FLOW CHARACTERISTICS OF RABRI

THESIS SUBMITTED TO THE
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(DAIRY ENGINEERING)

BY
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Bikram Kumar

DATED: 5 Dec., 2003

(Bikram Kumar)
MAJOR ADVISOR & GUIDE

सारांश

अधिक लाभांश व अधिक सामान्य अवधि पर सुरक्षित रहने के कारण भारत में एक महत्वपूर्ण मात्रा में दूध को पारंपरिक दूग्ध पदार्थ के लिये भेजा जाता है। अन्तर्राष्ट्रीय बाजार के खुल जाने के कारण, इन उत्पादों को निर्यात की बहुत सम्भावनायें उपलब्ध है। साफतौर पर, उत्पादो की गुणवता की बढ़ोतरी के लिए अन्तर्राष्ट्रीय खाद्य पदार्थो के मानकों को सन्तुष्ट कराने का उत्तरदायित्व संगठित क्षेत्र पर है। इसके लिए, संगठित डेरीयों को उत्पादन की निम्नतम लागत के साथ मशीनरीकरण व उत्पादन बढ़ाना है।

रबड़ी एक उष्मा से वाष्पित गाढ़े दूध का मीठा, हल्का पीले से कैरेमल रंग का पदार्थ है। इसमें फटी हुई दूध की मलाई की कई सतह होती है। आज तक, रबड़ी के अधिक मात्रा में उत्पादन के मशीनरीकरण की सहायता के लिये यन्त्र विज्ञान के विभन्न मापदण्डों में बदलाव के अध्ययन के प्रयास नही किये गये है। इस अध्ययन का मुख्य लक्ष्य, यन्त्र विज्ञान की रचना सम्बन्धित सूचना प्रदान करना था।

परीक्षण, दो उपकरणों पर लिये गये। घनीभूतीत दूध (15-45 प्रतिशत ठोस पदार्थ) बहाने की विशिष्टताओ को जानने के लिये कैपीलरी विस्कोमीटर का उपयोग किया गया और 50 से 65 प्रतिशत ठोस पदार्थ के रबड़ी के जलमिश्रित नमूनो के लिये टैक्सचर एनालाईजर (वापसी निचोड़ विधि के लिये), का उपयोग किया गया/अतः परिणामों से हम यह निष्कर्ष निकाल सकते है कि अध्ययन में प्रयोग किये तरल पदार्थ ने खींच वाले पतले होने वाले गुण (सयूडो पलास्टिक प्राकृत वाले) 15 से 65 प्रतिशत ठोस पदार्थ तक दिखाये जैसे कि बहने के व्यवहार के संकेतक (न) 15 प्रतिशत ठोस पदार्थ व अधिक तापमान (60-90 सैटीग्रेड) पर एक के बराबर था और उसके बाद तापमान की सभी स्तिथियों (और धनी भूतिकरण (15-65 प्रतिशत ठोस पदार्थ) पर एक से कम रहा। बहने के व्यवहार के संकेतक (न), किसी भी धनी भूतण (15 से 65 प्रतिशत ठोस पदार्थ) तापमान बढ़ने के साथ बढ़ गया। किन्तु (न) मूल्यांक, किसी एक स्थिर तापमान पर, धनीभूतण बढ़ने के साथ, कम हो गया। दृढ़ता गुणांक (म) दूसरी तरफ किसी दिये कुछ ठोस पदार्थ के धनीभूतण पर तापमान बढ़ने के साथ कम होता गया परन्तु इसके विपरीत, दृढ़ता गुणांक किसी स्थित तापमान पर, धनीभूतण बढ़ने पर बढ़ता गया। परिणामों ने फटी हुई मलाई की सतह का मीठे गाढ़े दूध का अनुपात 0.53 से 99 प्रतिशत (भार/भार) दिखाया। साफतौर पर यह करनाल के बाजार में उपलब्ध रबड़ी में बहुत अन्तर के होने को दर्शाता है अतः रबड़ी के लिये मानक बनाने की तुरंत आवश्यकता है।

ABSTRACT

A significant amount of milk in India is diverted for traditional milk products because of their higher profit margin & longer shelf life. With opening up of International markets, there exists a great potential to export these products. Clearly, the onus is on organized sector to increase the quality of products to satisfy the international food standards. For this, organized dairies have to mechanize & scale-up the process with minimum cost of production.

Rabri is a heat desiccated thickened milk sweet, pale yellow to light caramel in colour. It contains several layers of clotted cream. Till date, no efforts were made to study the variations in engineering parameters, to help mechanize large scale production system for rabri. The overall objective of study was to provide engineering design information.

The trials were carried out in two instruments. Capillary viscometer was used to find flow characteristics of condensed milk (of 15 to 45 %T.S.) and Texture Analyzer (for back extrusion method) was used for diluted *rabri* samples of 50 to 65 %T.S. Thus from the results we can conclude that the fluid under study showed shear thinning properties (pseudoplastic nature) from 15 to 65 %T.S. i.e. value of flow behaviour index (n) was equal to one at 15 %T.S. at higher temperatures (60-90 ^{o}C) and there after remained below one at all the conditions of temperature (20-90 ^{o}C) and concentration (15-65 %T.S.). The flow behaviour index (n) increased with rise in temperature at any given total solids concentration (from 15-65 % T.S.) however, 'n' value decreased with rise in concentration at any constant temperature. The consistency coefficient (m) on the other hand decreased with rise in temperature at any given total solids concentration but on the contrary, consistency coefficient increased with rise in concentration at any constant temperature. The results also showed, the clotted cream layer to sweetened condensed milk ratio of 0.53 to 99 %(wt./wt.). Clearly indicating existence of great variation in the Rabri available in the markets of Karnal. Hence, there is urgent need for formulation of standards for rabri.

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LIST OF ABBREVIATIONS

%=percentage

π= 22/7 = 3.14

ψ= angle between cone and plate

φ= dimensionless flowrate

λ= dimensionless radius

μ= viscosity

α=model parameter

μ_I=viscosity at infinite shear rate

τ_m=model parameter shear stress

μ_o=viscosity at zero shear rate

ΔP= applied pressure

τ_{rs}=shear stress for tube flow

* = Multiplication operator sign

A= Area

a= plunger radius

cm= centimeter

D= diameter of pipe

du/dy=shear rate

dv/dr= radial shear rate

F= Shear force

F_{cb}= Resedual buoyancy force (corrected)

F_t= Total force immediately before plunger is stopped

F_{te}= Equillibrium force after the plunger is stopped

I.D.= internal diameter

k= ratio of inner to outer radius

Kg_f/m^2= Kilogram force per sq. meter

$Kg_f sec^n/m^2$= Kilogram force.second per sq. meter

L= length of pipe

m=consistency coefficient $Kg_f sec^n/m^2$

Min=minute/s

mm= millimeter

N= revolutions per minute

n=flow behaviour index

Q= flow rate

R= outer radius

r= variable distance from center of pipe

s^{-1}=per second

sec= second

T.S.=Total solids

T= torque

u= linear velocity

Vp= plunger velocities

W_I =angular velocity

wt.= weight (grams/kilograms)

X= multiplication operator sign

1. INTRODUCTION

1.1 GENERAL

A significant amount of milk is diverted for preparing traditional products. This conversion of milk into indigenous milk products not only extends the shelf life at ambient temperature but also adds to nutritional value and makes it more profitable than selling fluid milk. In spite of the fact that the dairy industry has made rapid strides in last five decades, the method of manufacture of traditional Indian dairy products has remained essentially unchanged.

Being in the hands of *halwais*, the traditional Indian dairy products are rarely taken seriously for process mechanization. The increasing demand of these sweetmeats internationally presents a great opportunity for organized sector to mechanize and scale up the production. For this purpose mechanization and upgradation of equipment-based technology for large-scale production is the ultimate need of the hour. Upgradation of technology should ensure safety, wholesomeness of product with certain degree of homogeneity in the quality of the product. Hence, disparity in chemical composition, taste, and textural properties of product, can be diminished to the great extent.

Keeping in view importance of traditional Indian dairy products and limitations associated with existing techniques of manufacturing, National Commission on Agriculture in 1976 recommended production in organized sector. It also suggested standardizing techniques of production of various traditional Indian dairy products and exploring the possibility of large-scale production by improving their keeping quality and packaging with minimal expense.

The dairy scientists and milk processors have made significant strides in recent years for improving the existing technologies of traditional Indian dairy products. Currently some organized dairies are already handling some of these products namely-ghee, dahi, shrikhand, gulabjamun. However, *rabri* has not received adequate attention of the researchers.

Rabri is a heat desiccated thickened milk sweets pale yellow to light caramel color and flavor (Bandyopadhyey & Mathur, 1987). It contains several layers of clotted cream (De, 1980). It is made generally in the winter. Procedure being intricate in nature, a few *halwais* make *rabri*, and hence the cost of the product is generally higher than all other sweets of similar composition.

No efforts have been made to study the variations in engineering parameters viz. thermophysical parameters and rheological parameters to design the suitable system for large-scale continuous production to cater for domestic and foreign market. It is not possible to work under hygienic conditions as long as the production lies in the hands of unorganized sector.

Rheological properties of *rabri* are essential in estimating various engineering quantities such as heat transfer coefficient, evaporation rates, and pumping and heating requirements. Therefore, an attempt has been made through this dissertation work to study the flow behaviour of *rabri* at various stages of production.

Design problems related to non-Newtonian fluids flowing in tubes are common in food engineering. Typically, these fluids flow under laminar conditions and exhibit pseudoplastic or shear-thinning behaviour. Calculations to determine system drop requires experimental data to account for frictional losses occurring in valves, fittings; however this type of data have not been available for pseudoplastic fluids in laminar flow. The overall goal of this study is to provide engineering design information.

1.2 OBJECTIVES

The specific objectives under the investigation are:

1. To characterize the flow behaviour parameters of rabri for in-line production i.e. to determine the consistency coefficient and flow behaviour index of *rabri* at different temperatures and at different stages of processing.
2. To determine the weight by weight ratio of the sweetened condensed milk and clotted cream layer of the *rabri* available in markets of Karnal.

2. REVIEW OF LITERATURE

Rabri production in India is characterized by an unorganized nature of business mainly a cottage industry. Recently the organized dairy sector has realized the potential of *rabri* as an economically viable product. In spite of its high economic importance as a Traditional Indian Dairy Products, *rabri* has not received the attention it richly deserved from research workers. Studies have been reported on production techniques but no work until now is carried out to investigate flow and thermal characteristics of *rabri*, which is very useful for development of equipment for manufacture of *rabri*. Since not much published information is available on *rabri*, this chapter, therefore, deals with the literature pertaining to dairy products similar to *rabri* in chemical composition and method of manufacture such as clotted cream. The available information related to proposed project has been classified and reviewed under the following sub headings:

2.1 Rabri,

2.2 Clotted cream,

2.3 Rheology of food products.

2.1 RABRI

Rabri is essentially a clotted cream, skimmed off from evaporating milk and sweetened lastly (Srinivasan & Anantakrishnan 1964). According to De (1980), *rabri* is the sweetened indigenous milk product synonymous of clotted cream, a western dairy product.

Based on sensory evaluation of most selling *rabri* samples, collected from Delhi and Karnal market, Gayen and Pal (1991a,b) characterized the desirable attributes of *rabri*. The body and texture characteristics are important consideration in assessing sensory quality of rabri. The samples having hard layers of malai (clotted cream) along with some liquid portion is the important feature of the product. Rabri should have slightly cooked aroma and pleasant sweet creamy taste. The colour should be light yellow to white with slight tinge of browning.

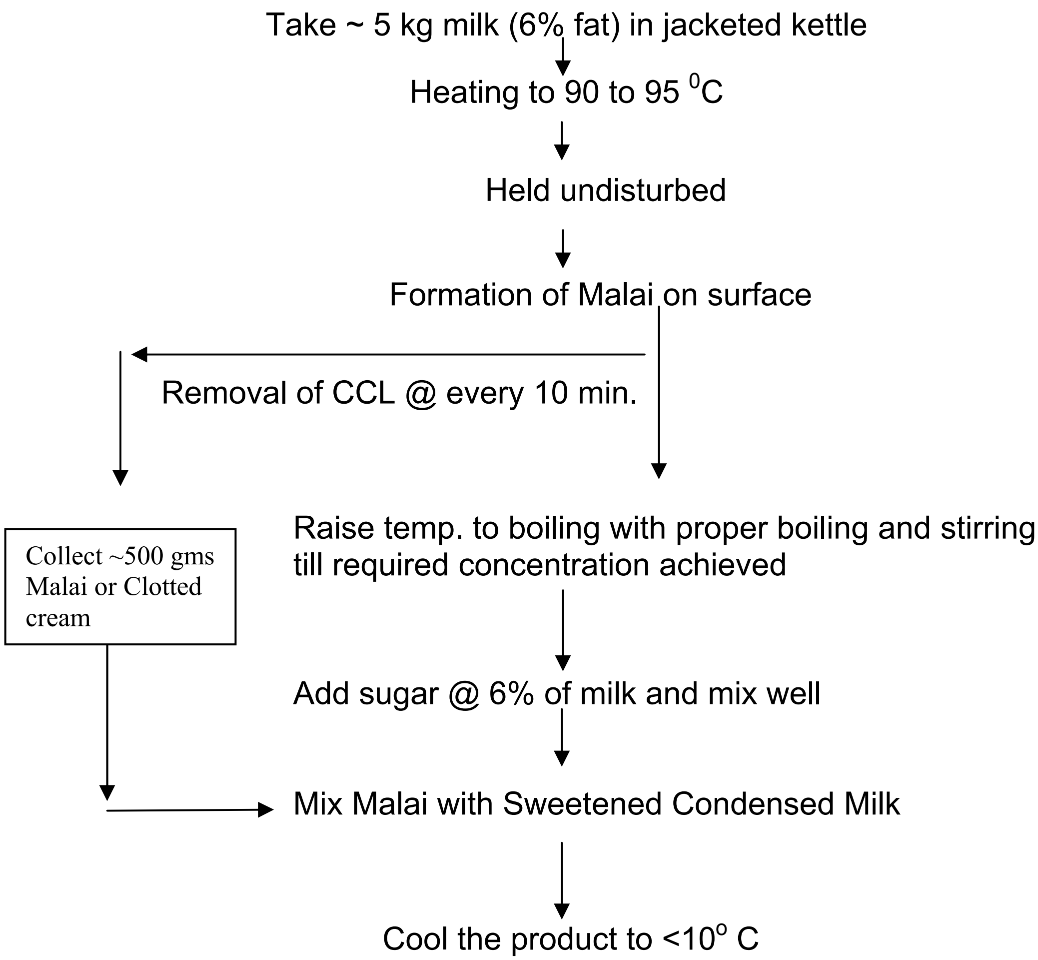
2.1.1. METHOD OF PRODUCTION

Rangappa and Acharya (1971) reported that during its preparation, milk is not stirred and the solids are separated from the milk by peeling off thin films of coagulated material successively from the surface using bamboo splints. These skins are laid aside on the cooler parts of the pan. When the milk has been reduced to about one-fifth to one-eighth of its initial volume, the pan is removed from the fire and the whole mass is gently mixed without injuring the flakes. Sugar is then added and the product allowed to cool. Srinivasan and Anantakrishnan (1964) reported similar method. They mentioned that if stirring was not done the product would have non-homogenous flakes of fat-rich milk solids floating in the milk sugar syrup. Bandyopadhyey and Mathur (1987) indicated that in the existing technology of rabri manufacture, buffalo milk is simmered in a shallow vessel with frequent scraping of the bottom. As some clots begin to appear, sugar is added and stirring continued until desirable plastic consistency is attained. None of the workers has, however mentioned about the optimum percentage of fat in milk, sugar requirement, packaging, and shelf life of rabri.

Gayen and Pal (1991,b) undertook a systemic study to standardize the method of rabri making based on market survey. They characterized the different desirable chemical and sensory attributes and subsequently attempted to simulate the same in the product while standardizing the method. For this they took 5 liters of buffalo milk in a steam jacketed stainless steel kettle. Milk was heated up to 90-95 ^{0}C and held undisturbed at this temperature. The malai (clotted cream) formed on the surface of milk was removed in a separate container after every 10 min. After removing about 500 gm of malai (clotted cream), the temperature of milk raised to boiling. When the required concentration was achieved, a predetermined level of sugar was added and mixed well.

Subsequently, malai (clotted cream) was mixed to this sweetened concentrated milk and the final product cooled to 10°C temperature.

METHOD OF PREPARATION OF RABRI



[Gayen & Pal, 1991]

They recommended that buffalo milk having 6% fat & 9.5 % SNF, its concentration to 3-fold after removal of malai (clotted cream) and addition of sugar @ 6% of initial milk quantity were the optimum processing conditions for production of most acceptable rabri.

2.1.2. COMPOSITION

The gross chemical composition of rabri reported by different workers is given in Table 2.1. PFA and BIS have not recommended any standards for rabri.

2.2 CLOTTED CREAM

Indian malai is nothing but synonymous of clotted cream. In western countries, clotted cream is also called as *'scalded cream'*. In Yugoslavia it is named as '*Kajmak*', whereas in Mongolia it is called as *'Cram'*. Clotted cream is the most important and desirable constituent of *rabri*.

2.2.1 DEFINITION

Clotted cream is moderately thick and has a soft granular texture and an pleasent characteristic nutty flavour. It has a high fat content usually over 55 % and is rich in SNF and vitamins (Chapman, 1953).

2. 2. 2 METHODS OF PRODUCTION OF CLOTTED CREAM

Different workers (Chapman, 1953; Maddever, 1962 and Towler, 1982) for the manufacture of clotted cream have suggested different methods. Some of them have been elaborated as follows:

Table 2.1 CHEMICAL COMPOSITION OF RABRI

CONSTITUENTS (by % weight)	Srinivasan & Anantkrishnan (1964)	Bandyopadhyay & Mathur (1987)	Gayan & Pal (1991 a,b)		
			Lab Sample	Delhi Sample	Karnal Sample
Moisture	30	35	49.2	-	-
Total Solids	-	-	55.29	55.29	49.84
Fat	20	20	16.10	16.64	12.90
Protein	10	13	10.01	-	-
Lactose	17	16	11.8	12.24	11.48
Sugar/Sucrose	20	15	11.9	11.83	12.29
Ash	3	3.5	1.99	-	-

(-) not reported

2.2.2.1. Farmhouse method

In this method of making clotted cream, warm milk from each milking was placed in tin or earthen pans each holding 45.5 to 54.5 liters. It was left to stand for 12 hrs. The pans were then placed on a broad iron plate, heated over fire and the contents exposed to gentle heat. When the body of cream had formed on the surface, the pans were cooled and the cream was removed. The heating process induced rapid fat rise and the fat agglomerated on the surface (Chapman, 1953).

2.2.2.2 Setting or gravitation methods

In this method, fresh whole milk was strained into setting pans followed by holding undisturbed in a cool place (15 ^{o}C) until the cream had risen. Setting time varied from 2-24 hrs, according to the richness of the milk and the season of the year. After the cream had risen, the scalding process was begun. The maximum temperature ranged between 76.6 to 90.5 ^{o}C and the length of time in which the scalding temperature was attained varied from 25 to 50 min (Maddever, 1962). Richer milk required less holding time for fat rise than compared to low fat milk.

2.2.2.3 Mechanical separation method

In mechanical separation method, use of centrifuge facilitates quick removal of cream & eliminates the setting time. According to Chapmen (1953) this method is popular as it reduces the risk of souring in hot weather. Separated milk is poured into the setting pans and the cream is poured very carefully onto the surface of the separated milk (two parts cream to one part separated milk). The scalding process and subsequent treatment is the same as that for the settling system.

2.2.2.4 Direct scald method

An alternative method of dealing with separated cream is to put it in shallow (4.5 inch) containers without any separated milk and carry out the scald directly on the cream. The cream is heated to 90-95 ^{O}C for about 50 min. The addition of 1/4th tea-spoonful castor sugar to each gallon (4.5 liters) of cream before scalding, helps to improve its flavour. The cream should be stirred two or three times during the first 15 min of the scald. The remainder of the process is carried out in the usual way.

2.2.3 COMPOSITION OF CLOTTED CREAM

The composition of clotted cream depends on the types of milk used and the method employed. Matovic et al. (1981) carried out an experiment for making Kajmak (clotted cream) with milk containing 12.5 % T.S. including 4% fat and 3.2 % protein. Milk temperature was 70, 80 & 90^{0}C, air temperature 60, 70 & 80^{0}C, milk depth 30, 60 & 90 mm, air flow rate 0.5, 1.0 & 1,5 m/sec and duration of experiment 2, 4 & 6 hrs respectively. The yields, based on 17 experiments ranged from 1.15 to 6.87 %

moisture contents from 34.95 to 45.46 % , fat contents from 43.33 to 54.6 % and protein contents ranged from 5.20 to 8.21 %.

Dozet et al. (1983) analyzed the samples of clotted cream produced in the Romanija district of Yugoslavia & made in his laboratory in the Agricultural Faculty of Sarajevo by the farm procedure. The average composition and range of nine samples were as shown in the table 2.2.

Table 2.2 Average composition of Clotted cream.

Constituent	Average Value(% by wt)	Range (% by wt)
Moisture	28.13	25.07-31.50
Fat	61.08	56.25-63.75
Total Protein	7.81	4.24-13.78
Soluble Proteins	2.13	1.34-2.59
Salt	1.788	0.501-3.703
Ash	2.499	1.038-4.564
Phosphorus	0.098	0.075-0.136
Lactic Acid	0.33	0.15-0.57

2.3 RHEOLOGY OF FOOD PRODUCTS

Knowledge of rheological properties of food products is essential for design and evaluation quality control, consumer acceptability and in the estimating various engineering quantities such as heat transfer coefficients, evaporation, and pumping and mixing requirements. The viscosity of a liquid food depends upon composition and temperature, and may depend on the shear rate or shear stress, the duration of shear, as well as previous shear history.

Rheological properties of Newtonian liquids are independent of shear rate and previous shear histories. Newtonian fluids can be classified as time-dependant or time-independent latter. For the latter at a constant temperature the viscosity depends only on the magnitude of shear stress or shear rate if the viscosity decreases. When shear rate is increased, the fluid is a shear thinning or pseudoplastic. If viscosity increases as shear rate increases, the fluid is a shear-thickening fluid.

2.3.1 DIFFERENT RHEOLOGICAL MODELS

Liquid food mostly presents special problems in flow and heat transfer application because of the complexity in their flow behaviour. Since the flow characteristics are dependent on the rheological properties of the liquid vast efforts have been made in the description of their behaviour by proposing different rheological models.

The strict definition of viscosity is the resistance to flow indicated by the coefficient of viscosity as given in the equation:

$$F/A = - \mu \,(du/dy) \qquad \text{………….(2.1)}$$

The proportionality constant μ is defined as the viscosity of the liquid, F/A is the shear stress and du/dy is the corresponding shear rate. This is also known as the Newton's law of viscosity in the food industry, however, the term viscosity is utilized quite broadly as a single parameter to describe the consistency of the product under any given condition. This approach leads to considerable confusion because of the non-Newtonian behaviour of many liquid food products.

The Bingham-plastic model is one in which finite yield stress (τY) is required before a viscous response is obtained. Such a response is described by the equation:

$$\tau = m\,(-du/dy) + \tau Y \qquad \text{..........(2.2)}$$

τ is the shear stress, du/dy is the corresponding shear rate, m is the plastic viscosity, and τY is the yield stress. This represents a two- parameter model. Two-parameter model of the following type:

$$\tau Y = m\,(-du/dy)^n \qquad \text{.........(2.3)}$$

Where m = consistency coefficient and n = flow behaviour index can be used to describe pseudoplastic and dilatant fluids. Pseudoplastic fluids, which exhibit a concave downward curve on the Shear stress-rate of shear axes, are probably the most common of the non-Newtonian fluids. This response implies a shear thinning as will occur with products, which have a lower shear stress as shear rate increases.

A general Power law equation given as follows:

$$\tau = m\,(-du/dy)^n + \tau Y \qquad \text{.........(2.4)}$$

could be utilized to describe fluids which would be called quasi-plastic or mixed types. In this case, the fluids would have either pseudoplastic or dilatant response after an initial yield point is reached .In most cases in the food industry, an attempt is made to measure a Newtonian viscosity regardless of whether the characteristics of the liquid are known. This results in a measurement of an apparent viscosity, which represents the viscosity of a Newtonian liquid exhibiting the same resistance to flow at the chosen rate of shear. In the most common case of a pseudoplastic liquid, the apparent viscosity decreases with increasing shear rate. If the shear stress becomes a function of time somewhat different terms are used to describe the behaviour of the liquid. Although the shear stress will rarely increase with time this type of material is called rheopectic. A behavior, which may occur among food products, is decrease in shear stress with time, this type of liquid being called thixotropic.

A generalized model has been proposed by Bird (1965) involving four parameters:

$$dv/dr=(-1/\mu_o)\mathbf{[}(1+(\tau_{rs}/\tau_m)^{\alpha-1})/(1+(\tau_{rs}/\tau_m)^{\alpha-1}(\mu_i-\mu_o))\mathbf{]}\tau_{rs} \quad .....(2.5)$$

where (dv/dr) is the shear rate (radial), τ_{rs} is the shear stress for tube flow, τ_m is the model parameter shear stress μ_o is the viscosity at zero shear rate, μ_i is the viscosity at infinite shear rate, and α is the model parameter.

2.3.2 RHEOMETERS

A large number of instruments have been utilized to measure viscosity and more generally, the rheological properties of fluid food products. These instruments are of two categories: Capillary tube rheometers or viscometers & Rotational rheometers or viscometers.

(a) Capillary Tube Rheometers

In general, capillary tube rheometers include a variety of instruments all of which force the fluids through a tube of known geometry. For these types of rheometers, the relationship between shear rate and shear stress is obtained from the measurement of pressure gradient and volumetric flow rate through the tube.

The relationship between shear stress and pressure required to force the fluid through a capillary tube is obtained by conducting a force balance on the cross-section of the tube, which leads to the following expressions:

$$\tau = (\Delta Pr/ 2L) \qquad \text{………….(2.6)}$$

In equation (2.6), ΔP is the applied pressure resulting in the movement of liquid through the tube while 'r' is the variable distance from the center of the tube at which the shear stress (τ) results.

The flow of a simple Newtonian fluid through a capillary tube of diameter 'D' and length 'L' is obtained by Poiseuille equation,

$$(D\,\Delta P)/4L = \mu(32\,Q)/(\pi\,D^3) \qquad \text{…………(2.7)}$$

Where, Q is the volumetric flow rate and D is the tube diameter. For a Newtonian fluid $(D*\Delta P)/L$ is equivalent to shear stress and, $(32\ Q)/(\pi\ D^3)$ is equivalent to wall shear rate. Thus the Poiseuille equation is similar to the fundamental equation of Newtonian's viscosity.

For a non-Newtonian fluid obeying power-law equation, the volumetric flow rates for a tube-viscometer could be developed by the integration of the velocity distribution (Heldman 1975).

$$Q = \int_o^R u(r) x 2\pi r dr$$

$$= (\Delta P/2mL)^{1/n} \times (n/(3n+1))R^{(3n+1)/n} \quad \text{........(2.8)}$$

Equation constitutes the basis of tube viscometery of Pseudoplastic fluids. It is a good approximation of the flow through small diameter tube when the following assumptions are made

- A laminar flow has developed a steady state
- The entrance and the exit flow effects are negligible.

These conditions are approximated when the tube diameter is small (usually less than 6 mm) and the length to diameter ratio is high (usually higher than 100)(Rao et al, 1974).

(b) Rotational Rheometers

Rotational rheometers subject the sample to a nearly uniform rate of shear while measuring the shear stress. Physically this is accomplished by measuring the torque required to move the inner cylinder of two coaxial cylinders, at a given number of revolutions per minute. One of the obvious advantages of this particular type of rheometer is that, it allows continuous measurement of the shear stress versus shear rate relationship and would allow the analysis of a time dependent behaviour in the sample.

One extensively used rotational rheometer is the coaxial cylinder rheometer. Heldman (1975) has described this in detail. For a Newtonian fluid, the relationship between shear stress and rate of shear in this type of rheometer is expressed as:

$$\tau = \mu \left(u/r - du/dr \right) \qquad \text{.......(2.9)}$$

Where, u is the linear velocity. The relationship between torque and angular velocity in a coaxial cylinder rheometer is obtained by first determining a relationship from the forces acting on the rotating cylinder. The force balance results in the following equation describing the relationship between torque and shear stress:

$$T = 2 \pi r h \tau_r \qquad \text{..............(2.10)}$$

Where, T is the torque

Utilizing equation (2.10) and the following expression for a Power-law fluid an expression for a pseudoplastic fluid can be developed as:

$$m[(-r)(dw/dr)]^n = m(u/r - du/dr)^n \quad \text{........(2.11)}$$

By equating equations (2.10) and (2.11) and integrating between the radius of inside and outside cylinder the following expression is obtained :

$$W_i = 2\pi N$$

$$= (n/2)(T/2\pi nm)^{1/n}[1/(R_i)^{2/n} - 1/(R_o)^{2/n}] \quad \text{......(2.12)}$$

Where W_i is the angular velocity and N is the r.p.m. at which the inner cylinder is rotating. Again, the rheological parameters m and n can be evaluated from experimental data by plotting log N versus the log T. The resulting slope is the value of flow behaviour index (n) while the value of the consistency coefficient can be determined from the Intercept (Heldman, 1975).

A second type of rotational rheometer is cone and plate rheometer (Heldman, 1975) and it involves direct measurement of shear stress-shear rate relationship. The rheometer consists of a flat plate and a rotating cone forming a very small angle with the plate. Since the cone and plate actually touch at the cone point, the fluid fills the narrow gap formed by the two. The angle between the cone and the plate is usually 2.5 and 3 degrees. The expression for shear stress in this particular case is given by the following equation:

$$\tau = 3T/(2\pi R^3) \qquad \text{..........(2.13)}$$

Where the rate of shear is equal to $W/\tan\Psi$, where Ψ is the angle between cone and plate of the rheometer.

Investigations on the flow properties of fluid foods indicate that the properties vary considerably depending upon the type of product considered. Several fruit juices and corn syrup behave as Newtonian. Products, which have been found to be pseudoplastic, include fruit and vegetable purees. These have been investigated in detail by Harper (1960), Charm (1971), Rao (1974) and Saravaces (1968,1970). The results allow the comparison of the three different rheometers on the same product and in general, results agree.

2.4 FLOW CHARACTERSTICS OF LIQUID FOODS

Bikram et al. (1984) investigated the various aspects of pumping requirements of khoa, flowing through stainless steel pipes. The set-up consisted of two different tubings of diameter 0.0158 m and 0.0266 m respectively. Compressed air was used as a source of pressure. Several trials were performed to determine the effect of pressure drop, flow rate, and temperature on the power requirement and frictional head loss of khoa, in the different stages of processing.

Sawhney (1980) investigated the rheological properties of khoa using the capillary tube viscometer. Capillary tube of 3, 4, and 5 mm diameter and more than 100 times base diameter length were used in the course of experiment. The effect of temperature on rheological parameters of khoa was also studied. Also investigated, was the effect of processing temperatures on the rheological properties of khoa.

Sawhney et al. (1984) investigated the rheological properties of ghee using the capillary tube viscometer. Capillary tube of 2 mm diameter and 355 mm length was used in the course of experiment. The rheological parameters consistency coefficient & flow behaviour index were evaluated utilizing the data obtained from the capillary tube viscometer. The flow properties of ghee were compared with that of hydrogenated vegetable oil and refined groundnut oil.

Sucrose solutions exhibit Newtonian behaviour. Bingham (1922) presented viscosity data of aqueous sucrose solutions as a function of temperature and suggested that they may be used as viscosity standards. Harvey (1953), based on unpublished data, concluded those for sugar solutions the logarithm of the viscosity and the concentration of solids are linearly related. Sucrose is the major carbohydrate in maple and sorghum syrups; for this reason they are also Newtonian fluids (Matz 1962). Harvey (1953) concluded that corn syrup is also a Newtonian liquid but presented no supportive data.

Saravacos (1970) studied the viscosity behaviour of several fruit juices as a function of concentration and temperature.

Newtonian behaviour was observed for depectinized and filtered clear apple Juice over the temperature range 20-70 ^{o}C and at all concentrations between 10 to 75^{0} Brix. Viscosity decreased rapidly as the temperature was increased; the effect of temperature was more pronounced at higher concentrations in contrast, undepectinized and filtered apple juice was Newtonian at 50^{0} Brix and below; at higher concentrations it was a Pseudoplastic fluid. In addition, temperature had a less pronounced effect on the viscosity; however, as in the case of clear apple juice the temperature effect was more pronounced at the higher concentrations. Concord grape juice below 50^{0} Brix and filtered orange juice of 10 and 18^{0} Brix were Newtonian fluids and the effect of temperature on the viscosity was similar to that for depectinized apple juice.

Using a rotational viscometer, Cornford et al. (1969) found raw whole egg and pasteurized whole egg to be Newtonian fluids at 70^{o} F (21^{0}C). Scalzo et al (1970) observed similar behaviour for raw whole egg, stabilized egg white (ph 7), plain yolk, sugared yolk (10% sucrose by wt) and salted yolk (10% salt by wt). The viscosity data were obtained with glass capillary viscometers over the temperature range of 5-60 ^{o}C.

In contrast to these findings, egg white (Tung et al. 1971) and thawed frozen whole egg (Cornford et al. 1969) were found to be non-Newtonian fluids. Concentrated cloudy (undepectinized and filtered) apple juice (50 and 65.5^{0} Brix), Concord grape juice

(64^0 Brix) and commercial orange juice (33 and 44^0 Brix) were found to be pseudoplastic fluids at temperatures between 25 and 70 ^{0}C (Saravacos 1970). Saravacos also computed activation energies of flow using apparent viscosities at shear rate of 100 s^{-1}; as in the case of Newtonian fruit Juices, these were higher when the solids content was higher.

Concentrated orange juice has been the subject of many studies. Using a Brookfield viscometer, Ezell (1959) found that commercial concentrated orange juices exhibit pseudoplastic and time-dependent flow behaviour. It was also shown that the apparent viscosity increased with an increase in the pulp content. Berk (1964) showed that the viscosity of 60^o Brix orange juice decreased markedly when subjected to ultrasonic waves (20,000 Hz); e.g., after a treatment of 15 min the viscosity was reduced to 25% of the initial value. The reduction in viscosity was attributed to a certain degree of disintegration of the suspended particles.

Mizrahi and Berk (1970) found concentrated orange juice at 60-65^0 Brix to be a pseudoplastic fluid with yield stress; it also showed time-dependent flow behaviour. Structure recovery from low-rate shear (e.g., mixing with a spoon at a low speed) was reversible, but shear at a high rate (15,000 s^{-1}) caused irreversible destruction in part due to disintegration of pulp particles. Concentrated serum was also a pseudoplastic fluid but yield stress and time-dependent behaviour were observed only when the pectin concentration was high. To describe the viscosity behaviour of concentrated orange juice Mizrahi and Berk (1972) developed a rheological equation based on the model of a suspension of interacting particle. In a pseudoplastic solvent Rheological properties of dairy cream have been studied extensively because not only is cream itself consumable, but it is also the starting point for butter. Structurally cream differs from milk because of the higher concentration of fat globules and it differs from concentrated milk because the serum is not concentrated. The amount of fat is one of the most important factors affecting the rheological properties of cream. Except for the loss of a small quantity of high-density particulate matter, cream has essentially the same constituents as milk (Prentice 1972).

The rheological properties of a sample of cream depend upon its origin, method of preparation and history. Increasing the temperature at any stage in the manufacturing process lowers the apparent viscosity. A sudden build up of pressure in the process lines results in a more viscous cream (Prentice 1972). The pseudoplastic nature of cream has been attributed to the tendency of fat globules to form a more ordered arrangement under shear than when cream is at rest Thawed frozen whole egg was found to be a pseudoplastic fluid (Cornford et al 1969). Unmixed egg white was found to exhibit pseudoplastic and time-dependent flow behaviour (Tung et al, 1970). The equilibrium flow data could be described accurately by the power law. A large number of purees of fruits and vegetables are produced commercially; some (such as apple sauce and pear puree) are usually consumed directly, while others (such as tomato puree) are used as intermediate products. In general, purees of fruits and vegetables are pseudoplastic fluids. The consistency of these products is an important quality parameter and often it is measured with a single point Instrument such as the Adams Consistometer, Boat wick Consistometer, Stomer viscometer and the efflux pipette. These instruments have proved to be satisfactory for quality control purposes but are not adequate for research purposes.

The back extrusion method was used to measure flow properties of five commercial *kochujang* samples on texture analyzer. Magnitudes of consistency coefficient (m) of diluted samples increased with increase in percentage total solid with a good linear correlation (R^2 =0.97)(Kim et al., 2000).

The review of the literature clearly shows that no attempts have been made to investigate the engineering parameters of *rabri* as the two-component system viz. sweetened condensed milk and Clotted cream layer.

3. SCOPE

3.1 SCOPE OF THE STUDY

The review of literature in the foregoing chapter reveals that there is not much published information available on *rabri* especially on large-scale production though it is highly popular traditional milk sweet in northern and eastern parts of India. In spite of economic importance of traditional dairy products, these products are still produced manually in small batches. Its manufacture is still confined to certain *halwais.* The small-scale method used for its production can not meet the growing demand of rabri in urban areas. Hence, it is sold at an exorbitant price. In the absence of standard large-scale method for production of rabri, large differences in its sensory, chemical, and microbial quality are likely to occur. At present, no legal standards are available on *rabri.* This situation has necessitated the need for undertaking a research project on the development of method for large-scale production. It is hoped that through this project the new direction will be sought for further development and upgradation of the technology for *rabri* production using the available equipment and processing lines.

The viscometric properties of *rabri* at different temperatures and at different stages of processing are essential in estimating various engineering quantities; such as heat transfer coefficients, evaporation rates and the pumping and mixing requirements. Improvements in the techniques of production is important for development of an indigenous industry, that *rabri* happens to be. Since there is scanty knowledge of basic research data pertaining to flow and thermal characteristics of *rabri*, it has been difficult to make ameliorative efforts to mechanize the process of *rabri* making. The shape and slope of the vessel, and essential component of *rabri* making equipment, the design of which require an exhaustive knowledge of the flow properties of the product. Keeping in view the significance of the proposed research, the present Investigation was undertaken to determine the changes in flow characteristics of *rabri* at different temperatures and stages of processing.

3.2 PLAN OF WORK

It was proposed to study the engineering parameters viz. flow properties of *rabri* in the form of two stages. The two components in which the *rabri* can be classified is

(a) Condensed milk

(b) Diluted rabri

For these both of the components the flow behaviour index and consistency coefficient was determined. From 15% total solids to 45%, total solids the flow characteristics were found in constant temperature capillary viscometer using 2 mm diameter capillary.

For total solids higher than 45% total solids, Back extrusion method was used. The reason for use of Back extrusion technique is that, when constant temperature capillary tube viscometer is used at higher total solids content there is rise in shear stress at walls of capillary resulting in higher values than normal. Higher values will result in the overestimation of pump capacity, which jeopardizes the very basic objective of minimizing the process cost.

3.2.1. CONSTANT TEMPERATURE CAPILLARY TUBE VISCOMETER

3.2.1.1. Experimental set up

A capillary tube viscometer was used that was immersed in the water bath to maintain isothermal conditions. The cover over the equipment was also developed so that the loss of temperature of the water is prevented. The outlet valve of the capillary side was corrected so that the leakage is prevented even at the high temperature and high-pressure conditions.

3.2.1.2. Temperature measurement

Temperatures chosen were 20,30,40,50,60,70,80 and 90 ^{o}C. The temperature observed under the study is taken to the maximum of 90 ^{o}C. As in the production of *rabri*, the agitation is absent. In any case, during production if the temperatures are taken more than the 90 ^{o}C, there will chances of burning where the product is in contact with the heat exchanger.

3.2.1.3. Stages of processing

The total solids in the milk were taken as 15,20,25,30,35,40 and 45%.

3.2.1.4. Air pressure

A set of observations for each sample was recorded at seven different pressures, viz. 0.2, 0.4,0.6,0.8,1.0,1.2 and 1.4 kg_f/cm^2, starting with the highest pressure. Four readings at each pressure and temperature were taken and average flow rate was used to compute the flow characteristics of the sample.

3.2.2. BACK EXTRUSION METHOD

3.2.2.1. Experimental set up

The texture analyzer was used to carry out the back extrusion of *rabri*. Texture analyzer is provided with the special attachment for this testing. A casing is provided on whole of the instrument to maintain the set temperature. This equipment is attached with the computer, which monitors accurate movement of the probe. The penetration velocity and penetration depth values are to be set before the actual test.

3.2.2.2. Temperature measurement

The temperature of measurement was 20 ^{o}C.

3.2.2.3. Velocity of Plunger

Velocity of plungers was kept at four different speeds viz. 1.5 mm/sec, 3 mm/sec, 4.5 mm/sec, and 6 mm/sec.

3.2.2.4. Depth of Plunger in Sample

Depth of plunger in the sample for all the trials was kept constant at 50 mm.

4. MATERIALS AND METHODS

4.1 EXPERIMENTAL SETUP FOR CONSTANT TEMPERATURE CAPILLARY TUBE VISCOMETER

The experimental set-up developed for the determination of the flow characteristics of rabri at various temperatures is shown in the figure 4.1 & 4.2.

It consisted the following:

4.1.1 Constant temperature capillary tube viscometer

4.1.2 Air-pressure regulating system

4.1.3 Temperature regulating system

4.1.4 Accessories

4.1.1. CONSTANT TEMPERATURE CAPILLARY TUBE VISCOMETER

The Capillary tube viscometer consisted of the following components:

a. Sample container

A vertical sanitary type sample container cylindrical in shape and having 2000 cubic centimeters volume made from a 10 cm O.D. stainless

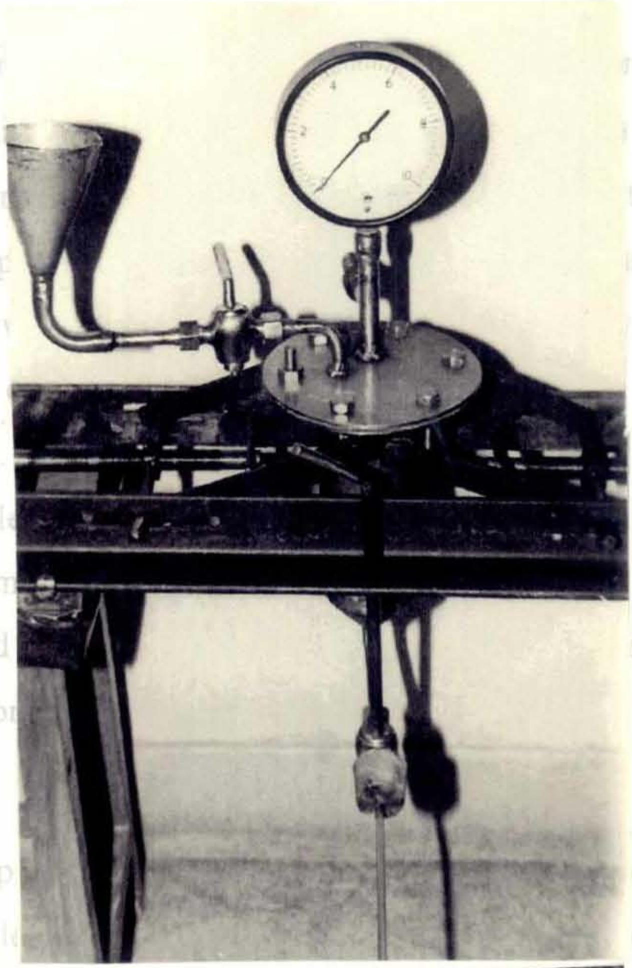


Plate-1:
Sample container with adjustable stand.

Plate-2:
Sample container, capillary tube & sample inlet pipe.

steel tubing was used. The top cover has connections for the sample inlet hopper, air pressure system, and pressure gauge as shown in the fig.4.2. The lower end of the container was provided with the half-inch stainless steel sample outlet valve. Glass capillary tube was attached to the sample outlet valve by a detachable rubber gasket along with the nut so that the capillary does not move out of the whole system at even the higher pressures. This arrangement of the system also helped to get the leakage proof outlet and the correct pressure drop values. Provision for filling the whole sample container is made through a half-inch stainless steel valve connected to the hopper to facilitate easy cleaning. All parts of the sample container were detachable.

b. Glass Capillary Tube

Capillary tube of 2 mm diameter and 34.8 cm length was selected. Here the length of the capillary was taken 100 times the base diameter as recommended by Rao et al (1939), for achieving fully developed laminar flow.

4.1.2 AIR PRESSURE REGULATING SYSTEM

The air pressure regulating system consisted of an air compressor, air pressure regulator, pressure gauge and shut off valve. Air pressure regulator with outlet pressure range up to 10 kg_f/cm^2 was employed. The regulator was installed close to the equipment to minimize the pressure drop between the viscometer and outlet of the air pressure regulator. The pipes and fittings used in the air pressure system were large enough to allow unrestricted airflow.

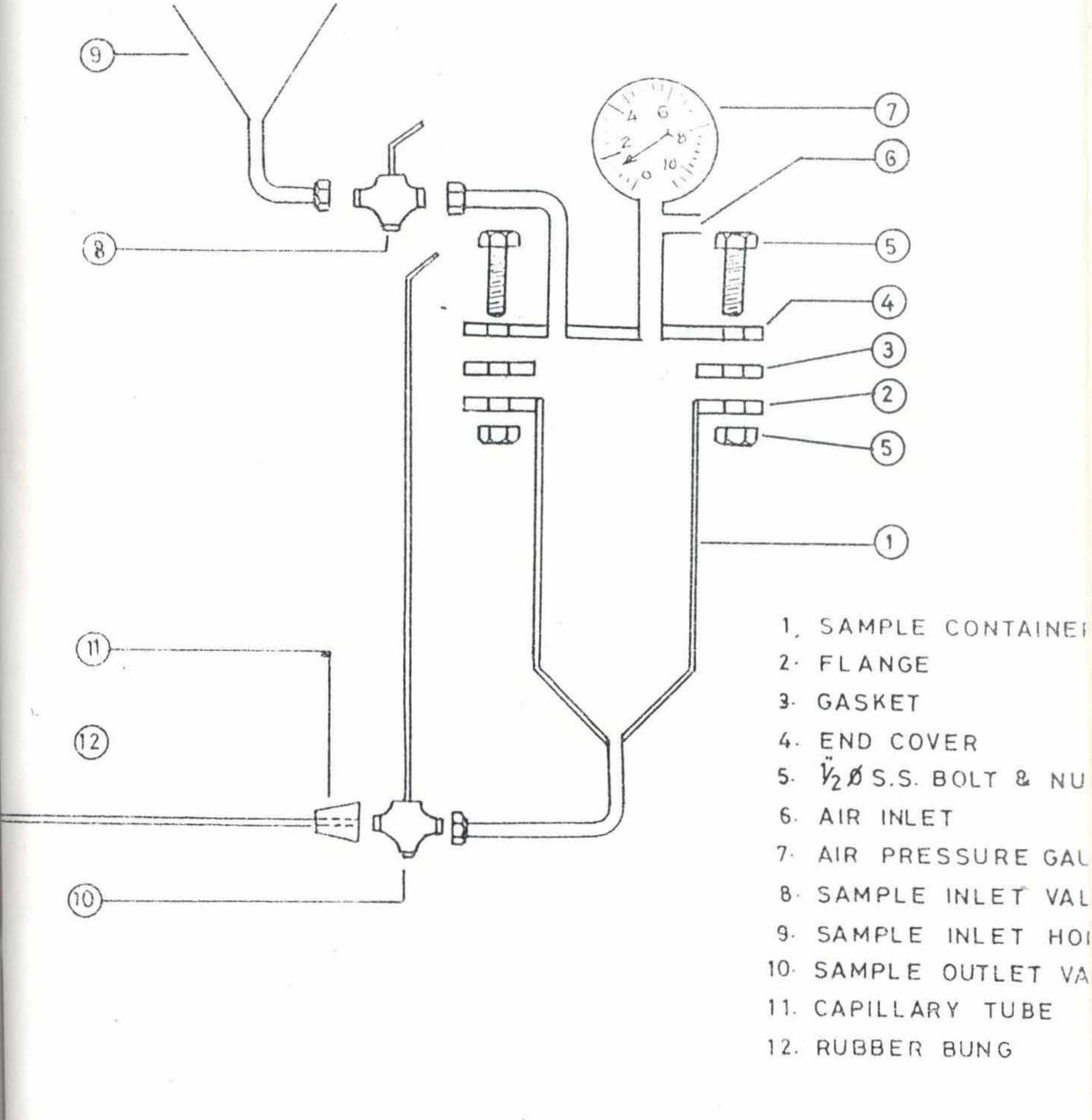


FIG. 4.2. SAMPLE CONTAINER

4.1.3. TEMPERATURE REGULATING SYSTEM

Most of the consistency measurement procedure requires the creation of isothermal conditions during experimentation. This can be achieved if we dip the sample container along with the capillary tube of the viscometer in a constant temperature water-bath. To ensure the uniformity of temperature at all points, the water-bath is provided with a mechanical stirrer.

One such constant temperature water bath with inside dimensions 50 cm × 50 cm × 45 cm and operation up to 300 ^{o}C was selected for the immersion of the sample container and capillary tube, to achieve the isothermal conditions. The tube was fitted with gaskets and lock nuts to prevent seepage of water from the bath into the incubator (fig.4.1).

4.1.4. ACCESSORIES

4.1.4.1. Hot air oven

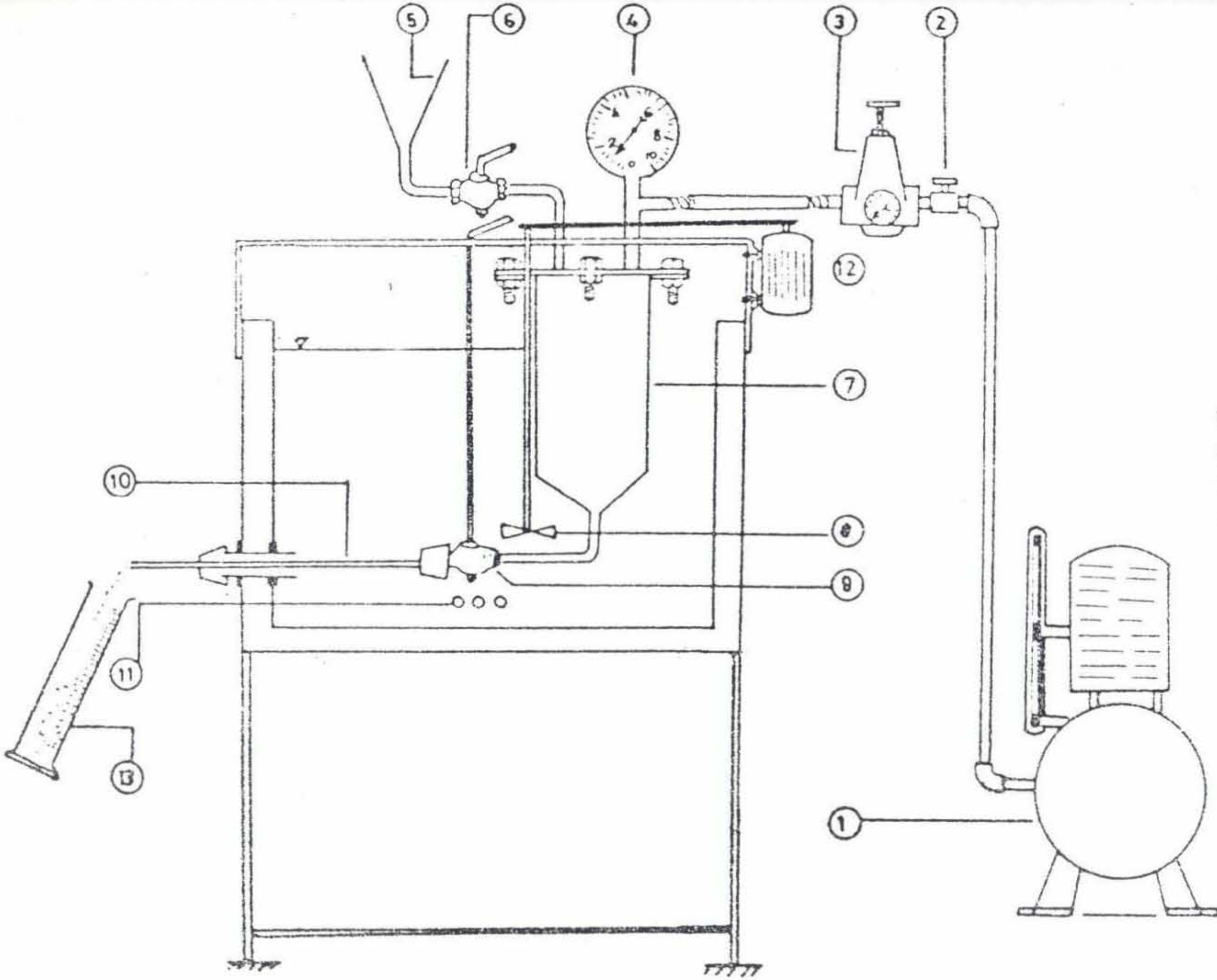
An electric hot air oven with a temperature range of 0^{o}C to 250^{o} C was used to keep the samples for the measurement of moisture contents.

4.1.4.2. Temperature measuring instrument

Mercury in glass thermometer of range 0^{o}C to 150 ^{o}C was used.

4.1.4.3. Stopwatch

Stopwatch of racer make, capable of recording 0.1 sec, was employed to record the duration of the sample flow during the experimentation.



1. AIR COMPRESSOR
2. AIR SHUT-OFF VALVE
3. AIR PRESSURE REGULATOR
4. AIR PRESSURE GAUGE
5. SAMPLE INLET HOPPER
6. SAMPLE INLET VALVE
7. SAMPLE CONTAINER
8. AGITATOR
8. SAMPLE OUTLET VALVE
10. CAPILLARY TUBE
11. ELECTRIC HEATER
12. AGITATOR MOTOR
13. SAMPLE COLLECTOR

FIG. 4.1. EXPERIMENTAL SET UP WITH CONSTANT TEMPERATURE CAPILLARY TUBE VISCOMETER

4.1.5 EXPERIMENTAL PROCEDURE

4.1.5.1. Preparation of the sample

The milk taken from the dairy was standardized for 6% fat and 9% SNF, after which it was concentrated to the desired levels. The desired concentration when reached, the samples were kept in the hot air oven.

4.1.5.2. Operation of viscometer

The constant temperature bath containing the capillary tube viscometer was set at the desired temperature. The sample was heated to desired temperature before pouring down through hopper into sample container. The compressor was started and air pressure was allowed to building up in receiver of air compressor. After opening the outlet valve of the air compressor, air pressure regulator was used to adjust the pressure. The whole set up was allowed to equilibrate for few seconds after which sample outlet valve was opened to allow flow of sample through capillary. The flow rate of the sample was measured.

4.1.5.3. Determination of flow behaviour index and Consistency coefficient

Equation (2.8) for the determination of flow behavior index and consistency coefficient is based on the following assumptions:

- The flow is steady and laminar.
- Liquid flow is independent of time.
- No slippage occours at wall.
- The liquid is incompressible.
- Liquid viscosity is not affected by pressure, and
- Measurement is conducted under isothermal conditions.

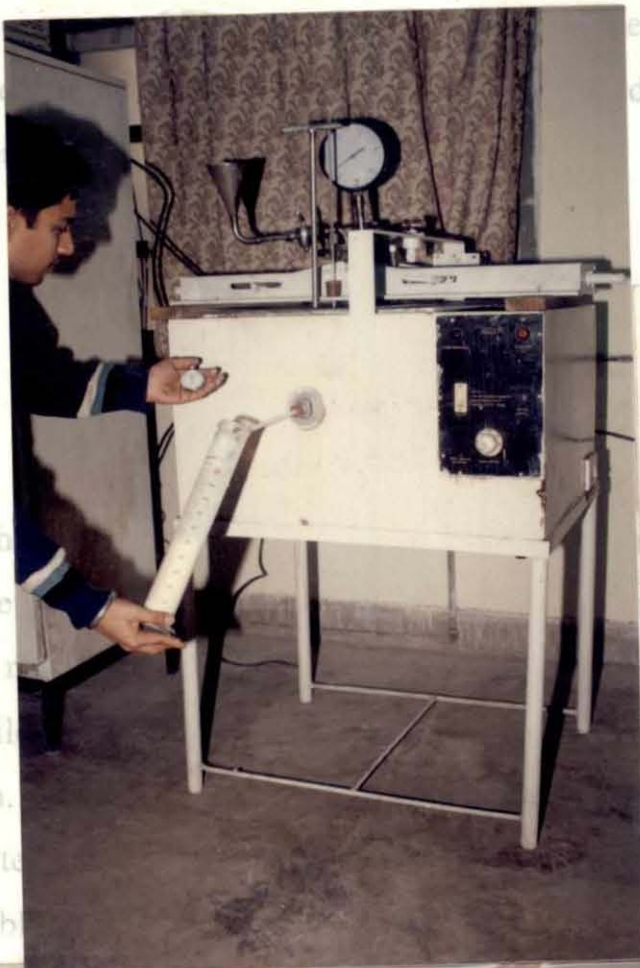


Plate-3: Constant temperature capillary tube viscometer in operation.

Plate-4: Texture analyzer in operation.

Heldman (1975) suggested a method to determine the rheological parameters (m & n), utilizing data obtained from capillary tube viscometer:

$$Q = {}_{o}^{R}\int u(r) \times 2\pi r\, dr$$

$$= (\Delta P / 2mL)^{1/n} \times (n / (3n+1))\, R^{(3n+1)/n} \ldots\ldots\ldots\ldots.(2.8)$$

This was accomplished by plotting the logarithm of the volumetric flow rate (Q) verses the logarithm of (ΔP /2L). The flow behaviour index (n) was measured as the slope of the straight line obtained from log-log plot while the consistency coefficient 'm' was evaluated from the above equation. Capillary tube 2 mm I.D. & 34.8 cm long was used in the viscometer and the following data for the sample of *rabri* at 60 ^{o}C, 25% T.S. (Table 4.1)

This data is used to show a sample calculation for flow parameters.

Rewriting equation (2.8) in the following form :

$$\text{Log}(\Delta P/2L)=[\log m - n\log\pi - n\log(n/(3n+1)) - (3n+1)\log R] + n\log Q \ldots\ldots \quad (4.1)$$

By plotting Log (ΔP /2L) verses log Q as illustrated in the fig.4.3, the value of n can be determined from the slope of resulting capillary flow diagram.

From figure 4.1 slope (= n) = 0.9649

Substituting this value of n in the equation 4.1 at P = $1\text{x}10^4$ kg_f/m^2.

$$\text{Log}\ ((1\times10^4)/(2\ \times0.348)) = [\ \text{logm} - 0.9649\ \log \pi - 0.9649\ \log (0.9649/(3 \times 0.9649+1)) - (3 \times 0.9649+1) \log R\ ] + 0.9649 \log Q$$

Table 4.1 Capillary flow data for *rabri* at 60 °C, 25%T.S.

ΔP $(10^4)(kg_f/m^2)$	$Q(10^{-6})(m^3/\text{sececond})$
0.2	5.34483
0.4	4.80769
0.6	14.2857
0.8	18.0
1.0	19.0
1.2	21.0
1.4	22.0

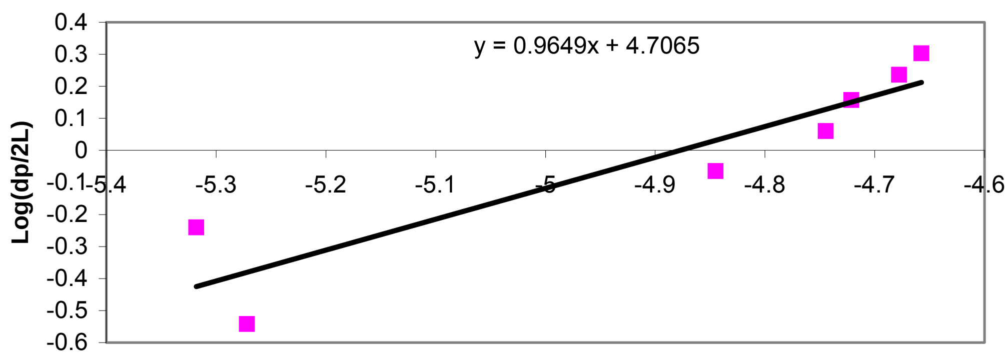


Fig.4.3 Figure shows calculation of slope .i.e. n

Rearranging the value of the consistency coefficient of *rabri* is found to be 83.8667 $kg_f\,sec/m^2$ at 60 °C, 25% T.S.

4.2. EXPERIMENTAL PROCEDURE FOR BACK EXTRUSION

The back extrusion of *rabri* was carried out on the texture analyzer present in the Dairy Technology Division.

4.2.1. PREPARATION OF SAMPLE

The samples of *rabri* were procured from the standard shops of the Karnal market. Diluted *rabri* samples were prepared by diluting a *rabri* samples with distilled water for 50%, 55%, 60% and 65% Total solids. Percent total solids were determined by drying in a dry oven at 105 ^{o}C to a constant weight.

4.2.2. BACK EXTRUSION METHOD

In back extrusion method, two physical methods are involved:

- A cylinder plunger is forced down into a fluid and
- The fluid flows upwards through a concentric annular space as shown in the figure 4.5.

Back extrusion forces were measured by compressing the *rabri* samples in a cylindrical container with a plunger using a Texture analyzer (TA-XT2i, England). 90ml of each sample was placed in a 120 ml graduated cylinder with a radius (R) of 2 inches at 20 ^{o} C and the plunger used had a radius (a) of 25 mm. The cylinder container and the plunger had a k=0.475 (k=a/R). Four different plunger velocities (1.5, 3, 4.5 & 6 mm/sec) were used and the length of the plunger immersed in samples was 25 mm. F_t (total force immediately before the plunger is stopped) and F_{te} (equilibrium force after the plunger is stopped) were determined from the force distance curve (Fig4.6) as

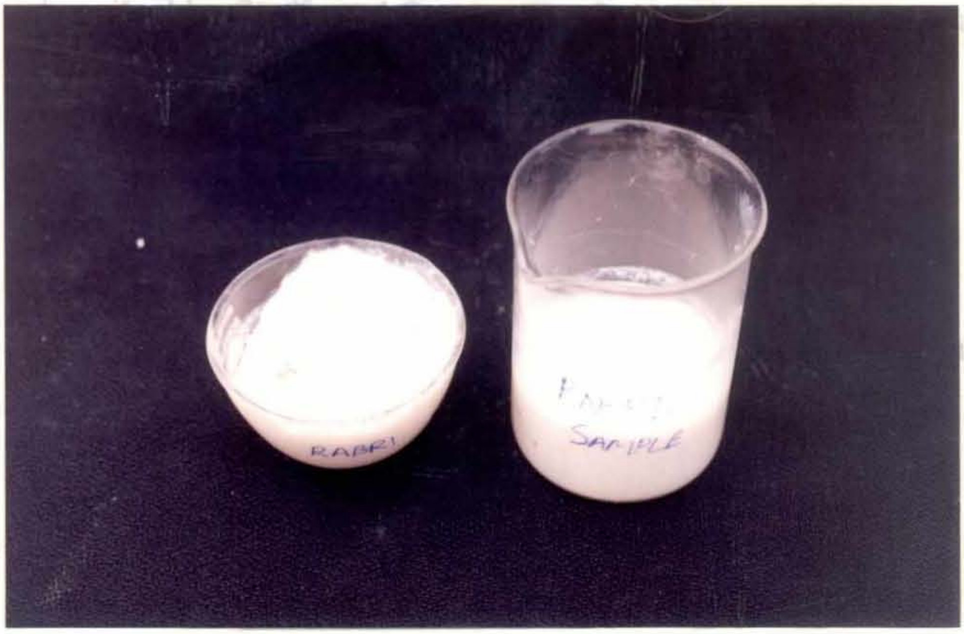


Plate-5:
Rabri Samples

Plate-6:
Preparation
Of Rabri

described by Steffe and Osorio. The force corrected for buoyancy (F_{cb}) is calculated as follows:

$$F_{cb} = F_t - F_{te} \qquad \ldots\ldots\ldots\ldots.(4.2)$$

The magnitudes consistency coefficient (m) and flow behaviour index (n) for the power law model as suggested by Steffe and Osorio are then calculated as:

$$n=[\ln(F_{cb_2}/F_{cb_1})/[\ln(V_{p_2}/Vp_1)] \qquad \ldots\ldots(4.3)$$

$$m=(RF_{cb}k/2\lambda^2\pi Ra\varphi)[R/V_pk^2]^n \qquad \ldots\ldots(4.4)$$

Where R= radius of container (m), φ= dimension less flow rate, λ=value of dimensionless radius where shear stress=0, k=a/R, V_p=plunger velocity (mm/sec), and 1, 2 subscripts referring to tests1 and 2, respectively. λ & φ values were determined from values presented by Osorio and Steffe (1987). Flow behaviour index and consistency coefficient values were the average of four estimated determined from all four possible data combinations.

4.2.2.1. DETERMINATION OF FLOW BEHAVIOUR INDEX AND CONSISTENCY COEFFICIENT

For calculating the flow behaviour index (n) we have to first calculate the force corrected for buoyancy (F_{cb}) using equation (4.2) as:

σ	n 0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
0.1	0.4065	0.4889	0.5539	0.6009	0.6344	0.6586	0.6768	0.6907	0.7017	0.7106
0.2	0.5140	0.5680	0.6092	0.6398	0.6628	0.6803	0.6940	0.7049	0.7138	0.7211
0.3	0.5951	0.6313	0.6587	0.6794	0.6953	0.7078	0.7177	0.7259	0.7326	0.7382
0.4	0.6647	0.6887	0.7068	0.7206	0.7313	0.7399	0.7469	0.7527	0.7575	0.7616
0.5	0.7280	0.7433	0.7547	0.7636	0.7705	0.7761	0.7807	0.7846	0.7878	0.7906
0.6	0.7871	0.7962	0.8030	0.8082	0.8124	0.8158	0.8186	0.8209	0.8229	0.8246
0.7	0.8433	0.8480	0.8516	0.8544	0.8566	0.8584	0.8599	0.8611	0.8622	0.8631
0.8	0.8972	0.8992	0.9007	0.9019	0.9028	0.9035	0.9042	0.9047	0.9052	0.9055
0.9	0.9493	0.9498	0.9502	0.9504	0.9507	0.9508	0.9510	0.9511	0.9512	0.9513

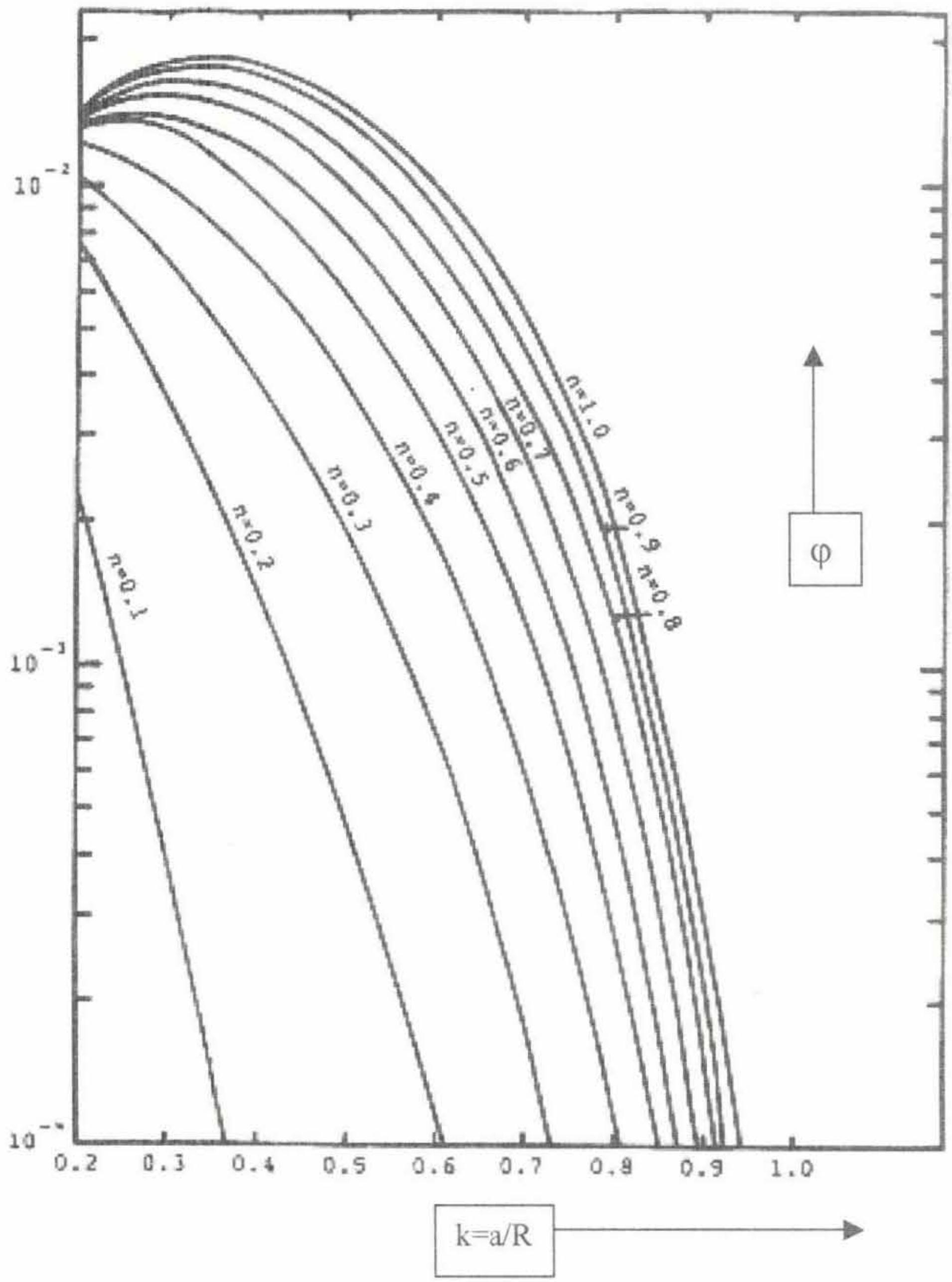
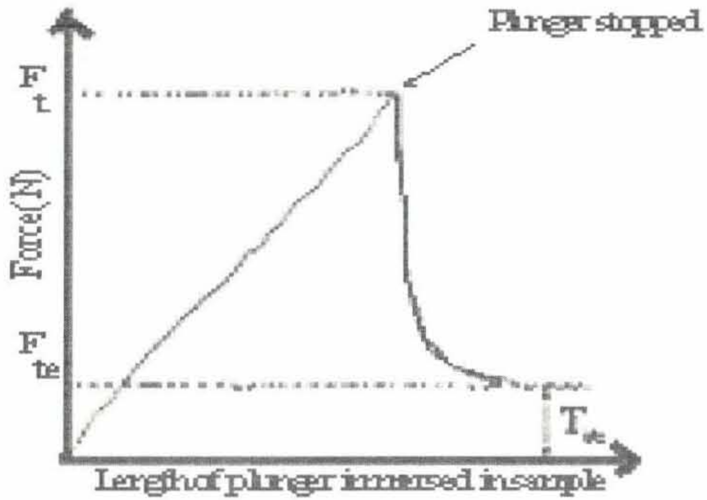


Fig.4.3 Dimensionless flow rate verses dimensionless plunger radius as a function of the flow behaviour index.

FIGURE & CURVES RELATED TO BACK EXTRUSION

Position of plunger at end of testing

Fig 4.5



Typical force distance curve obtained in back extusion method for RABRI

Fig 4.6

$F_{cb} = F_t - F_{te}$ ………….(4.2)

Table 4.2 Data from the Typical force distance curve obtained in back extrusion method for RABRI for 50% T.S.

TS	Vp(m/s)	VELOCITY	Ft	Fte	Fcb
50	0.0015	1.5	0.36	0.266	0.094
	0.003	3	0.39	0.251	0.139
	0.0045	4.5	0.402	0.244	0.158
	0.006	6	0.417	0.257	0.16
	0.003	3	0.39	0.251	0.139
	0.0045	4.5	0.402	0.244	0.158

From (Table no 4.4) we have to get value of dimensionless radius (λ), which can be found out by using our value of k (k= a/R) as 0.475 and depending upon the corresponding n value. Here the value of dimensionless radius comes to be 0.08 for n=0.56 by using the chart shown in (fig.4.4.), and using the value of F_{cb} we can easily calculate the value of flow behaviour index (n) by equation 4.3 as:

n_{12}=[ln(F_{cb2}/F_{cb1})/[ln(V_{p2}/Vp1)] ………(4.3)

=0.39/0.693

=0.564

Similarly, all the other values of flow behaviour index (n) are calculated. Then calculate value of consistency coefficient (m) by equation (4.4) as:

$m=(RF_{cb}k/2\lambda^2\pi Ra)[\varphi R/V_pk^2]^n$ ……(4.4) by substituting the values of R, F_{cb} , k, V_p, λ, □π, a and φ we have value of m as:

$$m=0.388173\ kg_f\ sec^n/m^2$$

Table 4.3 – Table shows, values calculated for different possible combinations of 'n' and respective 'm'.

Combinations	n values	n ave value	λ	chart value, φ	ans of m	m-ave
n12	0.564352221	0.3305677	0.73	0.008	0.442788216	0.388173
n13	0.472687459		0.76	0.006	0.387048079	
n14	0.383669622		0.76	0.0035	0.327153017	
n23	0.315985512		0.75	0.0015	0.28433062	
n24	0.202987022		0.74	0.0055	0.499543959	

5. RESULTS AND DISCUSSION

Pressure drop verses capillary flow data for *rabri* at different temperatures have been presented in the Appendix C. Similar data for *rabri* at different stages of processing are given in Appendix D. The values of consistency coefficient (m) and flow behaviour index (n) of *rabri* have been presented in Appendix A. The results of experimentation and their discussion are presented under the following sub-headings:

5.1 Clotted cream layer to sweetened condensed milk ratio analysis of market samples of *rabri*.

5.2 Effect of temperature on flow behaviour index of *rabri* from 15 to 45% T.S.

5.3 Effect of temperature on consistency coefficient of *rabri* from 15 to 45% T.S.

5.4 Flow behaviour index of *rabri* at different stages of processing of *rabri* from 15 to 45% T.S. at 90^{o}C.

5.5 Variation in consistency coefficient of *rabri* at different stages of processing from 15 to 45% T.S. at 90^{o}C.

5.6 Flow behaviour index of *rabri* at different stages of processing from 50 to 65% T.S. at 20^{o}C.

Table 5.1 Proportion of SCM & CCL present in samples procured from standard sweet shops of Karnal.

	SCM(gms)	CCL(gms)	CCL/SCM ratio
A-1	653	347	0.531393568
ARYA	578	422	0.730103806
BIKANER	12	988	82.33333333
SHIV	10	990	99

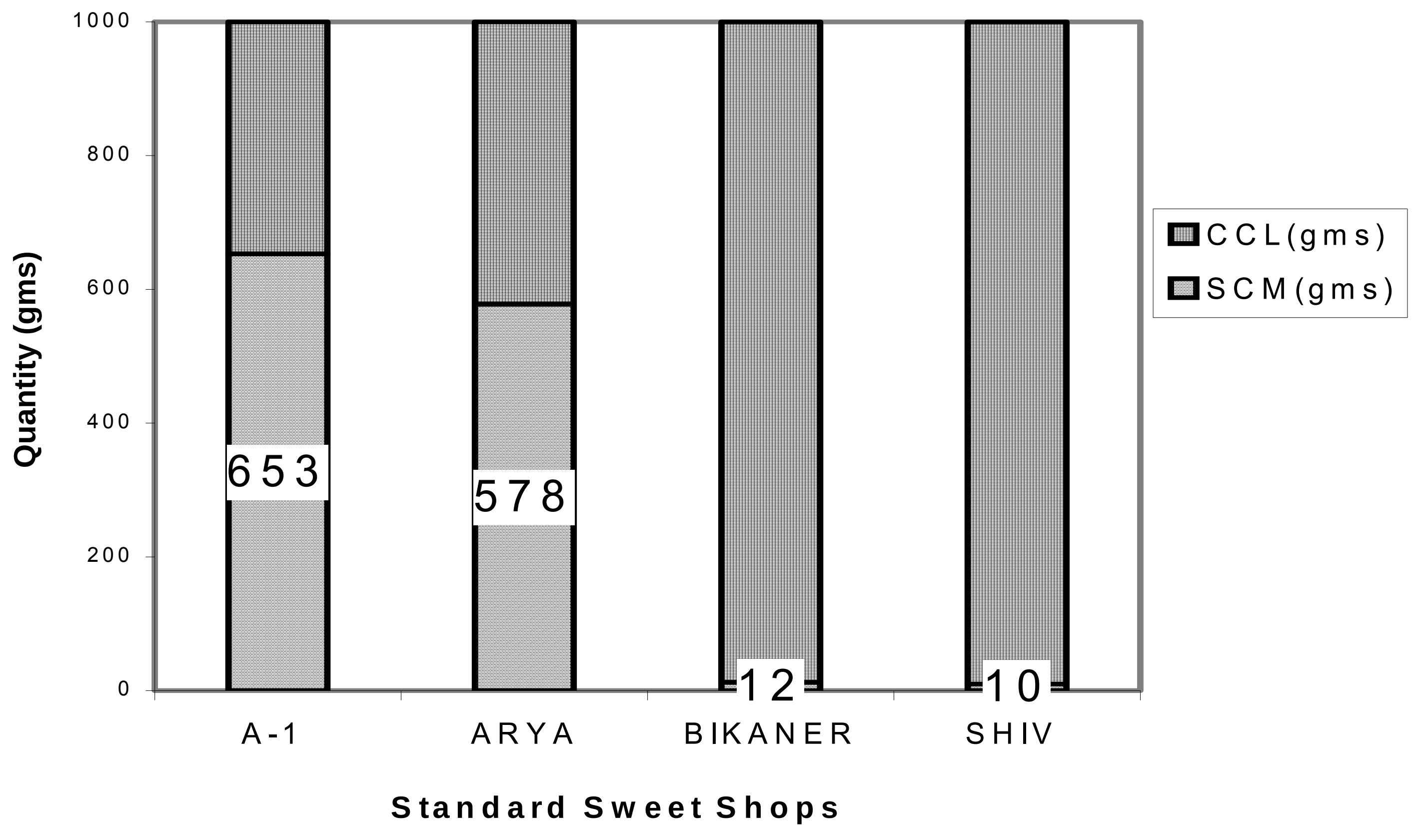


Fig 5.1 Proportion of SCM & CCL present in different samples of Rabri.

5.7 Variation in consistency coefficient of *rabri* at different stages of processing from 50 to 65% T.S. at 20^{o}C.

5.1. CLOTTED CREAM LAYER TO SWEETENED CONDENSED MILK RATIO ANALYSIS OF MARKET SAMPLES OF RABRI

To characterize the various types of *rabri* available in the market, the market samples from the standard sweet shops were collected and clotted cream layer to sweetened condensed milk ratio analysis of market samples of *rabri* was carried out. In the market, *rabri* was available in the two types namely "thinner rabri" and "thicker rabri". The difference between the two being that the "thinner *rabri*", has a total solids content in the range of 60% to 65% whereas "thicker *rabri*", has a total solids content in the range of 74% to 77%. Clotted cream layer to sweetened condensed milk ratio analysis of market samples of *rabri* collected from the standard sweet shops of the Karnal is presented in the fig.5.1. The values for the same have been summarized in Table 5.1.

The products were collected and the separation of the clotted cream layer and sweetened condensed milk was done with the help of stainless steel strainer with a care that no clotted cream layer part gets through to the sweetened condensed milk side. Then the weight of the two components was determined on the electronic weighing balance.

It may be observed from the fig.5.1 that the variation to the extremes persisted in the two types of the *rabri* available in the standard sweet shops of the Karnal. The “thinner *rabri*”, has a clotted cream layer to sweetened condensed milk ratio of 0.53 to 0.73 whereas the “thicker *rabri*”, has a clotted cream layer to sweetened condensed milk ratio of 82.33 to 99. Thus the clotted cream layer content in the “thicker *rabri*” was 285.3% to 234.12% more than the “thinner *rabri*”. The product with less of the clotted cream is liquid in state, and “thicker *rabri*” was in semi-solid in state.

5.2. EFFECT OF TEMPERATURE ON FLOW BEHAVIOUR INDEX OF RABRI FROM 15% T.S. TO 45% T.S.

Effect of temperature on flow behaviour index of *rabri* from 15% T.S. to 45% T.S. has been shown in the fig.5.2 to 5.8 respectively. The values of the flow behavior index of the *rabri* have been summarized in Appendix A, Table 1.

The flow behaviour index was calculated using capillary tube viscometer for total solids ranging from 15% T.S. to 45% T.S. The condensed milk was heated from 20 ^{o}C to 90 ^{o}C and flow data was collected at intervals of 10 ^{o}C temperature rise. The outlet temperature of the product was checked against inlet temperature for detection in any temperature drop. The observations below the temperature of 20 ^{o}C are not reported as samples formed the lumps, which restricted the flow of the product through the capillary tube of even larger diameter at any higher applicable pressures. The scope of using larger diameter (diameter greater than 2 mm) capillary was out of scope, as the larger diameter would differ to the greater extent in the measurement of actual shear rate at the walls of capillary.

In the case of 15% total solids, it was observed from the fig.5.2 that the value of flow behaviour index increases from 0.9562 at 20 ^{o}C to 1.0181 at 90 ^{o}C. The value of flow behaviour index is maximum at 90 ^{o}C. The rate of rise in the value of flow behaviour index decreases from 70 ^{o}C and remains constant above the temperature of 70 ^{o}C. At 70 ^{o}C, the value of flow behaviour index is 1.0117 and at 80 ^{o}C is 1.018, which is very close to the value at 90 ^{o}C. The value of flow behaviour index increase gradually from temperature of 60 ^{o}C to 70 ^{o}C, then remains constant till 50 ^{o}C and finally decreases gradually from 50 ^{o}C to 20 ^{o}C.

It was observed from the fig.5.3, that the value of flow behaviour index increases from 0.9414 at 20 ^{o}C to 0.9987 at 90 ^{o}C at 20% total solids. The value of flow behaviour index is maximum at 90 ^{o}C. The rate of rise in the value of flow behaviour index decreases from 80 ^{o}C and remains constant above the temperature of 80 ^{o}C. At 80 ^{o}C, the value of flow behaviour index is 0.9982, which is very close to the value at 90 ^{o}C. The value of flow behaviour index increases gradually from temperature of 40 ^{o}C to 80 ^{o}C then increases linearly from 20 ^{o}C to 40 ^{o}C .

In the case of 25% total solids, it may be observed from the fig.5.4, that the value of flow behaviour index increases from 0.8768 at 20 ^{o}C to 0.9884 at 90 ^{o}C. The value of flow behaviour index is maximum at 90 ^{o}C. The rate of rise in the value of flow behaviour index decreases from 70 ^{o}C and remains fairly constant above the temperature of 70 ^{o}C. At 70 ^{o}C, the value of flow behaviour index is 0.9859 and at 80 ^{o}C is 0.9871, which is

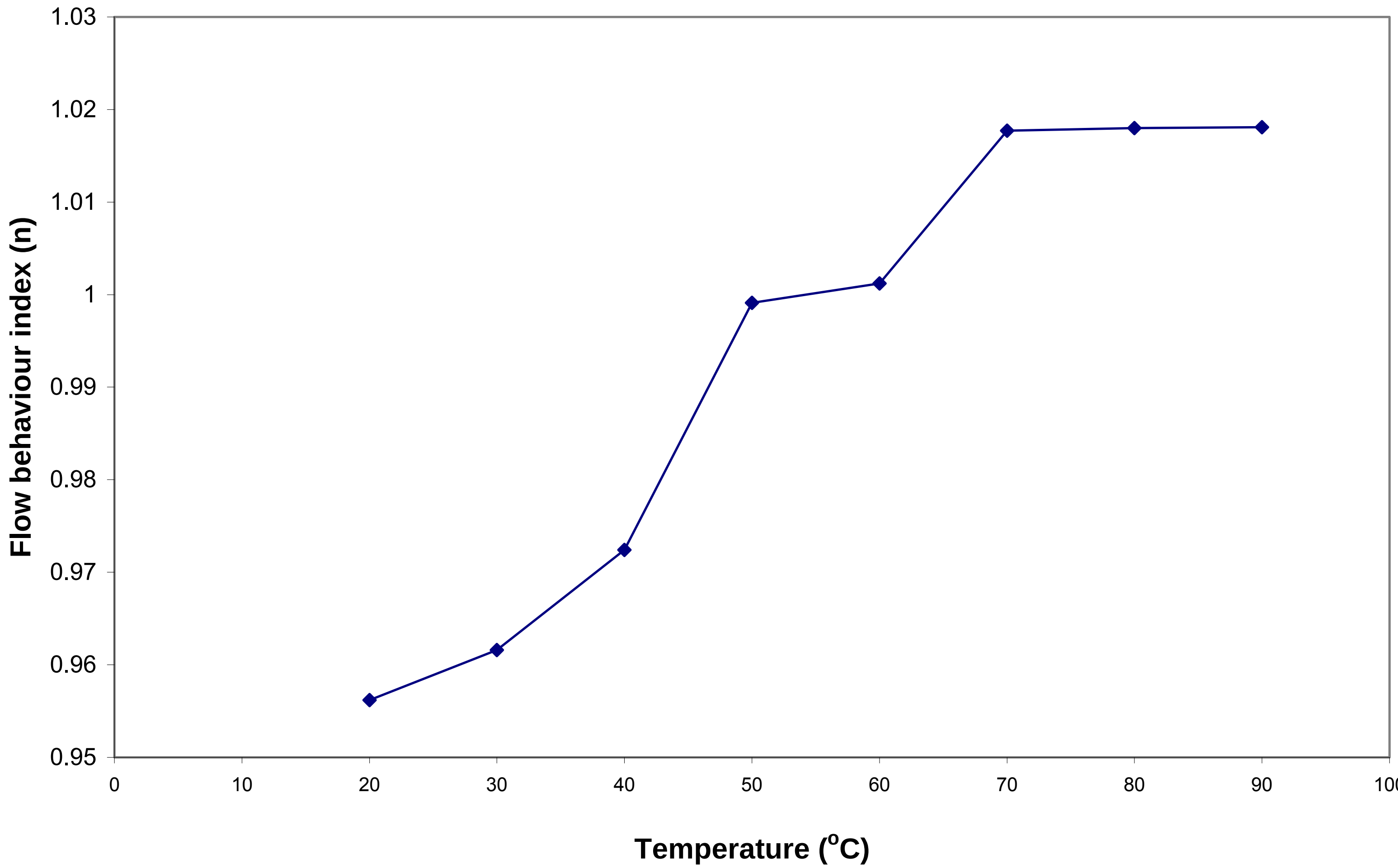


Fig.5.2 Effect of temperature at 15%T.S. on flow behaviour index (n)

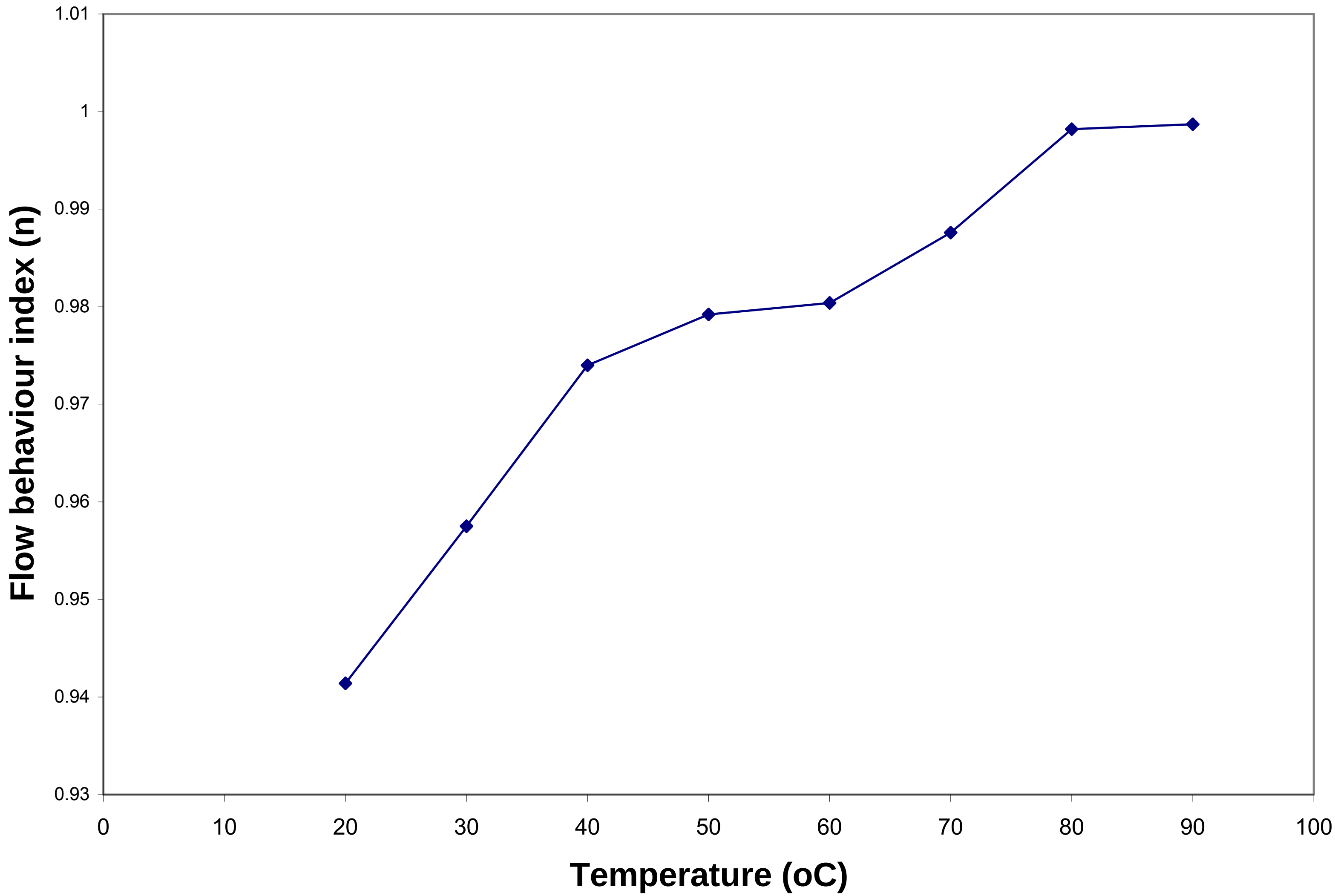


Fig.5.3 Effect of temperature at 20%T.S. on flow behaviour index (n)

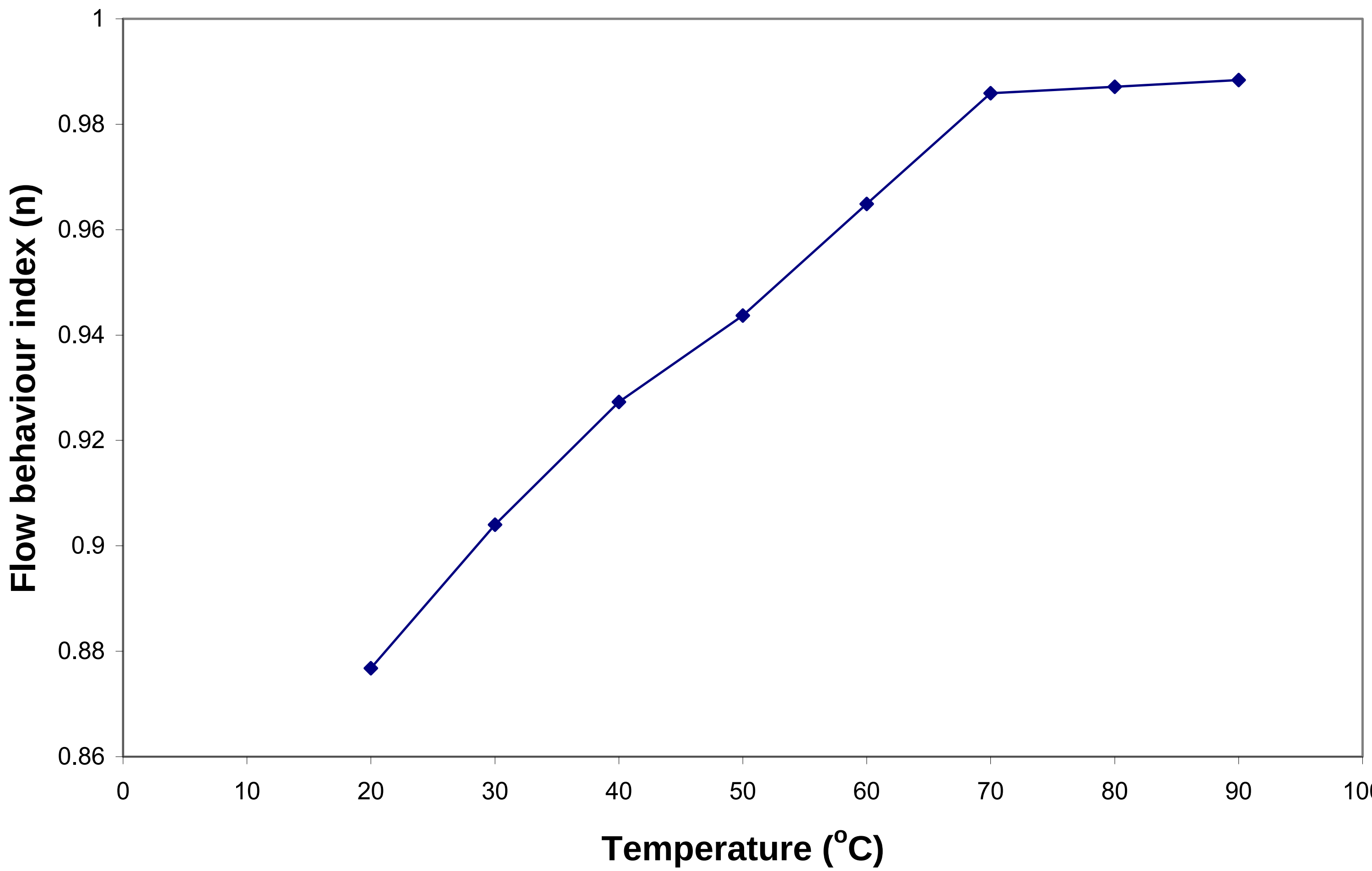


Fig.5.4 Effect of temperature at 25%T.S. on flow behaviour index (n)

very close to the value of flow behaviour index at 90 °C. The value of flow behaviour index increases gradually from temperature of 20 °C to 70 °C.

It may be observed from the fig.5.5, that the value of flow behaviour index increases from 0.8052 at 20 °C to 0.9833 at 90 °C at 30% total solids. The value of flow behaviour index is maximum at 90 °C. The rate of rise in the value of flow behaviour index decreases from 70 °C and remains constant above the temperature of 70 °C. At 70 °C, the value of flow behaviour index is 0.976 and at 80 °C is 0.9768, which is very close to the value of flow behaviour index at 90 °C. The value of flow behaviour index increases gradually from temperature of 70 °C to 20 °C.

In the case of 35% total solids, it may be observed from the fig.5.6, that the value of flow behaviour index increases from 0.7118 at 20 °C to 0.9734 at 90 °C. The value of flow behaviour index is maximum at 90 °C. The rate of rise in the value of flow behaviour index decreases from 70 °C and remains constant above the temperature of 70 °C. At 70 °C, the value of flow behaviour index is 0.9684 and at 80 °C is 0.9707, which is very close to the value of flow behaviour index at 90 °C. The value of flow behaviour index increases gradually from temperature of 30 °C to 70 °C. The value of flow behaviour index remains constant from temperature of 20 °C to 30 °C.

It may be observed from the fig.5.7, that the value of flow behaviour index increases from 0.5475 at 20 °C to 0.9611 at 90 °C at 40% total solids. The value of flow behaviour index is maximum at 90 °C. The rate of rise in the value of flow behaviour index decreases from 70 °C and remains constant above the temperature of 70 °C. At 70 °C, the value of flow behaviour index is 0.9549 and at 80 °C is 0.9598, which is very close to the

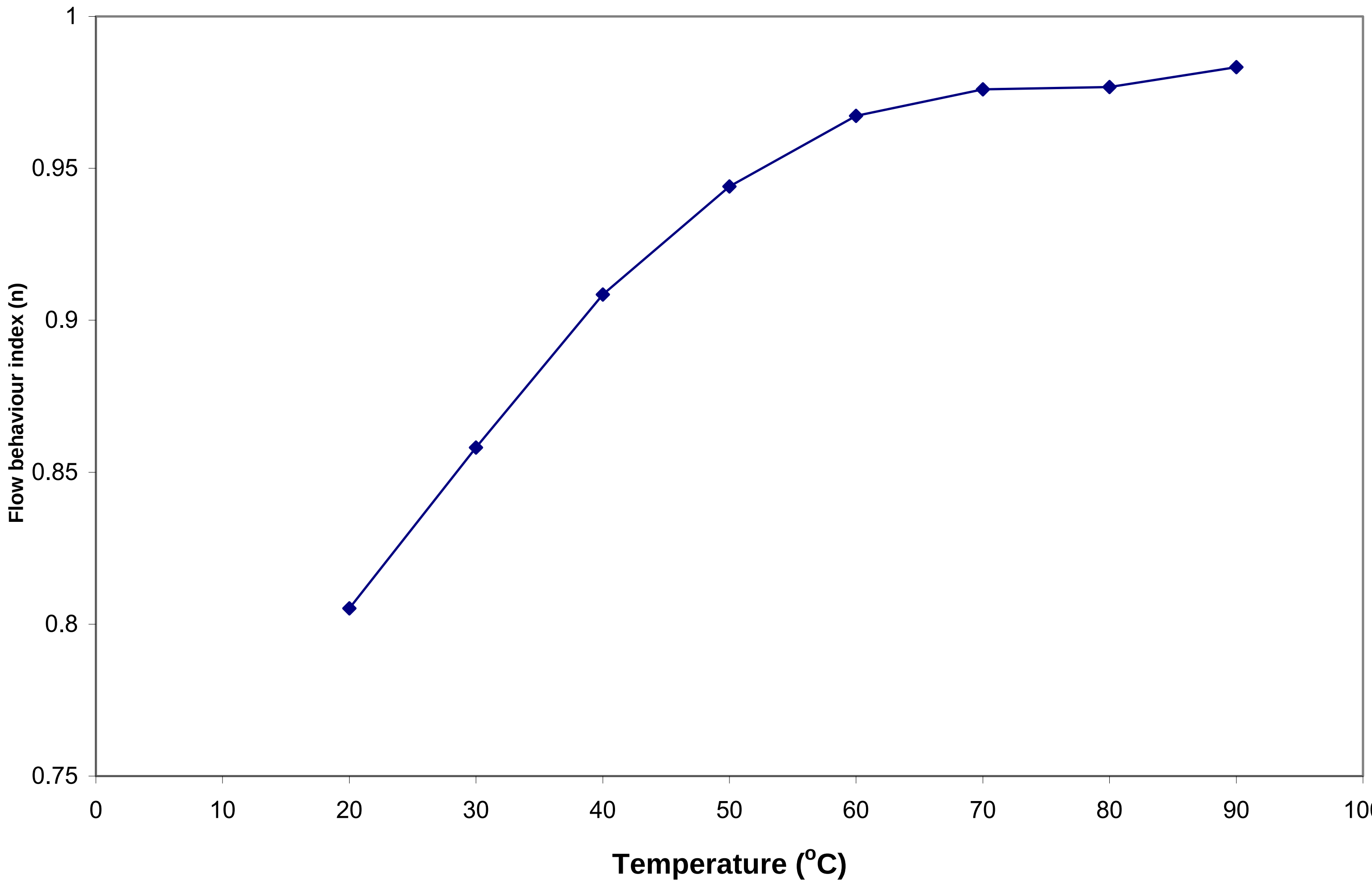


Fig.5.5 Effect of temperature at 30%T.S. on flow behaviour index (n)

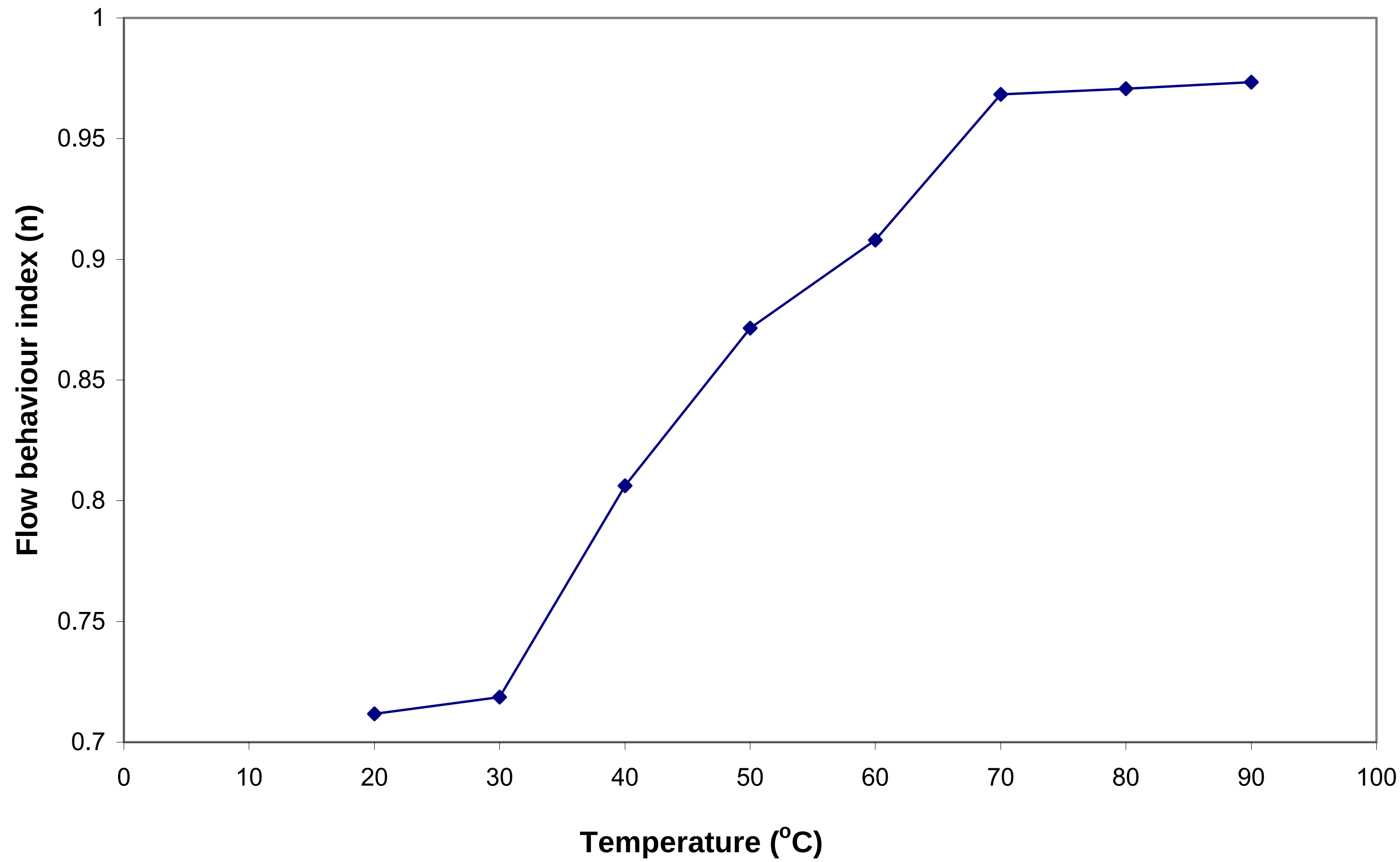


Fig.5.6 Effect of temperature at 35%T.S. on flow behaviour index (n)

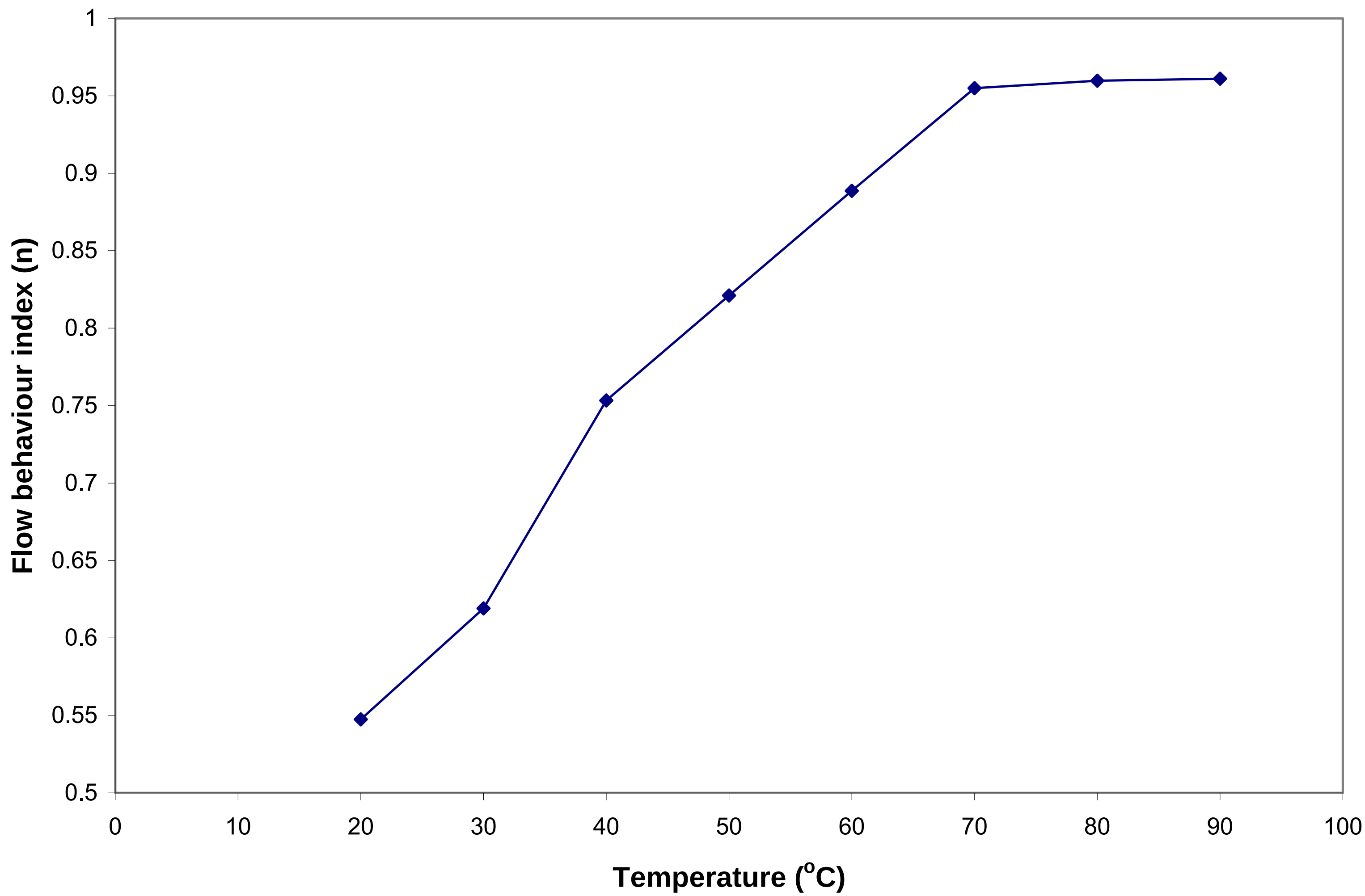


Fig.5.7 Effect of temperature at 40%T.S. on flow behaviour index (n)

value of flow behaviour index at 90 ^oC. The value of flow behaviour index increases gradually from temperature of 20 ^oC to 70 ^oC.

In the case of 45% total solids, it may be observed from the fig.5.8, that the value of flow behaviour index increases from 0.5095 at 20 ^oC to 0.953 at 90 ^oC. The value of flow behaviour index is maximum at 90 ^oC. The rate of rise in the value of flow behaviour index decreases from 70 ^oC and remains constant above the temperature of 70 ^oC. At 70 ^oC, the value of flow behaviour index is 0.9135 and at 80 oC is 0.9374, which is very close to the value of flow behaviour index at 90 ^oC. The value of flow behaviour index increases gradually from temperature of 20 ^oC to 70 ^oC.

5.3. EFFECT OF TEMPERATURE ON CONSISTENCY COEFFICIENT OF RABRI FROM 15% T.S. TO 45% T.S.

Effect of temperature on consistency coefficient of *rabri* from 15% T.S. to 45% T.S. has been shown in the fig.5.9 to 5.15 respectively. The values of the consistency coefficient of the *rabri* have been summarized in Appendix A, Table 1.

The calculation of the consistency coefficient was done using the values of flow behaviour index derived from the capillary tube viscometer. The equation no. 4.1 was used to calculate the consistency coefficient.

For 15% T.S., it was observed from the fig.5.9 that the consistency coefficient of *rabri* decreased from 20 ^oC to 90 ^oC from a value of $0.44 x 10^{-3}$ $kg_f sec^n/m^2$ to $0.33 x 10^{-3}$ $kg_f sec^n/m^2$. A steep fall in the value of consistency coefficient was observed from 20 ^oC to 40 ^oC.

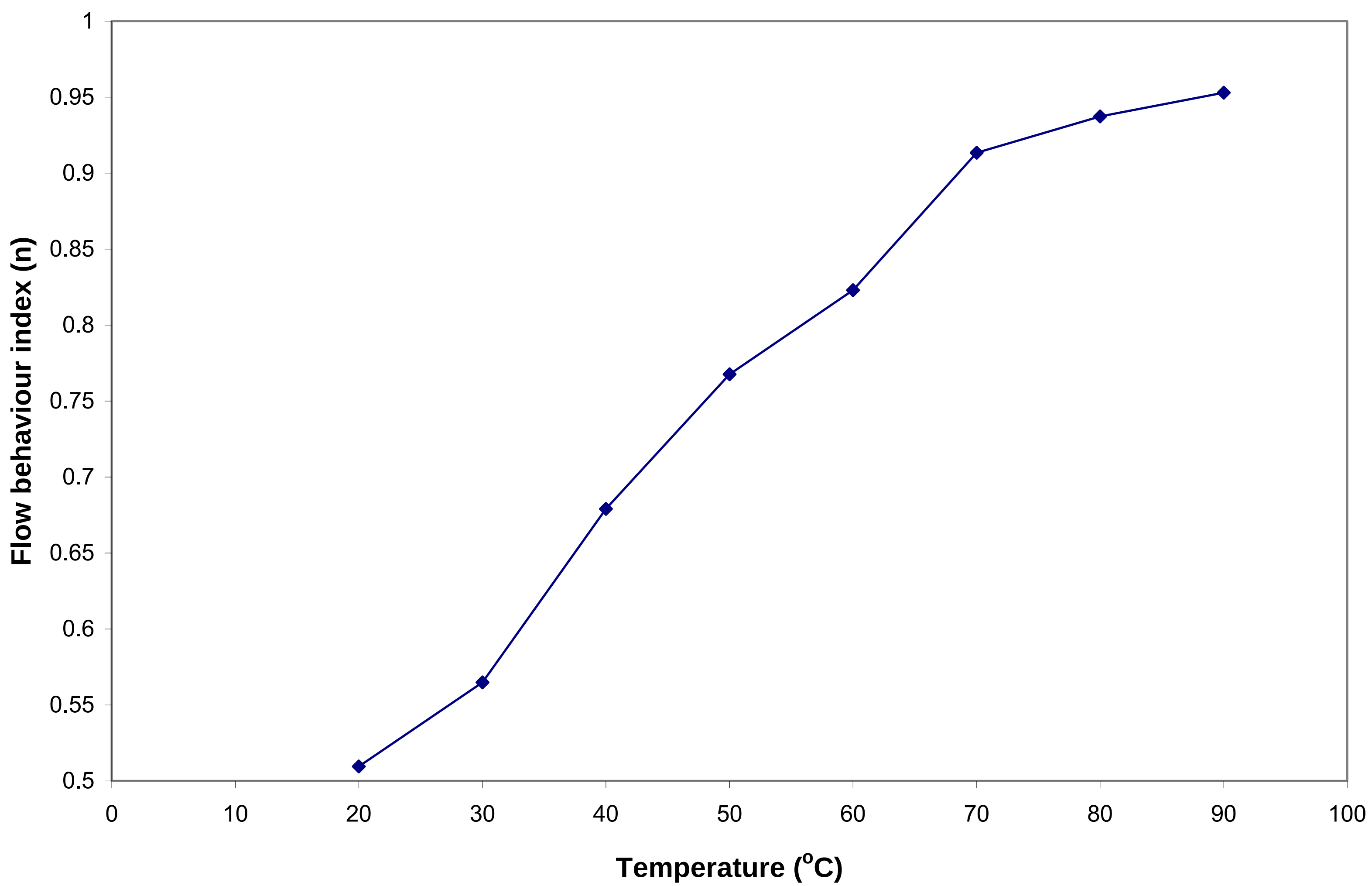


Fig.5.8 Effect of temperature at 45%T.S. on flow behaviour index (n)

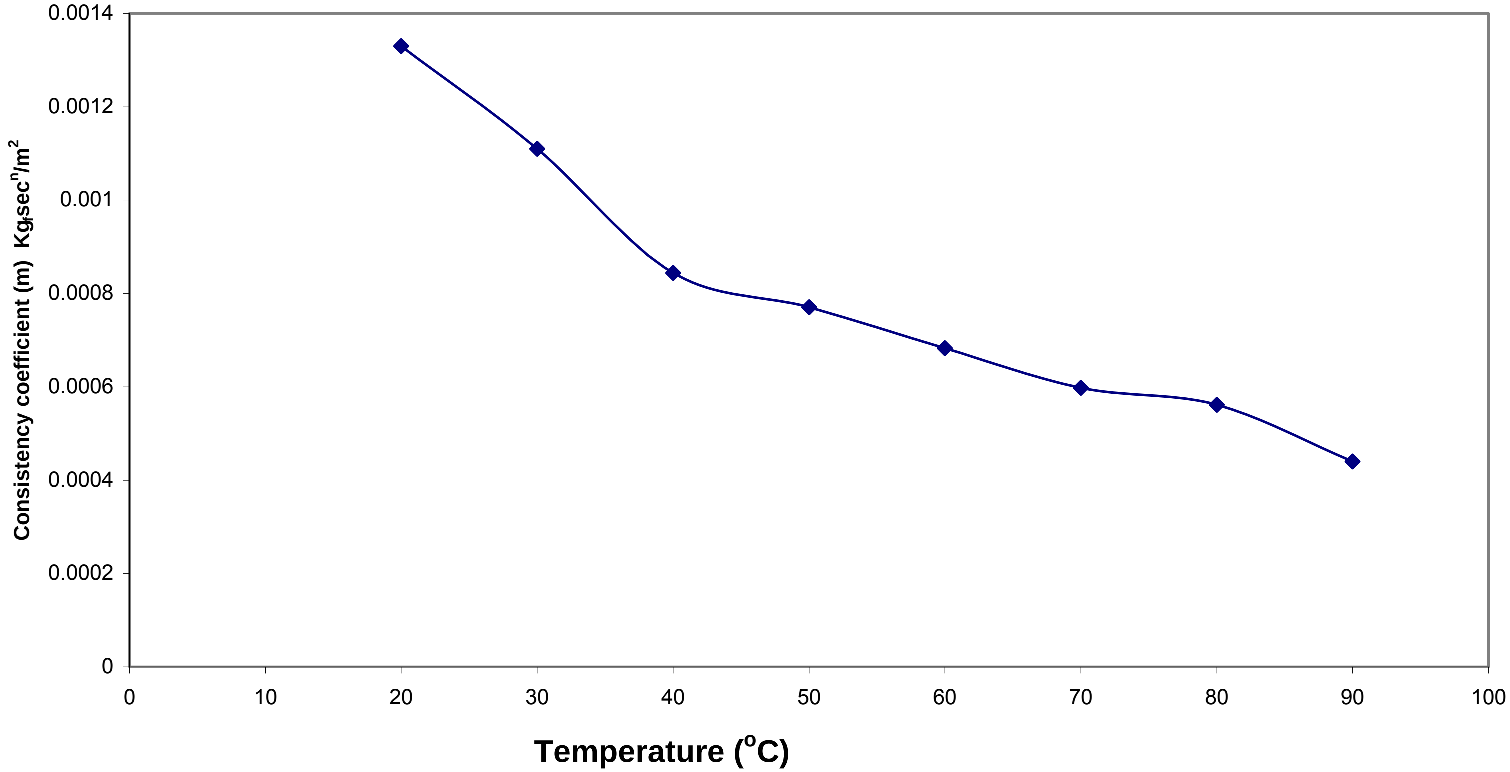


Fig5.9 Effect of temperature on Consistency coefficient (m) $Kg_f sec^n/m^2$ at 15%T.S.

It was observed from the fig.5.10 that the consistency coefficient of *rabri* decreased from 20 ^oC to 90 ^oC from a value of $1.61x10^{-3}$ kg_fsec^n/m^2 to $0.54x10^{-3}$ kg_fsec^n/m^2 at 20% T.S. A gradual decrease in the value of consistency coefficient was observed from 70 ^oC to 90 ^oC after which a slow fall in the value persisted from 60 ^oC to 70 ^oC. A steep fall in the value of consistency coefficient was observed from 60 ^oC to 20 ^oC.

For 25% T.S., it may be seen from the fig.5.11 that the consistency coefficient of rabri decreased from 20 ^oC to 90 ^oC from a value of $2.61x10^{-3}$ kg_fsec^n/m^2 to $0.6x10^{-3}$ kg_fsec^n/m^2. A gradual fall in the value of consistency coefficient was observed from 40 ^oC to 90 ^oC. A steep fall in the value of consistency coefficient was observed from 20 ^oC to 40 ^oC.

It was observed from the fig.5.12 that the consistency coefficient of rabri decreased from 20 ^oC to 90 ^oC from a value of $5.0x10^{-3}$ $kg_f\ sec^n/m^2$ to $0.58x10^{-3}$ kg_fsec^n/m^2 at 30% T.S. A gradual fall in the value of consistency coefficient was observed from 40 ^oC to 90 ^oC. A steep fall in the value of consistency coefficient was observed from 20 ^oC to 40 ^oC.

For 35% T.S., it may be seen from the fig.5.13 that the consistency coefficient of *rabri* decreased from 20 ^oC to 90 ^oC from a value- $85.87x10^{-3}$ $kg_f\ sec^n/m^2$ to $2.57x10^{-3}$ $kg_f\ sec^n/m^2$. A gradual fall in the value of consistency coefficient was observed from 40 ^oC to 90 ^oC. A steep fall in the value of consistency coefficient was observed from 20 ^oC to 40 ^oC.

It was observed from the fig.5.14 that the consistency coefficient of *rabri* decreased from 20 ^oC to 90 ^oC from a value of $44.54x10^{-3}$ kg_fsec^n/m^2 to $1.96x10^{-3}$ kg_fsec^n/m^2 at 40% T.S. A gradual fall in the value of consistency coefficient was observed from 40 ^oC to 90 ^oC. A steep fall in the value of consistency coefficient was observed from 20 ^oC to 40 ^oC.

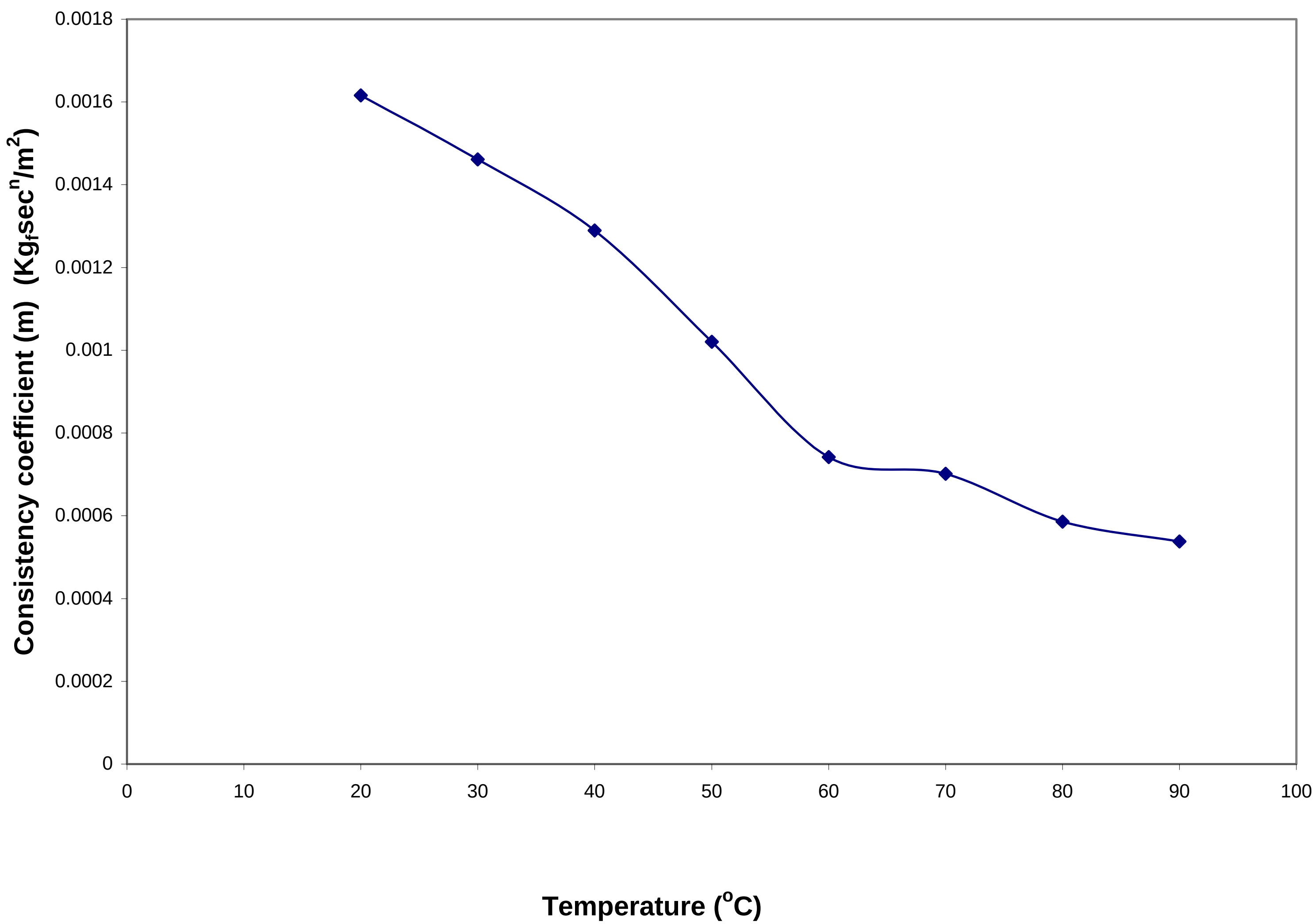


Fig 5.10 Effect of temperature on Consistency coefficient at 20% T.S.

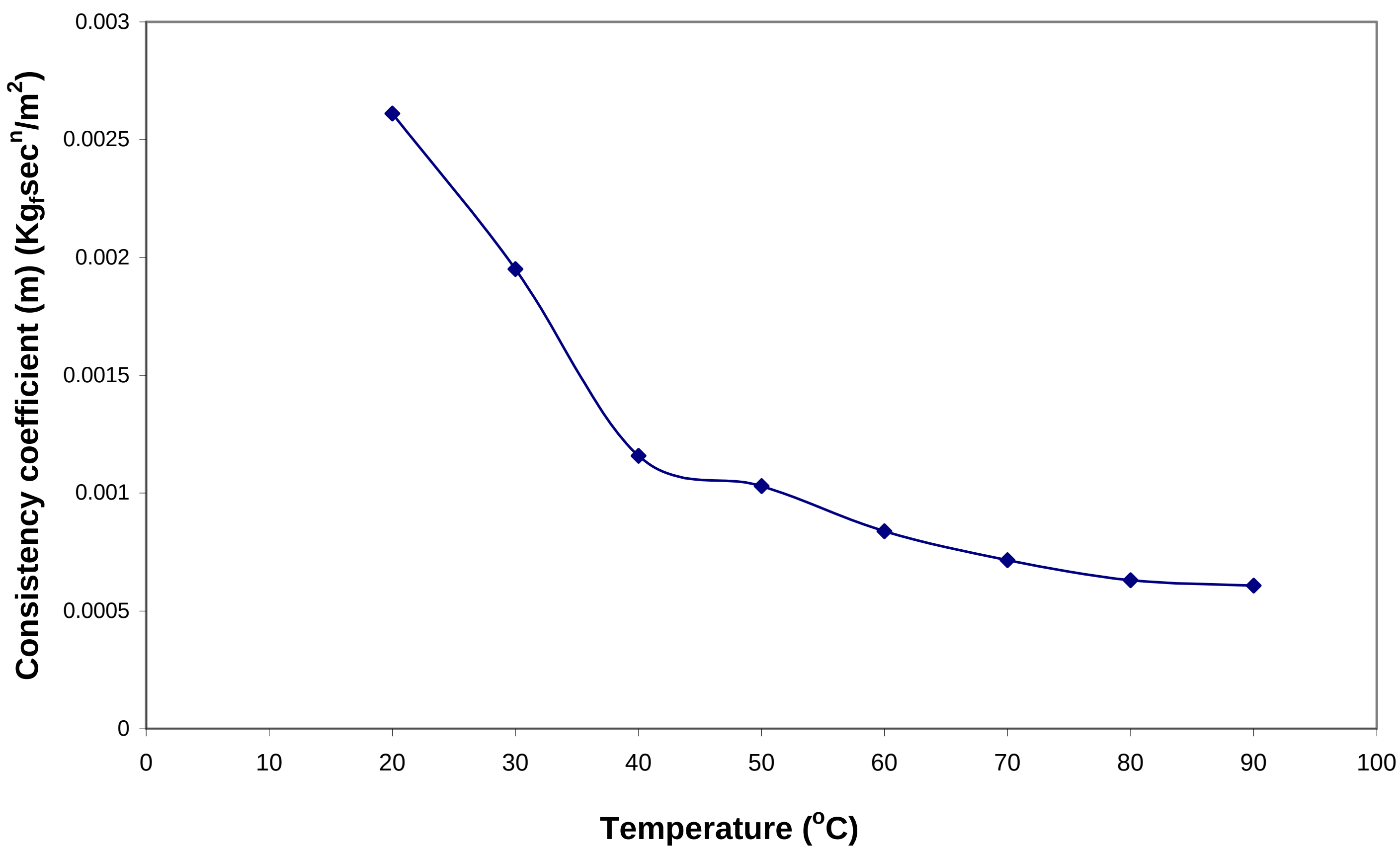


Fig5.11 Effect of temperature on Consistency coefficient (m) at 25% T.S.

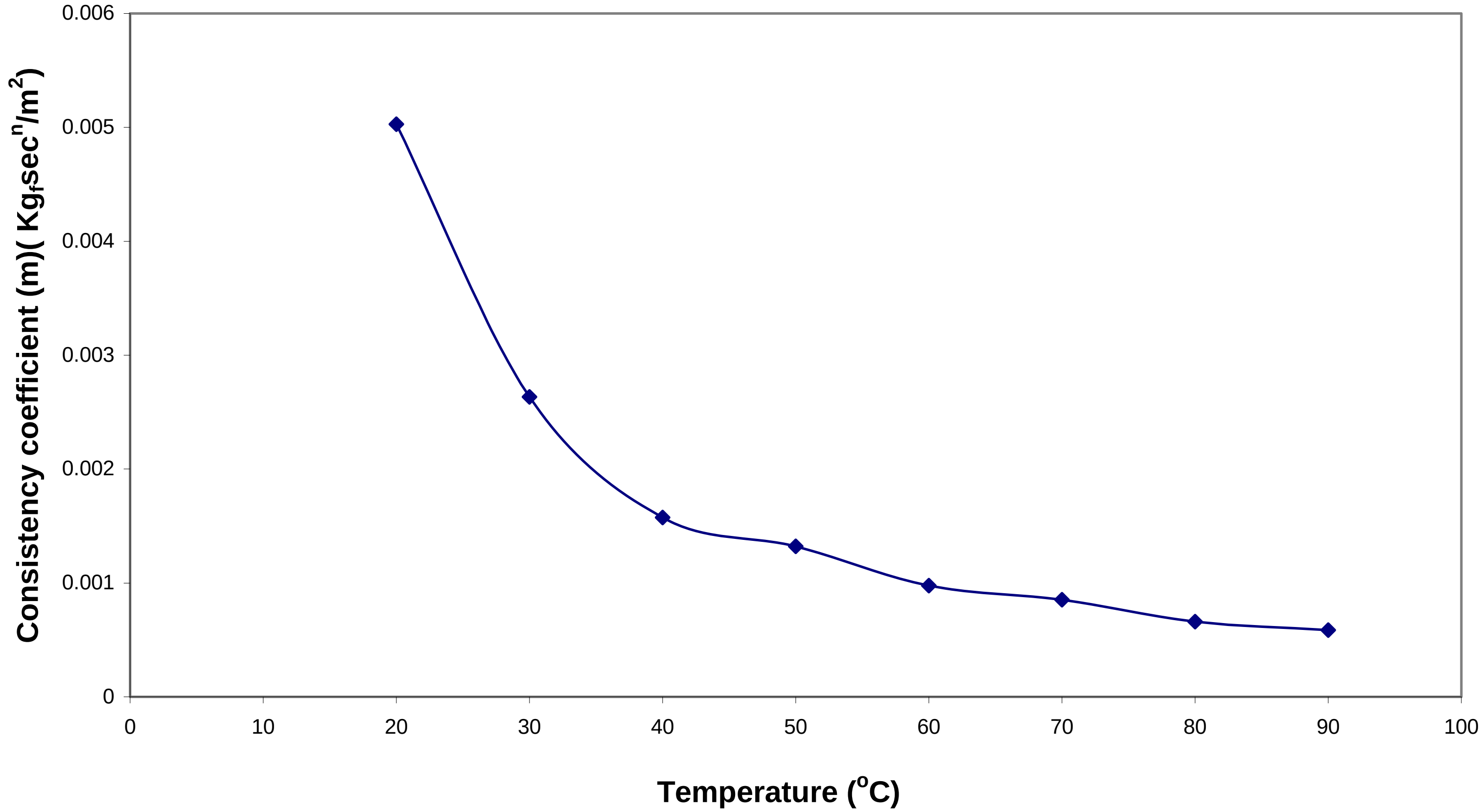


Fig5.12: Effect of temperature on Consistency coefficient (m) at 30% T.S.

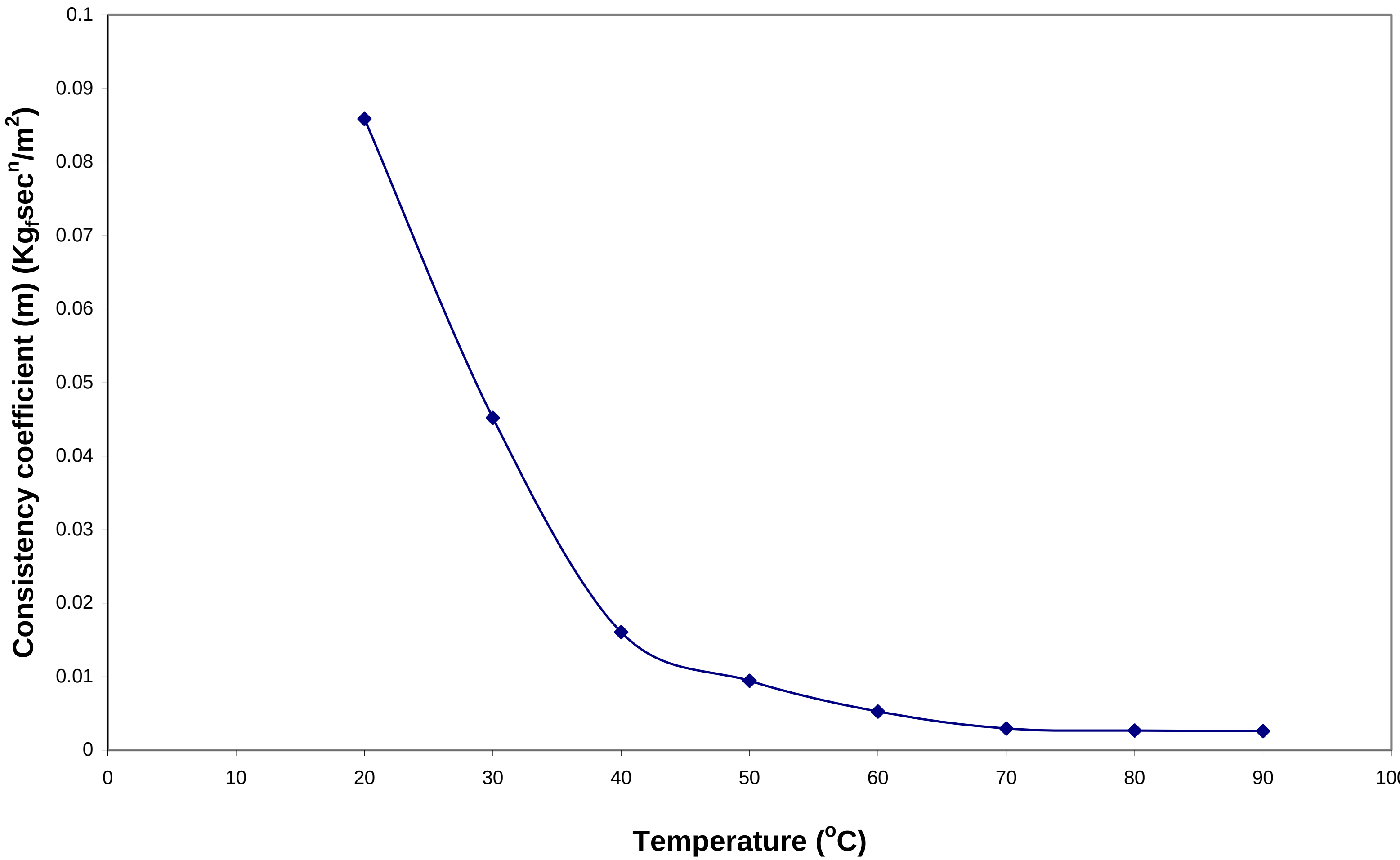


Fig5.13 Effect of temperature on Consistency coefficient at 35% T.S.

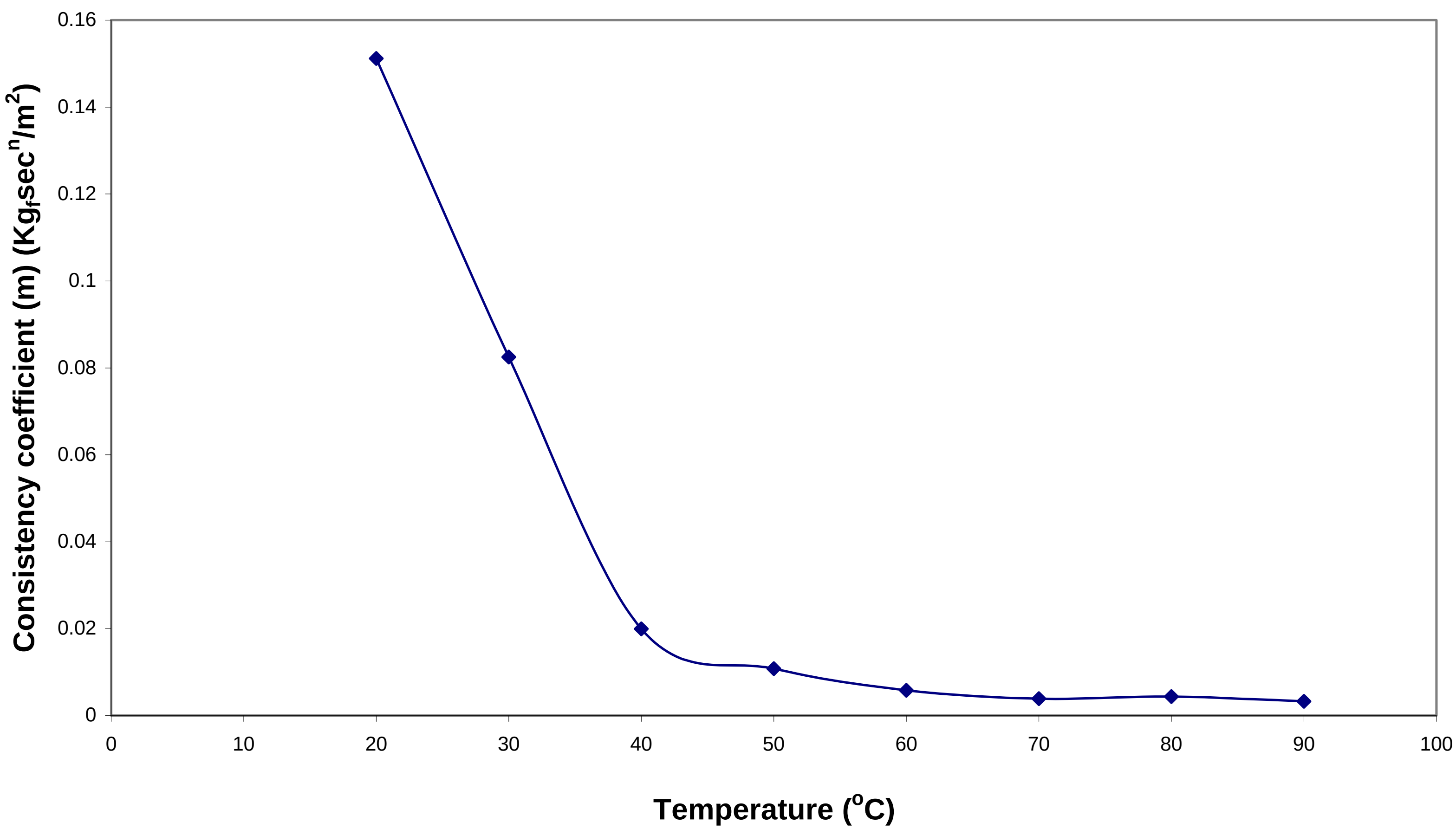


Fig5.14 Effect of temperature on Consistency coefficient (m) at 40% T.S.

For 45% T.S. , it may be seen from the fig.5.15 that the consistency coefficient of *rabri* decreased from 20 ^oC to 90 ^oC from a value of $151.16x10^{-3}$ $kg_f sec^n/m^2$ to $3.29x10^{-3}$ $kg_f sec^n/m^2$. A gradual fall in the value of consistency coefficient was observed from 40 ^oC to 90 ^oC. A steep fall in the value of consistency coefficient was observed from 20 ^oC to 40 ^oC.

5.4. FLOW BEHAVIOUR INDEX AT DIFFERENT STAGES OF PROCESSING OF RABRI FROM 15% T.S. TO 45% T.S. at 90^{o}C

The variation in the flow behaviour index derived by capillary viscometer at different stages of processing of *rabri* from 15% T.S. to 45% T.S. is shown in the Appendix B, Table 2 & in fig.5.16. The flow behaviour of *rabri* at all the stages of processing is found to be pseudoplastic in nature for all the practical purposes, i.e., the flow behaviour index was found to be less than unity. How ever, it has been observed that the flow behaviour index during the initial stages of processing of *rabri* showed a Newtonian behaviour at lower total solids content of the fluid. The value of the flow behaviour index was 1.0181 at 15% total solids and the value decreased to 0.953 at 45% total solids content. The rate of fall of the flow behaviour index decreased from 15% T.S. to 30%T.S., then rate of fall of flow behaviour index increased from 30%T.S. to 40%T.S. Finally the rate of fall of the flow behaviour index decreased from 40% T.S. to 45%T.S. The regression equation was found to be:

$y= -0.002x + 1.0435$ with $R^2 = 0.9782$.

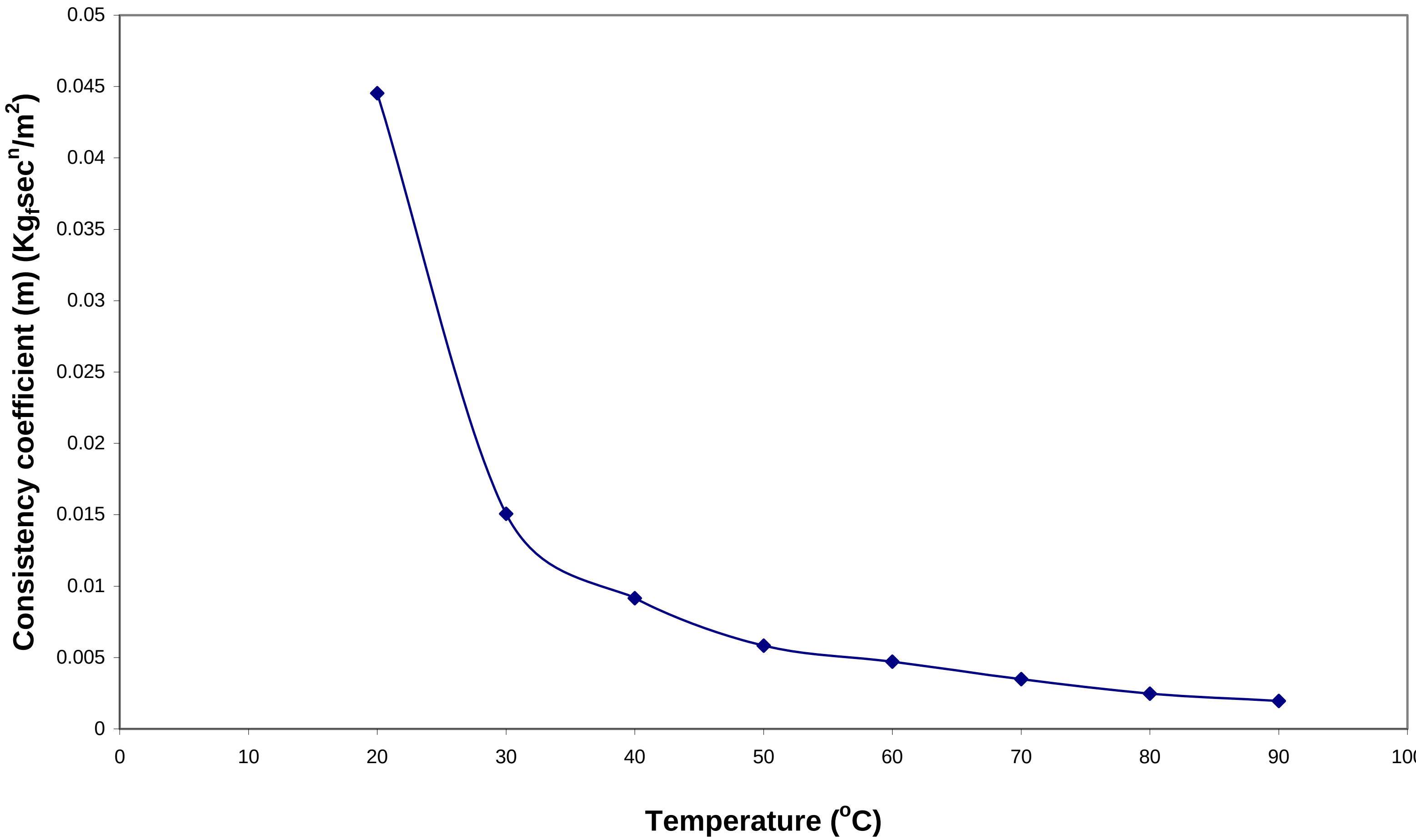


Fig5.15 Effect of temperature on Consistency coefficient (m) at 45% T.S.

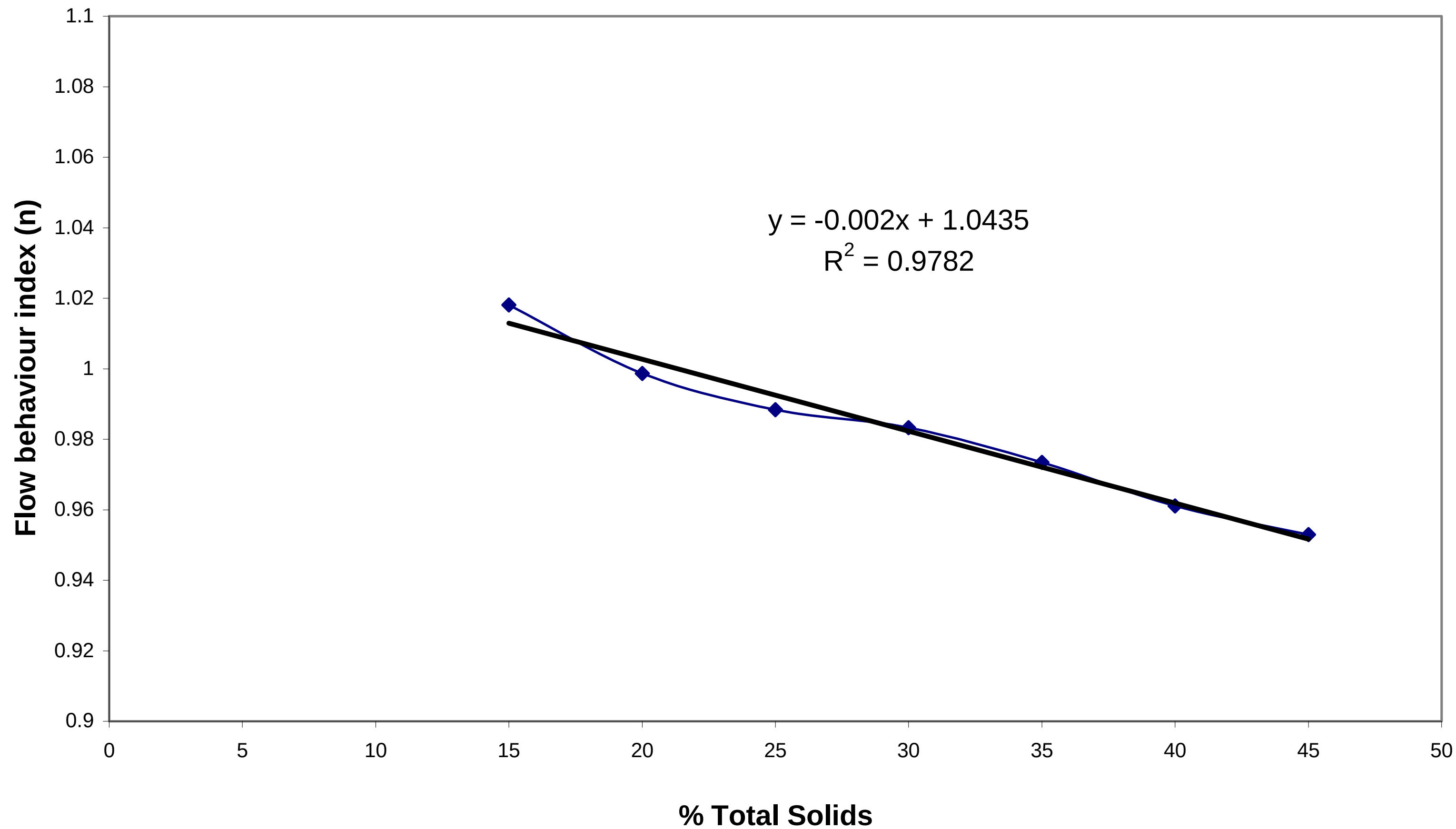


Fig5.16 Flow behaviour index at different stages of processing for 15 to 45% T.S.

5.5 VARIATION IN CONSISTENCY COEFFICIENT OF RABRI AT DIFFERENT STAGES OF PROCESSING FROM 15% T.S. TO 45% T.S. AT 90^{o}C

The variation in the consistency coefficient derived by capillary viscometer at different stages of processing of *rabri* from 15% T.S. to 45% T.S is shown in the Appendix B, Table 2. The consistency coefficient varied from $0.4113 x 10^{-3}$ kg_f sec^n/m^2 at 90^{o}C in the 15% total solids product to 151.16 $x10^{-3}$ kg_f sec^n/m^2 at 20oC in the 45% total solids product. The increase in the consistency coefficient as the moisture content decreased was gradual till the total solids increased from 15%T.S. to 30%T.S. as can be seen from the fig.5.17. However, as the total solids increased from 30%T.S. to 45%T.S., the consistency coefficient showed a exponential increase (Appendix B, Table 2). This shows clearly that the removal of moisture (or increase in the total solids content) during processing increases the consistency coefficient. This also shows that the increase in the consistency coefficient is observed when the temperature is decreasing. The regression equation was found to be:

$y= 9E\text{-}0.5E^{0.0644X}$ with $R^2=0.9442$.

5.6 FLOW BEHAVIOUR INDEX OF RABRI AT DIFFERENT STAGES OF PROCESSING FROM 50% T.S. TO 65% T.S. at 20 ^{o}C

The flow behaviour index of *rabri* determined by the method of back extrusion in texture analyzer at different stages of processing from 50% T.S. to 65% T.S. is shown in the Appendix D, table 4. The flow behaviour of *rabri* at all the stages of processing is found to be

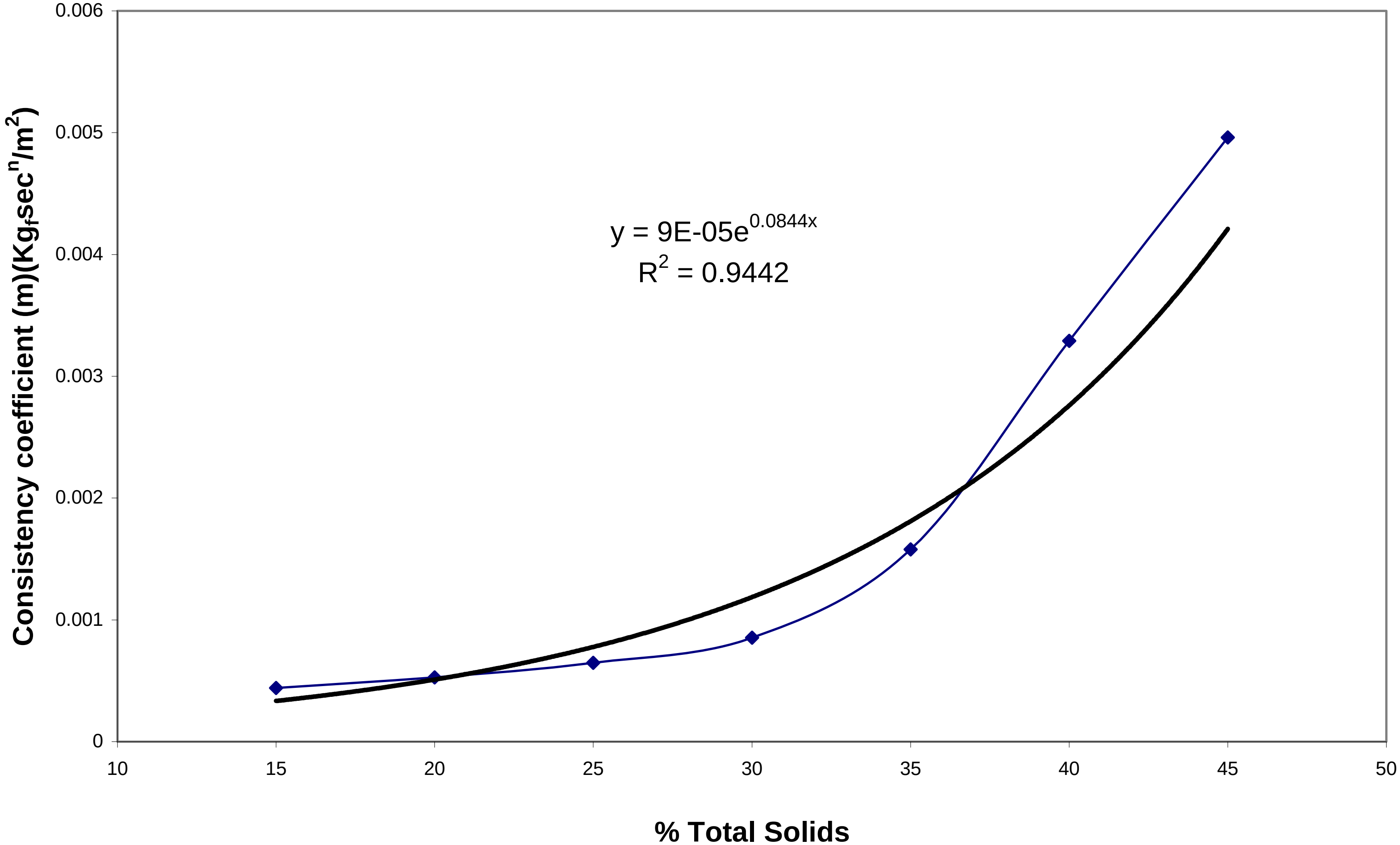


Fig5.17 Consistency coefficient at different stages of processing for 15 to 45 % T.S.

pseudoplastic in nature for all the practicle purposes, i.e., the flow behaviour index was found to be less than unity. The value of the flow behaviour index was 0.33 at 50% total solids and the value decreased to 0.23 at 65% total solids content as can be seen in fig.5.18. The rate of fall of the flow behaviour index decreased from 55% T.S. to 60%T.S., then rate of fall of flow behaviour index increased from 60%T.S. to 65%T.S. As the total solids content in the *rabri* increased the flow behaviour index decreased correspondingly. The regression equation was found to be:

$$y=-0.0061x + 0.6202 \text{ with } R^2=0.8457$$

5.7. VARIATION IN CONSISTENCY COEFFICIENT OF RABRI AT DIFFERENT STAGES OF PROCESSING FROM 50% T.S. TO 65% T.S. at 20^{o}C

The consistency coefficient of *rabri* determined by the method of back extrusion in texture analyzer at different stages of processing from 50% T.S. to 65% T.S. is shown in the Appendix D, Table 4. The consistency coefficient varied from $1095.7x10^{-3}$ $kg_f sec^n/m^2$ 50% total solids product to $1399.42x10^{-3}$ $kg_f\ sec^n/m^2$ at 65% total solids product. The increase in the consistency coefficient as the moisture content decreased was gradual for the total solids ranging from 50%T.S. to 65%T.S. as can be seen from the fig.5.19. However, the rate of the increase was decreasing as the total solids content increased from 50%T.S. to 65%T.S. This shows clearly that the removal of moisture (or increase in the total solids content) during processing increases the consistency coefficient. The regression equation was found to be:

$$= -0.0009x^2 + 0.1285x + 2.9809 \text{ with } R^2=0.9994.$$

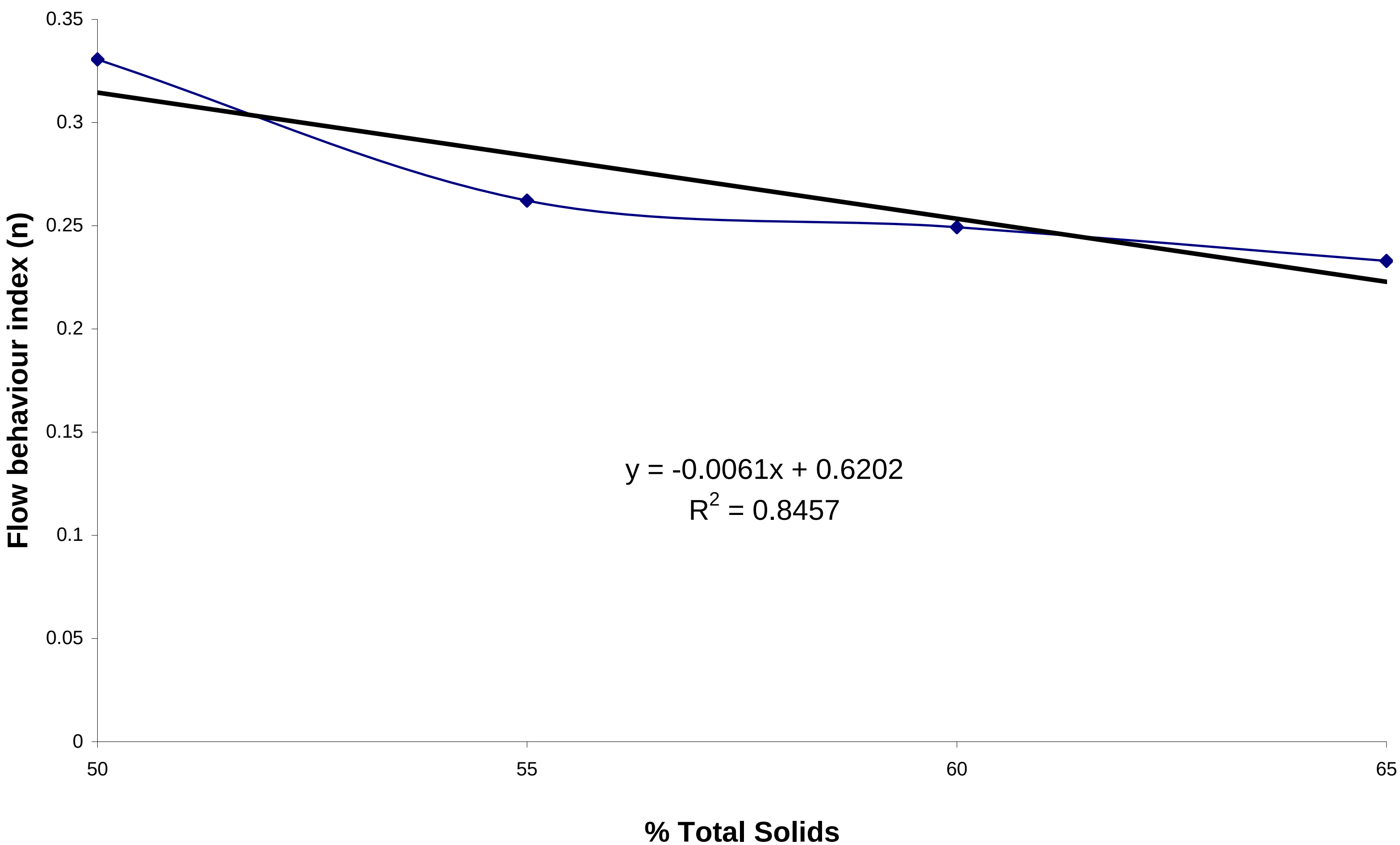


Fig5.18 Flow behaviour index at different stages of processing for 50 to 65% T.S.

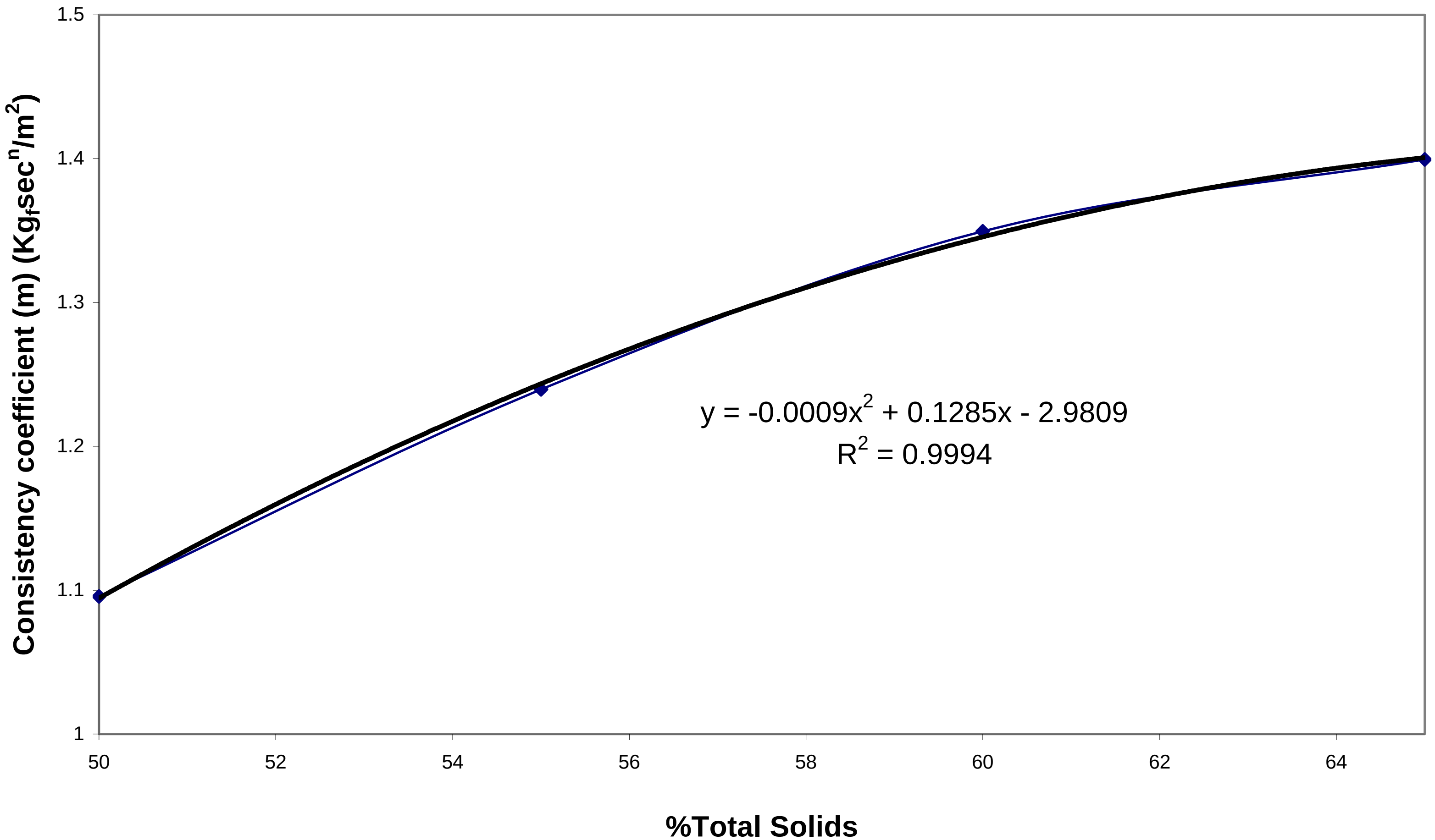


Fig5.19 Consistency coefficient at different stages of processing for 50 to 65% T.S.

6. SUMMARY & CONCLUSION

With opening of International markets, there exists an immense potential of exporting traditional Indian dairy products. For this purpose mechanization and upgradation of equipment based technology for large-scale production with cheaper cost and longer shelf life is the ultimate need of the hour. Up gradation of technology will also ensure safety, wholesomeness of product with certain degree of homogeneity in the quality of the product.

Rabri is a heat desiccated thickened milk sweets pale yellow to light caramel color and flavor (Bandyopadhyey & Mathur, 1987). It contains several layers of clotted cream (De, 1980). No efforts have been made to study the variations in engineering parameters viz. thermophysical parameters and rheological parameters to design the suitable and most appropriate system for large-scale continuous production to cater for domestic and foreign market. Rheological properties of *rabri* are essential in estimating various engineering quantities such as heat transfer coefficient, evaporation rates, and pumping and heating requirements.

The trials were carried out in two instruments namely Constant temperature capillary tube viscometer and Texture analyzer for back extrusion. The reason for using capillary tube viscometer upto 15% to 45%T.S. milk only is that as the T.S.% increases the particles suspended in the product increases. These increased suspended solids tend to intensify wall effects when the fluid is flowing in a small tube. Back extrusion method was used for 50% to 65% T.S. diluted *rabri*. This method is particularly useful with materials having consistency of paste or with suspensions which have large particles suspended in them. Thus we can conclude that:

1. Clotted cream layer to sweetened condensed milk ratio analysis of market samples of *rabri* showed T.S.% of *rabri* ranging from 60%T.S. to 75%T.S. The clotted cream to sweetened condensed milk ratio was found to be 0.53 to 99. Thus clearly indicating that there is urgent need for the standards to be made for *rabri*.
2. Effect of temperature on flow behaviour index of *rabri* from 15% T.S. to 45% T.S. shows that the value of flow behaviour index (n) does not depend on temperature, but when the constituents of fluid undergo changes under the influence of temperature change, the flow behaviour index (n) changes. We can conclude from the fig.5.2 to 5.8 that normally after 70 ^{o} C there is hardly any rise in the value of floe behaviour index (n). The constant value of 'n' may be because of denaturation of whey proteins present in the milk.
3. Effect of temperature on consistency coefficient of *rabri* from 15% T.S. to 45% T.S. shows that the value of consistency coefficient (m) increases at exponential rate between 20 ^{o} C to 40 ^{o} C. This may be due to the fact that as we proceed below 40 ^{o} C temperature the solidification of fat takes place at faster rate. This solidified fat increases the consistency coefficient (m) of *rabri* –a fat rich product.

4. Flow behaviour index of *rabri* at different stages of processing of *rabri* from 15% T.S. to 45% T.S. (at 90^{o}C) indicates the inverse relationship between T.S. & flow behaviour index (n) values. So as the T.S.% increases the 'n' value decreases.
5. Variation in consistency coefficient of *rabri* at different stages of processing from 15% T.S. to 45% T.S. (at 90^{o} C) suggests a positive relationship between T.S.% and consistency coefficient (m). From the fig.5.9 to 5.15. However as the T.S.% increased from 30% T.S. to 40%T.S. , the value of 'm' showed exponential rise.
6. Flow behaviour index of *rabri* at different stages of processing from 50% T.S. to 65% T.S. elucidated inverse relationship between T.S.% and flow behaviour index (n). As the 'n' value decreased the T.S.% increased, thus conversely as the moisture % decreased flow behaviour index (n) also decreased.
7. Variation in consistency coefficient of *rabri* at different stages of processing from 50% T.S. to 65% T.S shows a gradual increase in values. However, the rate of the increase was diminishing as the T.S.% was progressively increasing.

The overall goal of this study was to provide engineering design information; therefore, the future work should head in the direction to find the following parameters necessary for design of the equipment for in-line production of *rabri*.

–Mean velocity of product flow

–Energy losses due to friction in pipe

–Energy losses in pumping

–Energy losses in fittings

–Power requirement for pumping at different % T.S. & operating conditions.

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APPENDIX-A

Table 1: Flow Behaviour Index & Consistency coefficient of rabri at different % Total Solids & Temperature (for Constant temperature capillary tube viscometer).

% Total Solids	Temperature (^oC)	Flow Behaviour Index (n)	Consistency coefficient (m) ($Kg_f sec^n/m^2$)
15	90	1.0181	0.000439922
	80	1.018	0.000561699
	70	1.0177	0.000598107
	60	1.0012	0.000682666
	50	0.9991	0.000770482
	40	0.9724	0.000843812
	30	0.9616	0.001109716
	20	0.9562	0.001330384
20	90	0.9987	0.000538164
	80	0.9982	0.000585866
	70	0.9876	0.000701856
	60	0.9804	0.00074178
	50	0.9792	0.001020576
	40	0.974	0.00128939
	30	0.9575	0.001461284
	20	0.9414	0.001616234
25	90	0.9884	0.000607521
	80	0.9871	0.000630553
	70	0.9859	0.000715831
	60	0.9649	0.000838663
	50	0.9437	0.001030614
	40	0.9273	0.001158087
	30	0.904	0.001950694
	20	0.8768	0.002610602
30	90	0.9833	0.000585418
	80	0.9768	0.000659939
	70	0.976	0.0008544
	60	0.9673	0.000977049
	50	0.944	0.001319871
	40	0.9085	0.001574956
	30	0.8581	0.002634185
	20	0.8052	0.005028878

…contd.(Table 1)

% Total Solids	Temperature (^oC)	Flow Behaviour Index (n)	Consistency coefficient (m) ($Kg_f sec^n/m^2$)
35	90	0.9734	0.002578158
	80	0.9707	0.002649905
	70	0.9684	0.002951773
	60	0.908	0.00525545
	50	0.8715	0.009427251
	40	0.8062	0.016036989
	30	0.7187	0.045212806
	20	0.7118	0.08587139
40	90	0.9611	0.003291794
	80	0.9598	0.004353169
	70	0.9549	0.003867098
	60	0.8887	0.005818189
	50	0.821	0.01080413
	40	0.7534	0.019958143
	30	0.6191	0.08251241
	20	0.5475	0.151165944
45	90	0.953	0.001961508
	80	0.9374	0.002473685
	70	0.9135	0.003493401
	60	0.8229	0.004708445
	50	0.7677	0.005833901
	40	0.679	0.009157348
	30	0.5649	0.015072999
	20	0.5095	0.044541752

APPENDIX-B

Table 2: Flow Behaviour Index & Consistency coefficient of rabri at different stages of processing (for Constant temperature capillary tube viscometer).

% Total Solids	Flow Behaviour Index (n)	Consistency coefficient (m) ($Kg_f sec^n/m^2$)
15	1.0181	0.000439922
20	0.9987	0.000528164
25	0.9884	0.000647521
30	0.9833	0.000854181
35	0.9734	0.001578158
40	0.9611	0.003291794
45	0.953	0.004961508

APPENDIX-C

Table-3 : Pressure drop verses capillary flow data for condensed milk at Different temperatures.

Temperature	Pressure Drop	Flow Rate	Temperature	Pressure Drop	Flow Rate
(°C)	(10^4 Kg_f/m^2)	(Q) m^3/sec	(°C)	(10^4 Kg_f/m^2)	(Q) m^3/sec
15 % Total Solids			15 % Total Solids		
90	0.2	4.46	50	0.2	5.65
	0.4	5.31		0.4	5.85
	0.6	10		0.6	7.74
	0.8	14.28		0.8	9.33
	1	15.86		1	16.66
	1.2	21.73		1.2	22
	1.4	22.91		1.4	25
80	0.2	5.88	40	0.2	4.87
	0.4	7.25		0.4	5.85
	0.6	10.75		0.6	7.14
	0.8	11.84		0.8	1.75
	1	21.42		1	17.5
	1.2	22.27		1.2	21.15
	1.4	33.33		1.4	25.9
70	0.2	5.4	30	0.2	4.2
	0.4	6.25		0.4	5.55
	0.6	7.44		0.6	8.65
	0.8	11.07		0.8	9.52
	1	14.13		1	14.68
	1.2	20.27		1.2	23.63
	1.4	29.16		1.4	24.58
60	0.2	6	20	0.2	5.87
	0.4	6.33		0.4	6.11
	0.6	8.33		0.6	7.66
	0.8	9.44		0.8	9
	1	18.63		1	12.82
	1.2	20.41		1.2	22.14
	1.4	28		1.4	28.75

…contd.(Table-3)

Temperature	Pressure Drop	Flow Rate
(^oC)	(10^4 Kg_f/m^2)	(Q) m^3/sec
20 % Total Solids		
90	0.2	5.12
	0.4	5.41
	0.6	11.25
	0.8	16.66
	1	19.5
	1.2	23.15
	1.4	24.21
80	0.2	5.71
	0.4	5.89
	0.6	9.28
	0.8	13
	1	23.12
	1.2	23.52
	1.4	25
70	0.2	5.55
	0.4	5.44
	0.6	8.04
	0.8	15.66
	1	17.5
	1.2	21.11
	1.4	26.25
60	0.2	3.88
	0.4	6.42
	0.6	7.27
	0.8	14.66
	1	19.5
	1.2	20
	1.4	21.5

Temperature	Pressure Drop	Flow Rate
(^oC)	(10^4 Kg_f/m^2)	(Q) m^3/sec
20 % Total Solids		
50	0.2	6.4
	0.4	7.69
	0.6	8.52
	0.8	10.66
	1	9.33
	1.2	23.33
	1.4	25
40	0.2	40
	0.4	5.35
	0.6	6.5
	0.8	10.66
	1	14.16
	1.2	22.22
	1.4	22.5
30	0.2	2.87
	0.4	3.39
	0.6	8.25
	0.8	9
	1	10.33
	1.2	13.33
	1.4	18.75
20	0.2	2.77
	0.4	5.75
	0.6	11
	0.8	12.18
	1	15.38
	1.2	19.44
	1.4	20.52

…contd.(Table-3)

Temperature (^{o}C)	Pressure Drop (10^4 Kg_f/m^2)	Flow Rate (Q) m^3/sec
25 % Total Solids		
90	0.2	4.42
	0.4	6.75
	0.6	15.55
	0.8	15.62
	1	20.83
	1.2	24
	1.4	25
80	0.2	3.11
	0.4	5.4
	0.6	10.33
	0.8	17.33
	1	21.81
	1.2	25
	1.4	25
70	0.2	5.1
	0.4	5.2
	0.6	15.71
	0.8	18
	1	20
	1.2	22
	1.4	23.07
60	0.2	5.34
	0.4	4.8
	0.6	14.28
	0.8	18
	1	19
	1.2	21
	1.4	22

Temperature (^{o}C)	Pressure Drop (10^4 Kg_f/m^2)	Flow Rate (Q) m^3/sec
25 % Total Solids		
50	0.2	3.85
	0.4	5.38
	0.6	15.33
	0.8	17.14
	1	17.27
	1.2	20
	1.4	21.81
40	0.2	3.6
	0.4	5.68
	0.6	8.18
	0.8	16.66
	1	20
	1.2	20
	1.4	21.53
30	0.2	2.83
	0.4	4.1
	0.6	6.66
	0.8	9.66
	1	14.5
	1.2	15
	1.4	21.87
20	0.2	2.22
	0.4	3.4
	0.6	7.33
	0.8	9.33
	1	14
	1.2	15
	1.4	15.5

…contd.(Table-3)

Temperature (^oC)	Pressure Drop (10^4 Kg_f/m^2)	Flow Rate (Q) m^3/sec	Temperature (^oC)	Pressure Drop (10^4 Kg_f/m^2)	Flow Rate (Q) m^3/sec
30 % Total Solids			30 % Total Solids		
90	0.2	5.65	50	0.2	3.71
	0.4	5.8		0.4	4.35
	0.6	13.46		0.6	10
	0.8	18.88		0.8	14
	1	22.77		1	14.61
	1.2	28.57		1.2	18.66
	1.4	28.59		1.4	21.53
80	0.2	4.63	40	0.2	3.12
	0.4	5.4		0.4	4.64
	0.6	10.33		0.6	12.85
	0.8	15.29		0.8	14.28
	1	21.53		1	17.5
	1.2	25.83		1.2	17.85
	1.4	25.83		1.4	18.66
70	0.2	4.25	30	0.2	2.71
	0.4	6.66		0.4	3.8
	0.6	7.33		0.6	5.93
	0.8	12.5		0.8	11.66
	1	16.66		1	15.62
	1.2	18.33		1.2	17.02
	1.4	20		1.4	17.64
60	0.2	4.23	20	0.2	22.5
	0.4	5.14		0.4	2.83
	0.6	12.5		0.6	5
	0.8	15		0.8	8
	1	15.83		1	14.5
	1.2	17.5		1.2	14.5
	1.4	23.33		1.4	16.5

…contd.(Table-3)

Temperature (^oC)	Pressure Drop (10^4 Kg_f/m^2)	Flow Rate (Q) m^3/sec
35 % Total Solids		
90	0.2	1.28
	0.4	1.71
	0.6	3.75
	0.8	5.25
	1	5.5
	1.2	6.25
	1.4	7.89
80	0.2	1.51
	0.4	1.66
	0.6	2.7
	0.8	4.34
	1	5.47
	1.2	6.75
	1.4	8.42
70	0.2	1.28
	0.4	1.61
	0.6	2.5
	0.8	4.66
	1	5
	1.2	6.33
	1.4	7.33
60	0.2	1
	0.4	1.4
	0.6	1.8
	0.8	3.66
	1	4.66
	1.2	5.33
	1.4	6.5

Temperature (^oC)	Pressure Drop (10^4 Kg_f/m^2)	Flow Rate (Q) m^3/sec
35 % Total Solids		
50	0.2	8
	0.4	0.85
	0.6	1.57
	0.8	2.8
	1	3.4
	1.2	4.18
	1.4	5
40	0.2	8
	0.4	0.77
	0.6	1.6
	0.8	2
	1	3.4
	1.2	4.31
	1.4	5.5
30	0.2	0.45
	0.4	0.66
	0.6	1
	0.8	1.66
	1	2.16
	1.2	3.5
	1.4	5.88
20	0.2	0.33
	0.4	0.41
	0.6	1
	0.8	1.33
	1	2.3
	1.2	2
	1.4	4.25

…contd.(Table-3)

Temperature (^oC)	Pressure Drop (10^4 Kg_f/m^2)	Flow Rate (Q) m^3/sec
40 % Total Solids		
90	0.2	0.88
	0.4	2.2
	0.6	2.6
	0.8	3.2
	1	4.76
	1.2	5.52
	1.4	7.35
80	0.2	0.86
	0.4	1.06
	0.6	1.87
	0.8	3.2
	1	3.6
	1.2	4.31
	1.4	5
70	0.2	0.91
	0.4	1.42
	0.6	2.17
	0.8	3.33
	1	4.25
	1.2	5
	1.4	6.56
60	0.2	0.97
	0.4	1.28
	0.6	2.16
	0.8	3.4
	1	5
	1.2	6
	1.4	6.33

Temperature (^oC)	Pressure Drop (10^4 Kg_f/m^2)	Flow Rate (Q) m^3/sec
40 % Total Solids		
50	0.2	0.88
	0.4	1.07
	0.6	2.4
	0.8	4
	1	4.75
	1.2	5.95
	1.4	6.47
40	0.2	0.58
	0.4	0.87
	0.6	2.2
	0.8	3.75
	1	4.5
	1.2	5
	1.4	5
30	0.2	0.26
	0.4	0.42
	0.6	1.2
	0.8	2.5
	1	2.83
	1.2	3.22
	1.4	4.2
20	0.2	0.16
	0.4	0.36
	0.6	1.83
	0.8	2.5
	1	2.66
	1.2	3.06
	1.4	3.33

…contd.(Table-3)

Temperature (^oC)	Pressure Drop (10^4 Kg_f/m^2)	Flow Rate (Q) m^3/sec
45 % Total Solids		
90	0.2	2.17
	0.4	3.09
	0.6	3.77
	0.8	4.05
	1	8.8
	1.2	10.58
	1.4	12.05
80	0.2	1.91
	0.4	2.32
	0.6	3.45
	0.8	4.17
	1	8
	1.2	10
	1.4	10.21
70	0.2	1.4
	0.4	2.67
	0.6	3.26
	0.8	4.25
	1	6.93
	1.2	10.6
	1.4	9.33
60	0.2	1.03
	0.4	2.27
	0.6	3.07
	0.8	4.1
	1	6.83
	1.2	8.91
	1.4	10.47

Temperature (^oC)	Pressure Drop (10^4 Kg_f/m^2)	Flow Rate (Q) m^3/sec
45 % Total Solids		
50	0.2	0.92
	0.4	1.96
	0.6	4.39
	0.8	5.71
	1	8.12
	1.2	8.25
	1.4	10.58
40	0.2	0.67
	0.4	1.11
	0.6	2.28
	0.8	3.4
	1	6.25
	1.2	6.47
	1.4	10
30	0.2	0.44
	0.4	0.63
	0.6	2.36
	0.8	3.4
	1	6.56
	1.2	6.17
	1.4	9.11
20	0.2	0.31
	0.4	0.5
	0.6	1.5
	0.8	2.14
	1	6.17
	1.2	6.76
	1.4	8.33

All values are average of three replicas at each pressure.

APPENDIX-D

Table 4: Flow Behaviour Index & Consistency coefficient of rabri at different % Total Solids & Temperature (for Back extrusion method).

% Total Solids	Flow Behaviour Index (n)	Consistency coefficient (m)
50	0.3305677	1.095709
55	0.2621462	1.239671
60	0.249357	1.349443
65	0.2329615	1.399423

Table-5 : Recorded values of plunger speed and Force used for the calculation of Consistency coefficient (m) and Flow Behaviour Index (n).

% T.S.	Vp (mm/s)	F_t	F_{te}	F_{cb}
50	1.5	0.36	0.266	0.094
	3	0.39	0.251	0.139
	4.5	0.402	0.244	0.158
	6	0.417	0.257	0.16
	3			0.139
	4.5			0.158
	6			
55	1.5	0.372	0.258	0.114
	3	0.411	0.267	0.144
	4.5	0.436	0.269	0.167
	6	0.439	0.271	0.168
	3			0.144
	4.5			0.144
60	1.5	0.35	0.25	0.1
	3	0.387	0.241	0.146
	4.5	0.392	0.239	0.153
	6	0.388	0.233	0.155
65	1.5	0.369	0.26	0.109
	3	0.408	0.251	0.157
	4.5	0.428	0.264	0.164
	6	0.431	0.266	0.165

APPENDIX-E

Table-6 : Flow Behaviour Index (n) & Consistency coefficient (m) values for different possible combinations of plunger speeds.

% T.S.	combinations	n	Ave. of 'n'	Dimensionless Flowrate	Dimensionless Radius	Consistency coefficient (m)	Avg of m
50	n12	0.56	0.33	0.6006	0.03	1.13	1.09
	n13	0.47		0.5914	0.038	1.19	
	n14	0.38		0.5831	0.055	1.22	
	n23	0.31				1.29	
	n24	0.2		0.5625	0.074	0.6	
	n34	0.04		0.5525	0.004		
55	n12	0.33	0.26			1.41	1.23
	n13	0.34		0.5625	0.077	1.44	
	n14	0.27		0.5625	0.078	1.33	
	n23	0.36		0.5625	0.08	1.44	
	n24	0.22				0.55	
	n34	0.02		0.5776	0.076		
60	n12	0.52	0.23				1.31
	n13	0.37					
	n14	0.29				1.25	
	n23	0.1		0.5929	0.03	1.39	
	n24	0.07		0.583	0.054	1.31	
	n34	0.02		0.5676	0.075		
65	n12	0.54	0.24	0.5525	0.004	1.39	1.34
	n13	0.38				1.38	
	n14	0.31		0.5929	0.04	1.26	
	n23	0.11		0.5776	0.06		
	n24	0.08		0.5677	0.078		
	n34	0.04					