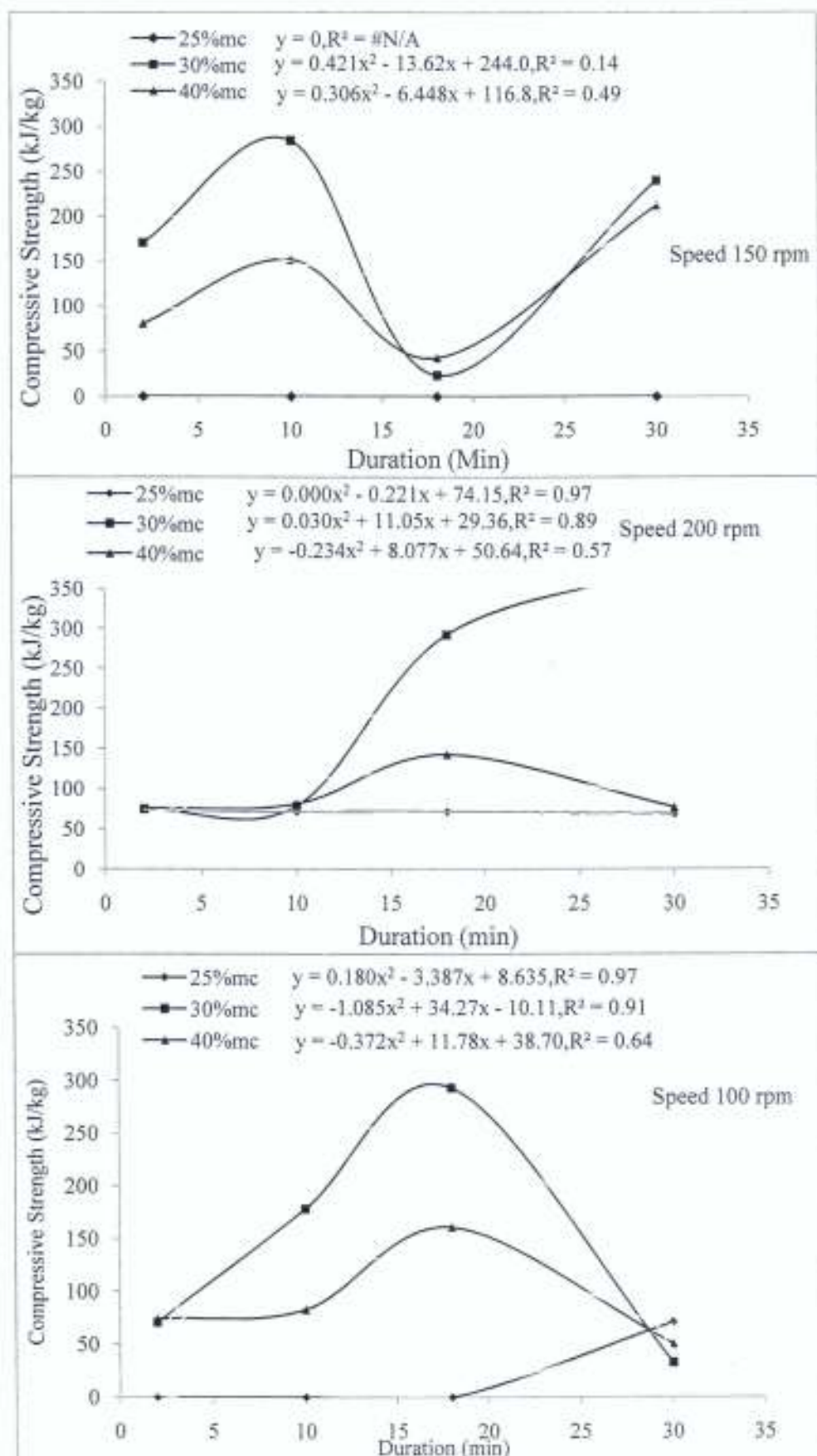


Figure A. 62: Compressive strength response of wheat flour to variable extrusion conditions.

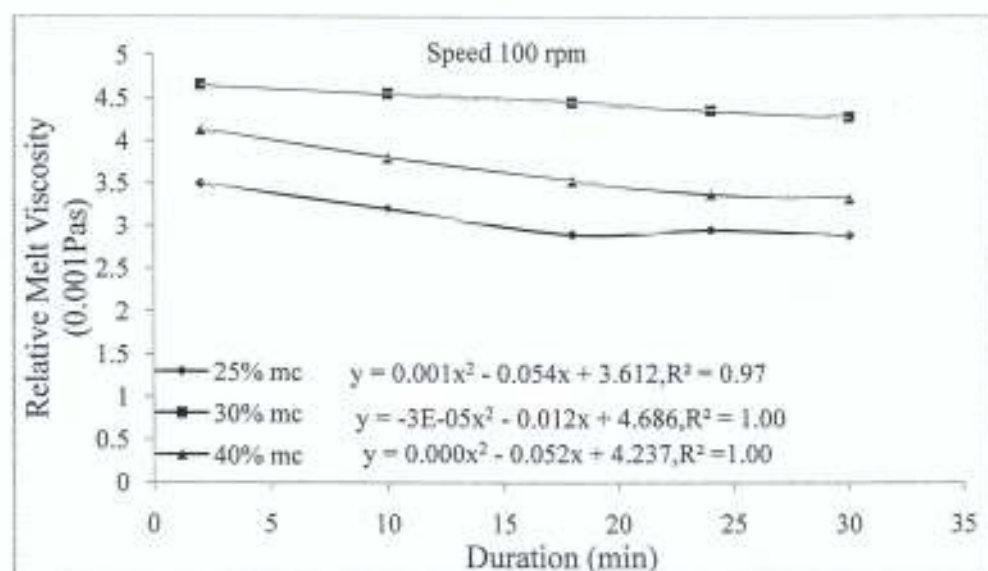


Figure A.64: Relative melt viscosity response of wheat flour to variable extrusion conditions.

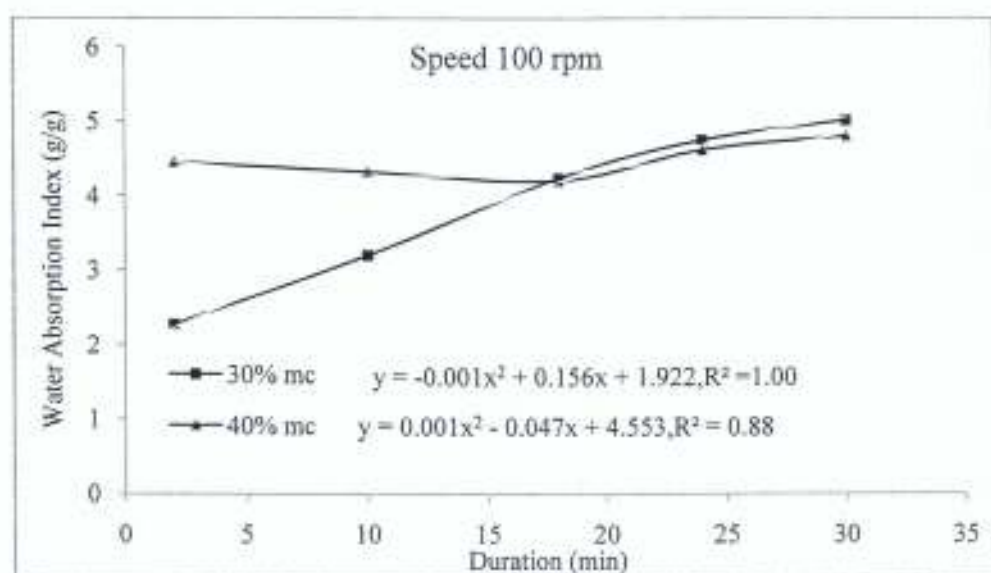


Figure A.65: Water absorption index response of wheat flour to variable extrusion conditions.

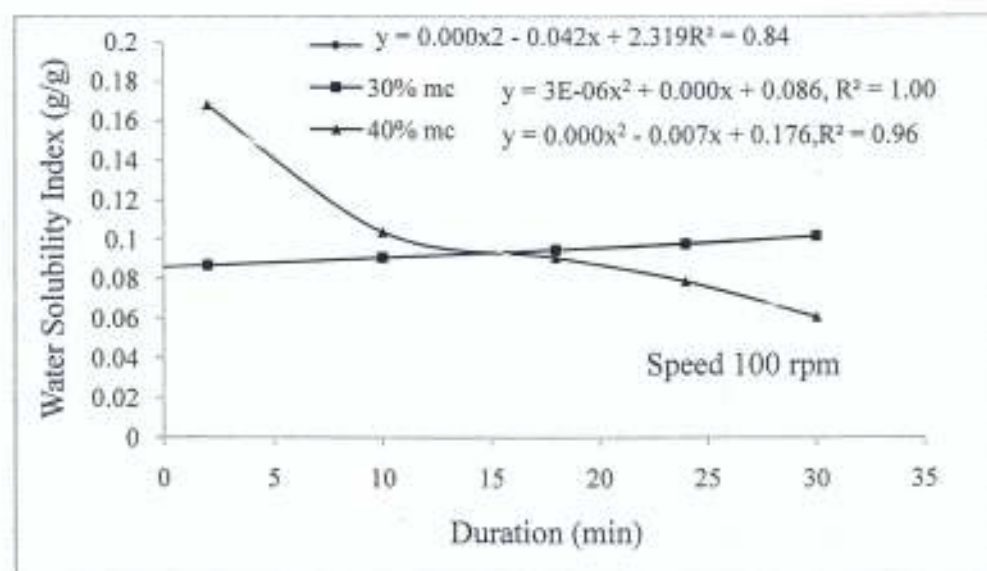


Figure A.66: Water solubility index response of wheat flour to variable extrusion conditions.

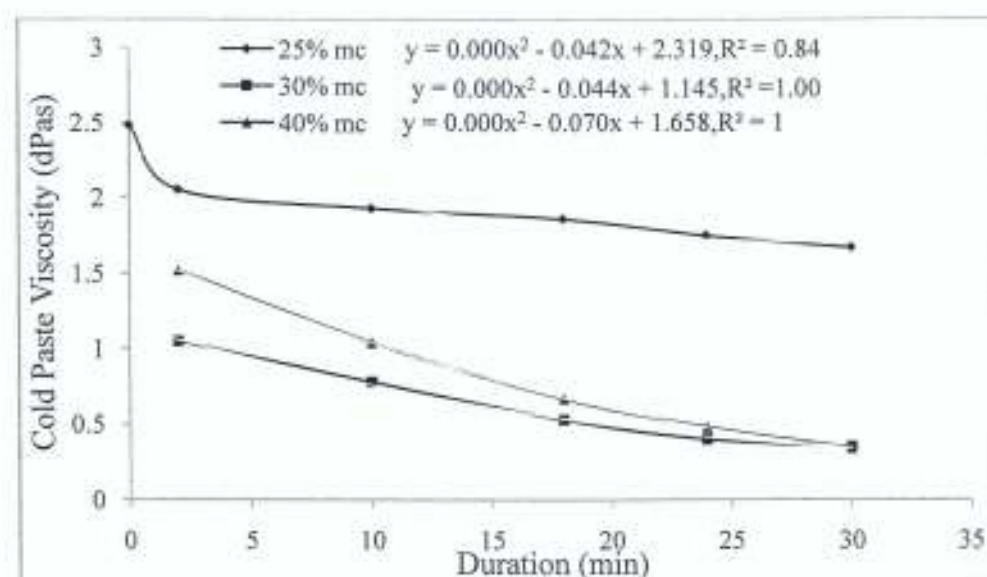


Figure A.67 Cold paste viscosity response of wheat flour to variable extrusion conditions.

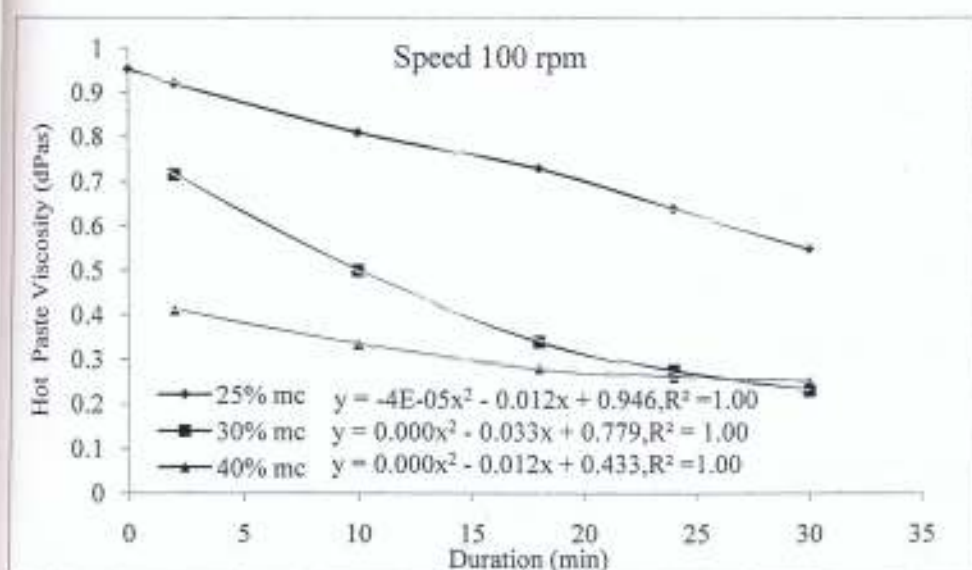


Figure A.68: Hot paste viscosity response of wheat flour to variable extrusion conditions.

APPENDIX 5

RESULT OF STEPWISE MULTIPLE LINEAR REGRESSION ANALYSIS

Stepwise regression analysis for cassava starch product temperature.

Models	Coefficients		T-test	Prob.	Adjusted R ²	F value	Prob.	VIF
1	B ₀	3.054	32.001	0.000	0.742	382.334	0.000	1.000
	Dt	0.139	19.553	0.000				
2	B ₀	3.847	18.520	0.000	0.755	202.987	0.000	1.000
	Dt	0.105	19.553	0.000				
	ds	0.022	-2.616	0.010				

Stepwise regression analysis for cassava starch specific mechanical energy requirement

Models	Coefficients		T-test	Prob	Adjusted R ²	F value	Prob	VIF
1	B ₀	12.72	1.41	0.167	0.677	74.29	0.00	1.000
	Dt	4.26	8.62	0.000				
2	B ₀	12.72	1.66	0.107	0.766	58.23	0.00	3.785
	Dt	6.89	8.62	0.000				
	dsm	-0.001	-3.73	0.001				

Stepwise regression analysis for cassava starch torque

Models	Coefficients		T-test	Prob.	Adjusted R ²	F value	Prob.	VIF
1	Bo	0.752	0.302	0.764	0.640	60.345	0.000	1.000
	Dt	1.061	7.768	0.000				
2	Bo	0.752	0.562	0.578	-0.899	146.662	0.000	3.785
	Dt	2.189	15.316	0.000				
	dsm	0.000	-9.198	0.000				
3	Bo	0.752	0.610	0.546	0.917	117.556	0.000	5.351
	Dt	2.411	15.316	0.000				
	Dsm	0.000	-3.890	0.000				
	ds	-0.004	-2.627	0.013				
4	Bo	0.752	0.681	0.501	0.935	111.961	0.000	125.853
	Dt	4.390	6.453	0.000				
	Dsm	0.000	1.728	0.094				
	ds	-0.016	-3.758	0.001				
	dm	-0.062	-2.972	0.006				

Stepwise regression analysis for cassava flour mean residence time.

Models	Coefficients		T-test	Prob.	Adjusted R ²	F value	Prob.	VIF
1	B ₀	66.211	48.156	0.000	0.951	652.951	0.000	1.000
	Ss	-0.226	-25.553	0.000				
2	B ₀	64.562			0.965	454.311	0.000	1.000
	Ss	-0.226						1.000
	Dt	0.110						

Stepwise regression analysis for cassava starch product moisture content

Models	Variable Entered	Coefficients		T-test	Prob.	Adjusted R ²	F value	Prob.	VIF
1	Mc	Bo	-3.943	-2.037	0.044	0.239	236.330	0.000	1.000
		Mc	0.955	15.373	0.000				
2	Mc, dm	Bo	0.521	0.375	0.708	-0.335	314.430	0.000	1.003
		Mc	0.981	22.889	0.000				1.003
		dm	0.012	-11.463	0.000				1.003
3	Mc, dm, Dt	Bo	-6.612	-2.449	0.016	0.394	227.540	0.000	4.370
		Mc	1.212	14.020	0.000				36.850
		Dm	-0.030	-4.961	0.000				39.031
		Dt	0.553	3.046	0.003				

Stepwise regression analysis for cassava starch expansion ratio

Models	Coefficients		T-test	Prob	Adjusted R ²	F value	Prob	VIF
1	B ₀	1.755	3.746	0.000	0.114	15.112	0.000	1.000
	dsm	0.00002	3.337	0.000				
2	B ₀	1.829	4.051	0.000	0.186	13.371	0.000	10.898
	Dsm	0.00008	4.301	0.000				10.898
	ds	-0.002	-3.229	0.002				

Stepwise regression analysis for cassava starch compressive strength

Models	Coefficients		T-test	Prob	Adjusted R ²	F value	Prob	VIF
1	Bo	1691.71	15.020	0.000	0.505	36.684	0.000	1.000
	Dt	-37.440	-6.057	0.000				
2	Bo	869.919	4.111	0.000	0.678	37.088	0.000	1.000
	Dt	-37.440	-7.458	0.000				
	Ss	5.479	4.307	0.000				

Stepwise regression analysis for cassava starch relative melts viscosity

Models	Coefficients		T-test	Prob	Adjusted R	F value	Prob	VIF
1	B ₀	1.755	3.746	0.002	0.106	15.112	0.000	1.000
	dsm	0.139	3.887	0.05				
2	B ₀	1.829	4.051	0.000	0.172	13.371	0.000	1.000
	D _{dsm}	0.00001	4.301	0.000				
	ds	-0.002	-3.229	0.000				

Stepwise regression analysis for cassava starch water absorption index

Models	Coefficients		T-test	Prob	Adjusted R	F value	Prob.	VIF
1	B ₀	1.755	3.746	0.000	0.114	15.112	0.000	1.000
	dsm	0.00002	3.337	0.000				
2	B ₀	1.829	4.051	0.000	0.186	13.371	0.000	10.898
	D _{dsm}	0.00008	4.301	0.000				
	ds	-0.002	-3.229	0.002				

Stepwise regression analysis for cassava starch water solubility index.

Models	Coefficients		T-test	Prob	Adjusted R	F value	Prob.	VIF
1	B ₀	1.755	3.746	0.002	0.106	15.112	0.000	1.000
	dsm	0.139	3.887	0.05				
2	B ₀	1.829	4.051	0.000	0.172	13.371	0.000	1.000
	D _{dsm}	0.00001	4.301	0.000				
	ds	-0.002	-3.229	0.000				

Stepwise regression analysis for cassava starch cold paste viscosity.

Models	Coefficients		T-test	Prob	Adjusted R	F value	Prob	VIF
1	B ₀	12.72	1.41	0.167	0.677	74.29	0.000	1.000
	Dt	4.26	8.62	0.000				
2	B ₀	12.72	1.66	0.107	0.766	58.23	0.000	3.785
	Dt	6.89	8.62	0.000				
	dsm	-0.001	-3.73	0.001				

Stepwise regression analysis for cassava cold paste viscosity.

Models	Coefficients		T-test	Prob	Adjusted R	F value	Prob	VIF
1	B ₀	-3.943	-2.037	0.004	0.667	236.330	0.000	1.000
	Dt	0.955	15.373	0.000				
2	B ₀	0.521	0.375	0.708	0.840	314.430	0.000	1.003 1003
	Mc	0.981	22.889	0.000				
	Dm	-0.012	-11.463	0.000				
3	B ₀	-6.612	-2.449	0.016	0.851	227.540	0.000	4.370 36.850 39.031
	Mc	1.212	14.020	0.000				
	Dm	-0.030	-4.961	0.000				
	Dt	0.553	3.046	0.003				

Stepwise regression analysis for cassava flour product temperature.

Models	Coefficients		T-test	Prob.	Adjusted R	F value	Prob.	VIF
1	B ₀	66.521	32.001	0.000	0.740	382.334	0.000	1.000
	Dt	2.101	19.553	0.000				
2	B ₀	71.254	18.520	0.000	0.751	202.907	0.000	1.000 1.000
	Dt	2.101	19.978	0.000				
	Ss	-0.58	-2.616	0.000				

Stepwise regression analysis for cassava flour specific mechanical energy.

Models	Coefficients		T-test	Prob.	Adjusted R	F value	Prob.	VIF
1	Bo	12.715	1.410	0.167	0.686	74.294	0.000	1.000
	Dt	4.264	8.619	0.000				
2	Bo	12.715	1.657	0.107	-0.779	58.230	0.000	3.785 3.785
	Dt	6.887	8.406	0.000				
	dsm	-0.001	-3.732	0.001				

Stepwise regression analysis for cassava flour torque.

Models	Coefficients		T-test	Prob.	Adjusted R	F value	Prob.	VIF
1	Bo	0.752	0.302	0.764	0.640	60.345	0.000	1.000
	Dt	1.061	7.768	0.000				
2	Bo	0.752	0.562	0.578	-0.899	146.662	0.000	3.785
	Dt	2.189	15.316	0.000				
	dsm	0.000	-9.198	0.000				
3	Bo	0.752	0.610	0.546	0.917	117.556	0.000	5.351
	Dt	2.411	15.316	0.000				
	Dsm	0.000	-3.890	0.000				
	ds	-0.004	-2.627	0.013				
4	Bo	0.752	0.681	0.501	0.935	111.961	0.000	125.853
	Dt	4.390	6.453	0.000				
	Dsm	0.000	1.728	0.094				
	ds	-0.016	-3.758	0.001				
	dm	-0.062	-2.972	0.006				

Stepwise regression analysis for cassava flour MRT.

Models	Coefficients		T-test	Prob.	Adjusted R	F value	Prob.	VIF
1	B ₀	66.211	48.156	0.000	0.951	652.951	0.000	1.000
	Ss	-0.226	-25.553	0.000				
2	B ₀	64.562	51.377	0.000	0.965	454.311	0.000	1.000
	Ss	-0.226	-29.917	0.000				
	Dt	0.110	3.699	0.001				

Stepwise regression analysis for cassava flour water absorption index.

Models	Coefficients		T-test	Prob.	Adjusted R	F value	Prob.	VIF
1	B ₀	1691.719	15.020	0.000	0.519	36.684	0.000	1000
	Dt	-37.440	-6.057	0.000				
2	B ₀	869.919	4.111	0.000	0.692	37.088	0.000	1.000
	Dt	-37.440	-7.458	0.000				
	Ss	5.479	4.307	0.000				

Stepwise regression analysis for cassava flour product moisture content

Models	Coefficients		T-test	Prob.	Adjusted R	F value	Prob.	VIF
1	Bo	-16.552	1.410	0.000	0.811	507.363	0.000	1.000
	Mc	1.262	8.619	0.000				
2	Bo	-16.517	-11.781	0.000	0.911	602.330	0.000	1.041
	Mc	1.351	34.373	0.000				
	dm	-0.011	-11.506	0.000				

Stepwise regression analysis for cassava flour expansion ratio.

Models	Coefficients		T-test	Prob.	Adjusted R	F value	Prob.	VIF
1	Bo	2.296	7.039	0.000	0.239	41.707	0.000	1.000
	ds	0.001	6.458	0.000				
2	Bo	5.886	6.717	0.000	-0.335	33.249	0.000	1.000
	Ds	0.001	6.884	0.000				
	Mc	-113	-4.372	0.000				
3	Bo	10.391	6.845	0.000	0.394	28.359	0.000	26.786
	ds	-0.001	-2.107	0.037				
	Mc,	-0.256	-5.435	0.000				
	dsm	-0.00006	3.562	0.001				

Stepwise regression analysis for cassava flour compressive strength.

Models	Coefficients		T-test	Prob.	Adjusted R	F value	Prob.	VIF
1	Bo	1691.719	15.020	0.000	0.519	36.684	0.000	1.000
	Dt	-37.440	-6.057	0.000				
2	Bo	211.587	4.111	0.000	0.661	37.088	0.000	1.000
	Dt	5.020	-7.458	0.000				
	Ss	1.272	4.307	0.000				
3	Bo	10.391	6.845	0.000	0.713	28.249	0.000	26.786
	Dt	-0.001	-2.107	0.037				
	Ss	-0.256	-5.435	0.000				
	Mc	-0.00006	3.562	0.001				

Stepwise regression analysis for cassava flour relative melt viscosity.

Models	Coefficients		T-test	Prob.	Adjusted R	F value	Prob.	VIF
1	B_0 Dt	3.054	3.869	0.002	0.442	11.103	0.005	1000
		0.139	3.332	0.05				
2	B_0 Dt Ss	3.054	8.664	0.000	0.947	57.436	0.000	8.868 8.868
		0.535	9.629	0.000				
		-0.012	-7.563	0.000				

Stepwise regression analysis for cassava flour water solubility index.

Models	Coefficients		T-test	Prob	Adjusted R	F value	Prob	VIF
1	B_0 Dt	0.158	6.930	0.000	0.670	31.431	0.000	1.000
		0.007	5.606	0.000				
2	B_0 Dt dm	0.158	17.374	0.000	0.944	136.263	0.000	8.868 8.868
		0.018	12.876	0.000				
		0.000	-8.660	0.000				

Stepwise regression analysis for cassava flour hot paste viscosity

Models	Coefficients		T-test	Prob	Adjusted R	F value	Prob	VIF
1	B_0 Dt	0.158	6.930	0.000	0.670	31.431	0.000	1.000
		0.139	3.332	0.000				
2	B_0 Dt dm	0.158	17.374	0.000	0.954	74.988	0.000	8.868 8.868
		0.018	12.876	0.000				
		0.000	-8.660	0.000				

Stepwise regression analysis for cassava flour cold paste viscosity.

Models	Coefficients		T-test	Prob.	Adjusted R	F value	Prob.	VIF
1	B_0 Dt	3.054	3.869	0.002	0.442	11.103	0.005	1000
		0.139	3.332	0.05				
2	B_0 Dt dm	3.054	8.664	0.000	0.947	57.436	0.000	8.868 8.868
		0.535	9.629	0.000				
		-0.012	-7.563	0.000				

Stepwise regression analysis for maize starch product temperature.

Models	Coefficients		T-test	Prob.	Adjusted R ²	Std. Error	F value	Prob.	VIF
1	B ₀	57.099	20.150	0.000	0.679	15.65	284.920	0.000	1.000
	Dt	2.630	16.880	0.000					
2	B ₀	66.778	13.984	0.000	0.691	15.35	151.151	0.000	1.000
	Dt	2.630	17.207	0.000					
	sm	0.002	-2.493	0.014					

Stepwise regression analysis for maize starch specific mechanical energy.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	11.809	7.562	0.000	0.414	20.19	28.566	0.000	1.000
	Mc	-6.5E-005	-5.345	0.000					
2	B ₀	21.043	9.562	0.000	0.595	17.19	26.677	0.000	1.000
	Mc	-5.7E-005	-6.279	0.000					
	Dt	-0.310	-3.732	0.001					

Stepwise regression analysis for maize flour torque.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	11.809	9.971	0.000	0.409	4.45	25.195	0.000	1.000
	dsm	-6.5E-005	-5.019	0.000					
2	B ₀	21.043	5.990	0.000	0.505	4.07	18.874	0.000	1.064
	dsm	-5.7E-005	-4.843	0.000					
	Mc	-0.310	-2.763	0.009					
3	B ₀	35.911	7.402	0.000	0.562	3.42	22.838	0.000	28.496
	dsm	0.000	2.716	0.008					
	Mc	-0.762	-5.071	0.000					
	ds	-0.007	-3.858	0.001					
4	B ₀	39.767	7.984	0.000	0.684	3.25	19.961	0.000	28.496
	dsm	0.000	2.852	0.008					
	Mc	-0.762	-5.325	0.000					
	ds	-0.006	-3.888	0.000					
	Ss	-0.029	-2.071	0.047					
5	B ₀	50.149	10.849	0.000	0.800	2.59	29.044	0.000	28.496
	dsm	0.000	3.586	0.001					
	Mc	-0.762	-6.695	0.000					
	ds	-0.002	-1.264	0.216					
	Ss	-0.094	-5.045	0.000					
	Dt	-0.692	-1.254	0.000					

Stepwise regression analysis for maize flour means residence time.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	65.718	40.339	0.000	0.931	2.57	47.600	0.001	1.000
	Ss	-0.228	-21.716	0.000					

Stepwise regression analyses for maize starch product moisture.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	-3.805	-2.671	0.000	0.785	3.17	485.470	0.000	1.000
	Mc	0.971	22.033	0.000					
2	B ₀	-3.805	-3.131	0.002	0.843	2.71	358.692	0.000	1.127
	Mc	1.066	26.711	0.000					
	dm	-0.006	-7.097	0.000					

Stepwise regression analysis for maize starch expansion ratio.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	1.485	12.012	0.000	0.042	0.38	5.776	0.018	1.000

Stepwise regression analysis for maize starch compressive strength.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	-94.723	-2.059	0.047	0.250	53.34	12.677	0.001	1.000
	Mc	5.076	3.560	0.000					

Stepwise regression analysis for maize starch relative melt viscosity.

Models	Coefficients		T-test	Prob	Adjusted R	F value	Prob	VIF
1	B ₀	3437	3.720	0.000	0.554	6.199	0.026	1.000
	Dt	0.004	2.490	0.026				

Stepwise regression analysis for maize starch water absorption index.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	0.709	0.517	0.613	0.293	1.07	7.206	0.018	1.000
	Mc	0.115	2.684	0.01					

Table 5.35 Stepwise regression analysis for maize starch water solubility index.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	0.067	5.672	0.000	0.350	0.01	9.068	0.009	1.000
	Mc	-0.001	-3.011	0.007					

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	4.025	5.361	0.000	0.326	1.66	8.260	0.012	1.000
	Dt	-0.14	-2.874	0.012					

Stepwise regression analysis for maize starch hot paste viscosity.

Stepwise regression analysis for maize flour cold paste viscosity.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	7.583	5.618	0.000	0.371	2.98	9.829	0.007	1.000
	Dt	-0.224	-3.135	0.007					
2	B ₀	16.918	5.786	0.000	0.642	2.25	14.437	0.000	1.010
	Dt	-0.205	-3.792	0.002					
	Mc	-0.308	-3.406	0.005					

Stepwise regression analysis for maize starch product temperature.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	61.962	32.744	0.000	0.662	11.01	293.218	0.000	1.000
	Dt	1.782	17.124	0.000					
2	B ₀	48.572	11.736	0.000	0.688	10.59	164.960	0.000	1.000
	Dt	1.782	17.803	0.000					
	Mc	0.348	3.602	0.000					

Stepwise regression analysis for maize flour specific mechanical energy.

Models	Coefficients		T-test	Prob.	Adjusted R ²	Std. Error	F value	Prob.	VIF
1	B ₀	167.176	7.083	0.000	0.413	28.32	25.626	0.000	1.000
	Mc	-2.927	-5.062	0.000					
2	B ₀	193.558	11.491	0.000	0.720	19.55	46.039	0.000	1.007
	Mc	-2.927	-7.332	0.000					
	Ds	-0.012	-6.191	0.000					
3	B ₀	258.575	11.296	0.000	0.796	16.69	46.590	0.000	0.369
	Mc	-4.552	-8.118	0.000					
	Ds	-0.041	-5.027	0.000					
	dsm	0.001	3.649	0.001					

Stepwise regression analyses for maize flour motor torque.

Models	Coefficients		T-test	Prob	Adjusted R	Std. Error	F value	Prob	VIF
1	B_0	15.897	9.646	0.000	0.403	6.21	24.552	0.000	1.000
	dsm	-7.1E-005	-4.963	0.000					
2	B_0	23.305	8.183	0.000	0.520	5.57	19.942	0.000	1.223
	dsm	-5.2E-005	-3.703	0.001					
	sm	-0.002	-3.043	0.005					
3	B_0	39.683	10.767	0.000	0.741	4.09	34.344	0.000	11.518
	dsm	0.000	3.698	0.002					
	sm	-0.004	-6.802	0.000					
	Dt	-1.092	-5.398	0.000					
4	B_0	45.609	10.678	0.000	0.773	3.83	30.791	0.000	11.518
	dsm	0.000	3.678	0.001					
	sm	-0.003	-5.802	0.000					
	Dt	-1.092	-5.768	0.000					
	Mc	-0.228	-2.352	0.025					
5	B_0	83.622	8.110	0.000	0.845	3.16	39.151	0.000	11.518
	dsm	0.000	4.475	0.000					
	sm	-0.003	1.640	0.111					
	Dt	-1.147	-6.980	0.000					
	Mc	-0.761	-4.637	0.000					
	Ss	-0.152	-3.924	0.000					

Stepwise regression analysis for maize flour mean residence time.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B_0	0.811	44.953	0.000	0.942	2.25	566.835	0.000	1.000
	Ss	0.095	-23.808	0.000					
2	B_0	0.380	46.003	0.000	0.949	2.11	326.109	0.000	1.000
	Ss	0.092	-25.425	0.000					
	dm	0.034	-2.403	0.022					

Stepwise regression analysis for maize flour product moisture content.

Models	Coefficients		T-test	Prob.	Adjusted R ²	Std. Error	F value	Prob.	VIF
1	B ₀	5.279	3.002	0.003	0.634	5.02	263800	0.000	1.000
	Mc	0.727	16.242	0.000					
2	B ₀	4.906	3.201	0.002	0.772	4.37	198.423	0.000	1.164 1.164
	Mc	0.837	19.915	0.000					
	dsm	-4.3E-005	-7.005	0.000					
3	B ₀	-2.399	-0.850	0.397	0.737	4.25	142.697	0.000	3.583 23.595 20.326
	Mc	1.017	14.163	0.000					
	dsm	0.000	-4.571	0.000					
	ds	0.003	3.049	0.003					
4	B ₀	-1.931	-0.688	0.492	0.742	4.21	110.089	0.000	4.409 23.775 20.337 2.396
	Mc	0.950	12.038	0.000					
	dsm	0.000	-4.770	0.000					
	ds	0.003	3.033	0.003					
	sm	0.000	1.977	0.050					

Stepwise regression analysis for maize flour expansion ratio.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	0.675	2.976	0.003	0.212	1.60	49.282	0.000	1.000
	dm	0.002	7.020	0.000					
2	B ₀	1.146	4.824	0.000	0.294	1.52	38.200	0.000	4.219 4.219
	dm	0.005	7.655	0.000					
	Dt	-0.124	-4.632	0.000					

Stepwise regression analysis for maize flour compressive strength.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	40.032	0.602	0.141	0.205	130.054	10.044	0.003	1.000
	sm	0.033	3.169	0.000					
2	B ₀	-1.285	-0.020	0.424	0.290	122.96	8.136	0.001	1.028 1.028
	sm	0.029	2.936	0.002					
	dm	0.106	2.244	0.007					
3	Bo	-99.954	-2.265	0.215	0.352	117.43	7.340	0.001	1.877 8.772 10.439
	sm	0.047	3.650	0.001					
	dm	0.359	2.725	.010					
	dsm	-0.002	-2.044	0.049					

Stepwise regression analysis for maize flour water absorption index.

Models	Coefficients		T-test	Prob.	Adjusted R ²	Std. Error	F value	Prob.	VIF
1	B ₀	-0.022	0.214	0.836	0.530	0.01	12.254	0.007	1.000
	Mc	0.001	0.218	0.833					

Table 5.47 Stepwise regression analysis for maize flour water solubility index.

Models	Coefficients		T-test	Prob.	Adjusted R ²	Std. Error	F value	Prob.	VIF
1	B ₀	0.811	1.536	0.141	0.683	0.01	44.080	0.000	1.000
	Mc	0.095	6.639	0.000					
2	B ₀	0.380	0.818	0.424	0.778	0.01	35.969	0.000	1.007
	Mc	0.092	7.640	0.002					
	Dt	0.034	3.015	0.007					

Models	Coefficients		T-test	Prob.	Adjusted R ²	Std. Error	F value	Prob.	VIF
1	B ₀	1.563	19.90	0.613	0.72	0.17	39.53	0.000	1.000
	Dt	-0.026	-6.29	0.01					

Stepwise regression analysis for maize flour hot paste viscosity.

Stepwise regression analysis for maize flour cold paste viscosity.

Models	Coefficients		T-test	Prob.	Adjusted R ²	Std. Error	F value	Prob.	VIF
1	B ₀	1.500	14.096	0.000	0.493	0.0.21	14.625	0.000	1.000
	Dt	-0.021	-3.82	0.002					

Stepwise regression analysis for wheat flour specific mechanical energy.

Models	Coefficients		T-test	Prob.	Adjusted R ²	Std. Error	F value	Prob.	VIF
1	B ₀	38.262	17.428	0.000	0.575	7.49	45.569	0.000	1.000
	dm	-0.025	-6.750	0.000					
2	B ₀	60.790	11.281	0.000	0.731	5.96	45.745	0.000	1.061
	dm	-0.021	-7.174	0.000					
	Mc	-0.751	-4.419	0.00					

Stepwise regression analysis for wheat flour torque.

Models	Coefficients		T-test	Prob.	Adjusted R ²	Std. Error	F value	Prob.	VIF
1	B ₀	7.505	16.008	0.000	0.652	1.65	62.815	0.000	1.000
	ds	-0.001	-7.926	0.005					
2	B ₀	10.135	13.531	0.000	0.767	1.35	55.201	0.000	1.072
	ds	-0.001	-8.291	0.000					
	sm	-0.001	-4.089	0.000					
3	B ₀	12.536	15.363	0.003	0.851	1.80	64.021	0.000	9.368
	ds	0.000	0.553	0.000					
	sm	-0.001	-6.702	0.000					
	Dt	-0.224	-4.322	0.000					
4	B ₀	15.235	19.775	0.000	0.918	0.80	123.640	0.000	3.095
	sm	-0.002	-10.524	0.000					
	Dt	-0.389	-9.546	0.000					
	dsm	4.02E-005	4.972	0.000					
5	B ₀	16.415	29.636	0.000	0.963	0.54	213.683	0.000	4.827
	sm	-0.001	-8.861	0.000					
	Dt	-0.389	-14.128	0.000					
	dsm	4.00E-005	7.354	0.000					
	Ss	-0.023	-6.093	0.000					
6	B ₀	22.467	28.263	0.000	0.977	0.42	355.308	0.000	9.484
	sm	4.88E-005	0.166	0.870					
	Dt	-0.392	-17.963	0.000					
	dsm	4.09E-005	9.788	0.000					
	Ss	-0.059	-21.882	0.000					
	Mc	-0.186	-12.143	0.000					

Stepwise regression analysis for maize flour product temperature.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	65.065	32.084	0.000	0.722	11.20	348.720	0.000	1.000
	Dt	2.083	18.874	0.000					
2	B ₀	81.398	21.684	0.000	0.765	10.30	218.583	0.000	1.000
	Dt	2.083	20.298	0.000					
	Dt	-0.109	-0.109	0.000					

Stepwise regression analysis for wheat flour mean residence time.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	Bo	63.071	28.243	0.000	0.874	3.41	228.926	0.000	1.000
	Ss	-0.215	-15.130	0.000					

Stepwise regression analysis for wheat flour product moisture.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	-3.615	-2.426	0.017	0.773	3.36	458.411	0.000	1.000
	Mc	0.986	21.411	0.000					
2	B ₀	-1.806	-1.202	0.231	0.794	3.21	258.488	0.000	1.000
	Mc	0.989	22.496	0.000					
	Dt	-0.119	-3.734	0.000					

Stepwise regression analysis for wheat flour expansion ratio.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	-0.513	0.873	0.384	0.122	0.129	19.705	0.000	1.000
	Mc	0.018	4.439	0.000					

Stepwise regression analysis for wheat flour compressive strength.

Models	Coefficients		T-test	Prob.	Adjusted R	F value	Prob.	VIF
1	B ₀	66.211	48.156	0.000	0.951	652.951	0.000	1.000
	Ss	-0.226	-25.553	0.000				
2	B ₀	64.562			0.965	454.311	0.000	1.000
	Ss	-0.226						
	Dt	0.110						

Stepwise regression analyses for wheat flour relative melt viscosity.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	7.174	9.861	0.000	0.671	0.33	19.322	0.000	1.000
	Mc	-0.090	-4.396	0.002					
2	B ₀	7.174	19.102	0.000	0.912	0.17	47.768	0.000	1.000
	Mc	-0.078	-7.165	0.000					
	dm	-0.001	-4.798	0.002					

Stepwise regression analysis for wheat flour water absorption index.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	2.807	7.357	0.000	0.559	0.72	13.671	0.005	1.000
	Dt	0.076	3.697	0.005					
2	B ₀	1.216	6.099	0.000	0.782	0.11	18.962	0.001	1.058
	Dt	-0.014	-4.614	0.002					
	Mc	-0.017	-2.882	0.020					
3	B ₀	-2.910	-4.446	0.003	0.954	0.23	70.070	0.000	35.319
	Dt	0.317	8.065	0.000					
	Mc	0.177	8.892	0.000					
	dm	-0.008	-6.484	0.000					

Stepwise regression analysis for wheat flour water solubility index.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	-0.120	-2.355	0.035	0.476	0.38	13.727	0.003	1.000
	Mc	0.006	3.705	0.003					

Stepwise regression analysis for wheat flour cold paste viscosity.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	1.621	8.317	0.000	0.674	0.37	21.640	0.001	1.000
	Dt	-0.049	-4.652	0.001					

Table 5.61 Stepwise regression analysis for wheat flour hot paste viscosity.

Models	Coefficients		T-test	Prob.	Adjusted R	Std. Error	F value	Prob.	VIF
1	B ₀	0.664	8.777	0.000	0.605	0.14	16.347	0.003	1.000
	Dt	-0.016	-4.043	0.003					
2	B ₀	1.216	6.099	0.000	0.782	0.11	18.962	0.001	1.058
	Dt	-0.014	-4.614	0.002					
	Mc	-0.017	-2.882	0.020					
3	B ₀	1.800	15.154	0.000	0.966	0.04	94.511	0.000	35.319
	Dt	0.061	-8.513	0.000					
	Mc	-0.035	-9.733	0.000					
	d _m	0.001	6.604	0.000					

APPENDIX 6

RESULT OF ONE WAY ANALYSIS OF VARIANCE

Least Significant Means of Products for Product Temperature.

SS	MC	GRP	PRODUCTS				
			CS	CF	MS	MF	WF
150	1	2	-10.6	15.6*	-17.933*	-7.333 ^{NS}	-10.533
		3	8.067	25.533**	3.667*	4.600 ^{NS}	-5.467
	2	1	10.6	-15.6*	17.933	7.333 ^{NS}	10.533
		3	18.667*	9.933	21.6*	11.933*	5.067
	3	1	-8.067	-25.533**	-3.667	-4.600 ^{NS}	5.467
		2	-18.667*	-9.933	-21.6*	-11.933*	-5.067
100	1	2	-11.133	13.467	-27.533*	-14.667*	-13.533*
		3	-4.533	35.933**	-12.6	-5.000 ^{NS}	0
	2	1	11.133	-13.467	27.533*	14.667*	13.533*
		3	6.6	22.467	14.933	9.667 ^{NS}	13.533*
	3	1	4.533	-35.933**	12.6	5.000 ^{NS}	0
		2	-6.6	-22.467**	-14.933	-9.667 ^{NS}	-13.533*
200	1	2	0.667	10.733	-9.867	-11.800*	-18.067**
		3	2.133	17.533*	-4.4	-6.000 ^{NS}	-2.267
	2	1	-0.667	-10.733	9.867	11.800*	18.067**
		3	1.467	6.8	5.467	5.800 ^{NS}	15.8*
	3	1	-2.133	-17.533**	4.4	6.000 ^{NS}	2.267
		2	-1.467	-6.8	-5.467	-5.800 ^{NS}	-15.8*

Significant at * $P \leq 0.05$; ** $P \leq 0.01$, pc - protein content, sc - starch content, Mc - Moisture content, Ss - screw speed Dt - duration of operation, PT Product temp ($^{\circ}\text{C}$). GRP - group, CS - Cassava starch, CF- Cassava flour, MS- Maize starch, MF- Maize flour, WF- Wheat flour (-ve means negative but sig effect)

Least Significant Means of Products for SME

SS	MC	GRP	PRODUCTS				
			CS	CF	MS	MF	WF
150	1	2	21.8600	31.003	7.900	-2.93867	1.20250
		3	38.8350	18.330	10.213	-.56800	2.07750
	2	1	-21.8600	-31.003	-7.900	2.93867	-1.20250
		3	16.9750	-12.673	2.313	2.37067	.87500
	3	1	-38.8350	-18.330	-10.213	.56800	-2.07750
		2	-16.9750	12.673	-2.313	-2.37067	-.87500
100	1	2	14.4875	11.820	5.27750	-2.64200	.5200
		3	71.3350	35.503	8.24250	-2.20533	1.1700
	2	1	-15.4875	-11.820	-5.27750	2.64200	-.5200
		3	71.8475	23.683	2.96500	.43667	.6500
	3	1	-27.3350	-35.503	-8.24250	2.20533	-1.1700
		2	-11.8475	-23.683	-2.96500	-.43667	-.6500
200	1	2	-4.59625	47.180	3.164500	-2.74800	.62750
		3	2.55025	27.015	3.206000	-1.24533	1.06125
	2	1	4.59625	-47.180	-3.1645	2.74800	-.62750
		3	7.14650	-20.165	.041500	1.50267	.43375
	3	1	-2.55025	-27.015	-3.206	1.24533	-1.06125
		2	-7.14650	20.165	-.041500	-1.50267	-.43375

Significant at *P ≤ 0.05; ** P ≤ 0.01, pc - protein content, sc - starch content, Mc - Moisture content, Ss - screw speed Dt - duration of operation, PT Product temp (°C). GRP - group, CS - Cassava starch, CF- Cassava flour, MS- Maize starch, MF- Maize flour, WF- Wheat flour (-ve means negative but sig effect)

Least significant means of products for TORQUE

			CS	CF	MS	MF	WF
150	1	2	20.210	5.850	7.900*	-2.939*	1.203
		3	37.185*	10.225	10.213	-.568*	2.078
	2	1	-20.210	-5.850	-7.900	2.939*	-1.203
		3	16.975*	4.375	2.313	2.371	.875
	3	1	-37.185	-10.225	-10.213*	.568*	-2.077
		2	-16.975	-4.385	-2.313	-2.371	-.875
100	1	2	4.588*	2.875	5.278	-2.642*	.520
		3	16.435	6.568	8.243*	-2.205*	1.170
	2	1	-4.588*	-2.875	-5.278	2.642	-.520
		3	11.848	3.693	2.965	.437*	.650
	3	1	-16.435	-6.568	-8.243*	2.205	-1.170
		2	-11.848	-3.693	-2.965	-.437*	-.6500
200	1	2	-.769	2.649	3.165	-2.748*	.628
		3	6.378	4.044	3.206	-1.245	1.061
	2	1	.769	-2.648	-3.165	2.74800*	-.628
		3	7.147	1.397	.042	1.50267	.434
	3	1	-6.378	-4.044	-3.206	1.24533*	-1.061
		2	-7.147	-1.397	-.042	-1.50267	-.434

Significant at * $P \leq 0.05$; ** $P \leq 0.01$, pc - protein content, sc - starch content, Mc - Moisture content, Ss - screw speed Dt - duration of operation, PT Product temp ($^{\circ}\text{C}$). GRP - group, CS - Cassava starch, CF- Cassava flour, MS- Maize starch, MF- Maize flour, WF- Wheat flour (-ve means negative but sig effect)

Least significant means of products for MRT

SS	MC	GRP	PRODUCTS				
			CS	CF	MS	MF	WF
150	1	2	4.175	.200	4.125*	1.275*	-8.900*
		3	6.450*	.325	4.375*	1.600*	-8.175*
	2	1	-4.175	-.200	-4.125*	-1.275*	8.900*
		3	2.275	.125	.250	.325	.725
	3	1	-6.450*	-.325	-4.375*	-1.600*	8.175*
		2	-2.275	-.125	-.250	-.325	-.725
100	1	2	1.250	.325	.325	1.100	1.805*
		3	2.625	.820	.517*	2.250	2.005*
	2	1	-1.250	-.325	-.325	-1.100	-1.805*
		3	1.375	.500	.192	1.150	.200
	3	1	-2.625*	-.825	-.517*	-2.250	-2.005*
		2	-1.375	-.500	-.192	-1.150	-.200
200	1	2	-.550	.475	.250	.575*	-8.900*
		3	.250	1.075	.400*	.700*	-8.175*
	2	1	.550	-.475	-.250	-.575*	8.900*
		3	.800	.600	.150	.125	.725
	3	1	-.250	-1.075	-.400*	-.700*	8.175*
		2	-.800	-.600	-.042	-.125	-.725

Significant at * $P \leq 0.05$; ** $P \leq 0.01$, pc - protein content, sc - starch content, Mc - Moisture content, Ss - screw speed Dt - duration of operation, PT Product temp ($^{\circ}\text{C}$). GRP - group, CS - Cassava starch, CF- Cassava flour, MS- Maize starch, MF- Maize flour, WF- Wheat flour (-ve means negative but sig effect)

Physical properties

Least significant means of products for product moisture

SS	MC	GRP	PRODUCTS				
			CS	CF	MS	MF	WF
100	1	2	-3.839**	-.375	-.844**	.000	-1.572**
		3	-.676	2.119**	.000	-2.748**	-1.702**
	2	1	3.839**	.375	.844**	.000	1.572**
		3	3.163**	2.493**	.844**	-2.748**	-.130
	3	1	.676	-2.119**	.000	2.748**	1.702**
		2	-3.163**	-2.493**	-.844**	2.748**	.1300
150	1	2	-4.585**	.666	-.404**	.000	-1.773**
		3	-4.024**	2.310*	-.267*	-2.939**	-1.358**
	2	1	4.585**	-.666	.404**	.000	1.773**
		3	.561**	1.644*	.137	-2.939**	.415
	3	1	4.024	-2.310*	.267*	2.939**	1.358**
		2	-.561**	-1.644*	-.137	2.939**	-.415**
200	1	2	-5.053	.253	-.237**	.000	-1.570**
		3	-1.653*	.441	-.033	-2.642**	-1.436
	2	1	5.053**	-.253	.237**	.000	1.570**
		3	3.399**	.188	.204**	-2.642**	.134
	3	1	1.653*	-.44133	.033	2.642**	1.43600
		2	-3.399**	-.18800	-.204**	2.642**	-.13400

Significant at *P ≤ 0.05;** P≤0.01, pc - protein content, sc - starch content, Mc - Moisture content, Ss – screw speed Dt - duration of operation, PT Product temp (°C). GRP – group, CS – Cassava starch, CF- Cassava flour, MS- Maize starch, MF- Maize flour, WF- Wheat flour (-ve means negative but sig effect)

Least significant means of products for expansion ratio

SS	MC	GRP	PRODUCTS				
			CS	CF	MS	MF	WF
150	1	2	21.860	31.003	7.900	-2.939**	1.203
		3	38.835*	18.330	10.213*	-.568	2.078
	2	1	-21.860	-31.003	-7.900	2.939**	-1.203
		3	16.975	-12.673	2.313	2.371**	.875
	3	1	-38.835*	-18.330	-10.213*	.568	-2.078
		2	-16.975	12.673	-2.313	-2.371**	-.875
100	1	2	15.488	11.820	5.278	-2.642**	.520
		3	27.335*	35.503	8.243*	-2.205**	1.17
	2	1	-15.488	-11.820	-5.278	2.642**	-.520
		3	11.848	23.683	2.965	.43667	.650
	3	1	-27.335*	-35.503	-8.243*	2.205**	-1.170
		2	-11.848	-23.683	-2.965	-.437	-.650
200	1	2	-4.597	47.180	3.165	-2.748**	.628
		3	2.550	27.015	3.206	-1.245*	1.061
	2	1	4.596	-47.180	-3.165	2.748**	-.628
		3	7.147	-20.165	0.042	1.503*	.434
	3	1	-2.550	-27.015	-3.206	1.245*	-1.061
		2	-7.145	20.165	-0.042	-1.503*	-.4338

Significant at * $P \leq 0.05$; ** $P \leq 0.01$, pc - protein content, sc - starch content, Mc - Moisture content, Ss - screw speed Dt - duration of operation, PT Product temp ($^{\circ}\text{C}$). GRP - group, CS - Cassava starch, CF- Cassava flour, MS- Maize starch, MF- Maize flour, WF- Wheat flour (-ve means negative but sig effect)

SS MCGRP		PRODUCTS				
		CS	CF	MS	MF	WF
1001	2	-1277.425**	333.225	-57.105	-198.725*	-143.725*
	3	-1242.075**	122.025	-71.200	-195.293*	-91.930
	2	1277.425**	-333.225	57.105	198.725*	143.725*
	3	35.350	-211.200	-14.095	3.435	51.795
	3	1242.075**	-122.025	71.200	195.293*	91.930
	2	-35.350	211.200	14.095	-3.433	-51.795
1501	2	-525.700**	-56.215	-44.100	-25.488	-179.575*
	3	-680.900	-238.590	-93.513*	-80.463	-121.850
	2	525.700*	56.215	44.100	25.488	179.575*
	3	-155.200	-182.375	-49.413	-54.975	57.725
	3	680.900*	238.590	93.513*	80.463	121.850
	2	155.200	182.375	49.413	54.975	-57.725
2001	2	859.100*	285.250	-75.675	-187.300	-134.295
	3	1248.225*	464.250	-83.850	-224.675*	-22.825
	2	-859.100*	-285.250	75.675	187.300	134.295
	3	389.125	179.000	-8.175	-37.375	111.470
	3	-1248.225*	-464.250	83.850	224.6750*	22.825
	2	-389.1250	-179.000	8.175	37.3750	-111.470

Significant at * $P \leq 0.05$; ** $P \leq 0.01$, pc - protein content, sc - starch content, Mc - Moisture content, Ss - screw speed Dt - duration of operation, PT Product temp ($^{\circ}\text{C}$). GRP - group, CS - Cassava starch, CF- Cassava flour, MS- Maize starch, MF- Maize flour, WF- Wheat flour (-ve means negative but sig effect).

Rheological behavior

Least significant means of products for melt viscosity

SS	MC	GRP	PRODUCTS		
			CS	CF	MS
100	1	2	-4.504**	3.272*	-.066
		3	-2.410*	1.760	-.034
	2	1	4.504**	-3.272*	.066
		3	2.094*	-1.512	.032
	3	1	2.410*	-1.760	.034
		2	-2.094*	1.512	-.032

Significant at * $P \leq 0.05$; ** $P \leq 0.01$, pc - protein content, sc - starch content, Mc - Moisture content, Ss - screw speed Dt - duration of operation, PT Product temp ($^{\circ}\text{C}$). GRP - group, CS - Cassava starch, CF- Cassava flour, MS- Maize starch, MF- Maize flour, WF- Wheat flour (-ve means negative but sig effect)

Functional properties

Least significant means of products for water absorption index

SS MCGRP			PRODUCTS		
		CS	CF	MS	MF
1001	2	2.637*	-2.444*	-2.216*	-0.437
	3	0.432	-0.961	-1.780*	-0.612*
2	1	-2.637*	2.444*	2.216*	0.437
	3	-2.205*	1.484	0.437	-0.175
3	1	-0.432	0.961	1.780*	0.612*
	2	2.205*	-1.484	-0.437	0.175

Significant at * $P \leq 0.05$; ** $P \leq 0.01$, pc - protein content, sc - starch content, Mc - Moisture content, Ss - screw speed Dt - duration of operation, PT Product temp ($^{\circ}\text{C}$). GRP - group, CS - Cassava starch, CF- Cassava flour, MS- Maize starch, MF- Maize flour, WF- Wheat flour (-ve means negative but sig effect)

Least significant means of products for water solubility index

MC	GRP	PRODUCTS		
		CS	CF	MS
1	2	-.256000	.107600	.0152
	3	-.183200	.056200	.0232
2	1	.256000	-.107600	-.0152
	3	.072800	-.051400	.0080
3	1	.183200	-.056200	-.0232
	2	-.072800	.051400	-.0080

Significant at * $P \leq 0.05$; ** $P \leq 0.01$, pc - protein content, sc - starch content, Mc - Moisture content, Ss - screw speed Dt - duration of operation, PT Product temp ($^{\circ}\text{C}$). GRP - group, CS - Cassava starch, CF- Cassava flour, MS- Maize starch, MF- Maize flour, WF- Wheat flour (-ve means negative but sig effect)

Pasting properties

Least significant means of products for cold paste viscosity

MC GRP		PRODUCTS		
		CS	CF	MS
1	2	6.74540	-2.164600	4.99200
	3	6.88340	-1.230000	4.94600
2	1	-6.74540	2.164600	-4.99200
	3	.13800	.934600	-.04600
3	1	-6.88340	1.230000	-4.94600
	2	-.13800	-.934600	.04600

Least significant means of products for hot paste viscosity

SS	MC	GRP	PRODUCTS				
100	1	2	CS	CF	MS	WF	MF
		3	3.553*	-.791	4.992	-4.360**	-.757**
	2	1	1.365	-.413	4.946	-3.530**	-.779**
		3	-3.553*	.791	-4.992	4.360**	-.552**
	3	1	-2.188	.378	-.046	.830**	.757**
		2	-1.365	.413	-4.946	3.530**	-.022
			2.188	-.378	.046	-.830**	.205*

Computer Programme developed for the Response Surface Regression

```

options ls=100 ps=1000 nocenter pageno=1;
PROC IMPORT OUT= WORK.summary3
DATAFILE= "C:\Documents and Settings\Desktop\Summary 3.xls"
        DBMS=EXCEL REPLACE;
        SHEET="Sheet5$";
        GETNAMES=YES;
        MIXED=NO;
        SCANTEXT=YES;
        USEDATE=YES;
        SCANTIME=YES;
        RUN;
proc sort data=work.summary3;
by Proco    Staco    MC    SS    Duration;
run;
title1 'Fitting Response Surface Regression Model- pm = Proco    Staco    MC    SS    Duration
proc rsreg data=WORK.summary3;
model pm = Proco    Staco    MC    SS    Duration /lackfit;
        ridge max;
        run;
        quit;
proc reg data=work.summary3;
model pm = Proco    Staco    MC    SS    Duration;
output out=results p=yhat r=residual rstudent=rstudent h=hatvalue;
run;
proc sort data=work.summary3;
by Proco    Staco    MC    SS    Duration;
run;
title1 'Fitting Response Surface Regression Model- pm = Proco    Staco    MC    SS    Duration
proc rsreg data=WORK.summary3;
model pm = Proco    Staco    MC    SS    Duration /lackfit;
        ridge max;

```

```

run;
quit;
proc reg data=work.summary3;
model pm = Proco Staco MC SS Duration;
output out=results p=yhat r=residual rstudent=rstudent h=hatvalue;
run;
quit;
data fit;
set results;
if pm=.;
pm=yhat;
run;
goptions reset=global gunit=pct border ftext=swissb htitle=6 htext=3;
proc g3d data=fit;
plot proco*Staco=pm/grid caxis=blue xticknum=7 yticknum=9 zticknum=6;
run;
goptions reset=global gunit=pct
cback=white colors=(black blue green red)
htitle=6 htext=3 ftext=zapf border;
proc gcontour data=work.summary3;
plot proco*Staco=pm;
run;
PROC IMPORT OUT= WORK.quality
DATAFILE= "C:\Documents and Settings\Desktop\PRODUCT Quality.xls"
DBMS=EXCEL REPLACE;
SHEET="Sheet2$";
GETNAMES=YES;
MIXED=NO;
SCANTEXT=YES;
USEDATE=YES;
SCANTIME=YES;
RUN;
proc sort data=work.quality;
by Proco staco MC Duration;

```

run;

title1 'Fitting Response Surface Regression Model- WAI-WSI = Proco staco MC Duration

proc rsreg data=WORK.quality;

model WAI WSI = Proco staco MC Duration/lackfit;

ridge max;

run;

quit;

PROC IMPORT OUT= WORK.fayose

DATAFILE= "C:\Documents and Settings\desktop\FAYOSE EDIT.xls"

DBMS=EXCEL REPLACE;

SHEET="2101830\$";

GETNAMES=YES;

MIXED=NO;

SCANTEXT=YES;

USEDATE=YES;

SCANTIME=YES;

RUN;

proc sort data=work.;

by Pc Sc Mc Ss Dt ;

run;

title1 'Fitting Response Surface Regression Model- Na Tq SME MRTs = Pc Sc Mc Ss Dt';

proc rsreg data=WORK;

model Na Tq SME MRTs Cs = Pc Sc Mc Ss Dt /lackfit;

ridge max;

run;

quit;

APPENDIX 8

Fitting Response Surface Regression Model - Product Moisture

pm = Proco Staco MC SS Duration 1

The RSREG Procedure

Coding Coefficients for the Independent Variables

Factor	Subtracted off	Divided by
Proco	6.655000	6.345000
Staco	84.895000	11.495000
MC	37.500000	12.500000
SS	150.000000	50.000000
Duration	16.000000	14.000000

Response Surface for Variable PM: PM

Response Mean	27.458420
Root MSE	3.204736
R-Square	0.8526
Coefficient of Variation	11.6712

Type I Sum

Regression	DF	of Squares	R-Square	F Value	Pr > F
Linear	5	37822	0.8090	736.54	<.0001
Quadratic	4	1052.9847	0.0225	25.63	<.0001
Crossproduct	10	984.27645	0.0211	9.58	<.0001
Total Model	19	39860	0.8526	204.27	<.0001

Sum of

Residual	DF	Squares	Mean Square	F Value	Pr > F
Lack of Fit	670	6827.210117	10.189866	0.16	0.9877
Pure Error	1	64.184450	64.184450		
Total Error	671	6891.394567	10.270335		

Parameter
Estimate

Parameter	DF	Estimate	Standard		from Coded	
			Error	t Value	Pr > t	Data
Intercept	1	48.408465	27.745163	1.74	0.0815	32.061492
Proco	1	7.499397	2.158482	3.47	0.0005	-6.052182
Staco	1	-0.383463	0.284548	-1.35	0.1782	-7.416898
MC	1	-0.696895	0.604535	-1.15	0.2494	11.538921
SS	1	-0.105097	0.096877	-1.08	0.2784	-0.106241
Duration	1	1.404454	0.439337	3.20	0.0015	-3.320687
Proco*Proco	1	-0.198909	0.039336	-5.06	<.0001	-8.007890
Staco*Proco	1	-0.082777	0.019483	-4.25	<.0001	-6.037368
Staco*Staco	0	0	.	.	0	.
MC*Proco	1	0.040175	0.010564	3.80	0.0002	3.186380
MC*Staco	1	0.015035	0.006139	2.45	0.0146	2.160371
MC*MC	1	0.003921	0.002379	1.65	0.0999	0.612613
SS*Proco	1	0.000395	0.001614	0.24	0.8066	0.125432
SS*Staco	1	0.000156	0.000938	0.17	0.8682	0.089526
SS*MC	1	-0.000399	0.000401	-1.00	0.3197	-0.249413
SS*SS	1	0.000355	0.000104	3.42	0.0007	0.887316
Duration*Proco	1	-0.021520	0.007612	-2.83	0.0048	-1.911640
Duration*Staco	1	-0.018630	0.004427	-4.21	<.0001	-2.998056
Duration*MC	1	-0.009873	0.001886	-5.24	<.0001	-1.727737
Duration*SS	1	-0.000275	0.000344	-0.80	0.4253	-0.192333
Duration*Duration	1	0.015455	0.001840	8.40	<.0001	3.029252

Sum of

Factor	DF	Squares	Mean Square	F Value	Pr > F	Label
Proco	6	1791.998289	298.666382	29.08	<.0001	Proco
Staco	5	1299.998434	259.999687	25.32	<.0001	Staco
MC	6	27615	4602.496797	448.14	<.0001	MC

SS	6	136.906467	22.817745	2.22	0.0394	SS
Duration	6	4231.490545	705.248424	68.67	<.0001	Duration

Canonical Analysis of Response Surface Based on Coded Data

Critical Value

Factor	Coded	Uncoded	Label
Proco	-4.222554	-20.137103	Proco
Staco	5.435410	147.375043	Staco
MC	-9.476832	-80.960395	MC
SS	-1.338783	83.060850	SS
Duration	-0.839584	4.245830	Duration

Predicted value at stationary point: -28.528711

Eigenvectors

Eigenvalues	Proco	Staco	MC	SS	Duration
4.082740	-0.014315	-0.393210	-0.340825	-0.018178	0.853633
0.934366	-0.016150	-0.048667	-0.291492	0.947770	-0.118888
0.551692	-0.287021	0.793938	0.229367	0.163616	0.455962
0.436126	0.254702	-0.323131	0.846445	0.273064	0.199197
-9.483633	0.923190	0.329037	-0.172602	-0.008170	0.097959

Stationary point is a saddle point.

Estimated Ridge of Maximum Response for Variable PM: PM

	Coded	Estimated	Standard	Uncoded Factor Values			
Radius	Response	Error	Proco	Staco	MC	SS	Duration
0.0	32.061492	0.557486	6.655000	84.895000	37.500000	150.000000	16.000000
0.1	33.562395	0.610203	6.441924	84.349305	38.475177	149.955324	15.677201
0.2	35.007284	0.658434	6.299302	83.831600	39.510053	149.890350	15.308954
0.3	36.414593	0.703445	6.217860	83.353863	40.585792	149.806264	14.886837
0.4	37.799912	0.746251	6.185784	82.925716	41.685507	149.705752	14.401968
0.5	39.176127	0.787430	6.191398	82.554910	42.795446	149.592566	13.845400

0.6	40.553987	0.827181	6.224456	82.247931	43.904437	149.471191
			13.208862			
0.7	41.942737	0.865461	6.276443	82.010148	45.002904	149.346573
			12.485833			
0.8	43.350625	0.902157	6.340459	81.845428	46.082187	149.223811
			11.672785			
0.9	44.785217	0.937263	6.411026	81.755470	47.134444	149.107733
			10.770223			
1.0	46.253545	0.971060	6.483942	81.739242	48.153004	149.002433
			9.783099			

APPENDIX 9

Fitting Response Surface Regression Model-WAI

$$\text{WAI} = \text{Proco} \text{ staco} \text{ MC} \text{ Duration}$$

Coding Coefficients for the Independent Variables

Factor	Subtracted off	Divided by
Proco	6.655000	6.345000
staco	84.895000	11.495000
MC	37.500000	12.500000
Duration	15.000000	15.000000

Response Surface for Variable WAI: WAI

Response Mean	4.695171
Root MSE	1.112913
R-Square	0.5424
Coefficient of Variation	23.7033

Type I Sum

Regression	DF	of Squares	R-Square	F Value	Pr > F
Linear	4	46.435972	0.3063	9.37	<.0001
Quadratic	3	12.169874	0.0803	3.28	0.0276
Crossproduct	6	23.621643	0.1558	3.18	0.0094
Total Model	13	82.227489	0.5424	5.11	<.0001

Sum of

Residual	DF	Squares	Mean Square	F Value	Pr > F
Lack of Fit	56	69.360177	1.238575	-	
Pure Error	0	0			
Total Error	56	69.360177	1.238575		

Parameter

Estimate

Standard

from Coded

Parameter	DF	Estimate	Error	t Value	Pr > t	Data
Intercept	1	27.990006	25.339291	1.10	0.2741	2.803478
Proco	1	-8.212656	2.750358	-2.99	0.0042	5.359573
staco	1	-0.252617	0.258147	-0.98	0.3320	5.929214
MC	1	-1.203730	0.678393	-1.77	0.0814	1.352182
Duration	1	1.128099	0.383710	2.94	0.0048	0.478943

Proco*Proco	1	0.185514	0.055938	3.32	0.0016	7.468612
staco*Proco	1	0.070520	0.024686	2.86	0.0060	5.143442
staco*staco	0	0	.	.	0	.
MC*Proco	1	0.021389	0.010725	1.99	0.0510	1.696429
MC*staco	1	0.012232	0.006733	1.82	0.0746	1.757575
MC*MC	1	0.001830	0.002768	0.66	0.5114	0.285874
Duration*Proco	1	-0.013383	0.006409	-2.09	0.0414	-1.273730
Duration*staco	1	-0.010639	0.003889	-2.74	0.0083	-1.834421
Duration*MC	1	-0.000406	0.001700	-0.24	0.8121	-0.076116
Duration*Duration	1	-0.002956	0.001587	-1.86	0.0678	-0.665165

Sum of

Factor	DF	Squares	Mean Square	F Value	Pr > F	Label
Proco	5	35.945746	7.189149	5.80	0.0002	Proco
staco	4	37.343310	9.335828	7.54	<.0001	staco
MC	5	42.156161	8.431232	6.81	<.0001	MC
Duration	5	14.927309	2.985462	2.41	0.0476	Duration

Fitting Response Surface Regression Model-WAI-WSI = Proco staco MC Duration

The RSREG Procedure

Canonical Analysis of Response Surface Based on Coded Data

Critical Value

Factor	Coded	Uncoded	Label
Proco	-0.104790	5.990105	Proco
staco	0.246901	87.733127	staco
MC	-2.775948	2.800647	MC
Duration	0.278722	19.180832	Duration

Predicted value at stationary point: 1.444579

Eigenvectors

Eigenvalues	Proco	staco	MC	Duration
8.496002	0.937573	0.307694	0.130246	-0.096525
0.472820	-0.280938	0.437016	0.824949	-0.222597
-0.291646	0.151317	-0.429942	0.481322	0.748720
-1.587853	-0.138325	0.727661	-0.266129	0.616888

Stationary point is a saddle point.

Fitting Response Surface Regression Model-WAI-WSI = Proco staco MC Duration

The RSREG Procedure

Estimated Ridge of Maximum Response for Variable WAI: WAI

Coded Radius	Estimated Response	Standard Error	Uncoded Factor Values			
			Proco	staco	MC	Duration
0.0	2.803478	0.741448	6.655000	84.895000	37.500000	15.000000
0.1	3.679457	0.595398	7.112901	85.665763	37.712274	15.041196
0.2	4.695305	0.451618	7.625748	86.323384	37.924075	15.014381
0.3	5.862905	0.379086	8.169348	86.902052	38.129927	14.947793
0.4	7.188921	0.487168	8.730467	87.426847	38.329216	14.857472
0.5	8.677206	0.751763	9.302030	87.914291	38.522739	14.752340
0.6	10.330098	1.106068	9.880135	88.375121	38.711514	14.637515
0.7	12.149080	1.524397	10.462527	88.816447	38.896449	14.516068
0.8	14.135134	1.998341	11.047842	89.243103	39.078281	14.389927
0.9	16.288935	2.524736	11.635219	89.658467	39.257589	14.260350
1.0	18.610961	3.102227	12.224093	90.064964	39.434829	14.128192

APPENDIX 10

Fitting Response Surface Regression Model- WSI

Response Surface for Variable WSI: WSI

Response Mean 0.146264

Root MSE 0.063605

R-Square 0.8085

Coefficient of Variation 43.4863

Type I Sum

Regression	DF	of Squares	R-Square	F Value	Pr > F
Linear	4	0.485298	0.4102	29.99	<.0001
Quadratic	3	0.379347	0.3206	31.26	<.0001
Crossproduct	6	0.091937	0.0777	3.79	0.0031
Total Model	13	0.956583	0.8085	18.19	<.0001

Sum of

Residual	DF	Squares	Mean Square	F Value	Pr > F
Lack of Fit	56	0.226553	0.004046		
Pure Error	0	0			
Total Error	56	0.226553	0.004046		

Parameter

Estimate

Standard

from Coded

Parameter	DF	Estimate	Error	t Value	Pr > t	Data
Intercept	1	-7.093355	1.448186	-4.90	<.0001	-0.143923
Proco	1	0.059361	0.157188	0.38	0.7071	0.502735
staco	1	0.071831	0.014754	4.87	<.0001	0.593677
MC	1	0.092849	0.038771	2.39	0.0200	0.004341
Duration	1	-0.066852	0.021930	-3.05	0.0035	0.001807
Proco*Proco	1	0.007337	0.003197	2.30	0.0255	0.295396
staco*Proco	1	-0.000415	0.001411	-0.29	0.7700	-0.030237
staco*staco	0	0	.	.	0	
MC*Proco	1	-0.001587	0.000613	-2.59	0.0123	-0.125844
MC*staco	1	-0.000773	0.000385	-2.01	0.0493	-0.111122
MC*MC	1	-0.000176	0.000158	-1.11	0.2705	-0.027512
Duration*Proco	1	0.001127	0.000366	3.08	0.0032	0.107280

Duration*staco	1	0.000772	0.000222	3.47	0.0010	0.133059
Duration*MC	1	-0.000206	0.000097150	-2.12	0.0388	-0.038536
Duration*Duration	1	0.000055525	0.000090727	0.61	0.5430	0.012493

Sum of

Factor	DF	Squares	Mean Square	F Value	Pr > F	Label
Proco	5	0.678724	0.135745	33.55	<.0001	Proco
staco	4	0.685281	0.171320	42.35	<.0001	staco
MC	5	0.054796	0.010959	2.71	0.0292	MC
Duration	5	0.123763	0.024753	6.12	0.0001	Duration

Canonical Analysis of Response Surface Based on Coded Data

Critical Value

Factor	Coded	Uncoded	Label
Proco	0.052214	6.986296	Proco
staco	0.887493	95.096732	staco
MC	0.809925	47.624067	MC
Duration	-3.773503	-41.602546	Duration

Predicted value at stationary point: 0.130993

Eigenvectors

Eigenvalues	Proco	staco	MC	Duration
0.317819	0.963385	0.026587	-0.190251	0.187048
0.085687	-0.199934	0.708980	-0.336685	0.586530
-0.028863	0.010878	-0.232018	0.693333	0.682157
-0.094266	0.178318	0.665439	0.608060	-0.394534

Stationary point is a saddle point.

Estimated Ridge of Maximum Response for Variable WSI: WSI

Coded	Estimated	Standard	Uncoded Factor Values			
Radius	Response	Error	Proco	staco	MC	Duration
0.0	-0.143923	0.042375	6.655000	84.895000	37.500000	15.000000
0.1	-0.064958	0.034116	7.082714	85.743450	37.480756	15.035485

0.2	0.016699	0.026030	7.544568	86.529523	37.412673	15.130760
0.3	0.101565	0.021402	8.037570	87.248714	37.302285	15.277893
0.4	0.190120	0.026051	8.557665	87.900290	37.156860	15.467841
0.5	0.282788	0.039597	9.100382	88.486725	36.983510	15.691650
0.6	0.379936	0.058389	9.661380	89.012692	36.788581	15.941301
0.7	0.481876	0.080856	10.236791	89.484033	36.577366	16.210109
0.8	0.588862	0.106474	10.823368	89.906932	36.354075	16.492775
0.9	0.701105	0.135036	11.418490	90.287372	36.121953	16.785247
1.0	0.818779	0.166440	12.020095	90.630847	35.883446	17.084501

APPENDIX 11

Fitting Response Surface Regression Model- SME

Coding Coefficients for the Independent Variables

Factor	Subtracted off	Divided by
Pc	6.655000	6.345000
Sc	84.895000	11.495000
Mc	37.500000	12.500000
Ss	150.000000	50.000000
Dt	16.000000	14.000000

Response Surface for Variable SME: SME

Response Mean	59.560618
Root MSE	30.398984
R-Square	0.6567
Coefficient of Variation	51.0387

Type I Sum

Regression	DF	of Squares	R-Square	F Value	Pr > F
Linear	5	158115	0.3717	34.22	<.0001
Quadratic	4	32011	0.0753	8.66	<.0001
Crossproduct	10	89225	0.2098	9.66	<.0001
Total Model	19	279351	0.6567	15.91	<.0001

Sum of

Residual	DF	Squares	Mean Square	F Value	Pr > F
Lack of Fit	158	146008	924.098252	.	.
Pure Error	0	0	.	.	.
Total Error	158	146008	924.098252		

Parameter
Estimate

Parameter Standard

from Coded

DF	Estimate	Error	t Value	Pr > t	Data	
Intercept	1	-1391.177827	510.863417	-2.72	0.0072	12.870292
Pc	1	165.209893	41.198178	4.01	<.0001	76.272877
Sc	1	15.437443	5.252534	2.94	0.0038	110.240281

Mc	1	-3.376566	11.215423	-0.30	0.7638	-25.580498
Ss	1	3.186023	1.790702	1.78	0.0771	-3.522257
Dt	1	-47.096740	6.738839	-6.99	<.0001	-5.713442
Pc*Pc	1	-1.873599	0.766926	-2.44	0.0157	-75.429269
Sc*Pc	1	-1.655800	0.370669	-4.47	<.0001	-120.767038
Sc*Sc	0	0	.	.	0	
Mc*Pc	1	0.117421	0.194049	0.61	0.5460	9.312940
Mc*Sc	1	-0.011938	0.113912	-0.10	0.9167	-1.715412
Mc*Mc	1	0.022188	0.043803	0.51	0.6132	3.466904
Ss*Pc	1	-0.025836	0.029614	-0.87	0.3843	-8.196600
Ss*Sc	1	-0.019202	0.017311	-1.11	0.2690	-11.036621
Ss*Mc	1	0.008204	0.007504	1.09	0.2759	5.127330
Ss*Ss	1	-0.005550	0.001936	-2.87	0.0047	-13.874177
Dt*Pc	1	0.736872	0.116863	6.31	<.0001	65.456333
Dt*Sc	1	0.531266	0.068131	7.80	<.0001	85.496576
Dt*Mc	1	-0.083279	0.029525	-2.82	0.0054	-14.573829
Dt*Ss	1	-0.006067	0.005371	-1.13	0.2604	-4.246864
Dt*Dt	1	0.022374	0.025690	0.87	0.3851	4.385287

Sum of

Factor	DF	Squares	Mean Square	F Value	Pr > F	Label
Pc	6	92696	15449	16.72	<.0001	Pc
Sc	5	134091	26818	29.02	<.0001	Sc
Mc	6	54699	9116.558565	9.87	<.0001	Mc
Ss	6	16736	2789.411369	3.02	0.0080	Ss
Dt	6	86691	14448	15.64	<.0001	Dt

Canonical Analysis of Response Surface Based on Coded Data

Critical Value

Factor	Coded	Uncoded	Label
Pc	1.170477	14.081677	Pc
Sc	-0.382880	80.493790	Sc
Mc	2.842757	73.034460	Mc
Ss	0.137737	156.886839	Ss
Dt	0.438747	22.142465	Dt

Predicted value at stationary point: -1.451820

Eigenvectors

Eigenvalues		Pc	Sc	Mc	Ss	Dt
50.356660	-0.219611	0.768122	-0.130506	-0.076434	0.582139	
8.721176	0.519910	-0.406503	-0.395997	-0.099224	0.630706	
2.007889	0.234533	-0.042758	0.902738	0.052699	0.354194	
-14.276522	-0.014539	-0.002333	-0.095723	0.989631	0.106071	
-128.260457	0.791358	0.492859	-0.045355	0.046541	-0.355837	

Stationary point is a saddle point.

Estimated Ridge of Maximum Response for Variable SME:

Coded Radius	Estimated Response	Standard Error	Uncoded Factor Values				
			Pc	Sc	Mc	Ss	Dt
0.0	12.870292	10.632769	6.655000	84.895000	37.500000	150.000000	
			16.000000				
0.1	25.806326	8.976402	6.958339	85.873979	37.241156	149.802384	
			16.057422				
0.2	37.744347	7.756768	7.140910	86.930733	36.945333	149.473373	
			16.368253				
0.3	49.384488	7.098502	7.209923	88.005947	36.642432	149.059811	
			16.890685				
0.4	61.258888	6.902676	7.201788	89.059833	36.353092	148.613595	
			17.540808				
0.5	73.683993	7.023085	7.148104	90.083394	36.082392	148.161770	
			18.258318				
0.6	86.834086	7.357172	7.067703	91.080207	35.828653	147.714042	
			19.011574				
0.7	100.807084	7.846483	6.970934	92.055941	35.588843	147.272969	
			19.784896				
0.8	115.660842	8.460414	6.863607	93.015475	35.360197	146.838645	
			20.570231				
0.9	131.431392	9.184040	6.749137	93.962520	35.140507	146.410416	
			21.363190				
1.0	148.142261	10.010904	6.629636	94.899820	34.928069	145.987478	
			22.161236				

APPENDIX 12

Fitting Response Surface Regression Model- MRTs

Response Surface for Variable MRTs: MRTs

Response Mean 31.901124

Root MSE 1.757693

R-Square 0.9711

Coefficient of Variation 5.5098

Type I Sum

Regression	DF	of Squares	R-Square	F Value	Pr > F
Linear	5	15568	0.9214	1007.79	<.0001
Quadratic	4	672.463554	0.0398	54.42	<.0001
Crossproduct	10	168.189025	0.0100	5.44	<.0001
Total Model	19	16408	0.9711	279.53	<.0001

Sum of

Residual	DF	Squares	Mean Square	F Value	Pr > F
Lack of Fit	158	488.138601	3.089485		
Pure Error	0	0			
Total Error	158	488.138601	3.089485		

Parameter

Estimate

Standard

from Coded

Parameter	DF	Estimate	Error	t Value	Pr > t	Data
Intercept	1	68.798600	29.538522	2.33	0.0211	26.819575
Pc	1	3.949266	2.382111	1.66	0.0993	2.922523
Sc	1	0.479504	0.303706	1.58	0.1164	3.939935
Mc	1	-0.508587	0.648485	-0.78	0.4341	-0.602898
Ss	1	-0.710982	0.103540	-6.87	<.0001	-10.896698
Dt	1	-1.404468	0.389645	-3.60	0.0004	-0.368878
Pc*Pc	1	-0.035168	0.044344	-0.79	0.4289	-1.415818
Sc*Pc	1	-0.047009	0.021432	-2.19	0.0297	-3.428624
Sc*Sc	0	0	-	-	-	0
Mc*Pc	1	0.013368	0.011220	1.19	0.2353	1.060274
Mc*Sc	1	-0.000193	0.006586	-0.03	0.9766	-0.027780
Mc*Mc	1	0.002971	0.002533	1.17	0.2425	0.464246

Ss*Pc	1	0.000987	0.001712	0.58	0.5651	0.313182
Ss*Sc	1	-0.000477	0.001001	-0.48	0.6342	-0.274258
Ss*Mc	1	0.001479	0.000434	3.41	0.0008	0.924431
Ss*Ss	1	0.001588	0.000112	14.18	<.0001	3.969276
Dt*Pc	1	0.020053	0.006757	2.97	0.0035	1.781280
Dt*Sc	1	0.015932	0.003939	4.04	<.0001	2.564005
Dt*Mc	1	-0.003556	0.001707	-2.08	0.0389	-0.622337
Dt*Ss	1	-0.000299	0.000311	-0.96	0.3365	-0.209601
Dt*Dt	1	0.002199	0.001485	1.48	0.1408	0.430944

Sum of

Factor	DF	Squares	Mean Square	F Value	Pr > F	Label
Pc	6	90.164219	15.027370	4.86	0.0001	Pc
Sc	5	136.444793	27.288959	8.83	<.0001	Sc
Mc	6	135.643458	22.607243	7.32	<.0001	Mc
Ss	6	16023	2670.471165	864.37	<.0001	Ss
Dt	6	92.108625	15.351437	4.97	0.0001	Dt

Canonical Analysis of Response Surface Based on Coded Data

Critical Value

Factor	Coded	Uncoded	Label
Pc	0.592324	10.413296	Pc
Sc	-0.421007	80.055528	Sc
Mc	-1.985276	12.684044	Mc
Ss	1.550051	227.502555	Ss
Dt	-0.600278	7.596112	Dt

Predicted value at stationary point: 19.119701

Eigenvectors

Eigenvalues	Pc	Sc	Mc	Ss	Dt
4.059785	0.056314	-0.074179	0.139704	0.984389	-0.052793
1.669946	-0.254746	0.712723	-0.224231	0.132253	0.599466
0.612644	0.570087	-0.202501	0.435654	-0.074179	0.662342
0.338002	-0.251211	0.390388	0.849743	-0.089321	-0.233344
-3.231729	0.737447	0.541400	-0.135447	-0.002569	-0.380403

Stationary point is a saddle point.

Estimated Ridge of Maximum Response for Variable MRTs: MRTs

Coded Radius	Estimated Response	Standard Error	Uncoded Factor Values				
			Pc	Sc	Mc	Ss	Dt
0.0	26.819575	0.614795	6.655000	84.895000	37.500000	150.000000	16.000000
0.1	28.046956	0.575117	6.792003	85.249975	37.433445	145.377107	15.974403
0.2	29.338417	0.541732	6.898360	85.564052	37.359190	140.644283	15.977498
0.3	30.698067	0.513353	6.980674	85.844990	37.277059	135.838665	16.001508
0.4	32.128862	0.489133	7.044102	86.099121	37.187355	130.984720	16.040737
0.5	33.632956	0.468737	7.092584	86.331462	37.090604	126.098495	16.091087
0.6	35.211944	0.452337	7.129118	86.545945	36.987417	121.190575	16.149610
0.7	36.867022	0.440584	7.155995	86.745655	36.878412	116.268013	16.214179
0.8	38.599106	0.434526	7.174980	86.933025	36.764171	111.335568	16.283247
0.9	40.408905	0.435461	7.187447	87.109991	36.645231	106.396487	16.355678
1.0	42.296978	0.444713	7.194475	87.278105	36.522072	101.453011	16.430629

APPENDIX 13

Fitting Response Surface Regression Model- CS

Response Surface for Variable Cs: Cs

Response Mean 596.448820

Root MSE 361.555408

R-Square 0.7760

Coefficient of Variation 60.6180

Type I Sum

Regression	DF	of Squares	R-Square	F Value	Pr > F
Linear	5	34189373	0.3708	52.31	<.0001
Quadratic	4	29102100	0.3156	55.66	<.0001
Crossproduct	10	8252969	0.0895	6.31	<.0001
Total Model	19	71544443	0.7760	28.81	<.0001

Sum of

Residual	DF	Squares	Mean Square	F Value	Pr > F
Lack of Fit	158	20654125	130722		
Pure Error	0	0			
Total Error	158	20654125	130722		

Parameter

Estimate

Standard

from Coded

Parameter	DF	Estimate	Error	t Value	Pr > t	Data
Intercept	1	-37600	6076.039533	-6.19	<.0001	-1138.656741
Pc	1	1118.818650	489.997421	2.28	0.0237	2642.610496
Sc	1	396.019625	62.471890	6.34	<.0001	3307.184057
Mc	1	206.725598	133.392514	1.55	0.1232	75.120844
Ss	1	-62.558724	21.298009	-2.94	0.0038	21.409877
Dt	1	375.477778	80.149511	4.68	<.0001	-4.598243
Pc*Pc	1	25.056204	9.121557	2.75	0.0067	1008.738331
Sc*Pc	1	-10.570009	4.408615	-2.40	0.0177	-770.931803
Sc*Sc	0	0	-	-	-	0
Mc*Pc	1	-3.361229	2.307949	-1.46	0.1473	-266.587467
Mc*Sc	1	-1.623567	1.354834	-1.20	0.2326	-233.286328
Mc*Mc	1	-0.027703	0.520973	-0.05	0.9577	-4.328645

Ss*Pc	1	0.594561	0.352221	1.69	0.0934	188.624359
Ss*Sc	1	0.594546	0.205890	2.89	0.0044	341.715511
Ss*Mc	1	-0.320716	0.089246	-3.59	0.0004	-200.447414
Ss*Ss	1	0.073074	0.023031	3.17	0.0018	182.685151
Dt*Pc	1	-6.351671	1.389930	-4.57	<.0001	-564.218940
Dt*Sc	1	-4.141755	0.810322	-5.11	<.0001	-666.532634
Dt*Mc	1	0.604433	0.351163	1.72	0.0872	105.775722
Dt*Ss	1	-0.083704	0.063886	-1.31	0.1920	-58.592805
Dt*Dt	1	0.248994	0.305550	0.81	0.4164	48.802856

Sum of

Factor	DF	Squares	Mean Square	F Value	Pr > F	Label
Pc	6	43414553	7235759	55.35	<.0001	Pc
Sc	5	53935625	10787125	82.52	<.0001	Sc
Mc	6	2497958	416326	3.18	0.0056	Mc
Ss	6	8302954	1383826	10.59	<.0001	Ss
Dt	6	5938755	989792	7.57	<.0001	Dt

Canonical Analysis of Response Surface Based on Coded Data

Critical Value

Factor	Coded	Uncoded	Label
Pc	0.358016	8.926613	Pc
Sc	0.625181	92.081458	Sc
Mc	2.663222	70.790276	Mc
Ss	1.321401	216.070040	Ss
Dt	4.293005	76.102067	Dt

Predicted value at stationary point: 472.493757

Eigenvectors

Eigenvalues		Pc	Sc	Mc	Ss	Dt
1178.255040	0.947886	-0.243106	-0.095834	0.062757	-0.171141	
487.239269	-0.002531	0.613976	-0.303452	0.494963	-0.534748	
131.581830	-0.020725	-0.215428	-0.152508	0.782491	0.563570	

-59.615689	0.040572	0.018754	0.922412	0.328589	-0.197956
-501.562757	0.315326	0.719147	0.156938	-0.175528	0.572676

Stationary point is a saddle point.

Estimated Ridge of Maximum Response for Variable Cs: Cs

Coded Radius Dt	Estimated Response	Standard Error	Uncoded Factor Values			
			Pc	Sc	Mc	Ss
0.0	-1138.6567	126.46262	6.6550	84.895	37.500	150.0000
16.0000						
0.1	-714.912349	105.318188	7.060807	85.778090	37.511674	150.070922
			15.969615			
0.2	-289.636029	88.827996	7.487141	86.627149	37.501859	150.234043
			15.881748			
0.3	138.514241	84.943349	7.935199	87.435346	37.470229	150.488768
			15.737884			
0.4	570.958669	101.248426	8.405788	88.196012	37.417054	150.831643
			15.541054			
0.5	1009.1724	136.391737	8.899209	88.903101	37.343237	151.256332
			15.295753			
0.6	1454.6570	185.326107	9.415176	89.551648	37.250274	151.753933
			15.007698			
0.7	1908.9096	245.065343	9.952800	90.138142	37.140153	152.313614
			14.683439			
0.8	2373.3911	314.347466	10.510628	90.660755	37.015196	152.923469
			14.329892			
0.9	2849.498	392.642416	11.086765	91.119371	36.877873	153.571426
			13.953871			
1.0	3338.541	479.675684	11.679016	91.515444	36.730635	154.246050
			13.561696			

APPENDIX 14

Fitting Response Surface Regression Model-MV

Response Surface for Variable MV: MV

Response Mean 4.386986

Root MSE 1.251956

R-Square 0.6342

Coefficient of Variation 28.5380

Type I Sum

Regression	DF	of Squares	R-Square	F Value	Pr > F
Linear	4	65.618384	0.2735	10.47	<.0001
Quadratic	3	33.638974	0.1402	7.15	0.0004
Crossproduct	6	52.931762	0.2206	5.63	0.0001
Total Model	13	152.189119	0.6342	7.47	<.0001

Sum of

Residual	DF	Squares	Mean Square	F Value	Pr > F
Lack of Fit	56	87.774074	1.567394	.	.
Pure Error	0	0	.	.	.
Total Error	56	87.774074	1.567394	.	.

Parameter Estimate

Standard

from Coded

Parameter	DF	Estimate	Error	t Value	Pr > t	Data
Intercept	1	-91.908853	28.505095	-3.22	0.0021	3.299250
Proco	1	3.479568	3.093978	1.12	0.2655	1.618400
staco	1	0.895200	0.290399	3.08	0.0032	2.592147
MC	1	2.263937	0.763149	2.97	0.0044	-0.214773
Duration	1	-0.936569	0.431649	-2.17	0.0343	0.215454
Proco*Proco	1	0.003191	0.062926	0.05	0.9597	0.128474
staco*Proco	1	-0.023598	0.027771	-0.85	0.3991	-1.721149
staco*staco	0	0	.	.	0	.
MC*Proco	1	-0.041775	0.012065	-3.46	0.0010	-3.313290
MC*staco	1	-0.019124	0.007574	-2.52	0.0144	-2.747889
MC*MC	1	-0.003762	0.003114	-1.21	0.2322	-0.587736
Duration*Proco	1	0.020197	0.007210	2.80	0.0070	1.922262
Duration*staco	1	0.013633	0.004375	3.12	0.0029	2.350735
Duration*MC	1	-0.006497	0.001912	-3.40	0.0013	-1.218189
Duration*Duration	1	-0.003242	0.001786	-1.82	0.0749	-0.729355

Sum of

Factor	DF	Squares	Mean Square	F Value	Pr > F	Label
Proco	5	58.562301	11.712460	7.47	<.0001	Proco
staco	4	53.385024	13.346256	8.51	<.0001	staco
MC	5	41.975042	8.395008	5.36	0.0004	MC
Duration	5	80.167675	16.033535	10.23	<.0001	Duration

Canonical Analysis of Response Surface Based on Coded Data

Critical Value

Factor	Coded	Uncoded	Label
Proco	0.225965	8.088747	Proco
staco	-0.333853	81.057356	staco
MC	0.421501	42.768761	MC
Duration	-0.444537	8.331939	Duration

Predicted value at stationary point: 2.956250

Eigenvectors

Eigenvalues	Proco	staco	MC	Duration
2.228628	0.513038	0.411797	-0.600871	0.454058
0.944694	-0.670469	0.731669	0.020615	0.121271
-1.281106	0.035152	-0.118914	0.564954	0.815752
-3.080831	0.534815	0.530041	0.565116	-0.337155

Stationary point is a saddle point.

Estimated Ridge of Maximum Response for Variable MV: MV

Coded Radius	Estimated Response	Standard Error	Uncoded Factor Values			
			Proco	staco	MC	Duration
0.0	3.299250	0.834081	6.655000	84.895000	37.500000	15.000000
0.1	3.608048	0.685771	6.974860	85.844787	37.258996	15.241820
0.2	3.933473	0.554837	7.271926	86.720066	36.789700	15.688904
0.3	4.288435	0.453472	7.558796	87.515402	36.198421	16.246182
0.4	4.679376	0.405436	7.843678	88.247752	35.544652	16.859158
0.5	5.109557	0.439743	8.130209	88.933291	34.856824	17.501605
0.6	5.580755	0.556113	8.419703	89.583789	34.148986	18.160629
0.7	6.094023	0.731213	8.712458	90.207482	33.428619	18.829473
0.8	6.650023	0.947338	9.008359	90.810204	32.699994	19.504368
0.9	7.249198	1.195917	9.307141	91.396185	31.965704	20.183100
1.0	7.891854	1.473142	9.608497	91.968567	31.227400	20.864308

APPENDIX 15

Fitting Response Surface Regression Model-CPV

Response Surface for Variable CPV: CPV

Response Mean 2.801843

Root MSE 2.073893

R-Square 0.7126

Coefficient of Variation 74.0189

Type I Sum

Regression	DF	of Squares	R-Square	F Value	Pr > F
Linear	4	373.528202	0.4458	21.71	<.0001
Quadratic	3	60.221559	0.0719	4.67	0.0056
Crossproduct	6	163.325706	0.1949	6.33	<.0001
Total Model	13	597.075468	0.7126	10.68	<.0001

Sum of

Residual	DF	Squares	Mean Square	F Value	Pr > F
Lack of Fit	56	240.857916	4.301034		
Pure Error	0	0			
Total Error	56	240.857916	4.301034		

Parameter

Estimate

Standard

from Coded

Parameter	DF	Estimate	Error	t Value	Pr > t	Data
Intercept	1	140.008064	47.219331	2.97	0.0044	-2.301297
Proco	1	-14.352875	5.125245	-2.80	0.0070	5.809426
staco	1	-1.027576	0.481053	-2.14	0.0371	6.343450
MC	1	-4.087274	1.264173	-3.23	0.0021	0.084363
Duration	1	-0.039672	0.715037	-0.06	0.9560	-1.191548
Proco*Proco	1	0.263767	0.104239	2.53	0.0142	10.618986
staco*Proco	1	0.105028	0.046003	2.28	0.0262	7.660290
staco*staco	0	0	.	.	.	0
MC*Proco	1	0.075231	0.019986	3.76	0.0004	5.966729
MC*staco	1	0.025742	0.012547	2.05	0.0449	3.698867
MC*MC	1	0.017268	0.005159	3.35	0.0015	2.698123

Duration*Proco	1	0.001350	0.011944	0.11	0.9104	0.128442
Duration*staco	1	-0.005659	0.007247	-0.78	0.4382	-0.975712
Duration*MC	1	0.007524	0.003168	2.38	0.0210	1.410745
Duration*Duration	1	0.004984	0.002958	1.68	0.0976	1.121288

Sum of

Factor	DF	Squares	Mean Square	F Value	Pr > F	Label
Proco	5	96.681928	19.336386	4.50	0.0016	Proco
staco	4	45.672400	11.418100	2.65	0.0423	staco
MC	5	218.601377	43.720275	10.17	<.0001	MC
Duration	5	216.076635	43.215327	10.05	<.0001	Duration

Canonical Analysis of Response Surface Based on Coded Data

Critical Value

Factor	Coded	Uncoded	Label
Proco	-0.489147	3.551365	Proco
staco	0.880712	95.018780	staco
MC	-0.388811	32.639868	MC
Duration	1.187120	32.806806	Duration

Predicted value at stationary point: -1.652409

Eigenvectors

Eigenvalues	Proco	staco	MC	Duration
12.991355	0.896876	0.309025	0.316222	0.010943
2.122504	-0.298754	0.033837	0.796089	0.525208
0.937549	0.243337	-0.289704	-0.435317	0.816919
-1.613011	-0.217132	0.905224	-0.277027	0.238076

Stationary point is a saddle point.

Estimated Ridge of Maximum Response for Variable CPV: CPV

Coded	Estimated	Standard	Uncoded Factor Values			
Radius	Response	Error	Proco	staco	MC	Duration
0.0	-2.301297	1.381675	6.655000	84.895000	37.500000	15.000000
0.1	-1.337927	1.110965	7.127491	85.645174	37.593105	14.822364
0.2	-0.160384	0.842835	7.657459	86.257413	37.803152	14.698931
0.3	1.253020	0.707611	8.211026	86.785817	38.078793	14.615243
0.4	2.912654	0.907934	8.774411	87.263832	38.391731	14.557863
0.5	4.823775	1.396717	9.342096	87.710176	38.727209	14.518021

0.6	6.989270	2.048864	9.911733	88.135561	39.077177	14.490255
0.7	9.410837	2.816069	10.482256	88.546431	39.436963	14.471095
0.8	12.089539	3.682317	11.053155	88.946855	39.803694	14.458267
0.9	15.026072	4.641476	11.624177	89.339520	40.175513	14.450223
1.0	18.220912	5.690854	12.195197	89.726267	40.551170	14.445880

APPENDIX 16

Fitting Response Surface Regression Model-HPV

Response Surface for Variable HPV: HPV

Response Mean	1.568586
Root MSE	1.510784
R-Square	0.6105
Coefficient of Variation	96.3150

Type I Sum

Regression	DF	of Squares	R-Square	F Value	Pr > F
Linear	4	129.202170	0.3937	14.15	<.0001
Quadratic	3	30.707991	0.0936	4.48	0.0068
Crossproduct	6	40.445289	0.1232	2.95	0.0142
Total Model	13	200.355450	0.6105	6.75	<.0001

Sum of

Residual	DF	Squares	Mean Square	F Value	Pr > F
Lack of Fit	56	127.818169	2.282467		
Pure Error	0	0			
Total Error	56	127.818169	2.282467		

Fitting Response Surface Regression Model- WAI,WSI,MV,CPV,HPV = Proco staco

MC Dt

The RSREG Procedure

Parameter	DF	Estimate	Standard Error	t Value	Pr > t	Parameter Estimate from Coded Data
Intercept	1	42.132779	34.398196	1.22	0.2258	-2.110281
Proco	1	-6.463265	3.733623	-1.73	0.0889	3.248031
staco	1	-0.172286	0.350436	-0.49	0.6249	3.925081
MC	1	-1.687620	0.920921	-1.83	0.0722	0.284489
Duration	1	-0.023459	0.520888	-0.05	0.9642	-0.457690
Proco*Proco	1	0.153875	0.075936	2.03	0.0475	6.194856
staco*Proco	1	0.045912	0.033512	1.37	0.1761	3.348655
staco*staco	0	0			0	
MC*Proco	1	0.026750	0.014559	1.84	0.0715	2.121576
MC*staco	1	0.006748	0.009140	0.74	0.4634	0.969668
MC*MC	1	0.011785	0.003758	3.14	0.0027	1.841429
Duration*Proco	1	0.001750	0.008701	0.20	0.8413	0.166569
Duration*staco	1	-0.002991	0.005279	-0.57	0.5732	-0.515764

Duration*MC	1	0.005038	0.002308	2.18	0.0332	0.944559
Duration*Duration	1	0.001544	0.002155	0.72	0.4766	0.347463

Factor	DF	Sum of		F Value	Pr > F	Label
		Squares	Mean Square			
Proco	5	35.533912	7.106782	3.11	0.0150	Proco
staco	4	13.840965	3.460241	1.52	0.2100	staco
MC	5	67.197086	13.439417	5.89	0.0002	MC
Duration	5	59.818487	11.963697	5.24	0.0005	Duration

The RSREG Procedure

Canonical Analysis of Response Surface Based on Coded Data

Critical Value

Factor	Coded	Uncoded	Label
Proco	-0.487659	3.560801	Proco
staco	1.231552	99.051693	staco
MC	-0.850340	26.870755	MC
Duration	2.845350	57.680251	Duration

Predicted value at stationary point: -1.257376

Eigenvectors

Eigenvalues	Proco	staco	MC	Duration
6.882216	0.943281	0.244553	0.223764	0.018543
1.736310	-0.224895	-0.003064	0.926365	0.302094
0.330388	0.138147	-0.365662	-0.255991	0.884124
-0.565165	-0.201390	0.898040	-0.162008	0.355977

Stationary point is a saddle point.

Estimated Ridge of Maximum Response for Variable HPV: HPV

Coded Radius	Estimated Response	Standard Error	Uncoded Factor Values			
			Proco	staco	MC	Duration
0.0	-2.110281	1.006518	6.655000	84.895000	37.500000	15.000000
0.1	-1.551084	0.808568	7.111229	85.682506	37.608203	14.882360
0.2	-0.884637	0.612907	7.640203	86.313252	37.776655	14.799833
0.3	-0.097678	0.514569	8.204655	86.838184	37.982095	14.746101
0.4	0.816807	0.663781	8.786006	87.295516	38.209689	14.712678
0.5	1.862588	1.025806	9.375737	87.708890	38.451066	14.693276
0.6	3.041802	1.508919	9.969841	88.092597	38.701459	14.683727
0.7	4.355734	2.078070	10.566332	88.455498	38.958035	14.681294

0.8	5.805197	2.721699	11.164167	88.803302	39.219022	14.684140
0.9	7.390731	3.435388	11.762775	89.139823	39.483266	14.691003
1.0	9.112707	4.217189	12.361830	89.467698	39.749980	14.70098

APPENDIX 17

Fitting Response Surface Regression Model- Product Temperature

Coding Coefficients for the Independent Variables

Factor	Subtracted off	Divided by
Proco	6.655000	6.345000
Staco	84.895000	11.495000
MC	37.500000	12.500000
SS	150.000000	50.000000
Duration	16.000000	14.000000

Response Surface for Variable ProTem: ProTem

Response Mean	97.024709
Root MSE	8.676244
R-Square	0.8580
Coefficient of Variation	8.9423

Type I Sum

Regression	DF	of Squares	R-Square	F Value	Pr > F
Linear	5	232206	0.6560	616.94	<.0001
Quadratic	4	56998	0.1610	189.29	<.0001
Crossproduct	10	14509	0.0410	19.27	<.0001
Total Model	19	303713	0.8580	212.35	<.0001

Sum of

Residual	DF	Squares	Mean Square	F Value	Pr > F
Lack of Fit	667	50157	75.198157	0.59	0.8075
Pure Error	1	128.000000	128.000000		
Total Error	668	50285	75.277201		

						Parameter
						Estimate
Standard						from Coded
Parameter	DF	Estimate	Error	t Value	Pr > t	Data
Intercept	1	-469.717594	75.211999	-6.25	<.0001	108.904973
Proco	1	-32.240762	5.866981	-5.50	<.0001	2.732802
Staco	1	4.123735	0.771082	5.35	<.0001	1.328377

MC	1	14.797367	1.639750	9.02	<.0001	-0.181788
SS	1	1.645263	0.263186	6.25	<.0001	-3.698031
Duration	1	11.562636	1.195732	9.67	<.0001	29.743527
Proco*Proco	1	0.843276	0.107261	7.86	<.0001	33.949471
Staco*Proco	1	0.402626	0.052945	7.60	<.0001	29.365846
Staco*Staco	0	0	.	.	0	
MC*Proco	1	-0.260785	0.028656	-9.10	<.0001	-20.683507
MC*Staco	1	-0.148084	0.016665	-8.89	<.0001	-21.277856
MC*MC	1	-0.004461	0.006445	-0.69	0.4890	-0.697053
SS*Proco	1	-0.006804	0.004378	-1.55	0.1206	-2.158614
SS*Staco	1	-0.000970	0.002546	-0.38	0.7033	-0.557713
SS*MC	1	-0.000479	0.001083	-0.44	0.6581	-0.299621
SS*SS	1	-0.005231	0.000283	-18.50	<.0001	-13.077014
Duration*Proco	1	-0.120839	0.020736	-5.83	<.0001	-10.734133
Duration*Staco	1	-0.061809	0.012060	-5.13	<.0001	-9.946855
Duration*MC	1	-0.006142	0.005132	-1.20	0.2318	-1.074932
Duration*SS	1	-0.000272	0.000933	-0.29	0.7710	-0.190078
Duration*Duration	1	-0.097363	0.004985	-19.53	<.0001	-19.083056

Sum of						
Factor	DF	Squares	Mean Square	F Value	Pr > F	Label
Proco	6	14877	2479.540998	32.94	<.0001	Proco
Staco	5	13586	2717.112502	36.09	<.0001	Staco
MC	6	8196.269715	1366.044953	18.15	<.0001	MC
SS	6	31029	5171.518662	68.70	<.0001	SS
Duration	6	254690	42448	563.89	<.0001	Duration

Canonical Analysis of Response Surface Based on Coded Data

Critical Value

Factor	Coded	Uncoded	Label
Proco	-0.004979	6.623408	Proco
Staco	-0.021408	84.648914	Staco

MC -0.312724 33.590948 MC
 SS -0.142728 142.863601 SS
 Duration 0.795816 27.141424 Duration
 Predicted value at stationary point: 121.011468

Eigenvectors

Eigenvalues	Proco	Staco	MC	SS	Duration
44.224797	0.876340	0.371835	-0.288544	-0.017394	-0.101029
0.956566	0.462017	-0.555760	0.690391	-0.031832	-0.004176
-9.951599	-0.123151	0.686213	0.630984	-0.038661	-0.338098
-13.105080	0.023513	0.006089	0.034911	0.998073	-0.045182
-21.032337	0.053383	0.286257	0.201850	0.032243	0.934571

Stationary point is a saddle point.

Estimated Ridge of Maximum Response for Variable ProTem: ProTem

Coded Radius	Estimated Response	Standard Error	Proco	Staco	MC	SS	Duration
0.0	108.904973	1.519648	6.655000	84.895000	37.500000	150.000000	16.000000
0.1	111.721276	1.497953	6.714433	84.924488	37.474748	149.351607	17.381214
0.2	114.148656	1.482185	6.778377	84.905983	37.410747	148.631006	18.758403
0.3	116.445150	1.105121	7.826869	85.671973	36.712576	148.186712	19.003388
0.4	119.540503	1.067135	8.595300	86.262660	36.214124	148.066502	18.807958
0.5	123.521456	1.382855	9.251573	86.767134	35.788426	147.963847	18.641033
0.6	128.385827	1.934578	9.868336	87.241237	35.388356	147.867376	18.484153
0.7	134.135143	2.635888	10.465748	87.700466	35.000838	147.773932	18.332193
0.8	140.767494	3.451098	11.051824	88.150981	34.620674	147.682263	18.183114
0.9	148.287595	4.367173	11.631034	88.596218	34.244963	147.591668	18.035782
1.0	156.690729	5.377952	12.205283	89.037641	33.872471	147.501849	17.889711

APPENDIX 18

Fitting Response Surface Regression Model-Expansion Ratio

Response Surface for Variable Expansion: Expansion

Response Mean 2.573737

Root MSE 1.639791

R-Square 0.4491

Coefficient of Variation 63.7125

Type I Sum

Regression	DF	of Squares	R-Square	F Value	Pr > F
Linear	5	668.725065	0.2051	49.74	<.0001
Quadratic	4	539.694804	0.1655	50.18	<.0001
Crossproduct	10	255.948526	0.0785	9.52	<.0001
Total Model	19	1464.368395	0.4491	28.66	<.0001

Sum of

Residual	DF	Squares	Mean Square	F Value	Pr > F
Lack of Fit	667	1796.194599	2.692945	3366.18	0.0137
Pure Error	1	0.000800	0.000800		
Total Error	668	1796.195399	2.688915		

Parameter
Estimate

Standard	Parameter	DF	Estimate	Error	t Value	Pr > t	Data
	Intercept	1	-76.972645	14.214905	-5.41	<.0001	2.039336
	Proco	1	2.987411	1.108847	2.69	0.0072	4.146175
	Staco	1	0.726568	0.145733	4.99	<.0001	4.787595
	MC	1	1.651168	0.309909	5.33	<.0001	0.394398
	SS	1	-0.055730	0.049742	-1.12	0.2629	0.121270
	Duration	1	-1.191087	0.225991	-5.27	<.0001	0.616815
	Proco*Proco	1	0.009631	0.020272	0.48	0.6349	0.387728
	Staco*Proco	1	-0.024659	0.010007	-2.46	0.0140	-1.798491
	Staco*Staco	0	0	.	.	.	0
	MC*Proco	1	-0.024812	0.005416	-4.58	<.0001	-1.967893

MC*Staco	1	-0.014145	0.003150	-4.49	<.0001	-2.032498
MC*MC	1	-0.004731	0.001218	-3.88	0.0001	-0.739246
SS*Proco	1	0.001535	0.000827	1.85	0.0641	0.486860
SS*Staco	1	0.001065	0.000481	2.21	0.0272	0.612208
SS*MC	1	0.000263	0.000205	1.29	0.1985	0.164632
SS*SS	1	-0.000191	0.000053441	-3.58	0.0004	-0.478240
Duration*Proco	1	0.020719	0.003919	5.29	<.0001	1.840435
Duration*Staco	1	0.014044	0.002279	6.16	<.0001	2.260065
Duration*MC	1	0.003856	0.000970	3.98	<.0001	0.674792
Duration*SS	1	0.000314	0.000176	1.78	0.0752	0.219883
Duration*Duration	1	-0.008959	0.000942	-9.51	<.0001	-1.756039

Sum of

Factor	DF	Squares	Mean Square	F Value	Pr > F	Label
Proco	6	771.034669	128.505778	47.79	<.0001	Proco
Staco	5	708.461441	141.692288	52.69	<.0001	Staco
MC	6	193.997985	32.332998	12.02	<.0001	MC
SS	6	75.345220	12.557537	4.67	0.0001	SS
Duration	6	552.592319	92.098720	34.25	<.0001	Duration

Canonical Analysis of Response Surface Based on Coded Data

Critical Value

Factor	Coded	Uncoded	Label
Proco	-0.628759	2.665527	Proco
Staco	-1.037687	72.966784	Staco
MC	2.276110	65.951371	MC
SS	-0.562109	121.894525	SS
Duration	-0.419499	10.127010	Duration

Predicted value at stationary point: -1.462763

Eigenvectors

Eigenvalues	Proco	Staco	MC	SS	Duration
1.154060	0.898640	-0.302824	-0.276874	0.072508	0.137212
0.984327	0.072831	0.813225	-0.451490	0.180325	0.311450
-0.420082	0.024130	-0.028061	0.427270	0.886500	0.173746
-0.988585	0.172605	0.160215	0.596717	-0.413824	0.645923

-3.315517 0.395938 0.469581 0.425284 -0.071362 -0.660884

Stationary point is a saddle point.

Estimated Ridge of Maximum Response for Variable Expansion: Expansion

Coded Radius	Estimated Response	Standard Error	Uncoded Factor Values			
			Proco	Staco	MC	SS
			Duration			
0.0	2.039336	0.287210	6.655000	84.895000	37.500000	150.000000
			16.000000			
0.1	2.672115	0.240562	7.067060	85.753835	37.524169	150.158123
			16.191235			
0.2	3.299461	0.205000	7.476251	86.599535	37.447715	150.436532
			16.477857			
0.3	3.926990	0.194473	7.880836	87.427448	37.282548	150.821892
			16.836037			
0.4	4.559128	0.220189	8.280275	88.235649	37.042267	151.298184
			17.245394			
0.5	5.199276	0.278826	8.674790	89.024001	36.739781	151.849806
			17.690204			
0.6	5.850021	0.360496	9.064995	89.793328	36.386262	152.463035
			18.159040			
0.7	6.513335	0.458475	9.451652	90.544868	35.990925	153.126434
			18.643857			
0.8	7.190724	0.569497	9.835537	91.279955	35.561201	153.830719
			19.139077			
0.9	7.883358	0.692118	10.217375	91.999868	35.103027	154.568441
			19.640859			
1.0	8.592148	0.825739	10.597819	92.705763	34.621146	155.333645
			20.146558			