DEWATERING AND DRYING CHARACTERISTICS OF COFFEE PULP

By

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THESIS SUBMITTED TO THE UNIVERSITY OF NAIROBI IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

DEPARTMENT OF AGRICULTURAL ENGINEERING

1991

DECLARATION

This thesis is my original work and has not been submitted for examination in any other university

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This thesis has been submitted with our approval as university supervisors

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ABSTRACT

MSc. THESIS

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The major constraint in the utilisation of coffee pulp is its high moisture content. For easy storage, the moisture content of the pulp needs to be lowered to about 15% wet basis. A two stage process comprising mechanical Dewatering followed by drying is effective in removing water from the coffee pulp. However, to design appropriate equipment for dewatering and drying coffee pulp, the dewatering and drying characteristics of the pulp need to be known. For this purpose, studies on dewatering and drying of coffee pulp were undertaken in order to identify and relate the parameters important to these two stages of processing.

The dewatering process was investigated by subjecting coffee pulp samples to consolidated drained (CD) triaxial compression tests. Four levels of constant cell pressures and continuously increasing axial pressure were used to vary the dewatering conditions.

Studies into the drying of coffee pulp were undertaken in a ventilated laboratory oven. Drying temperatures were between 75°C to 150°C because coffee pulp dries fastest within this range, besides the ease to achieve constant temperature and relative humidity in the oven. Drying experiments were conducted at four levels of initial moisture content obtained by mechanical removal of 0%, 5%, 10% and 20% of the fluid from four separate coffee pulp samples.

The results indicate that the behaviour of coffee pulp collected at different times of the picking season is generally very diverse even when subjected to similar dewatering conditions. For the increasing pressure conditions the relationship between expressed fluid and applied pressure was exponential. No relationship was found between expressed fluid and rate of applying pressure because the latter varied in unpredictable manner. However when under constant pressure an exponential relationship was identified between expressed fluid and pressing duration. Empirical equations for these relationships were developed.

A linear relationship was found to exist between expressed fluid and reduction in sample volume. However, the reduction in sample volume is bigger than the corresponding expressed fluid.

The drying studies culminated with the development of an empirical equation for predicting the moisture content of coffee pulp during drying. However, for this equation to be applicable in the field, further work is required to establish the equilibrium moisture content at different conditions of temperature and relative humidity.

The empirical equations developed for both dewatering and drying of coffee pulp seem to be dependent on other unknown factors inherent to the samples besides those covered by this study. These equations can be refined by studies into the physical and biological properties of coffee pulp.

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NOMENCLATURE

[ ]	brackets enclosing reference numbers
A	Cross sectional Area of filtering surface or specimen
A_o	initial area of the specimen
α	average specific cake resistance
a, b, c	empirical constants
c_1, c_2	empirical constants
db	dry basis
dl	Change in length of the specimen
dp/dx	pressure gradient
dp/dx_s	pressure gradient across the media
E	axial unit strain
E_f	expressed fluid
G	gross weight of petri dish with dry coffee pulp
h	hours
k	permeability constant
ln	natural logarithm
l_o	initial length of the specimen
m	Empirical constant
M	Moisture content, % dry basis
M_1	moisture content of wet pulp
M_2	moisture content of dry pulp
Me	equilibrium moisture content, % dry basis
Mo	initial moisture content
MR	moisture ratio
Mt	moisture content of coffee pulp at any time t

n	net weight of petri dish
N	Newton
p	pressure (Pa)
Pa	Pascals
P_a	axial pressure
P_c	cell pressure
p_f	total pressure drop across filtering medium and the cake deposit
r	filter medium resistance
t	time
μ	viscosity of filtrate
V	velocity of fluid flow (dx_f/dt)
v	volume of the expressed fluid per unit mass ml/kg
v_f	volume of the filtrate collected
v_m	reduction in the volume of the mash per unit mass of mash, ml/kg
w	mass of accumulated dry cake solids corresponding to V_f
W_1	weight of wet pulp
W_2	weight of dried pulp
wb	wet basis
x_f	position of an incremental volume of the fluid
x_s	position of an incremental volume of solids

ACKNOWLEDGEMENTS

The author wishes to express his deep felt gratitude to the Germany Academic Exchange Service (DAAD) for generously providing sponsorship for this programme.

Gratitude is also due to the project supervisors Dr D K Some and Dr L O Gumbe for their keen interest in guiding him through this period of hard work and also for their devotion in offering valuable guidance and any other needy assistance in the preparation of this thesis.

I am also greatly indebted to the Director of Research, Coffee Research Foundation (CRF) for permitting the implementation of this study at Coffee Research Station (Ruiru) using some of the station equipment.

The author is very pleased with the entire staff of the Chemistry Section of CRF who assisted in this project, in particular Mr P. K. Mwaura whose technical assistance in the conduct of the experiments is gratefully acknowledged.

CHAPTER 1

INTRODUCTION

At the coffee factories, two different methods of primary processing are used to obtain intermediate products that will subsequently be treated in exactly the same way to provide the coffee beans. These methods are wet processing, which produces parchment coffee and dry processing, which produces dried cherry coffee. While the former involves pulping ripe and fresh coffee berries, the latter is essentially a hulling process of the dry fruits. The various stages of the overall processes are illustrated in figure 1.1

In Kenya, the wet process is the most common method. This procedure requires the selective picking of the just ripe coffee berries [plate 1.1] from a coffee bush and feeding a stream of well sorted and uniformly ripe coffee cherry in water to a pulper that removes the outer skin of the berries and separates the pulp [Plate 1.2] and the parchment. Pulp is then disposed off as waste while parchment coffee is subjected to further processing as outlined in figure 1.1

There are two coffee picking seasons that normally coincide with the rainy season every year and each extends for about three months. The amounts of coffee cherry picked are quite variable throughout the season. Coffee processing factories are also scattered all over the coffee growing areas [Table 1.1] and are of different cherry intake capacities. The coffee pulp realised in any season is hence quite variable among coffee factories of different capacities, and is also scattered all over the coffee growing areas.

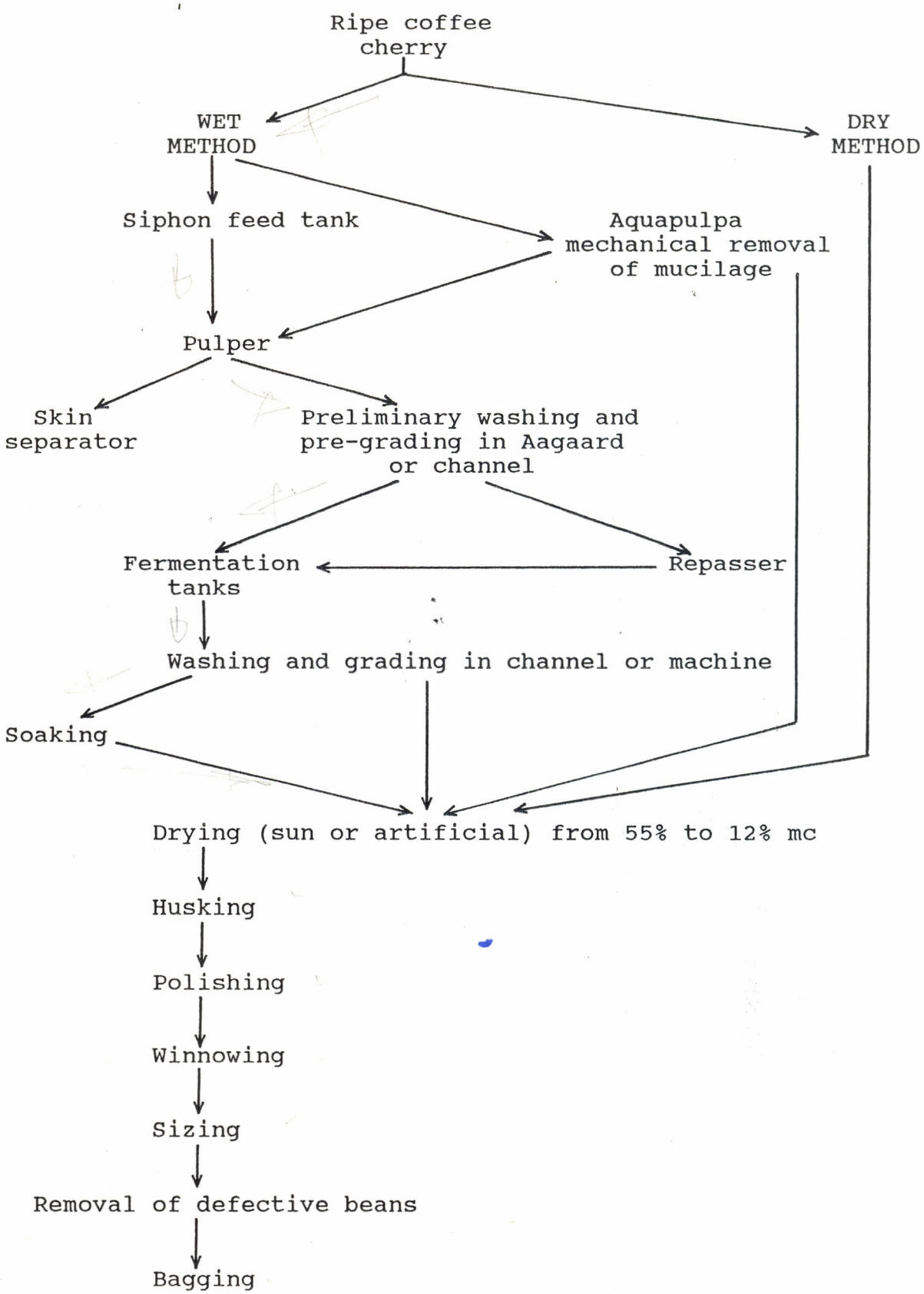


Figure 1.1: Stages in the conversion of cherry to clean coffee.
Source: Wringly [1]

Plate 1.1: Ripe coffee cherry at the sorting stage

Plate 1.2. Coffee Pulp at the disposal site

Table 1.1 Coffee Factory Distribution in Kenya

District	Cooperative (Operating)	(Approved/Under Construction	
		Private	Cooperative
Kiambu	67	48	2
Muranga	101	7	4
Kirinyaga	54	4	1
Nyeri	72	13	2
Kitui	2	-	-
Meru	147	1	-
Embu	44	4	-
Machakos	65	2	-
Taita	5	-	-
West Pokot	2	-	-
Baringo	5	-	-
Nandi	4	-	-
Kericho	3	-	-
Kisii	71	-	2
South Nyaza	13	-	-
Siaya/Kisumu	6	-	-
Bungoma	30	-	-
Kakamega	14	-	-
Kajiado	2	-	-
Total	684	79	11

Source: [1]

Kenya produces more than 100,000 tonnes of clean coffee annually [2]. Since about two tonnes of coffee pulp result from the production of every tonne of clean coffee [3], about 200,000 tonnes of coffee pulp would be expected annually [table 1.2]. Coffee production is also projected to triple by the year 2000 [4]. Consequently a proportionate increase in the amount of coffee pulp produced is expected.

Table 1.2 Coffee Production and the Corresponding Coffee Pulp

Year	Clean Coffee (tonnes)	Coffee Pulp (tonnes)
1980/81	9851	197502
1981/82	86923	173846
1982/83	85450	170900
1983/84	128941	257882
1984/85	93639	187278
1985/86	113926	227852

Source: [1]

Fresh coffee pulp from wet processing has a high initial moisture content that ranges from 75% to 88% wet basis of which 4% to 5% is free water gained during pulping [5]. It is also highly degradable and in the process likely to cause environmental pollution particulary if permitted to access natural waterways. Due to the expected increase in coffee pulp, there is need to ensure that disposal problems leading to serious pollution are not experienced in the future.

Previous research indicate that coffee pulp has some agricultural and industrial potential [5]. Such a potential is observed in the following possibilities for its utilisation.

i. Inclusion as an ingredient of feed rations for livestock, birds and fish [5,6,7,8].

ii. Composting it into a fertilizer and soil conditioner [5,7,9].

iii. Natural digestion to produce biogas. The digested sludge has a substantial manure value [3,5,7,9,10].

iv. Extraction of sugars, caffeine, pectic enzymes and protein rich feedstuff [5,7,11].

v. Growth of mushrooms and worms in fermenting and composting coffee pulp respectively [7].

vi. Production of vinegar [5,12].

viii. To provide heat energy [7].

However some economic and technical factors exist that tend to constrain its utilisation. Among such factors are its chemical composition, high moisture content, scattered manner of production and availability in varying amounts among coffee processing factories and within the coffee picking season [5,6,7]. The high moisture content has been identified as the major drawback in its utilisation for it makes it difficult to handle, transport, process, store and preserve the pulp [3,5,6,7]. As has been the case, attention is mainly placed on bean processing during the coffee picking season. It has also not been possible to use the fresh coffee pulp immediately it is produced. As the pulp is highly perishable and likely to suffer from microbial contamination, there is need then to store it in a preservable form if the intention is to use it "as is ", as some of its identified possible uses require [3,5,6,7]. Besides this aspect, some of the identified uses require the reduction of coffee pulp moisture content to specifically required levels [3,5,6,7]. To overcome such and other related problems, a sun drying process has been tried to provide the solution [5,6,7]. However, due to the high moisture content of coffee pulp, this process alone has been found rather unsatisfactory due to the long drying periods experienced together with high drying costs attributed to the labour and the drying space required [5,8]. A dewatering process preceding dehydration has been found to shorten the latter greatly [5,6]. However, suitable technology capable of effectively executing these processes technically and

economically have yet to be identified. This has primarily been due to the lack of data with regard to the dewatering and drying behaviour of this material [5]. This project aims to investigate the behaviour of coffee pulp subjected to a two stage process comprising of dewatering and drying. The importance of this study is seen in the role the results obtained will have in influencing the design of suitable dewatering and drying equipment.

1.2 Objectives

The broad objective of this study is to evaluate dewatering and drying characteristics of coffee pulp. Specifically the objectives of the study are:

i. To identify the physical characteristics that influence the dewatering and drying of coffee pulp.

ii. To develop predictive empirical equations by curve fitting for the factors identified in (i) above.

CHAPTER 2

LITERATURE REVIEW

2.1 General

The initial moisture content of coffee pulp lies between 75% and 88% of which 4% to 5% is surface water gained during pulping. This high water content has been viewed to represent the main drawback in the utilization of this by-product from the point of view of its transportation, handling, processing and preservation [3,5,6,7]. Most of the uses of coffee pulp require the reduction of the initial moisture content by specific levels to facilitate other processes that might be required [5,7].

In the utilisation of coffee pulp [5], the aspects to be considered include;

i. The seasonal availability of coffee pulp in large amounts.

ii. The implications of the high initial moisture content (75%- 85%) with respect to degradation and microbial contamination.

iii. The most immediate utilisation of coffee pulp is as an ingredient of animal feed rations [5,7,8].

iv. Transport and processing requirements since the animal producer is not necessarily a coffee processor nor are the animal production facilities necessarily located at the same site as the coffee processing industry.

In some cases like where coffee pulp is to be used as a feed, fresh coffee pulp has to be processed immediately after production and within a relatively short period to avoid any

likely contamination. A two stage process consisting of a mechanical dewatering followed by a drying process is the most suitable for this purpose [5,7].

The major factors which limit the utilization of coffee pulp by some animal species can be overcome by inventing suitable technologies and processing techniques which are capable of improving its potential as a feed [5,6,7].

The optimum composting condition of coffee pulp for instance is influenced by moisture content among other factors [3,5,7]. The composting process is reported to require the environmental conditions to be manipulated to optimise it in order to produce in as short time as possible a final product that can easily be handled, stored and applied to land without adverse effects [9].

The moisture content of coffee pulp is an important consideration in composting, in that below about 12% (wb) all biological activities cease while at levels of about 60% (wb) compaction and water logging of the composting pile will create an anaerobic conditions within it which is a slow process. The recommended optimum moisture content for composting coffee pulp in a windrow is around 50% (wb) [3].

In the synthesis of protein rich product from coffee pulp, the first step in this process involves pressing out the juice [5]. The juice can also be used to produce biogas.

Biogas has been produced from a mixture of coffee pulp and cow dung mixed in the ratio of 1:3. Coffee pulp alone has been observed to perform poorly in this aspect mainly because of its large particle sizes. Finely ground coffee pulp or/and juice pressed out of coffee pulp are more effective in terms of gas

production than coffee pulp obtained straight from a pulper [13].

Although the effects of some of the operations intended to reduce the moisture content of coffee pulp have been observed, development of technically and economically suitable technologies for processing coffee pulp into suitable form is limited by lack of information describing the behaviour of coffee pulp when subjected to a set of dewatering and drying conditions [5].

2.2 Dewatering

The water that coffee pulp gains during pulping can drain off given time if coffee pulp is left to stand on a meshed or sloppy surface. The balance that form the bulk of the water content is intracellular water. This does not drain unless the pulp has undergone through certain chemical changes like happens in ensiled coffee pulp [5,7]. Drainage of water gained during pulping can be improved if the coffee pulp is stirred continuously. The surface water drains easily and within a short time but if the pulp is left to stand for long, more water can drain from the pulp but its state would have changed [5,7]. However, due to the high moisture, coffee pulp has been observed to be very perishable and starts changing its state immediately after pulping.

Drainage of water from a coffee pulp pile or silo takes considerably long and is capable of reducing the water content down to about 70% (wb) [3,5]. If microbial contamination of coffee pulp is to be avoided, physical means have to be considered in order to lower the moisture content down to a safe level and at a rate fast enough to prevent any undesirable

changes [5].

Coffee pulp drying methods considered in previous research include; a pressing action prior to drying, addition of calcium salts (Calcium carbonate or calcium hydroxide prior to drying, addition of enzymes like Ultrazym-100 (from Ciba-Geigy Switzerland) to fresh coffee pulp and ensiling.

A pressing action preceding drying that reduces the moisture content by 6%-8% (wb) shortens the drying period by one-eighth to one-sixth [5]. This is possible due to the elimination of some of the mucilaginous pectin like constituents of the pulp and some of the simple sugars, and thus makes the pulp easier to dry. Besides the above effects, the pressing action was also observed to reduce the pulp volume by 20%-50% which facilitates the drying operation and increases the capacity of the drier as well [4]. A pressing action has been observed as the most suitable drying method among the others. This process lowers the moisture of coffee pulp to 34-36% (db) or to 6-8% [ie. from 85 to 78% wb]. The pulp volume also decreases by 20-50% expressing out sugars and mucilaginous substances and the particles get desegregated facilitating further the drying operation and increasing the capacity of the drier. Ensiled coffee pulp with a moisture of about 70% also dries faster after being subjected to a pressing action [5].

Experiments on pressing coffee pulp showed that the time required to sun dry coffee pulp in good, dry weather is reduced from 16 to 4 hours [5]. Such an effect could be attributed not only to the elimination of sugars and pectines through the pressing action but also to the desegregation of the pulp

consequently increasing the drying rate. The reduction in drying time for coffee pulp with 5% molasses ensiled for three months prior to pressing was less than that for fresh pulp [5]. Further research concerning the possible nutritional changes in materials subjected to pressing was recommended for a cost-benefit figure for the system as a whole to be calculated [5].

Addition of calcium salts to coffee pulp enhances water removal either by pressing or drying. Coffee pulp treated in this manner had the best final appearance. Use of these salts in excess of 5% of the wet weight of the pulp is however detrimental to the nutritional quality of coffee pulp [5,6,7]. Results from the addition of enzymes like Utrazym-100 had been poor [5].

Studies of the dewatering process in other agricultural materials like cassava mash and alfalfa led to the modelling of representative equations for the respective dewatering process [14,15].

Attempts to compare mechanical dewatering to the flow of fluid in porous media [15] as described by Darcy's law [Eq 2.1]

$$V=k\frac{dp}{dx_s} \qquad [2.1]$$

observed that this law cannot be used to predict mechanical dewatering because this process normally causes deformation and creep of the material leading to a reduction in porosity and hence permeability. Material thickness in the direction of load applied is also reduced such that at a constant load the pressure gradient increases with time [15]. Instead, mechanical dewatering has been viewed as being similar to filtration which can

therefore be represented by Poisseuille's equation which may be adapted as;

$$\frac{dVf}{Adt} = \frac{\Delta p}{\mu[\alpha(\frac{W}{A}) + r]} \qquad [2.2]$$

The same source reported that when a material is subjected to pressure over time it tends to approach an equilibrium moisture content which dependent only on the pressure exerted. Equation [2.3] was developed for this relationship.

$$Me = ap^b \qquad [2.3]$$

The importance of the equilibrium moisture content is seen in its capability to describe the final attainable moisture content of the product when subjected to a set of dewatering conditions.

The factors investigated had no effect on both the solid content and the density of the expressed fluid. The reduction in volume of the cassava mash over time was observed to be greater than the volume of the expressed fluid possibly due to the compaction and creep that occurs during the process [14]. For the volume of the expressed liquid per unit mass of mash the model with the best fit can be expressed as in equation 2.4 where $72Pa<p<789Pa$ and $0<t<48h$.

$$V = 0.0423p^{0.2245}t^{0.1475} \qquad [2.4]$$

For the reduction in the volume of the mass per unit mash the model that gave the best fit was;

$$V=0.0420p^{0.2243}t^{0.1527} \qquad [2.5]$$

Among the many models developed to relate moisture content at any time during dewatering to the factors investigated, the model that gave the least standard error of the estimate of moisture content was;

$$\frac{(M-Me)}{(Mo-Me)}=\exp(-2.366p^{-0.217}t^{0.259}) \qquad [2.6]$$

That study [14] concluded that, the equilibrium moisture content of the dewatered mash was affected only by the applied pressure. The solid content of the expressed liquid did not change significantly during dewatering and was unaffected by such factors as the applied pressure from 72 to 789 Pa, screen porosity from 2.9 to 34.5% and material depth from 35 to 12 cm.

Mechanical dewatering of coffee pulp through a pressing action reduces the moisture content by only 6% to 8%(wb). This implies that dewatering possibly facilitates the drying process of coffee pulp mainly by a conditioning effect [5]. Such an observation is supported by work on mechanical conditioning of alfalfa using intermeshing rubber rolls [16]. It was also reported that an increase in the drying rate of first cutting of alfalfa with a small effect on second cutting and no effect on latter cuttings. [16]. Chemical conditioning with aqueous potassium carbonate can increase the drying rate of alfalfa in any cutting, but has the greatest effect under the crop and drying conditions of second and third cutting. Both mechanical

and chemical conditioning processes were observed to posses additive effects.

2.3 Drying

Little information is available on the basic drying characteristics of coffee pulp. The limited work undertaken to date indicate that, drying of coffee pulp is greatly influenced by temperature and sample properties which are thought to include altitude at which coffee was grown, degree of ripeness, cultural practices, time of storage prior to drying, variety and pulverisation of pulp by the pulper or a dewatering equipment [5]. Two distinct drying phases of coffee pulp are known to exist; the constant and the falling rate periods [5]. Depending on the temperature employed, the length of either phase varies inversely or at the expense of the other [table 2.1]. For coffee pulp to dry at a fast rate, the constant rate drying phase has to be made as long as possible since it is faster than the falling rate. It is possible to dry coffee pulp at a constant rate to 10-15% moisture, which is considered necessary for its stability against microbial activity. It is then possible to achieve this through a constant rate drying period with air temperatures set between 75°C and 150°C. Use of air temperatures higher than 150°C shortens the constant rate drying period thereby lengthening the retention time and possibly ruining the nutritive value of the dry pulp [5]. Due to the high moisture content and other inherent properties of coffee pulp it is normally rather expensive to lower its moisture content down to between 10% and 15% by drying alone because of the high

temperatures required for fast drying. Use of low drying temperatures would make the drying period so long that the pulp would have degenerated due to microbial contamination during the drying process [5].

Table 2:1 Drying Phases of Coffee Pulp at Different temperatures

Temperature (°C)	Change in Moisture Content	Drying Phase
75 to 150	70% to 12%	Constant rate
	12% to 6%	Falling rate
170 to 200	85% to 40%-45%	End of Constant rate

Source: [4]

Experiments conducted using various driers and drying systems identified sun drying as being still the most common and viable system in terms of technical and economic considerations despite the long weather dependent drying time which might lead to microbial contamination [5,6]. However due to the cumbersome aspects inherent to sundrying, there is need to develop suitable mechanical drying and/or drying aid system for coffee pulp [5,6]. In this respect a rotary drier, coupled to a burner utilising agricultural, agro-industrial or industrial by-products either alone or in combination with petroleum based fuels appear to be the most technically and economically sound [5]. In all the trials on mechanical drying the change in chemical composition and nutritive value of coffee pulp was insignificant [5,7].

Ensiling permits the storage of coffee pulp during the busy coffee processing season for latter drying using the same facilities as the coffee bean. Preliminary observations indicate that the ensiled material requires a relatively shorter drying time than fresh coffee pulp when sun dried. An ensiling operation

prior to pressing has also been seen to increase the effectiveness of this operation in reducing the drying time [5,6,7].

Drying can also be facilitated if it is preceeded by mechanical dewatering. The implication of dewatering to drying of coffee pulp are that the drying process starts with material at a lower initial moisture content that is likely to dry within a relatively shorter time [5]. The heat energy requirements are also drastically reduced. This is an important aspect since the fuel requirements for the drying process more than any other aspect contribute to increasing the cost of drying system [5,6,7,8].

Chances of coffee pulp for immediate use as an animal feed is limited by its availability at a time when grass is also plenty. However, if coffee pulp is dried to a moisture content of 14%, it can be stored without deterioration in quality for periods of upto 17 months within which it can be used whenever need arises [17].

CHAPTER 3

3.0 THEORETICAL CONSIDERATIONS

3.1 Dewatering

Coffee pulp is a compressible biological residual. When adequately squeezed, some of the intracellular fluid is expressed out accompanied by very minimal loss in nutrients. The fluid from each pulp particle passes through the porous coffee pulp matrix to the outside. As the pressure on the pulp is maintained, it is accompanied by volume reduction. However, reduction in volume of the pulp would not be expected to equal the corresponding expressed fluid because of the air spaces in the void. This type of consolidation during dewatering coffee pulp by pressing leads to the following changes [5];

The mucilaginous substances coating the inner surface of the pulp gets removed. This facilitates easy passage of water from inside the pulp during drying [5,6,7]. The pulp particles also undergoes changes in shape and size resulting in easier drying because of possible rupturing of cells.

Being a compressible bio-residue, volume is reduced during dewatering. The capacity of the dryer is then increased thereby enhancing drying.

As coffee pulp is compressed its porosity changes leading to a reduction in the permeability of the pulp matrix. Darcy' law that describes the flow of fluid through a porous media fails to predict the flow of fluid through a coffee pulp matrix because of changes in permeability. Instead, dewatering is more of a filtration process because the reduction in permeability plays a similar role of resisting the flow of fluid like the build up

of the cake in filtration.

For an axial load on a solid material with very low compressibility, the axial unit strain [E] can be computed by dividing the change in length of the specimen, by the initial length of the specimen [Eq.3.1].

$$E=\frac{dL}{L_o} \qquad [3.1]$$

Each corresponding cross-sectional area of the specimen can be computed by use of the equation 3.2

$$A=\frac{A_o}{(1-E)} \qquad [3.2]$$

Each corresponding applied axial load in the triaxial test can be determined by multiplying the proving ring [Plate 4.3] dial reading by the proving ring calibration. Finally, each unit axial load can be computed by dividing each applied axial load by the corresponding cross-sectional area. However, a compressible material like coffee pulp behaves differently because it can consolidate in the direction of the applied load with minimal transverse expansion as in a consolidated drained triaxial compression test under constant cell pressure in which case the cross sectional area remains fairly constant. This makes it possible to express axial pressure as shown in equation 3.3.

$$P_a = f_f / A_o \qquad [3.3]$$

The various pressures that act on a coffee pulp sample are illustrated in figure 3.1. The minor principal stress P_c in a sample subjected to controlled dewatering conditions is equal to the cell pressure. The major principal stress denoted by P is expressed as

$$P = P_a + P_c \qquad [3.4]$$

The factors thought to be most important to mechanical dewatering by pressing and which are considered in this research are applied pressure, material thickness [Fig.3.2], pressing duration and volume reduction. As expressed fluid is a function of these and other possible factors, equation 3.5 can serve to illustrate this relationship.

$$E_f = f(p, h, t, v, \ldots) \qquad [3.5]$$

The actual relationship between expressed fluid and the other parameters can be derived by curve fitting techniques of the numerical method.

3.2 Drying

Coffee pulp drying is extremely slow at low temperatures and inefficient in terms of heat utilization. The temperatures at which the drying period is shortest lies between 75°C and 150°C. At temperatures above 150°C, the drying rate decreases due to some unknown changes that take place in the pulp [5]. In order to record reproducible measurements of the drying process, it is necessary to conduct the experiments under controlled conditions

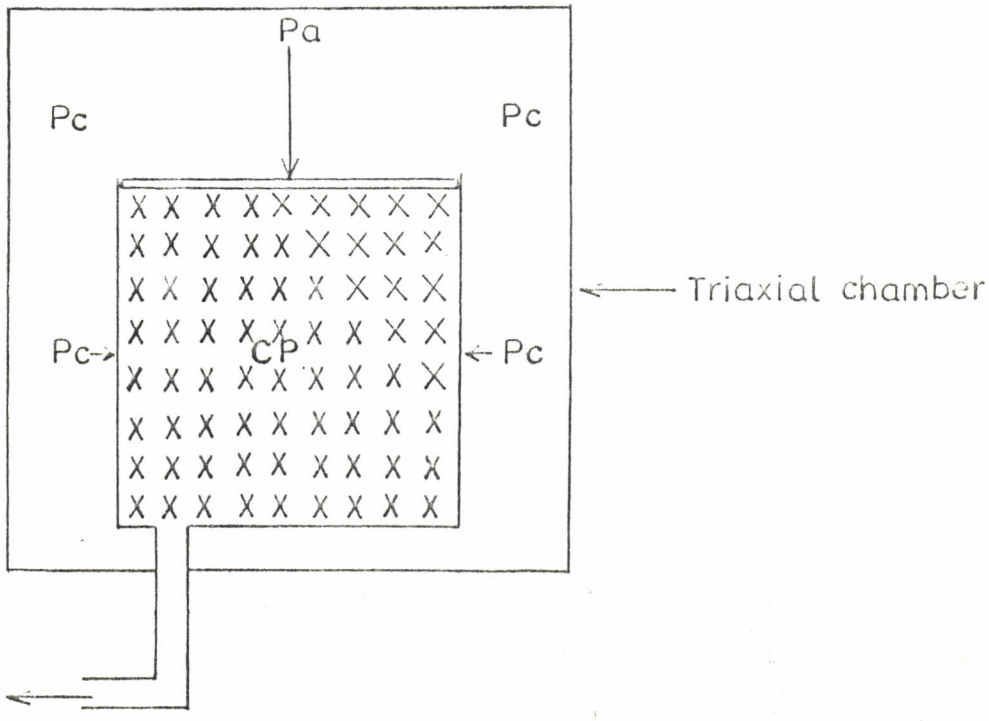
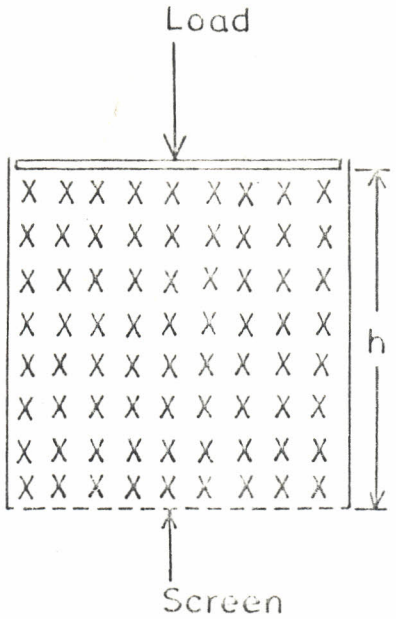


Figure 3.1. Coffee pulp sample subjected to axial and cell pressure.



h— Thickness of coffee pulp sample.

Figure. 3.2. Illustration of material thickness with respect to direction of applied load and flow of fluid.

of temperature and relative humidity. For this purpose coffee pulp was dried at high temperatures which were maintained constant for each experiment.

When ambient air enters into a ventilated oven which has been set at between 75°C to 150°C, it gets heated such that its relative humidity is lowered down to a negligible and relatively constant value (ie zero percent) regardless of the changes in ambient air conditions normally experienced as can be inferred from [fig.3.3]. Based on this assumption drying of coffee pulp in a ventilated oven maintained at temperatures of 100°C and above can be assumed to occur at fairly constant and controlled conditions.

Once again curve fitting can be used to develop empirical equations relating the current moisture content to the initial moisture content, equilibrium moisture content and drying time.

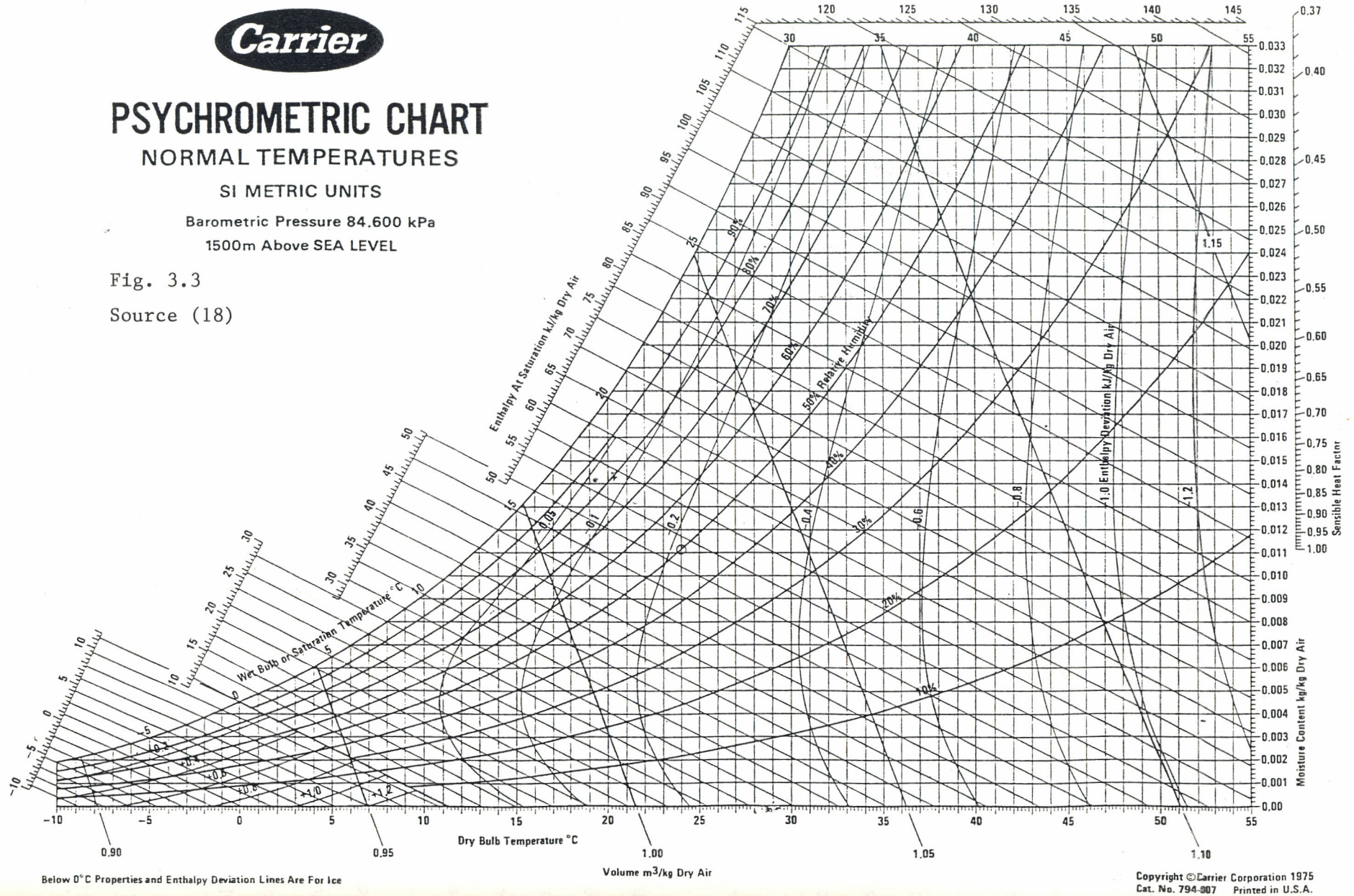


Fig. 3.3

Source (18)

CHAPTER 4

4.0 METHODOLOGY

4.1 Dewatering

4.1.1 Experimental Design

This experiment was designed to establish the effects of applied axial pressure, confining cell pressure, changes in sample height and process time on expressed fluid. These factors were investigated by conducting consolidated drained triaxial compression tests on fresh coffee pulp at cell pressures of 0.7, 1.2, 2.2, 3.1×10^{-3}Pa. Each test was conducted under a constant cell pressure replicated four times. Other sets of experiment were conducted at constant cell pressures in the absence of axial pressure to determine the relationship between applied constant pressure and expressed fluid with respect to time. Similarly, these experiments were replicated four times.

4.1.2 Procedure

Studies into the behaviour of fresh coffee pulp subjected to a set of controlled dewatering conditions were undertaken by way of consolidated drained triaxial compression tests. Coffee pulp samples were collected from a coffee factory during pulping and kept under refrigeration until the following day. They were then packed in an ice box and transported to the Civil Engineering Department of University of Nairobi for the test.

Details of the triaxial chamber used in this experiment are shown in figure 4.1. The experiment was set up as follows;

Using a plastic tubing a burette was connected to the triaxial chamber. Some clean water was added to the burette from

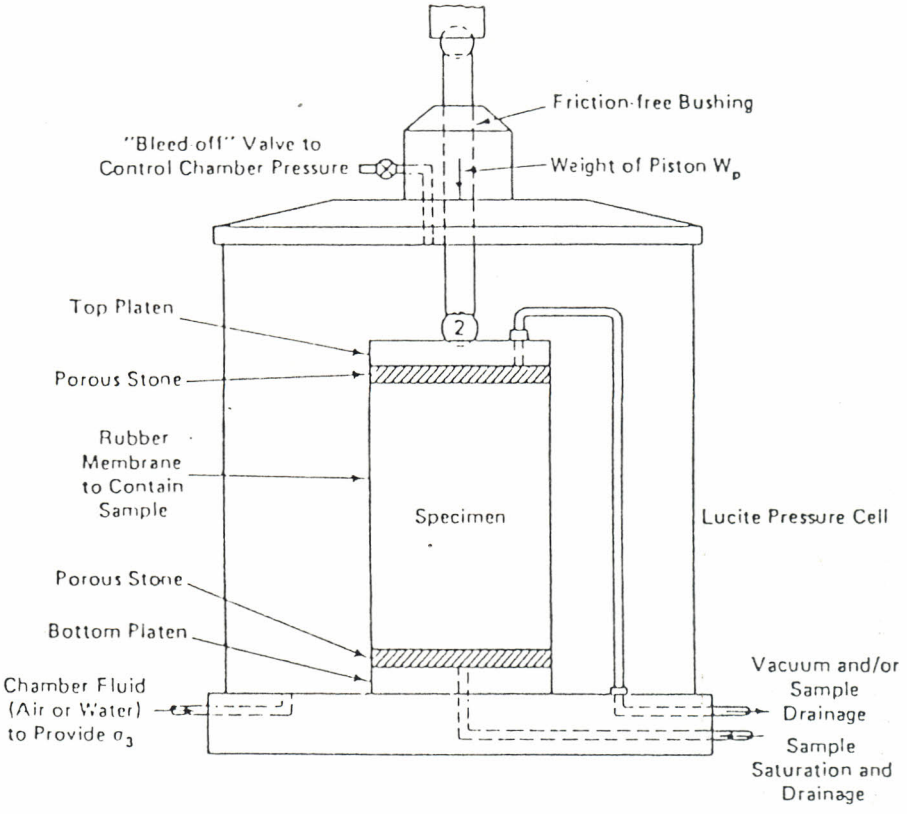


FIGURE 4.1 Schematic Diagram of the Triaxial Chamber [1]

a wash bottle to the lowest mark possible. The burette reading against the water level was then recorded.

The porous stones were first removed and cleaned by brushing them with a wire brush in hot water. The bottom stone was placed at the position shown [fig.4.1] and tested for porosity using pressurized water. A rubber membrane was then secured using two rubber bands. Some of the coffee pulp was transferred from the ice box to a plate and the contents weighed. Coffee pulp from the plate was put in the rubber membrane without compacting until it was adequately filled.

The upper porous stone and the top platen were then secured in place by two rubber bands [Plate 4.1]. The sample height was then measured using a ruler and recorded to ensure that it remained constant in all the experiments.

The balance of coffee pulp in the plate was then weighed. The difference between the gross weight and the balance weight gave the sample weight. The rest of the experiment was set up as shown in plate 4.2.

The chamber surrounding the rubber membrane was filled with water. On filling the chamber, the inlet valve to the chamber was closed before closing the "bleed off" valve to control chamber pressure. All this time the burette valve remained closed. The initial strain gauge reading was noted. The burette valve was opened and the required cell pressure applied simultaneously.

While further adjustments were made to maintain the cell pressure constant the sample was allowed to consolidate and drain. On achieving stable conditions of pressure the new strain gauge reading was recorded and application of axial load

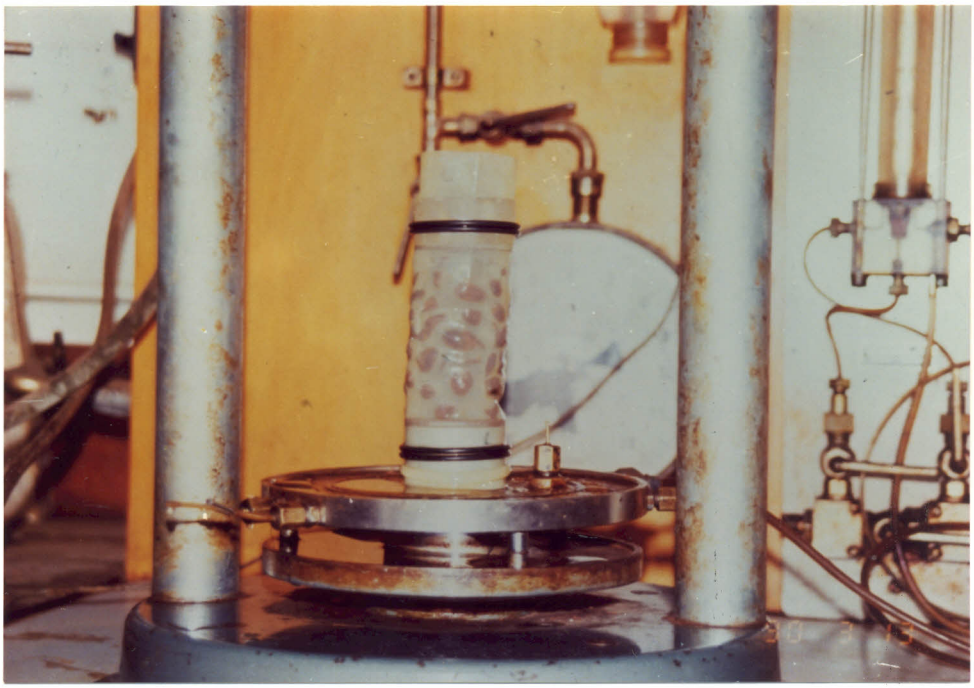


Plate.4.1. Coffee pulp in the rubber membrane

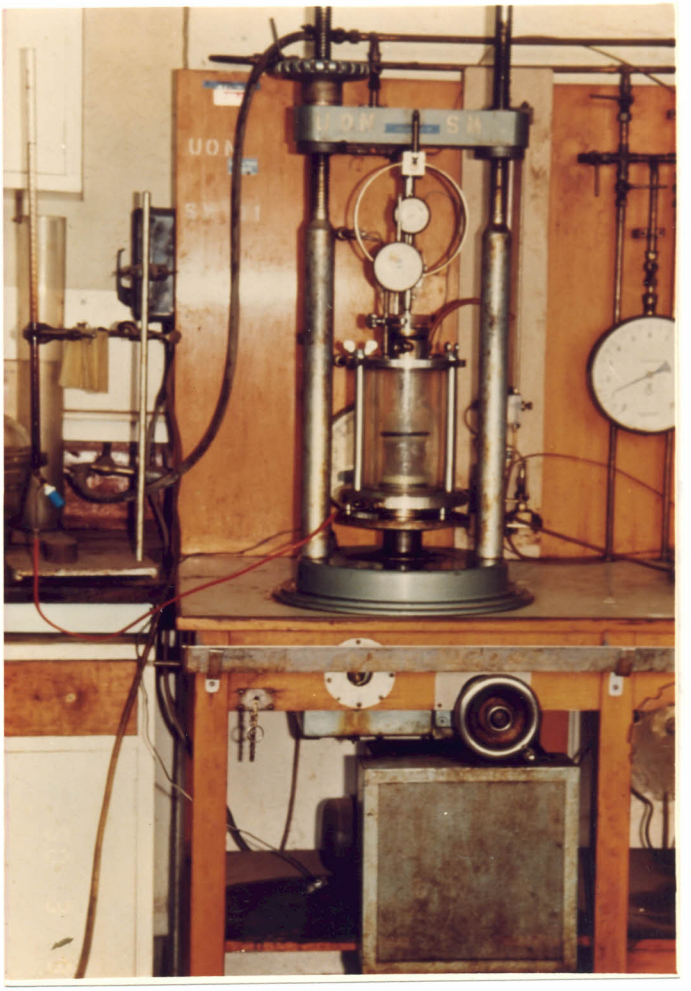


Plate 4.2. Triaxial compression test in progress

commenced immediately. As compression progressed, records of the axial load, time, expressed fluid, strain gauge reading were all taken at the same time. This test continued until the sample height changed by about 55% of the original height. This was the maximum reduction in height possible for this equipment.

Following this procedure experiments were run based on constant cell pressures of 0.7, 1.2, 2.2, and 3.1×10^{-3}Pa replicated four times.

4.2 Drying

4.2.1 Experimental Design

Studies on the drying of coffee pulp were undertaken in a ventilated oven set and maintained at 105°C, 130°C and 150°C. The initial moisture contents of the coffee pulp samples dried at each temperature were varied by 5%, 10% and 20% through a dewatering process. At each temperature and dewatering level the experiments were replicated four times.

4.2.1 Procedure

4.2.1.1 Determination of initial Moisture Content of Coffee Pulp

Coffee pulp samples were sampled from a coffee factory during pulping. These samples were then transferred to the laboratory in polythene bags immediately.

The moisture content of the pulp was then determined by the standard oven method while closely adhering to the following procedure.

i. Four flat glass petri dishes were washed, dried and weighed.

ii. A fresh coffee pulp sample was then weighed in each petri dish. This weight less that in (i) gave the weight of wet pulp.

iii. The dishes together with their contents were placed in a ventilated oven maintained at 130°C and allowed to dry for 5 hours.

iv. The gross weights of the petri dishes were then monitored by removing the samples from the oven and cooling them in a desiccator before weighing until three constant consecutive readings were noted. This final weight less that in (i) gave the final weight of dry coffee pulp at which the moisture content is assumed to be zero.

v. The initial moisture content of fresh coffee pulp was then determined by use of equation 4.1. described in [18]. The results obtained are presented in table 5.3.

$$M_2 = 100 - W_1 \frac{(100 - M_1)}{W_2} \qquad [4.1]$$

4.2.1.2 Drying Coffee Pulp Under Controlled Conditions

The initial moisture content of fresh coffee pulp whose drying behaviour was to be studied was first determined as outlined in section 4.2.1

Fresh coffee pulp from the same sample was then put in a meshed tray of known weight [Plate 4.3]. The tray with a coffee pulp sample was then suspended in a ventilated oven with a metallic wire through the top vent to a spring balance above the oven [Plate 4.4]. A sheet of paper was used to protect the balance from the direct oven heat.

The oven was then set at a specified temperature lying between 75°C and 150°C. The loss in weight of the pulp in the tray was regularly recorded at specified time intervals until three consecutive readings were observed. This experiment was undertaken at four different temperatures with four replicates at every temperature.

Similar experiments were undertaken using coffee pulp whose initial moisture content had been reduced mechanically by 5%, 10%, and 20%. Unpressed coffee pulp samples were dried to act as control indicated by 0% level of dewatering.

The moisture content of coffee pulp at any time during the drying process was determined by using equation 4.1.

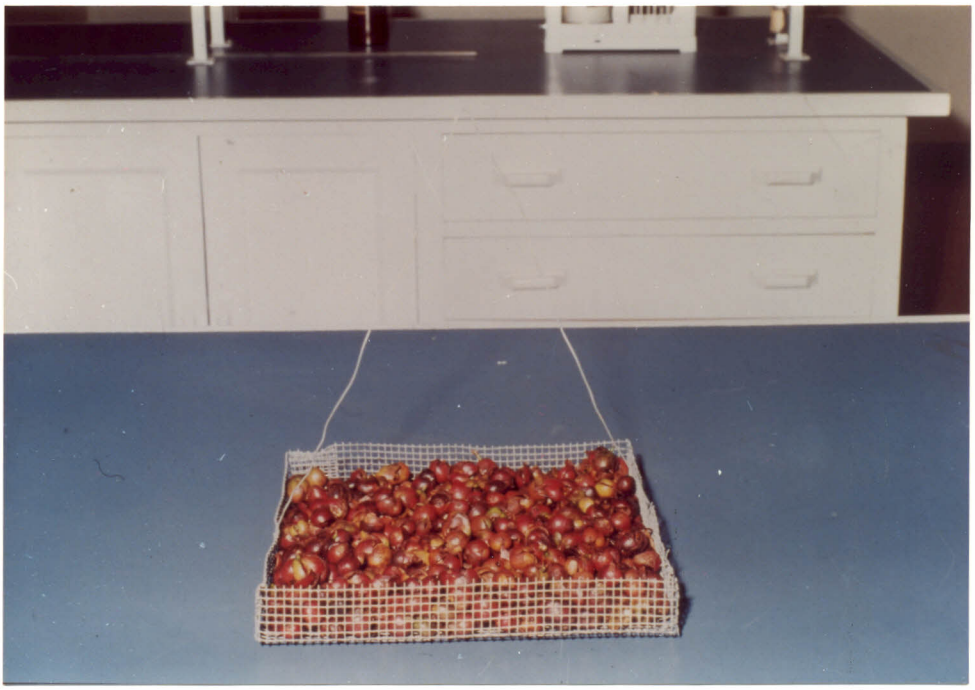


Plate 4.3. Coffee pulp in a meshed tray

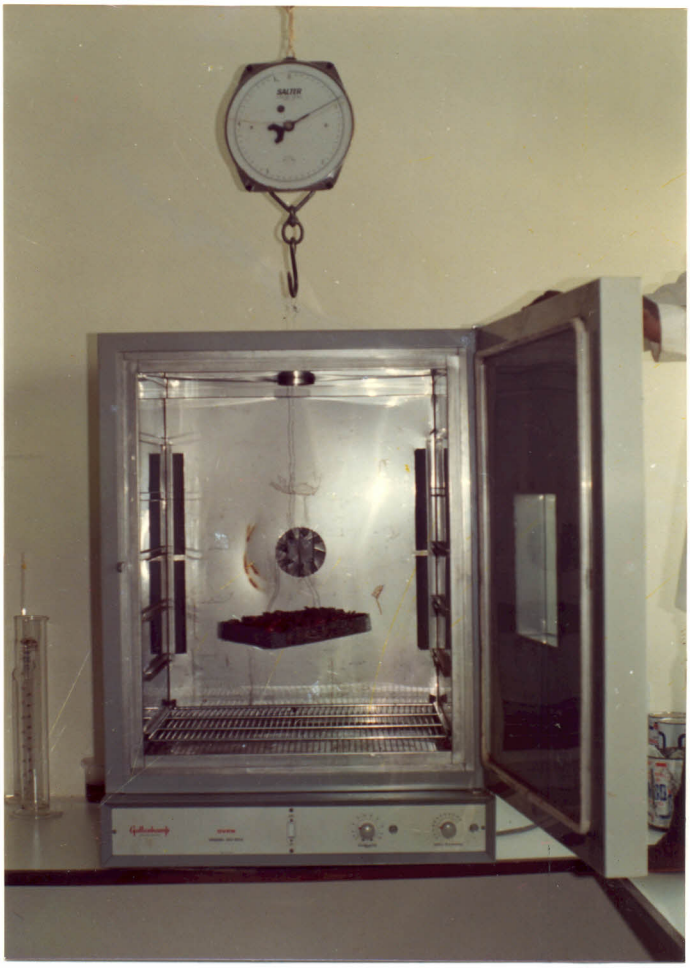


Plate 4.4. Equipment used to dry coffee pulp.

CHAPTER 5

5.0 RESULTS AND DISCUSSION

5.1 Results

5.1.1 Dewatering

The data collected from the triaxial compression tests is presented in appendix 1.0. This data was analyzed by curve fitting techniques. In this program, attempts were made to relate various parameters graphically to the expressed fluid (E_f) from coffee pulp subjected to a set of dewatering conditions.

In order to perceive the effect of applied pressure (P) to expressed fluid (E_f) with respect to time, the three parameters at constant cell pressures were plotted together and the curves drawn by the computer traced as shown in figures 5.1a to 5.1d. The labels E_i and P_i refer to the corresponding values of E_f and P recorded at the same time in each experiment (ie E_1 and P_1 are corresponding values of expressed fluid and pressure for experiment 1). These figures show that, even before the pulp responds to the increasing axial pressure, some fluid is normally expressed due to the influence of the cell pressure. Thereafter expressed fluid is effected by the major principal stress (axial pressure + cell pressure). It was observed that, results from various samples collected at different times of the picking season [table A1.0] and subjected to similar dewatering conditions were not consistent. The results varied so much that average values could not be used to plot representative curves. However, a general trend was observed in the family of curves plotted. Although application of pressure on coffee pulp caused some fluid to be expressed, the highest P did not necessarily

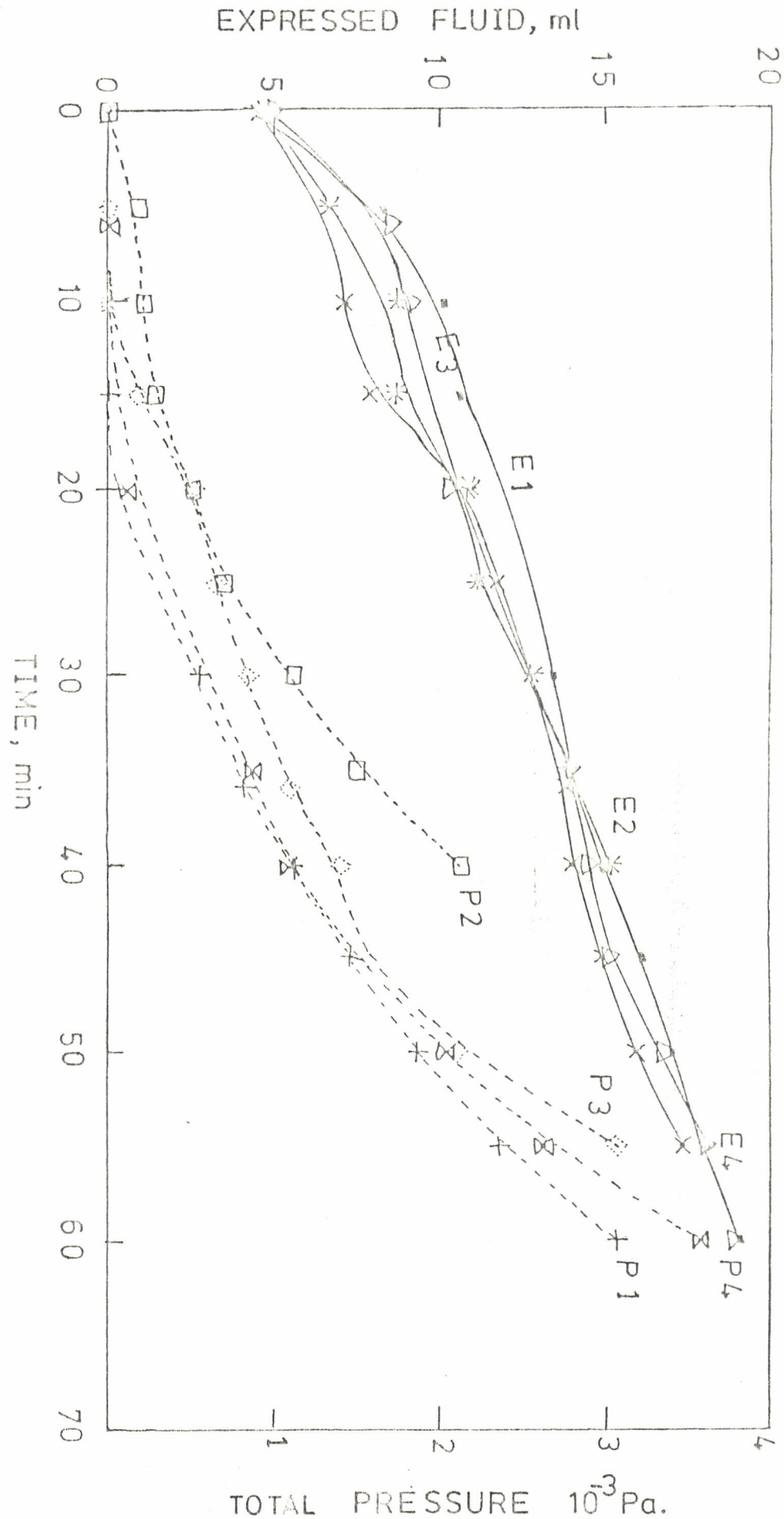


Figure. 5.1a. Expressed fluid and the corresponding total pressure as functions of time and a cell pressure of 0.7×10^{-3} Pa.

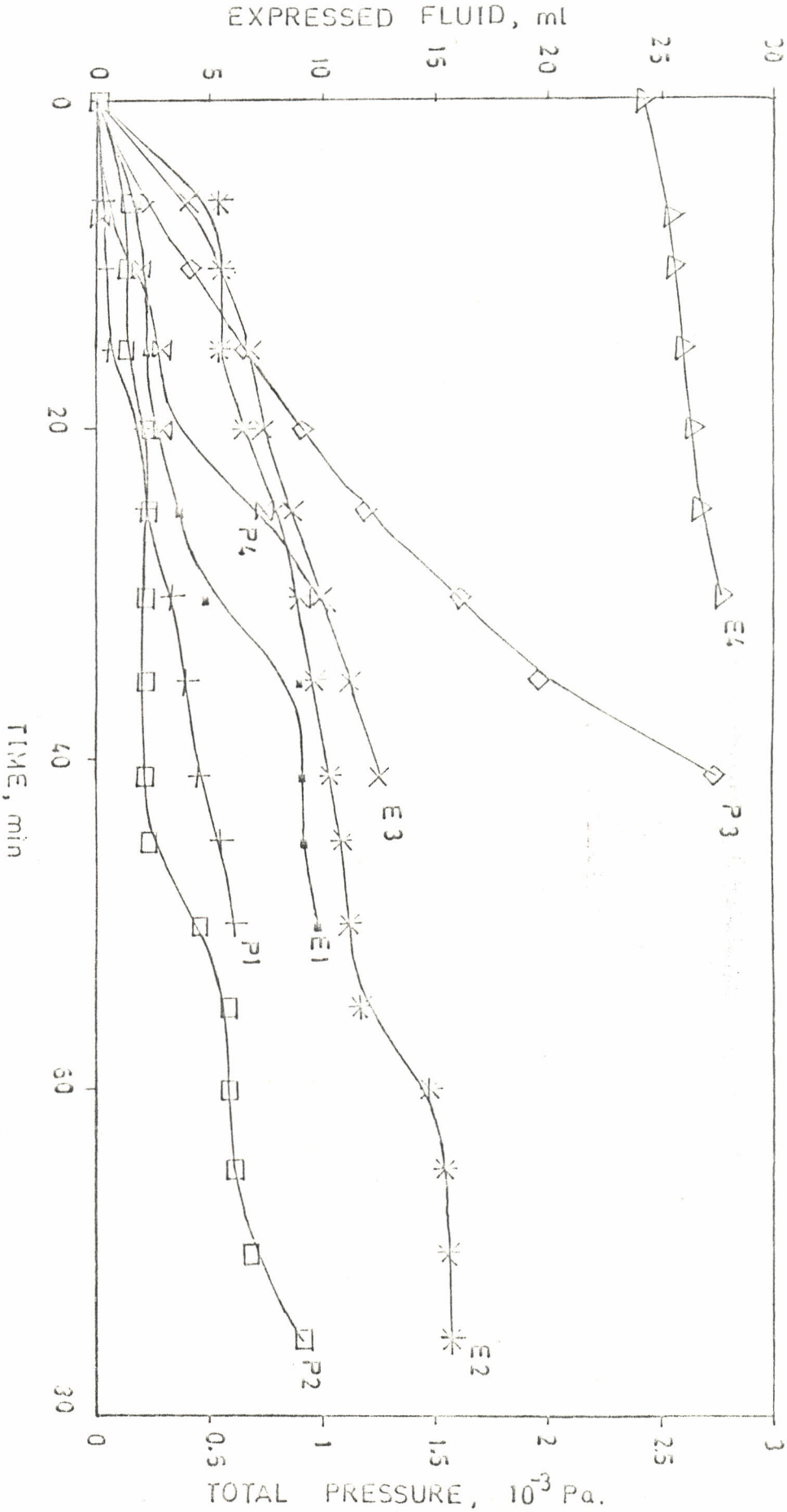


Figure. 5.1b. Expressed fluid and the corresponding total pressure as functions of time and a cell pressure of 1.2×10^{-3} Pa.

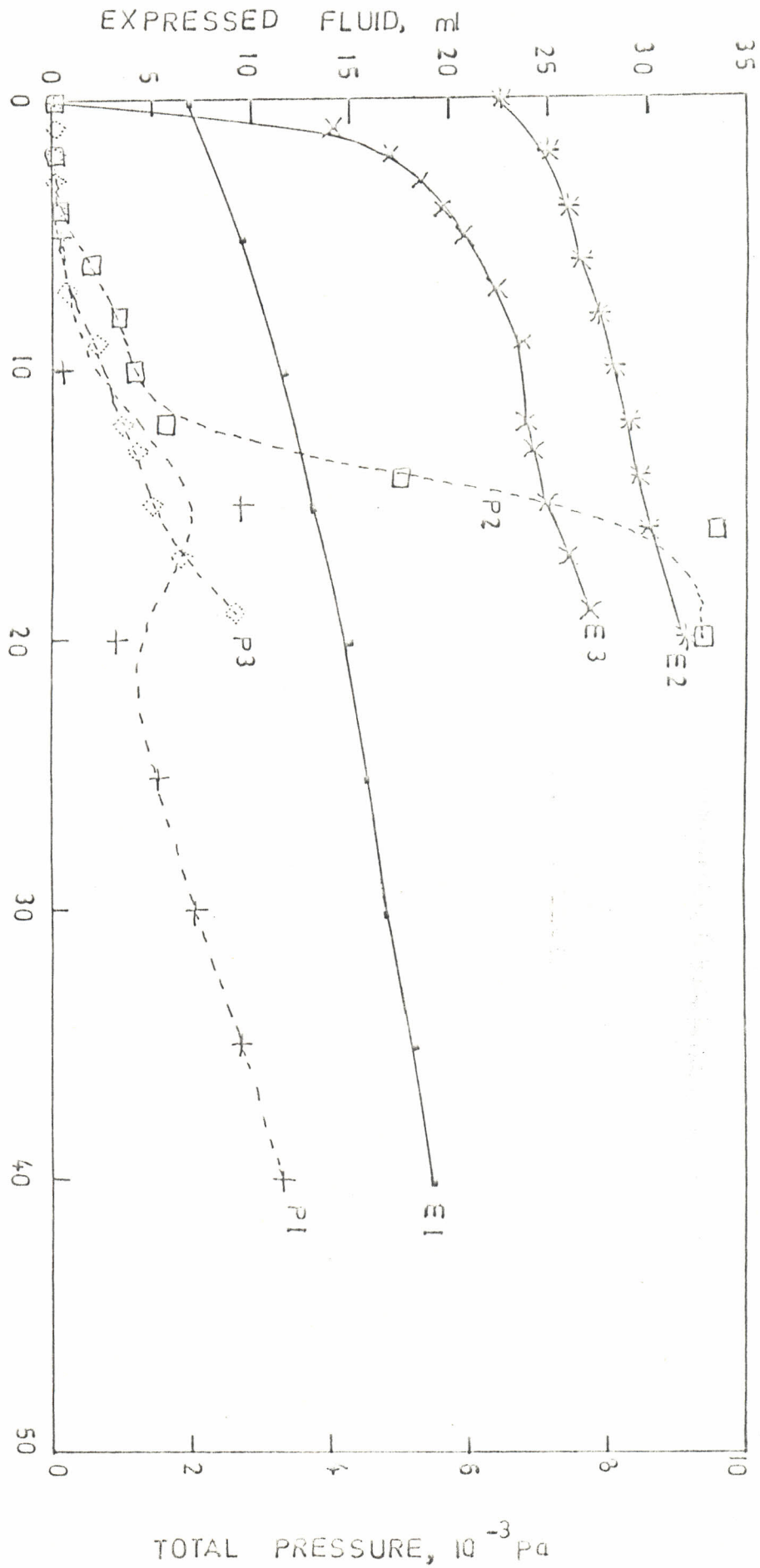


Figure 5.1c. Expressed fluid and the corresponding total pressure as functions of time and a cell pressure of 2.2×10^{-3} Pa.

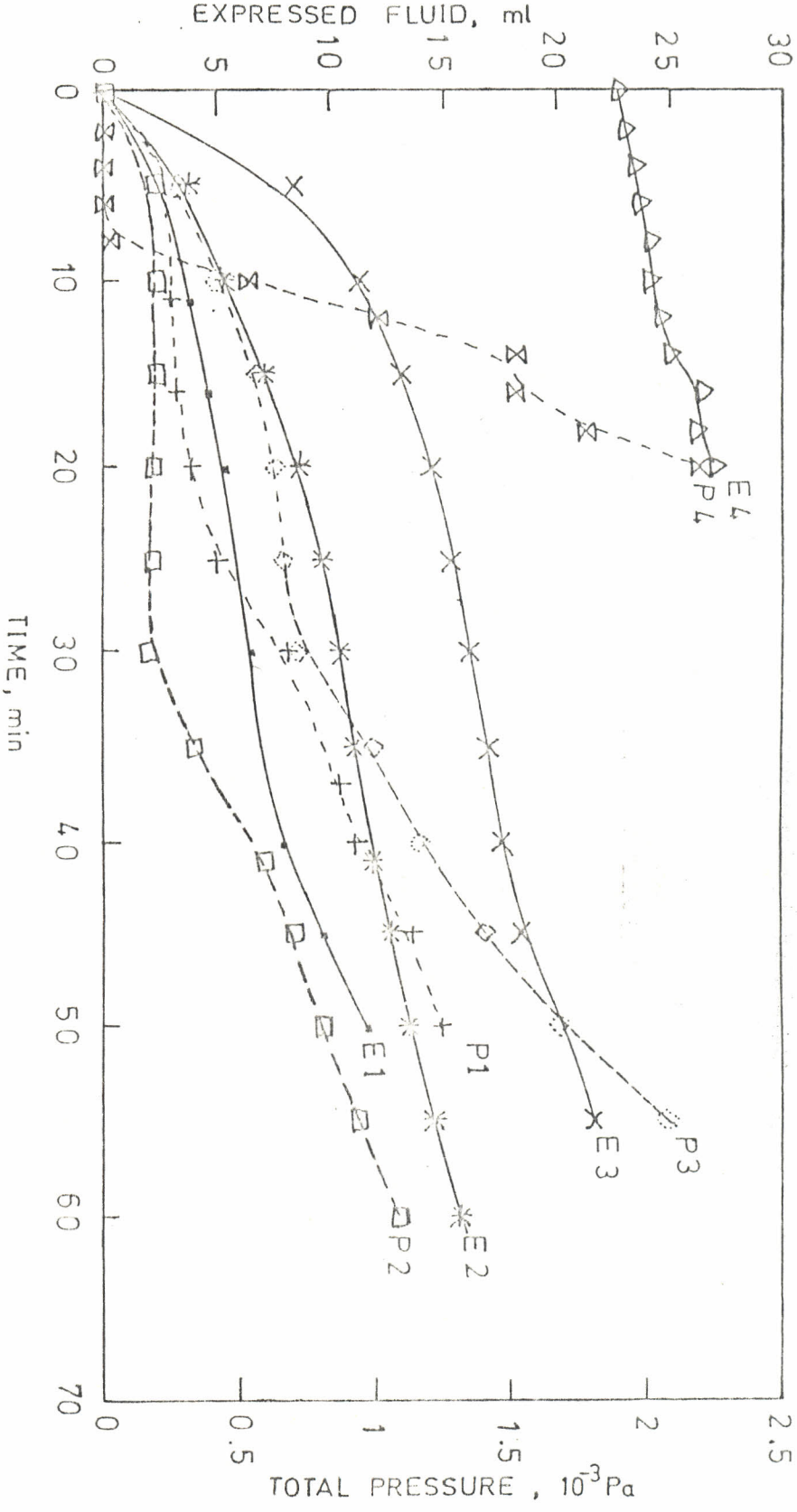


Figure. 5.1d. Expressed fluid and the corresponding total pressure as functions of time and a cell pressure of 3.1×10^{-3} Pa.

cause the production of the highest E_f. However, in relation to time, E_f increases at a decreasing rate while P increases at an irregular rate. That is dP/dt varies in an unpredictable manner in the course of pressing.

Although the trajectory of the curve illustrating E_f would be expected to reflect the corresponding changes in applied pressure, this was not always the case. Even where the effect of P is reflected in the corresponding E_f, the two are out of phase with E_f lagging behind P. This is because, E_f takes time to flow out of the sample after the application of P. Otherwise increased P induced more E_f. The extent to which P influences E_f again lacks consistency for samples collected at different times of the picking season and from different sources. Close consistency in the triaxial compression results is however observed when the samples used are from the same source and collected on the same day [fig.5.1a]. In such a case, the family of curves for E_f and P respectively with respect to time are not as scattered as those in fig.5.1b to 5.1d. The differences in consistency of results observed among these figures serves as an indication of the great influence that other sample properties have on the E_f for any externally applied pressure.

The unpredictable behaviour of P is probably due to the heterogeneous mode of consolidation of the material. Also by virtue of the fact that coffee cherry is never completely homogenous in terms of degree of ripeness the resulting pulp within a coffee picking season is similarly in a variable state. Although the final E_f is a function of the compression duration and the applied pressure, the actual amount varies with samples

collected at different times of the picking season [table A1.0]

The influence of P on expressed fluid is observed in figures 5.2a to figure 5.2d. As for figure 5.2a the results are of a homogeneous sample collected on the same day and average values have been used to plot a representative curve while for figures 5.2b to 5.2d they are of samples collected at different times of the picking season. Although these illustrations show that there is a relationship between P and E_f, the curves obtained from different samples vary more than those from a homogeneous sample even at one cell pressure. Despite these variations these curves are observed to display a common trend which can be best fitted with power regression curves whose general equation was developed as follows;

The logarithm of P values were determined and plotted against the corresponding E_f because the curves display exponential characteristics. The relationship between these two parameters is linear [fig.5.3a to 5.3d] and can be described by a general expression [eq.5.1].

$$E_f = a\log(P) + b \qquad [5.1]$$

The constants a and b for the empirical regression equations for different cell pressures [table 5.1] were derived from the triaxial compression tests data using the method of the least squares [19]. These values of a and b are not related to cell pressure [figure 5.4a and 5.4b].

At a constant cell pressure, the values of a and b varied also with samples collected at different times of the coffee

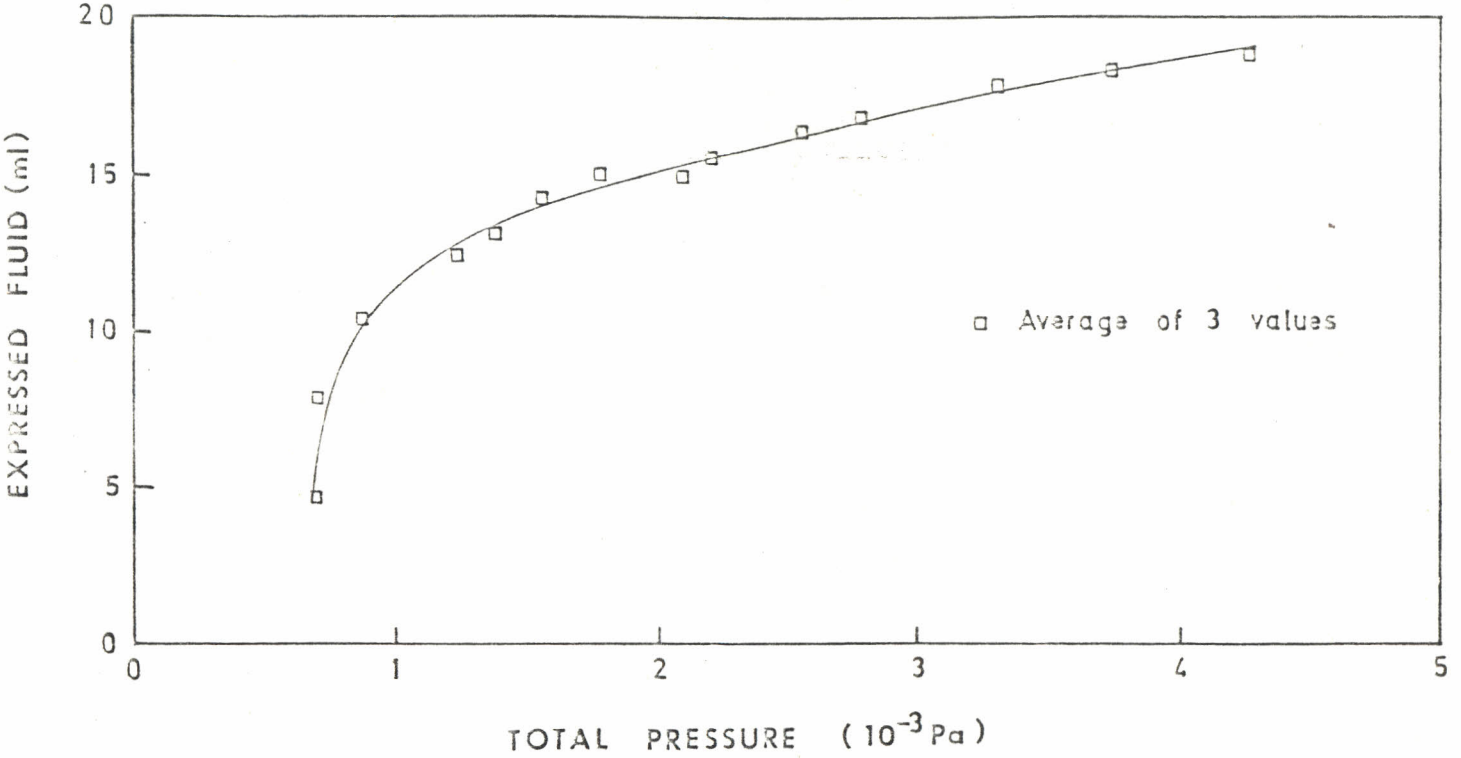


Figure 5.2a. Influence of total pressure on expressed fluid at a cell pressure of 0.7×10^{-3} pa.

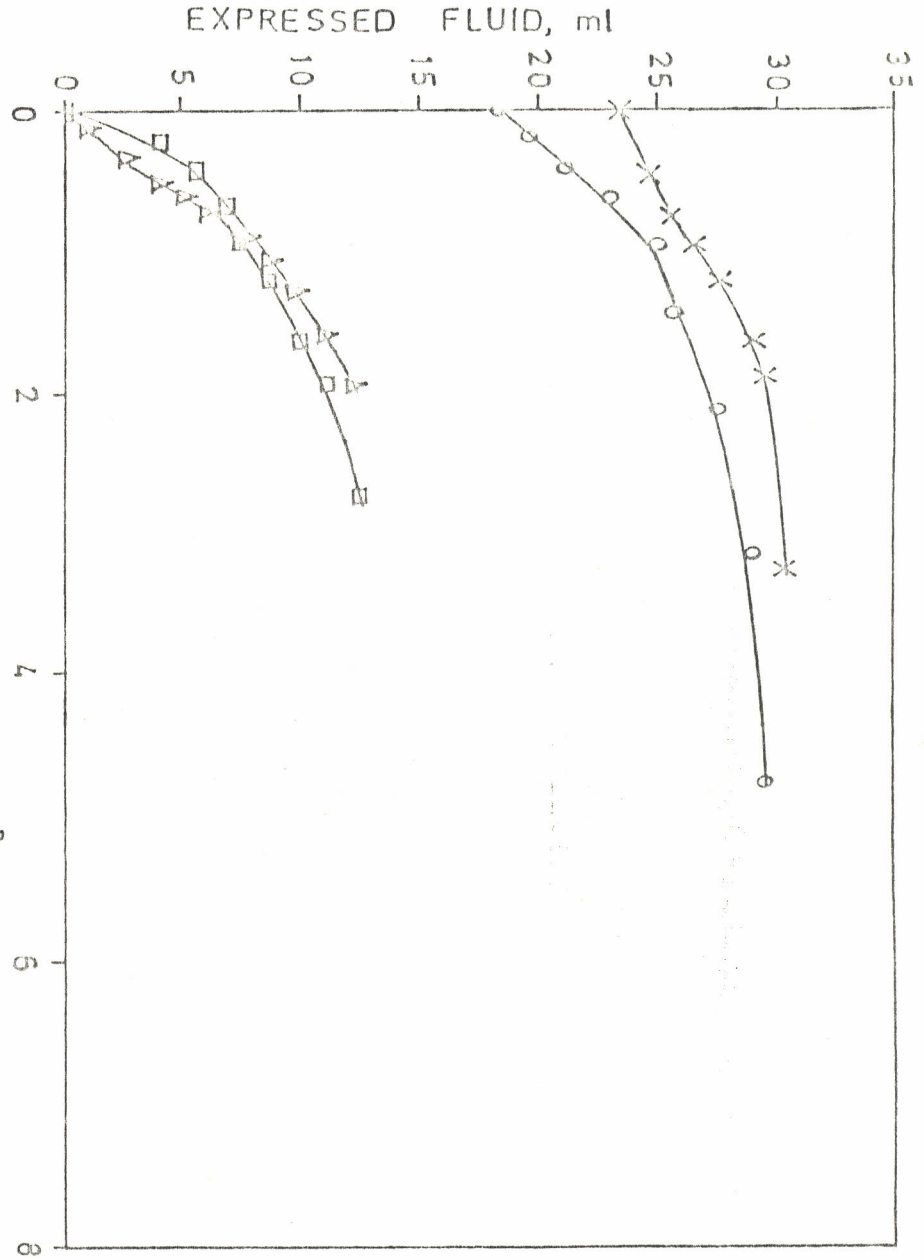


Figure. 5.2b. Influence of total pressure on expressed fluid at a cell pressure of 1.2×10^{-3} Pa.

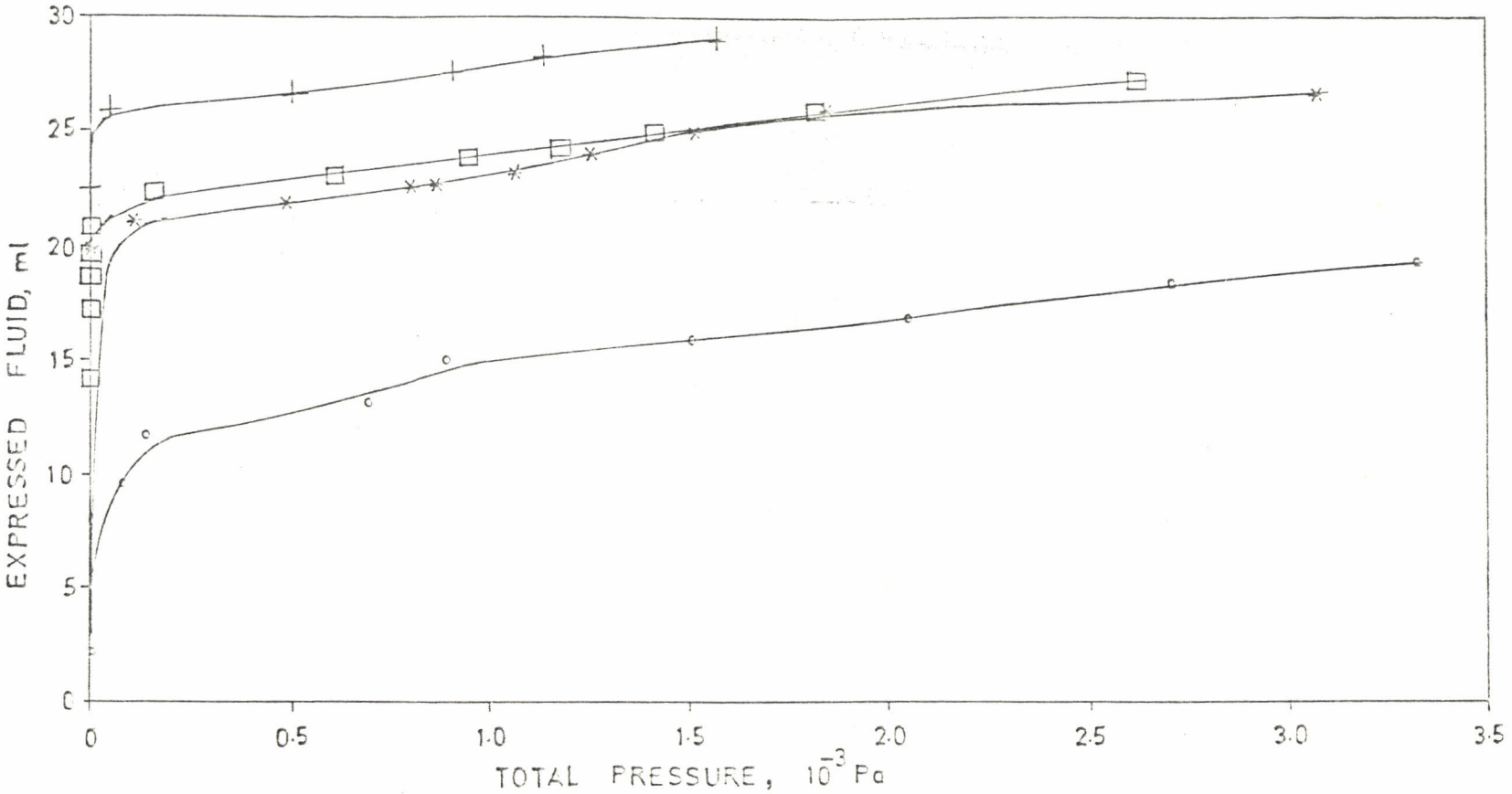


Figure. 5.2c. Influence of total pressure on expressed fluid at a cell pressure of 2.2×10^{-3} Pa.

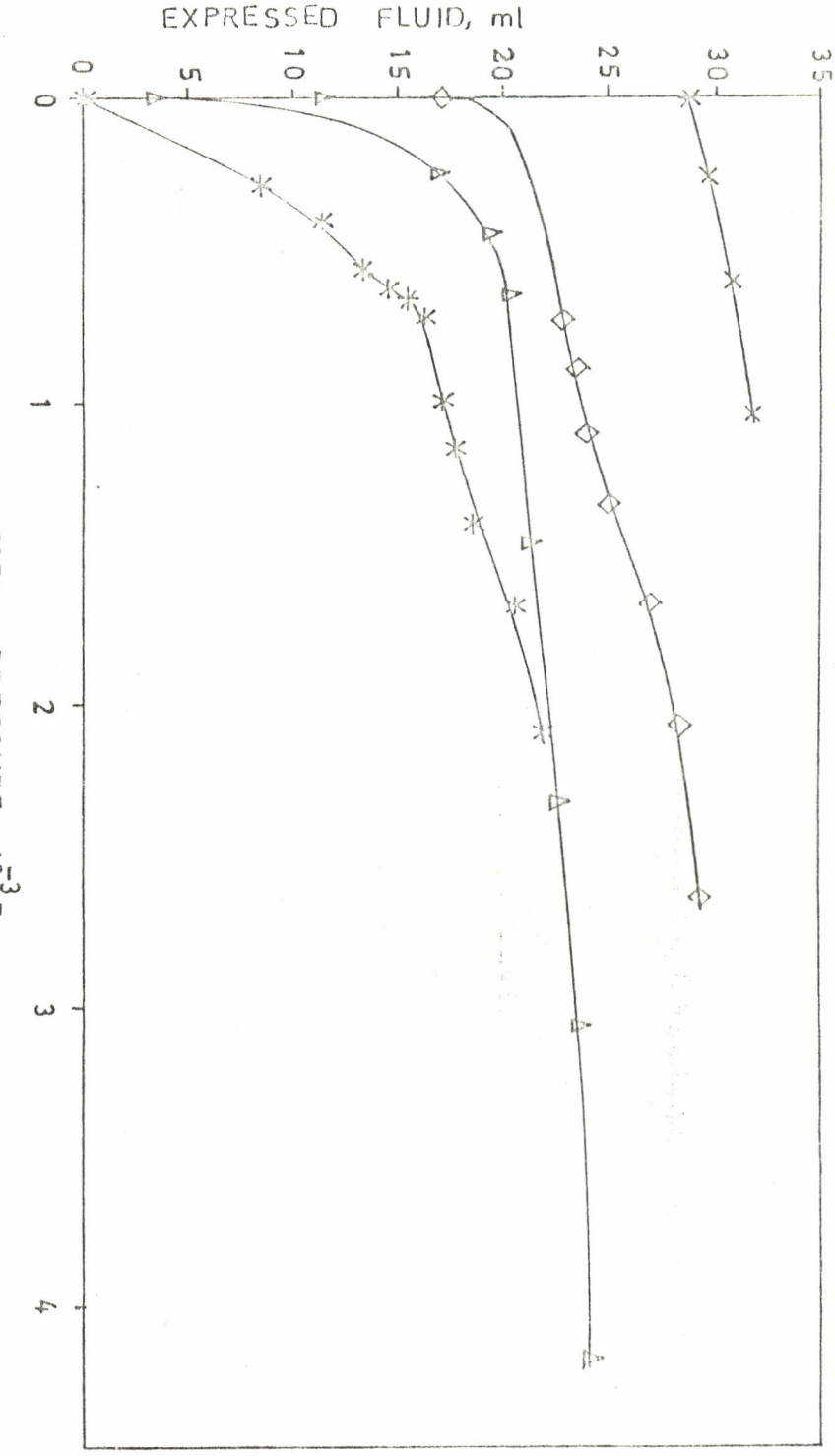


Figure. 5.2d. Influence of total pressure on expressed fluid at a cell pressure of 3.1×10^{-3} Pa.

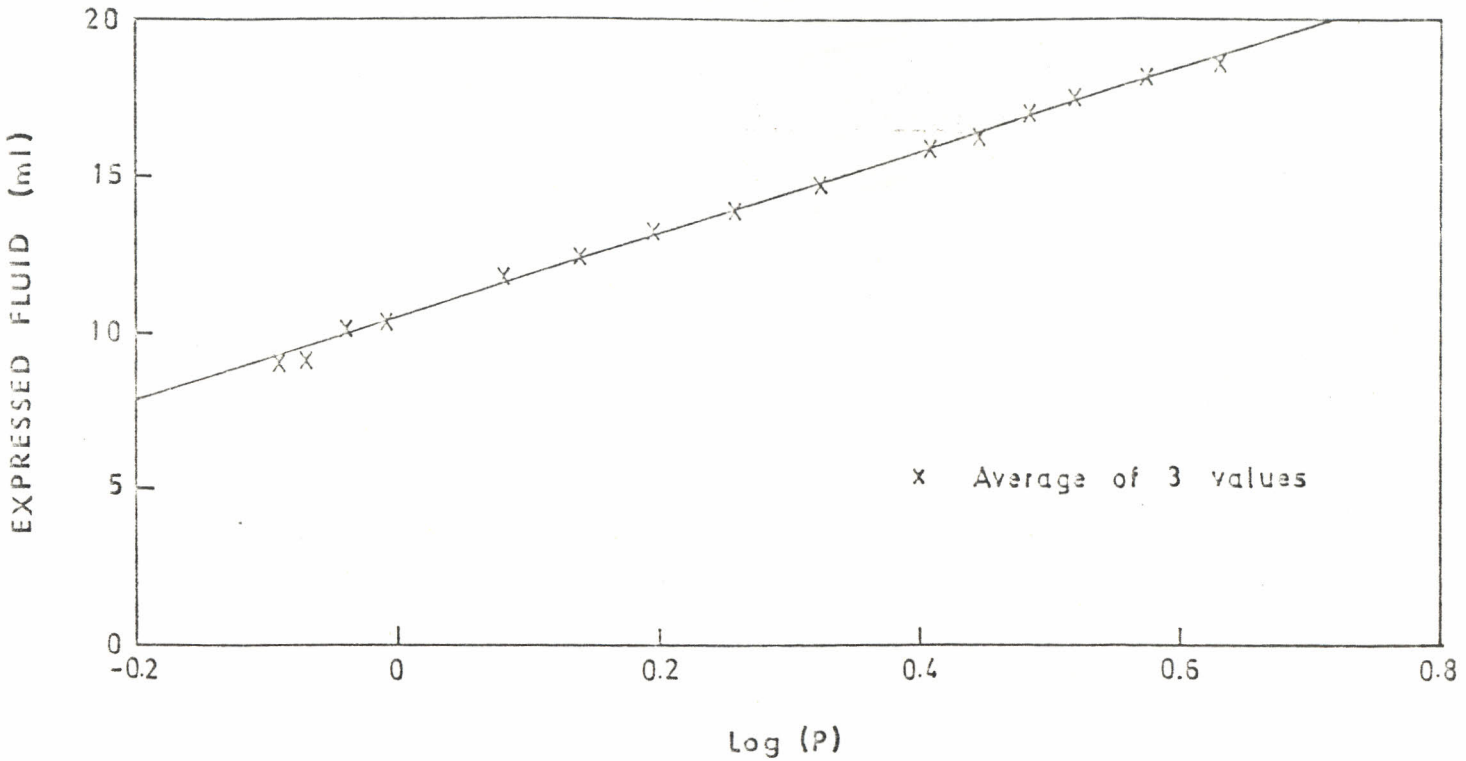


Figure 5.3a. Expressed fluid versus logarithm of pressure at a cell pressure of 0.7×10^{-3} Pa.

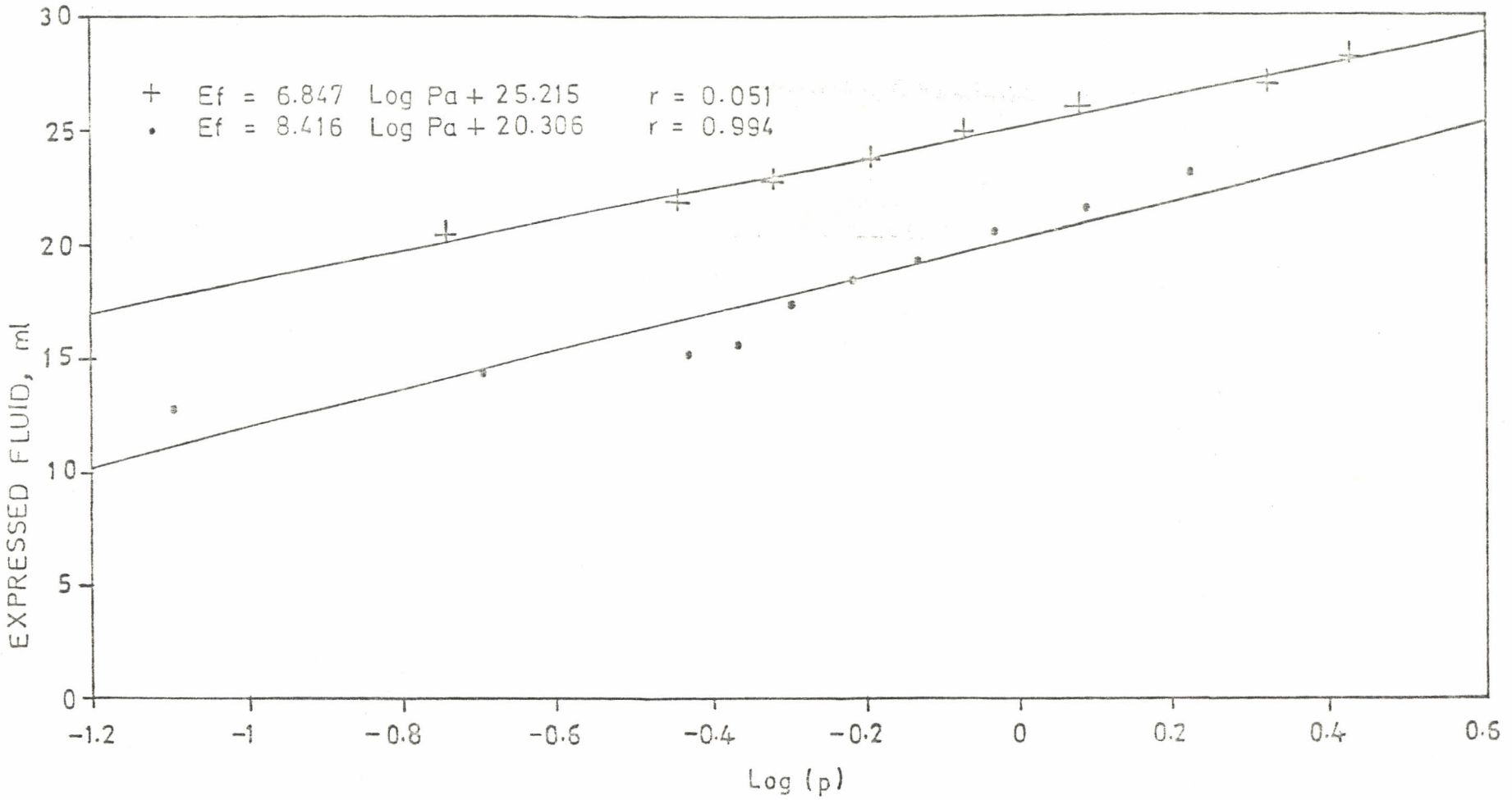


Figure. 5.3b. Expressed fluid versus logarithm of total pressure at a cell pressure of 1.2×10^{-3} Pa.

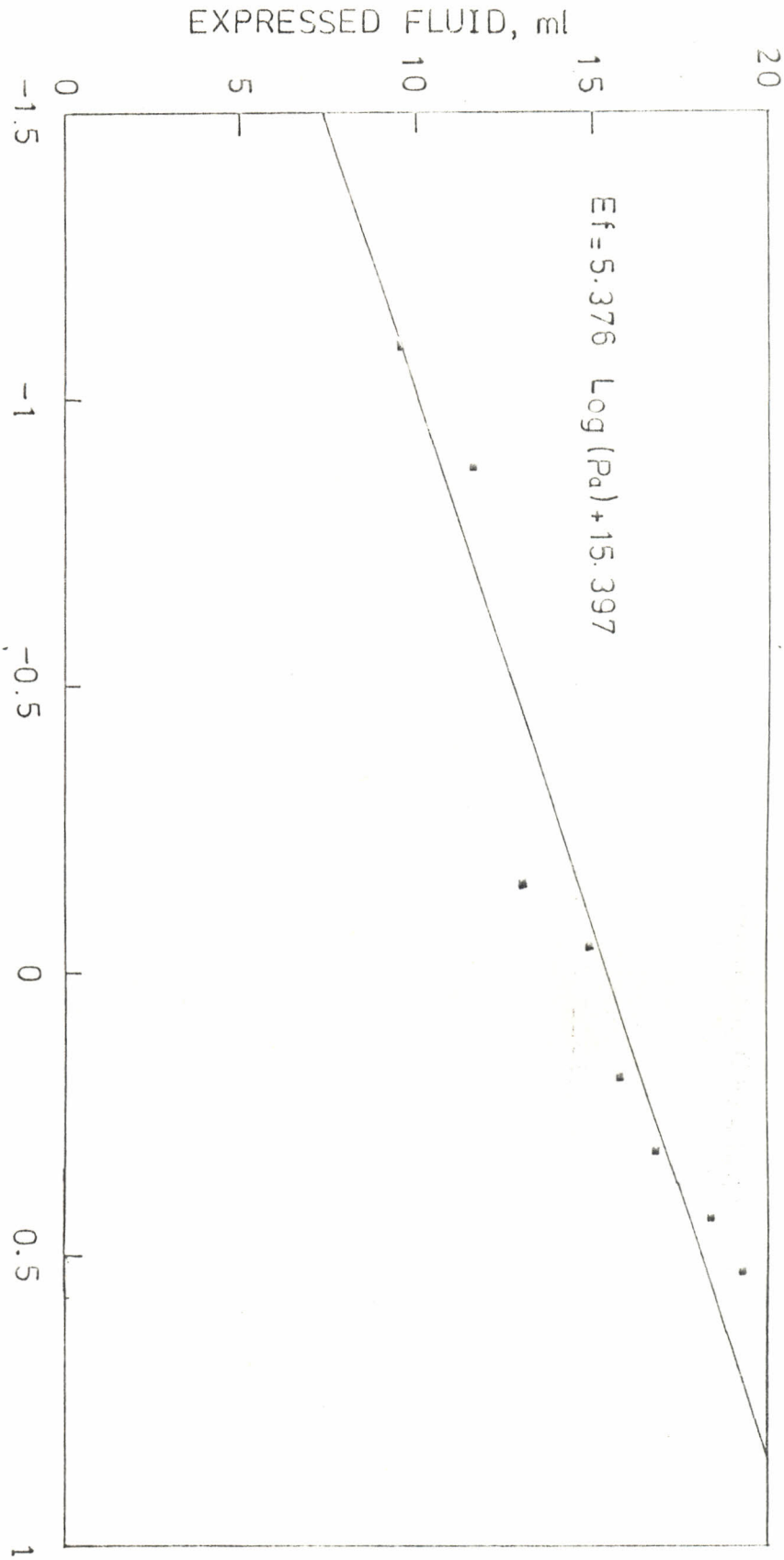


Figure. 5.3c. Expressed fluid versus logarithm of total pressure at a cell pressure of 2.2×10^{-3} Pa.

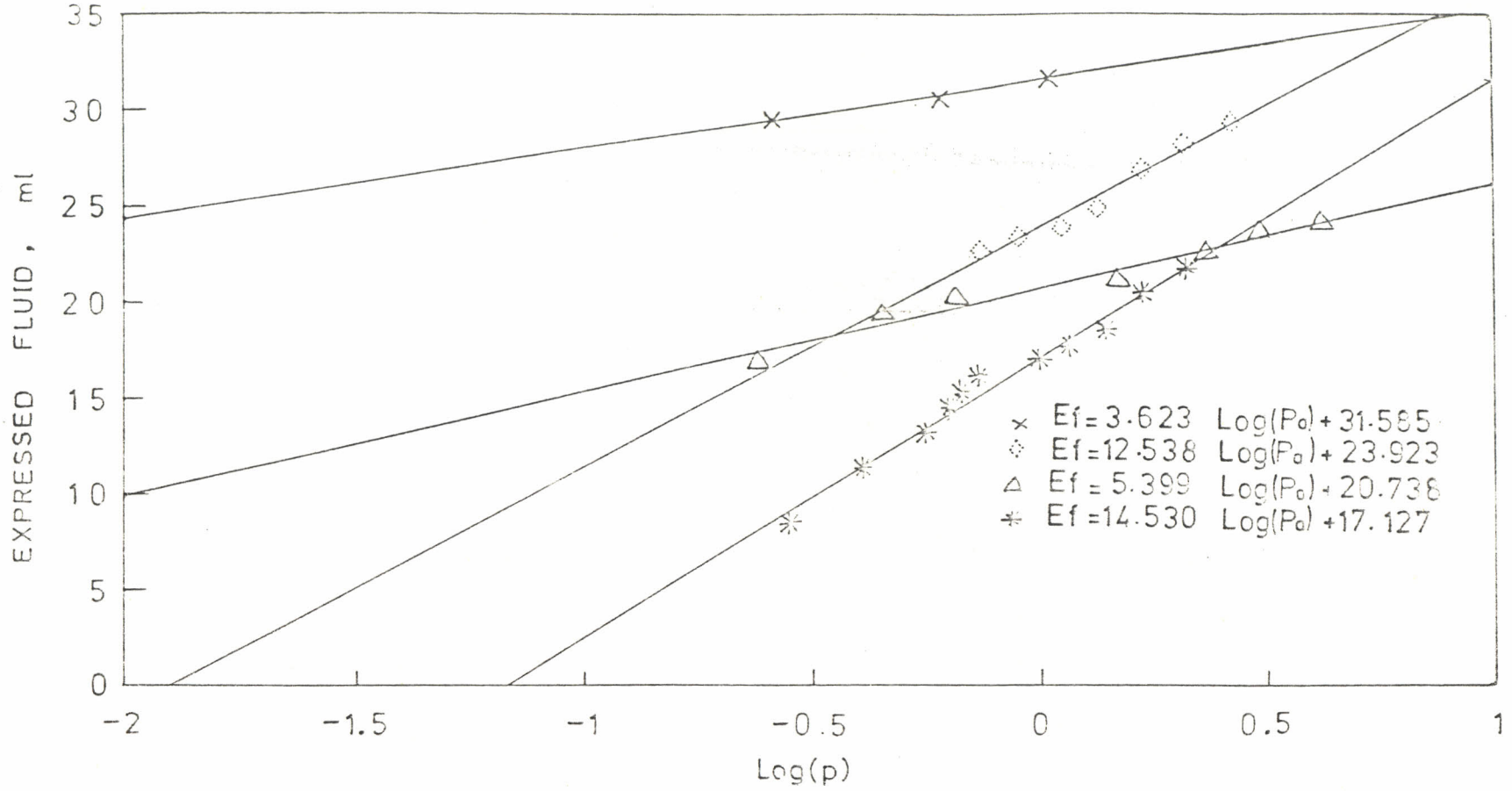


Figure. 5.3d. Expressed fluid versus logarithm of total pressure at a cell pressure of 3.1×10^{-3} Pa.

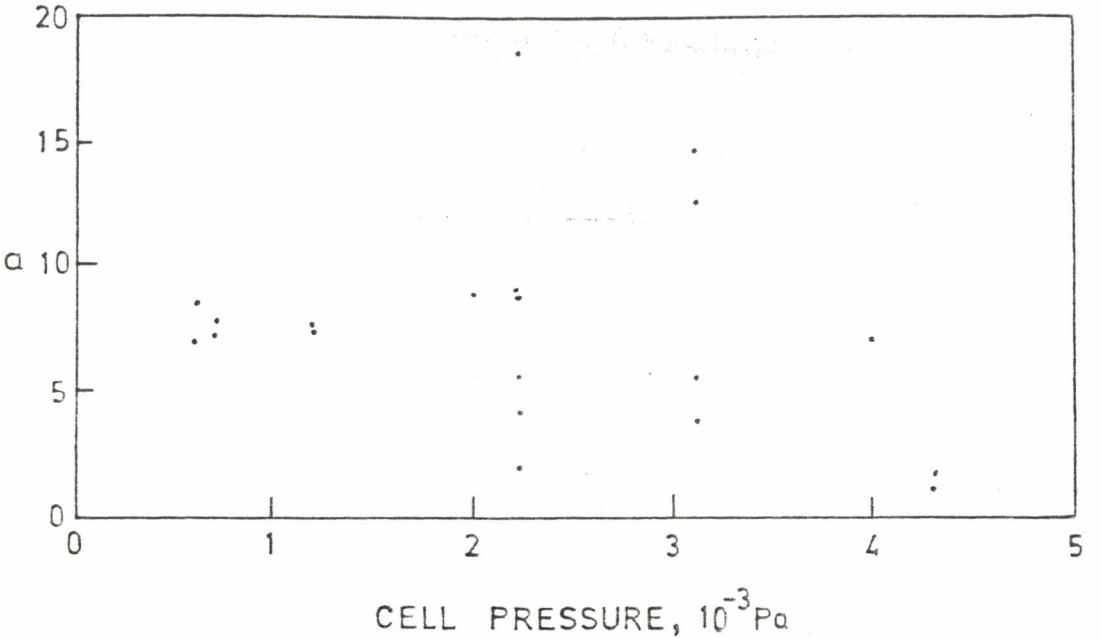


Figure. 5.4a. Relationship between the parameter a of equation 5.1 and cell pressure.

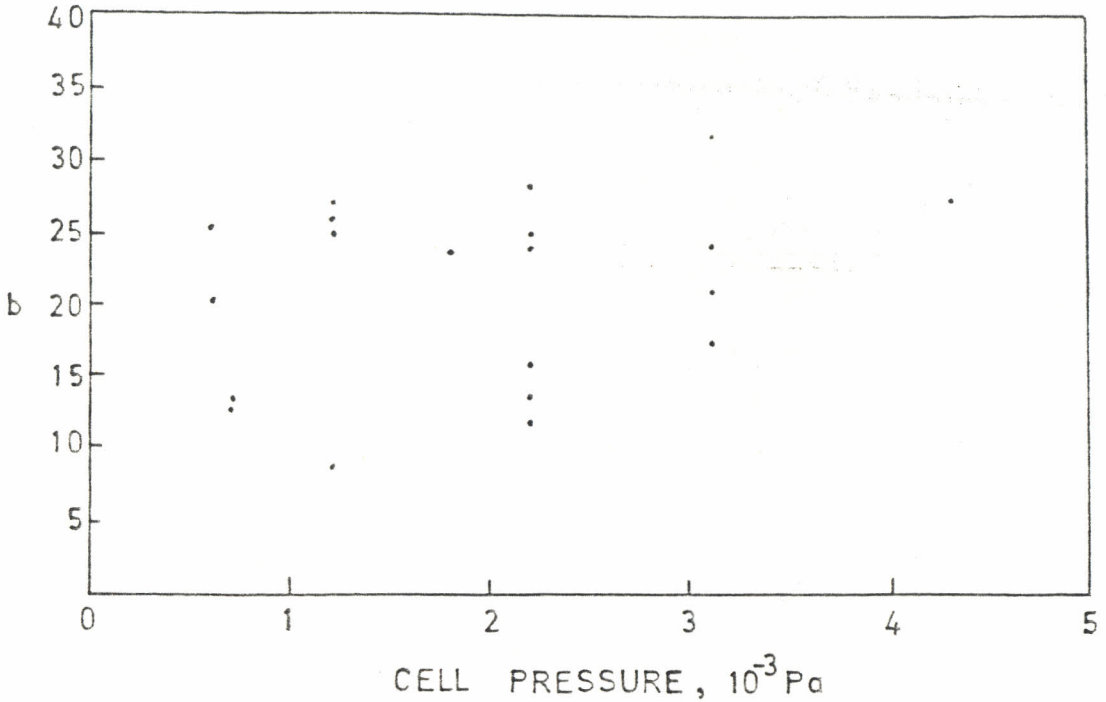


Figure. 5.4b. Relationship between the parameter b of equation 5.1 and cell pressure.

picking season. This reveals an effect of other factors besides pressure that tend to influence the expressed fluid. The cell pressure values of the triaxial compression tests were also plotted against the expressed fluid at different times of pressing [fig.5.5a to 5.5d] and varying P_a.

Table 5.1 Regression constants for equation 5.1 at various cell pressures

Cell pressure	Regression Constants		
	a	b	r
0.7	7.760	14.949	0.989
	7.112	12.652	0.988
	7.556	13.365	0.996
1.2	7.560	25.764	0.996
	7.416	24.750	0.993
	7.461	26.989	0.980
2.2	5.376	15.397	0.967
	8.669	15.455	0.962
	8.889	11.417	0.893
3.1	14.530	17.127	0.988
	5.399	20.738	0.983
	12.538	23.923	0.985

The graphs obtained are essentially constant time curves relating expressed fluid to the maintained cell pressure values and axial pressure. Although there seems to exist a trend of proportionality between E_f and P_c [fig 5.5b to 5.5d], this is not always the case as figure 5.5a shows. The data of P_a for which a downward trend in E_f is observed as cell pressure increases indicate that the P_a values at the same time trace a similar falling trend. Due to the wide variation in the graph characteristics, the great difficulty of having a specific

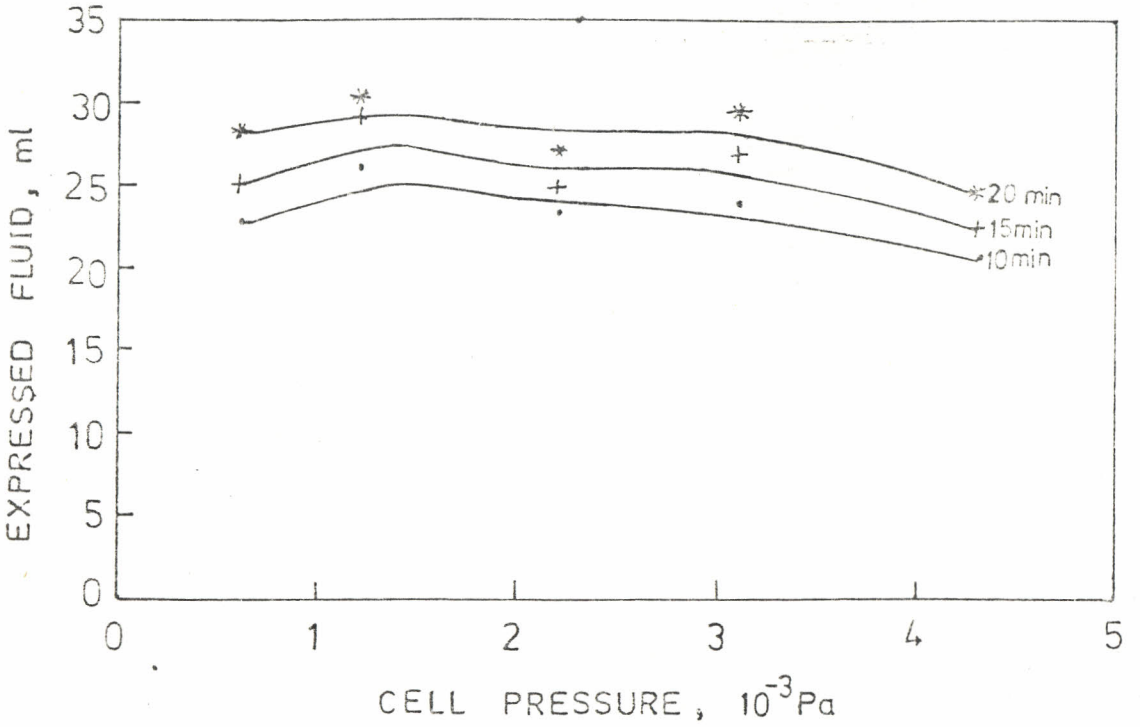


Figure. 5.5a. Observed expressed fluid at various pressing intervals and cell pressures.

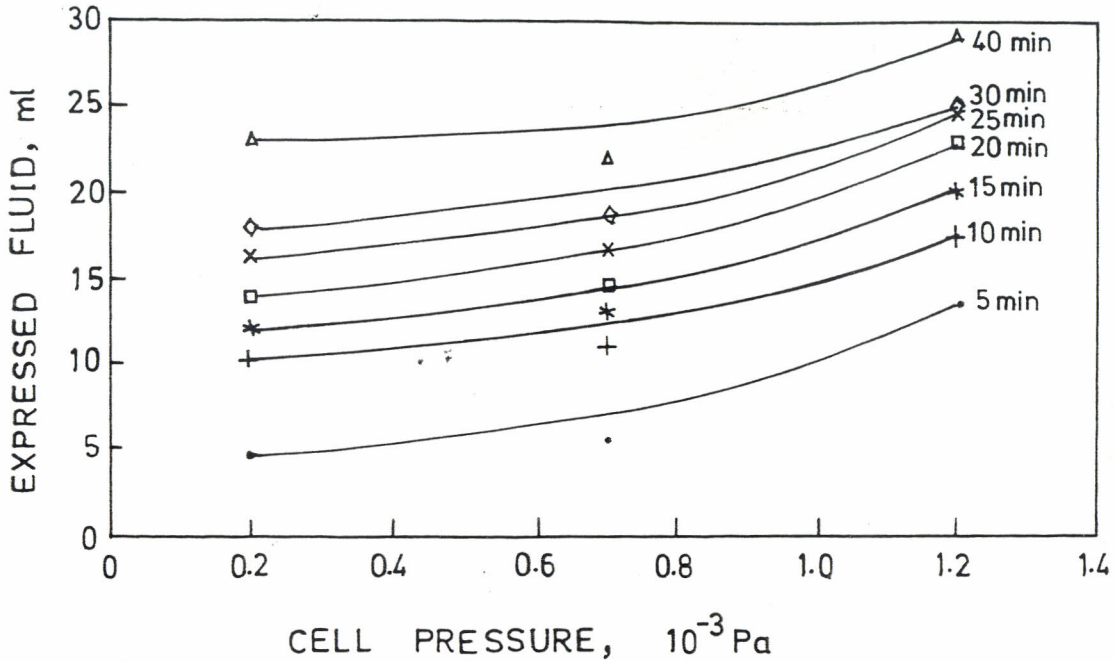


Figure. 5.5b. Observed expressed fluid at various pressing intervals and cell pressures.

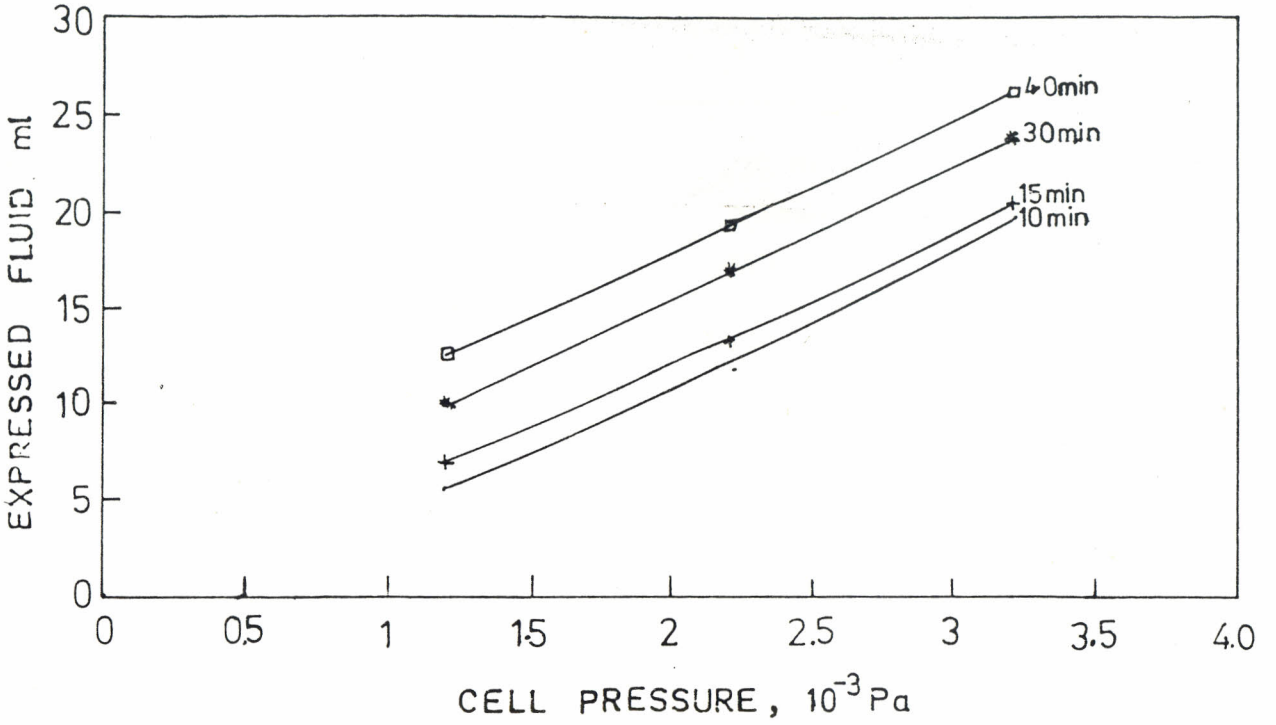


Figure. 5.5c. Observed expressed fluid at various pressing intervals and cell pressures.

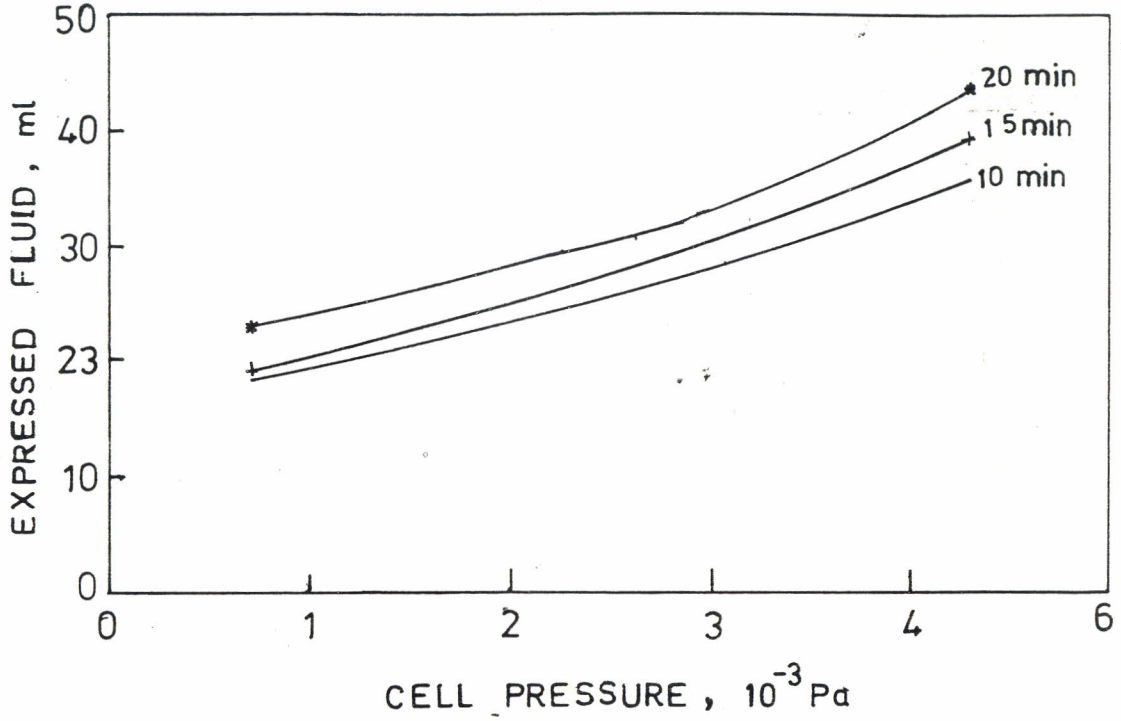


Figure. 5.5d. Observed expressed fluid at various pressing intervals and cell pressures.

relationship between expressed fluid and cell pressure values is implied due to the unpredictable effects of axial pressure.

The effect of constant cell pressure on E_f is illustrated in figure 5.6 in which P_a=0. For a constant cell pressure (P_c), expressed fluid takes to a family of exponential curves falling in a relatively wide range but depicting more or less a common trend. Besides the effect of pressure on the expressed fluid, it appears there are other factors inherent to the sample to which the family of curves can be attributed. This explains lack of homogeneity in coffee pulp samples within a coffee picking season. The influence of these factors is seen in their capability to distort the effect of cell pressure on E_f in that E_f from different samples is not proportional to the cell pressure. After four minutes of pressing for instance more fluid (22.5 ml) is expressed due to a pressure of $1.2x10^{-3}$Pa than 20 ml by $2.2x10^{-3}$Pa [fig 5.6]. Different values of E_f are also observed at the same pressing times and cell pressure of $0.7x10^{-3}$Pa.

The curves in fig.5.6 have exponential characteristics and on transforming the data for these curves by plotting it on a log log scale, the resultant plots were linear [figure 5.7] indicating that the relationship between expressed fluid and pressing duration is exponential. The regression lines through these plots can be expressed by equation 5.2 which is general for all the data.

$$\ln(t)=c_1\ln(E_f+c_2) \qquad [5.2]$$

From equation 5.2;

$$t=c_2(E_f)^{c_1}$$

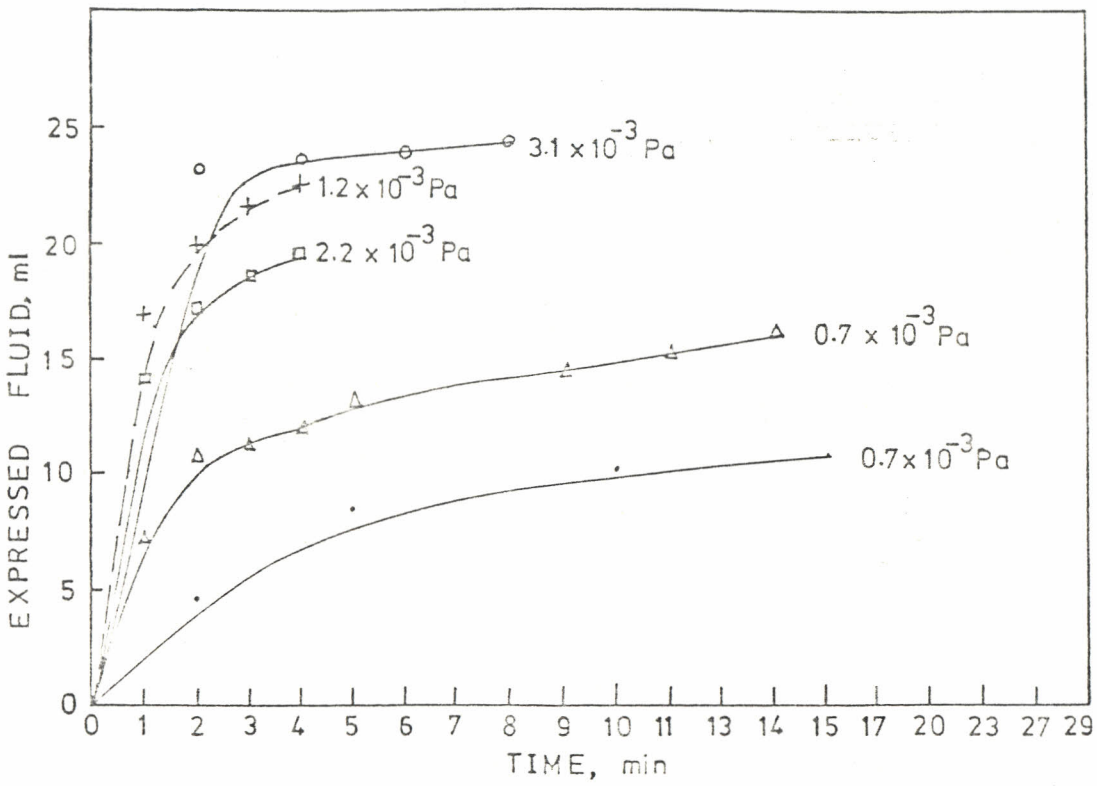


Figure. 5.6. Pattern of expressed fluid at various cell pressures.

Δ 0.7 $Ln(t) = 0.278\ Ln(E_f) + 0.901$ $r = 0.965$
□ 1.2 $Ln(t) = 0.200\ Ln(E_f) + 1.233$ $r = 0.936$
• 2.2 $Ln(t) = 0.210\ Ln(E_f) + 2.688$ $r = 0.932$
X 3.1 $Ln(t) = 0.036\ Ln(E_f) + 1.349$ $r = 0.931$

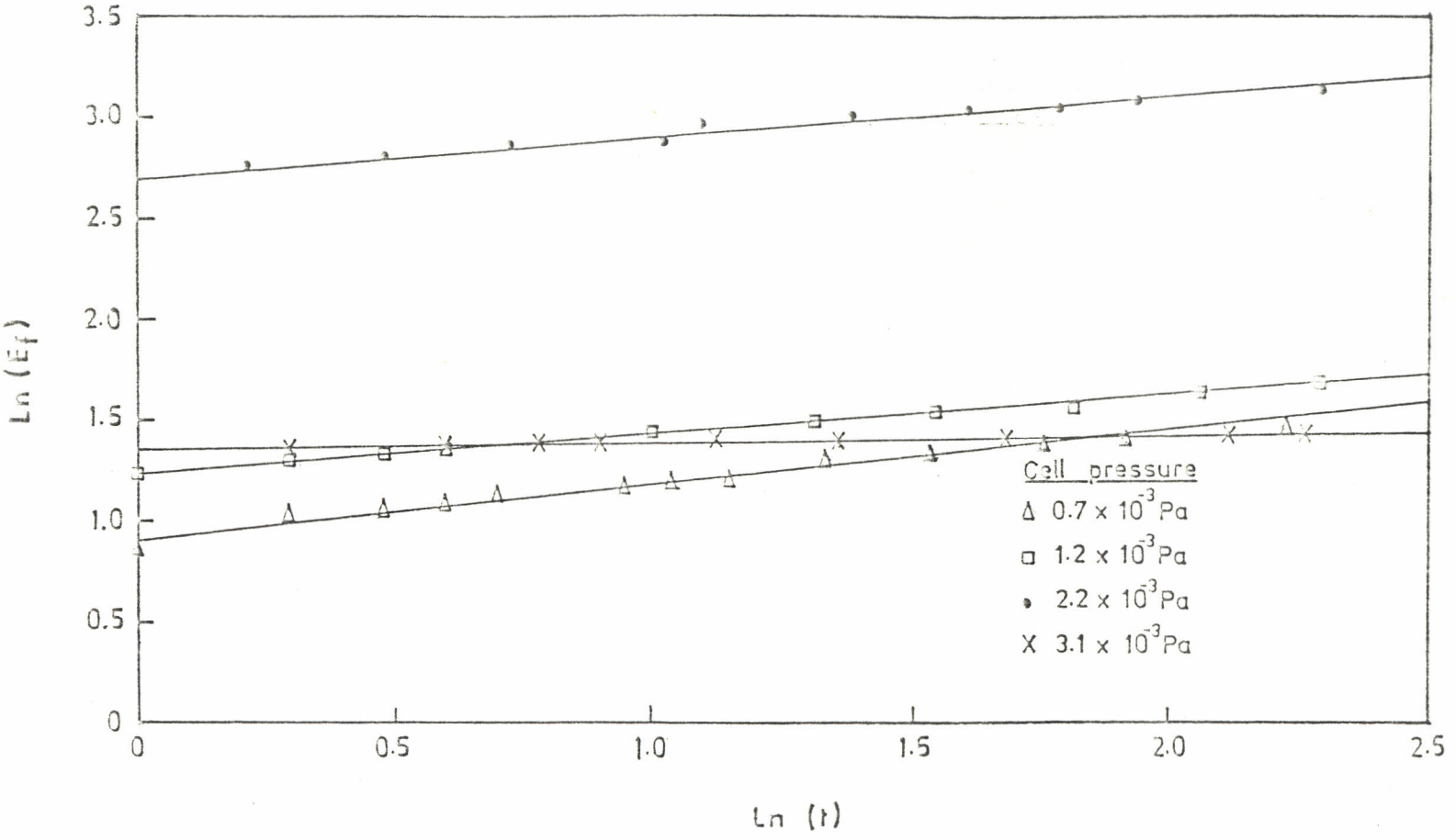


Figure 5.7. Regression of $Ln(E_f)$ on $Ln(t)$.

$$E_f = \left(\frac{t}{c_2}\right)^{\frac{1}{c_2}} \qquad [5.3]$$

Observed values of c_1 and c_2 are presented in table 5.2. It can be inferred from this table that the variation of these indices can hardly be predicted for any of he constant pressures used to conduct the experiment. This perhaps is due to other unknown factors inherent to the sample which respond differently to the applied pressure.

Average values of c_1 and c_2 for some specific regression equations for various samples dewatered at various cell pressures are given in table 5.2.

Table 5.2 Average values of c_1 and c_2 of equation 5.2 at various cell pressures

Cell pressure, 10^{-3}Pa	c_1	c_2	r
0.7	0.687	1.187	0.982
	0.444	0.544	0.961
	0.278	0.901	0.965
1.2	0.446	1.808	0.956
	0.200	1.233	0.996
2.2	0.210	2.688	0.982
	0.581	1.708	0.975
3.1	0.036	1.349	0.981
	0.121	1.322	0.979

The relationship between expressed fluid and the corresponding reduction in coffee pulp sample volume during

triaxial tests as illustrated in figure 5.8 is linear. However, as the gradients of the regression lines are all less than unity, then the volume reduction of each sample is more than the expressed fluid observed. For this particular case, the sample volume changes by 3.00, 1.77, 1.79 and 1.85 times more than a unit of expressed fluid for 0.7, 1.2, 2.2 and $3.1*10^{-3}$Pa respectively. Such ratios can be used to predict one of these two parameters if the other one plus the constant cell pressure are known.

5.1.2 Drying

The results of the determination of the initial moisture content of coffee pulp are as presented in table 5.3. It can be observed from this table that the initial moisture content of coffee pulp lies between 80% and 85%(wb). The age of coffee pulp from the time of pulping to drying does not seem to affect its moisture content so long as it is kept in a refrigerator and packed in polythene bags [table A2.0].

Table 5.3 The Initial Moisture Content of Coffee Pulp.

Condition of coffee pulp		Moisture content (%) Replications				Average
Stored	12 days	83.94	83.68	83.85	83.50	83.74
Fresh		84.12	83.84	84.30	83.91	84.04
"		80.48	81.17	81.60	81.47	81.18
Stored	28 days	84.86	84.92	84.43	84.52	84.68
Fresh		83.40	84.14	83.58	84.27	83.85
"		79.76	80.32	80.87	82.24	80.80

Observations made on the drying of coffee pulp are presented in appendix 2. In all the experiments, coffee pulp was

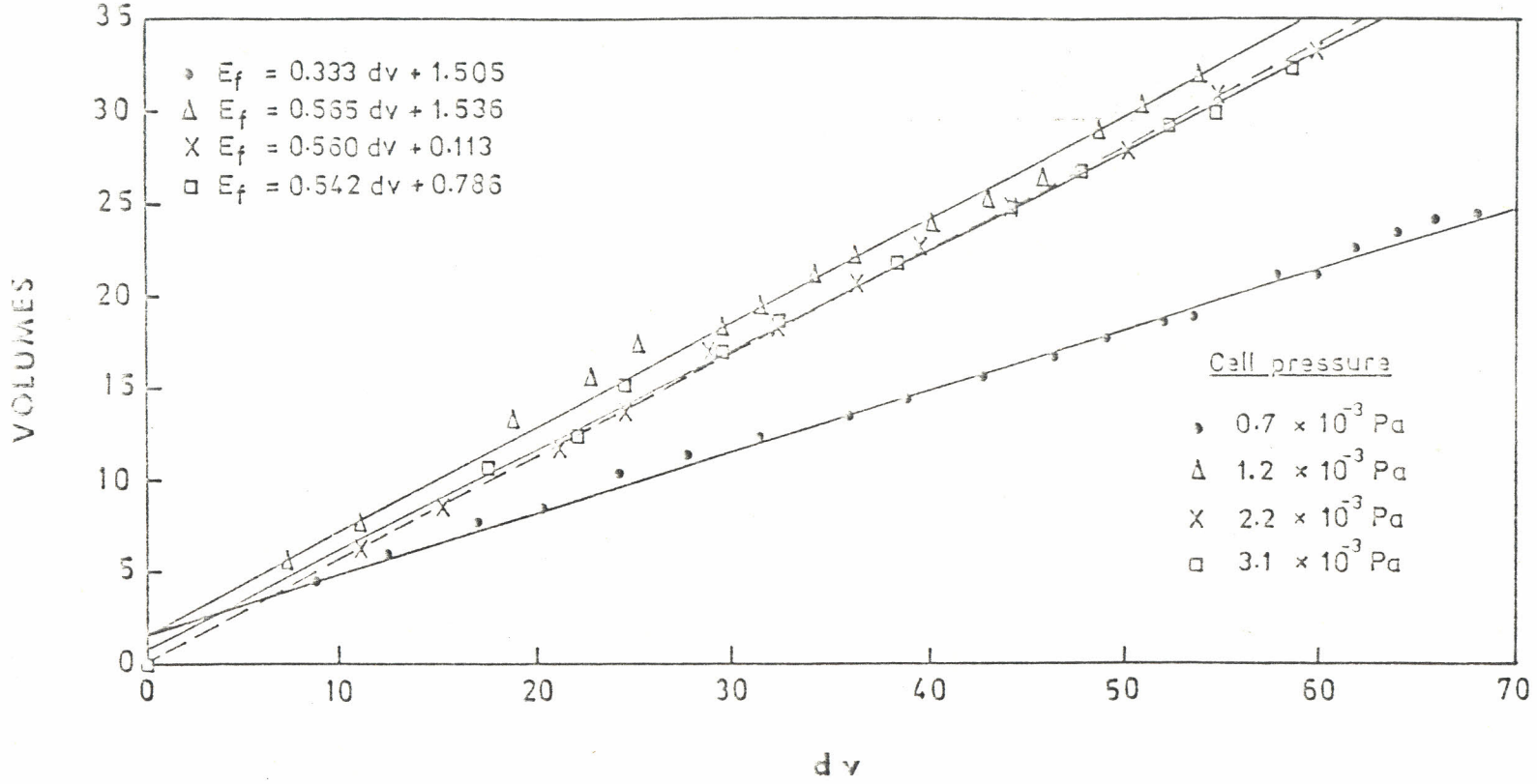


Figure 5.3. Relationship between expressed fluid and reduction in volume of coffee pulp at different cell pressures.

dried to zero moisture. On examining the time required to lower the moisture content to zero at various temperatures [table 5.4], it can be deduced that the higher the initial moisture content the longer the recorded drying time for each temperature. This trend is more pronounced at 105°C than at 130°C and 150°C.

The difference between time taken to dry coffee pulp samples at 130C and 150°C is considerably small compared to that observed between 105°C and 130°C at all the initial moisture contents investigated. The sudden drop in drying time observed between 130°C and 150°C implies the existence of a critical drying temperature possibly between 105°C and 130°C beyond which further increase in drying temperature does not shorten the drying time significantly.

Table 5.4 Drying time in hours of fresh coffee pulp subjected to different drying temperatures

Initial MC%	Temperature °C 105	130	150
66	3.00	2.00	2.00
74	3.42	2.37	2.33
80	3.49	2.38	2.35
85	6.80	2.75	2.60

Further analysis of the drying process was undertaken using the curve fitting techniques and the method of least squares. This was done by plotting the current moisture content at various drying temperatures and initial moisture contents against drying time [fig.5.9a to 5.9d]. Also presented [fig 5.10a to 5.10c] are

dried to zero moisture. On examining the time required to lower the moisture content to zero at various temperatures [table 5.4], it can be deduced that the higher the initial moisture content the longer the recorded drying time for each temperature. This trend is more pronounced at 105°C than at 130°C and 150°C.

The difference between time taken to dry coffee pulp samples at 130C and 150°C is considerably small compared to that observed between 105°C and 130°C at all the initial moisture contents investigated. The sudden drop in drying time observed between 130°C and 150°C implies the existence of a critical drying temperature possibly between 105°C and 130°C beyond which further increase in drying temperature does not shorten the drying time significantly.

Table 5.4 Drying time in hours of fresh coffee pulp subjected to different drying temperatures

Initial MC%	Temperature °C 105	130	150
66	3.00	2.00	2.00
74	3.42	2.37	2.33
80	3.49	2.38	2.35
85	6.80	2.75	2.60

Further analysis of the drying process was undertaken using the curve fitting techniques and the method of least squares. This was done by plotting the current moisture content at various drying temperatures and initial moisture contents against drying time [fig.5.9a to 5.9d]. Also presented [fig 5.10a to 5.10c] are

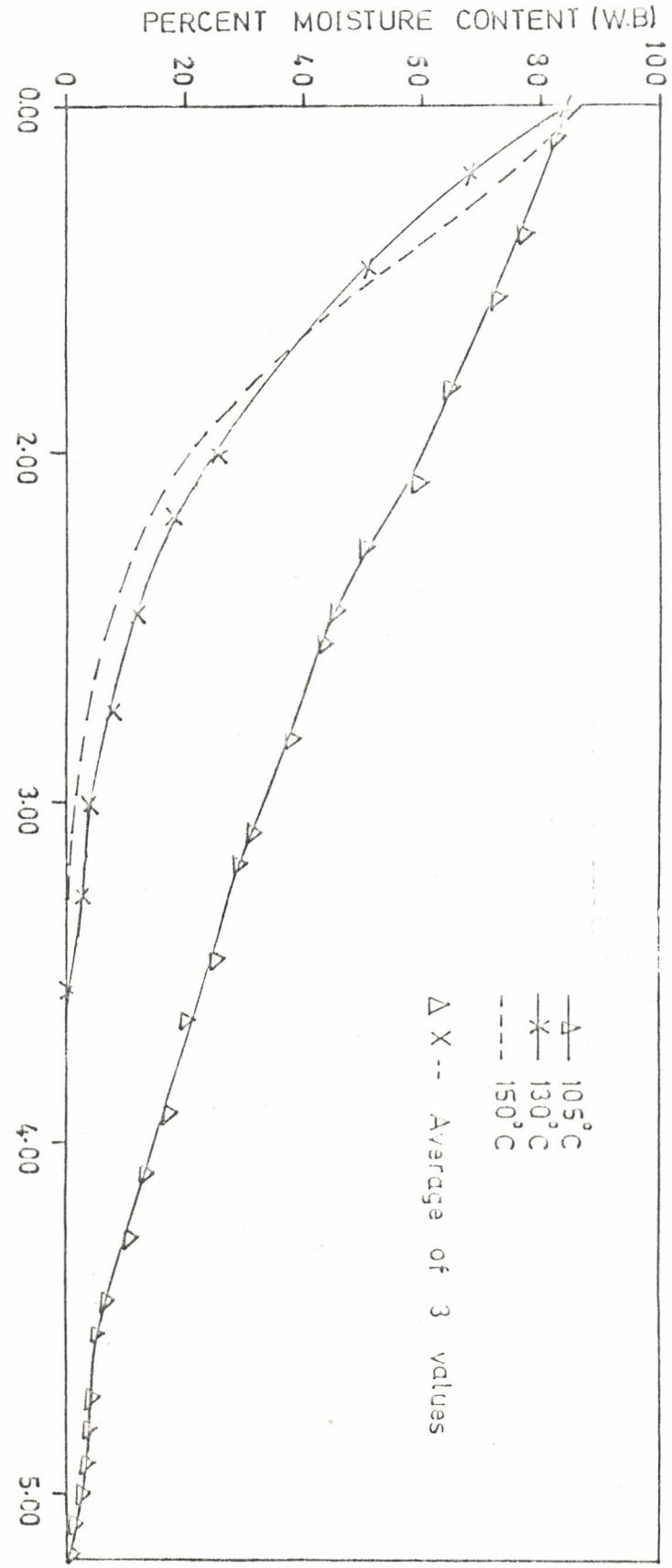


Figure. 5.9a. Drying curves of unpressed coffee pulp at various temperatures.

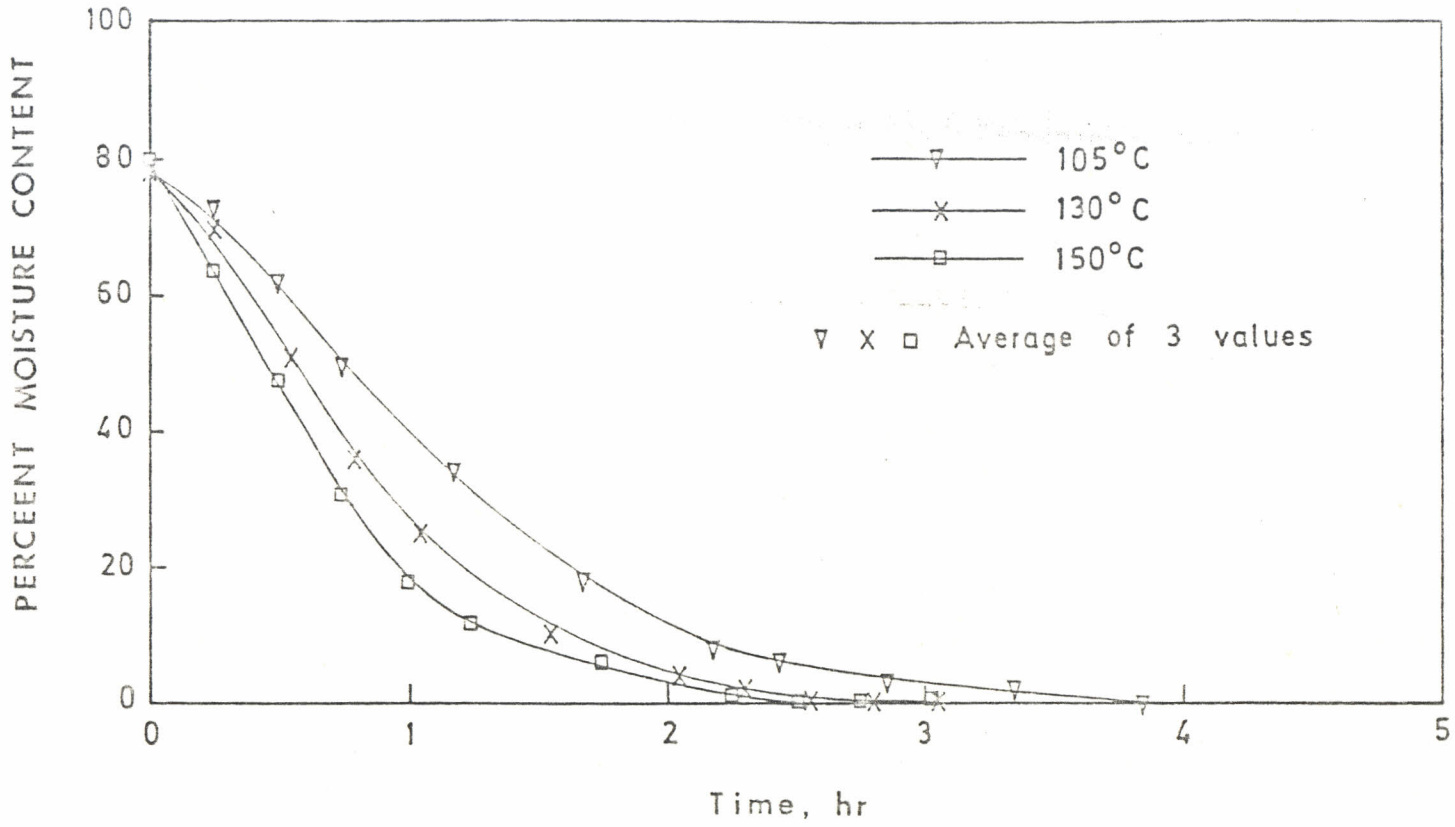


Figure 5.9b. Drying curves of coffee pulp (from which 5% of its water has been expressed out) at various temperatures.

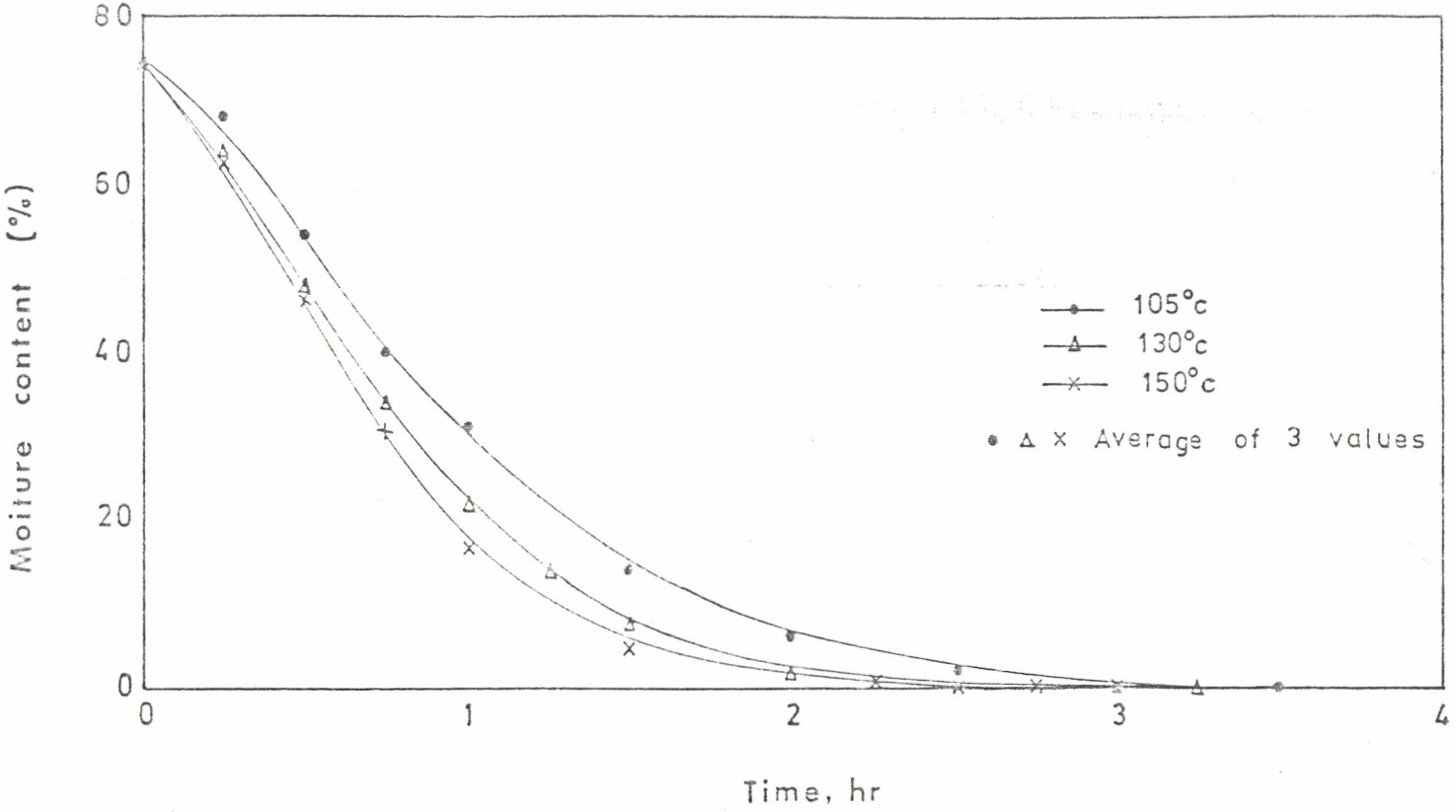


Figure 5.9c. Drying curves of coffee pulp (from which 10% of fluid has been expressed out) at various temperatures.

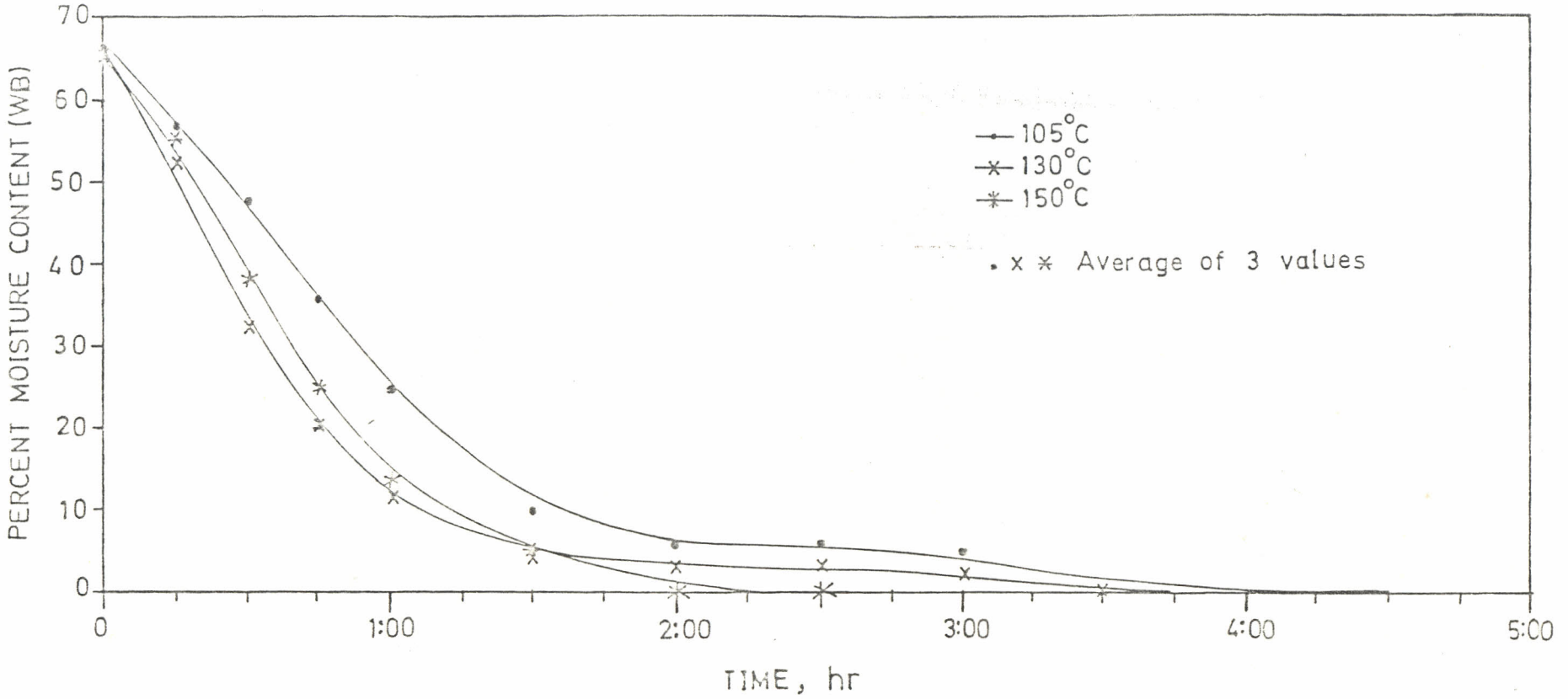


Figure. 5.9d. Drying curves of coffee pulp (from which 20% of fluid had been expressed out) at various temperatures.

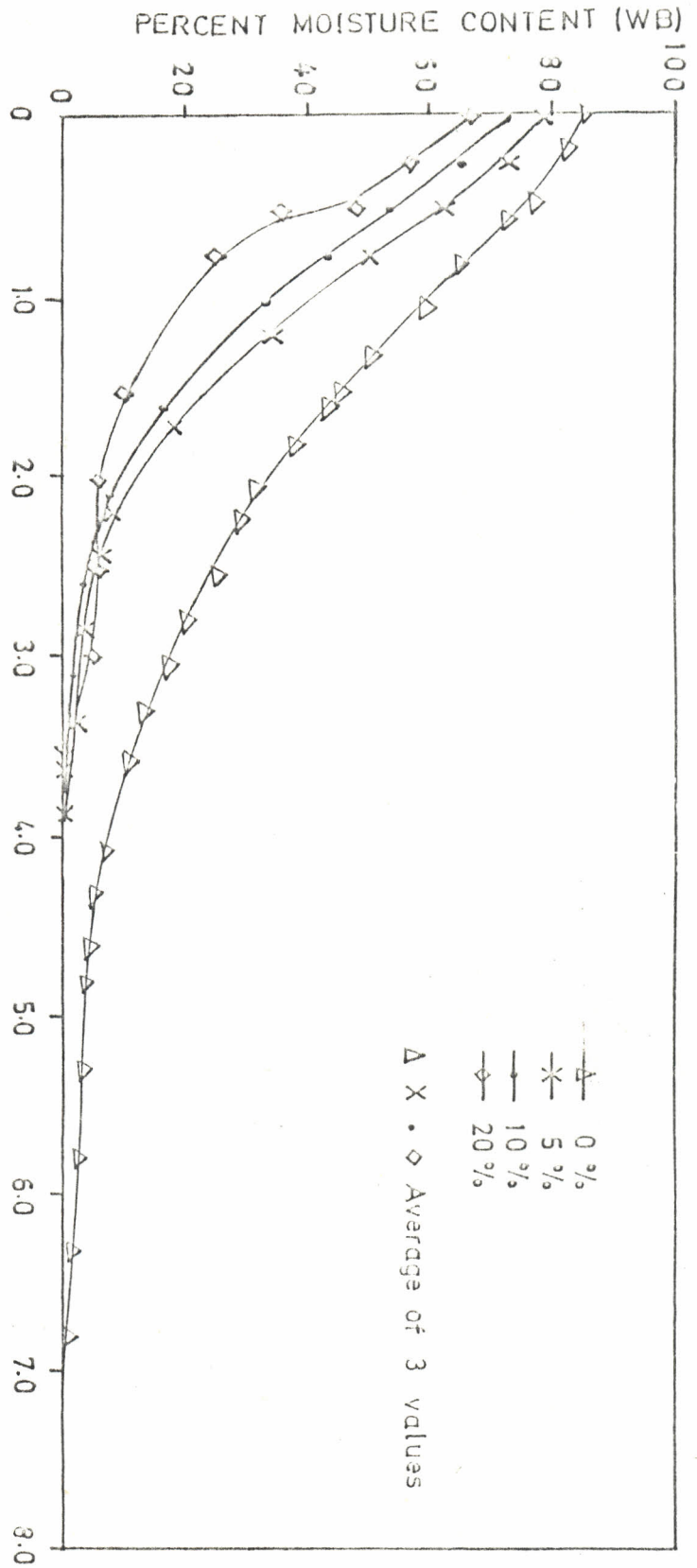


Figure. 5.10a. Drying curves of coffee pulp at 105°C and different dewatering levels.

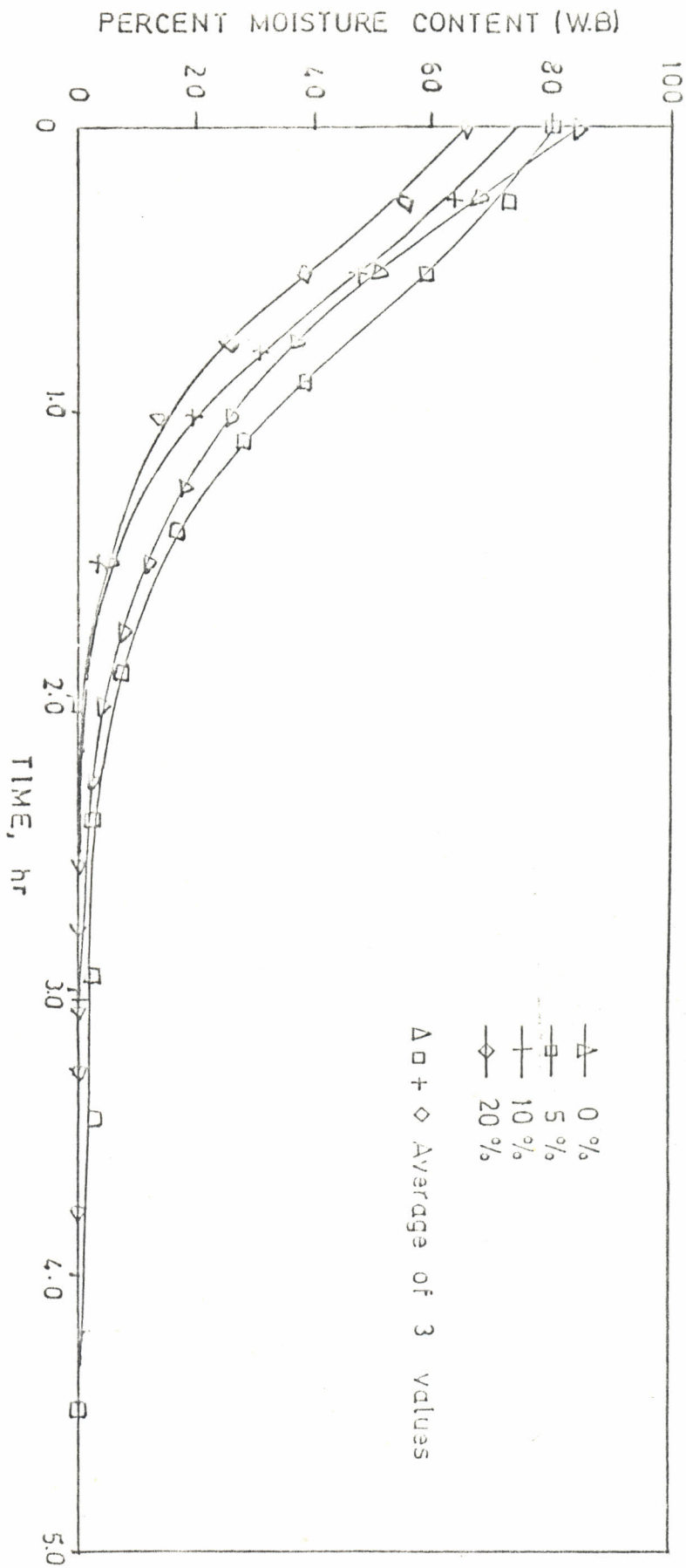


Figure. 5.10b. Drying curves of coffee pulp at 130°C and different dewatering levels.

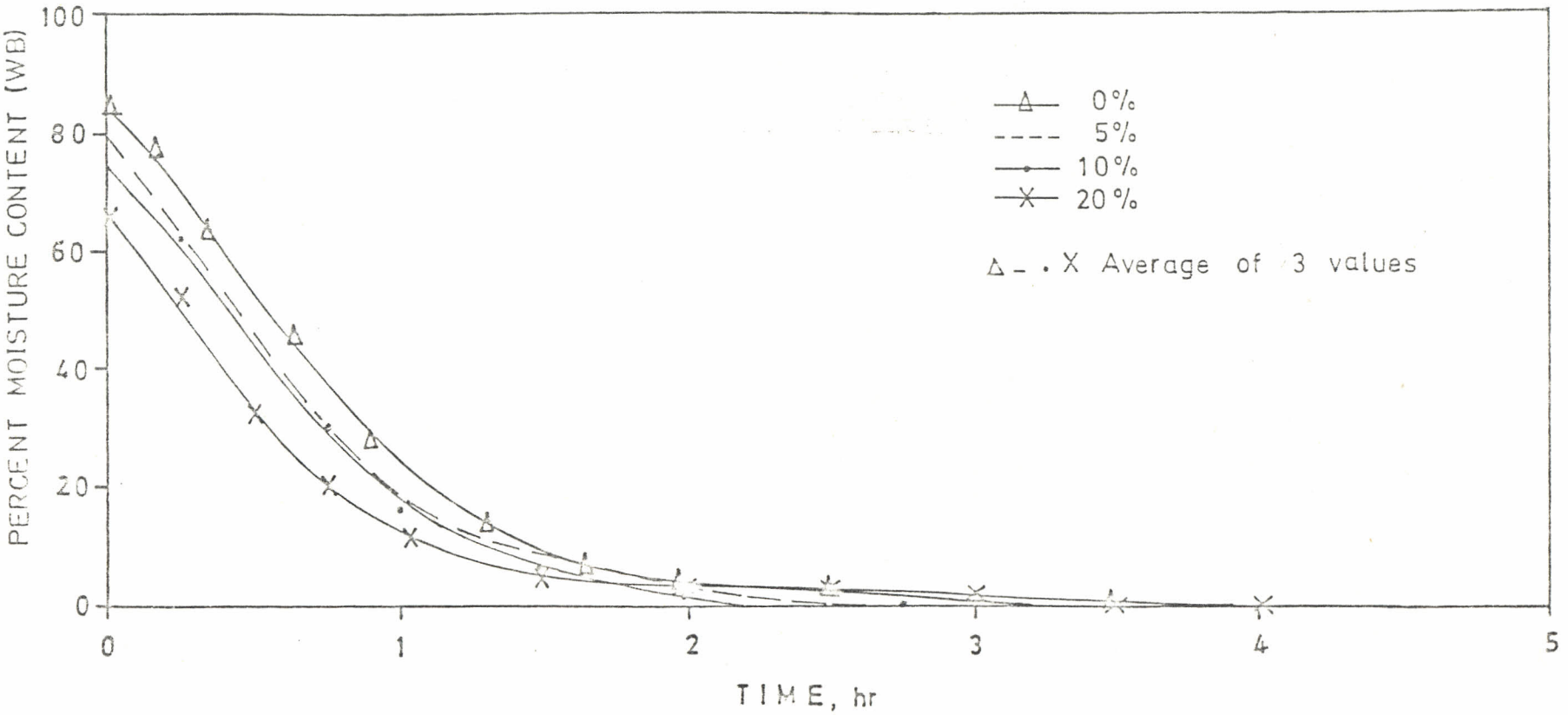


Figure. 5.10c. Drying curves of coffee pulp at 150°C and different dewatering levels.

representative drying curves of coffee pulp dewatered by 5%, 10%, and 20% levels and dried at different temperatures. At all the dewatering levels the curves portray similar trends. Since the relationship between the moisture content and drying time is not linear, the data needed to be transformed by curve fitting methods in order to derive a suitable expression for the drying process. For this purpose the following procedure was followed;

1. The moisture ratios of coffee pulp at 0%, 5%, 10%, and 20% dewatering levels with respect to the drying time was determined using equation 5.5 in which $M_e=0$ since all the samples were dried to zero moisture

$$MR=\frac{Mt-Me}{Mo-Me} \qquad [5.5]$$

2. Values of the moisture ratio were then plotted against time [fig.5.11a to 5.11c].
3. The data contributing to curves in 2. above was plotted onto semilog and log charts using Harvard graphics computer programme in order to determine the type of curves.
4. A linear relationship was identified between ln(t) and ln(-ln(MR)) [fig.5.12a to 5.12c] indicating that the curves are exponential.
5. Appropriate functions were fitted to the data plotted in 4. above by means of linear regression and the method of least squares.

The regression lines obtained can be described by a general equation as;

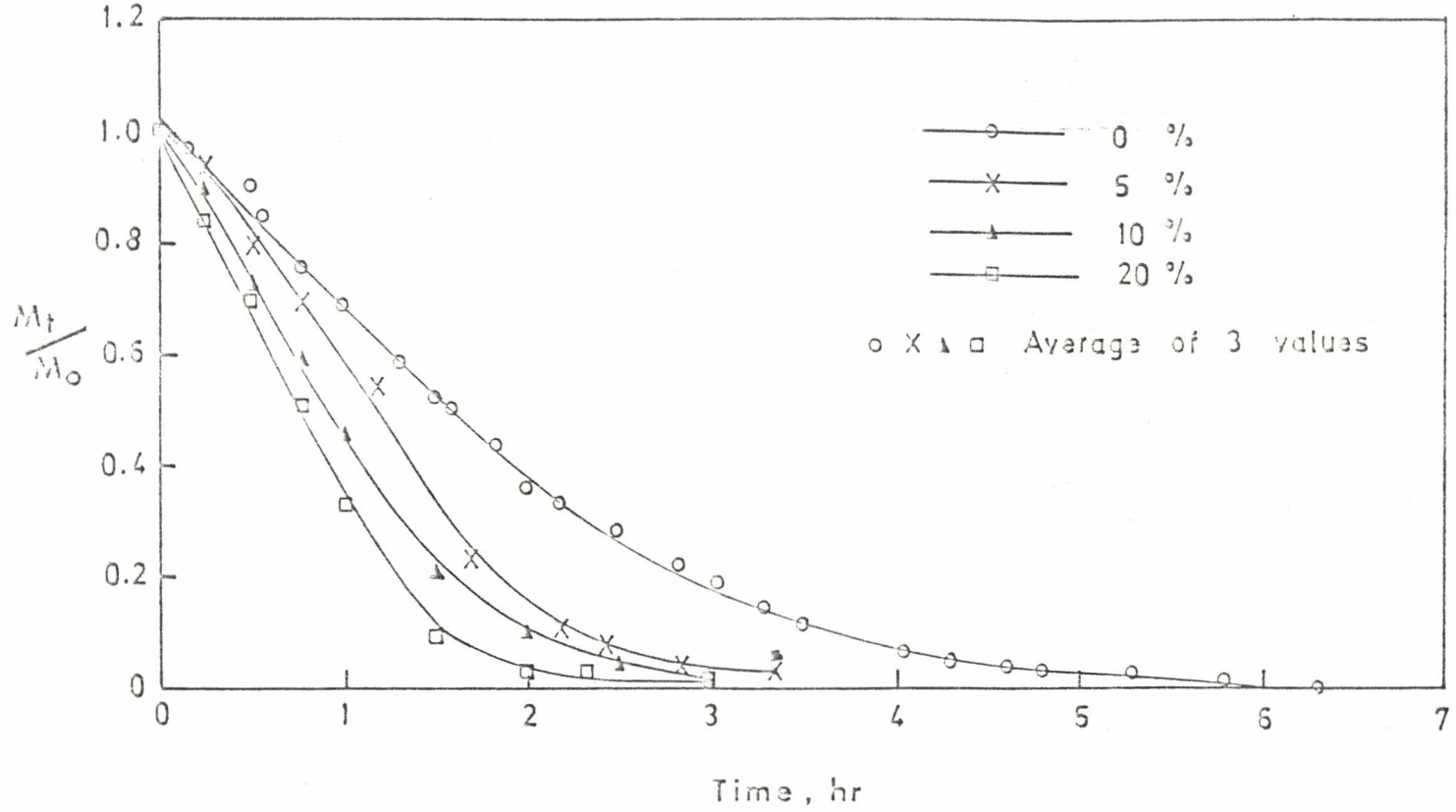


Figure 5.11a. Variation of moisture ratio with time at 105°C and different dewatering levels.

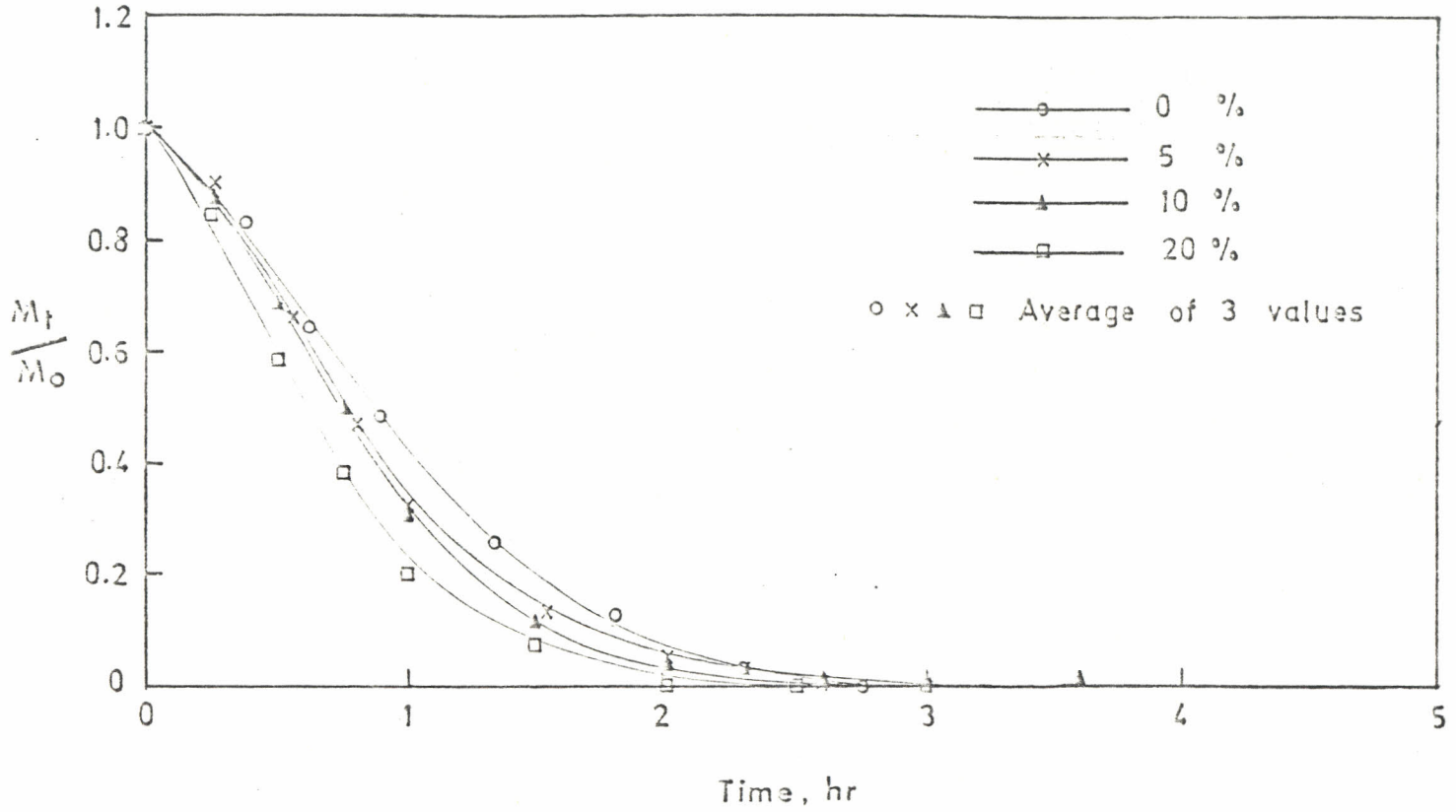


Figure 5.11b. Variation of moisture ratio with time at 130°C and different dewatering levels.

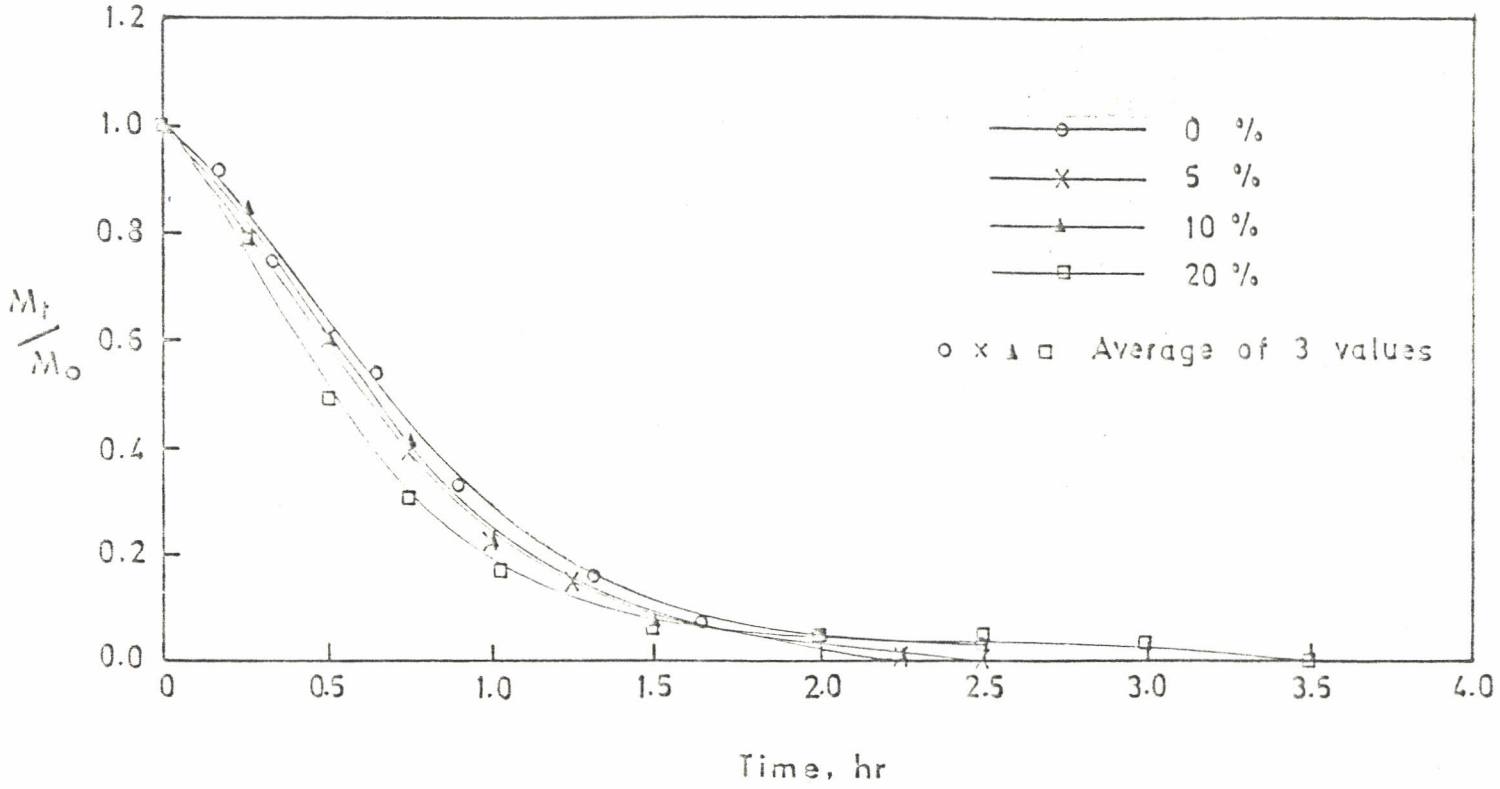


Figure 5.11c. Variation of moisture ratio with time at 150°C and different dewatering levels.

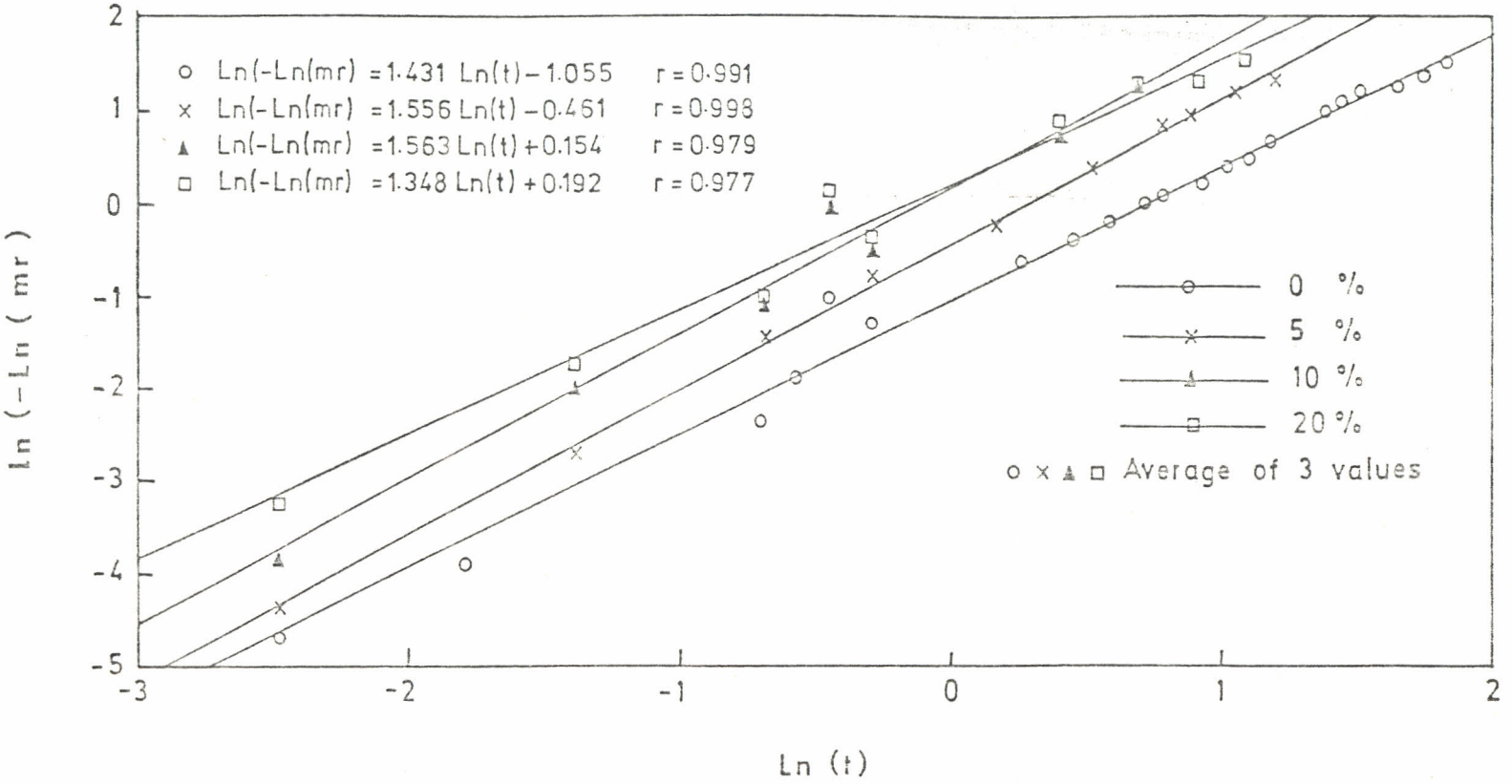


Figure 5.12 a. Relationship between natural logarithm of moisture ratio and drying time at 105°C and different dewatering levels.

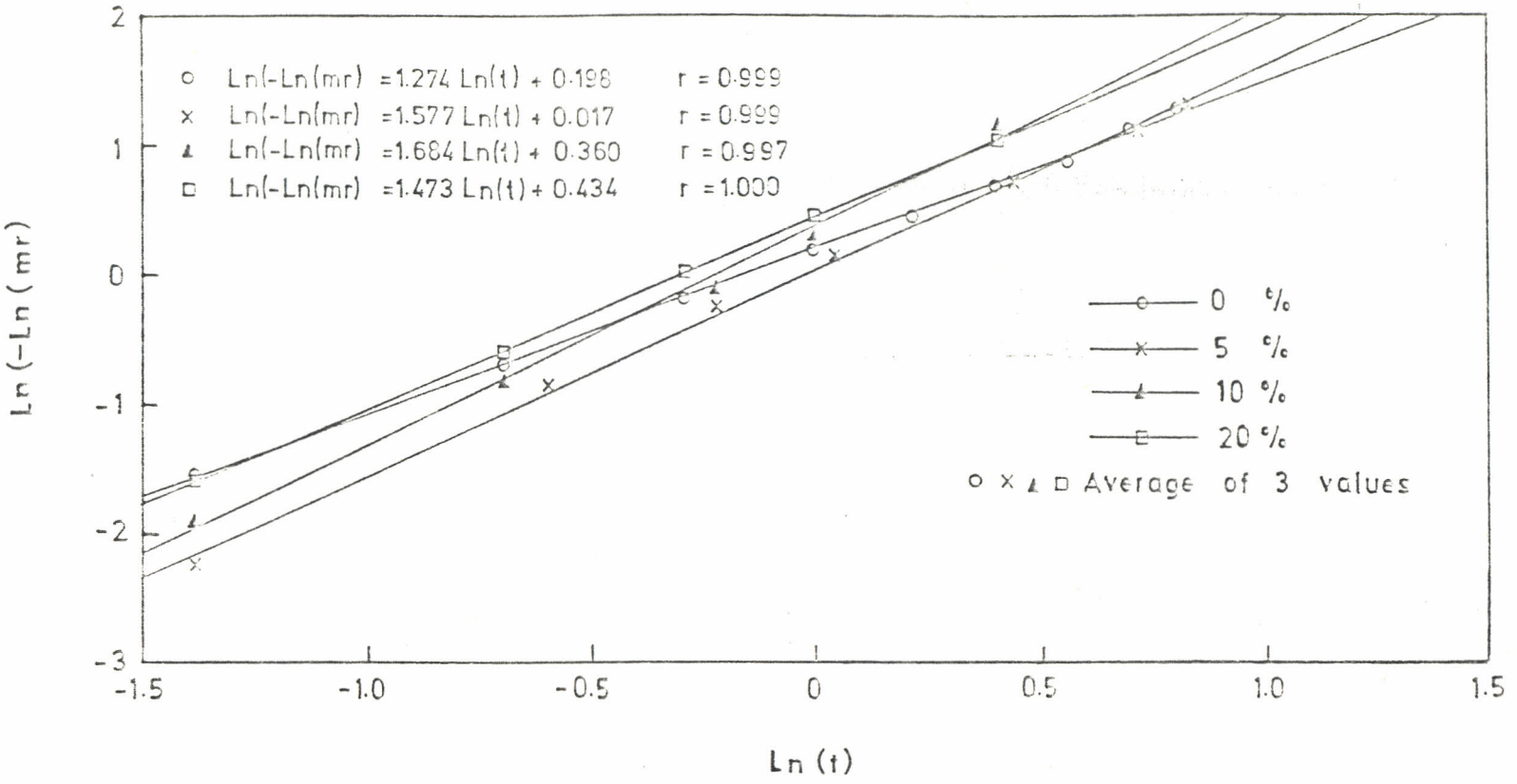


Figure 5.12 b. Relationship between natural logarithm of moisture ratio and drying time at 130°C and different dewatering levels.

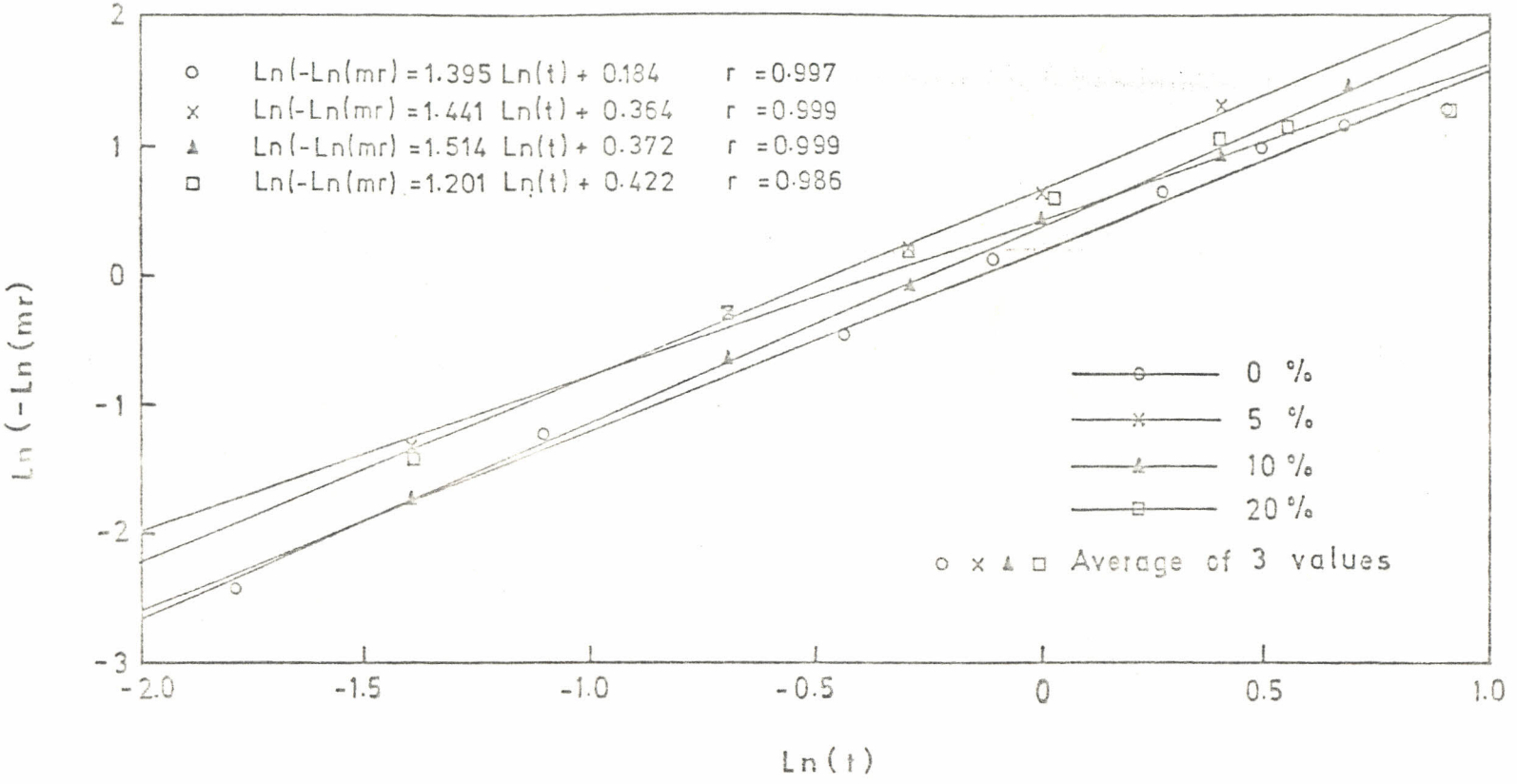


Figure 5.12c. Relationship between natural logarithm of moisture ratio and drying time at 150°C and different dewatering levels.

$$\ln(t)=m\ln(-\ln MR)+c \qquad [5.6]$$

The respective regression constants m and c for each set of dewatering level and drying temperature are shown in table 5.5. From equation [5.6], an expression for the coffee pulp drying curve can easily be obtained as follows.

$$t=e^{c}(-\ln(MR))^{m} \qquad [5.7]$$

let $e^{c}=k$ where k=constant equation 5.7 becomes;

$$t=k(-\ln(MR))^{m}$$

$$\ln(MR)=-\left(\frac{t}{k}\right)^{\frac{1}{m}} \qquad [5.8]$$

$$MR=\mathrm{Exp}\left(-\left(\frac{t}{k}\right)^{\frac{1}{m}}\right) \qquad [5.9]$$

In accordance to the definition of MR [Eq.5.5] equation 5.9 becomes;

$$\frac{M_t - M_e}{M_o - M_e} = Exp\left(-\left(\frac{t}{k}\right)^{\frac{1}{m}}\right) \qquad [5.10]$$

$$M_t = (M_o - M_e)\, Exp\left(-\left(\frac{t}{k}\right)^{\frac{1}{m}}\right) + M_e \qquad [5.11]$$

Experimental values of m and c [table 5.5] for coffee pulp drying indicate that;

1. When coffee pulp samples with different initial moisture contents were dried at a constant temperature m and k generally increased with a reduction in the initial moisture content.

   The implications of such variations are that, the value of $-(t/k)^{1/m}$ decreases with reduced initial moisture content thereby decreasing the value of $Exp-(t/k)^{1/m}$. Therefore, from equation 5.11, the current moisture content M_t at any time t during the drying process is always lower for samples which had started with a lower initial moisture content.

2. For coffee pulp samples with the same initial moisture content (i.e. equal levels of expressed fluid), values of m and k increases when the drying temperature is raised from 105°C to 130°C. The resulting effect is that the valuable $(t/k)^{1/m}$ gets smaller. The $Exp-(t/k)^{1/m}$

becomes smaller thereby indicating that the current moisture content of coffee pulp during the drying process is at any time lower at 130°C than at 105°C for the same drying period. This means that coffee pulp will dry faster at 130°C than at 105°C. However, when the drying process at 130°C is compared to that at 150°C it is observed that the higher temperature does not necessarily result in faster drying. This phenomenon as explained in inferences made to table 5.4 (Sub section 5.1.2) can be linked to the existence of a hypothetical critical drying temperature between 105°C and 130°C and a possible surface hardening of coffee pulp at high temperatures above the critical temperature hence slowing down the drying process.

Table 5.5 Values of m, c, k and for coffee pulp samples dried at various temperatures and different levels of expressed fluid.

Temperature (°C)	Expressed fluid (%)	m	c	k	r
105	0	1.431	-1.055	0.348	0.991
	5	1.556	-0.461	0.631	0.998
	10	1.563	0.154	1.167	0.979
	20	1.348	0.192	1.212	0.977
130	0	1.274	0.198	1.219	0.999
	5	1.577	0.017	1.017	0.999
	10	1.684	0.360	1.433	0.997
	20	1.473	0.434	1.543	1.000
150	0	1.395	0.184	1.202	0.997
	5	1.441	0.364	1.439	0.999
	10	1.514	0.372	1.451	0.999
	20	1.201	0.422	1.525	0.986

The time required to dry coffee pulp to a moisture content of 15% (wb) is provided in table 5.7. The drying time for the

respective temperature is the actual duration that coffee pulp would be expected to take for it to be considered stable enough for storage. Dewatering is observed to shorten the drying time appreciably particularly at 105°C. At 130°C and 150°C the differences in drying times for coffee pulp dewatered by different levels of expressed fluid become quite marginal implying that no extra benefits are derived by using drying temperatures above the critical one that seems to lie between 105°C and 130°C.

Table 5.6 Drying time (hr) of coffee pulp to 15% moisture content at various temperatures and dewatering levels

Temperature (°C)	Expressed fluid (%)			
	0	5	10	20
105	3.29	1.88	1.71	1.29
130	1.39	1.51	1.18	1.05
150	1.30	1.15	1.10	0.93

5.2 Discussions and Conclusion

5.2.1 Dewatering

1. The behaviour of coffee pulp subjected to a set of controlled dewatering conditions keeps on changing within a coffee picking season as reflected in the relationship between expressed fluid and either applied pressure or pressing duration
2. The extent to which the moisture content of coffee pulp can be reduced (in terms of expressed fluid) by a mechanical dewatering process depends on applied

pressure, pressing duration and time of picking the coffee cherry in a season.

3. A specific dewatering behaviour of coffee pulp in terms of expressed fluid and a continuously increasing pressure is not possible to predict because dp/dt follows no specific description. Otherwise the process can generally be described by;

$$E_f = a\log(P) + b$$

4. When subjected to a constant pressure, the relationship between E_f and t can be expressed as;

$$E_f = \left(\frac{t}{C_2}\right)^{\frac{1}{C_1}}$$

5. The pressures recorded in the triaxial compression tests and which can be considered for design purposes ranged from 4.43×10^{-3}Pa to 16.05×10^{-3}Pa.
6. The critical cell pressure on coffee pulp in a dewatering process under a continuously increasing axial pressure is 1.2×10^{-3}Pa. This is capable of expressing out about 45% of the juice in coffee pulp which is equivalent to lowering the moisture content by 34%. Higher pressures did not necessarily influence more E_f.

5.2.2 Drying

1. The critical amounts of expressed fluid by mechanical dewatering beyond which further dewatering pressures fails to have any more effect on the subsequent drying

process is 20% of the fresh pulp weight. To express this fluid, the pressure required ranges from 1.2×10^{-3}Pa to 4.3×10^{-3}Pa.

2. A general equation of the following general form effectively describes the drying process at all levels of drying after dewatering.

$$M_t = (M_o - M_e)\,\mathrm{Exp}\left(-\left(\frac{t}{k}\right)^{\frac{1}{m}}\right) + M_e$$

3. Dewatering shortens the drying period but the extent to which this happens diminishes at high temperature.
4. Although at these high temperatures, a dewatering process does not appear to shorten the total drying time appreciably, its advantage is seen at the initial stages when drying is enhanced by dewatering.
5. A critical drying temperature exists between 105°C and 130°C beyond which the effect of temperature in shortening the drying period diminishes.
6. At temperatures above 100°C it is difficult to quantify the advantages that a dewatering process affords to the subsequent drying process. Such an effect may probably be observed with clearer distinction at lower drying temperatures.
7. The results of this research observed that coffee pulp dries mainly at a falling rate.

5.3 Suggestions For Further Work

From this study, it is apparently necessary to pursue the following studies

1. Construction of dewatering and drying models to verify the results of this study.
2. To conduct detailed studies on the physical and biological properties of coffee pulp aimed at identifying and quantifying those which are important to this work in terms of their influence in the prediction of specific expressions for the dewatering and drying process. The study of variation of such properties with respect to time of picking within a season, variety, altitude of origin, degree of ripeness, cultural practices and pulper effect.
3. To study the physical changes which occur to coffee pulp after being subjected to a dewatering process besides the obvious water loss. An improved drying process observed in dewatered pulp may be attributed to such changes.
4. To study other methods of dewatering coffee pulp besides pressure application e.g. free drainage and centrifugal techniques.
5. To develop a time dependent model capable of predicting the equilibrium moisture content of coffee pulp subject to various mechanical dewatering conditions.
6. To study the dewatering and drying characteristics of coffee pulp at temperatures below 100°C.
7. To establish the equilibrium moisture content of coffee

pulp at all relevant conditions of temperature and relative humidity.

8. To determine the critical moisture content of coffee pulp beyond which an increase in drying temperature fails to reduce the drying time proportionately.

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APPENDIX

Appendix 1.0: Data of triaxial compression tests on coffee pulp (Tables A1.11 to A1.64)

Table A1.11 cell pressure 0.6×10^{-3}Pa
Sampling date 2.4.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	2.00	0.00	0.00
0	10.1	19.34	0.00	0.00
6	12.6	22.61	0.00	0.00
8	12.7	25.51	0.95	0.08
10	14.3	28.17	2.31	0.20
13	15.1	32.21	4.20	0.37
14	15.5	33.57	4.83	0.43
16	17.3	36.25	5.67	0.50
18	18.4	38.92	6.83	0.60
20	19.3	41.62	8.30	0.73
22	20.6	44.31	10.50	0.93
24	21.3	47.10	12.93	1.14

Table A1.12 Cell pressure 0.6×10^{-3}Pa
Sampling date 2.4.90

Pressing time (min)	Expressed Fluid (ml)	Sample Height (mm)	Axial Load (N)	Axial Pressure (10^{-3}Pa)
0	0.0	2.00	0.00	0.0
0	16.3	2.00	0.00	0.0
0	16.8	21.74	0.00	0.0
1	17.8	24.00	0.00	0.0
4	19.3	26.58	0.00	0.0
6	20.4	24.23	2.00	0.1
8	21.8	32.40	4.10	0.3
10	22.8	35.63	5.46	0.4
12	23.8	37.28	7.25	0.6
14	25.0	40.90	9.66	0.8
16	26.1	42.52	13.65	1.2
18	27.1	44.01	24.05	2.1
20	28.3	47.60	30.45	2.6

Table A1.21 Cell pressure 0.7×10^{-3}Pa
Sampling date 14.3.90

Pressing time (min)	Expressed Fluid (ml)	Sample Height (mm)	Axial Load (N)	Axial Pressure (10^{-3}Pa)
0	4.4	7.76	0.00	0.0
5	8.3	11.10	0.00	0.0
10	10.1	14.49	0.11	0.1
15	10.6	17.81	0.05	0.1
20	12.2	21.26	0.00	0.0
30	13.4	27.75	6.20	0.5
36	14.1	31.67	9.35	0.2
40	14.9	34.28	12.60	1.1
45	16.1	37.63	16.49	1.5
50	17.0	40.87	21.11	1.6
55	17.9	42.10	26.78	2.6
60	19.0	47.30	34.65	3.6

Table A1.22 Cell pressure 0.7×10^{-3}Pa
Sampling date 14.3.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	0.00	0.00	0.00
0	4.5	11.05	0.00	0.00
5	6.7	15.05	0.00	0.00
10	7.1	17.85	0.00	0.00
15	7.9	21.11	2.00	0.18
20	11.0	24.42	5.88	0.52
25	11.7	27.72	7.35	0.65
30	12.8	31.38	9.56	0.84
36	13.8	35.01	12.39	1.09
40	14.0	37.75	15.86	1.40
45	14.9	38.77	17.01	1.50
50	15.9	42.00	23.84	2.10
55	17.3	45.90	34.65	3.06
56	17.7	47.00	37.43	3.30

Table A1.23 Cell pressure 0.70×10^{-3}Pa
Sampling date 14.3.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	5.0	7.43	0.00	0.00
6	8.5	11.76	0.00	0.00
10	9.1	13.76	0.00	0.00
20	10.3	20.38	1.26	0.11
35	14.0	30.20	9.87	0.87
40	14.5	34.10	12.29	1.08
45	15.1	36.75	17.12	1.51
50	16.7	36.00	23.10	2.04
55	18.0	43.23	29.72	2.62
60	18.8	46.45	40.43	3.57
61	18.9	47.00	42.30	3.73

Table A1.31 Cell pressure 1.2×0^{-3}Pa
Sampling date 5.3.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	0.00	0.00	0.00
5	5.3	3.02	1.42	0.13
10	5.4	6.41	1.39	0.12
15	5.4	9.81	1.34	0.12
20	6.4	16.19	2.42	0.21
25	8.0	16.58	2.36	0.21
30	8.8	18.00	2.26	0.20
35	9.5	23.40	2.26	0.20
40	10.2	27.80	2.15	0.20
45	10.7	30.20	2.42	0.21
50	11.1	33.58	5.04	0.44
55	11.6	36.88	6.41	0.57
60	14.7	39.28	6.62	0.58
65	15.4	43.70	6.93	0.61
70	15.6	47.07	7.67	0.68

Table A1.32 Cell pressure 1.2×10^{-3}Pa
Sampling date 14.3.90

Pressing Time (min)	Expressed Fluid (ml)	Sample height (mm)	Axial Load (N)	Axial pressure (10^{-3}Pa)
0	0.0	18.37	0.00	0.00
6	4.0	22.00	2.05	0.19
10	5.5	24.69	4.62	0.41
15	6.8	27.85	7.35	0.65
20	7.3	31.11	10.19	0.90
25	8.6	33.40	13.34	1.18
30	9.9	38.25	18.17	1.60
35	11.1	40.87	22.05	1.94
41	12.4	44.73	30.98	2.73
45	13.2	47.00	36.29	3.20

Table A1.33 Cell pressure 1.2×10^{-3}Pa
Sampling date 2.4.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	5.11	0.00	0.00
0	0.0	9.33	0.00	0.00
0	15.9	16.60	0.00	0.00
2	18.4	19.20	0.00	0.00
4	19.6	21.79	1.89	0.17
6	21.1	24.42	4.52	0.40
8	22.9	27.08	7.04	0.62
10	24.9	29.67	10.92	0.96
12	25.6	32.52	16.17	1.43
14	27.4	35.38	24.26	2.14
16	28.9	37.88	35.70	3.15
18	29.6	40.32	54.60	4.81
21	32.7	43.52	95.45	8.42
22	36.3	44.45	124.90	11.02
25	40.4	47.01	168.42	14.85

Table A1.34 Cell pressure 1.2×10^{-3}Pa
Sampling date 2.4.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	2.00	0.00	0.00
4	0.4	21.68	1.68	0.15
6	1.1	23.41	1.05	0.09
8	2.5	26.07	4.10	0.36
10	4.1	28.70	5.88	0.52
12	5.0	31.40	7.04	0.62
14	6.0	34.11	7.88	0.69
16	6.8	37.81	8.92	0.79
18	7.8	39.47	10.29	0.91
20	8.7	42.15	12.18	1.07
22	9.8	44.92	14.49	1.28
24	11.0	47.53	17.96	1.58

Table A1.35 Cell pressure=1.2×10^{-3}Pa
Sampling date 2.4.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	2.00	0.00	0.00
1	16.8	20.08	0.00	0.00
2	19.9	20.08	0.00	0.00
3	21.6	22.23	0.00	0.00
4	22.6	22.23	0.00	0.00
5	23.4	29.69	0.00	0.00
7	24.6	35.48	5.04	0.44
9	25.5	38.10	8.51	0.75
11	26.5	40.95	10.71	0.94
13	27.6	43.40	13.44	1.19
16	29.0	47.30	18.59	1.64

Table A1.36 Cell pressure 1.2×10^{-3}Pa
Sampling Date 22.2.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	0.00	0.00	0.00
0	13.0	26.92	0.00	0.00
0	14.5	26.92	0.00	0.00
5	17.0	30.16	0.00	0.00
10	18.5	33.52	1.26	0.11
15	20.4	36.87	2.21	0.20
21	22.0	41.90	3.89	0.34
25	23.4	42.58	5.35	0.47
30	25.2	46.60	19.95	1.76
33	25.8	47.53	70.35	6.20

Table A1.41 Cell pressure 2.2×10^{-3}Pa
Sampling Date 2.4.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	2.00	0.00	0.00
0	0.1	13.46	0.00	0.00
0	19.7	23.28	0.00	0.00
3	21.0	33.87	1.26	0.11
5	21.8	34.88	5.57	0.49
8	22.5	37.50	9.14	0.81
9	22.6	38.79	9.87	0.87
11	23.1	41.50	12.18	1.07
13	24.0	44.13	14.28	1.26
15	25.0	46.75	17.33	1.52

Table A1.42 Cell pressure 2.2×10^{-3}Pa
Sampling Date 5.3.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10-3Pa)
0	0.0	0.00	0.00	0.00
5	3.1	3.30	2.59	0.23
11	3.2	7.35	4.67	0.41
15	3.8	10.10	4.67	0.41
20	5.0	13.46	4.78	0.42
25	7.6	16.90	4.67	0.41
30	8.8	20.25	4.73	0.42
35	9.6	23.57	7.56	0.67
40	11.0	27.59	9.03	0.80
45	11.7	30.24	10.01	0.89
50	12.5	33.60	11.03	0.97
55	13.0	36.95	12.08	1.07
60	14.2	40.26	13.55	1.19
65	17.1	43.63	15.75	1.39
70	18.3	46.94	18.17	1.60

Table A1.43 Cell pressure 2.2×10^{-3}Pa
Sampling Date 14.3.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	0.00	0.00	0.00
0	2.1	0.00	0.00	0.00
0	6.8	17.90	0.00	0.00
5	9.5	21.00	0.95	0.08
10	11.6	24.39	1.47	0.13
15	13.0	27.72	30.45	2.69
20	14.9	31.88	10.08	0.89
25	15.8	34.08	17.01	1.50
30	16.8	37.25	23.10	2.04
35	18.3	41.08	30.66	2.70
40	19.2	43.66	37.59	3.31
47	20.4	47.07	46.50	4.10

Table A1.44 Cell pressure 2.2×10^{-3}Pa
Sampling date 2.4.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	2.37	0.00	0.00
0	0.0	9.76	0.00	0.00
0	22.5	25.46	0.00	0.00
2	25.0	27.92	0.00	0.00
4	25.9	30.43	0.53	0.05
6	26.5	34.98	5.67	0.50
8	27.5	36.50	10.29	0.91
10	28.2	38.16	12.92	1.14
12	29.0	40.78	17.75	1.57
14	29.5	42.70	56.49	4.98
16	30.0	44.30	108.15	9.54
18	30.7	47.08	107.40	9.47

Table A1.45 Cell pressure 2.2×10^{-3}Pa
Sampling date 2.4.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	2.00	0.00	0.00
1	14.0	28.25	0.00	0.00
2	17.0	30.25	0.00	0.00
3	18.5	30.25	0.00	0.00
4	19.5	32.06	0.00	0.00
5	20.7	34.74	0.00	0.00
7	22.3	35.61	1.79	0.16
9	23.0	39.20	6.93	0.61
12	23.8	42.10	10.82	0.95
13	24.2	43.38	13.34	1.18
15	24.9	46.00	15.96	1.41
16	25.3	47.07	17.81	1.57

Table A1.51 Cell pressure 3.1×10^{-3}Pa
Sampling date 5.3.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	0.00	0.00	0.00
5	3.8	3.00	2.10	0.19
10	5.3	6.34	2.10	0.19
15	7.1	9.73	2.10	0.19
20	8.7	13.13	2.02	0.18
25	9.7	16.51	2.00	0.18
30	10.5	19.07	17.85	0.16
35	11.1	23.22	3.78	0.33
41	11.9	27.19	6.72	0.59
45	12.7	29.85	7.98	0.70
50	13.5	33.33	9.03	0.80
55	14.6	36.54	10.61	0.94

Table A1.52 Cell pressure 3.1×10^{-3}Pa
Sampling Date 5.3.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	5.20	0.00	0.00
5	8.4	8.13	3.20	0.28
10	11.3	11.50	4.62	0.41
15	13.2	16.75	6.31	0.56
20	14.5	18.11	7.14	0.63
25	15.4	21.54	7.46	0.66
30	16.2	22.48	8.19	0.72
35	17.0	28.19	11.24	0.99
40	17.6	31.58	13.13	1.16
45	18.5	34.90	15.99	1.41
50	20.5	38.13	19.07	1.68
55	21.7	46.45	23.63	2.08

Table A1.53 Cell pressure 3.1×10^{-3}Pa
Sampling Date 2.4.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	2.00	0.00	0.00
0	20.7	14.28	0.00	0.00
0	21.1	20.23	0.00	0.00
0	22.7	20.20	0.00	0.00
0	22.8	22.60	0.00	0.00
2	23.1	24.50	0.00	0.00
4	23.5	27.15	0.00	0.00
6	23.8	29.88	0.00	0.00
8	24.2	32.62	0.21	0.02
10	24.2	33.82	6.09	0.53
12	24.7	36.41	11.45	1.01
14	25.1	39.05	17.22	1.52
16	26.6	41.78	17.22	1.52
18	26.3	44.45	20.16	1.78
20	27.1	47.08	24.99	2.20

Table A1.54 Cell pressure 3.1×10^{-3}Pa
Sampling Date 2.4.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	2.00	0.00	0.00
0	0.0	14.19	0.00	0.00
3	17.6	27.71	0.00	0.00
5	19.1	30.84	0.00	0.00
7	25.6	33.65	0.00	0.00
9	27.3	35.40	0.00	0.00
11	27.9	38.15	0.00	0.00
13	28.4	40.70	0.00	0.00
15	28.8	43.16	0.21	0.02
17	29.5	45.75	2.94	0.26
18	30.1	47.08	4.76	0.42

Table A1.55 Cell pressure 3.1×10^{-3}Pa
Sampling Date 2.4.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial Load (N)	Axial pressure (10^{-3}Pa)
0	0.0	2.00	0.00	0.00
1	6.2	17.45	0.00	0.00
2	8.0	19.42	0.00	0.00
3	9.0	19.42	0.00	0.00
4	17.0	19.42	0.00	0.00
5	20.7	34.61	0.00	0.00
8	22.7	37.40	8.30	0.73
9	23.4	38.70	10.08	0.89
11	23.9	41.30	12.60	1.11
13	24.9	43.94	15.23	1.34
15	26.9	46.75	18.90	1.67

Table A1.56 Cell pressure 3.2×10^{-3}Pa
Sampling date 14.3.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	0.00	0.00	0.00
0	3.4	18.56	0.00	0.00
0	11.3	18.56	0.00	0.00
5	16.8	21.57	2.73	0.24
10	19.4	24.88	5.15	0.45
15	20.3	28.18	7.35	0.65
20	21.1	31.30	16.80	1.48
25	22.6	34.55	26.25	2.32
30	23.6	37.56	34.86	3.07
36	24.0	41.42	47.25	4.17
40	26.1	44.95	57.12	5.04
42	27.3	47.07	62.94	5.55

Table A1.61 Cell pressure 4.3×10^{-3}Pa
Sampling Date 2.4.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	2.00	0.00	0.00
3	6.9	16.58	0.00	0.00
7	28.30	16.58	0.00	0.00
9	24.40	18.00	0.00	0.00
12	25.20	23.10	0.00	0.00
13	25.40	24.50	0.00	0.00
15	25.70	37.02	0.53	0.05
17	26.00	39.74	0.95	0.08
19	26.20	42.40	4.94	0.44
22	27.00	46.35	9.87	0.87
23	27.30	47.65	11.66	1.03

Table A1.62 Cell pressure 4.3×10^{-3}Pa
Sampling date 2.4.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	2.00	0.00	0.00
0	0.0	15.49	0.00	0.00
0	0.0	24.83	0.00	0.00
3	20.3	39.41	0.00	0.00
6	22.7	42.39	0.42	0.04
9	23.7	46.32	4.41	0.39
10	23.9	47.08	5.22	0.46

Table A1.63 Cell pressure 4.3×10^{-3}Pa
Sampling Date 2.4.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	2.00	0.00	0.00
1	14.2	29.10	0.00	0.00
2	17.0	29.10	0.00	0.00
3	18.2	29.10	0.00	0.00
4	19.2	29.10	0.00	0.00
5	19.6	32.55	0.21	0.02
7	19.8	33.50	0.44	0.04
9	20.0	36.13	1.06	0.09
11	20.4	38.65	1.34	0.12
14	21.6	42.64	1.76	0.16
15	22.3	43.98	1.92	0.17
17	23.8	46.65	2.34	0.21

Table A1.64 Cell pressure 4.3×10^{-3}Pa
Sampling Date 2.4.90

Pressing time (min)	Expressed fluid (ml)	Sample height (mm)	Axial load (N)	Axial pressure (10^{-3}Pa)
0	0.0	2.00	0.00	0.00
0	9.8	22.91	0.00	0.00
2	17.8	22.91	0.00	0.00
3	18.5	22.91	0.00	0.00
4	19.5	22.91	0.00	0.00
5	20.1	29.00	0.00	0.00
9	21.6	31.50	0.00	0.00
11	22.2	34.70	0.84	0.07
14	23.0	37.70	5.57	0.49
18	23.3	39.30	9.03	0.80
19	23.4	39.85	9.56	0.84
22	24.0	42.50	12.60	1.11
25	24.8	44.90	15.75	1.39
28	25.8	47.44	18.90	1.67

Appendix 2.0: Results (data) of Drying coffee pulp
(Tables A2.11 to A2.73)

Experiment 1

Expressed fluid ; 10%

Table A2.11 Drying temperature 105^{0}C
Sampling date 21.2.90

Drying time	Ambient conditions			Moisture content
	Temperature (db)	(wb)	Relative humidity	
min	^{0}C	^{0}C	%	%
0	23.0	18.0	59	73.0
15	23.0	18.0	59	65.0
30	23.3	18.5	63	53.0
45	23.8	19.0	60	43.0
60	23.8	18.8	60	33.0
95	24.0	18.8	60	16.0
125	24.5	19.0	54	7.0
155	24.5	19.0	54	3.0
185	25.0	19.5	61	1.0
215	25.5	19.5	55	0.0
275	25.5	19.5	55	0.0
335	25.5	19.5	55	0.0

Table A2.12 Drying Temperature 130°C
Sampling Date 21.2.90

Drying time	Ambient conditions			Moiture content
	Temperature (Db)	(Wb)	Relative humidity	
min	°C	°C	%	%
0	22.0	19.0	74	73.4
15	22.0	19.0	74	64.4
30	22.3	19.3	74	50.4
45	22.3	19.3	74	36.4
62	22.3	19.3	74	22.4
92	22.5	19.5	75	8.4
126	23.0	19.3	67	2.4
156	22.5	19.5	75	0.4
186	23.0	19.3	67	0.4
216	23.5	19.5	68	0.0
279	23.0	19.5	71	0.0

Table A2.13 Drying temperature 150^{0}C
Sampling Date 21.2.90

Drying time	Ambient conditions			Moisture content
	Temperature (Db)	(Wb)	Relative humidity	
min	°C	°C	%	%
0	22.0	18.5	70	74.0
15	22.0	18.5	70	62.0
30	22.3	18.5	66	44.0
45	22.3	18.2	66	30.0
60	22.5	18.5	66	16.0
90	23.0	18.5	67	6.0
120	23.0	18.5	67	1.0
135	23.0	18.5	67	0.0
165	23.5	19.0	68	0.0
195	24.0	19.0	60	0.0

Experiment 2

Age of coffee pulp=14days

Samples:	1	2	3
Final wt. gm	474.24	473.13	473.32
Expressed fluid %	5.15	5.37	5.34
Drying temperature ^{0}C	105	130	150

Table A2.21 Drying temperature 105^{0}C
Sampling Date 21.2.90

Drying time	Ambient conditions			Moisture content
	Temperature (Db)	(Wb)	Relative humidity	
min	°C	°C	%	%
0	20.5	17.0	69	78.0
15	20.8	17.3	69	73.0
30	20.8	17.5	69	62.0
45	21.0	17.5	69	50.0
71	21.0	17.8	73	34.0
101	21.5	18.0	70	18.0
131	22.0	17.8	66	8.0
146	22.5	17.3	59	6.0
171	23.0	17.8	59	3.0
201	23.5	18.0	64	2.0
216	23.5	17.8	57	0.0
231	24.0	18.0	53	0.0
291	24.5	19.0	58	0.0

Table A2.22 Drying temperature 130°C
Sampling date 21.2.90

Drying time	Ambient conditions			Moisture content
	Temperature (Db)	(Wb)	Relative humidity	
min	°C	°C	%	%
0	25.0	19.0	54	78.0
15	25.0	18.5	51	70.0
33	25.0	18.8	51	51.0
48	25.0	18.5	51	36.0
63	25.5	18.8	52	25.0
93	25.5	18.8	52	10.0
123	25.5	19.0	52	4.0
138	25.5	19.0	54	0.0
153	25.0	19.0	54	0.0
168	24.8	18.8	54	0.0
183	24.5	18.8	54	0.0

Table A2.23 Drying temperature 150°C

Drying time	Ambient conditions			Moisture content
	Temperature (Db)	(Wb)	Relative humidity	
min	°C	°C	%	%
0	25.7	20.0	59	79.6
15	26.0	20.5	59	63.6
30	26.0	20.5	59	47.6
45	26.0	20.7	59	30.6
60	25.5	21.0	66	17.6
75	25.5	20.5	62	11.6
105	25.0	20.5	66	5.6
135	25.0	20.7	66	0.6
150	25.0	21.0	68	0.0
165	24.5	20.5	68	0.0
182	24.7	20.0	65	0.0

Experiment 3

Sampling Date 21.2.90
Age of coffee pulp = 35 days.
Initial wt of coffee pulp = 500gm

Samples	1	2	3
Final weight (gm)	398.04	395.25	396.92
Expressed fluid (%)	20.39	20.95	20.61
Drying temperature °C	105	130	150

Table A2.31 Drying temperature 105°C

Drying time	Ambient conditions			Moisture contents
	Temperature (Db)	(Wb)	Relative humidity	
min	°C	°C	%	%
0	22.2	19.0	74	66.6
15	22.5	19.0	71	56.6
30	22.5	19.0	71	47.6
45	23.0	19.2	67	35.6
60	23.0	19.0	67	24.6
90	23.5	19.0	64	9.6
120	24.0	19.0	60	5.6
151	25.0	19.0	54	5.6
180	25.5	19.0	52	4.6
210	25.7	18.5	49	0.0
270	25.5	18.7	49	0.0
287	26.0	18.5	46	0.0

Table A2.32 Drying temperature 130°C

Drying time	Ambient conditions			Moisture content
	Temperature (Db)	(Wb)	Relative humidity	
min	°C	°C	%	%
0	26.5	19.0	47	65.0
15	26.5	19.0	47	55.0
30	26.5	18.5	44	38.0
45	26.0	19.5	52	25.0
60	26.5	19.5	50	13.0
90	26.2	19.4	49	5.0
120	26.0	19.5	52	0.0
152	26.0	19.5	52	0.0
182	25.5	20.0	59	0.0

Table A2.33 Drying temperature 150°C

Drying time	Ambient conditions			Moisture content
	Temperature (Db) °C	(Wb) °C	Relative humidity %	
min				%
0	25.0	20.0	61	66.0
15	25.8	20.5	59	52.0
30	25.8	21.0	62	32.0
45	25.8	21.0	62	20.0
62	25.7	21.0	62	11.0
90	26.0	21.3	62	4.0
120	26.0	21.0	62	3.0
150	26.0	21.0	62	3.0
180	26.5	20.5	56	2.0
210	26.0	20.2	55	0.0
240	26.5	20.5	56	0.0
252	26.0	19.5	52	0.0

Experiment 4

Sampling Date 23.4.90
Age of coffee pulp =2 days, Hand pulped.
Initial weight of coffee pulp = 500gm

Samples	1	2	3
Final weight gm	449.33	447.96	448.37
Drying temperature °C	105	130	150
Expressed fluid %	10.13	10.4	10.32

Table A2.41 Drying temperature 105°C

Drying time	Ambient conditions			Moisture content
	Temperature (Db) °C	(Wb) °C	Relative humidity %	
min				%
0	23.0	19.7	75	74.0
15	23.2	19.7	75	65.0
30	23.5	19.7	68	54.0
45	23.5	19.3	60	42.0
60	23.5	19.3	60	31.0
90	24.0	20.0	68	11.0
120	24.0	20.3	68	4.0
150	24.5	20.5	68	2.0
180	24.5	20.5	68	2.0
220	24.5	20.0	61	0.0
235	24.5	20.0	61	0.0

Table A2.42 Drying temperature 130°C

Drying time	Ambient conditions			Moisture content
	Temperature (Db)	(Wb)	Relative humidity	
min	°C	°C	%	%
0	24.5	19.5	61	73.0
15	25.0	20.0	61	63.0
30	25.0	19.5	58	47.0
47	24.9	19.5	58	30.0
60	24.5	20.0	65	19.0
90	24.0	19.5	64	3.0
120	24.0	20.0	68	0.0
150	23.5	19.5	68	0.0
180	24.0	20.0	68	0.0

Table A2.43 Drying temperature 150°C

Drying time	Ambient conditions			Moisture contents
	Temperature (Db)	(Wb)	Relative humidity	
min	°C	°C	%	%
0	22.5	19.5	75	74.0
15	22.7	19.7	75	64.0
30	22.5	19.5	75	46.0
45	23.0	19.5	71	29.0
60	23.5	19.5	68	16.4
90	23.5	19.5	68	5.4
120	24.0	19.5	64	3.0
150	24.5	19.7	61	0.0
180	25.0	20.0	61	0.0
211	25.0	19.7	55	0.0

Experiment 5

Sampling Date 11.4.90

Age of coffee pulp =7days,
Initial weight of coffee pulp = 500gm

Samples	1	2	3
Final weight gm	449.28	447.13	446.37
Expressed fluid gm	50.72	52.87	53.63
Expressed fluid %	10.14	10.57	10.73
Drying temperature °C	105	130	150

Table A2.51 Drying temperature 105°C

Drying time	Ambient conditions			Moisture contents
	Temperature (Db)	(Wb)	Relative humidity	
min	°C	°C	%	%
0	22.5	20.0	79	75.0
15	22.5	20.0	79	68.0
30	22.5	20.0	79	68.0
45	22.7	20.3	79	40.0
60	22.7	20.0	79	31.0
91	22.5	20.0	79	14.0
120	23.5	20.5	75	6.0
152	24.0	20.5	71	2.0
180	24.0	20.3	68	0.0
210	24.5	20.5	68	0.0

Table A2.52 Drying temperature 130°C

Drying time	Ambient conditions			Moisture content
	Temperature (Db)	(Wb)	Relative humidity	
min	°C	°C	%	%
0	25.5	20.3	62	74.0
15	25.3	20.7	65	63.0
31	25.3	20.7	65	47.0
45	25.3	20.7	65	33.0
60	25.3	20.7	65	21.0
75	25.3	20.0	58	13.0
90	25.5	18.7	55	7.0
120	25.5	20.0	59	1.0
150	25.3	20.5	61	0.0
174	25.0	20.5	65	0.0
192	24.5	20.5	68	0.0

Table A2.53 Drying temperature 150°C

Drying time	Ambient conditions			Moisture content
	Temperature (Db)	(Wb)	Relative humidity	
min	°C	°C	%	%
0	22.5	20.0	79	74.4
15	22.5	19.7	75	62.4
30	22.5	19.7	75	46.4
45	22.5	19.7	75	30.4
60	22.5	19.5	75	16.4
90	23.0	20.0	75	4.4
130	23.7	20.0	68	0.4
150	23.7	19.7	68	0.0
165	24.0	20.0	68	0.0

Experiment 6

Sampling Date 2.4.90

Age of coffee pulp =17 days.
Initial weight of coffee pulp =500 gm.

Samples	1	2	3
Final weight gm	474.53	474.31	472.93
Expressed fluid gm	25.47	25.69	27.07
Expressed fluid %	5.1	5.1	5.4
Drying temperature °C	105	130	150

Table A2.61 Drying temperature 105°C

Drying time	Ambient conditions			Moisture content
	Temperature (Db)	(Wb)	Relative humidity	
min	°C	°C	%	%
0	25.5	20.0	59	81.0
15	25.5	20.2	62	75.0
31	25.5	19.7	55	62.0
45	25.7	19.7	55	43.0
77	26.0	20.0	55	25.0
92	25.7	20.0	55	16.0
112	25.7	20.0	55	9.0
142	25.5	19.7	55	6.0
172	25.3	19.3	54	1.0
202	24.5	18.5	54	1.0
234	25.7	18.7	49	0.0

Table A2.62 Drying temperature 130°C
(Age of coffee pulp = 8 days)

Drying time	Ambient conditions			Moisture content
	Temperature (Db)	(Wb)	Relative humidity	
min	°C	°C	%	%
0	23.0	19.5	63	80.0
15	23.0	19.5	63	72.0
30	23.0	19.5	63	58.0
55	23.0	19.7	71	38.0
65	23.5	20.0	71	27.0
83	23.5	19.7	68	16.0
113	23.7	19.7	68	7.0
143	24.3	19.7	64	2.0
175	24.7	19.7	61	2.0
205	25.2	20.0	61	2.0
265	25.3	20.0	61	0.0

Table A2.63 Drying temperature 150°C

Drying time	Ambient conditions			Moisture content
	Temperature (db)	(wb)	Relative humidity	
min	°C	°C	%	%
0	25.5	19.0	59	80.0
15	25.7	19.3	52	62.0
32	26.5	20.5	56	40.0
45	25.5	20.5	56	25.0
60	26.7	20.0	50	14.0
90	26.5	20.5	56	4.0
100	26.5	20.7	56	2.0
120	26.5	21.0	60	0.0
190	26.5	21.0	60	0.0
200	26.5	20.3	56	0.0

Experiment 7

Dewatering level 0%
Drying temperature (°C) (i) 105 (ii) 130 (iii) 150 (iv) 150.
Sampling Date 21.2.90

Table A2.71 Drying temperature 105°C

Drying time	Ambient conditions			Moisture content
	Temperature (wb)	(db)	Relative humidity	
min	°C	°C	%	%
0	23.0	19.3	67	85.1
10	24.0	19.5	64	82.6
28	25.0	21.0	68	77.1
34	25.0	21.0	68	72.6
48	25.0	21.0	68	64.7
63	25.0	21.0	68	59.2
78	24.0	20.0	64	50.3
90	24.0	19.0	60	45.3
95	25.0	20.0	61	43.3
108	24.5	19.0	58	37.7
123	24.5	19.0	58	31.3
133	26.0	20.0	52	28.9
153	25.5	19.5	55	24.9
168	25.5	19.5	55	19.9
183	25.5	19.5	55	16.9
198	26.0	20.0	52	12.9
213	25.5	19.5	55	10.5
243	26.0	20.0	55	6.5
258	25.5	19.5	55	5.0
276	25.0	19.5	58	4.0
288	25.0	19.5	58	3.5
318	24.0	21.0	75	3.0
348	23.0	20.0	75	2.0
378	24.5	19.0	58	1.0
408	24.0	21.5	79	0.5

Table A2.72 Drying temperature 130°C
Sampling Date 21.2.90

Drying time	Ambient conditions			Moisture content
	Temperature (wb)	(db)	Relative humidity	
min	°C	°C	%	%
0	24.0	20.5	71	84.0
15	23.0	19.0	67	67.9
30	23.0	19.0	67	50.4
45	23.0	19.5	71	36.6
60	24.0	20.0	68	25.2
75	25.0	21.0	68	17.6
90	25.0	21.0	68	11.5
105	24.5	20.0	68	7.6
120	24.0	19.5	64	3.8
135	24.0	19.5	64	2.3
165	25.0	20.5	65	0
195	25.0	20.0	61	0
225	25.0	20.0	61	0

Table A2.72 Drying temperature 150°C
Sampling Date 21.2.90

Drying time	Ambient conditions			Moisture content
	Temperature (db)	(wb)	Relative humidity	
min	°C	°C	%	%
0	23.0	19.5	63	84.5
10	23.0	19.5	63	77.4
20	23.0	19.0	67	63.1
39	23.0	18.0	59	45.2
54	24.0	19.0	60	27.4
79	24.0	19.0	60	13.1
99	24.0	18.0	57	6.0
119	24.0	19.0	60	3.6
149	25.0	19.5	58	2.4
179	25.0	19.5	58	0.0
209	25.0	19.5	58	0.0
269	25.0	18.5	51	0.0

Table A2.73 Drying temperature 150°C
Sampling Date 21.2.90

Drying time	Ambient conditions			Moisture content
	Temperature (db)	(wb)	Relative humidity	
min	°C	°C	%	%
0	26.0	19.5	52	86.9
15	26.0	20.0	55	77.4
30	26.0	20.0	55	53.6
45	26.0	20.0	55	35.7
60	26.0	20.0	55	20.0
75	26.0	20.0	55	13.1
105	26.0	20.0	55	2.4
135	26.0	20.0	55	0.0
165	25.0	19.5	58	0.0
180	25.0	19.5	58	0.0