STUDIES ON THE INFLUENCE OF EXTRUDER AND PROCESSING PARAMETERS ON THE CHARACTERISTICS OF CASSAVA FLOUR EXTRUDATES

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CERTIFICATE

This is to certify that the thesis entitled "**STUDIES ON THE INFLUENCE OF THE EXTRUDER AND PROCESSING PARAMETERS ON THE CHARACTERISTICS OF CASSAVA FLOUR EXTRUDATES**" submitted in part fulfillment of the requirements for the degree of **DOCTOR OF PHILOSOPHY** in **AGRICULTURAL PROCESS ENGINEERING** to the Tamil Nadu Agricultural University, Coimbatore is a record of bona fide research work carried out by **Mr.J.THAJUDHIN SHERIFF**,(I.D.No.92-818-007) under my guidance and that no part of this thesis has been submitted for the award of any other degree, diploma, fellowship or other similar titles or prizes and that the work has not been published in part or full in any scientific or popular magazine.

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ABSTRACT

STUDIES ON THE INFLUENCE OF EXTRUDER AND PROCESSING PARAMETRS ON THE CHARACTERISTICS OF CASSAVA FLOUR EXTRUDATES

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The extrusion cooking process represents one of the fastest growing process technologies in recent years. An attempt has been made in this research programme to explose the possibilities of extrusion of cassava flour to produce extruded food item.

The physical properties of cassava flour, like bulk density, particle size, shear strength and thermal properties such as thermal conductivity and specific heat were determined.

A single screw food extruder experimental set-up was developed with to a provision to change the barrel temperature and screw speed.

Performance of the extruder was studied by varying the moisture content of the cassava flour (14-18 per cent d.b), extrusion temperature (100 to 120°C) and Screw speed (100 to 200 rpm).

The machine parameters, such as, volumetric flow rate, energy and pressure requirement and viscosity of dough inside the extruder were studied. The experimental volumetric flow rate was compared with the theoretical volumetric flow rate. The flow behaviour index n, showed that cassava flour is pseudo-plastic in nature.

The physical parameters of the extrudates were studied for the expansion ratio of the cassava product ranged from 2.0133 to 2.9577, bulk density from 166.178 to 295.238 kg/m^3 and porosity from 58.327 to 69.340 per cent. The relationship between expansion ratio and bulk density was negatively correlated($r=-0.6862$). Porosity of the extrudate was positively correlated with expansion ratio.

The functional properties, the water absorption index ranged from 2.1543 to 4.343 g gel/g of sample and water solubility index ranged from 37.403 to 49.867 per cent.

The expansion ratio was positively correlated with water solubility index (r=0.8241). The water absorption index is negatively related to water solubility index (r=-0.7896).

The mechanical properties such as shear strength, compression strength and tensile strength values ranged from 1.723 to 3.440, 5.123 to 5.570 and 0.540 to 2.310 kg/cm^2, respectively.

The extrudate sample obtained at 16 per cent(d.b) moisture content, 110°C barrel temperature and 100 rpm screw speed had scored high during the sensory evaluation.

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LIST OF SYMBOLS AND ABBREVIATIONS

a	Shape constant
b	Screw flight width measured horizontally
B_c	Axial channel width measured horizontally
C_p	Specific heat of cassava flour
d_d	Diameter of the die
D_s	Mean diameter of extruder screw
D	Internal diameter of extruder barrel
D_1	Outer diameter of extruder barrel
D_i	Average opening of the ith screen
D_m	Mass mean diameter
D_{vs}	Volume surface mean diameter
dE	Energy input per differential of extruder screw channel
dE_H	Viscous energy dissipation in channel
dE_P	Energy to raise pressure of food dough
dE_f	Viscous energy dissipation in flight
dE_K	Clearance energy in increase kinetic energy
e	Flight width
E	Specific energy
EA	Energy of activation of flour
f	Coefficient of friction
F	Force of friction
F_D	Drag flow shape correction factor
F_P	Pressure flow shape correction factor
h_1	Clearance between the screw and barrel at the feed section
h_2	Clearance between the screw and barrel at the die end of the screw
H	Flight height of the screw
H_1	Flight height of the feeding section of the screw

H_2	Flight height at the die end of the screw
H_C	Heat capacity of the capsule
H_f	Heat capacity of flask calorimeter
k	Thermal conductivity of cassava flour
K	Consistency coefficient
K_d	die constant
K_α	apparent kinetic factor in equation 2.7
l	pitch of the screw
l_d	length of extruder die
L	Total length of extruder screw
L_1	length of feed-transition section of the screw
L_2	length of metering section of the screw
M	moisture content
n	flow behaviour index
N	screw speed
ΣNi	Number of particles per g retained on ith screen
P	Internal pressure
p	pressure difference
q	heat input
Q	Volumetric flow rate
Q_D	volumetric drag flow along the channel
Q_L	volumetric leakage flow across flights
Q_P	volumetric pressure flow along channel
Q_e	experimental volumetric flow rate
Q_t	Theoretical volumetric flow rate
Q_i	Weight fraction of total sample retained by ith screen
r_c	Radius of the die
R	Universal gas constant
S_t	Allowable stress
T_{cv}	Temperature of cold distilled water
T_o	Equilibrium temperature of mixture
T_c	Temperature of capsule with cassava flour

V_d	Average velocity of the fluid at die
VE	Volume of extrudate
V_p	Volume of the powdered extrudate
V	Average velocity of fluid
W	Channel width
W_f	force normal to the surface of contact
W_{cv}	weight of cold distilled water
W_g	weight of feed
X_w	Fractional moisture content
X_p	Fractional protein component
X_c	Fractional carbohydrate component
X_f	Fractional fat component
X_a	Fractional ash component
γ	Shear rate
γ_s	Apparent shear rate
γ_w	wall shear rate
δ	clearance between flights of screw and barrel
η_0	apparent viscosity at reference moisture
η	apparent viscosity
η_∞	apparent viscosity at extremely high temperature
η^*	apparent viscosity at reference temperature
μ	viscosity of newtonian fluid
μ_s	apparent viscosity of food dough in the screw metering section
τ	shear stress
τ_w	wall shear stress
ϕ	Helix angle of the extruder screw
θ_1, θ_2	time corresponding to temperature t_1 and t_2
θ_0	time correction for finite diameter
ρ_p	particle density

$\Sigma\theta_i$	weight fraction of total sample retained by ith screen
d_E	Energy input per
ANOVA	Analysis of variance
°C	degree centigrade
C.R	Compression ratio
CFTRI	Central Food Technology Research Institute
CTCRI	Central Tuber Crops Research Institute
d.b	dry basis
WAI	Water Absorption Index
WSI	Water Solubility Index
%	Per cent
L.C.E	Low Cost Extruder
hp	horse power

INTRODUCTION

1. INTRODUCTION

Cassava (**Manihot esculenta Crantz**) is a perennial tuber crop grown throughout the low land tropics. It is the fourth most important source of food energy in the tropics (Cock, 1982). In India, cassava is grown on about 0.2 million hectares and the production of 5.1 million tonnes. The area and production of cassava in different states of India are shown in Table 1.1. It is grown mainly in two southern states, viz., Kerala and Tamilnadu. Of these two states, around 60.6 per cent of the area under cassava in India is being cultivated in Kerala alone while the area in Tamil Nadu is 29.4 per cent (Anon.1994).

Cassava tubers are utilised as human food in various processed forms. In most parts of the world, the tubers are directly consumed after cooking, baking or frying. The consumption of cassava in India is mostly as mashed tubers though there are some traditional food preparations made with cassava flour as puttu, dosai, uppuma., chapathis, etc.(Padmaja, 1994). One of the major constraints in the utilisation of cassava tuber is its rapid perishability. Normally cassava cannot be stored for more than 4-6 days. The poor shelf life of the roots is overcome by cutting the roots into chips and sun dried. The chips and flour have relatively better keeping quality. One of the promising uses of cassava flour is as wheat flour substitute in the production of bread (Defloor et al.,1991. Eggleston et al.,1992), cake, cookies, macaroni(Subramanian et al.,1958) and noodles.

Table 1.1 Statewise area and production of tapioca for the year 1990-91

State	Area (Hectares)	Production (Tonnes)
Andhra Pradesh	15,000	1,46,100
Assam	2,294	9,812
Karnataka	955	8,314
Kerala	1,47,252	27,98,980
Meghalaya	4,046	23,718
Mizoram	129	1,196
Nagaland	350	900
Rajasthan	324	615
Tamilnadu	71,587	21,07,934
Tripura	500	2,200
Andaman and Nicobar Islands	241	1,928
Pondicherry	469	10,240
Total	2,43,147	51,11,937

(Source: Agricultural Situation in India.49(4),305-306.1994.

There has been an increasing acceptance of convenient, quick-to-serve food in many developing countries. Today's time-pressurised consumer is demanding foods that can be prepared more conveniently, in less time, and with less energy. The demand for quick cooking or instant food products is expanding at a phenomenal rate in developed and developing countries. Hrishi and Nair(1978) suggested that the food uses of cassava could be expanded only if utilisation was based on processed products. But in Indian market it has to make its appearance yet. The reasons for such non-appearence are not well known. Probably it may be because of its higher production cost.

The major problem facing those who attempted to remodel ingredients into acceptable foods is texture. To achieve this, several processing techniques have been developed, such as flaking, puffing and baking, the most important of which is thermal extrusion.

Food extrusion is the process in which a low-water, powder like raw material is pressed and heated simultaneously in a shear field, converted into a plastic mass, forced through a shaping die and rapidly hardened by cooling. Extrusion processing has become an increasingly popular procedure in food industries which will utilize starchy and proteinaceous raw materials. It exhibits several advantages. The major advantage is that the ingredients undergo a number of unit operations including mixing, shearing, cooking, drying and texturization in one energy-efficient and rapid process. Labour requirements and floor space requirements per ton of production are smaller than for other cooking systems. Further, nutrient degradation is minimized and most bacterial and other pests are destroyed, resulting in an excellent shelf life of the final product.

The principal constituents of all cereal and root crops is the biopolymer starch(Harper, 1981). The chemical basis of extrusion texturization is believed to be the formation of covalent bonds between polypeptide chain or between chains and other constituents. Sanderude(1969) and Matson et al.(1982) proposed a list of several food starch materials which can be utilized for producing extruded snack foods, including tapioca flour also. Badrie and Mellowes(1991a &b) had shown that cassava flour was a satisfactory food ingredient in the puffed snack product.

Till to-day, food extruders are very costly and need to be imported involving higher foreign exchange. Thus, it is essential to develop food extruders suitable for our processing conditions and products. An attempt towards the development of indigenous food extruder and process technology for the production of extruded cassava based snack foods will add additional ways of utilising cassava.

Although the food extruder is capable of handling a variety of ingredients, the processing conditions need to be standardized as much as possible with respect to both equipment and ingredients. The final product properties could be manipulated by varying extrusion process variables such as moisture content of the feed material, temperature of the barrel and screw speed. However, very little information is available on the effects of these variables and their interactions on the characteristics of cassava extrudate. This calls for a systematic research in establishing the relationships between extrusion process variables and final product properties and standardisation of extrusion process for cassava food system.

In the light of these views, the present study was undertaken with the following specific objectives:

1. To determine the physical and thermal properties of cassava flour and also proximate composition and gelatinization temperature.

2. To develop a laboratory scale extruder for studies on extrusion cooking of cassava flour based food product.

3. To investigate the effects of different process variables on extrusion cooking of cassava flour

4. To determine the various physical, functional and mechanical characteristics of the extrudate

5. To evaluate cassava flour extrudate with regard to its product quality through sensory evaluation.

It is hoped that the present study will help in finding additional ways of utilization of cassava for food product and setting up new agro industries in cassava growing areas for employment generation in rural sectors.

REVIEW OF LITERATURE

2. REVIEW OF LITERATURE

This chapter deals with the review of the research work carried out by various investigators on the utilisation of cassava, development of extruded foods, the influence of various process variables on the physical and mechanical properties of the extrudate. Studies on effect of extrusion parameters on functional properties, like, water absorption index, water solubility index, viscosity are also discussed. Influence of extrusion processing variations on dough rheology in the extruder, torque, energy and pressure requirement for extrusion are also reviewed along with the work done on sensory evaluation and presented in this chapter.

2.1 Cassava

Cassava (Manihot esculenta Crantz.) is a dicotyledonous plant belonging to the botanical family Euphoriblaceae (Onwueme, 1978). The tuber is circular in cross section. In internal structure, the tuber is divisible into three regions. The outer most layer is the corky periderm, a few layer of cell thick, composed mostly of dead cork which effectively seal the surface of the tuber. Just beneath the periderm is the cortex which is only 1-2 mm thick. It is usually white but may sometimes be pinkish or brownish. The peel of the tuber is composed essentially of the cortex with the outer periderm layer adhering to it which is usually removed in processing of the tuber. The central portion of the tuber is the flesh. This consists mostly parenchymatous cells containing large amounts of stored starch. Thin vascular bundles ramify randomly throughout the flesh and a large strand of vascular tissues runs through the centre of the flesh(Onwueme,1978).

2.1.1 Cassava flour

In commercial production of cassava flour, freshly harvested roots are peeled, washed, chipped and dried. The dried slices are ground to flour in a disintegrator or other type of grinding mill. The color of the cassava flour is white to light cream and is free from rancidity, foreign matter and insect infestation(Ingram,1975).

Cassava flour develops stickiness during cooking which is a disadvantageous feature compared to cereal flours. Textural improvement of cassava flour was attempted by Raja et al(1980). Their studies revealed that the fineness of the flour had a direct correlation with the stickiness developed during cooking. Simple dry heat treatment of the whole flour at 70° ± 1°C for 30 minutes to one hour was reported to improve the textural quality.

2.1.2 Traditional modes of utilisation of cassava

In India the most popular mode of consumption of cassava is as mashed tuber. Boiled cassava is sometimes grated and mixed with shredded coconut (Rao, 1951, Subramanyan, 1951) known as puttu. Cassava flour can be made into a sort of porridge by mixing with water (Subrahmanyan, 1951). Sometimes it is mixed with rice before cooking. Often the flour is used to make traditional Indian foods such as chappati, uppuma, idli and dosa (Anonymous, 1952; Hiranandani and Advani, 1955).

2.1.3 Value added cassava food products

A wide variety of techniques involved in the preparation of cassava based foods and beverages on a world wide basis have been reviewed by Lancaster et al.(1982) and Etejere and Bhat (1985).

A product, 'Cassava macaroni', was developed by Central Food Technology Research Institute(CFTRI). The ingredients for cassava macaroni were 60% cassava flour, 15% groundnut flour and 25% wheat semolina. The ingredients were mixed well and moisture was maintained at 10-11 per cent level. The dough was formed with 31-33% of boiling water. Boiling water gelatinized part of the cassava starch and bound together the dough. The dough was then extruded through the macaroni press to a desired shape. The extruded product was dried to a final moisture content of 10 per cent. Further exposure of the macaroni to high temperatures of

115-120°C for 15 minutes brought down the moisture to 5 per cent(Subrahmanyan et al., 1958).

Cassava rava is a partially gelatinised starch preparation modified and developed at Central Tuber Crops Research Institute(CTCRI). It was prepared from peeled tubers after slicing, washing, steaming for 5 minutes at 5 psi drying and disintegrating into 0.5 to 3 mm fractions (Balagopalan et al.,1988).

Gold finger is a popular snack food item, manufactured using 50 per cent wheat flour and 50 per cent cassava starch in the traditional process(Padmaja, 1994). Cassava vermicelli and noodles are made from cassava starch, wheat flour, soyaflour and groundnut flour and fortified with vitamin A, calcium, phosphorus and iron(Thakkar, 1982).

2.1.4 Theory of Extrusion Cooking

Extrusion cooking process, one of the fastest growing technologies, is a process that involves forcing a material to flow under a variety of controlled conditions and then to pass through a shaped hole or slot at a predetermined rate . Raw materials such as modified cereal flour and starches, textured proteins, snack foods, breakfast cereals and pet foods may be produced (Harper 1981b). Badrie and Mellowes (1991a, 1991b, 1992) have shown that cassava flour can be used as a satisfactory feed ingredient for puffed products using suitable extrusion conditions.

Extrusion technology has its note in the metallurgical industry. Joseph Bramah, a British engineer was the first to apply the extrusion principle in 1797. He developed a hand operated piston press to extrude seamless lead pipe. The first food applications of extrusion process was applied for the production of sausage and processed meat during mid to late 19th century(Harper, 1981). Two kinds of extruders were used for these applications, a piston or ram type extruder to stuff casings, and a simple food chipper or mincer employing a single screw to force soft food stuffs through a die plate (Harper, 198).

Another early application of extrusion was in pasta production following the invention of a hydraulically operated, cylindrical ram macaroni press. This device was used in a batch operation to shape pasta dough. It was replaced by the first single-screw-extruder to be used in the food industry - the pasta press which was introduced in 1935(Dziezak,1989).

At the same time roller extruders were developed to form cereal dough products and screw extrusion began to gain wider acceptance. By the late 1930s General Mills of Minneapolis was the first used to introduce an extruded Ready To Eat(RTE) cereal based on this process. Expanded corn curls or 'Collets' were first extruded by Adams Corporation in 1939. The product was not marketed until after world war II (1946)(Lusas and Riaz,1994).

Simple, inexpensive extruders were initially developed in the united states for on-farm cooking of soybeans and cereal feeds in the 1960s. The low-cost extruder (LCE) designs were quickly adapted in the mid-1970s for use in nutrition intervention projects in many less-developed countries. Numerous mechanical problems were experienced with early LCEs, but later models were more reliable and were widely used for processing gruel-like and crudely texturised foods in LCEs.

An extruder is basically a screw pump that simultaneously transports, mixes, shears and stretches and shapes material under elevated pressure and temperature. It may be considered as a screw reactor for physical, chemical and biochemical transformations. A typical extrusion system consists of feed assembly, extrusion barrel, extrusion screw, extrusion drive and extrusion discharge.

The screw is the key element of the single-screw extruder, as its geometry influences the operation of the extruder (Harper, 1978). It consists of a helical flight wound around a metal shaft enclosed within a cylindrical barrel. As the material is moved along the screw in extrusion cooking, it is transformed under conditions of heat, pressure and mechanical shear from a granular state into a viscomorphic mass, and finally into a product with specific properties. These changes in the product correspond to effects of specific zones of the extruder screw. Extruder barrel has three processing zones: the feed zone, the kneading zone and the final cooking or metering zone (Matson, 1982).

The feed zone generally has deep channels which receive the feed. This section mixes the feed ingredients and slightly compresses the feed into a more homogeneous state in the screw flights. The kneading zone, where the depth of screw flights decreases, applies compression, mild shear and thermal energy to the feed. By the end of this zone, the feed material is a viscoamorphic mass at or above 100°C (Faubion et al., 1982). The point at which the extrudate completely fills the screw channels and begins to become worked is termed the 'Choke point' because the barrel is full-choked-from this point forward (Anon, 1983). The choke point is located at the point where the dough enters the final cooking zone.

The final cooking zone has the shallowest channel depths and functions in compressing and pumping the material in the form of plasticized mass to the die. Shear is highest in this zone, and the temperature of the material increases rapidly, reaching a maximum that is held for less than 5 seconds before the product is forced through the die (Harper, 1978). The die determines the shape of the finished product and affects the extruders back pressure.

Table 2.1 Typical operating data for five types of food extruders (Rossen and Miller, 1973)

Measurement	Typical operating data				
	Pasta press	High pressure forming extruder	Low shear cooking extruder	Collect Extruder	High shear cooking extruder
Feed moisture, %	22	25	28	11	15
Product moisture,%	22	25	25	2	4
Maximum product temperature,°C	52	79	149	199	149
Ratio of screw diameter to flight height D/H	6	4.5	7-15	9	7
Number of parallel screw flights,P	1-2	1	1	2-4	1-3
Screw speed,N rpm	30	40	60	300	450
Shear rate in screw,Sec^{-1}	9.5	9.5	22-47	140	165
Mechanical energy input,Kw-hr/kg	0.05	0.03	0.02	0.16	0.11
Portion of mechanical energy input dissipated as heat, Kw-hr/kg	0	0	0.05	0	-0.04
Net energy input to product(Kw-hr/kg)	0.02	0.02	0.07	0.10	0.07
Product type	Pasta	RTE cereals	Soft moist products starch and soup bases	Puffed snacks	TPP dry pet foods

Throughout the extrusion process, heat input to the product comes from several sources. This includes steam injection into the extruder barrel, frictional heat developed at the barrel wall and in the die area during rotation of the screw, or heat transfer from a steam jacket encasing the barrel or from a steam quill in a Rollow-cored screw. Frictional heat can be a significant source of energy for highly viscous material.

Table 2.2 Extrusion cooked products to replace conventional processes

Product group	Product example	Conventional process
Modified cereal flour	Baby food	Drum Dryer
Animal food	pet food	Autoclave or oven
Dairy food	Caseinate	Stirred tank reactor
Flavours	Roast flavours,	Roasting tank
	Caramel, Cracknel	
Baked articles	Flat bread, biscuits	Baking oven
Breakfast cereals	Puffed rice,	Puffing gun
	cereal flakes	Batch cooker
Farinaceous food	glass noodles	cooker
	fish noodles	
Sweet articles	Liquorice, fruit gums	Cooker and
	Chocolate	mogul conche

2.2 Theory of Gelatinization

The principal constituent of all cereals and starchy root crops is the biopolymer called starch. Starch consists of α - D glucose units linked together into large macromolecules existing in the form of insoluble granules in the raw food products. In the raw or native state, starch exists in the form of granules. Two polysaccharide fractions exist in starch are amylose and amylopectin, which are biopolymers of D-glucose.

The starch granule is considered a spherocrystal consisting of concentric layers of starch molecules. In each layer the intermingled molecules are deposited in radial fashion around a central region called the hilum. When raw starch granules contact water, they swell and absorb some of the water. Once removed from the water, the granules can be dried and so return to their native state. The reversible swelling of starch granules occurs upto some maximum temperature called the gelatinization temperature (Harper, 1981).

When an aqueous suspensions of starch granules are heated, a temperature is reached at which hydrogen bonding forces are weakened to the point where water cannot be absorbed by the granules. At this temperature, called the 'initial gelatinization temperature', the granules swell tangentially and simultaneously lose their birefringence. Gelatinization starts in the intercellular areas where the hydrogen bondings are weaker. As the temperature of the aqueous suspensions is increased, water molecules become attached to hydroxyl groups and the granules continue to swell. As a direct result of granule swelling, there is an increase in starch solubility, paste consistency and paste clarity. With the continued swelling of granules, starch particles that have became fully hydrated separate themselves from the intricate micellar network and diffuse into the aqueous medium. In a concentrated starch paste, the individual granules gelatinize and swell freely until all the available water has been inhibited. As they swell, the swollen starch granules become increasingly susceptible to shear disintegration. The bonding forces in the granule also became weaker as heating continued and the susceptibility of the granule to mechanical and thermal breakdown increased (Olluku and Rha,1978).

Gelatinization is believed to result from the formation of a three-dimensional network which binds the swollen granules(Miller et al., 1973).

In summary, the gelatinization of starch takes place as follows:

i) Granules hydrate and swell to several times their original size
ii) Granules lose their birefringence
iii) Clarity of the mixture increases
iv) Marked, rapid increase in consistency occurs and reaches a peak

v) Linear molecules dissolve and diffuse from ruptured granules
vi) Mixture retrogrades to a paste-like mass or gel.

Gelatinization of starch is a basis for many types of food production. Processes such as the baking of bread, the gelling of pie fillings, the production of pasta products, the fabrication of starch-based snack foods and the thickening of sauces are all dependent on proper gelatinization of starch to produce a desirable texture or consistency of end product.

Several criteria have been used to measure the degree of gelatinization. These criteria, given by Chiang and Johnson, (1977) are :

(i) loss of birefringence (crystallinity) in polarised light
(ii) binding of dyes
(iii) swelling
(iv) increase in solubility
(v) increase in viscosity
(vi) proton magnetic resonance
(vii) X-ray diffraction patterns
(viii) proton magnetic resonance
(ix) differential scanning calorimetry, and
(x) enzyme susceptibility.

2.2.1 Low moisture gelatinization

Extensive literature exists on the gelatinization of dilute mixtures of starch with water. In contrast, very little information is available on gelatinization of starch at moistures less than 50 per cent, the range where extrusion processing is practised.

Water is a very important constituent in the gelatinization process. Stable starch/water gels with moisture levels of 95 per cent are possible. Based on stoichiometry, with one water molecule bound to each available hydroxyl group on the starch, a minimum 25% moisture level would be required. Low levels of water are sufficient to interact with the starch in extrusion ingredients to plasticize the mass and form a dough.

2.2.2 Effect of extrusion process variables on gelatinization of starch

Gomez et al.(1983 and 1984) reported that decreasing moisture content resulted in a higher degree of gelatinization for both ground white corn and corn starch extrudates. In the same study Gomez et al.(1984) found that reduced extrusion moisture content resulted in a change from gelatinized-like to dextrinized like properties. In a similar study El-Dash et al.(1983) concluded that degree of gelatinization and hot paste viscosity of extruded corn starch can be effectively controlled by controlling the moisture content of raw material and extrusion temperature. They also observed that starch with 25-26 per cent moisture content extruded at 135-145°C produced an extrudate with a cold paste viscosity similar to that produced by the extrusion of starch with 15-16 per cent moisture content at 200-210°C. They further reported that starch with a high moisture content produced an extrudate with a high retrogradation capacity when the screw speed was moderately low (upto 130 rpm), but the extrudate produced from starch with a low moisture content exhibited a very low retrogradation capacity.

Lawton et al.(1972) observed that product moisture content and extruder barrel temperature had the greatest effect on gelatinization of corn starch. The maximum gelatinization occurred at higher moisture content and lower barrel temperature or vice versa. Extrusion cooking of corn was studied by Anderson et al.(1969) and they concluded that starch degradation was enhanced by low moisture content and high temperature. Kim and Rottier(1980) found that complete destruction of starch granules was obtained above 125°C for wheat extruded in a single screw extruder. Chiang and Johnson(1977) studied the influence of extrusion variables on the gelatinization of wheat flour. At temperature above 80°C, gelatinization of starch in the sample sharply increased.

El-Dash et al.(1983) reported that at low moisture content, changing the screw speed did not result in a significant change in the degree of gelatinization, but when the moisture content of raw material increased, the effect of speed became more marked and relatively small increase in rpm resulted in an increase in degree of gelatinization. They obtained the least degree of gelatinization when the moisture content was high with lower speed. They concluded that controlling the degree of gelatinization by controlling the screw speed was only effective at higher moisture contents. They found that increasing screw speed resulted in higher degree of gelatinization. At lower speeds, the degree of gelatinization was more sensitive to temperature changes and the minimum degree of gelatinization was obtained at a low speed and a temperature of 145 - 205° C. Chiang and Johnson(1977) extruded wheat flour in a single screw extruder and found that increase in the screw speeds and die diameter gave lower levels of gelatinization, since they reduced the residence time. They also obtained the complete gelatinization of the product at 110°C and 24-27 percent moisture content.

2.3 Energy and pressure requirements in extrusion

In a food extruder, the dough enters the feed port and advances along the helical channel to the screw. At the end of the screw, the pressure that has been built up, forces the food dough through the die. Through viscous dissipation, the mechanical energy input from the drive motor to the screw is converted into heat in the dough but some goes to increase the pressure in the food dough and its kinetic energy. Estimation of power input allows the calculation of drive power requirements, an essential parameter in extruder specification.

The total energy input to the shaft of an extruder can be expressed as

$$dE = dEH + dEp + dE\delta + dEk \qquad ....(2.1)$$

where dE = energy input per differential down channel distance

dEH = viscous energy dissipation in channel

dEp = Energy to raise pressure of food dough

$dE\delta$ = viscous energy dissipation in flight clearance

dEk = Energy in increase kinetic energy

Since velocities in an extruder are low, the term dEk is assumed negligible.

The specific energy, is the energy per unit flow rate and is a common way of expressing energy requirements. Since in food extrusion, flow rate is nearly equal to the drag flow, the specific power would be expected to increase linearly with screw speed, for Newtonian doughs at constant temperature. For food doughs, generally being pseudo-plastic, the viscosity is proportional to shear rate which is in turn proportional to N^{n-1}, so specific energy would be expected to increase as N^{n}. The existing model describing the power inputs for extruder are based on Newtonian fluid. These models can be used to approximate the power inputs for non-newtonian fluids after substitution of non-Newtonian viscosity i.e., apparent viscosity.

References to the application of the models describing the power inputs to a food extruder are relatively few. Total power inputs to the extruder are commonly measured with a wattmeter in the electrical drive motor and also indirectly by torque meter.

2.3.1 Effect of extrusion process variables on energy consumption

Harper(1976) measured the power requirement of soybean-cereal blends with feed rate, water content and temperature of extrusion as variables. The specific power obtained was in the range of 0.102 to 0.210 hp-h/kg. Also, increase in dough temperature or water content resulted reduction in specific power requirements. The results indicated that specific power requirement was more for wheat-soy and sorghum-soy blends as compared to corn-soy and rice-soy mixtures. Bruin **et al.**(1978) and Harmann and harper(1973) have studied the power requirements for corn grits and found power requirements decreasing with increase in dough temperatures and moisture content. Over the range of conditions studied, specific powers of 0.10 to 0.13 KW-h/kg were found.

Bruin et al.(1978) also extruded diamylopectin phosphate at different moisture level through an extruder with varying dies and extrusion screw. The data showed reduction in specific power with increase in moisture, but increased at higher moisture. They attributed these results to the increased extent of gelatinization at higher moistures and similar findings were reported by Harmann and Harper(1973) and Van Zuilichem **et al.**(1975).

Bongirwar **et** al.(1979) measured power requirements for extrusion of corn flour and ground flour and found that as the fat content of the dough increased the specific power requirement decreased. Similar results were obtained when the feed rate was increased. The specific power requirement for extrusion of the above materials varied from 0.662 to 2.2 KVA-h/kg.

Bhattacharya and Hanna(1987b) reported that an increase in moisture content caused the specific energy requirement to decrease. Lin and Armstrong(1990) extruded cereal starches and reported that specific energy consumption increased from 0.90 to 1.75 W min/g for the moisture range of 30 to 20 per cent.

Bhattacharya et **al.**(1987a) studied that at a constant barrel temperature of 120°C and a screw speed of 100 rev/min the specific energy at 14, 20 and 26 per cent moisture was 0.264, 0.076 and 0.046 Kw-h/kg, respectively. Similarly, an increase in temperature from 120°C to 170°C decreased the specific energy requirement from 0.264 to 0.046 Kwh/kg at 14 per cent feed moisture. On comparison, the effect of screw speed on specific energy was found to be negligible. An increase in screw speed from 40 to 160 rev/min resulted in approximately 8 to 10 per cent variation in specific energy consumption. Sahagun(1977), for the blend of 70 per cent corn and 30 per cent soy, found that specific energy increased by 15 per cent with a doubling of extrusion speed at constant extrusion temperature. Lin and Armstrong(1990) studied that specific energy consumption was found to decrease with increase in barrel temperature and screw speed.

Das et al.(1988) carried out experiments to study the effect of production rate, screw speed and die diameter on specific energy requirements of corn-soy-milk blend at 90°C extrusion temperature. They found that at higher screw speed (70 rpm) and smaller die opening (4.75 mm), the specific energy requirement was minimum. The results indicated that as the extruder output increased, the specific energy requirement decreased. A low moisture content (below 15 %) can increase power requirements and surging (Conway, 1971) and can also result in excessive browning and stoppage of extrudate at die nozzle opening.

2.3.2 Effect of extrusion process variables on pressure requirements for extrusion

Pressure measurements in the food extruders, behind the die are useful in determining the steady flow conditions and monitoring the operation of the extruder (Harper, 1979). Lin and Armstrong(1990) mentioned that the pressure at the die increased from 18 x 10^5 to 46 x 10^5 Pa for a change in the feed moisture from 30 to 20 per cent. Bongirwar et al.(1979) studied the effect of process variables such as temperature and screw speed on the pressure requirements to the extruded defatted groundnut flour at 9.1 per cent moisture. They found that an increase in temperature of extrusion decreased the specific pressure requirements, where as increase in the screw speed increased the specific pressure. Bhattacharya and Hanna(1987b) studied the effect of process variables on extrusion pressure requirements of corn gluten meal (CGM) at moisture contents of 14, 20 and 26 per cent and extruder barrel temperatures of 100, 150 and 200 rev/min. The results revealed that specific pressure was found to decrease with an increase in all these three independent variables. They concluded that specific pressures may be assumed to be directly proportional to the apparent viscosity of the dough in the extruder.

Pigot et al.(1951) observed that the relation between discharge rate and pressure was an inverse linear for rubber like materials. They found increase in screw speed increased the head pressure and discharge rate. Bhattacharya and Hanna(1986) used dimensional analysis to develop mathematical model of food extruder and observed that any change in the product composition would lead to a change in both rheological and thermal properties thus causing a change in specific pressure and specific energy. Bhattacharya and Hanna(1987a) measured the pressure exerted by the food dough during extrusion. The data was used to calculate the change in viscosity of food dough as it comes out of the die. The analysis of data reveals that increase in screw speed and temperature of extrusion decreased the specific pressure requirement for extrusion of fish-wheat flour blend. Lorenz et al.(1974) processed triticale in a Brabender plasticorder. They studied that increased temperature significantly lowered torque and seemed to be most important variable affecting the torque. Grossmann et al.(1988) extruded cassava starch for ethanal production at different moisture content, extrusion temperatures and screw speed and proposed a regression equation.

2.4 Dough Rheology

Food extrusion is a flow process requiring the characterization of food dough rheology for the mathematical description of many important extrusion parameters. In extrusion cooking viscosity of food dough is an important process characteristics for energy requirement and finished product characteristics. The food extrudates are highly non-newtonian, exhibiting shear thinning behaviour. This behaviour is normally described by the power law model(Levine,1992).

$$T = K(\gamma)^{n} \qquad ....(2.2)$$

Where T and γ are shear stress and shear rate, respectively. The constants K and n are the consistency coefficient and flow behaviour index of the dough.

Defining viscosity as the ratio of shear stress to shear rate, the apparent viscosity is,

$$\eta = K(\gamma)^{n-1} \qquad \text{....(2.3)}$$

Table 2.3 shows the values of the constants K and η using the power law model. The food dough used for extrusion were typically pseudoplastic (Clark, 1978) which was proved by the low magnitude of flow behaviour index, n as shown in Table 2.3.

A few other viscosity models are also available for food during extrusion. Cervone and Harper(1978) and Remsen(1977) gave theoretical justification for the model which incorporates moisture and temperature effect in addition to shear rate.

$$\eta = \eta\alpha \exp(E_a/RT) \qquad \text{....(2.4)}$$

Where n and n_α are apparent viscosities at temperature T and at very high temperature respectively. The term E_a represents energy of activation for flow and R is gas constant.

To account for changes in apparent viscosity with changes in moisture Morgen et al.(1978) have used an exponential form of equation with some success.

$$\eta = \eta_o \exp\ (CM) \qquad \text{....(2.5)}$$

Where η_o and η are apparent viscosities at reference moisture and at moisture content M respectively. The term C is a constant.

A semi empirical model was proposed by Harper et al.(1981b) as follows.

$$\eta = \eta^{*}(\gamma)^{n-1} \exp(K1/T + K2M) \qquad ....(2.6)$$

Where η^{*} is reference apparent viscosity

Temperature and moisture have a pronounced effect on food dough viscosity, as shown above. Some authors (Morgen et al., 1978; Remsen et al., 1978) have attempted to include the time-temperature history into the viscous model of the extrudate. This has been accomplished by assuming that the flow consistency is controlled by a first-order equation.

$$\eta = \eta^{*}(\tau)n-1 \exp(\ En/RT) \exp\int_{t_0}^{t} K\alpha \exp(\ EK/RT)\ dt \qquad ....(2.7)$$

Where η and η^{*} are apparent viscosities at temperature T and reference temperature. The constant $K\alpha$ is the apparent kinetic factor at infinite time t and t_0 the time at start of cooking.

Morgan et al.(1979) developed a theoretical model which described the effect of temperature time history, temperature, shear rate and moisture content on the apparent viscosity of defatted soyflour dough.

Harper(1981) and Bhattacharya and Hanna (1986a) mentioned that even though a number of models did exists, no single model had won the universal acceptance. Moreover, no single model describes apparent viscosity as a function of composition, variability in ingredients, time, temperature, moisture and other extrusion parameters.

2.4.1 Effect of extrusion process variables on viscosity of extrudate

The effect of moisture variation on dough viscosity was investigated by Rogers et al.(1970). They observed a decrease in n value from 0.7 to 0.2 when the feed moisture content was changed from 32 to 22 per cent. Clark(1978) mentioned that the dependence of rheological parameters upon moisture was very significant and would be helpful for over all process optimization. Chen et al.(1978) developed a viscosity model for defatted soy dough and concluded that added moisture caused reduction in dough viscosity.

Harper et al.(1971) extruded corn grit-out flour dough between temperature range of 85 to 130°C with feed moisture of 25-30 per cent and found that the increase in temperature decreased the viscosity of food dough.

Davidson et al.(1984a) extruded wheat starch through a single screw cooking extruder with 20 and 25 per cent moisture. They used the viscosity model developed by Harper(1971) and found that a change in melt temperature from 177 to 121°C increased the viscosity by a factor of 2.2. Bhattacharya and Hanna(1987b) while studying the influence of process and product variables on extrusion energy requirements observed that a one per cent increase in moisture content, temperature and shear rate (screw speed) would cause a 4.88, 3.67 and 0.413 per cent reduction in viscosity of corn gluten meal.

Peri **et al.**(1983) and Paton and Spratt(1984) reported contradictory results on extrudate viscosity as a function of temperature. Peri **et al.**(1983) extruded blends of corn germ flour and milk protein with extrusion temperatures of 150°C and 170°C at feed moisture content of 80 per cent. They found that with the increase in temperature of extrusion, the viscosity of the dough increased to change from Newtonian to non-newtonian character (i.e. Pseudoplasticity). By increasing the temperature from 150°C to 170°C a increase in viscosity was resulted probably due to excessive heating and consequent heat denaturation of constituents, particularly proteins. Paton and Spratt(1984) extruded wheat flour through a modified Brabender plastic extruder and varied the temperature of metering zone and at die from 120°C to 163°C. They found that increase in temperature did not always lead to an improvement in the extend of cook of the starch component. He indicated that dough viscosity was largely dependent on the presence of uncooked macromolecules. Lin and Armstrong (1990) reported that high extrusion temperature decreased the viscosity of cereal starch at the die which tended to reduce the restriction of flow through the die.

The effect of shear(screw speed) during extrusion was investigated by several researchers. Chen et al.(1978) reported that increase in shear rate decreased the viscosity of soy dough. Paton and Spratt(1984) concluded that an increase in screw speed did not always lead to an improvement in the extent of cook of starch components. Davidson et al.(1984a and 1984b) found that increase in screw speed usually decreased the intrinsic viscosity of wheat starch which suggested that shear forces were responsible for starch degradation. Bhattacharya(1987) studied the effect of extruder screw speed on viscosity of fish-wheat flour blend. The apparent viscosity was found to be negatively correlated with screw speed.

The dependence of rheological properties on food dough composition is pronounced(Clark, 1978) but till today, the information available is limited. Bhattacharya and Hanna (1986) extruded defatted soy grits and wheat corn gluten meal on ratios of 1:1, 1:2 and 1:3(dry basis) through Brabender 1.9 cm diameter laboratory food extruder and found higher percentage of soy had higher apparent viscosities. Blends with high soy content also indicated pseudoplastic behaviour as indicated by low values of flow behaviour index. Studies conducted by Lorenz(1976) also showed a similar trend. Addition of protenacious material in the feed increased the viscosity of extrudate. Das et al.(1988) extruded corn-soy-milk mixtures in the proportion of 62:28:10 at feed moisture level of 30 per cent and extrusion temperature of 90°C. They pointed out that the extrudate behaved as a pseudoplastic non-newtonian fluid having a flow behaviour index, of 0.3 and consistency coefficient, of 13826 $Pa.S^n$.

Table 2.3 Table Constants for power law model expressing the viscosity of food materials at extrusion conditions.

Dough material	Moisture content % (w.b)	Temperature (°C)	Constant coefficient K NS^n/m^2	Flow behaviour index n	Viscometer
Corn grits	13	177	2.8×10^4	0.5	slit die
	13	193	1.7×10^4	0.5	
	13	207	7.6×10^3	0.5	
Full fat soybeans	15-30	120	3.44×10^3	0.3	Extrusion model
Moist food product	35	95	2.23×10^2	0.78	Round die
Pregelatinized corn flour	32	88	1.72×10^4	0.34	Round die
Soy grits	32	160	1.78×10^4	0.16	Round die
Wheat flour	43	33	4.45×10^3	0.35	Rotating concentric cylinders
Defatted dough	25	54	1.210×10^3	0.49	
	50	54	8.68×10^2	0.45	
	75	54	7.00×10^2	0.43	
	85	54	1.580×10^3	0.37	
	100	54	2.360×10^3	0.31	
	110	54	2.270×10^3	0.31	
Semolina flour	30	45	2.0×10^4	0.50	Capillary tube

Reference Harper(1981) and Levine(1992).

2.5 Effect of process variables on physical characteristics of the extrudates

Physical properties are the important criteria of extruded foods from the consumer point of view. These characteristics of the extruded products depend upon the conditions of the operation of extruder and the main raw material used in the formulations (Sanderude, 1969). Most common physical properties are the expansion ratio, bulk density and porosity.

2.5.1 Expansion property of extrudate

One of the most important physical characteristics of an extrusion-cooked product is its expansion or puffing property. The degree of expansion affects product density, friability and tenderness. When the product exits through the die , the sudden drop in pressure permits all of the water to vapourize. The product quickly loses temperature as the water vapourizes and when the temperature reaches 100°C vapourization of water ceases. The vapourization of water is the principal cause of puffing of the product. One Kilogram of water heated to 150°C within the extruder will vapourise to 0.40 m^3 of steam. Another minor cause for puffing is the pressure differential between the interior and the exterior of the extruder. On the contrary, a less expanded high density product results due to low flash-off of moisture, which may be either due to low process temperature or high moisture of the feed. Expansion of the product increases with the increase in starch content when the operating temperature is above the gelatinization temperature of starch. Heating the starch in the presence of water causes swelling and expanded structure is achieved.

Bongirwar **et al.**(1979) got a highly expanded product from corn flour having an expansion ratio of 36, when the dough (25 per cent moisture content) was extruded at 177°C in an indigenously developed single screw extruder. Chauhan and Bains(1985) obtained an expanded snack product from rice flour having expansion ratio of 2.6. The addition of proteinacous substances have a negative effect on product expansion (Harper, 1981b). The effect of feed moisture on product expansion was studied by (Mercier and Feillet, 1975; Chiang and Johnson, 1977: Gomez and Aguilera, 1984; Paton and Spratt, 1984; Chinnaswamy and Hanna, 1988 and Das **et al.** 1992). The results obtained by these researchers indicated that an increase in feed moisture gave a less expanded product i.e. as the feed moisture increased the expansion decreased. Chiang and Johnson(1977) found that greater degree of starch gelatinization results in better product expansion.

It was further reported that moisture content affected this phenomenon only at higher temperatures. Bhattacharya and Hanna(1987a) reported that an increase in feed moisture from 17.8 to 42.4 per cent decreased the expansion of extruded corn from 8.2 to 4.5 mm, when a die of 3 mm was used. This decrease in expansion is attributed to increase in moisture content which lowers the dough temperature resulting in lower degree of gelatinization.

Gomez and Aguilera(1984) observed that decrease in moisture content from 32.90 to 14.21 per cent, increased the expansion ratio of corn starch from 1.36 to 2.78. Das et al.(1992) studied extrusion of soy grit using response surface methodology. They predicted that expansion increases with decrease in moisture content and also explained that decrease in extrusion moisture resulted in improved moisture distribution and a more elastic dough, favoured the expansion.

The effect of process temperature on the expansion was investigated by Seib and Stearns(1972), Chiang and Johnson (1977), Bhattarcharya and Hanna(1987a) and Chinnaswamy and Hanna (1988). Seib and Stearns(1972) reported 170°C as the temperature for wheat starch when maximum product expansion occurred. Chiang and Johnson(1977) concluded that higher temperature, above 80°C affected gelatinization and thus expansion of the product. Bhattacharya and Hanna(1987b) observed that an increase in extrusion temperature caused an increase in expansion of extruded corn. Higher temperatures cause molecules to be stretched further because of a higher degree of gelatinization.

Badrie and Mellowes(1991b) reported an increase in expansion of extruded cassava flour extrudate from 2.27 to 2.34 when the extrusion temperature was raised from 100°C to 120°C. Conflicting results were obtained by Peri et al.(1983) when extruding corn starch and milk protein at temperatures of 150° and 170°C. Maximum expansion of 2.5 was found at 150°C.

Paton and Spratt(1984) reported that the expansion index of corn starch increased as the screw speed increased. Bhattacharya and Hanna(1987a) observed the highest expansion of extruded corn at higher screw speeds. The increase in screw speed would increase shear rate, which tends to increase product expansion, but decreases the residence time within the extruder. Bhattacharya(1987a), while extruding fish-wheat flour blend has reported that an increase in expansion of product from 1.63 to 1.95 times when the screw speed was increased from 30 to 90 rev/min. Chinnaswamy and Hanna(1988) also reported an increase in expansion of extruded corn starch for an increase in the screw speed. Badrie and Mellowes(1991b) observed that an increase in screw speed from 425 to 560 rpm resulted in lower expansion indices of 2.38 to 2.24.

The bulk density and expansion ratio of an extrudate describe the degree of puffing of the extrudate as it exits the die nozzle. Some of the studies have shown that these two properties are not interrelated(Phillips et al. 1984, Falcone and Phillips, 1988). Expansion ratio considers expansion only in the direction perpendicular to extrudate flow, whereas bulk density considers expansion in all directions.

2.5.2 Bulk density

According to Harper(1981b), the extruded products and textured plant protein (TPP) may have density in the ranges of 0.2 to 1.3 g/cc depending on moisture content and its degree of expansions. The lower densities are characteristic of highly expanded extruded products such as dry TPP used as meat extender or expanded cereals used as snacks. Through the modifications of extruder geometry and its components, the die configuration, raw ingredients selection and processing conditions, it is possible to control the density of the end product. During the final cooking and drying of the texturized product the density also increases. Often higher density products are desired for use in food products which are further heat processed since they retain their integrity better.

A number of researchers studied the effect of process variables like moisture content of feed, screw speed, temperature of extrusion on bulk density of the product. Bongirwar et al.(1979) extruded corn starch at 177° and 25 per cent moisture content. The material with anextremely low bulk density of 0.1 g/cc was characteristic of a highly expanded extruded product. Lawton et al.(1985) extruded wheat gluten and reported that maximum bulk density of about 0.53 g/cc at 130°C with feed moisture level of 29 per cent whereas extrusion at 190°C with feed moisture as 20 per cent resulted in a minimum product bulk density of 0.20 g/cc.

Badrieet al.(1991b) showed that cassava flour was a satisfactory feed ingredient for puffed products and reported that increase in feed moisture percent increased bulk density of the extrudates. Working with Soymeal (cumming et al.1972), corn grits(Harmann et al., 1973) and rice flour (Chauhan et al.,1985), these researchers found that the increase in moisture level of the feed increased the density of the extrudate product.

Harper(1981b) found that processing conditions were responsible for the product density after extrusion. Density of the product was found to fall sharply with the increase in temperature of extrusion (Cumming et al.,1972; Harmann et al.,1973; Toranto et al., 1975; Lawton et al., 1985; Bhattacharya et al., 1987a).

Chauhan et al.(1988) reported that density of rice and legume extrudate reduced from 0.68 g/ml to 0.43 g/ml when extrusion exit temperature was increased from 60°C to 95°C. Harmann and Harper(1973) explained two reasons for the decrease in density with increase in extrusion temperature.

i) Decrease in viscosity as temperature increases, allows the dough to expand more readily, and
ii) Increased vapour pressure as temperature increases, causing increased flashing and puffing.

Bhattacharya and Hanna(1987b) reported an increase in bulk density of extruded corn from 204 to 722 kg/m^3 when the extrusion temperature was raised from 116°C to 164°C. Singh **et** al.(1994) observed that the density increased from 0.55 to 0.59 g/cm^3 for sound wheat grain flour and 0.37 to 0.62 g/cm^3 in flour milled from 48 h sprouted wheat grains, when the temperature of extruder die section was raised from 145°C to 190°C.

The screw speed had very significant effect on extrudate density. Badrie and Mellows(1991b) reported that an increase in screw speed from 425 to 560 rpm lowered the bulk density of cassava extrudate from 0.33 to 0.30 g/cc. Harmann and Harper(1973) also observed that the density decreased with increase in screw speed. They explained three possible causes.

i) viscosity decreases as screw speed increases for a non-newtonian dough

ii) as screw speed increases, free moisture is more evenly distributed throughout the dough which gives uniform puffing and

iii) forces normal to the flow direction increases with increased flow rate.

2.6 Water absorption and solubility indices(WAI and WSI)

Biopolymer transformations introduced by thermal treatment markedly affect the functional properties such as water absorption index(WAI), Water Solubility Index(WSI) and rheological behaviour. Consequently, such functional properties in the product are the excellent indicators of the phenomena that occur in the HTST extrusion reactor. Further more, they give valuable information on the suitability of the process of the products for specific applications(Linko et al., 1982). Water Solubility Index(WSI) is frequently used by the industry, since it can be determined quickly and has been linked to other important product characteristics(Anderson,et al 1969 and 1971; Mercier and Feillet, 1975). Water absorption index correlates well with cold paste viscosity because only damaged starch granules absorb water at room temperature and swell, resulting in increased viscosity. The water absorption index is a measure of cold paste viscosity and water solubility index is a measure of gelatinization (Mercier and Feillet, 1975).

2.6.1 Effect of extrusion process variables on water absorption index(WAI) and water solubility Index(WSI)

Moisture content of feed was found to alter the water absorption index and solubility index to a great extent. Anderson et al.(1969) observed that water absorption index increased from 3.2 to 5.8 g gel/g of dry sample and a decrease of water solubility index from 11.1 to 5.0 per cent when the moisture content of sorghum grits varied from 15 to 35 per cent.

Gomez and Aguilera(1983) observed that decrease in extrusion moisture content resulted in increased water solubility index and decreased water absorption index. Paton and Spratt(1984) extruded a combination of wheat starch, vital gluten and wheat flour solubles in a single screw extruder and reported no apparent difference in water absorption index for wheat starch. But they found the water solubility index pattern was closely associated with variations in feed moisture content of starch. As the feed moisture content decreased, water solubility index increased, which is in agreement with the results reported for other pure starches(Mercier and Feillet, 1975) and for corn grits(Conway et al., 1971). Park et al.(1993) extruded defatted soy flour, corn starch and raw beet blends in a single screw extruder. Badrie and Mellowes(1991b) reported that as feed moisture increased, water absorption index increased while water solubility index decreased for cassava extrudate. This indices were higher than the WAI and WSI of unprocessed cassava flour. (WAI 2.5 g gel/g dry sample; WSI 4.48%). Gomez and Aguilera(1983), reported the high values of water absorption index in gelatinized corn starch were due to presence of undamaged polymer chains and greater availability of hydrophilic group which can bind water molecules.

Williams et al.(1977) discussed the extrusion of yellow corn grits and indicated that maximum WAI can be obtained at the moisture of 27 per cent and discharge temperature of 135°C. At higher temperature and drier conditions, dextrinization occurred with increased WSI and decreased WAI. At 15% moisture and an extrusion temperature of 205°C, they reported 75 per cent WSI with about 30 per cent of the starch being dextrinized.

Anderson et al. 1969 observed that the water absorption index for sorghum grits extrudates increased progressively with barrel temperature upto about 188° to 193°C and then decreased as decomposition or degradation began to take place. The water solubility index increased progressively with barrel temperature throughout the entire temperature range. Mercier et al.(1975) extruded various starches and observed that water solubility index of corn and common wheat products steadily increased with extrusion temperature. They reported a dramatic effect on waxy corn water solubility index, which reached 70 at 135°C and 90 at 170°. Rice water solubility index had a maximum value at 185°C whereas amylose 5 and 7 were not modified until 200°C.

Badrie et al.(1991b) studied that increase in extrusion temperature from 100-105°C to 120-125°C lowered the overall WAI from 3.87 to 3.76 g gel/g sample and higher overall WSI of 40.64% and 41.37%, respectively. They concluded that at lower temperatures there was probably less molecular degradation of cassava flour. In a similar study Mercier(1980) studied that the water solubility index increased with the extrusion temperature and the water absorption index decreased, for manioc starch. The increased solubility of extruded starches was related to stickiness of the end product. Generally water absorption index increased with the temperature of the processing with a maximum 180° -

200°C and 18 per cent moisture content for various products

Badrie et al.(1991b) reported that increase in screw speed from 425 to 520 rpm reduced overall water absorption index of cassava extrudate from 3.74 to 3.44 g gel/g sample and increased the overall water solubility index of 42.04 and 43.02 per cent. Das et al.(1992) extruded defatted soy grits and concluded that screw speed showed a quadratic relationship with water absorption.

Anderson et al. (1969) reported that for an increase in the temperature from 107°C to 204°C, the viscosity of the uncooked cold paste(29°C) increased to a maximum for 177°C and then decreased with further increase in temperature at 25 per cent moisture content. Final cooked paste viscosity(50°C) decreased progressively from 395 B.U at 107°C to 100 B.U for 204°C. Uncooked cold paste viscosity(29°C) was reduced from 250 B.U. without a die to 110 B.U with a 6 mm die. Final cooked paste viscosity (50°C) was reduced from 100 to 70 B.U. A blend of 70 per cent corn and 30 per cent soy extruded at lower extrusion temperatures had lower uncooked product viscosities (cold paste viscosity) as found by Maga et al.(1978).

Viscosity is important because it relates to consistency and caloric density in the prepared product. Anderson et al.(1969) studied that uncooked cold paste viscosity(29°C) and final cooked paste viscosity(50°C) were the highest at 25 per cent moisture content and lowest for 15 per cent moisture content for corn grit sample extruded at 107°C barrel temperature. Mottern et al.(1969) extruded brewers rice, white and brown rice and compared the amylographic data and reported that extrusion at higher temperature gave higher initial and cooked paste viscosity(50°C). The extruded samples had very low viscosities than non-extruded rice flour during the entire heating/cooling cycle of the test. These researchers attributed the findings to partial dextrinization of starch during the extrusion process. Gomez and Aguilera (1984) reported that decreasing extrusion moisture content of the feed resulted increase in degree of gelatinization and decreased the paste viscosity of corn starch extrudates. A similar trend was also reported by Mercier and Feillet(1975).

MATERIALS AND METHODS

3. MATERIALS AND METHODS

This chapter deals with the various experimental set up and techniques used for the determination of physical and thermal properties of cassava flour. Also describes the development of a food extruder, instrumentation and methodology used for the measurement of both measuring and controlling parameters. Determination of physical, functional, mechanical and organoleptic qualities of the extrudate product are also discussed in detail.

3.1 Preparation of Cassava Flour Samples

The cassava flour was purchased from the local market and sieved through ISS Mesh No. 70(0.710 mm) to remove clots and other foreign materials. The moisture content of the flour was determined according to the method 13.003(AOAC, 1965). Accurately weighed five gram of sample was taken and dried in an oven at 98 - 100°C to constant weight(approximately five hours). The reduction in weight was found by a balance with an accuracy of 0.001 g and the per cent of moisture was calculated. The desired moisture contents of a cassava flour was obtained by adding calculated amount of distilled water; sealed in polyethylene bag and stored at about 5°C inside the refrigerator for at least 10 days, with frequent agitation to ensure uniform distribution of moisture throughout the sample. During the time of experimentation these samples were taken out and kept in ambient condition to reach the equilibrium temperature.

3.2 Physical Properties of Cassava Flour

The various physical properties of cassava flour, such as, bulk density, particle size, coefficient of friction and shear strength were determined as described below.

3.2.1 Bulk density of cassava flour

A container of known volume ($9x10^{-4}m^3$) was taken and cassava flour was filled with a gentle shaking of the container and without compaction. The excess flour was leveled off and the content was weighed. Bulk density was calculated as the ratio between the mass of the flour and the corresponding volume. The average of three replications were reported.

3.2.2 Particle size distribution of cassava flour

The method of sieve analysis, employing a vibratory type mechanical sieve shaker, was used for the determination of particle size. The cassava flour at 14 per cent(d.b) moisture content was used for the sieve analysis. A set of Indian standard sieves, ISS 60(0.600 mm), 40(0.425 mm), 30(0.300 mm), 20(0.212 mm), 15(0.140), 10(0.106 mm), 8(0.075 mm), 6(0.053 mm) and pan were used.

Cassava flour (250 g) was placed on the top sieve and shaken for 20 min. which was found to be adequate to sieve the flour in all the sieves. The fractions retained on all the sieves were collected and weighed using a physical balance, having an accuracy of ± 0.001 g. The analysis was repeated three times and the weight retained in the same sieves were added and the weight fractions were calculated.

Since the particle size of the cassava flour was expected to be within the range from 0.075 to 3 mm, differential sieve analysis was adopted(Henderson and Perry, 1966). In the differential sieve analysis, the mass mean diameter, arithmetic mean diameter and volume surface mean diameter of cassava flour were estimated using the following formulae (Mccabe and Smith, 1967; Sreenarayanan, 1983).

$$\text{Mass mean diameter, } Dm = \frac{\Sigma Q_i D_i}{\Sigma Q_i} \qquad \ldots.(3.1)$$

Where, Q_i - weight fraction of total sample retained by ith screen, and

D_i - average opening of the ith screen, mm

$$\text{Arithmetic mean diameter, } Da = \frac{\Sigma N_i D_i}{\Sigma N_i} \qquad \ldots.(3.2)$$

Where,

$$Ni = \frac{1}{a\ \ p} \times \frac{Q_i}{Di^3}$$

Ni = Number of particles per g retained on ith screen,

a = shape constant

p = Particle density

$$\text{Volume surface mean diameter, Dvs} = \frac{1}{\Sigma \; Q_i/D_i} \quad \ldots. \; (3.3)$$

The observations and calculations made for the cassava flour are given in Appendix A.

3.2.3 Coefficient of friction of cassava flour

The experimental set up used by Sreenarayanan, et al.(1990) for soybean was used with mild steel, galvanized iron, stainless steel and aluminium surfaces. The co-efficient of friction was calculated as follows:

$$\text{Coefficient of friction } f = \frac{F}{W_s} \quad \ldots. \; (3.4)$$

Where,

f - Coefficient of friction

F - Force of friction, g

W_s - Force normal to the surface of contact, g

3.2.4 Shear strength

A simple apparatus was fabricated to measure the shear strength of cassava flour (Plate 1). The device consists of a horizontally split circular cells loading pan. The lower half is

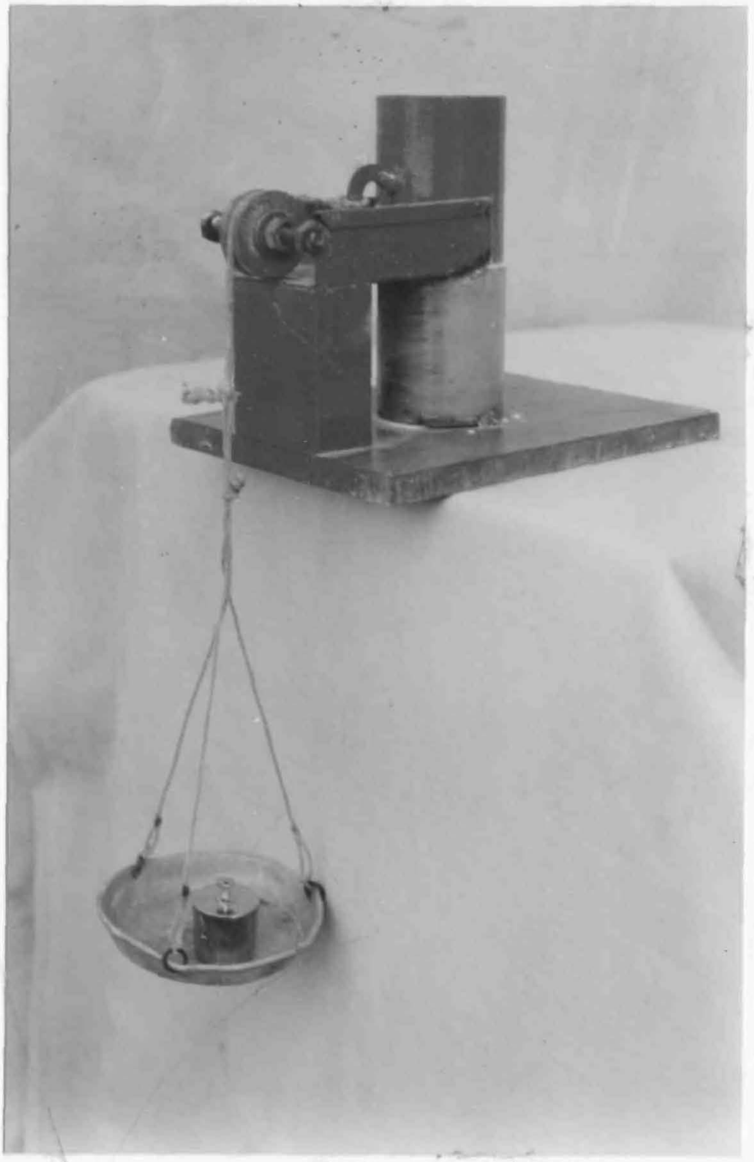


PLATE 1. Shear strength apparatus

fixed and the upper portion is movable. The cassava flour is placed inside the cells and is made to shear by adding weights gradually on the pan. The weight per unit area of rupture is found out and reported as the shear strength of the powder at particular bulk density and moisture content.

3.3 Thermal Properties of Cassava Flour

The thermal properties like thermal conductivity, specific heat and gelatinization temperature were determined using the standard test procedures for the cassava flour. Also the proximate composition of the cassava flour was determined and the values were fitted in the predicted models of thermal conductivity and specific heat developed by Choi and Okas(1983), Sweat(1986) and Heldman and Singh(1981). The predicted values were compared with the experimental results.

3.3.1 Thermal conductivity of cassava flour

A transient heat flow method for the determination of thermal conductivity was used. The methodology and apparatus employed by Sreenarayanan and Chattopadhyay(1986b) were found useful. The apparatus(Plate 2) consisted of a 26 S.W.G constantant heating wire stretched inside a brass tube which in turn was fixed at the middle of an aluminium test cylinder. The top and bottom covers were made of ebonite sheet to minimize the axial conduction of heat. The power circuit included a 12V D.C. Power source(2), rheostat(3) and a temperature indicator(4). The thermocouple was placed to record the temperature change. Observations were made for every 30 seconds for 10 minutes.

Thermal conductivity of cassava flour was calculated using the equation given by Hopper et al.(1950).

$$K = \frac{q \ln (\theta 2-\theta o)/(\theta 1-\theta o)}{4\pi \ (t2 - t1)} \qquad \ldots.(3.5)$$

Where,

K - thermal conductivity (W/m°C);

q - heat input, W/m

θ1,θ2 - time corresponding to temperatures t1 and t2 respectively, and

θo - time correction for finite diameter of probe

3.3.2 Specific heat of cassava flour

The method of mixtures used by Sreenarayanan et al.(1986a) for rice bran was employed in the present investigation to determine the specific heat of cassava flour. The apparatus(Plate 3) consisted of a calorimeter, capsules for holding the samples, instruments for precise measurement of temperatures and an oven

The test capsule and the reference capsule were filled with the cassava flour and kept in the oven which was set to the desired temperature. After the temperature of the reference

PLATE 2. Experimental set up for measuring thermal conductivity

PLATE 3. Experimental set up for measuring specific heat

capsule had reached the desired level, the capsules were kept at this temperature for about 2 hours to ensure uniformity of temperature across the diameter of the sample. The test capsule was quickly transferred from the oven beaker to the flask calorimeter and the equilibrium temperature of the mixture was recorded. The specific heat of the samples was then calculated using the following equation.

$$Cp = \frac{(Hf+Wcv)(To-Tcv) - Hc(Tc-To)}{Wg\ (Tc - To)} \quad \ldots.\ (3.6)$$

Where,

Cp - Specific heat of cassava flour, KJ/kg °C

Hf - heat capacity of flask calorimeter, KJ/kg °C

Wcv - weight of cold distilled water, kg

Hc - heat capacity of the capsule, KJ/kg °C

Wg - weight of feed, kg

Tcv - temperature of cold distilled water, °C

To - equilibrium temperature of mixture, °C

Tc - temperature of capsule with cassava flour, °C

3.3.3 Gelatinization temperature and viscosity of cassava flour

Viscography was carried out in Brabender viscoamylograph, the slurry concentrations from 5 to 7 per cent (dry weight basis) were employed maintaining the total slurry weight at 400 g. The slurry was treated upto 95°C and held for 15 minutes at this temperature and cooled to 50°C ambient. The gelatinization temperature was calculated from the amylogram.

3.3.4 Proximate composition

The proximate composition of cassava flour was determined by methods of AOAC(1965), with the exception of crude fibre which was determined by AACC(1983). Total carbohydrate was determined by difference.

3.3.5 Comparison of experimental and theoretical values of thermal conductivity and specific heat

Choi and Okas, 1983(equation 3.7) and Sweat, 1986(equation 3.8) developed the following empirical equation for determining thermal conductivity of food material based on chemical components.

$$K = 0.61Xw + 0.20\ Xp + 0.205\ Xc + 0.175\ Xf + 0.135\ Xa \quad ....(3.7)$$

$$K = 0.58\ Xw + 0.155\ Xp + 0.25\ Xc + 0.16\ Xf + 0.135\ Xa \quad ....(3.8)$$

Similarly Heldman and Singh,1981 (equation 3.8) and Choi and Okas,1983 (equation 3.9) developed empirical equations for determining specific heat on pure chemical component basis.

$$Cp = 4.187\ Xw + 1.549\ Xp + 1.424\ Xc + 1.675\ Xf + 0.837\ Xa \quad ....(3.9)$$

$$Cp = 4.180\ Xw + 1.711\ Xp + 1.547\ Xc + 1.928\ Xf + 0.908\ Xa \quad ....(3.10)$$

Where

K - thermal conductivity, W/m°C
Cp - specific heat, kJ/kg°K
Xw - moisture component, fraction
Xp - protein component, fraction
Xc - carbohydrate component, fraction
Xf - fat component, fraction
Xa - ash component, fraction

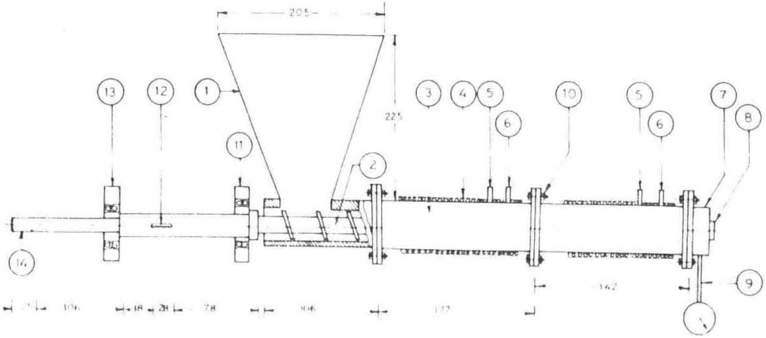
3.4 Development of a Food Extruder

A laboratory scale, food extruder based on the specifications of food extruders described by Harper(1981a) was developed and the details of design and construction are described.

3.4.1 Design of extruder

The major components of the extruder, screw and barrel were designed considering the design calculations proposed by the earlier researchers.

3.4.1.1 Design of extruder screw: The screw of an extruder normally has three distinct sections (Fig.3.1, Plate 6). The screw diameter in most of the laboratory model single screw food extruder ranged from 19 to 32 mm (Anonymous 1994). The screw diameter of the extruder was decided as 26 mm. Sanderude(1969) described that length of the screw affects the retention time



[illegible] DETAILS OF FOOD EXTRUDER

ALL DIMENSIONS ARE IN mm
SCALE 1:4

REF	PART NAME	DESCRIPTION	ST
1	FEED HOPPER	REFER FIG. 3.4	1
2	EXTRUDER SCREW	REFER FIG. 3.2	1
3	EXTRUDER BARREL	REFER FIG. 3.3, 3.5, 3.6	3
4	BAND HEATER	500 WATTS	2
5	THERMO COUPLE ADAPTER	BRASS	2
6	THERMOSTAT ADAPTER	BRASS	2
7	DIE HEAD ASSEMBLY	REFER FIG. 3.7	1
8	[illegible]	BRASS	1
9	PRESSURE GAUGE	0-70 kg/cm²	1
10	SEGMENT JOINING BOLTS & NUTS	6 ϕ × 50 mm	18
11	PLUMMER BLOCK BEARING		1
12	KEY WAY FOR SPROCKET	28×6×4	1
13	PILLOW BLOCK BEARING		1
14	KEY WAY FOR TORQUE METER	25×6×4	1

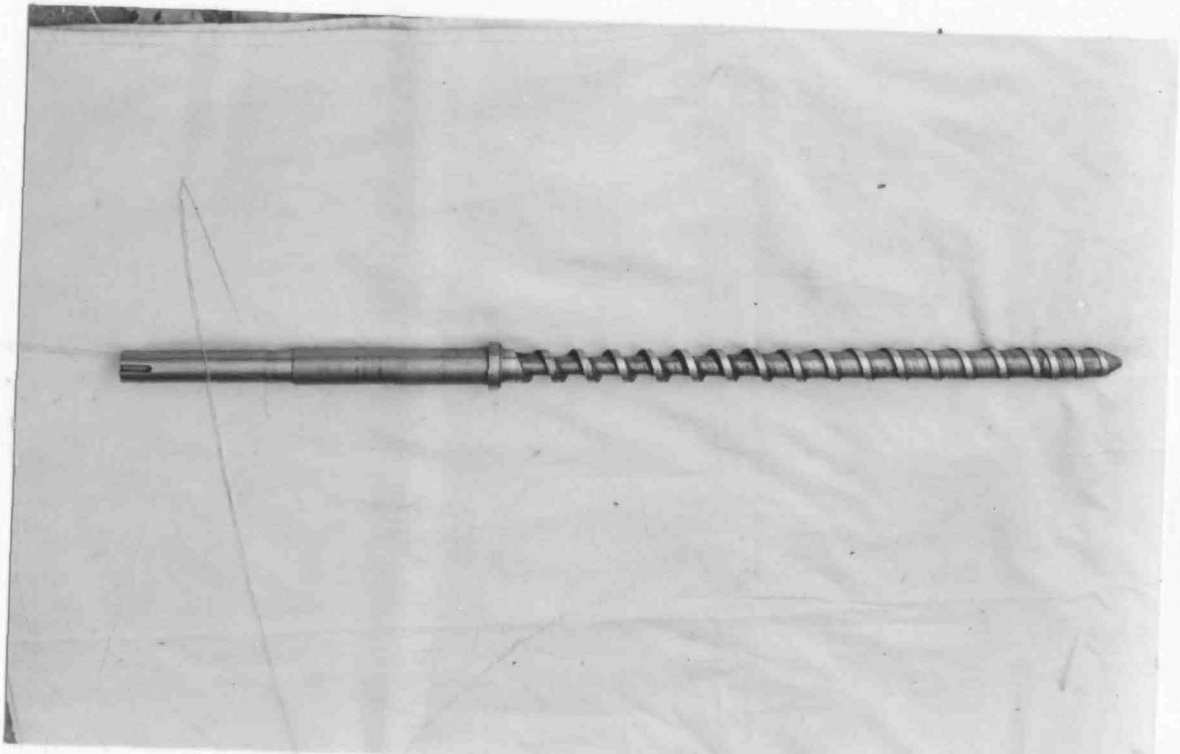


PLATE 4. View of extruder screw

which governs the product quality. Harper(1978) reported that longer extrusion screws in relation to their diameter (L/D>10) tend to have greater operating flexibility and allow greater precision of control of the process so L/D ratio of 15.7 was selected.

The length of feed cum transition section, L1 of the screw forms 2/3rd (1/4 + 5/12) of the whole length of the screw (Harper, 1978). In the developed extruder the length L1, was fixed at 283 mm. The length of metering section, L2 of the screw was 142 mm, Levine and Rockwood(1985) described that the thread depth compression screw consumed less power than a simple screw. So a thread depth compression screw was chosen. The ratio of screw depth in the feed section (H_1) and metering section (H_2) are considered as an important parameter in food extrusion (Harmann and Harper, 1974; Bain 1979) and termed as compression ratio (C.R). This value ranges from 1:1 to 5:1 (Harper, 1981; Levine(1985). A value of 3:1 is optimum (Harper,1981). The over hanging screw which rotates inside the barrel without any support throughout its length of screw profile must be structurally strong to bear the load. Hence, a diameter at the feed end of the screw should be as high as possible. This would make the value of H1 low. In the present case, the value of H1 was fixed at 6 mm. Since the value of H1/H2 has already been decided as 3:1, the value of H2 becomes 2 mm.

From the point of minimum power consumption and maximum efficiency of the extrusion process the helix angle, ϕ (Fig.3.2) of the developed extruder was selected as 18°.

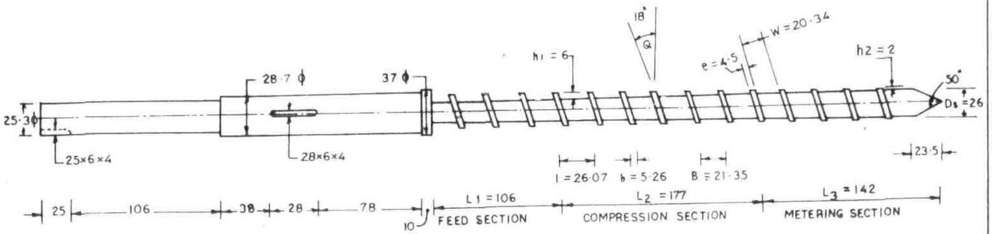
According to equation, the clearance, δ between the flight of screw and the barrel affects the extruder output, due to leakage flow. Carley et al.(1953) have studied that leakage flow which retards the extruder output is proportional to the third power of the clearance. The backward leakage flow is less for a smaller clearance values. In the present case the value of δ selected was 0.5 mm. The channel depths in the feed section and metering section of the screw are designated as h1 and h2. These were equal to H1 + δ and H2 + δ i.e. 6.5 mm and 2.5 mm, respectively.

The relationship between lead or pitch of the screw l, screw diameter D, and helix angle ϕ is given as

$$\phi = \tan^{-1} \frac{1}{\pi D} \qquad \text{....(3.11)}$$

If the values of ϕ and D are known, the value of l was calculated to be 26.07 mm.

The flight width, e, reduces the extruder output (Carley et al., 1953) and should be as small as possible. In order to make the screw structurally strong, the value of e was taken as 5 mm.



ALL DIMENSIONS ARE IN mm

FIG.3.2 EXTRUDER SCREW GEOMETRY

Since, the axial flight width, $b = e/\cos \phi$, its value was 4.72 mm. Thus the value of axial channel width, $B = 1-b$ becomes 21.35 mm.

Further, the channel width, W measured as perpendicular to the flight is given as $B \cos \phi$ which worked out to be 20.34 mm. The dimension of the screw as per the design of calculations are shown in Fig.3.2.

3.4.2 Design of extruder barrel

The operating pressure, P in the extruder barrel (Plate 5) is less than 14 MPa (Harper, 1981) so the design pressure is taken as 14×10^6 Pa.

For a 27 mm internal diameter D,of the laboratory extruder barrel, the length, L of the screw was required to be 425 mm for the corresponding L/D ratio of 15.7.

The thickness (D_1-D) of the extruder barrel depends mainly on the expected pressure inside the extruder. According to Lame's equation for pressure vessels the allowable stress is calculated as,

$$St = \frac{P_1(D_1^2 + D^2)}{(D_1^2 - D^2)} \qquad ....(3.12)$$

The ultimate strength of mild steel, St = 450 MPa (Popov, 1983) considering a factor of safety of 6 for pressure vessel (Brownell and Young, 1968) was calculated to be 75 MPa and D = 27 mm into equation 3.12, the value of D1 calculated to be 32.6 mm. From the point of fixing of pressure and temperature sensing devices on the hand wall, the outside barrel diameter D was considered as 45 mm.

3.4.2.1 **Feed zone barrel**: The feeding zone barrel(No.1 Plate 5) which is the entry for the feed material consisted of a hopper (Fig.3.4). The internal diameter of the feeding zone is fixed as 27 mm and the length of the barrel is 114 mm. A mild steel stand was welded beneath this zone to fix the barrel to the base of the frame.

3.4.2.2 **Compression zone barrel**: The compression barrel segment(No.2 Plate 5) is fixed with feeding section barrel through segment joining nuts and bolts (No.10 in Fig.3.1). The diameter of this barrel is 27 mm and length of the barrel is fixed as 177 mm.

3.4.2.3 **Metering zone barrel**: The metering zone barrel segment(No.3 Plate 5) is fixed at the end of compressing zone barrel. This barrel have similar kind of hand heater and adopter hole as compression zone. A mild steel plate is welded to fix the barrel with the base of the frame. The diameter and length of the barrel was fixed 27 mm and 142 mm, respectively.

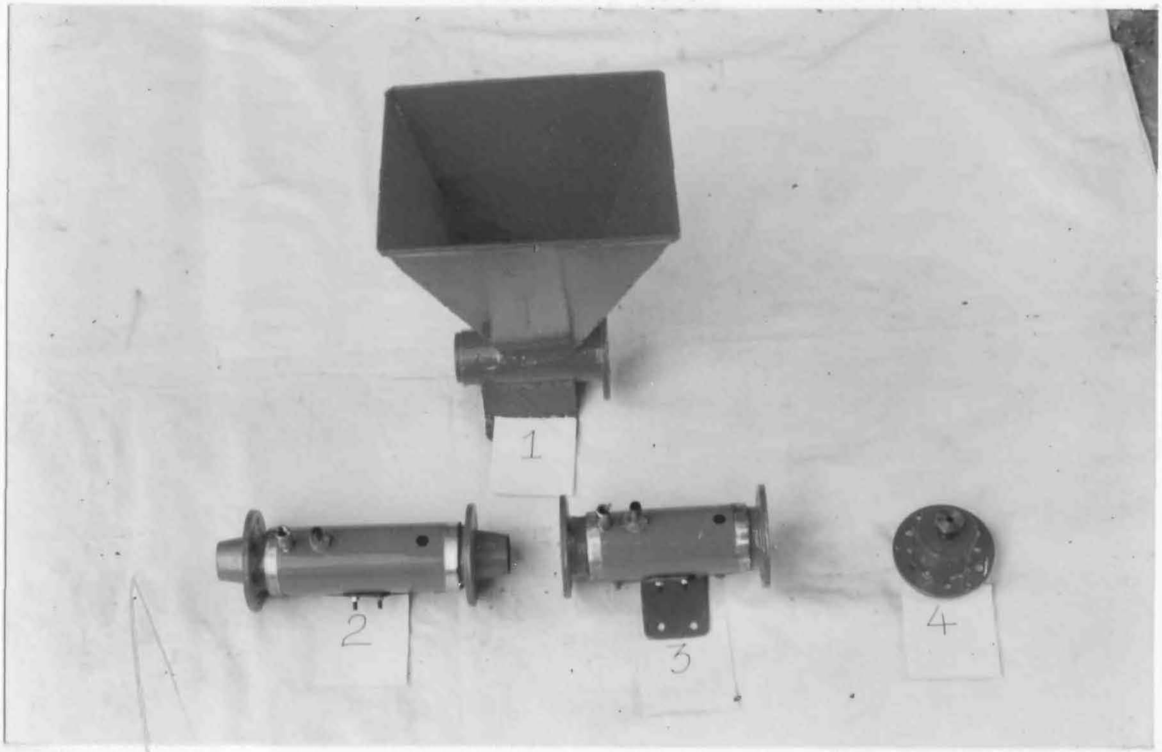


PLATE 5. Unassembled view of barrels

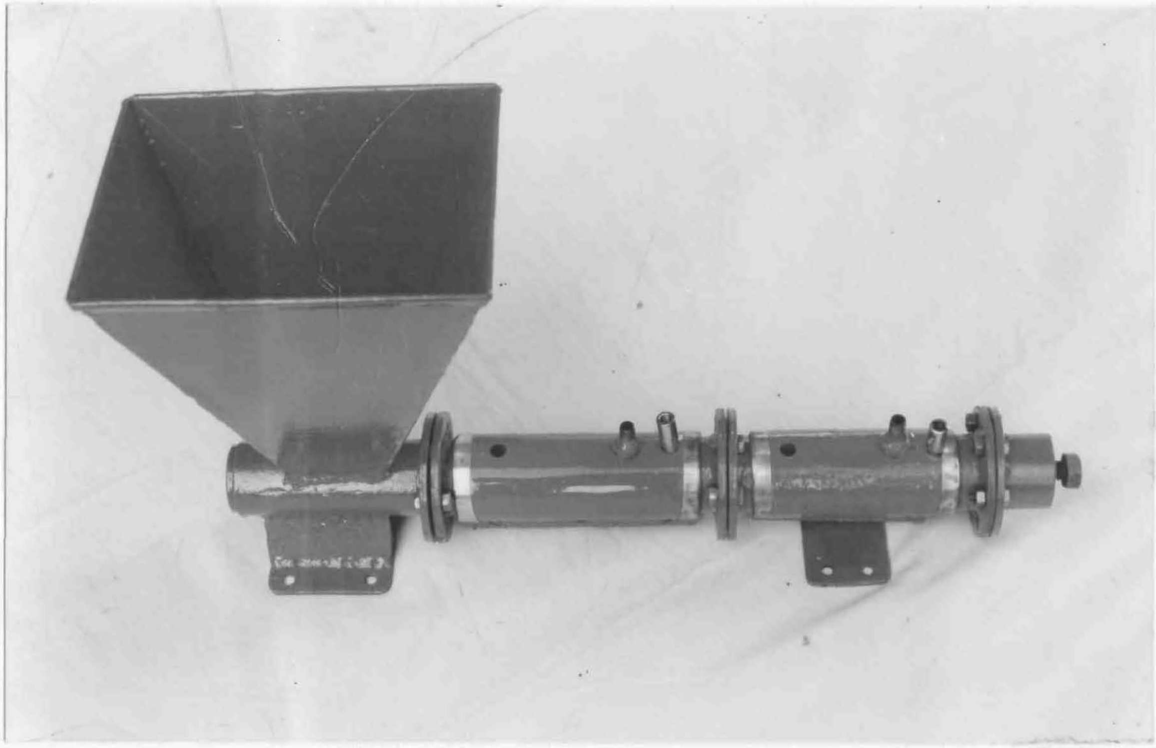


PLATE 6. Assembled view of barrels

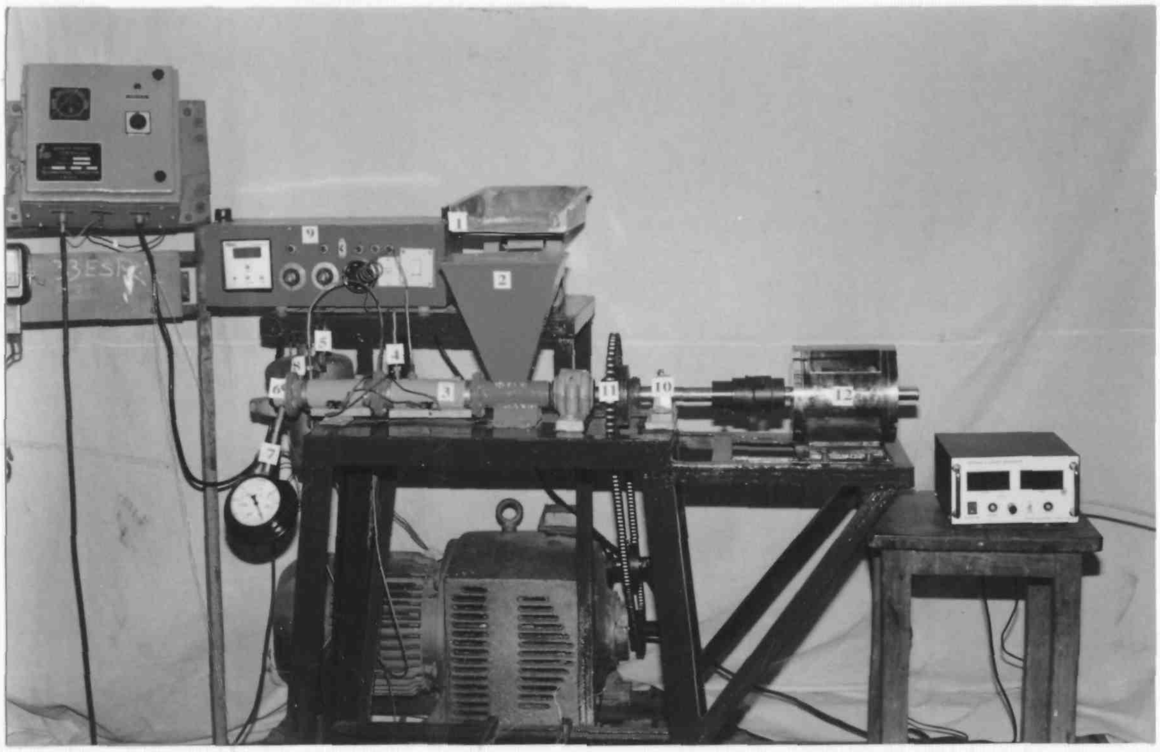


PLATE 7. View of developed experimental food extruder

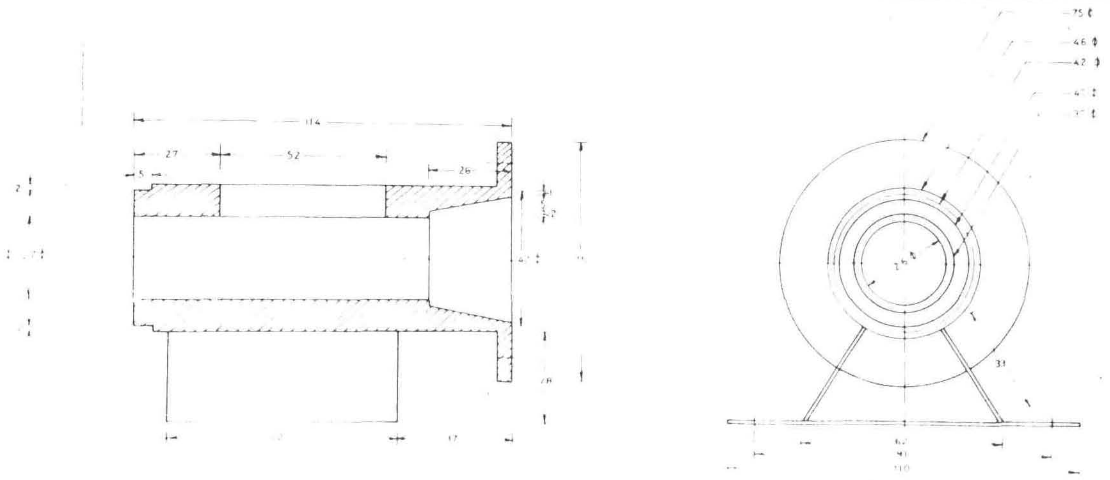
3.4.3 Fabrication for extruder

The lab scale food extruder designed as per section 3.4.1 has been fabricated. The developed extruder consists of a feed hopper, barrel, screw, die, main frame and heaters with instrumentation for control of temperature.

3.4.3.1 Barrel and feed hopper: Feeding zone barrel, compression zone barrel and metering zone barrel were made by machining 50 mm mild steel rod as per figures 3.3, 3.5 and 3.6. A rectangular slot was made in the feeding barrel to fix the hopper. A 2 mm thick plate was bent and ends were joined by welding to form a hopper (Fig.3.4). At the end of the barrels 75 mm diameter mild steel flanges were welded to join the barrels together to form a barrel assembly(Plate 6). In the compression and metering zone barrels 6 mm drills were made to accommodate the thermocouple and thermostat oil points.

3.4.3.2 Extruder screw: A 30 mm polished mild steel rod was machined to form a screw as per in Fig.3.2 and Plate 4. Two steps were made to accommodate self aligned bearings. Two key ways were made, one for fixing the sprocket and another for fixing the torque-cum-speed meter.

3.4.3.3 Extruder die: Die design is very critical in the extruders as it affects the shape of the product and the operation of the extruder. Die head(No. 4 Plate 5) was made using mild steel



ALL DIMENSIONS ARE IN mm
SCALE 1

FIG 3.3 FEEDING SECTION BARREL

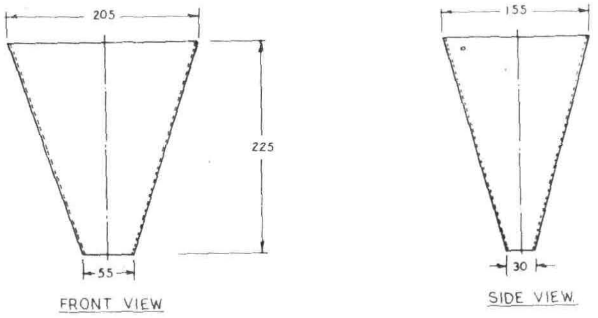


FIG.3.4 HOPPER

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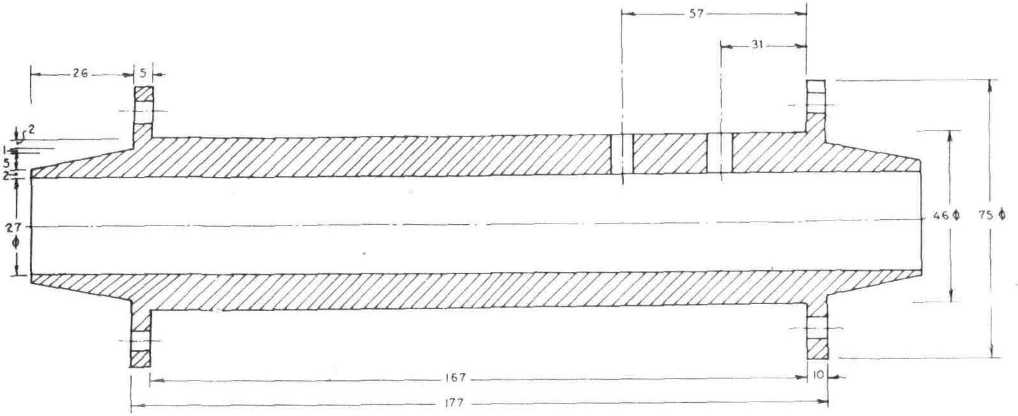

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FIG.3.5 COMPRESSION SECTION BARREL

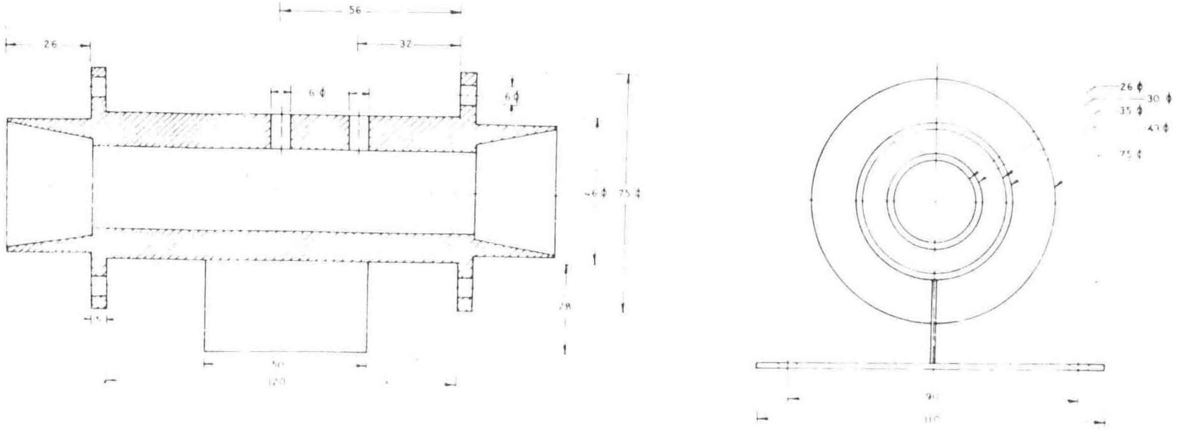


FIG 3.6. METERING SECTION BARREL

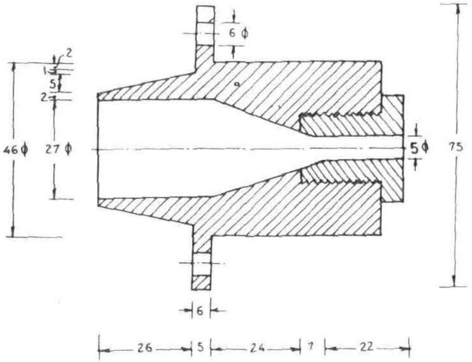
ALL DIMENSIONS ARE IN mm
SCALE 1:1

and the nozzle with brass as per the dimensions shown in Fig.3.7. The die head was attached as the last segment of the barrel such that it left a gap of 2 mm between the screw tip and die opening to prevent the clogging of the die. Die nozzles of different sizes could be attached to the die head. During the present experimentation, the length of the die nozzle was kept 22 mm whereas the diameter was selected as 5 mm.

3.4.3.4 Drive mechanism: The power from a five hp, variable speed, motor (415V, 2.5A, 120-1200 rpm 50 HZ, 4.8 kg-m torque) was transmitted to the extruder screw by a chain sprocket drive system (No.11 in Plate 7). The controller unit attached to the motor, provided the selection of desired speed at the motor shaft and thus the screw speed.

3.4.3.5 Main frame: The screw flights exert the forward thrust on the food to discharge the material through the die resulted in a back pressure which was absorbed by two self aligned bearings. (No.11 and 13, in Fig.3.1, No.10 in Plate 7). The whole assembly was mounted on the frame made of 50 x 50 x 6 mm angle. Also temperature indicator, vibratory feeder and torque-cum-speed meter were fixed on this frame work.

3.4.3.6 Heating and cooling systems: Two electrical band heaters of 500 watts each (No.4 in Fig.3.1 and No.3 in Plate 7) were placed around the compression and metering barrels to heat the dough inside the extruder. Power was supplied to the heaters



ALL DIMENSIONS ARE IN mm
SCALE : 1:1

FIG.3.7 DIE HEAD ASSEMBLY

through thermostats to regulate the temperature input. The extruder was heated by the band heaters, controlled thermostatically to give a desired temperature. A hand blower was fixed on the frame to cool the barrel when the temperature of barrel exceeds the set temperature due to added heat from the viscous flow of the material.

3.4.4 Instrumentation for measurement of extrusion variables

The control of extrusion temperature, screw speed and pressure are necessary to produce uniform quality products and to allow meaningful experimental development.

3.4.4.1 Temperature: The temperature of the dough during extrusion was measured with the help of thermocouples (No.4 plate 7) placed in the oil points. Iron-Constantant thermocouple junctions were used along with a digital temperature indicator (No.9 Plate 7).

3.4.4.2 Screw speed: A torque cum speed meter (No.12 Plate 7) was fixed at the tail end of the drive shaft and the speed of the screw shaft was monitored continuously

3.4.4.3 Pressure: Simonsky et al.(1982) installed a Bourdon type pressure gauge to measure the pressure developed inside the extruder. In the present experimentation a similar type Bourdon type pressure gauge (No.7 Plate 7) was mounted just before the die to measure pressure developed inside the extruder barrel.

3.4.4.4 Energy: The drive motor was connected to a three phase 15 ampere energy meter for measurement of energy. The energy meter readings were recorded before and after the extrusion trials, and the difference was the energy required. The motor power consumption was subtracted from the measured total power to get the actual power consumption. The values of specific energy consumption, E was obtained by dividing the energy requirement during extrusion by the rate of production.

3.4.5 Working of the extruder

The extruder was allowed to get heated until the barrel temperature reached the desired temperature. The machine was started and allowed to run for sometime and the screw speed was set at the desired speed. The conditioned cassava flour was fed to the screw by means of a vibratory feeder. The extruder screw was kept full of material and fed at all times while in operation, in order to ensure continuously a successful run. Inconsistence feeding, results in surging and non-uniform shapes and sizes of the product. When there is a rise in temperature observed in a temperature indicator the blower is switched on to cool the barrel surface to the set temperature. The extruder was operated at a steady state for each set of conditions. Attainment of steady state was judged by a regular flow of extrudate at the die. The extrudate coming out of the die in 10 s. is noted, simultaneously the pressure and energy readings were taken. The extrudates were collected and stored in sealed polyethylene bags for further investigation(Plate 9).

3.5 Preliminary performance trials on the developed extruder

Preliminary trials were conducted on the developed extruder for establishing the range of processing variables, such as moisture content of the feed, screw speed of the extruder, extrusion barrel temperature and die size.

It was observed that the low moisture content of cassava flour (between 12 or 13 per cent d.b) restricted the rotation of the screw as there was no phase change from the original floury nature to a 'melted' state, typical of most extrusion processing. Further the decreased screw speed created a longer residence time and eventually the temperature of the product increased. Colonna et al.,1984, reported that such conditions led to the starch degradation. Maximum expansion of cassava extrudate was found at 14 per cent moisture content (d.b). Extrusion processing using 19 per cent (d.b) feed moisture resulted in adherence of the feed material to the hopper. A range of feed moisture levels from 14 to 18 per cent (d.b) were selected for further experimental work.

The effect of extrusion temperature is not simple because temperature affected both the physical properties of the polymer melt and the chemical reaction kinetics. So, several extrusion trials were performed using different combinations of temperature at compression and metering zone. At low temperatures melting of flour did not take place. It was observed that a combination of compression zone and metering zone temperatures kept at 70°C and 100-120°C, respectively produced regular and puffed products. At high temperatures (above 120°C) the exit product became over cooked. Chiang and Johnson, 1977 showed that as the temperature exceeded 110°C, extrusion cooking produced virtually complete gelatinization.

Screw speeds lower than 100 rpm resulted poorly expanded products. Extrusion of cassava flour beyond 200 rpm exhibited a regular ridged surface distortion (Shark Skin) (Plate 8). This phenomena was reported by Lue et.al.,1991. The mechanism of shark Skin was postulated to be caused by rapid acceleration of surface layers of the extrudate when polymer leaves the die. If the stretching rate is too high, the surface layer of the polymer can actually fail and form the characteristic ridges of the shark Skin surface (Plate 8). So the range of 100 - 200 rpm was selected for further investigation.

Originally three die sizes ranging from 3, 5 and 7.5 mm were taken for the experimental study. It was found that 3 mm die diameter blocked the flow near the die end raised the pressure and backward thrust. At 7.5 mm die the volumetric flow rate was higher but proper puffing did not take place due to lack of gelatinization. The optimum die diameter was found to be 5 mm.

PLATE 8. View of ridged surfac

Based on the above preliminary trials the range of processing variables selected for further investigations were moisture content - 14 to 18 per cent (d.b), screw speed - 100 to 200 rpm, temperature of compression barrel 70°C, temperature of metering barrel 100 to 120°C and die size 5 mm. The performance of the extruder was found satisfactory in the above range of operating conditions. Desired pressure rise at the die end could be achieved by changing the screw speed. The rate of production could well be increased by elevating the screw speed.

3.6 Experimental design

A factorial complete randomized design was used, with the overall ranges and selected variables tabulated in Table 3.7

Table 3.7 Operating ranges of the developed extruder

Independent variables	Levels
Moisture, %	14, 15, 16, 17, 18
Temperature, °C	100, 110, 120
Screw speed, rpm	100, 150, 200

The dependent variables considered in the study are

a) Machine parameters
  - (i) Energy requirement
  - (ii) Pressure
  - (iii) Volumetric flow rate
  - (iv) Specific energy consumption
  - (v) Viscosity of dough

b) Product parameter
  - (i) Expansion ratio
  - (ii) Bulk density
  - (iii) Porosity
  - (iv) Water absorption index
  - (v) Water solubility index
  - (vi) Shear strength
  - (vii) Compressive strength
  - (viii) Tensile strength

The experiments were replicated three times and the data were analysed by Duncans multiple range test.

3.7 Measurement of Various Process Parameters

A number of process parameters were measured during the course of investigation. These include volumetric flow rate, pressure, temperature, screw speed, specific energy and viscosity. The following paragraphs outline the procedure, instruments and methods adopted for the measurement of the process parameters.

3.7.1 Volumetric flow rate

The experimental volumetric flow rate through the extruder die, Q_{expt} were found out by measuring the length of extrudate, l_{expt} coming out of the die per unit time. The readings were taken during steady state operation. Diameter of the extrudate were measured with the help of vernier calipers at five different positions for each sample. Assuming the extrudate as perfect cylinder, the experimental volumetric flow rate was given by

$$Q\ expt = \pi(\frac{de}{2})^2\ l_e \qquad ....(3.13)$$

The mean of three observations were reported.

3.7.2 Viscosity of cassava dough

Food extrusion is a flow process requiring the characterization of food dough rheology for description of many important extrusion parameters, such as energy requirement, pressure profiles along the screw, heat transfer between the barrel and screw. Also the rheological behaviour of a fluid influences the velocity profiles in the extrusion screw channel leading to defining the extrusion rate. The velocity profile in a conduit having circular cross section is of particular interest in food extrusion as the geometry of the die is often circular.

The flow of a Newtonian fluid through cylindrical tube is described by the Hagen - poiseuille law where apparent shear rate (γ_s) and shear stress (τ_w) are given by r_c and a pressure drop.

$$\gamma w = \frac{4Q}{\pi r_c^3} \qquad \text{....(3.14)}$$

and $$\tau w = \frac{Pr_c}{2L_d} \qquad \text{....(3.15)}$$

Where,

Q - volumetric flow rate
r_c - radius of die
p - pressure drop across die
L_d - length of die

According to Hagen-poiseuille's law,

When the fluid is Newtonian and the flow is laminar under isothermal conditions, the viscosity, μ is given by

$$\mu = \frac{pr_c/2L_d}{4Q/\ \pi\ r_c^3} \qquad \text{....(3.16)}$$

$$= \frac{p\cdot\ r_c^2}{8\ Ld\ V} \qquad \text{....(3.17)}$$

Where V is the average velocity of the fluid through the tube.

γ_w is the shear rate τw (Eq.3.14) at the walls for a Newtonian fluid. In case of non-newtonian power law fluid, the wall shear rate becomes(Middleman, 1977).

$$\gamma w = \frac{3n+1}{4n} \cdot \frac{4V}{r_c} \qquad \ldots.(3.18)$$

Where
n is the flow behaviour index of the power law fluid. The factor (3n+1)/4n is called as wall shear rate correction factor.

Since, the relation between the shear stress and shear rate for a power law fluid is given by

$$\tau = K(\gamma)^n \qquad \ldots.\ 3.19$$

Where

k - consistency coefficient of the fluid.

The shear stress at the wall of the tube will be

$$\tau w = K(\gamma w)^n \qquad \ldots.\ 3.20$$

putting the values of τw and γw from Eqn.(3.10) and 3.13, respectively into Eqn.3.15 and taking logarithm on both sides.

$$\log\left(\frac{p\ r_c}{2L_d}\right) = \log\left[K\left(\frac{3n+1}{4n}\right)^n\right] + n \log \frac{4V}{r_c} \qquad \ldots.3.21$$

The value of flow behaviour index, n can be obtained from the slope of the straight line of the plot of log $pr_c/2L_d$ and log $4V/r_c$. The intercept of the straight line on the ordinate would be equal to log $[K(3n+1/4n)^n]$.

The value of K can be obtained as the value of n which has already been obtained.

The apparent viscosity at the barrel wall in the metering section of the screw, μs is given by

$$\mu s = K(\gamma s)^{n-1} \qquad ....(3.22)$$

The rate of relative movement of layers of fluids is depressed as shear rate γ. In the screw channel the nominal shear rate is defined as (Harper, 1986).

is

$$\gamma s = \frac{\pi DN}{H} \qquad ....(3.23)$$

Where

πDN is the maximum tip velocity of the screw

D internal diameter of the barrel

N rotational speed of the extruder screw, and

H gap between the inside of the barrel and root of the screw in the metering section

The apparent viscosity at the die, $\mu d = K(\gamma d)^{n-1}$ ...(3.24)

where

γd is the apparent shear rate at the die condition and in Equation (3.13)

$$\gamma d = \frac{4Vd}{r_c} \quad \frac{3n+1}{4n} \qquad ....(3.25)$$

Where Vd and rd denote the average velocity of the fluid at die and radius of die, respectively.

The flow behaviour index, n, categorized the fluids into Newtonian $(n=1)$ or non-newtonian $(n\ 1)$ whereas the later is divided into pseudoplastic $(n<1)$ and dilatent $(n>1)$ fluids.

3.7.3 Expansion ratio

The expansion ratio is taken as the index of increase in volume of the product due to extrusion cooking. It is expressed as the ratio between the extrudate diameter of the rod shaped product , and the diameter of die. The diameter of the extrudate was measured with the help of a vernier caliper. The experiment was replicated thrice to obtain the average values.

3.7.4 Bulk density

The bulk densities of the dried extrudates were measured by weighing 10 cm long cylindrical section and their diameter by caliper measurement (average of three diameter measurements for each specimen). Bulk density determinations of each extrudate lot were averaged.

$$\text{Bulk density} = \frac{\text{Weight}}{\pi/4 \times \text{diameter}^2 \times 0.1}\ \text{kg/m}^3 \qquad \ldots.3.26$$

3.7.5 Porosity

The volume V_E of dried extrudate was calculated by measuring the length and diameter of the cylindrical section of the extrudate. Then it was powdered using a Wiley mill to a fineness of Particle size of ISS mesh No. 60(Aperture opening 0.600 mm). The volume of the powder (V_p) was measured in a volumetric cylinder. The porosity is calculated as

$$(V_P - V_E)/V_P \qquad \ldots.(3.27)$$

3.7.6 Shearing strength

A simple tool(Plate 10) for measurement of extrudate shear strength was fabricated similar to a jig for direct shear of alfalfa stems (Mohsenin, 1970). Different diameter of the holes were made for inserting different sizes of the extrudates in the tool. The device was mounted on a tensile testing machine and loaded at a speed of 1.35 mm/sec. When the specimen fails the maximum load(kg) recorded was noted from the dial.

3.7.7 Compression strength

A 10 mm of dry cassava extrudate was kept in vertical position on the platform of Kiya hardness tester(Plate 11). A mild steel plate measuring dimensions 43 x 43 x 3 mm was kept on top of the extrudate to avoid the penetration of the plunger, while

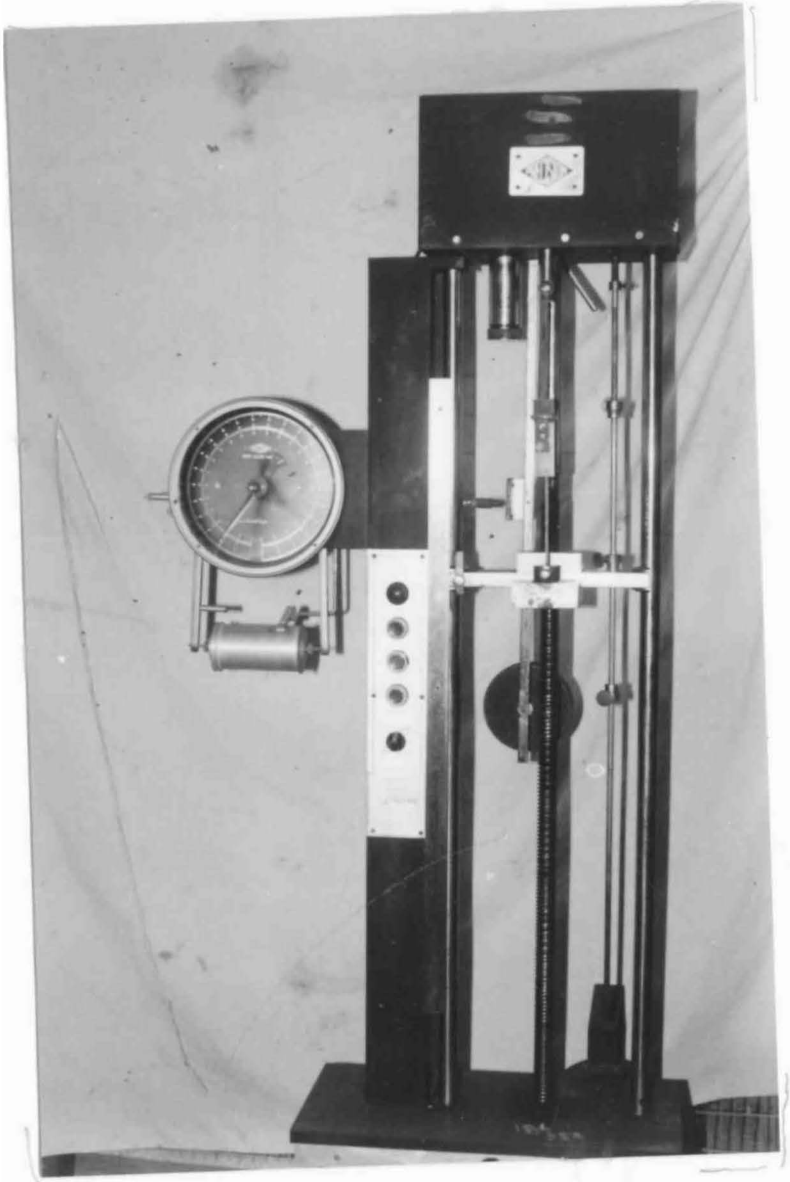


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PLATE 10. Experimental set up for measuring shear strength of extrudate

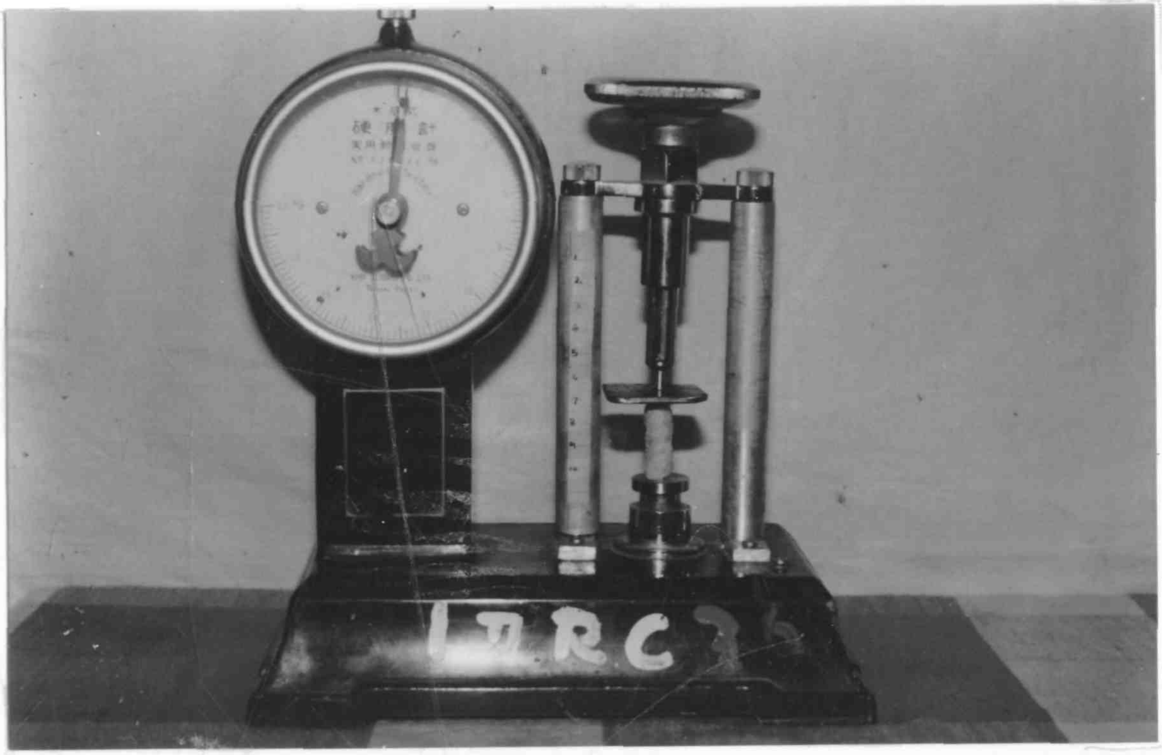

PLATE 11. 'Kiya' Hardness tester for compression measurement of extrudate

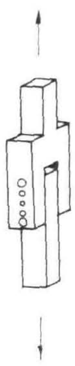

FIG.3-8 JIG FOR MEASURRING SHEAR STRENGTH OF EXTRUDATE

compressing. When the hand wheel was rotated the plunger moved down and compressed the extrudate and the pointer in the dial starts moving. The maximum force(kg) attained was recorded when the sample failed

3.7.8 Tensile strength

A simple experimental set up was arranged to measure the tensile strength of cassava extrudate rods (Fig. 3.9). About 50 mm length of dry extrudate was taken. The top of the extrudate was tied to a stand and at the bottom a pan s fixed. Weights were added to the pan until the extrudate breaks. The force at which the extrudate failed was the tensile strength and expressed in kg/cm².

3.7.9 Water absorption(WAI) and Water solubility indices(WSI)

Water absorption and water solubility indices were determined as outlined by Anderson et al.(1969). The water absorption index (WAI) is the weight of gel obtained per gram of dry sample.

A 2.5 g sample of ground extrudate product sieved to 60 mesh was suspended in 30 ml. of water at 30°C in a 5 ml. centrifuge tube, stirred intermittently over a 30 min. period, and centrifuged at 3000 x g for 10 min. The supernatant liquid was poured carefully into a tared evaporating dish. The remaining gel was weighed and the WAI calculated from its weight.

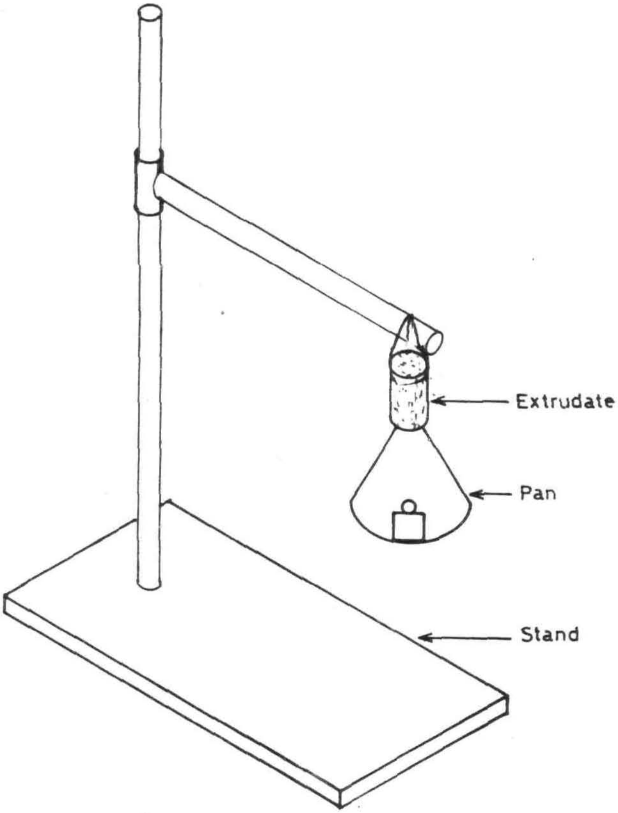

Fig. 3·9 Experimental set up for measuring tensile strength

As an index of water-solubility, the amount of dried solids recovered by evaporating the supernatant from the water-absorption test was expressed as percentage of dry solids in the 2.5 g sample.

3.8 Sensory Evaluation of the Extruded Product

The extruded food product was tested for its organoleptic attributes as per the method prescribed by IS: 6273 - 1972 II. Preliminary screening to narrow down the number of samples for organoleptic studies were done by rejecting the extrudate samples having expansion ratio less than 2.5. Also the extrudate with brownish and dark brown colour were excluded from the studies.

Finally, six extruded samples were selected for sensory evaluation after deep frying in refined vegetable oil. All the samples were fried in same manner till their colour charged to yellowish brown. Salt and pepper were dusted onthe surface at 2.0 per cent level to add taste of the extrudate. A commercially available corn puff was taken as control. All these seven samples(Plate 12) were presented to the judges for scoring

The score record sheets were prepared for the present investigation using the Indian standard procedure. The results are discussed in chapter 5. The responses of the panelists were subjected to statistical analysis of variance and means separated by Duncan's multiple range test (DMRT) to establish if there are any significant differences between the samples.

THEORETICAL CONSIDERATIONS

4. THEORETICAL CONSIDERATIONS

Most of the mathematical work on food extruders has been adopted from the plastic industry (Harmann and Harper 1973). Mathematical model relating to the flow rate equation for a gradually varying depth of a single screw plastic extruder was given by Carley and Strub, 1953; Carley, mallouk and Mekelvey, 1953b. McKelvey 1953a and Carley and McKelvey, 1953b in a series of papers.

4.1 Volumetric Flow Rate

The net rate of discharge from the extruder is equal to the algebraic sum of the drag flow (Q_D), the pressure flow (Q_P), and the leakage flow (Q_L). The out put Q of the extruder is defined by the equation of continuity(Carley et al.1953).

$$Q = Q_D - Q_P - Q_L \qquad \ldots.(4.1)$$

The flow resulting from viscous drag(Q_D) is proportional to screw speed N. The pressure flow, is proportional to the pressure gradient down the screw channel. Pressure is highest at the discharge of the extruder, causing a negative pressure gradient, pressure flow is in opposite direction to the drag flow. The flow between the barrel and the tops of the screw flights directs a backward flow along the axis of screw and is called as the leakage flow, Q_L. This flow is caused by the buildup of the pressure from the rear to the front of the screw, from one turn of the thread to the next.

4.1.1 Drag flow

The expression for drag flow as quoted by Carley and Strub,1953 and Shirato,1983 is

$$Q_D = \pi\ DNb^2 \cos^3 \phi\ F_D \qquad \text{....(4.2a)}$$

or

$$Q_D = \frac{\pi\ DNHB}{2} \cos^2 \phi\ FD \qquad \text{....(4.2b)}$$

Where F_D is a shape factor for drag flow given as

$$F_D = \frac{8}{\pi^3} \sum_{i=1,3,5\ ..}^{\alpha} \frac{2W}{H} \left[\frac{1}{i^3}\ \frac{\text{Cos h}}{\text{Sin h}}\ \frac{(i\pi H)/W)-1}{(i\pi H/W)} \right] \qquad \text{....(4.3)}$$

4.1.2 Pressure flow

The pressure flow in an extruder is a special case of pipe flow in which the pipe has a rectangular or semielliptical cross section. The Navier differential equation of flow is given as

$$\frac{\delta^2 u}{\delta x^2} + \frac{\delta^2 v}{\delta y^2} = -\frac{1}{\mu} \left[\frac{dp}{dz} \right] \qquad \text{....(4.4)}$$

Where Z is distance measured along the helical axis of the channel, and V is the velocity of any point in the channel, in the steady state.

In 1868 Boussinesq solved this differential equation introducing the correct boundary conditions for the pressure flow in pipes of elliptical and rectangular cross sections. Carley and Strub, 1953 expressed the Bovssinesq equation in simpler form and is given by

$$Q = \frac{BH^3 \ \mathrm{Sin}\emptyset \ \ \mathrm{Cos}\emptyset}{12\mu} \times \frac{d_p}{d_L} F_p \qquad \ldots.(4.5)$$

Where F_p is given by,

$$F_p = 1 - \frac{192H}{W\pi^5} \sum_{i=1,3,5\ \ldots}^{\alpha} \frac{1}{i^5} \tan h \left[\frac{i\pi W}{2H}\right] \qquad \ldots.(4.6)$$

4.1.3 Leakage flow

The leakage past the flights as previously mentioned is a form of pressure flow, and it therefore must behave according to the differential equation for pressure flow. In this case the geometry is little different. Here the liquid is flowing through a very thin ring between land and barrel. The two dimensional equation reduces to a one-dimensional equation since the annulus may be thought of as a long narrow slit without ends(Carley and Strub, 1953).

$$Q_L = \frac{\pi^2 D^2 \delta^2 \tan \emptyset}{12\ e\ \mu} E \frac{d_p}{d_L} \qquad \ldots.(4.7)$$

The factor E1 is a correction for possible eccentricity o the screw flights in the barrel, and it varies from 1 for perfectly centered screw to 2.5 for a screw that is rubbing o the barrel. A value of 1.2 is reasonable approximation fo general use (Carley and Strub, 1953). with the value of E a 1.2, the equation 4.7 becomes,

$$Q_L = \frac{\pi^2 D^2 \delta^3 \tan \phi}{10\ e\ \mu}\ E\ \frac{d_P}{d_L} \qquad \text{....}\ (4.8)$$

4.2 Theoretical volumetric flow rate

Substituting the values of Q_D, Q_P and Q_L from equations 4.2b, 4.5 and 4.8 into equation 4.1 the flow equation for an extruder is found to be

$$Q = \frac{\pi DBH \cos^2 \phi}{2} F_D N - \frac{BH^3 \ \sin \phi \ \cos \phi}{12\mu} \frac{d_P}{d_L} F_P$$

$$- \frac{\pi^2 D^2 \delta^3 \tan \phi}{10\ e\ \mu} \frac{d_P}{d_L} \qquad \text{....}(4.9)$$

$$= AH - \frac{CH^3}{\mu} \frac{d_P}{d_L} - \frac{r}{\mu} \frac{d_P}{d_L} \qquad \text{....}(4.10)$$

Where

$$A = \frac{\pi DB \cos^2 \phi}{2} F_D N \qquad \text{....}(4.11a)$$

$$C = \frac{B \sin \phi \ \cos \phi}{12} F_P \qquad \text{....}(4.11b)$$

$$r = \frac{\pi^2 D^2 \delta^3 \tan \phi}{10e} \qquad \text{....}(4.11c)$$

Shritato et al.1982 and Bhattacharya, 1987 rearranged and simplified the flow equation

$$Q = AH - \left(\frac{CH^3 + r}{\mu}\right) \frac{d_P}{d_L}$$

or

$$\frac{d_P}{d_L} = \frac{(AH - Q)\mu}{CH^3 + r} \qquad \ldots.(4.12)$$

The food material is fed through hopper at atmospheric pressure and the extrudate comes out at atmospheric pressure. If P is the pressure measured at the end of extruder screw (before the die) then,

$$P = \int_0^L \frac{(AH-Q)\mu}{CH^3 + r} \qquad \ldots.(4.12a)$$

Where L is total length of the extruder. Since the length, is divided into two parts i.e., tapered section (L1) and metering section (L2). Therefore,

$$P = \int_0^{L1} \frac{AH\mu}{CH^3+r}\, dL + \int_0^{L2} \frac{AH\mu}{CH^3+r}\, dL - Q\mu\left[\int_0^{L1} \frac{dL}{CH^3+r} + \int_0^{L2} \frac{dL}{CH^3+r}\right] \qquad 4.12b)$$

In the tapered zone (L1), the channel height (H) is a function of L but in the metering section (L2), H remains constant and is equal to H_2. Therefore equation 4.12 b becomes

$$P = \int_0^{L1} \frac{AH\mu}{CH^3+r}\, dL + \frac{AH_2L2\mu}{CH_2^3+r}\, dL - Q\mu\left[\int_0^{L1} \frac{dL}{CH^3+r} + 0 \frac{L2}{CH_2^3+r}\right]$$

rearranging,

$$Q = \frac{\int_{O}^{L1} \frac{AH}{CH^3 + r} dL + \frac{AH_2L_2}{CH_2{}^3+r}}{\int_{O}^{L1} \frac{dL}{CH^3+r} + \frac{L2}{CH_2{}^3+r}} - \frac{AP/\mu}{\int_{O}^{L1} \frac{dL}{CH^3+r} + \frac{L2}{CH_2{}^3+r}} \quad ....(4.12c)$$

Now, for Newtonian fluids, the flow through a die of diameter, d and length, ld is given by

$$Q = kd \frac{P}{\mu_d} = kd \frac{P}{\mu} \quad ....(4.13$$

Where μ_d is the viscosity at the die, μ is the viscosity in th extruder. If both the viscosities are assumed to remain constan then the same equation 4.13 can be used in either of the forms a shown. P is the pressure at the upstream side of the die and k is the die constant for circular die,

$$k_d = \frac{\pi d_d{}^4}{128\ ld} \quad ....(4.13a)$$

from equation 4.13,

$$\frac{P}{\mu} = \frac{Q}{k_d} \quad ....(4.14$$

putting the values of P/μ from equation 4.14 into equation 4.12c and rearranging

$$Q = \frac{\left[\int_{O}^{L_1} \frac{AH}{CH^3+r} dL + \frac{AH_2L_2}{CH^3+r}\right] kd}{1+ kd\left[\int_{O}^{L_1} \frac{dL}{CH^3+r} + \frac{L_2}{CH^3+r}\right]} \quad ....(4.15)$$

In the tappered zone, the channel width, H changes from H_1 to H_2 over the length L_1 and thus and relation between H and L_1 is given by

$$H = H_1 - \frac{H_1 - H_2}{L_1} L \qquad \ldots.(4.16)$$

Putting the value of H from equation 4.16 into equation 4.15

$$Q = \frac{\left[\int_0^{L_1} \frac{A\left[H_1 - \frac{H_1 - H_2}{L_1} L\right]}{C\left[H_1 - \frac{H_1 - H_2}{L_1} L\right]^3 + r} dL + \frac{AH_2L_2}{CH_2{}^3 + r}\right] kd}{1 + kd\left[\int_0^{L_1} \frac{dL}{C\left[H_1 - \frac{H_1 - H_2}{L_1} L\right]^3 + r} + \frac{L_2}{CH_2{}^3 + r}\right]} \qquad (4.17)$$

The exact solution of equation 4.17 as given by Bhattacharya (1987) and Samuel et al.(1989) is

$$Q = \frac{\left[\frac{A}{3mct}\left[\begin{array}{l} -2 \ln \cos(\tan^{-1} \sqrt{H_2/t}) + \\ 2 \ln \mathrm{Cos}(\tan^{-1} \sqrt{H_1/t}) + \\ \ln \mathrm{Cos} \tan^{-1}((2H_2 - t)/\sqrt{3t}) - \\ \ln \mathrm{Cos} \tan^{-1}((2H_1 - t)/\sqrt{3t}) - \\ \sqrt{3} \tan^{-1}((2H_2 - t)/\sqrt{3t}) + \\ \sqrt{3} \tan^{-1}((2H_1 - t)/\sqrt{3t}) \end{array}\right] + (AH_2L2/CH_2^3 + r)\right] kd}{1 + K_d\left[\frac{-1}{3mct^2}\left[\begin{array}{l} -2 \ln \cos(\tan^{-1} \sqrt{H_2/t}) + \\ 2 \ln \mathrm{Cos}(\tan^{-1} \sqrt{H_1/t}) + \\ \ln \mathrm{Cos} \tan^{-1}((2H_2 - t)/\sqrt{3t}) - \\ \ln \mathrm{Cos} \tan^{-1}((2H_2 - t)/\sqrt{3t}) - \\ \sqrt{3} \tan^{-1}((2H_2 - t)/\sqrt{3t}) + \\ \sqrt{3} \tan^{-1}((2H_2 - t)/\sqrt{3t}) \end{array}\right] + (L2/CH_2^3 + r)\right]} \qquad \ldots.(4.18)$$

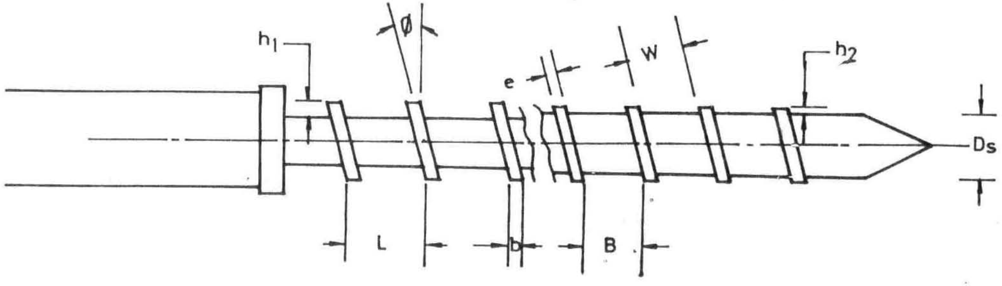

Fig. 4.1 Extruder screw geometry

Where

$m = (H_1 - H_2)L_1$ ....(4.19A)

$t = \sqrt[3]{r/c}$ ....(4.19b)

The specifications of the present extruder is given below an details of extruder screw is shown in Fig.3.2 and 4.1.

L_1 = Length of tapered screw measured horizontally = 283 mm

However, it is desired that L_1 be that length of the tapere screw where food is compressed. Thus L_1 is taken as the lengt of the tapered screw measured from the end of the feeding slot t the end of taper on the screw i.e.188 mm,

L_2 = 142 mm
W = 20.34 mm
e = 5 mm
$D = D - 2 = 27-2 \times 0.5 = 26$ mm
$\delta = 18°$
B = 21.35 mm
h_1 = 6.5 mm
h_2 = 2.5 mm
d_d = 5 mm
l_d = 22 mm
H_1 = 6 mm
H_2 = 2 mm

These dimensions are substituted in the earlier equation and the corresponding values are presented in Table 4.1

Table 4.1 Theoretical values obtained for the developed extruder

Equation No.	Symbol	Values
4.3	F_D	0.8759
4.11a	A	690.89 N mm^2/min
4.6	F_P	0.8766
4.11b	C	0.4584
4.11c	r	5.42 mm^4
4.13a	k_d	0.70 mm^3
4.19a	m	0.0213
4.19b	t	10363.801 N

Substituting these values in equation 4.18. The volumetric flow rate Q becomes 1585.96 N mm^3/min. The theoretical volumetric flow rate obtained at different screw speeds are shown in Table 4.2.

Table 4.2 Theoretical volumetric flow rate of the developed extruder

Generalized flow equation (N, rpm)	Volumetric flow rate, Q mm^3/min		
	100 rpm	150 rpm	200 rpm
1585.9559 N	158596	237893	317191

RESULTS AND DISCUSSION

5. RESULTS AND DISCUSSION

In this chapter the results of different investigations carried out on properties of cassava flour, effects of processing variables on cassava flour extrusion and on the final extrudate are presented and discussed in detail.

5.1 Properties of Cassava Flour

Extrusion cooking of cassava flour involves heating the flour at a high temperature in a shear environment. To understand the effect of temperature on the physiochemical changes in the cassava dough, a knowledge of thermal conductivity, specific heat and bulk density is needed. These properties affect the specific energy consumption and specific pressure of the extruder.

Particle size decides the expansion ratio, water absorption index, water solubility index and texture of the final extruded product. And the coefficient of friction is important in evaluating the flow model. For ideal situations the screw should be frictionless and barrel should have high coefficient of friction with the food material.

5.1.1 Physical Properties

The bulk dnesity of the cassava flour taken for the extrusion experiments ranged from 423.52 to 486.76 Kg/m^3 in the moisture content range of 14 to 18 per cent (d.b).

The particle size distribution of the cassava flour as obtained from the market with 14 per cent (d.b) moisture content is presented in Table 5.1.

Table 5.1 Particle size distribution of cassava flour by differential sieve analysis

ISS No.	Average mesh opening Di, mm	Weight fraction retained,
60	0.600	0.00080
40	0.425	0.00328
30	0.300	0.01850
20	0.212	0.52510
15	0.140	0.24630
10	0.106	0.16060
8	0.075	0.02410
6	0.053	0.00580
Pan	-	
	Total	1.00000

The average particle sizes calculated using equation 3.1, 3.2 and 3.3 are 0.1700, 0.1690 and 0.1593 mm for mass mean diameter, arithmatic mean diameter and volume surface mean diameter, respectively.

The cassava flour retained was on ISS no.60 (0.600mm) minimum (0.081 per cent) and maximum (52.51 per cent) on ISS No.20 (0.212 mm).

The coefficient of friction between cassava flour and four different surfaces, viz., stainless steel, aluminium, mild steel and galvanized iron is presented in the Table 5.2.

Table 5.2 Coefficient of friction of cassava flour with different metal surfaces

Sl.No.	Surface	Coefficient of friction
1.	Stainless steel	0.4889
2.	Aluminium	0.4828
3.	Galvanized iron	0.4884
4.	Mild steel	0.5628

The coefficient of friction of cassava flour was highest at mild steel surface (0.5628) and lowest at Aluminium surface (0.4828).

The shear strength of cassava flour was determined by using shear strength apparatus. the shear strength value of the flour was 8.26×10^{-3} kg/cm^2 at 495.8 kg/m^3 density (14 per cent moisture content).

5.1.2 Proximate composition

The cassava flour was analysed for proximate composition. The details are presented in Table 5.3.

Table 5.3 Proximate composition of cassava flour

Parameter	Per cent
Moisture content, per cent (d.b)	14.00
Total ash	2.01
Crude fibre	2.10
Carbohydrate	81.99
Protein	1.50

The values were used in the empirical equation to predict the thermal conductivity and specific heat of cassava flour.

5.1.3 Thermal Properties

The thermal conductivity of cassava flour determined by transient heat flow method ranged from 0.2542 to 0.2957 w/m°C.

This value is in line with the results obtained by others for similar products(Ojha **et al.**,1967, Farrel **et al.**,1970 and Wallapapan and Sweat, 1982 and 1985). The values predicted by using equations 3.7 and 3.8 as suggested by Choi and Okas 1983 and Sweat 1986 were 0.263 and 0.2947 W/m °C, respectively.

The specific heat of the cassava flour was found by the method of mixtures. The specific heat values varied from 1.638 to 1.853 kJ/kg°K for the moisture contents varying from 14 to 18 per cent (d.b). The values predicted by using equations 3.9 and 3.10 as suggested by Heldman Singh(1981) and Choi and Okas(1983) were in the range of 1.827 to 2.056 KJ/kg°K for cassava flour.

The difference in theoretical and experimental values may be due to the fact that the thermal properties of protein and carbohydrate vary depending on their source. To be more accurate, one should know the thermal properties of the specific protein and carbohydrate present in cassava flour.

5.1.4 Gelatinization temperature of cassava flour

The gelatinization temperature of cassava flour was determined using Brabender Viscoamylograph. The gelatinization temperature ranged from 60 to 73°C. This range of temperature is in confirmation with earlier findings(Moorthy,1985).

5.2 Performance Evaluation of the Extruder

Based on the preliminary trials, as discussed in Chapter 3, the extrusion variables selected for further investigations were moisture content, (14 to 18, per cent d.b), screw speed, (100-200 rpm), temperature of compression barrel (70°C), temperature of metering barrel (100 to 120°C) and die size (5 mm diameter). The extrudate (Plate 12) obtained for all the combination of process variables were analysed for their properties and the various machine parameters studied are such as volumetric flow rate, specific energy consumption, pressure and viscosity of the dough.

5.2.1 Volumetric flow rate

Volumetric flow rate is a vital performance characteristic of an extruder. The experimental volumetric flow rate (Q_e) of the developed single screw extruder was measured.

The analysis of variance of the above experiments is presented in Table 5.4. It is observed that the factors, moisture content and screw speed, have significant ($P<0.01$) effect on volumetric flow rates. It is also seen that the interactions between the variables are also significant ($P<0.01$) except the interaction between screw speed and extrusion temperature which is not significant.

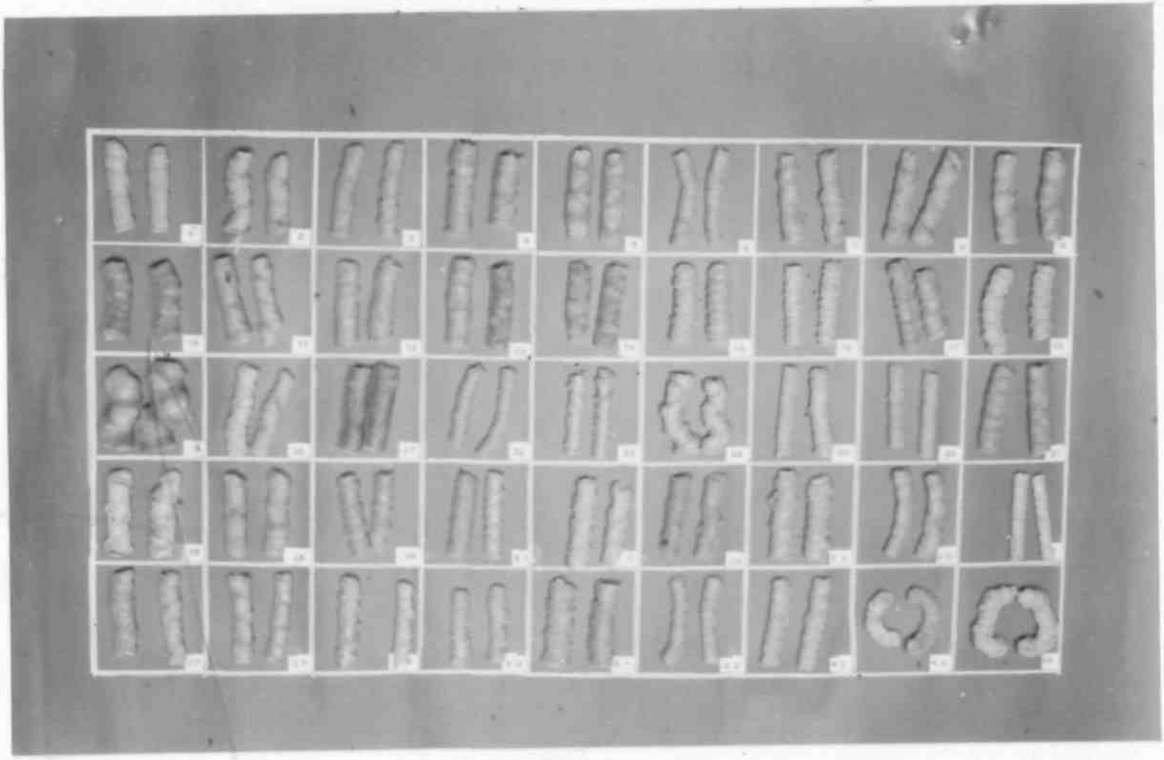

PLATE 12. View of extrudate from all the trials

APPENDIX-B .

Table 5.4 Analysis of variance table for volumetric flow rate and specific energy consumption

SV	DF	Volumetric flow rate			Specific energy consumption		
		SS	MS	F	SS	MS	F
Treatment	44	172.7210	3.9255	909.95**	32585.768	740.586	1947.73**
Screw speed, rpm	2	166.7310	83.3655	19324.71**	822.134	411.067	1081.10**
Temperature, °C	2	0.0112	0.0056	1.31ns	17469.045	8734.523	22971.70**
Moisture content, % d.b.	4	4.5075	1.1269	261.22**	13752.271	3438.068	9042.08**
Screw speed x temperature	4	0.0264	0.0066	1.53ns	40.021	10.005	26.31**
Screw speed X moisture content	8	0.5100	0.0638	14.78**	39.455	4.932	12.97**
Temperature X moisture content	8	0.7141	0.0893	20.69**	364.948	45.619	119.98**
Screw speed x temperature x moisture content	16	0.2210	0.0138	3.20**	97.893	6.118	16.09**
Error	90	0.3883	0.0043		34.221	0.380	
Total	134	173.1100			32619.990		

** Significant at 1 % level

ns Non-significant

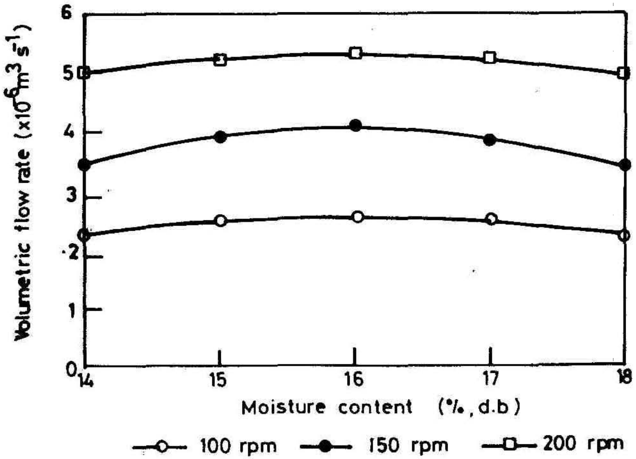

Fig.5·1 Effect of moisture content on volumetric flow rate at different screw speeds

Table 5.5 Effect of extrusion process variables on volumetric flow rate and specific energy consumption

Moisture content (%, db)	Screw speed	Volumetric flow rate, x 10^{-6} m3/s at			Specific energy consumption, KJ/kg		
	rpm	100°C	110°C	120°C	100°C	110°C	120°C
14	100	2.2033	2.2640	2.3380	142.580	125.413	107.547
15		2.4780	2.5420	2.5037	135.380	118.027	102.410
16		2.5413	2.5457	2.6143	126.430	111.110	98.293
17		2.5080	2.4917	2.5100	118.447	101.427	94.600
18		2.2410	2.3623	1.9863	110.480	92.680	84.377
14	150	3.2643	3.4640	3.6777	143.540	128.460	114.613
15		3.8533	3.9427	3.9457	138.513	121.993	103.713
16		4.0550	4.0433	4.1850	128.593	113.037	102.587
17		3.9383	3.8523	3.7277	120.440	103.460	95.730
18		3.5860	3.3533	3.2487	112.717	96.407	88.333
14	200	4.9117	5.0517	5.0643	144.323	130.690	116.760
15		5.1937	5.2457	5.2050	139.800	123.540	107.070
16		5.2567	5.3160	5.3310	131.530	115.847	108.377
17		5.2403	5.1667	5.1613	123.313	110.403	97.493
18		5.0430	4.9613	4.8113	115.347	102.507	92.830

5.2.1.1 Effect of moisture on volumetric flow rate: The volumetric flow rates of the extruder at various treatment combination are given in Table 5.5. Fig.5.1 indicated that the overall volumetric flow rate increased initially from 3.582 x 10^{-6} to 3.9876 x 10^{-6} m^3/s as the moisture content increased from 14 per cent to 16 per cent, and then declined to 3.5104 x 10^{-6} with further increase in moisture content. Similar results were also obtained by Das et al.(1992) when extruding defatted soya grits. The reason for reduced volumetric flow rate at very low moisture contents may be due to the lack of polymer transformations (gelatinization) and thus restriction of flow inside the extruder barrel. According to Das et al.(1992) the high moisture content feed produced caking of the material in the hopper reducing the feed rate and output.

5.2.1.2 Effect of temperature on volumetric flow rate: The effect of temperature on volumetric flow rate is non-significant(Table 5.4). Mitchell et al.(1986) observed that temperature had a very little influence on polymer transformations than moisture did. Bhattacharya (1987a) while extruding fish-wheat flour blend, discussed that volumetric flow rate decreased little with increase in extrusion temperature. However, in the present experimental range of extrusion temperature (100-200°C), the effect of temperature was not significant on volumetric flow rate.

5.2.1.3 **Effect of screw speed on volumetric flow rate:** The screw speed has a most significant (F value = 19324.71) effect on volumetric flow rate as seen in Table 5.4. Table 5.5 shows that the over all volumetric flow rates increased linearly from 2.4086 x 10^{-6} to 5.1306 x 10^{-6} m^3/s when the screw speed was changed from 100 to 200 rpm. The data fitted linearly in the form of

$$Q_e = m_o + m_1 N \qquad \text{....(5.1)}$$

where

N is rpm of the screw

m_1 is the constant of proportionality and

m_o is the intercept.

The straight line relationship holds good between the screw speed limits of 100 - 200 rpm. The values of coefficients mo, m1 and correlation coefficient (r) are -0.3224 x 10^{-6}, 0.02722x10^{-6} and 0.99, respectively. It is clear that the flow increased linearly with screw speed as has been predicted by the developed mathematical model (Eqn.19 and 21) and are in agreement with Harmann et al.(1973) and Bhattacharya (1987a). Also it is evident from equation 4.2a that the drag flow was dependent on screw speed.

According to theoretical assumption all the regression lines should pass through origin since at zero rpm there was no flow in the extruder. However, all the experimental regression straight lines had negligible intercepts. Correlation coefficients (r) were high in these cases, showing the adequacy of the model to predict the volumetric flow rate at different screw speeds.

5.2.1.4 Comparision between experimental and predicted volumetric flow rates

The theoretical flow rates (Q_t) is directly proportional to screw speed, N and the equation is in the form of $Q_t = m_1N$ where m1 is constant of proportionality or the slope of the straight line and its value is 2.6433×10^{-6} and the equation becomes,

$$Q_t = 2.6433 \text{ N} \times 10^{-6} \text{ m}^3/\text{S} \qquad \text{.... (5.2)}$$

The predicted volumetric flow rates were compared with experimental volumetric flow rates and presented in Fig.5.2. Harmann and Harper(1974) suggested that the under prediction and over predictions of flow rates are due to the non-newtonian effects and errors in geometric constants of the extruder screw. Similar results were also reported by Bruin et al.(1978) for corn flour grits. Van Zuilichem et al.(1983) demonstrated that the differences existed in the experimental and theoretical volumetric flow rates are due to the slip phenomena of the food products inside the extruder.

5.2.2 Specific energy consumption of the extruder

The effects of the processing variables such as moisture content, extrusion temperature and speed of the screw on specific energy consumption were statistically analysed and the analysis of variance is presented in Table 5.4.

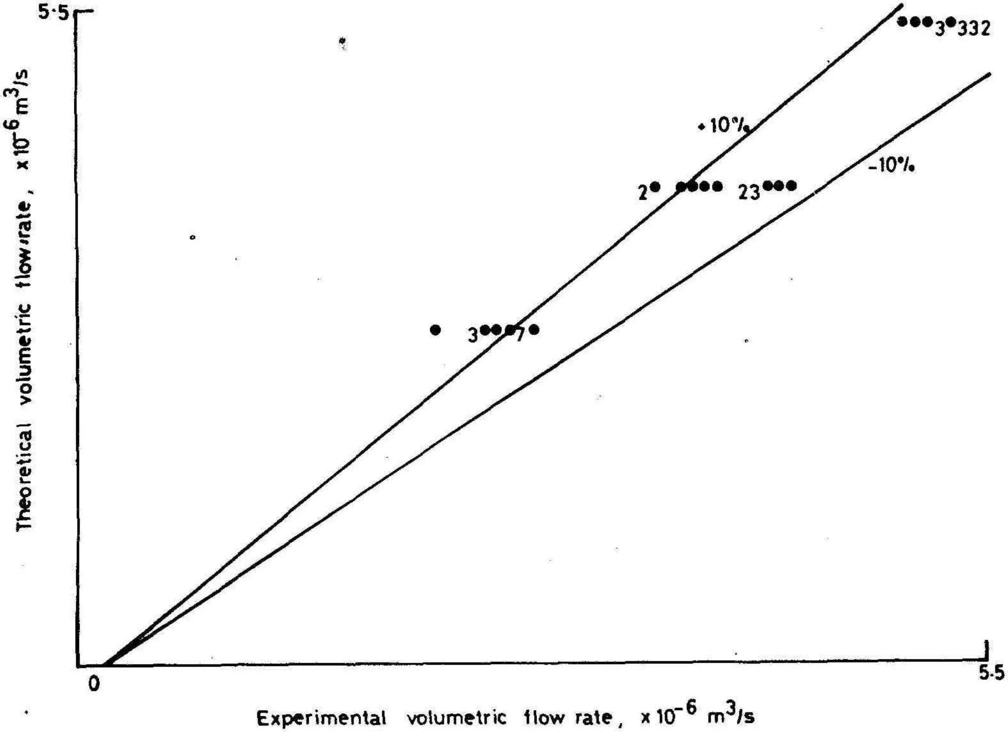

Fig.5·2 Comparision of experimental volumetric flow rate and theoretical

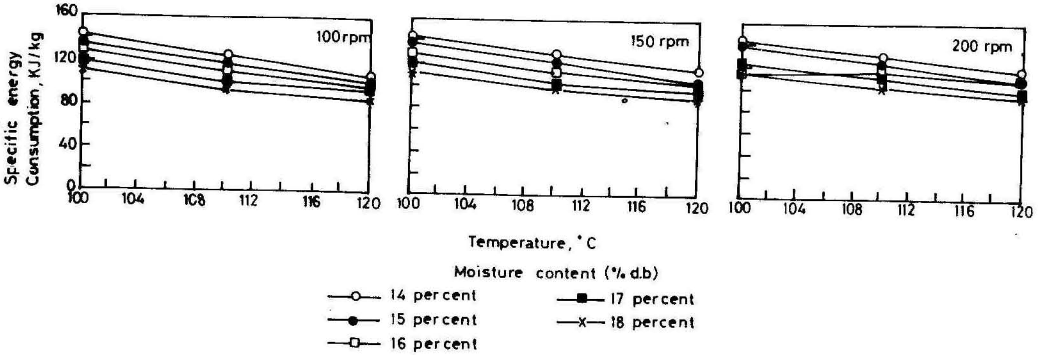

Fig.5·3 Effect of temperature and screw speed on specific energy consumption of the extruder

It can be seen from the Table 5.4 that all the variables considered for the study and their interactions are significant (P<0.01). The mean values of specific energy consumption are provided in Table 5.5.

The specific energy consumption, a good index for energy requirement for extrusion of food, was found to lie in the range of 84.377 and 144.333 kJ/kg. The net specific energy values are smaller than that of the values (3599.97 kJ/kg for high-shear cooking extruder, reported by Rossen and Miller(1973).

5.2.2.1 Effect of moisture content on specific energy consumption: The effect of moisture content on specific energy consumption at various speeds is shown in Fig.5.3. It could be seen from the figure that specific energy consumption decreased from a mean value of 128.214 to 99.520 kJ/kg with increase in moisture content from 14 to 18 per cent. Studies of Harmann and Harper (1973) and Senouci,(1986) have also shown the same trend for the extrusion of corn grits and potato starch. Also Harper(1981) suggested that low moisture conditions resulted in higher mechanical energy inputs. A possible reason for decreased specific energy consumption with increase in moisture content may be due to the increased lubrication effect during extrusion. According to Bruin(1978) a strong rate of gelatinization under high moisture environment could result low energy consumption.

5.2.2.2 Effect of temperature on specific energy consumption: The F value in the Table 5.4 shows that temperature had no significant (P<0.01 and F = 22971.70) effect on specific energy consumption. From the Fig.5.3 it can be seen that when the process temperature increased from 100 to 120°C the specific energy consumption decreased from a mean value of 128.762 to 100.982 kJ/kg. The results obtained are in good agreement with the findings of Harmann and Harper(1973) and Singh et al(1994). A decrease in the viscosity of the pseudo-plastic melt within the extruder caused by higher temperature might have contributed to lower specific energy consumption.

5.2.2.3 Effect of screw speed on specific energy consumption: It is observed from Table 5.6 that specific energy consumption value increased from 111.28 to 117.32 kJ/kg for increase in screw speed from 100 to 200 rpm. Similar trend was observed by Lin et al.(1990) while extruding cereals in an intermeshing, counter rotating, twin screw extruder. On comparing the Table 5.5, it was observed that increase in screw speed increased the volumetric flow rate to a good extend whereas the corresponding rise in energy required was rather slow leading to lesser specific energy at high screw speeds. It may, therefore, be concluded that to achieve higher economical operation with an extruder it should be operated at its higher screw speed and in the present investigation, it was found to be 200 rpm.

Table 5.6 Combined effect of screw speed and temperature on specific energy consumption

Temperature °C	Specific energy consumption, KJ/Kg Screw speed , rpm 100	150	200	Temperature mean
100	126.663	128.761	130.863	128.762
110	109.731	112.671	116.597	113.000
120	97.445	100.995	104.506	100.982
Screw speed mean	111.280	114.142	117.322	114.248

5.2.3 Viscosity of the dough inside the extruder

Food doughs are non-bewtonian in nature, with apparent viscosity varies with shear rate. In the present experimental setup extruder die itself was considered as a capillary tube as stated in Chapter 3. The shear rate of the cassava dough was calculated in the same way as per Newtonian fluids using equation (3.25). And the values of flow behaviour index, n and consistency coefficients, K were estimated for all combination of extrusion variables and presented in Appendix C. It is clear from the table that the change in process variables had pronounced effects on μs, K and n. The flow behaviour index ranged from 0.17 to 0.75 where as the consistency ranged from 871.231 to 100130.44 PaSn. The flow behaviour index of less than unity indicates that the dough exhibited pseudoplastic behaviour.

5.2.3.1 Effect of moisture content on viscosity of dough: The general trend of variation of viscosity at five different moisture levels (14-18 per cent d.b) is given in Fig.5.4. The overall viscosity varied from 763.97 to 4810.64 Pa.s. Bhattacharya and Hanna(1986) suggested that the high moisture content of feed material lowered the flow resistance inside the extruder and water acted as a plasticiser to lubricate and soften the starch making them mouldable. The viscosity depended on this mouldability of dough. These results were also confirmed by Fletcher et al.(1985) and Senouchi et al.(1988).

5.2.3.2 Effect of temperature on viscosity: Temperature and moisture content are the two variables that control the magnitude of viscosity and act in opposite directions as the material gets heated up and loses moisture due to gelatinization. It can be seen from the Fig.5.4 that the apparent viscosity decreased with increasing temperature in many cases. Lin and Armstrong (1990) extruded cereals in an intermeshing, counter rotating turn screw extruder and obtained the similar results. It may be pointed out that a few researchers, however, observed an increase in dough

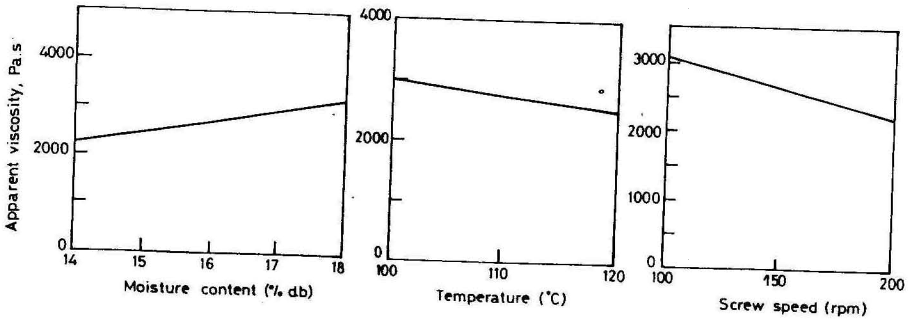

Fig.5.4 Effect of processing variables on apparent viscosity.

viscosity with increase in temperature (Peri et al.,1983 and Valle et al.,1987).

5.2.3.3 Effect of screw speed on viscosity: The influence of screw speed on viscosity is presented in Fig.5.4. The figure shows an inverse relationship between apparent viscosity and screw speed. When the screw speed increased from 100 to 200 rpm the average apparent viscosity lowered from 2985.35 Pa.s to 2106.77 Pa.s. The fact is that the screw speed affected the shear rate which in turn affected the apparent viscosity. Similar findings were also reported by Harmann and Harper(1973) and Jao et al.(1978) and Vallee et al.(1987).

5.2.4 Specific pressure

The pressure profile inside an extruder is a function of viscosity of the feed material. If the viscosity of the feed increases, high pressure is formed to pump out the melt through the die. The decrease in viscosity of the dough decreased the specific pressure and vice versa.

5.2.4.1 Effect of moisture content on specific pressure: The Fig.5.5 shows the decreasing trend of pressure at the die end, when the moisture was increased from 14 to 18 per cent (d.b). This result is in consistent with the findings reported by Senouci et al.(1986), and Vallee et al.(1987). A decrease in the moisture content of cassava flour resulted in increase in viscosity of the feed in the extruder and this in turn restricted the flow and increased the specific pressure.

5.2.4.2 **Effect of temperature on specific pressure:** It can be seen in the Fig.5.5 that the specific pressure decreased from 2.17 MPa to 1.60 MPa when the extrusion temperature increased from 100 to 120°C. As the temperature increased the viscosity of molten polymers generally decreases along with the pressure at the die. This finding was in confirmation with the result of Vallee et al.(1987).

5.2.4.3 **Effect of screw speed on specific pressure:** The variation of the pressure for different screw speeds can be seen in Fig.5.5. When the screw speed varied from 100 to 200 rpm, the specific pressure decreased from 2.3 to 1.9 MPa. The decreasing trend of the specific pressure with increase in screw speed may be due to the fact that as screw speed raised, shear forces increased and in turn decreased the viscosity of the dough, resulting in the decrease of specific pressure. This result is in agreement with the findings of Lin et al.,(1990).

5.3 Physical Properties of Cassava Extrudate

The physical properties of the extruded product, such as expansion ratio, bulk density, porosity and their interrelations were studied and reported.

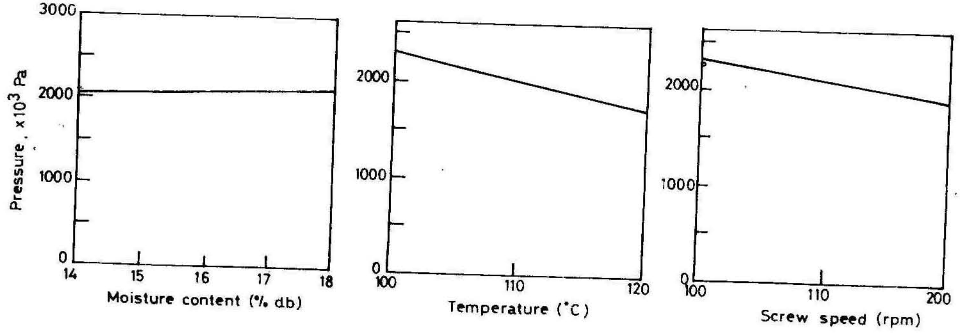

Fig.5·5 Effect of extrusion variables on pressure requirement

5.3.1 Expansion ratio

Crispness, a typical quality attribute of many foods, is strongly related to the expansion which in turn is indicated by various extrusion parameters. The extrusion process was carried out with a temperature of extrusion at 100 - 120°C and screw speeds at 100 - 150 rpm. The moisture content of the feed varied from 14 to 18 per cent (d.b). The analysis of variance for the physical character of the extrudates with respect to the processing variables is given in Table 5.7. From the table it can be seen that all the processing variables considered for the present experimentation have significant $(P<0.01)$ effect on expansion ratio. But none of their interactions showed any significance. The mean value of expansion ratio under varying extrusion process conditions are presented in Table 5.8. The table indicates that the expansion of dry extrudates are between 2.0133 and 2.9577. Also it was observed higher values of expansion ratio in the lowest processing conditions.

5.3.1.1 Effect of moisture on expansion ratio: By comparing the F-values in Table 5.7 it is discerned that moisture content of the feed mass exerted the maximum influence on expansion ratio (F - 368.81). At all levels of temperature, the increase in moisture content was associated with a decrease in expansion ratio. The overall expansion indices decreased from 2.8486 to 2.1676 for the increase of moisture content from 14 to 18 per cent (d.b.) as seen from Fig.5.6. The similar effect of moisture content on

Table 5.7 Analysis of variance table for expansion ratio and bulk density of cassava extrudate

SV	DF	Expansion ratio			Bulk density		
		SS	MS	F	SS	MS	F
Treatment	44	8.8920	0.2021	38.66**	167500.17	3806.82	771.21**
Screw speed, rpm	2	1.0100	0.5049	96.59**	15729.61	7864.80	1593.31**
Temperature, °C	2	0.1240	0.0622	11.90**	3846.48	1923.24	389.62**
Moisture content, % d.b.	4	7.7110	1.9278	368.81**	1121110.44	30277.61	6133.85**
Screw speed x temperature	4	0.0105	0.0026	<1.00	2415.20	603.80	122.32**
Screw speed X moisture content	8	0.0080	0.0010	<1.00	5817.81	727.23	147.33**
Temperature X moisture content	8	0.0147	0.0018	<1.00	7868.888	983.619	199.27**
crew speed x emperature x oisture content	16	0.0132	0.0008	<1.00	10711.748	669.488	135.63**
rror	90	0.4704	0.0050	<1.00	444.255	4.9362	
otal	134	9.3628					

* Significant at 1 % level

s Non-significant

Table 5.8 Mean value of expansion ratio at different extrusion process conditions

Moisture content %, db	Screw speed rpm	Expansion ratio at temperatures 100°C	110°C	120°C
14	100	2.9577	2.9313	2.9413
15		2.7447	2.7733	2.8107
16		2.5677	2.6133	2.6403
17		2.4050	2.4350	2.4697
18		2.2313	2.2613	2.3113
14	150	2.8407	2.8463	2.9387
15		2.6527	2.6557	2.7457
16		2.4603	2.5320	2.5630
17		2.3123	2.3563	2.3933
18		2.1380	2.1917	2.2133
14	200	2.6863	2.7417	2.7530
15		2.5087	2.5333	2.5953
16		2.3533	2.4617	2.4403
17		2.1850	2.2587	2.2563
18		2.0133	2.0520	2.0957
Temperature mean		2.4705	2.5096	2.5448

expansion ratio of cassava flour extrusion has also been reported by Badrie and Mellowes, (1991b). Chinnaswamy and Hanna(1988), while extruding corn starch, suggested that the low moisture content of starches restricted flow inside the barrel, increased shear rate and residence time caused increased degree of starch gelatinization and expansion. This phenomena was further supported by Chiang and Johnson(1977), Colonna et al.(1984) and Bhattacharya and Hanna(1987a).

5.3.1.2 Effect of temperature on expansion ratio: Effect of temperature on extrudate expansion was significant (P<0.01). As the temperature increased from 100 to 120°C, higher overall expansion indices of 2.4705 to 2.5448 were obtained(Fig.5.6 and Table 5.8). Higher temperature caused starch molecules stretched further because of a higher degree of gelatinization. Similar findings were reported by Badrie and Mellowes(1992). Mercier et al.,(1980) observed the maximum expansion of manioc starch at 200°C. Blanshard(1979) studied the physio-chemical aspects of starch gelatinization and reported higher moisture content of flour required higher temperature for melting of starch. The findings of the present study are in close agreement with the earlier works.

5.3.1.3 Effect of screw speed expansion ratio: The increase in screw speed from 100 to 200 rpm decreased the overall expansion ratio from 2.6063 to 2.3950(Table 5.9). Increasing screw speed, increased the shear rate, which intended to increase expansion of product, but simultaneously decreased the residence time. A

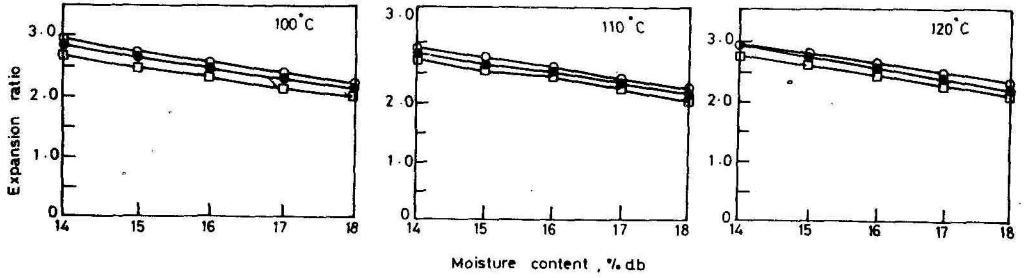

Fig.5.6 Effect of moisture content on expansion ratio at different screw speeds and temperature

decrease in residence time would cause a decrease of heat input from the hot barrel wall and which in turn affects the degree of gelatinization and thus expansion. Similar effects were also observed by Lawton et al.,(1972); Chiang et al.,(1977) and Bhattacharya (1987). Table 5.7 shows that the interaction of processing variations had no impact on expansion ratio.

Table 5.9 Effect of screw speed and moisture content on expansion ratio

Moisture content %, db	Expansion ratio at the screw speeds of			Moisture means
	100 rpm	150 rpm	200 rpm	
14	2.9434	2.8752	2.7270	2.8486
15	2.7762	2.6847	2.5458	2.6689
16	2.6071	2.5184	2.4197	2.5151
17	2.4366	2.3540	2.2333	2.3413
18	2.2680	2.1810	2.0573	2.1676
Screw speed	2.6063	2.5227	2.3950	2.5083

5.3.2 Bulk density

The analysis of variance (Table 5.7) showed significant $(P<0.01)$ effects of moisture content, temperature and screw speed on bulk density of extrudate. And also the interactions of processing variations have significant ($P<0.01$) effect over the response (bulk density). The average value of data recorded are presented in APPENDIX D. In the present experimentation with cassava flour, the bulk density of extrudate varied between 166.178 and 295.238 kg/m^3 for the moisture content, temperature and screw speeds of 14 per cent, 120°C and 200 rpm and 18 per cent, 100°C and 100 rpm respectively.

5.3.2.1 Effect of moisture content on bulk density: Comparing the F-values of the variables to judge their relative effects on product bulk density, moisture content exerted the maximum influence on bulk density ($F=6133.85$). Relationship between moisture content of cassava flour and bulk density at three levels of temperature and screw speed are shown in Fig.5.7. The increase in moisture content from 14 to 16 per cent (d.b.) increased the bulk density at a slow rate and further increase in moisture content beyond 16 per cent increased the bulk density rapidly. This higher rate of increased bulk density may be due to the condensation of trapped steam in extrudate on cooling.

The effect of moisture content and temperature on bulk density is given in Table 5.10. It can be seen from the table that when the percentage of moisture increased from 14 per cent to 18 per cent, the overall bulk density of the extrudate increased from 185.310 kg/m^3 to 226.805 kg/m^3 which is in conformity with the findings of the early works(Harmann and Harper,1973,

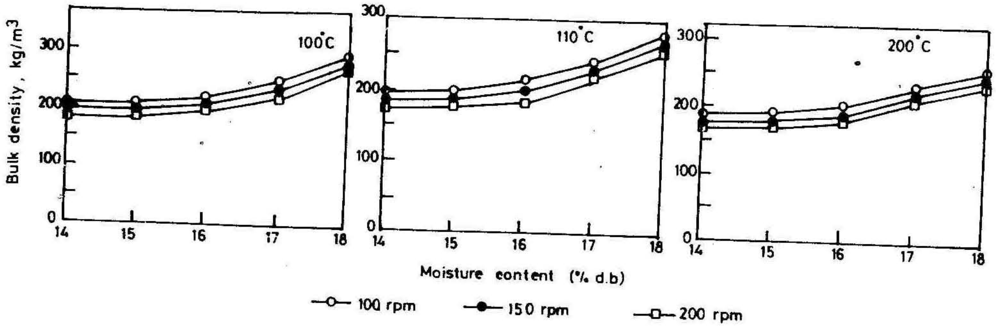

Fig.5.7 Effect of moisture content on bulk density at different screw speeds and temperatures

Lawton et al.,1985 and Badrie and Mellowes, 1991). This phenomena may be due to the fact that samples of higher moisture appeared to expand initially to the same degree as lower moisture samples, but it is likely that when a smaller percentage of water was driven off and resulted in wet extrudate. This might have allowed starch to contract, producing a denser product.

Table 5.10 Effect of moisture content of the cassava flour and extrusion temperature on bulk density of cassava extrudate

Moisture content %, db	Bulk density of cassava extrudate			Moisture means
	100°C	110°C	120°C	
14	193.792	184.763	177.374	185.300
15	196.947	188.749	179.968	188.555
16	208.539	198.877	225.222	210.879
17	235.244	230.316	223.063	229.541
18	283.019	268.637	248.758	266.805
Temperature means	223.508	214.268	210.877	216.218

5.3.2.2 Effect of temperature: The effect of temperature is significant (P<0.01) on bulk density(Table 5.7). Table 5.10 shows that the overall bulk density decreased from 223.508 kg/m^3 to 210.877 kg/m^3 when temperature increased from 100 to 120°C. Harmann amd Harper(1973) explained that increase in temperature decreased the viscosity of the dough and allowed to expand more readily. The raised vapour pressure caused increased flashing and puffing upon the exit from the die.

5.3.2.3 **Effect of screw speed on bulk density:** From the Table 5.7 it can be noted that the effect of screw speed was signfiicant ($P<0.01$) on bulk density of the extrudate. From Table 5.11 it is evident that the increase in the screw speed from 100 to 200 rpm lowered the average bulk density of the extrudate from 226.529 to 201.314 kg/m^3 and the results are in agreement with Bhattacharya(1987) and Badrie et al.(1991). Harmann and Harper(1973) described the reasons for decreased density with increasing screw speed.

a) Viscosity decreased when increasing screw speed for a non-newtonian dough. A dough of low viscosity expanded more readily than a dough of high viscosity, when moisture flashed off at the die.

b) Free moisture was more evenly distributed throughout the dough and gave a finer cell structure with more uniform puffing as the dough came out of the die.

Table 5.11 Effect of screw speed and temperature on bulk density of cassava extrudate

Temperature °C	Bulk density at the screw speeds of 100 rpm	150 rpm	200 rpm	Temperature means
100	235.872	224.193	210.460	223.508
110	227.510	214.375	200.919	214.268
120	216.204	223.865	192.562	210.877
Screw speed means	226.529	220.811	201.314	216.218

Among the interaction terms, the interaction between moisture and temperature was not significant (F=99.27). At higher temperature and at low feed moisture, greater super heating of moisture in the dough, increased puffing of extrudate and correspondingly lowered the bulk density. In the present experimentation the value is 177.374 kg/m^3. Similar findings were obtained by Badrie (1991b).

5.3.2.4 Relationship between expansion ratio and bulk density of extrudate: The expansion ratio and bulk density of an extrudate describe the degree of puffing of the extrudate as it exits the nozzle. Some researchers interrelated these two properties (Bhattacharya, 1987 and Park et al.,1993).

The experimental data of expansion ratio and bulk density for all the processing variables were fitted in a scatter plot

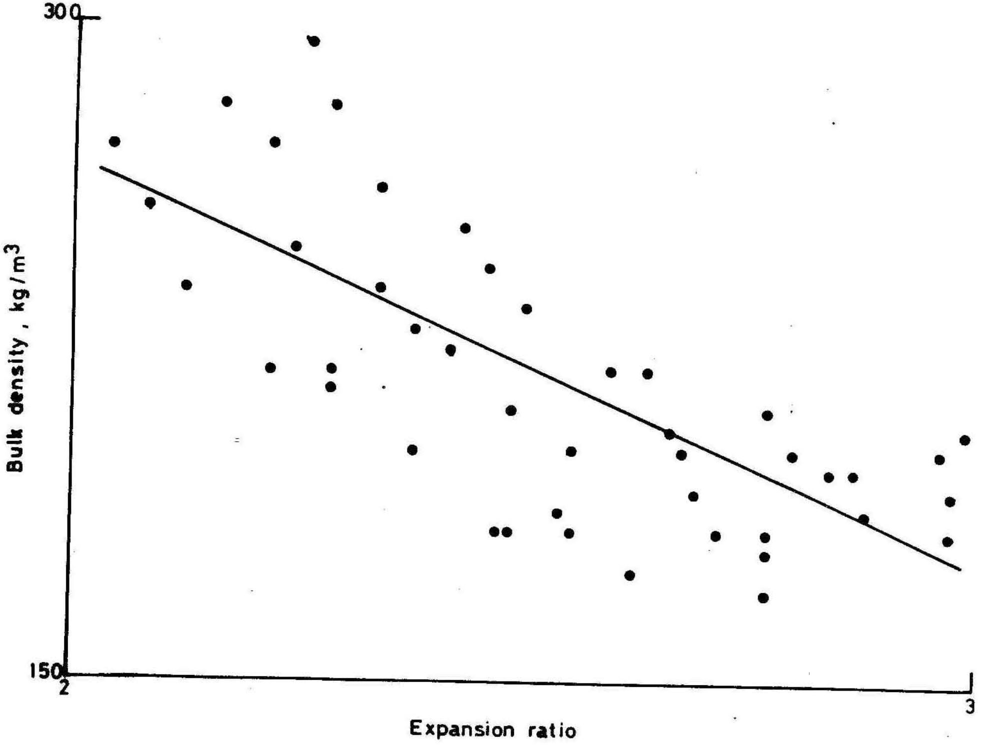

Fig. 5.8 Relationship between expansion ratio and bulk density of cassava extrudate

and shown in Fig. 5.8. The figure showed a negative relationship between expansion ratio and bulk density. The correlation coefficient was only -0.6862, where as Bhattacharya(1987) found the same relationship of the expansion ratio and bulk density with a high correlation coefficient (r = 0.95). Park **et al.**,(1993) also observed the same trend with a correlation coefficient of -0.75. Expanded product entrap air and contain open cell structures leading to decrease in bulk density. Park et al.(1993) explained that expansion ratio considered expansion only in the direction perpendicular to extrudate flow, where as bulk density considered expansion in all directions.

5.3.3 Porosity of the extrudate

Statistical analysis indicated that moisture content, temperature and screw speed and all their interactions significantly (P<0.01) affected the porosity of the extrudate during extrusion processing (Table 5.12). The value of porosity ranged from 58.327 to 69.34 per cent.

5.3.3.1 Effect of moisture content of cassava flour, barrel temperature and screw speed on porosity of extrudate: The analysis of variance (Table 5.12) shows the moisture content was the most signfiicant (P<0.01) factor affecting the porosity of the extrudate. The variations of porosity for different moisture contents are shown in Fig.5.9. It may be seen from the figure that the porosity of the extrudate decreased linearly with increase in

Table 5.12 Analysis of variance table for porosity of cassava extrudate

SV	DF	Porosity		
		SS	MS	F
Treatment	44	1145.8818	26.0428	179.32**
Screw speed, rpm	2	21.3688	10.6843	73.57**
Temperature, °C	2	140.5524	70.2762	483.90**
Moisture content, % d.b.	4	956.5068	239.1270	1646.55**
Screw speed x temperature	4	0.6226	0.1557	1.07ns
Screw speed X moisture content	8	11.3911	1.4239	9.80**
Temperature X moisture content	8	9.4666	1.1833	8.15**
Screw speed x temperature x moisture content	16	5.9736	0.3733	2.57**
Error	90	13.0710	0.1452	
Total	134	1158.9520		

** Significant at 1 % level

ns Non-significant

moisture content. Increasing the moisture content from 14 per cent to 18 per cent decreased the overall porosity from 68.67 per cent to 60.06 per cent. At low moisture contents starch cells burst and coalesce into large voids and increased the porosity. (Gomez and Augilera,1984 and Wen et al.,1990). Barret and Peleg(1992) suggested that extrudate processed at lower moisture levels, which had the lowest bulk densities, could have had inherently weaker cell walls due to reduction of average molecular weight of starch. Faubion et al.,(1982) discussed that as moisture content was increased, extrudate cells became smaller and less uniform in size.

The effect of temperature on porosity is shown in Table 5.13 and Fig.5.9. This figure shows that increase in temperature increased the porosity of the extrudate. The overall porosity of the extrudate increased from 62.947 per cent to 65.443 per cent for an increase in the temperature from 100 to 200°C. The reason being the formation of larger air fissures at higher temperature increased the porosity.

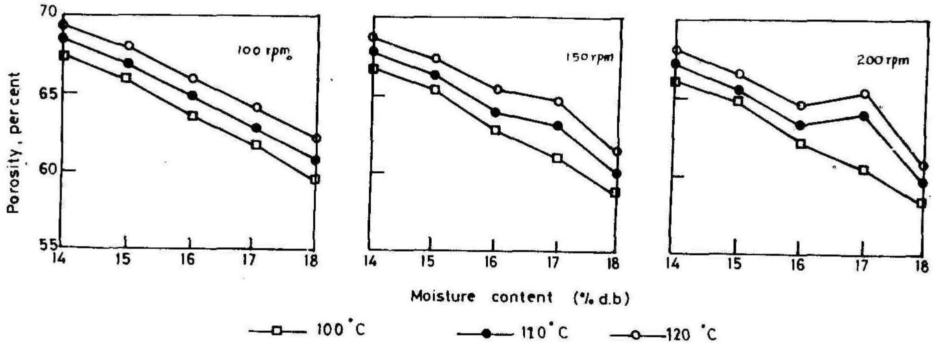

Fig.5.9 Effect of moisture content on porosity of extrudate at different temperatures and screw speeds

Table 5.13 Effect of screw speed and temperature on porosity of cassava extrudate

Temperature °C	Porosity of extrudate at the screw speeds of 100 rpm	150 rpm	200 rpm	Temperature means
100	63.561	62.924	62.357	62.947
110	64.755	64.295	63.861	64.304
120	65.851	65.452	65.027	65.443
Screw speed means	64.722	64.224	63.478	64.237

Fig. 5.9 and Table 5.13 show that the overall porosity decreased from 64.72 per cent to 63.78 per cent when the screw speed increased from 100 to 200 rpm. The reason for the reduction in porosity may be due to the shorter residence time. A decrease in residence time caused a decrease in degree of gelatinization and less formation of pores in the extrudate.

5.3.2 Relationship between porosity, expansion ratio and bulk density: The interactions between porosity and expansion ratio of the extrudate obtained at various combinations of process variables were plotted in a scatter diagram as shown in Fig.5.10. The Figure shows that porosity and expansion ratio

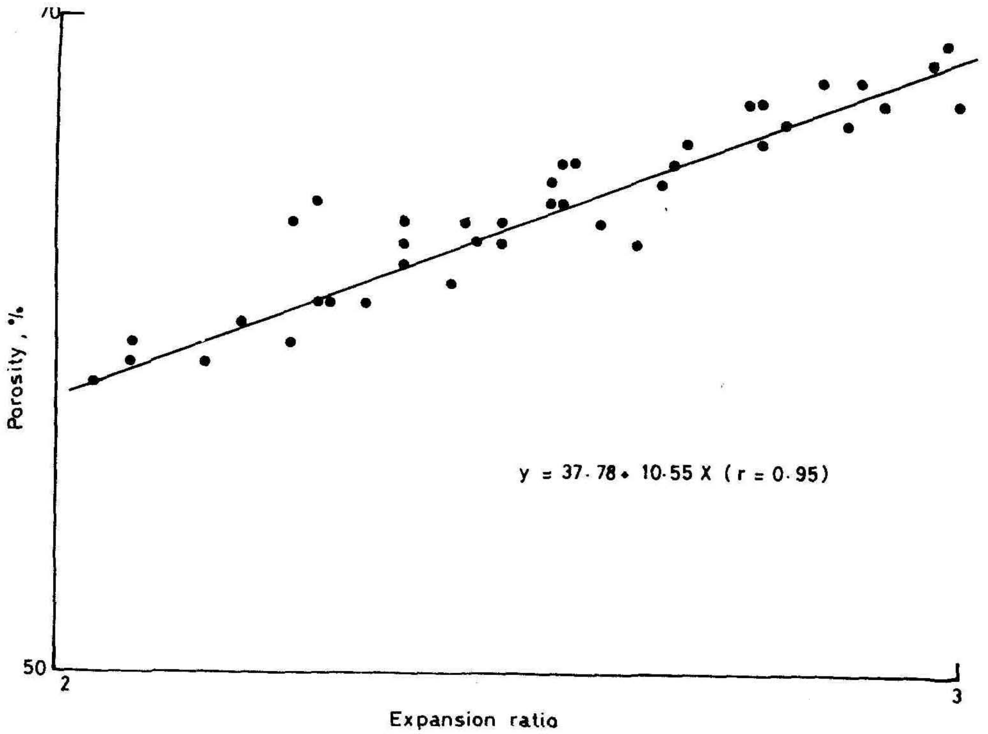

Fig. 5.10 Relationship between expansion ratio and porosity of the cassava extrudate

have a positive relationship with a high correlation coefficient (r=0.9463). The equation for the straight line is

$$Y = 37.78 + 10.55X$$

Whereas, X = Expansion ratio

Y = Porosity, per cent

Similarly the porosity and bulk density had a relation but the correlation coeffcient was very less (0.78).

5.4 Water absorption index (WAI)

Water absorption depends on the availability of hydrophilic groups which bind water molecules and on the gel-forming capacity of macromolecules.

Table 5.14 presents results of the analysis of variance showing effects of extrusion variables on water absorption index. The table reveals that all the processing variables considered for the study have significant ($P<0.01$) effect on water absorption index. Among the interaction terms, only the interaction between moisture and temperature have significant effect ($P<0.01$) over the response function, i.e., water absorption index.

5.4.1 Effect of moisture on water absorption index

The feed moisture is the most significant (F=789.81) on the water absorption index. Relationships between moisture content of cassava flour and water absorption index at three different temperature and screw speeds are shown in Fig.5.11. As the flour moisture increased from 14 to 18 per cent the water absorption index increased from 2.47 to 3.90 g of gel/g of dry sample. Gomez and Aguilera (1983) reported the high values of water ab-

Table 5.14 Analysis of variance table for water absorption index(WAI) and water solubility index(WSI) of cassava extrudate

SV	DF	Water absorption index(WAI)			Water solubility index(WSI)		
		SS	MS	F	SS	MS	F
Treatment	44	43.8480	0.9965	92.66**	1295.922	29.453	186.72**
Screw speed, rpm	2	7.2370	3.6183	336.45**	437.695	218.848	1387.42**
Temperature, °C	2	1.6830	0.8414	78.24**	59.637	29.819	189.04**
Moisture content, % d.b.	4	33.9760	8.4939	789.81**	790.814	197.703	1253.37**
Screw speed x temperature	4	0.0679	0.0167	1.56	0.124	0.0310	<1.00
Screw speed X moisture content	8	0.1127	0.0139	1.30	5.767	0.7209	4.57**
Temperature X moisture content	8	0.5274	0.0659	6.13**	0.846	0.1058	<1.00
Screw speed x temperature x moisture content	16	0.2477	0.0154	1.43	1.038	0.0649	<1.00
Error	90	0.9680	0.0108		1310.118		
Total	134	44.8160			32619.990		

** Significant at 1 % level

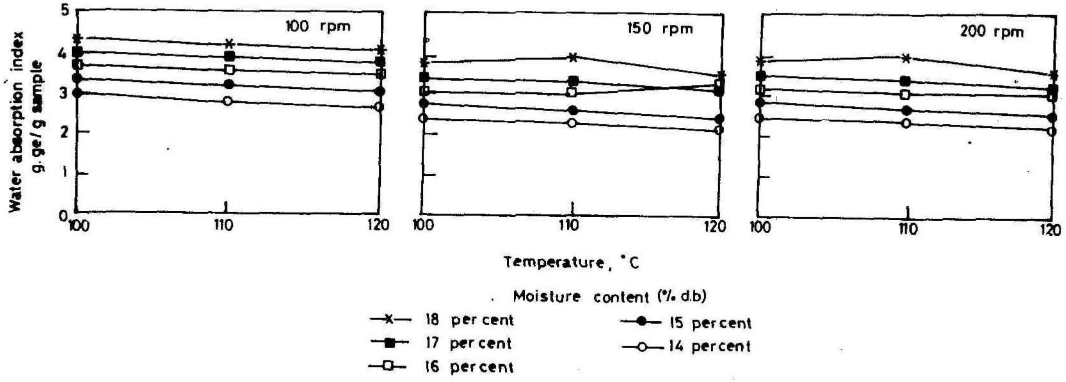

Fig.5.11 Effect of temperature and screw speed on water absorption index

sorption index in gelatinized, corn starch were due to presence of undamaged polymer chains and greater availability of hydrophlic groups which can bind water molecules.

5.4.2 Effect of temperature on water absorption index

Table 5.15 shows that overall WAI(Water absorption index) decreased from 3.3189 to 3.0467 g of gel/g of sample, when the temperature increased from 100 to 120°C. Mercier and Feillet (1975) and Badrie and Mellowes,(1991) obtained similar results. Colonna and Mercier (1983), have demonstrated that extrusion cooking of manioc could lead to some macromolecular degradation of amylose and amylopectin molecules of starch. Thus at lower temperature, there was probably less molecular degradation than at high temperature.

Table 5.15 Effect of screw speed and temperature on water absorption index(WAI)

Temperature °C	Water absorption index (WAI)			Temperature mean
	Screw speed , rpm			
	100	150	200	
100	3.6778	3.1283	3.1507	3.3189
110	3.5018	3.0493	3.0653	3.2055
120	3.3738	2.9073	2.8591	3.0467
Screw speed mean	3.5178	3.0283	3.0250	3.1904

5.4.3 Effect of screw speed on Water absorption Index

The increase in screw speed lowered the overall WAI from 3.5178 to 3.0250 g of gel/g of sample. The results are in good agreement with the findings of Badrie and Mellowes, (1991). The lower WAI of cassava extrudate on increasing the screw speed from 100 to 200 rpm could be related to an increase in shear rate and resulting in structural modification.

5.4.4 Water solubility index(WSI)

The results of analysis of variance (Table 5.14) indicates that all the extrusion vairables have significant ($P<0.01$) effect on WSI. Among the interaction variables only screw speed and moisture content had significant ($P<0.01$) effect on WSI.

5.4.4.1 Effect of moisture content on WSI: Relationships between moisture content of cassava flour and WSI at three different temperatures and screw speeds are shown in Fig.5.12. The increase in moisture content from 14 to 18 per cent (d.b) decreased the average WSI from 46.57 to 39.94 per cent. The findings are in good agreement with results reported by others for pure starches (Mercier and Feillet, 1975), corn grits(Conway 1971) and cassava flour (Badrie and Mellowes, 1991). The reason for such a behaviour may be that the number of broken linkages in the highest

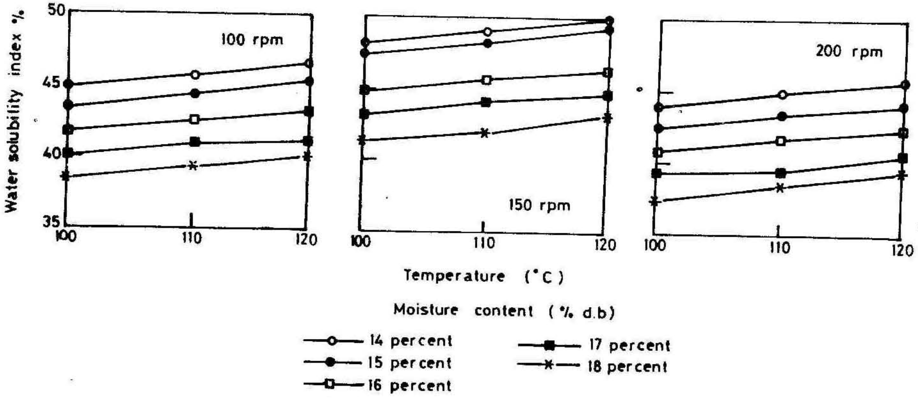

Fig.5.12 Effect of temperature on water solubility index at different moisture contents and screw speeds

molecular fraction decreased with increase in moisture content of flour.

5.4.4.2 Effect of temperature on water solubility index: Degradation of starch occurs at high extrusion temperatures (Mercier et al., 1979). Table 5.16 shows that the WSI increased from 42.53 to 44.16 per cent with increase in the barrel temperature throughout the entire temperature range of 100 - 120°C. The results obtained are in good agreement with Anderson et al.(1969).

Table 5.16 Effect of screw speed and temperature on water solubility index(WSI)

Temperature °C	Water solubility index (WSI) Screw speed, rpm 100	150	200	Temperature mean
100	41.782	44.999	40.803	42.528
110	42.608	45.814	41.525	43.316
120	43.373	46.631	42.463	44.156
Screw speed mean	42.588	45.814	41.597	43.333

5.4.4.3 Effect of screw speed on Water Solubility Index: WSI is associated with degradation of starch. Davidson et al.,(1984) explained that degradation was due to combination of mechanical and thermal factors. For purely mechanical degradation shear stress was the only critical factor. Table 5.14 shows that screw speed had most significant (F=1387.42) effect on WSI. An increase in the screw speed from 100 to 150 rpm increased the WSI from 42.58 to 45.81 per cent. On further increase in the screw speed from 150 to 200 rpm, WSI decreased to 43.33 per cent. A similar trend was noticed by Badrie and Mellowes, (1991).

The increase in WSI, when the speed of screw increased from 100 to 150, may be due to increase in shear rate resulting in structural modification. The decrease in WSI of cassava extrudate on further increase of screw speed from 150 to 200 rpm could be related to shorter residence time.

5.4.4.4 Relations among expansion ratio, water absorption index and water solubility index: The product characteristics like expansion ratio and water solubility index are inter-related (Linko et al., 1982 and Badrie and Mellowes, 1991). The Fig.5.13 shows that expansion ratio was found to be positively correlated to water solubility index with a correlation coefficient of 0.8241 ($P<0.01$). The data fittedd linearly in the form of

$$Y = 18.62 + 9.85X$$

where X = expansion ratio and

Y = water solubility index

The Fig. 5.14 shows that the water absorption index was negatively related to water solubility index with a correlation coefficient of -0.7896 ($P<0.01$). The equation for this straight line

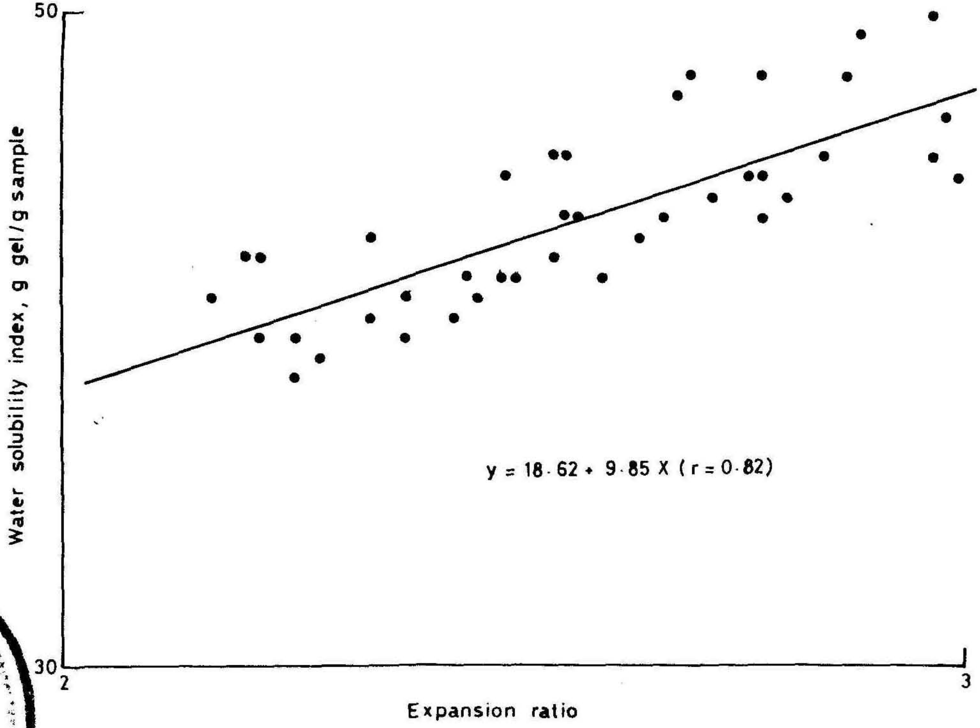

Fig.5·13 Relationship between expansion ratio and water solubility index of the cassava extruclate

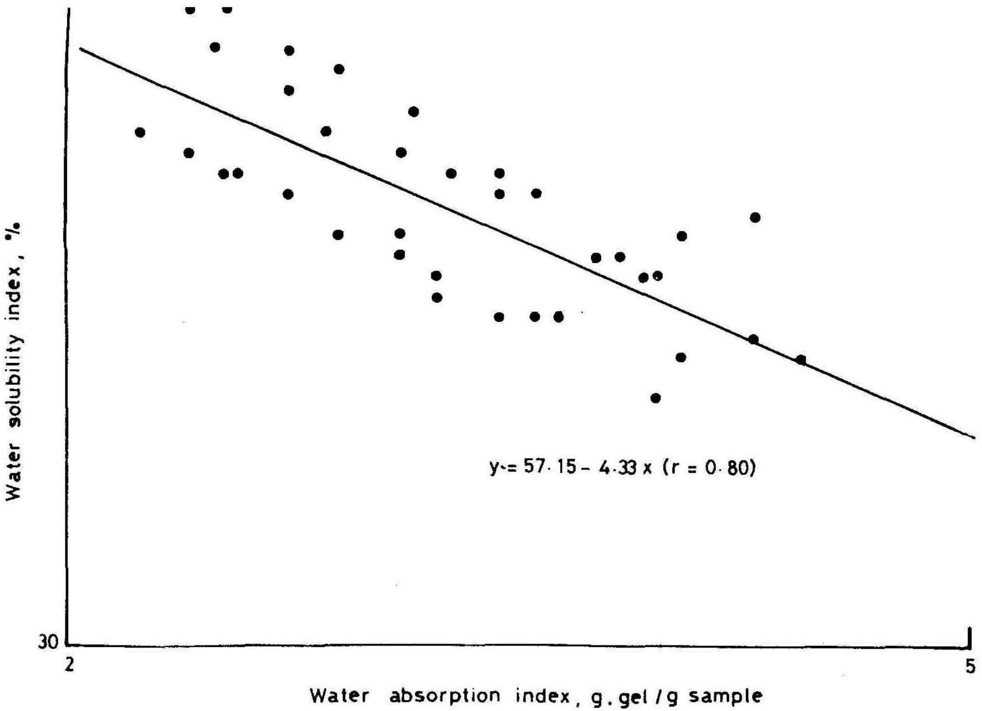

Fig. 5.14 Relationship between water absorption index and water solubility index of the cassava extrudate

is $Y = 57.15 - 4.33\ X$

where Y = water solubility index and

X = water absorption index

The results obtained are very close with the findings of Badrie and Mellowes,(1991b), who obtained correlation coefficients of 0.80 ($P<0.05$) respectively.

5.5 Mechanical Properties of Cassava Flour Extrudate

The food texture is a result of micro structure, which in turn, depends upon the influence of physical forces on chemical components. Thus, the structural properties of food products dictate mechanical properties.

Analysis of variance Table 5.17 and 5.18 shows that all the extrusion variables and their interactions have significant($P < 0.01$) effect on mechanical properties such as shear strength, compressive strength (sometimes known as hardness or breaking strength) and tensile strength of extrudates. Table 5.17 and 5.18 reveals that all the interaction of variables had signfiicant($P < 0.01$) effect on mechanical characteristics of cassava extrudates. The range of the shear strength, compressive strength and tensile strength of the extrudate varied from 1.983 to 2.906 kg/cm^2, 3.876 to 5.090 kg/cm^2 and 0.638 to 1.801 kg/cm^2 respectively(Table 5.19).

Table 5.17 Analysis of variance table for shear strength and compression strength of cassava extrudate

SV	DF	Shear strength			Compression strength		
		SS	MS	F	SS	MS	F
Treatment	44	20.7146	0.4710	153.18**	39.869	0.906	218.71**
Screw speed, rpm	2	1.0150	0.5080	165.18**	0.906	0.453	109.35**
Temperature, °C	2	2.6420	1.3210	429.78**	16.264	8.132	1962.82**
Moisture content, % d.b.	4	9.0800	2.2700	738.59**	13.894	3.474	838.43**
Screw speed x temperature	4	3.1960	0.8000	260.19**	8.073	2.018	487.16**
Screw speed X moisture content	8	0.6340	0.0790	25.77**	0.173	0.022	5.21**
Temperature X moisture content	8	0.9180	0.1150	37.33**	0.154	0.019	4.66**
Screw speed x temperature x moisture content	16	3.2280	0.2020	65.64**	0.405	0.025	6.11**
Error	90	0.2770	0.0030		0.373	0.004	
Total	134	20.9910			40.242		

** Significant at 1 % level

ns Non-significant

Table 5.18 Analysis of variance table for Tensile strength of cassava extrudate

SV	DF	Tensile strength		
		SS	MS	F
Treatment	44	30.6880	0.6970	134.55**
Screw speed, rpm	2	2.3790	1.1900	229.50**
Temperature, °C	2	6.7220	3.3610	648.39**
Moisture content, % d.b.	4	15.6460	3.9120	754.59**
Screw speed x temperature	4	2.8070	0.7020	135.35**
Screw speed X moisture content	8	0.7270	0.0910	17.53**
Temperature X moisture content	8	0.8270	0.1030	19.94**
Screw speed x temperature x moisture content	16	1.5800	0.0987	19.05**
Error	90	0.4670	0.0050	
Total	134			

** Significant at 1 % level

ns Non-significant

Table 5.19 Mechanical properties of cassava extrudates as affected by extrusion parameters

Moisture content (%,db)	Temperature °C	Screw speed rpm	shear strength	Compression strength	Tensile strength
14	100	100	2.480	4.727	1.32
		150	2.053	4.413	1.08
		200	2.070	4.280	0.85
	110	100	2.523	3.777	0.36
		150	1.757	4.003	0.60
		200	2.157	4.350	1.05
	120	100	1.947	3.123	0.79
		150	2.427	3.657	0.23
		200	1.723	3.913	0.54
15	100	100	2.820	5.053	1.63
		150	2.403	4.730	1.22
		200	2.190	4.283	0.94
	110	100	2.163	4.127	0.73
		150	2.017	4.270	0.83
		200	2.350	4.540	1.14
	120	100	2.163	3.423	1.01
		150	2.537	3.753	0.37
		200	2.010	4.153	0.88
16	100	100	3.030	5.180	1.85
		150	2.513	4.810	1.32
		200	2.470	4.463	1.26
	110	100	2.933	4.297	1.74
		150	2.277	4.470	1.12
		200	2.527	4.740	1.31
	120	100	2.360	3.630	1.15
		150	2.913	4.117	0.73
		200	2.047	4.243	0.85
17	100	100	3.027	5.417	2.03
		150	3.010	5.167	1.85
		200	2.677	4.463	1.48
	110	100	2.213	4.513	1.93
		150	2.497	4.670	1.32
		200	2.773	5.073	1.60
	120	100	2.617	3.890	1.44
		150	2.150	4.343	1.01
		200	2.433	4.630	1.24
18	100	100	3.440	5.570	2.31
		150	3.070	5.373	1.99
		200	2.937	5.140	1.76
	110	100	2.370	4.647	1.19
		150	2.617	4.937	1.46
		200	3.050	5.237	1.85
	120	100	2.913	4.177	1.73
		150	2.763	4.550	1.26
		200	2.663	4.893	1.46

5.5.1 Effect of moisture content of flour on mechanical properties of the extrudate

The most influencing contributor to shear strength and tensile strength of the extrudate is the moisture content. Table 5.20 showed that increase in moisture content from 14 to 18 per cent (d.b) increased the shear strength from 2.13 to 2.87 kg/cm², compressive strength from 4.03 to 4.95 kg/cm² and tensile strength from 0.76 to 1.67 kg/cm² respectively for many cases. The probable reason for this may be that the increased moisture content might have caused the extrudate tougher and denser, and increased the mechanical strength. Similar results were also observed by Mercier and Feilet,(1975) and Stanley(1986) while extruding cereal starches.

Table 5.20 Effect of moisture means on mechanical properties of cassava extrudate

Moisture content (%, d.b.)	Shear strength	Compression strength	Tensile strength
14	2.216	4.027	0.759
15	2.295	4.259	0.972
16	2.563	4.455	1.260
17	2.620	4.685	1.544
18	2.869	4.947	1.667

5.5.2 Effect of barrel temperature on mechanical properties of the extrudate

Increase in temperature from 100 to 120°C decreased the shear strength from 2.69 to 2.38 kg/cm^2, compressive strength from 4.88 to 4.03 kg/cm^2 and tensile strength from 0.98 to 1.53 kg/cm^2. This was due to the development of lighter texture with increased temperature. Mercier and Feilet (1975) found a similar trend while extruding corn starch and observed a decrease in breaking strength for increase in moisture content.

Increasing screw speed from 100 to 200 rpm reduced the shear strength from 2.61 to 2.41 kg/cm^2 and tensile strength from 1.42 to 1.21 kg/cm^2, but increased the compressive strength from 4.37 to 4.57 kg/cm^2. Among the interactions, screw speed and temperature had most significant effect on all the mechanical characteristics of cassava extrudate. Hence the combination of screw speed and temperature can be considered for adjustments to improve the texture of the extrudate. The shear strength has negatively correlated with expansion ratio(Fig.5.15) with a low correlation coefficient of -0.6006 ($P<0.01$). The same trend was observed for the relationship of compressive strength and expansion ratio(Fig.5.16) ($r = -0.6374$, $P<0.01$) and tensile strength and expansion ratio ($r = -0.6913$, $P<0.01$)(Fig.5.17).

5.6 Sensory Evaluation

Based on expansion ratio, colour and appearance of the cassava extrudates, six samples were selected and fried in re-

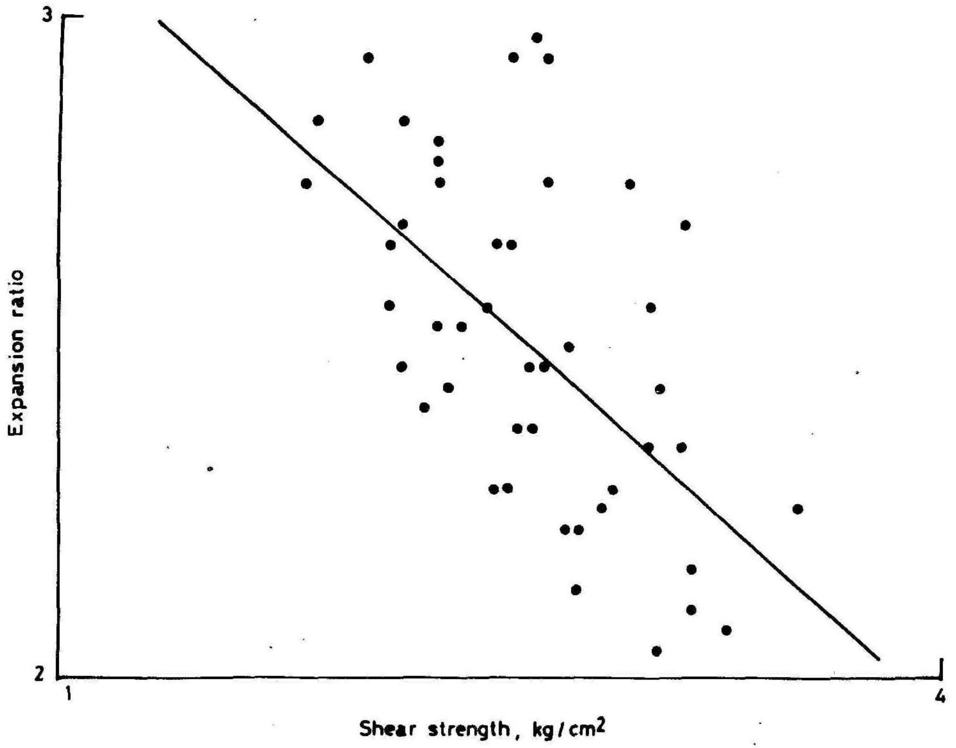

Fig. 5.15 Relationship between shear strength and expansion ratio of the cassava extrudate

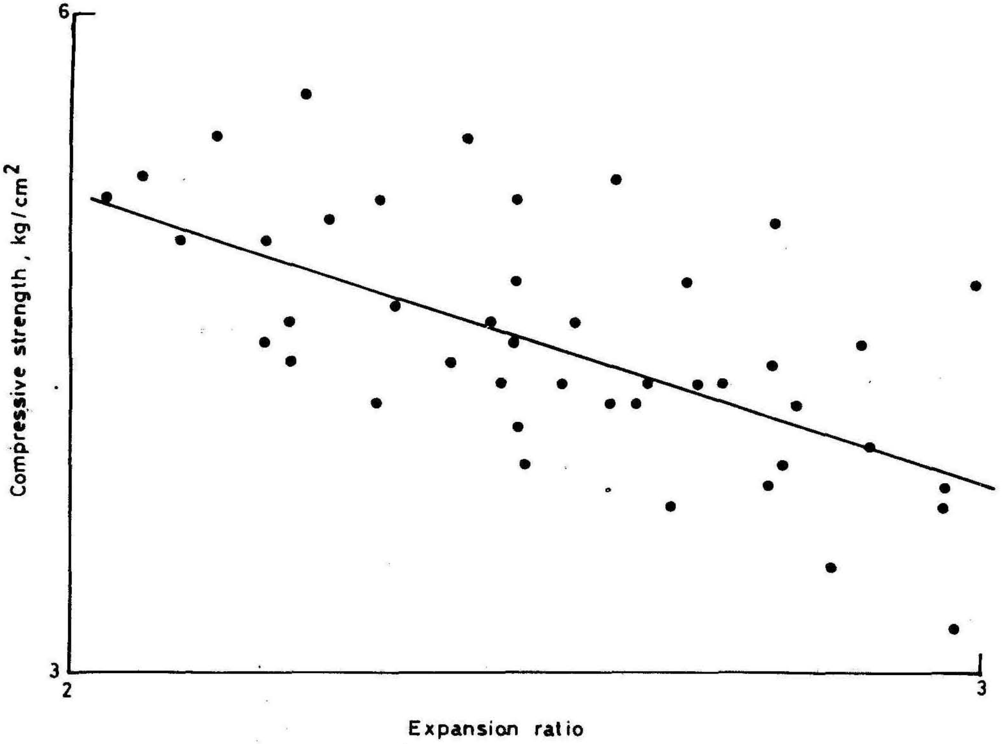

Fig.5.16 Relationship between expansion ratio and compressive strength of cassava extrudate

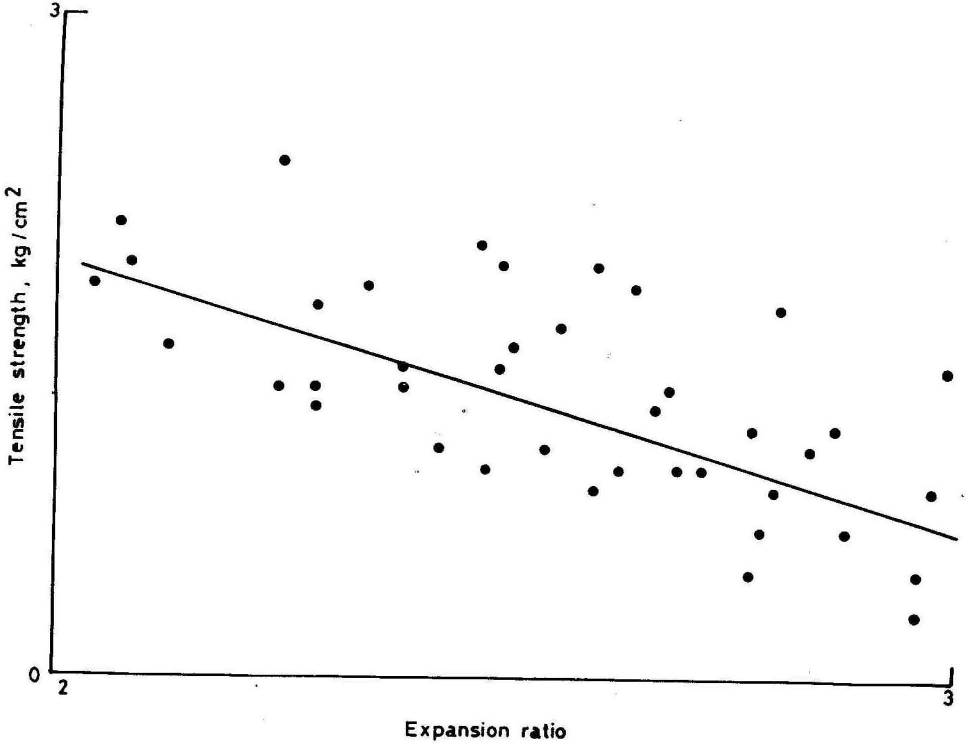

Fig.5.17 Relationship between expansion ratio and tensile strength of the cassava extrudate

fined groundnut oil. Salt and pepper were dusted to add taste uniformly on all samples. A commercially available corn puff was considered as control. These seven samples(Plate 13) were presented to judges for their organoleptic quality evaluation such as, color appearance, texture, taste, odour and overall quality. A multi-comparision scoring differences test was used to determine if there are any perceived differences among cassava extrudates.

Table 5.21 Mean scores for sensory evaluation of cassava flour extrudate

Sample No.	Colour	Appearence	Texture	Taste	odour	Overall acceptability
I	6.000d	6.67c	7.567a	7.87a	8.07a	7.467a
II	8.133a	7.60ab	7.167a	8.30a	8.20a	8.070a
III	8.000ab	7.50ab	6.400b	7.96a	8.00a	8.100a
IV	6.530cd	6.37c	7.167a	7.93a	8.27a	7.800a
V	7.667ab	7.47ab	7.330a	8.23a	7.90a	7.500a
VI	6.900c	6.93bc	7.400a	8.27a	7.90a	7.300
VII*	7.500b	8.23	5.970b	4.93	6.20	6.030

1. Mean scores with same superscripts in a column are not significantly different
2. * Commercially produced corn puff

For each characteristics of the product, numeral scoring was given by the judges ranging from one to ten representing four quality grades, namely, poor, fair, good and excellent. The mean scores for individual characteristics of cassava extrudates are presented in Table 5.21. It can be seen from the table that all

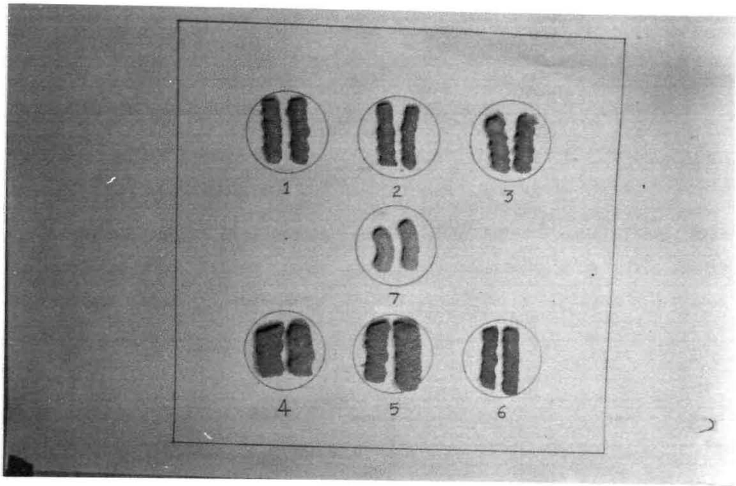

PLATE 13. View of selected samples for sensory evaluation

APPENDIX-B

the characteristics of all the extruded samples and control are rated above the mean score of 6 (good and excellent as per quality description of IS: 6273 - 1972).

The table reveals that there were no significant differences for texture, taste and odour between the test cassava extrudates and only the control had a significant ($P < 0.05$) difference.

Sample No.II has more favourable colour (mean score of 8.133) and significantly differed from the samples I, II, IV and control. In appearance the control has most favourable appearance. Further the Table 5.21 reveals that the most acceptable extruded product with a mean score of 8.1 was obtained at a moisture content of 16 per cent (d.b) extrusion teperature of 110°C and a screw speed of 100 rpm which falls in the category of good.

Cassava is rich in carbohydrates and poor in protein. So a proteein source like defatted soybean flour or fish can be added to fortify the product. This extrusion cooking technology can be expended furtherfor other tuber crop starches such as sweet potato, taro and colocasia.

SUMMARY AND CONCLUSIONS

6. SUMMARY AND CONCLUSIONS

Cassava(**Manihot esculenta** Crantz) is a perennial crop grown in India on about 0.2 million hecatres and the production is 5.1 million tonnes. The principal mode of utilization of cassava is as fresh roots after boiling or baking. However, the extremely high perishability of cassava roots require their processing within a few days after harvest. Roots normally processed into chips converted as flour have relatively better keeping quality.

One of the promising uses of cassava flour is as a substitute for wheat flour in the production of bread, cake, cookies, macaroni, noodles. etc. There has been an increasing acceptance of convenient, quick to serve food in western countries. The market for such products is expanding at a phenomenal rate in the developing countries. But in India many of them never appeared in the market because of high cost of production due to expensive imported equipments and process technology. Several processing techniques like flaking, puffing and baking have been developed.

Extrusion cooking has become an increasingly popular technology in food industries which will utilise starchy and proteinaceous raw materials. It exhibits several advantages, the principal one being that the ingredients undergo a number of unit operations including mixing, shearing, cooking, drying and texturization in one-energy efficient and rapid process. Several researchers have reported that cassava flour can be used as a satisfactory ingredient in the extruded food.

Although the extruder is capable of handling variety of ingredients, the processing conditions need to be standardised for a particular food system. The final product properties could be manipulated by varying extrusion process variables. This called for a systematic research establishing the relationship between extrusion process variables viz., moisture content of feed, extrusion temperature and screw speed and the product qualities like expansion ratio, bulk density, porosity, water absorption index, water solubility index and mechanical properties.

To open a new avenue in utilisation of cassava, an attempt has been made to develop an extruder and process technology for the production of extruded cassava based snack foods.

The various physical properties of cassava flour like bulk density, particle size, coefficient of friction, shear strength and thermal properties, such as, thermal conductivity and specific heat were determined at 14 to 18 per cent moisture content (d.b) of the flour using standard procedures.

A laboratory scale single screw extruder was developed with 26 mm of extruder barrel with 425 mm length. A circular die of

22 mm length and 5 mm diameter were used. Heaters were provided on the circumference of the barrel to heat the material inside the extruder. A 5 hp variable speed motor was used to operate the extruder at various desired screw speeds. Provisions were made for measuring temperature, screw speed and energy consumption during extrusion operation.

During extrusion operation the machine parameters, such as volumetric flow rate, specific energy consumption, specific pressure and viscosity of the dough were measured. The effect of process variables on these machine parameters were studied in detail.

The effect of extrusion variables on the physical, functioning and mechanical qualities of the extrudates were studied.

The physical properties of the extrudate viz., expansion ratio, bulk density and porosity were determined for all combinations of process variables. The functional properties of extrudate such as, Water absorption index and Water solubility index were determined by using the method of Anderson et al.(1969).

The food texture is the resultant of physical forces on chemical components of the food. The structural property of food dictates the mechanical properties. The mechanical properties viz., shear strength, compressive strength (Hardness/breaking strength) were measured. The shear strength was measured using a jig fabricated for this purpose. Compressive strength was measured with the help of Kiya hardness tester and tensile strength by using pan and weight system. The effect of extrusion variables on these mechanical properties were analysed.

Based on expansion ratio, color and appearance of the cassava extrudate, six samples were selected and fried in refined groundnut oil. A commercially available corn puff was considered as control. These seven samples were presented to judges for their organoleptic quality evaluation as per description of IS: 6273-1972.

The specific conclusions drawn from the present investigation are the following.

i) The bulk density of cassava flour ranged between 423.52 to 486.76 kg/m^3 for the moisture content range of 14 to 18 per cent d.b.

ii) The average particle sizes of cassava flour determined by sieve analysis, namely, the mass mean diameter, arithmetic mean diameter and volume surface mean diameter are 0.1700, 0.1690 and 0.1593 mm, respectively at a moisture content of 14.00 per cent (d.b).

iii) The coefficient of static friction between cassava flour and different surfaces, viz., stainless steel, aluminium, mild steel and galvanized iron, ranged from 0.4469 to 0.5100, 0.4259 to 0.6000, 0.4905 to 0.7493 and 0.4500 to 0.5333, respectively at 14 to 18 per cent moisture contents (d.b).

iv) The shear strength of the cassava flour measured by a split barrel apparatus was 8.26 x 10^{-3} at 496 kg/m^3 and 14 per cent(d.b) moisture content.

v) Thermal conductivity and specific heat of the cassava flour ranged from 0.2542 to 0.2957 w/m°C and 1.827 to 2.056 kJ/kg°K at 14 to 18 per cent moisture content (d.b), respectively.

vi) The gelatinization temperature of the cassava flour measured with the Brabender viscoamylograph ranged from 60 to 73°C.

vii) The developed extruder performed well in the operating range of 14 to 18 per cent moisture content of cassava flour, 100 - 120°C barrel temperature and 100 - 200 rpm screw speed.

viii) The overall volumetric flow rate of the extruder increased from 3.582 x 10^{-6} to 3.9876 x 10^{-6} m^3/s as the moisture content increased from 14 per cent to 16 per cent and then declined to 3.5104 x 10^{-6} m^3/s for further increase in moisture content. When the screw speed was changed from 100 to 200 rpm the volumetric flow rate increased linearly from 2.4086 x 10^{-6} to 5.136 x 10^{-6} m^3/s. Theoretical volumetric flow rates were calculated using developed equations and their values were compared with experimentally determined flow rates.

ix) The specific energy consumption decreased from a mean value of 128.214 to 99.520 kJ/kg with increase in moisture content from 14 to 18 per cent. When the process temperature increased from 100 to 120°C the specific energy consumption decreased from a mean value of 128.762 to 100.982 kJ/kg. The specific energy consumption increased from 111.28 to 117.32 kJ/kg for the increase in screw speed from 100 to 200 rpm.

x) The flow behaviour index for the cassava dough ranged from 0.17 to 0.75, whereas the consistency coefficient ranged from 871.231 to 100130.44 Pa S^n. The flow behaviour index less than unity indicates that the dough is pseudo-plastic. The overall viscosity ranged from 763.97 to 4810.64 Pa.s.

xi) The specific pressure inside the barrel of the extruder had decreased from 2.17 to 1.60 MPa when the extrusion temperature increased from 100 to 120°C and when the screw speed varied from 100 to 200 rpm the specific pressure decreased from 2.3 to 1.9 MPa.

xii) The overall expansion ratio decreased from 2.8486 to 2.1676 for the increase of moisture content from 14 to 18 per cent (d.b). As the temperature increased from 100 to 120°C, higher overall expansion ratios of 2.4705 and 2.5448 were obtained. Increase in screw speed from 100 to 200 rpm decreased the overall expansion ratio from 2.6063 to 2.3959.

xiii) The bulk density of cassava extrudate increased with increase in moisture content from 14 to 18 per cent (d.b), decreased from 223.508 to 210.877 kg/m^3 when temperature increased from 100 to 120°C and the increase in screw speed from 100 to 200 rpm lowered the average bulk density from 226.529 to 201.314 kg/m^3.

xiv) Increase in the moisture content of the cassava has decreased the overall porosity from 68.67 to 60.06 per cent and increased from 62.947 to 65.443 per cent when temperature increased from 100 to 200°C. When the screw speed was increased from 100 to 200 rpm the overall porosity of the extrudate decreased from 64.72 to 63.74 per cent.

xv) The expansion ratio and bulk density of the extrudate had a negative relationship. Porosity and expansion ratio had a positive relationship.

xvi) As the flour moisture was increased from 14 to 18 per cent (d.b) the water absorption index of the extrudate also increased from 2.47 to 3.90 g of gel/g of sample. But it decreased from 3.318 to 3.0467 g of gel/g of sample when the temperature was increased from 100 to 120°C. Increase in screw speed from 100 to 200 rpm lowered overall water absorption index from 3.5178 to 3.02050 g of gel/g of sample.

xvii) Increase in moisture content of the flour from 14 to 18 per cent (d.b) decreased the average water solubility index. It had increased from 42.53 to 44.16 per cent when the barrel temperature was increased from 100 to 120°C. The water solubility index had increased from 42.58 to 45.81 per cent when the screw speed was increased from 100 to 150 rpm then it decreased for further increase in screw speed.

xviii) Increase in the moisture content of the feed material from 14 to 18 per cent (d.b) increased the shear strength of the extrudate from 2.13 to 2.87 kg/cm², compressive strength from 4.03 to 4.95 kg/cm² and tensile strength from 0.76 to 1.677 kg/cm². Increase in temperature from 100 to 120°C decreased the shear strength of the product from 2.69 to 2.38 kg/cm², compressive strength from 4.88 to 4.03 kg/cm² and tensile strength from 0.98 to 1.53 kg/cm². Increasing screw speed from 100 to 200 rpm reduced the shear strength from 2.61 to 2.41 kg/cm² and tensile strength from 1.42 to 1.21 kg/cm² but increased the compressive strength from 4.37 to 4.57 kg/cm².

xix) The extrudate samples obtained at 16 per cent(d.b) 110°C and 100 rpm of moisture content, barrel temperature and screw speed, respectively was rated as excellent and exhibited a good marketable potentiality.

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APPENDICES

APPENDIX - A

article size distribution of cassava flour

SS Mesh o.	Average opening Di,mm	Di3	Weight of fraction g Øi	Øi /Di3 g/mm3	Øi/Di g/mm	ØiDi	Ni $=\frac{1}{a\rho} \cdot \frac{\phi_i}{D_i^3}$	NiDi
60	0.600	0.8434	0.0008	0.00095	0.0013	0.00048	3.1013	1.8608
40	0.425	0.7518	0.0033	0.00440	0.0078	0.00014	18.0620	7.6760
30	0.300	0.6694	0.0119	0.01780	0.0340	0.00360	79.0850	23.7260
20	0.212	0.5963	0.5251	0.80860	2.4790	0.11130	5766.2200	1222.4400
15	0.140	0.5192	0.2463	0.47440	1.7593	0.03450	1098.1480	153.7400
10	0.106	0.4733	0.1606	0.33930	1.5151	0.01700	785.4170	83.2540
8	0.075	0.4270	0.0241	0.05710	0.3213	0.00181	747.3530	56.0520
6	0.053	0.3756	0.0221	0.05880	0.4170	0.00120	969.9540	51.4088
an			0.0058					

hape constant, $a = 0.90$

article density, $p = 0.00048$ g/mm^3

APPENDIX B

Experimental levels for different trials

Trial No.	Moisture Content %,db.	Temperature •C	Screw speed rpm	Trial No.	Moisture Content %,db.	Temperature •C	Screw speed rpm
1.	14	100	100*	25.		120	100*
2.			150	26.			150
3.			200	27.			200
4.		110	100	28.	17	100	100
5.			150	29.			150
6.			200	30.			200
7.		120	100	31.		110	100*
8.			150	32.			150
9.			200	33.			200
10.	15	100	100	34.		120	100
11.			150	35.			150
12.			200	36.			200
13.		110	100	37.	18	100	100
14.			150	38.			150*
15.			200	39.			200
16.		120	100	40.		110	100
17.			150	41.			150
18.			200*	42.			200
19.	16	100	100	43.		120	100
20.			150	44.			150
21.			200	45.			200
22.		110	100**				
23.			150				
24.			200				

* Samples selected for sensory evaluation

** Most acceptable product

APPENDIX C

Effect of extrusion variables on pressure requirement, flow behaviour index, consistency coefficeint and apparent viscoity

Moisture Content %,db.	Temperature °C	Screw speed rpm	Pressure Pa	Flow behaviour index n	Consistency coefficient k PaS^n	Apparent viscoity μd Pa s
14	100	100	3384641.4	0.18	100130.44	4504.77
		150	3762813.3			3055.24
		200	3628479.0			1944.14
	110	100	3432345.0	0.21	61600.431	3202.19
		150	3040077.0			2178.31
		200	3412028.6			1522.69
	120	100	1480855.4	0.17	34761.653	1381.04
		150	1447147.1			944.30
		200	1176804.0			649.75
15	100	100	686469.0	0.27	18810.761	1151.58
		150	1176804.0			946.46
		200	2843943.0			586.72
	110	100	1863273.0	0.34	17448.045	1556.18
		150	1863428.2			1102.17
		200	1282368.0			858.94
	120	100	228040.9	0.61	996.251	266.22
		150	4903350.0			219.08
		200	294179.70			188.34

APPENDIX C(contd..)

16	100	100	1885874.0			2199.40
		150	1189906.0	0.75	5311.9174	1915.50
		200	1036364.8			2217.99
	110	100	2215708.7			4274.40
		150	1667295.8	0.60	17680.261	3466.71
		200	1863273.0			3039.87
	120	100	4413015.0			9273.01
		150	3628479.0	0.50	12634.120	8628.45
		200	980670.0			8280.44
17	100	100	2059407.0			6717.36
		150	1974752.5	0.71	7851.29	6450.97
		200	1947657.9			6277.58
	110	100	2235180.8			342.11
		150	2451956.0	0.19	871.231	307.38
		200	2306814.5			285.88
	120	100	205940.0			11000.60
		150	2255541.0	0.43	96913.87	8463.09
		200	1372938.0			11245.79
18	100	100	3392443.8			4748.31
		150	3628479.0	0.38	54770.074	3364.67
		200	3806384.6			2527.81
	110	100	3530412.0			1164.80
		150	1756206.0	0.40	12435.95	909.33
		200	1372938.0			664.19
	120	100	1471005.0			1013.53
		150	1863273.0	0.25	19917.76	656.86
		200	882603.0			450.71

APPENDIX D

Physical and functional properties of cassava extrudates as affected by extrusion parameters

Moisture Content %,db.	Temperature °C	Screw speed rpm	Expansion ratio	Bulk density kg/m^3	Porosity %	Water absorption index	Water solubility index
14	100	100	2.9577	205.447	67.387	3.016	44.963
		150	2.8407	194.651	66.637	2.424	48.230
		200	2.6863	181.277	66.057	2.451	44.040
	110	100	2.9313	197.388	68.533	2.752	45.750
		150	2.8463	184.666	67.830	2.329	49.037
		200	2.7417	172.234	67.283	2.330	44.927
	120	100	2.9413	189.208	69.340	2.637	46.560
		150	2.9387	176.736	68.623	2.154	49.867
		200	2.7530	166.178	68.053	2.159	45.720
15	100	100	2.7447	208.249	65.833	3.348	43.450
		150	2.6527	197.093	65.367	2.818	47.610
		200	2.5087	185.499	64.830	2.826	42.493
	110	100	2.7737	200.427	66.870	3.156	44.423
		150	2.6577	188.458	66.407	2.634	48.267
		200	2.5333	177.362	65.497	2.648	43.327
	120	100	2.8107	192.251	67.923	3.014	45.340
		150	2.7457	179.686	67.307	2.459	49.270
		200	2.5953	167.967	66.543	2.471	44.143

APPENDIX D(contd...)

16	100	100	2.5677	220.085	63.443	3.675	41.817
		150	2.4603	209.353	62.787	3.125	44.747
		200	2.3533	196.178	62.060	3.148	40.720
	110	100	2.6133	215.953	64.823	3.551	42.637
		150	2.5320	200.457	63.957	3.012	45.630
		200	2.4617	180.221	63.290	3.030	41.603
	120	100	2.6403	204.438	65.873	3.472	43.277
		150	2.5630	190.910	65.293	3.309	46.297
		200	2.4440	179.318	64.527	2.998	42.397
17	100	100	2.4050	250.340	61.723	4.007	40.150
		150	2.3123	237.750	61.070	3.452	43.220
		200	2.1850	217.642	60.510	3.474	39.357
	110	100	2.4350	242.749	62.843	3.870	40.953
		150	2.3563	229.738	63.253	3.333	44.177
		200	2.2587	218.459	64.050	3.355	39.410
	120	100	2.4697	234.509	64.030	3.733	41.530
		150	2.3933	222.583	64.667	3.155	44.577
		200	2.2563	212.096	65.340	3.146	40.627
18	100	100	2.2313	295.238	59.417	4.343	38.530
		150	2.1380	282.118	58.760	3.823	41.187
		200	2.0133	271.702	58.327	3.854	37.403
	110	100	2.2613	281.032	60.707	4.180	39.277
		150	2.1917	268.558	60.027	3.939	41.960
		200	2.0520	256.320	59.183	3.964	38.360
	120	100	2.3113	260.612	62.090	4.013	40.157
		150	2.2133	248.410	61.370	3.460	43.143
		200	2.0957	237.250	60.670	3.521	39.430